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A STUDY OF
HEATING AND INSULATION METHODS
FOR LMFBR SODIUM PIPING

TECHNICAL REPORT 223

PREPARED FOR

U S ATOMIC ENERGY COMMISSION

CONTRACT NO AT(04-3)-781

BRAUN PROJECT 4122-W

UNITED NUCLEAR PROJECT 2351

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MARCH 1968

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March 7, 1969

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Dear Mr Fry

HEATING AND INSULATING REQUIREMENTS
TECHNICAL REPORT 223
LMFBR PIPING DESIGN GUIDE
AEC SAN FRANCISCO
PROJECT 4122-W

Transmitted herewith are two copies of the draft report covering studies of Heating and Insulating Methods as related to sodium piping for LMFBR piping systems.

The purpose of the study was to review the various methods applicable to heating and insulating sodium piping and provide an evaluation to compare their advantages and disadvantages. The results of the study will be utilized later in the development of sections of the design guide.

A four-week period is allowed for review and return of comments to Braun. Comments should be mailed by April 4 to

C F Braun & Co
Dr R F Detman, Project Manager
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Yours very truly

Roger Detman
Project Manager

RFD IV

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Mr H B Fry

Page 2

March 7, 1969

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A STUDY OF
HEATING AND INSULATION METHODS
FOR LMFBR SODIUM PIPING
TECHNICAL REPORT 223

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Prepared for US Atomic Energy Commission

Contract No AT (04-3) -781

Braun Project 4122-W

United Nuclear Project 2351

C F BRAUN & CO

Alhambra California

February 28, 1969

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PRELIMINARY

A STUDY OF
HEATING AND INSULATING METHODS
FOR LMFBR SODIUM PIPING

TECHNICAL REPORT 223

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1 INTRODUCTION

C F Braun & Co has been awarded a contract (1) by the US Atomic Energy Commission for the development and verification of a Piping Design Guide for sodium-cooled fast breeder reactor power plants (LMFBR). The work is a Priority 1 Task under The LMFBR Program Plan (2) prepared for the USAEC Division of Reactor Development and Technology (RDT) by the LMFBR Program Office, Argonne National Laboratory. It is identified in the Program Plan as Task 3-8.2, Development of Design Technology for Piping.

This Technical Report describes heating and insulating requirements for liquid sodium piping, and summarizes results of a study of heating methods. Advantages and disadvantages of various methods are outlined and the methods evaluated.

It is anticipated that the criteria developed in this Technical Report will be subject to revision and/or expansion as the work progresses. A review procedure has been established to ensure consistency under interdependent studies currently being performed under this and other task areas of the LMFBR Program Plan.

Under the review procedure, the Liquid Metal Engineering Center, (LMEC), is the coordinating agency. Technical Reports prepared by Braun under this contract will be distributed by LMEC to appropriate Review Agencies designated by USAEC. Comments from Review Agencies will be evaluated by Braun to determine their validity. Valid comments will then be incorporated into subsequent revisions to the Technical Reports.

Figure 223-1 shows the interrelationship of tasks under Task Area 3-8, Coolant Transport and Storage Systems.

- (1) AT(04-3)-781, AEC San Francisco Operations Office (SAN)
- (2) Liquid Metal Fast Breeder Reactor Program Plan, LMFBR Program Office, Argonne National Laboratory - AEC R&D Report, Reactor Technology, WASH-1101, August 1968

FIGURE 223-1 INTERRELATIONSHIP DIAGRAM - TASK AREA 3-0, COOLANT TRANSPORT AND STORAGE SYSTEMS

2 GENERAL DISCUSSION

2.1 DESCRIPTION OF LMFBR PIPING SYSTEMS

The nature of LMFBR power systems presents many piping problems which are not collectively encountered in other systems. These are brought on by the operating characteristics of fast breeder reactors and by the properties of the liquid metal coolant. Currently, sodium is the coolant of most interest.

In LMFBR systems, the primary coolant is pumped through the reactor where it may be heated to some 1200 F, through the intermediate heat exchanger where it is cooled, and back to the reactor. Since this primary sodium becomes radioactive, any maintenance or repair to the system requiring direct access by personnel becomes time consuming and costly.

The secondary coolant serves to transfer heat from the radioactive primary coolant to the working fluid by means of a steam generator. The danger of sodium fires, as well as the necessity to shut down the plant for any repair, make it essential that everything possible be done to eliminate piping failures.

2.2 NECESSITY FOR PREHEATING

The combination of high temperatures, rapid transients, and 0.5 to 1.0-inch pipewalls results in thermal stresses of prime importance. This condition is aggravated by the thermal conductivity and coefficient of thermal expansion of austenitic stainless steel, the material presently considered to be the most suitable for LMFBR sodium piping.

Because the melting point of sodium is above room temperature, and its properties give very high heat transfer coefficients, a sudden flow of the liquid metal into an empty pipe at room temperature would result in extreme temperature gradients across the pipewall in contact with sodium, but no appreciable gradient in the "empty" portion. To alleviate this condition, some means of preheating the pipe must be employed so that its temperature is somewhere near that of the sodium when flow is initiated. The purpose of this report is to study and to evaluate methods for heating and insulating sodium lines.

3 DESCRIPTION OF HEATING METHODS

3.1 ELECTRICAL METHODS

3.1.1 INDUCTION HEATING When an alternating current is passed through a coil which is wrapped around a magnetic material, eddy currents are induced in the material and it is heated. This is called induction heating. It has been used successfully on piping systems.

In induction heating applications, the coil is wrapped around (but not touching) the pipe, so that the heat is generated directly in the pipe. Although high frequency current is employed most often in industrial applications, a frequency of 60 Hz is commonly used for piping. Its advantage is mainly simplicity, since no equipment is required for conversion of 60 Hz power to higher frequencies.

In induction heating, the heat induced in the pipe is proportional to the frequency and the magnetic flux density. For 60 Hz power, therefore, the flux density must be increased to compensate for the low frequency. This can be done by increasing the number of turns in the coil, by increasing the current in the coil, or by decreasing the distance between the coil and the pipe. Single-phase current is more suitable than three-phase because of magnetic field cancellation from phase differences in polyphase systems.

As mentioned previously, the pipe is heated by eddy currents. For magnetic materials, eddy currents are a significant part of the electrical losses, but for a nonmagnetic material, they are very small. Consequently, heating of stainless steel (the most common material for sodium piping) is inefficient, because most austenitic stainless steels are nonmagnetic. To increase efficiency, a jacket of magnetic carbon steel can be placed between the pipe and the coil. The jacket is then heated by induction and heat is transferred from it to the lower-temperature pipewall by convection and radiation.

Because of the high inductive reactance of induction systems, the power factor is low, leading to low efficiency. Capacitors are therefore sometimes used in the circuit so that the power factor can be increased.

Advantages of induction heating are uniform circumferential heating and good reliability. A disadvantage is that the coils are generally outside the thermal insulation for protection from heat, and so are subject to mechanical damage. For stainless steel piping, a magnetic jacket is required, but this may serve as secondary containment if properly designed. Further disadvantages are that instrumentation is often affected by the magnetic field, saturation of the core (pipe) can result in uneven axial heating, and parasitic heating of adjacent components may be a problem.

3.1.2 RADIANT HEATING A radiant heater is actually an electrical resistance heater designed to transmit heat primarily by radiation. It is designed to operate at high temperatures, since the amount of heat transmitted by radiation is proportional to the fourth power of the absolute temperature. The heaters are installed a short distance off the pipewall and are designed to radiate inward.

One type is composed of ceramic semicylindrical shells with longitudinal grooves on the inside. Spirally wound wire elements are laid in the grooves. Two such shells are then clamped around a pipe to form an ovenlike enclosure. High specific outputs are easily attained with these heaters, but some types are heavy because of the thick ceramic shell which increases the support problem.

3.1.3 TRANSFORMER AND DIRECT SERIES HEATING Transformer and direct series heating are similar in that they both use the pipe as the heater. In both methods, current is made to flow through the pipe, and heat is generated by the resistance of the pipe itself. But here the two methods differ.

In direct series heating, line voltage is used as the direct source of current. However, transformer heating employs a transformer between the power source and the pipe. The transformer may use either the pipe itself as a single secondary winding, or conventional secondary conductors may be connected in series with segments of the pipe.

The resistance of the pipe is proportional to the cross-sectional area of metal. Therefore, any change in line size or wall thickness, or any sodium left in the pipe, causes variation in heating. Also, any leakage through supports or branches decreases heating. But, since voltages for transformer heating are very low, electrical insulating can often be easily accomplished.

In a properly designed system, heating is even over the entire pipe length. But most piping systems are complex enough to cause difficulty in design. Also, if copper conductors are connected to stainless steel piping, diffusion of the copper into stainless steel can be a problem. Furthermore, oxidation of copper at temperatures over about 400 F reduces electrical efficiency.

3.1.4 RESISTANCE HEATING Electrical resistance heaters are self-contained units which develop heat from their own resistance when a current is passed through them. There are several different types manufactured, each suitable for certain applications.

TUBULAR HEATERS The tubular heater is comprised of a spiral-wound heating element, usually of nichrome, surrounded by an insulator such as magnesium oxide and enclosed in an outer metal sheath. The sheath material depends on the temperature range. The elements are swaged to compress the magnesium oxide. Diameters of the elements are in the range of 0.3 to 0.5 inches, with varying lengths up to around 20 feet. The elements are usually run parallel to the pipe and insulation is applied over both pipe and heater. The elements may be bent to assume the contour of the heated piping. Terminals are at opposite ends of an element, but the complete element may be bent into a U-shape, if desired.

Quantitative evidence is not available to establish characteristics of tubular heater operation above about 1000 F. The magnesium oxide dielectric strength begins to decrease rapidly above about 500 F, and Inconel sheaths oxidize at around 1400 F. The magnesium oxide is hygroscopic and must therefore be adequately sealed to preclude absorption of moisture from the atmosphere.

Installation problems may arise from bending of tubular heaters. If a bend location is known in advance, the heater may be fabricated with a cold section in that length, i.e., a length of nonwound heater element. If this procedure cannot be followed, precaution must be taken against using too small a radius in bending the element, causing the wound element to bunch and result in a "hot spot."

If the heaters are installed so that they cannot sufficiently emit the generated heat, their temperature may rise high enough to cause burnout or unacceptable sheath temperature. Such a condition can occur when insulation is permitted to contact an element. A thin metal spacer is generally adequate to prevent insulation packing against the heater.

Presently, one of the most common causes of failure in tubular heaters is damage to terminals. If terminals are not sufficiently protected, they are vulnerable to mechanical damage which is likely to result in failure. Rigidly mounted terminal boxes are the usual solution.

FLEXIBLE CABLES Mineral insulated (MI) cable is similar in construction to tubular heaters, except that a nonwound heating element is used and the units are continuously extruded into lengths of up to about 500 feet. Diameters are usually less than tubular heaters, typically 0.3 inches. The flexible cable can be formed into irregular shapes.

FLEXIBLE CABLES Continued

Other cables are also available, consisting of a nonwound element, asbestos and glass insulation, and braided metal outer jacket. Most of the limitations on tubular heaters also apply to flexible cables. However, bending is, of course, no problem.

CARTRIDGE HEATERS Cartridge heaters are again similar in construction to tubular heaters, but are much shorter (about 12 inches maximum) and are rigid. Both terminals are brought out the same end. High power densities can be attained. Cartridge heaters are generally used to apply heat to a localized area.

STRIP HEATERS Strip heaters are somewhat like flattened tubular heaters, except that the outer metal sheath consists of top and bottom strips joined together along the edges. One or more heating element may be used in a single heater. Terminals may be at opposite ends or both at the same end. Heating elements are closer to one side than the other, so that maximum heat can be transferred through that side. Common dimensions are on the order of 1 to 1 1/2 inches wide by 0.3 to 0.5 inches thick by 1 to 10 feet in length. High power densities can be attained.

FLEXIBLE TAPES AND MANTLES Flexible tapes are composed of small-gage nichrome wire insulated with a silica alumina magnesium oxide or with metal sheathed magnesium oxide and woven with fiberglass, silica, compound, or stainless steel into a mesh. The tapes are basically one inch in width. They may be sewn into fiberglass insulation to form mantles. Complete blankets can also be formed using similar construction.

3.2 FLUID METHODS

3.2.1 ANNULAR FLUID HEATING Preheating may be accomplished by circulating hot air, or some other gas, through an annular jacket around the sodium line. A blower forces the gas through a heater to provide a heat source. Heating is even and can be easily controlled by varying the degree of heating and the air flow rate.

If the piping is long or complex, manifolding and distribution become more difficult. Ducting may become quite large. Also, the jacket must be constructed so that leakage is held to an absolute minimum.

A type of annular heating sometimes called adiabatic ducting has been used in various process plants. An annular duct carrying hot air contains burners at intervals to maintain the desired air temperature.

3.2.2 HEAT TRACING Heat tracing is similar to annular fluid heating except that the hot fluid is carried through a small diameter pipe next to the sodium line, rather than in an annulus. Various substances may be used as the heating fluid, such as hot oil or air. Individual short loops may be manifolded to provide good control over heating.

Although heating is not as even as with the annular method, distribution is usually simpler. Control is accomplished in the same manner. Local control is difficult, but there is little danger of overheating the piping.

4 REVIEW OF CURRENTLY USED HEATING METHODS

Several liquid metal cooled reactors and test installations have been built and operated to date. Of the various heating systems, tubular resistance heaters have been used most frequently. Induction heating has been used at Enrico Fermi and EBR-II, annular heating on the Rapsodie mockup, flexible electric blankets at Dounreay, and a hot air tracing system on the SCTI. Several experiments have been made on transformer heating.

In most cases, preheating temperature was around 300 F, and all available information indicates that none of the facilities had operating temperatures above about 1000 F. Problems associated with preheating to 400 F and heating sodium filled lines to 800 F are as yet undefined. Reliability of some electrical systems when subjected to a 1200 F environment has not been established. Some difficulty has been experienced with control of electric resistance heaters and with hot spots using induction heating. Melting of solidified sodium in a pipeline by transformer or direct series heating has proven practically impossible.

Regardless of the fact that several different heating methods are used, little information can be found in the current literature pertaining to actual operating experience with any but tubular heaters.

5 COMPARISON OF HEATING METHODS

5.1 CONSIDERATIONS IN HEATING

In selecting a heating system for sodium lines, a number of requirements must be kept in mind. These are summarized as follows.

- 1 The system must preheat the empty piping evenly to the range of 350 to 400 F. The system must also heat full piping to a maximum of 800 F for pipes up to about 8-inch size.
- 2 Heater reliability must be retained through a reasonable lifetime during which pipewall temperatures could reach 1200 F.
- 3 Control must be adequate to prevent uneven heating and permit melting away from a free surface in the event solidification occurs.
- 4 Materials must not be damaged by contact with liquid sodium, and must be compatible with other piping components.
- 5 The system must be designed to permit surveillance of the piping and to have negligible effect on instrumentation.
- 6 The system must be designed to withstand any mechanical damage likely to occur, including pipe movement and vibration.
- 7 Ease of assembly and disassembly is desirable to minimize installation defects and facilitate maintenance or repair.
- 8 The system must withstand nuclear radiation, if such is present.
- 9 Installation of the system should not contribute materially to pipe stresses.

Of the various methods of heating described in Section 3, none satisfies all of the requisites for LMFBF systems. However, for most of the above requirements, at least some degree of compromise is acceptable.

Table 223-1, Page 5-2, lists the various heating methods with an indication of how each fulfills the specific requirements. The ratings of Good (G), Fair (F), or Poor (P) are somewhat arbitrary and are based on typical designs of the various methods. Any final selection should be based on the merits of a particular design and installation, rather than on the chart.

TABLE 223-1
PIPING PREHEATER PERFORMANCE FOR LMFBR USAGE

	EVEN PREHEAT TO 350 F - 400 F HEAT FULL PIPE TO 800 F	RELIABLE UNDER PIPE TEMPERATURES OF 1300 F - 1500 F (3)	CONTROLLABILITY	MATERIALS COMPATIBILITY (5)	EASE OF SURVEILLANCE	RESISTANT TO MECHANICAL DAMAGE	EASE OF ASSEMBLY AND DISASSEMBLY	RESISTANT TO NUCLEAR RADIATION	NONCONTRIBUTORY TO STRESS
ELECTRICAL METHODS									
INDUCTION	F (1)	G	F	G	P	P	P	P	G
RADIANT	G	G	G (4)	G	F	F	F	G	G
TRANSFORMER	P	P	P	F	G	G	G	P	G
DIRECT SERIES	P	P	P	F	G	G	G	P	G
TUBULAR	(4)	G (6)	G (4)	G	G (4)	G (4)	F (4)	G	(4)
CABLE	(4)	G (6)	G (4)	G	G (4)	G (4)	F (4)	G	(4)
CARTRIDGE	P	G (6)	G (4)	G	G (4)	G	G	F	(4)
STRIP	(4)	P	G (4)	G	G (4)	G (4)	F (4)	G	(4)
TAPES	(4)	G	G (4)	G	G (4)	G (4)	F	G	(4)
MANTLES	G (4)	G	G (4)	G	P (4)	G (4)	F	G	G
BLANKETS	G (4)	G	G (4)	G	P (4)	G (4)	F	G	G
FLUID METHODS									
ANNULAR FLUID HEATING	G (2)	G	F (4)	G	F	G (4)	G	G	G
FLUID TRACING	(2) (4)	G	F (4)	G	G	G (4)	F	G	(4)

G GOOD
F FAIR
P POOR

NOTES

- (1) MAY REQUIRE JACKET.
- (2) LIMITED BY FLUID TEMPERATURE.
- (3) DEPENDENT ON MATERIALS.
- (4) DEPENDENT ON INSTALLATION.
- (5) RATINGS BASED ON AVAILABLE MATERIALS.
- (6) QUALITATIVE INFORMATION INDICATES METHOD IS GOOD WHEN PROPERLY INSTALLED. QUANTITATIVE INFORMATION IS LACKING.

5.2 SUITABILITY OF METHODS TO LMFBR REQUIREMENTS

5.2.1 HEATING CAPABILITY The desired degree of heating can be obtained by proper design of any of the methods described. Even, well-controlled heating is usually more difficult to achieve, however. Table 223-1, Column 1, shows that only four of thirteen methods are good for even heating.

No ratings are given in the first column for tubular, flexible cable, strip, flexible tape, or fluid trace heaters. These methods are all characteristically a concentrated heat source. This can create uneven heating problems unless the installation is such that high heat is not applied to a small surface area of the pipe.

To illustrate, consider a single tubular electric heater mounted axially against a pipe. As the heater temperature becomes greater than the pipe temperature, heat begins to flow from heater to pipe. Most of the heat is transferred by radiation and by conduction across the air gap (see Appendix A). In both cases, the heat is concentrated on that area of the pipe directly beneath the heater. The heat then flows around the pipe circumferentially. If the rate of heat addition is too great, the temperature differential from the heater around the pipe causes the pipe to bend from uneven expansion; or, if movement is restricted, the pipe is stressed.

Multiple heaters tend to alleviate this condition. Nonetheless, internal stresses are generated, and if circumferential heater spacing is uneven, control is poor, or one heater fails, the situation can be serious.

Appendix B contains a one-dimensional thermal analysis of this condition. An equation is obtained for temperature difference as a function of heater output, thermal conductivity of the pipe, pipewall thickness, heater spacing, and a dimensionless parameter known as the Fourier number. By simplification and employment of a minimum heating time, the required heater spacing to obtain a given ΔT can be derived as the following.

$$s = \frac{k}{0.427} \frac{\Delta T}{q_e} t$$

where s = distance between heaters, inches
 k = thermal conductivity of pipe, Btu/hr -ft -F
 ΔT = maximum ΔT allowable
 q_e = heater output, watts/ft
 t = pipewall thickness, inches

5.2.1 HEATING CAPABILITY Continued

This equation is plotted in Figure 223-2 for stainless steel, and holds so long as heating time is in excess of the value plotted in Figure 223-3. If heating time is less than this value, the equation is no longer valid, and the more general relationship given in Appendix B must be used.

As the heater moves away from the pipe, conduction across the air gap ceases to be significant. The amount of heat transferred by radiation is now spread over a greater circumferential area of pipewall, and in some cases, convection becomes significant. The net effect is to heat the pipe much more uniformly. In certain cases, a "standoff" mounting is mandatory.

5.2.2 RELIABILITY As previously noted, sufficient information is not available to categorically approve tubular, flexible cable, or cartridge heaters for high-temperature service. Their reliability can be improved, however, by operating them at less-than-rated voltage.

Materials of construction must be selected carefully. Certain insulations for flexible tapes and blankets such as fiberglass, are not suitable for high temperatures.

5.2.3 CONTROL Equipment is generally available to provide good control of electric resistance heaters. Unfortunately, a number of short elements, while providing good flexibility for local heating, are more difficult to control uniformly than larger elements.

With fluid methods, the piping is generally broken down into individually heated segments. The segments are often even longer than electric resistance heaters, and so lack the flexibility of control. Balancing can also be difficult.

5.2.4 COMPATIBILITY Most heating systems can be designed for good compatibility with liquid sodium. However, a distinct problem with transformer or direct series heating is diffusion of copper into stainless steel at elevated temperature.

5.2.5 SURVEILLANCE The type and degree of surveillance necessary for LMFBR piping has not yet been established. Generally, heating elements which do not blanket the pipe are to be preferred because they permit direct access once the insulation is penetrated.

5.2.6 DURABILITY Heaters of significant length must be mounted so that differential expansion may freely take place between heater and pipe. Any wiring or ducting external to the insulation is susceptible to mechanical damage and must be adequately protected.

Figure 232-2

Figure 223-3
LOWER HEATING TIME LIMIT FOR

EQUATION: $s = \frac{k}{0.427} \frac{\Delta T}{q_e} t$

5.2.7 EASE OF ASSEMBLY Heaters may, in some cases, be assembled in units with prefabricated insulation. This construction is often advantageous for purposes of maintenance. Oven-type enclosures often present sealing problems to the enclosure design, particularly for ease of assembly and disassembly. Provision for thermal expansion must be taken into consideration in designing these enclosures.

5.2.8 RADIATION Nuclear heating of pipe heating components is of small concern in present-day plants because shielding gives adequate protection. However, future designs could conceivably present problems to such heating methods as induction, where excessive heat might be generated in the high-density copper coils and lead to damage.

5.2.9 STRESS CONTRIBUTION When any component is in contact with the pipewall, uneven heating will result during transients. The uneven heating contributes to pipe stress. If the components are thin, their effect is negligible, but a thick mass may cause a significant stress increase.

Uneven heating is present when tubular heaters are mounted against pipes. For instance, during a transient in which the sodium temperature is increasing, and the heater is not working, the heater and the pipewall absorb heat. The temperature profile through a section away from the heater may therefore be considerably different from a section through the heater, depending on the wall thickness, heater material, and transient conditions. A further discussion of this condition is given in Appendix C.

6 INSULATION

6.1 CONSIDERATIONS IN INSULATING FOR LMFBR PIPING

Primary considerations in insulating for LMFBR piping are similar to those in more conventional installations - good resistance to heat loss, sufficiently high maximum service temperature, compatibility with piping and piped fluid, adequate personnel protection, and maintenance of a satisfactory thermal environment in areas adjacent to the piping. However, for liquid sodium piping, the requirements are more severe.

Besides having to withstand high operating temperatures, sodium piping insulation is frequently used with preheaters that are considerably hotter than the piping. The insulation must therefore endure a heavily concentrated heat load. Thus, both pipe and heater temperatures must be taken into account when selecting an insulating material.

Because sodium has a highly reactive nature, materials compatibility is important. The issue is made more complex because of the violent reaction that takes place between sodium and water, both free and chemically bound. It is therefore desirable that the insulating materials be essentially nonhygroscopic and should be inert to reaction with sodium.

Frequently, a stainless steel sheet is placed between the pipe and its insulation to prevent liquid sodium from permeating the insulation in event of a leak. If electric resistance heaters are used, the sheet is installed between heaters and insulation to serve the additional functions of reflecting heat inward and of separating heater from insulation to guard against burnout.

Prefabricated blocks of insulation make assembly and replacement easier. There has been some use of insulation encased in sheet metal which is formed to fit the piping. Some heaters are readily adaptable to in-unit construction with insulation which further facilitates assembly. In any case, insulation should be fastened to the pipe and in-line components by external straps. Methods of attachment which require welding of studs or support rings to the pipewall should be excluded.

6.2 INSULATING MATERIALS

Several types of insulating materials are available which satisfy most of the requirements for LMFBR application. Some of these are as follows.

6.2 INSULATING MATERIALS Continued

<u>MATERIAL</u>	<u>MAXIMUM SERVICE TEMPERATURE, F</u>	<u>DENSITY LB/CU FT</u>
Amosite asbestos	1500	16
Mineral wool	1900	17
Diatomaceous silica	1900	24
Ceramic wools	2300	3-24
Calcium silicate	1200	11
Unbonded fiberglas	1000	9-11
Reflective insulation	1500	-

Materials with high service temperatures frequently have higher thermal conductivities. For this reason, two layers of dissimilar insulations are sometimes used.

6.3 APPLICABILITY TO PARTICULAR HEATING METHODS

There are no particular restrictions against using any suitable insulation with any of the heating methods. However, blanket insulation tends to pack in around a tubular heater element and so leads to burnout.

7 CONCLUSIONS AND RECOMMENDATIONS

From the foregoing discussion, several conclusions may be drawn pertaining to usage of the various heating systems, and certain types may be eliminated from consideration. The prime requisites of heating systems are that the piping be heated evenly and to a sufficient degree, and that reliability be assured. Transformer and direct series heating can be eliminated on both counts - any residual sodium in the piping causes inadequate and uneven heating, and metal diffusion at the terminals and oxidation of the cable leads to reduced efficiency and/or failure.

Cartridge heaters can be eliminated except for specialized application because of uneven heating characteristics. Strip heaters are unreliable at LMFBR operating temperatures, since the seams along the edges are subject to failure.

The disadvantages of induction heating - surveillance problems, difficulty of assembly and disassembly, susceptibility to mechanical damage, and, in many cases uneven heating - indicate that this method is unsuitable for most systems.

The remaining systems fall into the two broad categories of concentrated heating methods and full circumferential heating methods. Electrical resistance and fluid trace systems fall into the former. Radiant, electric blanket, and annular fluid heating fall into the latter. The full circumferential methods are preferable from a stress standpoint because of the very even heating, but lack of local control, difficulty of surveillance, and/or assembly problems may preclude their use. These problems are not of primary concern to the concentrated heating methods, but these methods may suffer from the concentration itself. The installation design is of paramount importance for these systems to guard against overstress of the piping. Each design should undergo thorough thermal and stress analyses.

While reliability is still questionable with electric resistance heating for LMFBR piping, it can be improved by redundancy of elements and by operating at lower-than-rated voltage. It is recommended that appropriate tests be made to establish the reliability of electric resistance heaters at LMFBR operating temperatures.

It is also recommended that any failures and/or difficulties experienced with liquid metal heating systems in existing plants be recorded and made available to the industry. The importance of eliminating heater malfunctions which may, in turn, cause piping failure, cannot be too strongly emphasized. And unless this information is available for designers, it is of little use.

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APPENDIX A

HEAT CONDUCTION ACROSS AN AIR GAP

APPENDIX A

HEAT CONDUCTION ACROSS AN AIR GAP

When two bodies having different temperatures are separated by a gas at rest, heat is transferred from the hotter body to the colder by radiation and convection. The relative fraction of the total transferred heat which is contributed by each method depends on several factors, such as, temperature, fluid properties, and distance between the bodies. If the bodies are brought closer together, the convective contribution becomes less, and finally at very small separations, the convective term may be approximated by conduction equations. Because the thermal conductivity of most gases of interest is low compared to that of solids, the conduction term is sometimes thought to be insignificant.

When a tubular electric resistance heater is strapped to a pipe, there is line contact only. Moreover, the contact resistance at the interface is likely to be rather large. Since there is generally some containment around heater and pipe restricting convective air movement, conduction across the relatively stagnant air gap between heater and pipe becomes significant.

The unit surface conductance across an air gap is defined as the thermal conductivity of air divided by the gap width. A plot of conductance as a function of temperature for various gap widths is presented as Figure 223-4. This parameter is comparable to the heat transfer coefficient by radiation between the two surfaces, h_r , which is on the order of 5 Btu/hr ft² F.

To better establish the conductance for a heater, an "effective" distance may easily be approximated. Assuming the pipe diameter to be large in comparison to the heater, the effective gap width, x_e , can be expressed as

$$x_e = \frac{\text{area across which heat is transmitted}}{\text{heater diameter}}$$

$$= 0.1073 d$$

where d is the heater diameter

Unit conductance between a heater and pipe is shown graphically as a function of heater diameter and air temperature in Figure 223-5.

Figure 223-4

UNIT CONDUCTANCE $\frac{k}{x}$ ACROSS AIR GAP

Figure 223-5
UNIT CONDUCTANCE $\frac{k}{x}$ ACROSS
AN AIR GAP BETWEEN TUBULAR
HEATER AND PIPE

APPENDIX B

LOCALIZED HEATING ANALYSIS

APPENDIX B LOCALIZED HEATING ANALYSIS

Consider an enclosed volume, as shown, that would result if tubular heater elements were installed directly against a pipe, with insulation against the heaters.

HEATER MOUNTING

For top or bottom of the pipe, or if the heaters are of small diameter, convection in such a gap would be essentially nil. Therefore, the generated heat flows primarily into the pipewall with a small amount being lost through the insulation. If the pipe contains a stagnant gas, the quantity of heat used for heating the pipe is much greater than that used for heating the gas because of the differences in density and specific heat. The effect of the gas is therefore primarily to equalize temperatures between points around the pipe, due to convection.

Any such convection, however, depends upon pipe size and location of the heater on the pipe circumference, so that the largest temperature differential is when no convection exists. The problem then simplifies to one which is essentially one dimensional, and a transient thermal analysis can be made for circumferential temperature distribution.

The problem as stated is identical to the classic one of an infinite plate at uniform initial temperature, insulated on one side, and with a constant heat source on the other. Solutions for this case appear in the literature*, assuming constant properties, and the resulting equation is as follows.

$$T_x - T_i = \left(\frac{q}{A} \right) \frac{l}{k} \left[N_{Fo} - \frac{1}{6} + \frac{1}{2} \left(\frac{x}{l} \right)^2 - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp \left(-n^2 \pi^2 N_{Fo} \right) \cos \left(n \pi \frac{x}{l} \right) \right], \quad 0 \leq x \leq l$$

where

T_x = temperature at distance x measured from the midpoint between the heaters

T_i = initial temperature of the pipe

$\frac{q}{A}$ = heat flux into the pipe

l = circumferential length from the midpoint between heaters to a heater

k = thermal conductivity of pipe

N_{Fo} = Fourier number, $\frac{\alpha \theta}{l^2}$

α = thermal diffusivity

θ = time from instant heat is applied

*Carslaw, H S and Jaeger, J C, Conduction of Heat in Solids, Oxford, 1947, Page 104.

APPENDIX B Continued

Thus, the maximum temperature difference will occur between the locations $x = 0$ and $x = \ell$, and an expression for this can be obtained directly,

$$T_{x=0} - T_i = \left(\frac{q}{A} \right) \frac{\ell}{k} \left[N_{Fo} - \frac{1}{6} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp \left(- n^2 \pi^2 N_{Fo} \right) \right]$$

$$T_{x=\ell} - T_i = \left(\frac{q}{A} \right) \frac{\ell}{k} \left[N_{Fo} + \frac{1}{3} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp \left(- n^2 \pi^2 N_{Fo} \right) \cos (n\pi) \right]$$

The first term in the summation of this equation has the sole function of changing the sign from one term in the series to the next, and its effect is cancelled by the cosine term. The equation is then simplified to

$$T_{x=\ell} - T_i = \left(\frac{q}{A} \right) \frac{\ell}{k} \left[N_{Fo} + \frac{1}{3} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(- n^2 \pi^2 N_{Fo} \right) \right]$$

The temperature difference, ΔT , is the desired parameter.

$$\Delta T = T_{x=\ell} - T_{x=0}$$

$$= \left(\frac{q}{a} \right) \frac{\ell}{k} \left\{ \frac{1}{2} - \frac{2}{\pi^2} \left[\sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(- n^2 \pi^2 N_{Fo} \right) - \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp \left(- n^2 \pi^2 N_{Fo} \right) \right] \right\}$$

APPENDIX B Continued

Both series in this equation can be proven convergent, so corresponding terms may be subtracted. The equation then reduces to

$$\Delta T = \left(\frac{q}{A} \right) \frac{l}{k} \left[\frac{1}{2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{1 - (-1)^n}{n^2} \exp \left(- n^2 \pi^2 N_{Fo} \right) \right]$$

For the particular case of electric tubular heaters, with outputs given in watts per foot, employment of conversion factors yields

$$\Delta T = 0.853 \frac{q_e}{k} \frac{s}{t} \left[\frac{1}{2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{1 - (-1)^n}{n^2} \exp \left(- n^2 \pi^2 N_{Fo} \right) \right] \quad (1)$$

where

q_e = heater output, watts/ft

k = conductivity of pipe, Btu/hr -ft² -°F/ft

s = circumferential length between heater elements (= 2 l), inches

t = wall thickness of pipe, inches

This equation has been solved on a computer and the results appear as a plot of $\Delta T/q_e$ versus N_{Fo} in Figure 223-6.

After a period of time, corresponding to a Fourier number of approximately 0.6, the $\Delta T/q_e$ term becomes essentially constant. Using the asymptotic value of 0.5 for the bracketed term of Equation (1), a simple expression results

$$\frac{\Delta T}{q_e} = \frac{0.427}{k} \left(\frac{s}{t} \right) \quad (2)$$

or, with s as the dependent variable,

$$s = \frac{k}{0.427} \frac{\Delta T}{q_e} t \quad (3)$$

Figure 223-6

CIRCUMFERENTIAL TEMPERATURE
DIFFERENCE IN A PIPEWALL DURING
HEATING BY A CONCENTRATED
HEAT SOURCE

APPENDIX B Continued

This equation, plotted in Figure 223-2, can be used for any value of Fourier number greater than about 0.6 which represents a specific combination of heater spacing and heating time (time heater is "on"). This time can be expressed as the following.

$$\theta \geq 0.38 s^2$$

where

θ = heating time, minutes

s = spacing between heaters, inches

A plot of the limiting condition $\theta = 0.38 s^2$ is given in Figure 223-3.

APPENDIX C

TRANSIENT HEATING IN A PIPEWALL OF VARYING THICKNESS

APPENDIX C TRANSIENT HEATING IN A PIPEWALL OF VARYING THICKNESS

If a large pipe with wall thickness δ_1 at uniform initial temperature t_0 is subjected to a change in the fluid temperature within it, the temperature t at any point inside the pipewall is a function of radial location, x , and time, θ . Mathematically, the temperature history is given by the Fourier equation*,

$$\frac{\partial^2 t}{\partial x^2} = \frac{1}{\alpha} \frac{\partial t}{\partial \theta}$$

where α is a property of the material known as the thermal diffusivity, considered here to be constant.

If then another pipe having a different wall thickness δ_2 is at the same initial temperature and subjected to the same transient, no change is experienced in the temperature history, provided that $t_{x=\delta_1} = t_0$. As soon as θ increases to a time when this condition no longer holds, the temperature gradients across the two pipewalls will become unequal. The two gradients set up different internal stresses with the most severe ones occurring in the thicker wall, owing to a larger Δt . Any external mass fastened to the pipe causes an analogous situation.

This problem is particularly important in liquid sodium piping. Because the properties of sodium yield very high heat transfer coefficients, the buffer effect ordinarily present in the boundary layer is small. Accordingly, the pipewall is subject to temperature changes almost as severe as those of the liquid itself. Any attachments used for heaters or insulation should therefore make minimum contact with the pipewall in order to minimize thermal stresses.

In the case of components strapped to the pipe, dissimilarity of materials may aggravate the situation. To give some idea of the magnitude of the problem, consider a pipe having wall thickness δ_w and thermal diffusivity α_w . A rod of rectangular cross-section with thickness δ_B and diffusivity α_B is clamped to the outside of the pipe and parallel to it. Neglecting contact resistance and assuming one-dimensional heat flow, an equivalent thickness of wall material, δ_e , may be computed as

$$\delta_e = \delta_B \sqrt{\frac{\alpha_w}{\alpha_B}}$$

*The basic equations used in this Appendix may be found in any good heat transfer text. Jakob, Heat Transfer, Volume I, Wiley, 1949, is recommended.

APPENDIX C Continued

Solutions of the Fourier equation contain a dimensionless group of numbers which is a measure of heating time. This group is known as the Fourier number, N_{Fo} , and is defined to be

$$\left(N_{Fo} = \frac{\alpha \theta}{\delta^2} \right)$$

For the total thickness δ_T through the pipewall and rod,

$$\left(N_{Fo} \right)_T = \frac{\alpha_w \theta}{\delta_T^2}$$

where

$$\delta_T = \delta_w + \delta_e$$

$$= \delta_w + \delta_B \sqrt{\frac{\alpha_w}{\alpha_B}}$$

Substituting,

$$\begin{aligned} \left(N_{Fo} \right)_T &= \frac{\alpha_w \theta}{\left(\delta_w + \delta_B \sqrt{\frac{\alpha_w}{\alpha_B}} \right)^2} \\ &= \frac{\left(N_{Fo} \right)_w}{\left(1 + \frac{\delta_B}{\delta_w} \sqrt{\frac{\alpha_w}{\alpha_B}} \right)^2} \end{aligned}$$

The significance of this equation is not readily apparent, but may be clarified by an example. Using some rather broad assumptions, an analysis was made in which a tubular heater 0.5 inches in diameter was considered to be a rectangular bar having equal cross-sectional area and width corresponding to the heater diameter. Wall thickness of the pipe was 0.75 inches.

Using the above equations, the thickness δ_T was computed to be 2.08 inches, or almost three times that of the wall itself. The Fourier number increased by a factor of 7.7. By use of a standard temperature response chart*, a 4F/sec transient on the inside of the pipe resulted in a variation in outside wall temperature of 150 F between a location at the heater and some distance away from it.

*P J Schneider, Temperature Response Charts, Wiley, 1963, Chart 16.

APPENDIX C Continued

For this example, the heater material was taken to be compressed magnesium oxide and the pipe was stainless steel. Heater material with a greater diffusivity, or a smaller diameter heater, would tend to lessen this temperature difference.