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INSULATION OF THE FFTF
CLOSED LOOP TUBES

November 1968

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INSULATION OF THE FFTF CLOSED LOOP TUBES

By

G. R. Sawtelle

Engineering Mechanics and Materials Section

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INSULATION OF THE FFTF CLOSED LOOP TUBES

G. R. Sawtelle

ABSTRACT

The FFTF closed loop tubes will operate in liquid sodium at a temperature level of up to 1400 °F with a wall temperature difference of 400 °F. Methods of providing insulation to reduce heat transfer and thermal stresses to acceptable levels are evaluated. A twin-wall tube was chosen to provide an annular gap, isolated from the sodium, for the insulating materials, and to provide a gas circulation channel for controlling the thermal conductivity of the tube wall.

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NOMENCLATURE

A	Area
E	Elastic modulus
F	Grey body shape factor
n	Number of thermal shields
Q _r	Net heat transfer rate
S _t	Axial and tangential thermal stress
T	Surface temperature
ΔT	Temperature difference across the tube wall
α	Coefficient of linear thermal expansion
ε	Total emittance
ν	Poisson's ratio
σ	Stefan-Boltzmann constant

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INTRODUCTION

The Fast Flux Test Facility (FFTF) will be used to investigate the behavior of materials in typical and extreme conditions of fast neutron environments that will be encountered in future fast breeder reactors. The principal component of the facility is the fast test reactor (FTR) which is designed to meet the process and handling requirements of multiple closed test loops.

The closed test loops will provide a highly instrumented, controlled, isolated (except for neutron flux) system for testing coolant, fuels, and material specimens in an environment different from that found elsewhere in the reactor core. Each closed loop includes equipment for heat removal, purification, and circulation of the coolant, and instrumentation for operational control, safety, and test data collection. The independence of each loop makes possible the control of the temperature level and coolant flow rate, and hence the temperature increase across the test section. Furthermore, since the system is isolated, it will be possible to investigate the effect of contaminated sodium, other liquid coolants, and possibly gaseous coolants.

The in-pile closed loop tube walls will be exposed to large temperature differences during startup, running, and shutdown operations. In order to maintain isolation or independence of the closed loops, sufficient thermal insulation must be provided to limit or control the effect of the heat transfer between the closed loops and the bulk reactor coolant. This report is an initial review and evaluation of insulation methods for the closed loop tubes.

SUMMARY AND CONCLUSIONS

Both the re-entrant and the U-tube design concepts being actively considered for the FFTF closed loop tubes require that considerable insulating capability be incorporated into a thin wall structure

in a minimum thickness. Achieving the required insulation is complicated by many factors:

- Operating temperatures will be up to 1400 °F.
- Temperature differences of up to 400 °F or more across the tube walls must be maintained.
- The structure must be reliable, particularly with respect to thermal stresses associated with large temperature differences.
- The insulation must be compatible with the neutron environment and it should be compatible with sodium or other liquid metals.
- Increasing the thermal conductivity of the insulant during a closed loop coolant blockage is necessary to prevent closed loop tube failure.
- At least part of the tube structure will be of stainless steel, which has a relatively high thermal expansion coefficient.

The insulation problem was considered from the viewpoint of related tube experience, insulants available, and basic heat transfer considerations, with the effects of gamma-heating omitted. A twin-wall tube with an annular insulation gap utilizing vacuum, inert gas, inert gas mixtures, or inert gas and low density solid fibrous or metallic foil material for the insulant appears to be the most desirable concept. With this concept, for example, a 1/8 in. helium gas gap with oxidized internal surfaces which is a relatively poor insulation, most of the temperature difference is within the insulation gap, and thus acceptable tube wall thermal stresses are maintained. However, the difference in thermal expansion between the outer and inner tube walls requires a slip joint, bellows, or some other accommodation at one end of the tube. The inner tube wall surface conditions are important; heat transfer by a 1/8 in. argon gas gap at a mean temperature of 1200 °F is theoretically 67% less for polished surfaces (emittance 30%) than for oxidized surfaces (emittance 80%).

Selection of the insulating gap filler offers several alternatives. A vacuum of 1 Torr or less would effectively reduce the portion of heat transfer due to gas conduction, which would be appreciable in the case

of helium, and it would be adaptable to rapid coolant flooding for increasing heat transfer. Expensive provisions might be required to maintain the vacuum. The use of a recirculating inert gas or gas mixture as an insulant appears attractive since heat transfer could be controlled to some extent during normal operations by varying the gas mixture and/or by coolant flooding; gas recirculation and purification equipment would be needed. A solid insulant such as a ceramic in a fibrous form or a metallic foil insulation could be combined with a stagnant or recirculating gas scheme for effective insulation. The solids may maintain the gap spacing between the inner and outer tubes, but they would also incur gamma heating.

The twin wall tube using an annular insulation gap requires development work in the following areas for final design:

- Determination of the insulation effectiveness provided by the selected structure under various simulated reactor operating conditions, gas (or vacuum) quality, and tube surface emissivity ranges.
- Experimental verification of structural adequacy, particularly in maintaining a uniform insulating gap by spacers or other means and avoiding hot spots that could produce tube distortion or excessive thermal stresses.
- Experimental verification of slip joints, bellows, or other designs to accommodate relative movement between the inner and outer tube walls and spacers (including limiting stresses, galling, fretting, etc.).
- Prototype closed loop tube assembly testing.

DISCUSSION

THE INSULATION PROBLEM

The most recent closed loop tube conceptual designs consist of a U-tube and a re-entrant tube configuration (Figure 1). Development work, including this insulation study, has been concentrated on the re-entrant tube concept. However, the U-tube configuration could be selected for initial or future experiments and will present similar insulation problems.

FIGURE 1. A Schematic of Closed Loop Re-entrant and U-Tube Configurations with Typical Operating Temperatures

The temperature profiles of the closed loop tubes, the coolant, and the surrounding sodium will present severe operating conditions. Closed loop tube walls must provide for temperature differences across the wall of 400 °F or more at loop operating temperatures in excess of 1200 °F.^{*(1)} Furthermore, since the closed loop test space is small, the insulation for the closed loop tube wall must be provided in a minimum of space to allow the largest possible test section. The tube configurations and these operating conditions, particularly the expected temperature gradients, establish the requirements for insulation to reduce heat transfer and provide a closed loop test system thermally isolated from the reactor sodium.

The design must avoid excessive thermal stresses that can result from the difference in thermal expansion across a tube wall due to the large temperature gradient. The axial and tangential thermal stress level (S_t) in a thin tube from a wall with a temperature difference ΔT is given by

$$S_t = \frac{1}{2} \frac{E\alpha\Delta T}{(1-\nu)}$$

where α is the coefficient of linear thermal expansion, E is the modulus of elasticity, ν is Poisson's ratio, and a thin tube is one in which the ratio of wall thickness to radius is much less than unity.⁽²⁾ As pointed out by Aungst,⁽³⁾ for a ΔT of 500 °F, the hoop stress will be about 50,000 psi or nearly 5 times the yield stress of 304 SS at a reactor operating temperature of 1200 °F. Townsend⁽⁴⁾ suggests that the maximum allowable temperature difference in the tube wall should be less than 50 °F.

* See Table I and Figure 1 for additional operating conditions.

TABLE I. Operating Conditions Relevant to the Closed Loop Tubes

<u>Reactor Core Conditions</u>	
Coolant Inlet Temperature	550 to 800 °F
Coolant Outlet Temperature	800 to 1000 °F
Coolant Inlet Pressure	120 to 160 psig
Coolant Outlet Pressure	0 to 40 psig
Cover Gas Pressure	<10 in. of H ₂ O
Cover Gas Temperature	350 to 500 °F
Temperature Above Nozzles	200 to 300 °F
<u>Closed Loop Tube Conditions</u>	
Coolant Inlet Temperature	500 to 1100 °F
Coolant Outlet Temperature	800 to 1200 °F
Coolant Inlet Pressure	20 to 150 psig
Coolant Outlet Pressure	20 to 50 psig
Coolant Flow Rate	70 to 600 gpm
Test Section Temperature (a)	1600 °F
Test Section ΔT	20 to 400 °F
Test Section ΔP	1 to 130 psi
Maximum Test Diameter	3 1/2 to 4 in.
Maximum Test Length	15 ft
Maximum Test Length below Core	2 to 3 1/2 ft
Total Power (a)	0.6 to 5 MW
Flux	0.5 to 0.6 x 10 ¹⁶ n/cm ² /sec

(a) Power and temperature limits determined by testing requirements and material limitations.

The gaseous or solid insulants must be compatible with the environment including the following:

- Flux levels to 0.6×10^{16} n/cm²/sec, total accumulated flux, and gamma heating.
- Temperatures to 1400 °F, thermal cycling, and thermal shock.
- Tube structural materials and other insulants that are present.
- Sodium or other liquid metal coolants (possibly for only short periods of time).
- Vibration.

During normal operating conditions, maximum thermal isolation of the loop system from the reactor sodium is desired; the isolation is to be provided by minimizing the heat transfer rate. There may be conditions, however, such as a scram situation caused by a closed loop system failure, when it will be necessary to remove heat from the closed loop system. It may therefore be necessary to increase the thermal conductivity and dump the heat generated in the loop to the bulk coolant, or provide an additional heat removal channel, or do both. The result is that a controllable thermal conductivity concept deserves some consideration.

RELATED INSULATED TUBE EXPERIENCE

A literature survey on insulated tubes for reactor service was made. Solid insulated tube studies have been conducted for the AECL in connection with the heavy water and organic cooled reactor programs.⁽⁵⁻⁸⁾ These solid insulated tubes consisted of a stress tube with an external or internal insulation and liner tube. The stress tube and liner tube were rigidly connected at each end either by a rolled joint construction or a mechanical clamp mechanism without a slip joint, bellows, or other arrangements to allow for different wall expansion. They have performed with only limited success for several cycles at limited pressure and temperature levels. Since this concept could provide a tube construction with a minimum wall thickness, the applicability to a 304 SS system deserves consideration.

Using $E\alpha\Delta T$ /yield stress as a modeling parameter for a first approximation in comparing operating stress, 304 SS would have an expected stress ($E\alpha\Delta T$) to yield stress ratio from 2.4 to 27 times larger than the tubes examined, and therefore, the rigid connection concept appears questionable for 304 SS.

The Min-K* insulation used in the aforementioned tubes was chosen as an insulant because of its desirable properties, including

* Min-K is the trade name of a fibrous silica-asbestos insulation material manufactured by the Johns Manville Company.

relatively low neutron capture cross section, and high temperature, low thermal conductivity characteristics. Irradiation tests have shown Min-K to be stable to at least 3×10^{20} n/cm² ($E > 1$ MeV). Additional information necessary for comparison and determination of applicability of these studies to the closed loops is indicated in Appendix A.

A report⁽⁹⁾ describing a French patent on a pressure tube, fuel cartridge, moderator-insulant concept has been reviewed. In this concept, the tube is designed to allow a portion of the coolant to pass between the pressure tube and the insulating jacket, thereby reducing the temperature and increasing the strength properties of the pressure tube. However, the insulating jacket is subjected to a large temperature difference which may only be acceptable to graphite that also serves as a moderator in this application.

A German patent⁽¹⁰⁾ of an end connection for a power tube of a nuclear reactor which consists of an inner pressure tube and a concentric jacket tube has been reviewed. The annular space between the tubes provides a passage for coolant flow. This connection is designed to allow for differential thermal expansion by providing a suction-seal mechanism at the joints. The connection consists of many joints, seals, and annular passages, and it does not appear to be of practical application for the closed loop tubes.

The PRTR incorporates a gas annulus concept.⁽¹¹⁾ The PRTR fuel channels are insulated from the calandria tubes by a 0.270 in. helium annulus. The helium is essentially stagnant since circulation is at a rate just sufficient for leak detection. The operating temperature of the insulating annulus is in the order of 575 °F maximum tube temperature with a temperature drop of less than 275 °F.

Insulation tests were conducted at Oak Ridge National Laboratory (ORNL) and Orenda Engines Limited (OEL)⁽¹²⁾ to define the operating characteristics of insulation configurations that would best suit the gas-cooled in-pile loops (ORR No. 1, ORR No. 2) in the Oak Ridge Research

Reactor and the Experimental Gas-Cooled Reactor. Tests were conducted with helium and carbon dioxide at temperatures up to 1000 °F and pressures to 1000 psig, in a 5 ft vertical annulus, 0.275 in. to 1.5 in. thick. The chief insulation method tested was a spirally wrapped foil in which 1/8 in. spacing between adjacent foil turns was maintained by strips of corrugated sheet metal 1 in. wide. Results from this arrangement in an atmosphere of helium have shown gross effective thermal conductivity values to be approximately 150% to 200% of the values for the gas itself. Tests at ORNL indicated that the specimen composed of spirally wrapped shim stock spaced by intermittent corrugated strips had the best insulating characteristics of the configurations tested. It exceeded the performance of the stainless steel wool by 50% and was 10% superior to the insulation using sandwiched, corrugated foil.

The ATR high temperature helium loop model⁽¹³⁾ at BNW utilizes metallic foil (Inconel) insulation in the test sections. The loop contains two test sections, one horizontal and one vertical into which the ultra-pure helium (less than 1 ppm) flows at a maximum inlet temperature of 2100 °F and 1800 °F respectively. Helium is allowed to flow between the foil layers which are wrapped 30 layers per inch to a thickness of 3 in. in the horizontal and 1 1/4 in. in the vertical test section.

Both Westinghouse⁽¹⁴⁾ and Phillips Petroleum Company⁽¹⁵⁾ have suggested in their alternate concept studies, a twin-walled tube with a helium gas jacket as the insulation concept.

The literature survey for articles on insulated tube concepts, and operating or experimental results, yielded little information. Since the FFTF will be operating at conditions more severe than previous reactor facilities, the applicability of those reports cited is limited.

HEAT TRANSFER MODES

Heat transfer occurring in vacuum, solids, liquids, gas, and circulating gas or liquids (as seems pertinent to the closed loop tube insulation problem) is discussed in this section. In a thermally perfect

vacuum (one in which gas conduction is negligible) heat is transferred by thermal radiation. The net rate of heat transfer by radiation Q_r is given by

$$Q_r = F \sigma A (T_H^4 - T_C^4) \quad ,$$

where F is a gray-body shape factor which compensates for geometry and departure of the surface from black-body conditions. Since the annular space is small compared to the mean diameter, the gray-body shape factor for two parallel flat plates with the same emittance (ϵ) will be a good approximation and reduces to⁽¹⁶⁾

$$F = \frac{1}{2/\epsilon - 1} \quad .$$

For a given operating temperature and gap width, the rate of heat transfer can be reduced only by changing the emittance. Emittance for stainless steel surfaces ranges from about 80% (oxidized) to about 22%^(16, 17) for a highly polished surface. Thus, a highly polished surface can reduce radiation heat transfer to less than 1/4 that of an oxidized surface.

A narrow gas-filled insulation gap will contribute to heat transfer by thermal radiation and gas conduction. Convection heat transfer is negligible for narrow annular gas gaps at moderate pressures.⁽¹⁸⁾ That is, it is negligible when the Grashop-Prandtl number product is less than 3000, which is the critical value for suppression of natural convection.⁽¹²⁾ Furthermore, radiation heat transfer will be the same order of magnitude as in a vacuum gap since gas absorption is minimal in a narrow gap.

Gas conduction will contribute to heat transfer in all insulation gaps where the pressures are not severely reduced. That is, the thermal conductivity of gases is nearly independent of pressure down to about 1 Torr, (approximately 1 mm Hg). Between 1 and 1×10^{-4} Torr, the thermal conductivity goes from a value that is very close to its value at atmospheric pressure to nearly zero.⁽¹⁹⁾ In addition, for a temperature range of a few hundred degrees, the thermal conductivity of gases increases slightly (see Figure 2).

FIGURE 2. Thermal Conductivity Versus Temperature for Noble Gases and Air

The major modes of heat transfer in a liquid filled insulation gap will be by conduction and convection. Thermal conduction is about an order of magnitude larger in liquids⁽¹⁶⁾ than in gases, and convection currents will also be more evident since the Grashop-Prandtl number product will be much larger. The effectiveness of a liquid as an insulator is dependent on the thermal resistance of the film coefficient produced at the liquid solid interface.

Circulating fluids could provide an insulation method with a large thermal conductivity range by changing the flow rate and/or the fluid or fluid mixture. The flowing insulant method differs from other forms of insulation in that the closed loop loses heat to the circulating fluid, thereby reducing the amount of heat absorbed by the bulk coolant. Furthermore, temperature gradients in the tube walls will be larger than for stagnant fluids. Hence, the effective thermal conductivity must be limited to some maximum value corresponding to a maximum acceptable thermal stress level in each wall.

The dominating modes of heat transfer in solids depends on the particular material and its characteristics including density and geometry. There are several types of insulant materials commercially available in the form of fibers, ceramics, powders, and foils.

Fibrous insulating materials reduce thermal radiation and convection, the effectiveness of which depends not only on the thermal conductivity of the material but also on the thermal properties of the interstitial gas and the material density. Metallic foils are used as thermal radiation shields, and theoretically reduce heat transfer by a factor of $1/(1 + n)$, where n is the number of shields. These foils also reduce convection currents, provide additional solid-liquid interfaces in a liquid environment, and contribute to metallic conduction. Ceramics and powders are quite dense, and the principal heat transfer mode is solid conduction, although gas conduction is appreciable in the coarse powders and ceramics that have large gas entrapment cavities.

INSULATION MATERIALS

There is a variety of insulation materials available for use in the closed loop tubes. The noble gases are of interest because of their inert or stable character around other materials such as stainless steels at high temperatures. The thermal conductivity of the noble gases as a function of temperature are shown in Figure 2. Since krypton has the lowest conductivity of the noble gases it would be preferred. However, krypton like xenon is not abundant. This leaves argon, neon, and helium, which increase in conductivity and decrease in abundance in that order.

Liquids do not appear to be good candidates for insulation because of their poor insulating quality relative to gases, because of their density (gamma heating potential), and because of their general incompatibility with the environment.

Solid materials are available in the form of fibers, solids (either blown or particulate), and metallic heat shields. The fiber insulation materials are most desirable because of their low density and conductivity properties. Solids and metallic heat shields or foils tend to be better

conductors than fibers although foil materials may help reduce radiation significantly. Solid ceramics are quite dense and brittle, and will significantly contribute to gamma-heating. The thermal conductivity of selected solid insulants is presented in Appendix B.

CLOSED LOOP TUBE INSULATION METHODS

Single-wall and twin-wall closed loop tubes have been considered. In the single-wall tube, thermal insulation can be provided by attaching a low thermal conductivity layer to the tube wall. This can be provided by such arrangements as fins or baffles or a canned or attached insulation. The fins or baffles must not introduce excessive stresses in the tube, nor should they seriously disturb the flowing sodium coolant. The attached insulant materials must meet the following requirements:

- They must possess thermal expansion characteristics compatible with stainless steel such that thermal stresses will be acceptable to both the insulant and the tube wall.
- Since they are exposed to the sodium coolant they must be compatible with sodium and be able to withstand vibrations and shear stresses induced by the high velocity sodium.

The twin-walled tube concept provides an annular space isolated from the coolant for insertion of insulating materials. The possible insulation gap fillers are vacuum, stagnant gases, stagnant liquid, circulating gases or liquids, solids, or the possible combinations. The twin-walled concept will require some form of spacers to maintain a uniform gap width, and a slip joint or bellows to allow for differential expansion of the two walls.

The single-wall concept appears to be inadequate because there is no known material available that has a low thermal conductivity and a thermal expansion compatible with 304 SS, and because there is no apparent alternate method of removing heat from the loop. Baffles may provide enough thermal resistance to limit thermal stresses, but they would also induce coolant flow disturbances and perhaps local tube wall stress problems.

The double-wall insulation gap concept appears to be versatile and desirable. The proper selection of a gap filler will provide a relatively low thermal conductivity insulated wall. The double wall configuration will require a slip joint or bellows to limit stresses due to differential thermal expansion, and some form of spacers to maintain gap width. Furthermore, this concept provides a method for circulating a gas or liquid through the annular space. Although the limit on wall temperature difference appears to be severe, a heat transfer analysis of a twin-walled tube indicates that a 1/8 in. helium gas gap will be sufficient to limit the temperature difference (ΔT) in each wall (and hence the thermal stresses) to an acceptable level.

A good insulation gap filler appears to be a low thermal conductivity gas or vacuum pumped space, with or without a solid insulant material. A vacuum will reduce the gas conductivity; however, the amount of reduction in thermal conductivity may not warrant the equipment required to maintain a vacuum. (Recall that a minimum pressure of 1 Torr must be obtained before gas conduction is reduced.) As suggested earlier, argon is a desirable gas because of its low thermal conductivity and abundance. Argon may be used as a cover gas and would therefore appear to be acceptable from a nuclear compatibility standpoint. However, in the insulation gap, the gas will be exposed to a much higher neutron environment.

A gas circulating system may be required, regardless of the gas used, to filter the excess radioactive gases and other impurities. This system could also provide the means for controlling the thermal conductivity of the insulation gap and/or for a backup heat removal system.

A plain gas gap without solid materials will require polished radiating surfaces to reduce thermal radiation. The relative contribution to heat transfer by gas conduction and radiation at various emissivity values is shown in Figure 3. The relative contribution of gas conduction and thermal radiation indicates that a vacuum pressure would appreciably reduce the thermal conductivity in a helium gap, but would have limited effect in an argon gap even if the emissivity is as low as 30%.

FIGURE 3. Effective Thermal Conductivity Versus Temperature for Various Surface Emittance. (The effective thermal conductivity is based on and only applies to a 1/8 in. gap width)

The use of solid materials in the insulation gap will eliminate the need for polished radiating surfaces with the possible exception of metallic foil fillers. The total thermal conductivity versus temperature for several combinations of gap fillers is indicated in Figure 4. Although the contribution of thermal conductivity due to spacers has not been included, it is expected that the added heat conduction will not seriously affect the choice of insulation materials.

If the gas conduction is minimal, only the Min-K insulation material of those commercial insulants considered appears to provide a lower thermal conductivity than a gas gap. Solid materials will also reduce the rate at which a gas can be circulated through the annular gap for a given pressure drop, and therefore may not be acceptable. However, if Min-K or some other solid material could provide sufficient strength to maintain gap width and distribute the load between the tube walls without introducing excessive stress, the wall thickness could be reduced, and thereby increase the test section volume. Solid insulants would also limit the rate at which sodium could be flooded into the gap. Furthermore, the particular material may not be compatible with sodium even for the relatively short time necessary to remove decay heat from the loops. If an insulation gap filler could be found to provide a much lower thermal conductivity for a 1/8 in. gap than is necessary, the gap width could be reduced, again increasing the space available for test section enlargement.

EXPERIMENTAL VERIFICATION AND EVALUATION

The effective thermal conductivity of the insulated tube for the materials selected can most accurately be determined by experimental data. An analysis based on known thermal conductivity values and heat transfer principles will, at best, yield a good estimate. Variables or indeterminates that add to the inaccuracy of an analysis include the following: the contribution to heat transfer by the gap spacers, attainment and maintenance of surface emissivity on a given material under simulated operating conditions, and the thermal conductivity for a 1/8 in. thickness of a given material as used in a closed loop tube structure (the manufacturers suggested values are based on a thicker specimen).

FIGURE 4. Thermal Conductivity Versus Temperature for Several Insulation Gap Fillers

The selection of a spacer configuration will require consideration of the added heat transfer, local temperature gradients, attachment method, and differential wall expansion effects. Little information is available concerning the techniques for polishing 316 or 304 SS to obtain a low emissivity. Since the alloy content is a critical variable, methods used to produce the emissivity values given in Reference 16 and 17 may not be applicable to the alloys used in the closed loop tubes. Maintaining a given emissivity through several thermal cycles, and at elevated temperatures, will require a relatively inert atmosphere. That is, the degree of gas purity required must be determined. The need for spacers with solid materials must be determined prior to experimental verification of thermal conductivity of the insulated tubes. The spacer design may or may not differ when used in smaller gap widths with or without solid insulants.

The twin wall tube using an annular insulation gap requires development work in the following areas for final design:

- Determination of the insulation effectiveness provided by the selected structure under various simulated reactor operating conditions, gas (or vacuum) quality, and tube surface emissivity.
- Experimental verifications of structural adequacy, particularly in maintaining a uniform insulating gap by spacers or other means and avoiding hot spots that could produce tube distortion or excessive thermal stresses.
- Experimental verification of slip joint, bellows, or other design to accommodate relative movement between the inner and outer tube walls and spacers (including limiting stresses, galling, fretting, etc.).
- Prototype closed loop tube assembly testing.

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APPENDICES

APPENDIX A

RESULTS OF INSULATED TUBE STUDIES

The results of insulated tube studies performed by Hawker Siddeley and Canadian General Electric⁽⁵⁻⁸⁾ relating to the closed loop tube insulation problem are presented as follows.

Tube I was constructed with the liner tube external to the stress tube; "Refrasil" and 80 mesh compacted Silica sand provided the insulation material. The ends of the tube were rigidly clamped such that they would expand and contract together. The clamps also provided parts for internal stress tube heating, insulation gap pressure monitoring, and vacuum pressure lines.

The first 50 thermal cycles were used to evaluate the tube at the thermal stress level expected in a Zircaloy-2 tube construction operating at typical CANDU conditions. Since the tube showed no signs of instability, the stress tube temperature was increased each cycle. After the pressure was released on cycle 77, a diamond stress pattern, probably due to buckling, appeared on the surface of the liner tube. The stress tube had reached 510 °F, and the liner tube was at 181 °F, or a 329 °F temperature difference had been imposed on the tube.

Results of the test also indicated a permanent elongation of the liner tube of 0.03% with no evidence of insulation deterioration. In addition, the thermal conductivity was determined for insulation gap pressures of 0 and 29 in. Hg, and a ΔT of 74 and 326 °F.

Tubes II, III, and IV were constructed with Zircaloy-2 stress tubes, Min-K insulation (6 in. long, 120° cast sections), and either SAP-895 or Zircaloy-2 external liner tubes. The stress tube and liner tube were rigidly attached at each end by forming a rolled joint. Thermal cycling exposed these tubes to a 645 °F temperature difference by maintaining the stress tube cooling water temperature at 70 to 80 °F while thermally cycling the liner tube to a maximum of 725 °F.

The liner tube in Tube II and the stress tube in Tube III were unstable in axial compression. The change in unstable member from liner to stress tube indicates the importance of liner/stress tube thickness ratio, and furthermore, the ratios used bracketted the optimum for the materials used. Reference 8 indicates that the thermal conductivity of the Min-K material was not adversely affected by the thermal cycling. Tube IV was identical to Tubes II and III except that the liner tube was Zircaloy-2 and the stress/liner tube wall thickness ratio was 1/1. Thermal cycling results indicate slight liner tube wrinkles and joint leakage, and consequently the tube was not of reactor quality.

Table A.1 summarizes the Hawker Siddeley and Canadian General Electric results.

TABLE A. 1. Related Insulated Tube Studies Data

Description	Tube Identification				
	I Hawker Siddeley	II #4	III Canadian General Electric #6	IV #5	V Closed Loops
Stress Tube OD, in.	3.305	3.645	3.640	3.644	
Wall Thickness, in.	0.090	0.031	0.021	0.031	0.10 to 0.150
Material	4130 Steel	Zry-2	Zry-2	Zry-2	304 SS
Insulation Thickness, in.	0.034 Refrasil 0.048 Silica Sand	0.087 Min-K	0.085 Min-K	0.086 Min-K	0.125 ?
Liner Tube OD, in.	3.5	3.372	3.370	3.372	
Thickness, in.	0.016	0.062	0.060	0.032	0.10 to 0.150
Material	321 SS External	SAP-895 Internal	SAP-895 Internal	Zry-2 Internal	304 SS
Specimen Length, in.	36	113 7/8	100.9	114	
Liner/Stress Tube Wall Thickness Ratio		2/1	3/1	1/1	
Internal Pressure, psi	1500	300	300	300	250+
<u>Thermal Cycles</u>		Stress Tube Cooling Water Maintained at 70 to 80 °F. Number of Thermal Cycles on Liner Tube as Indicated Below:			
Liner Temperature 60 to 90 °F		20	7	20 at 70 to 725 °F	
Pressure tube, 50 cycles at 80 to 150 °F		130	124	208 at 200 to 725 °F	
		150	131	228	
	72nd cycle-liner 54 to 126 °F Pressure tube 70 to 270				
	77th cycle-liner 61 to 181 °F Pressure tube 70 to 510 °F				
Thermal Conductivity (Btu/hr-ft-°F)	0.045 at 74 °F, 0 in. Hg 0.173 at 326 °F, 0 in. Hg 0.135 at 74 °F, 29 in. Hg 0.206 at 326 °F, 29 in. Hg				
ΔT Maximum, °F	329	645	645	645	400 +
Total Wall Thickness, in.	0.1795	0.199	0.195	0.167	0.425
Coefficient of Thermal Expansion, (μin./in./°F)	4130 Steel 6.5 321 Steel 9.3	Zry-2 3 ^(a)	Zry-2 3 ^(a)	SAP-895, 12 ^(a)	304 SS, 9.9 ^(a)
Modulus of Elasticity (10 ⁻⁶ psi)	4130 Steel 29 ^(a) at 510 °F 321 Steel 28 ^(a) at room temperature	SAP-895, 10.6 at 70 °F Zry-2 (cold worked) 13.43 at 70 to 200 °F	SAP-895, 10.6 at 70 °F Zry-2 (cold worked) 13.43 at 70 to 200 °F	Zry-2, 10.5 at 700 °F ^(a)	304 SS 28 ^(a) at room temperature 24 ^(a) at 1200 °F
Yield Stress (10 ⁻³ psi)	4130 Steel 100 ^(a) at 510 °F 321 Steel 35 ^(a) at room temperature	SAP-895, 32 at 70 °F 14.9 at 700 °F Zry-2, 62 at 70 to 200 °F	SAP-895, 32 at 70 °F 14.9 at 700 °F Zry-2, 62 at 70 to 200 °F	Zry-2, 75 at 70 °F Zry-2, 28 at 700 °F	304 SS 35 ^(a) at room temperature 10 ^(a) at 1200 °F
<u>E_{0.2}T</u>	321 Steel 2.45 at room temperature	Zry-2, 0.3455 at 70 °F	Zry-2, 0.3455 at 70 °F		
Yield Stress	4130 Steel 0.62 at 510 °F	0.726 at 700 °F SAP-895, 3.98 at 700 °F	0.726 at 700 °F SAP-895, 3.98 at 700 °F		304 SS 9.5 at 1200 °F

(a) Materials Handbook, vol. 1, "Properties and Selection of Metals," 8th ed., ASM, 1961.

APPENDIX B

PROPERTIES OF SOLID INSULANT MATERIALS APPLICABLE
TO THE CLOSED LOOP TUBES;* TABLE B. 1 AND FIGURE B. 1.

* This information was taken from Doman's^(21, 22) reports and revised.

TABLE B.1. Properties of Various Commercially Available Insulation Materials Applicable to the Closed Loop Tubes

Note: The manufacturers have made specific claims for their materials in this particular usage. Information given here is not to be construed that any product is superior to another in general usage, nor do the results indicate performance under any condition other than here specified.

Trade Name	Manufacturer	Type	Composition	Approx Bulk Density, lb/ft ³	K _{bulk} at 1600 °F, Btu/hr-ft-°F		T max for continuous use in air and He, °F	Limitations of this Application
					In Air (1 atm)	In He (300 psia (a))		
Fiberfrax	Carborundum	Blanket (Long Fiber)	Al ₂ O ₃ + SiO ₂	6	0.196	0.285	2300	4, 5, 7, 8
Fiberfrax	Carborundum	Cast (Porous)	Al ₂ O ₃ + SiO ₂	24	0.115	0.275	2300	7, 8
Cerafelt	Johns-Manville	Felt, Fibrous	Al ₂ O ₃ + SiO ₂	3 to 24	0.15	0.285	2300	4, 5, 7, 8
Dyna Quartz	Johns-Manville	Felt, Fibrous	SiO ₂	4.5 to 10.0	0.086	0.215	2750	4, 5, 7, 8, 10
Micro Quartz	Johns-Manville and Libby-Owen Ford	Blanket, Fibrous	SiO ₂	3 to 9	0.121	0.215	2000	4, 5, 7, 8
Refrasil	H. I. Thompson	Fiber	SiO ₂	3 to 9	0.205	0.215	2000	4, 5, 7, 8
Carbon and Graphite Felt	Nat'l Carbon and Great Lakes Carbon Co.	Felt, Fibrous	Carbon	7	Oxidizes	0.10	4750 He, oxidizes in air	4, 5, 7, 8, 9
Min-K	Johns-Manville	Molded	Silica-Asbestos-Metal Clad	14 to 20	0.038	0.15	1850	8, 10, 14
Min-K	Johns-Manville	Fibrous, Metal Clad	Silica-Asbestos Clad	14 to 20	0.038 For insulation only	0.15 For insulation only	unknown	1, 8, 10, 12, 14
Tipersul	du Pont	Fibrous, Cast	K ₂ TiO ₃	3 to 72	0.074	0.2	2100	4, 5, 8, 10, 11, 14 (fibrous)
Zircoa	Zirconium Corp. of America	Cast	ZrO ₂	265	0.63	0.86	4600	2, 8, 10, 11, 13
Silicon	Carborundum	Porous SiC	SiC	low density 0.17 high density 0.35	low density 0.57 high density 1.1	2.6 4.1	4000 He 3000 Air	2, 6, 8, 10, 14
Cercor	Corning Glass	Cast	Pyroceramic	30	0.034	unknown	2012	3, 6, 10, 14
Solami (Corrugated Foil)	Solar Aircraft Div. Intern'l Harvester	Metallic	Inconel 600	40	unknown	0.36 0.45	2150	2, 3, 10
Separated Flat Foil	Hawker-Siddeley, Inc.	Metallic Foil	Inconel 600	20	unknown	0.54	2150	2, 3, 10
Thermaflex	Johns-Manville	Felt	Al ₂ O ₃ + SiO ₂	3 to 24	0.15	0.285	2300	4, 8, 12, 14
Kaowool	Babcock and Wilcox	Blanket, Fibrous	Al ₂ O ₃ + SiO ₂	3 to 10	0.285	unknown	2012	4, 5, 8, 14

(a) Thermal conductivities in helium are calculated and extrapolated values only; experimental testing could change the values significantly.

- Maximum continuous operating temperature too low or marginal.
- Relatively high thermal conductivity.
- Not readily formed into moderately intricate shapes of elbows, reducers, and internal cavities.
- Not self-supporting.
- Encasement necessary to retain required dimensions.
- Relatively fragile.
- Shrinks at temperatures above 816 °C (1500 °F).
- Relatively difficult to outgas.
- Possibility of chemical or metallurgical reaction with hot inner pipe.
- Relatively high priced (compared with cast Fiberfrax as base).
- Integrity of cladding must be guaranteed.
- High density, may give gamma heating problems in core.
- Radiation effects unknown.

B.2

BNWL-755

FIGURE B.1. Thermal Conductivity Versus Temperature for Several Solid Insulant Materials

LEGEND TO FIGURE B. 1

(Values in Air Except Where Noted)

1. Fiberfrax Blanket (long fiber), 6 lb/ft³
2. Castable Fiberfrax, 24 lb/ft³
3. Fiberfrax Blanket, long fiber (in helium), 6 lb/ft³
4. Cerafelt and Thermoflex (insulation only), 6 lb/ft³
5. Kaowool bulk fibers, 3 lb/ft³
6. Micro Quartz, 3 lb/ft³
7. Dyna-Quartz, 6.2 lb/ft³
8. Refrasil, 3 lb/ft³
9. SiO₂ (in helium), 3 lb/ft³
10. Carbon Felt (in helium) Los Alamos Data
11. Min-K #2000 Molded Insulation, 20 lb/ft³
12. Min-K #2000 Molded Insulation, (in helium), 20 lb/ft³
13. Tipersul, 3.4 lb/ft³
14. Tipersul, 71.5 lb/ft³
15. Zr O₂ (helium), 265 lb/ft³
16. SiC foam low density
17. SiC foam, high density (in helium)
18. Cercor
19. 17.0 psia Solami Metallic insulation, Solar data (in helium)
20. 314.3 psia Solami Metallic insulation, Solar data (in helium)
21. Hawker-Siddeley Metallic Foil (in helium)
22. Solami, Los Alamos Data

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