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PRESTARTUP THAWING OF LITHIUM
COOLANT IN A NUCLEAR REACTOR
FOR A SPACE POWERPLANT

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1. Report No. NASA TM X-2177	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PRESTARTUP THAWING OF LITHIUM COOLANT IN A NUCLEAR REACTOR FOR A SPACE POWERPLANT		5. Report Date February 1971
		6. Performing Organization Code
7. Author(s) Paul H. Lustig		8. Performing Organization Report No. E-5771
		10. Work Unit No. 120-27
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A calculational study was made assuming heated argon gas being pumped through an annular space between the reactor primary loop and a surrounding jacket. Pumping power requirements and time to melt as a function of radial and axial temperature differences were plotted. Heating power and energy requirements were also determined. The lithium in the reactor could be completely melted in less than 24 hours without exceeding a temperature difference of 25° R (13.9 K) radially or 30° R (16.6 K) axially or a pumping power of 1 kilowatt. An annular gap of 1/4 inch (0.635 cm) was needed and the initial reactor temperature was greater than 200° R (111 K). Constant-heat-flux and constant-inlet-temperature modes of heating were studied, the latter of which can reduce the time to melt by a factor of 4 and the energy requirement by a factor of 2.5. The heating power was 27.5 kilowatts initially for a constant-inlet-temperature mode compared to less than 1 kilowatt of pumping power. Therefore, the heating mode may be dictated by the availability of auxiliary power.

17. Key Words (Suggested by Author(s)) Nuclear reactors Liquid metals Melting Heat transfer Coolant	18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 29	22. Price* $3.00

PRESTARTUP THAWING OF LITHIUM COOLANT IN A NUCLEAR

REACTOR FOR A SPACE POWERPLANT

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SUMMARY

The uranium-nitride-fueled fast reactor being studied at Lewis will probably require that the lithium coolant be thawed prior to startup at some point during its operating history. Temperature differences must be limited during melting so that the increased volume of the melted lithium does not cause excessive stresses in the system. In this study thawing was accomplished by pumping heated argon through an annular space between the reactor primary loop and a surrounding jacket.

This investigation was conducted to determine pumping power and time to melt the lithium as functions of radial and axial temperature differences in the lithium. Argon flow annulus size, heating power, and energy requirements were also determined.

The calculations showed that thawing of the lithium can be performed using argon gas. The lithium can be completely melted in the reactor within 24 hours without exceeding a radial temperature difference at melting of 25° R (13.9 K) or an axial difference of 30° R (16.6 K). And the maximum pumping power required to accomplish this will not be greater than 1 kilowatt. This assumes a 1/4-inch (0.635-cm) annulus and an initial reactor temperature of 200° R (111 K).

Two heating modes were studied: constant heat flux and constant gas inlet temperature. The time to melt, and heating and pumping power requirements, depend on the heating mode. The constant-inlet-temperature mode can reduce the time to melt by a factor of 4 and the pumping energy by a factor of 2.5 below those for the constant-heat-flux mode.

The heating power requirement can be much greater than the pumping power. For example, in constant-inlet-temperature heating an initial heating power of 27.5 kilowatts was calculated compared to a maximum of 1 kilowatt of pumping power. For this reason the mode of heating may be dictated by the availability of auxiliary power sources.

INTRODUCTION

A uranium-nitride-fueled, lithium-cooled fast reactor is being considered as a heat source for electrical power systems to be used in space applications. At some point in its operating history it can be expected that startup of the reactor will have to be accomplished after the lithium coolant has solidified in the reactor and primary heat-transfer loop. Control drums within the reactor pressure vessel are to be cooled by the main lithium flow (fig. 1). This requires that the coolant be thawed before the drums can be rotated. Once the drums are mobile, reactor power may be used to melt the remaining coolant.

Temperature differences should be limited during heating and especially during melting so that volume expansion upon melting does not cause excessive pressures and stresses on the pressure vessel and internal components. It is not known at present what this temperature difference limitation is, but it must be small enough that once melting begins the remainder of the solid lithium will be sufficiently weak to be easily pushed into the voids left on freezing. It would depend on the geometry and strength of the reactor materials as well as on the strength of solid lithium at temperatures near its melting point. The change in volume on melting of lithium and its coefficient of thermal expansion are also factors in determining the maximum acceptable temperature differences.

One of several possible methods of thawing the lithium is to use a heated fluid flowing in the space between the primary loop and a close-coupled surrounding jacket. This jacket could also serve other purposes. If it were leaktight to the lithium, it could be used to prevent complete loss of coolant in the event of a serious leak in the primary system. It could also serve as a barrier to heat losses from the surfaces of the primary loop, or it could protect the refractory components in the primary loop from contamination by surrounding substances, like lunar soil in the case of a powerplant for a lunar base.

This investigation was conducted to determine pumping power and time to melt the lithium as functions of radial and axial temperature differences in the lithium and the argon flow area. Heating power requirements, energy requirements, and pressure drops were also calculated.

Only the heating of the reactor and the primary loop piping were studied in this report. In addition, other components of the system will have to be thawed, such as the primary heat exchanger and pump and any auxiliary components containing lithium coolant. The design of these components is not complete. Neither time limitations or the availability of auxiliary power to both heat and pump the preheating fluid can be specified until a mission assignment is established. However, the range of conditions studied covers those which may be practical. Thus radial and axial temperature differences of as much as 80° R (44.4 K), pumping powers as high as 5 to 10 kilowatts, and times to

melt as long as 100 hours (3.6×10^5 sec) were studied for thawing of the reactor. Annular spaces of 1/16, 1/8, and 1/4 inch (0.159, 0.317, and 0.635 cm) were studied.

The heating fluid selected was argon. The use of gas has advantages over the use of other types of fluids such as organic liquids or liquid metals. The possibility of freezing in the lines makes liquid metals unattractive. Decomposition at the higher temperatures makes the use of organic liquids very unattractive. Argon gas is chosen because of its compatibility with materials and, in particular, because of its consideration as the working fluid in a Brayton-cycle power conversion loop. Hence, it could be obtained from there. Gas is more difficult to pump than other fluids, but the calculations show it would not require excessive auxiliary power to obtain reasonable thawing times and temperature differences.

Two modes of heating were investigated. These were constant-heat-flux input to the reactor and piping and constant inlet temperature of the heating fluid. Graphs were drawn for the constant-heat-flux mode of heating, allowing selection of operating ranges based on limits placed on the aforementioned parameters. The constant-heating-fluid-inlet-temperature mode of heating was studied as a means of improving the performance of the thawing system and providing a more simply controlled alternative to the constant-heat-flux mode.

This study can provide a means of evaluating an argon heating-fluid system once the mission requirements are known. If such a system is used, the variety of heating techniques discussed herein can be used to design the most efficient heating mode. This report may also serve as a guide for analyzing other preheating and thawing systems.

SYSTEM DESCRIPTION

The reactor design is discussed in detail in reference 1. The lithium-cooled fast reactor shown schematically in figure 1 has a six-pointed star-shaped array of fuel elements surrounded by six rotating molybdenum control drums and molybdenum side reflectors. Each drum contains a tantalum absorber piece and several fuel pins. The whole is enclosed in a cylindrical pressure vessel capped by torispherical heads. The control-drum drive nozzles contain the drive shafts, bearings, and penetration devices and protrude from either end of the pressure vessel. There is a molybdenum reflector at the inlet and outlet ends of the core.

Lithium is present throughout the whole assembly except in the fuel pins. Thus lithium surrounds the control drums up to the penetration device, surrounds the molybdenum side reflectors, is inside the coolant annuli surrounding the fuel pins, and is in the inlet (bottom) and outlet (top) plenums between the reflectors and the pressure vessel. To give an idea of dimensions: the outside diameter of the pressure vessel is

22.7 inches (57.7 cm), the fuel length is 14.8 inches (37.6 cm), and the reflector thickness at inlet and outlet is 2 inches (5.1 cm). The primary piping has an inside diameter of 3 inches (7.6 cm).

MODEL AND APPROACH

Mathematical Model

The calculations are based on a model of the reactor which is cylindrical and has an outside diameter of 1.90 feet (0.579 m) and is 2 feet (0.610 m) long, as shown in figure 2. Values of the annular space between the reactor and jacket were chosen to be 1/16, 1/8, and 1/4 inch (0.159, 0.317, and 0.635 cm).

The piping was assumed to have a 3-inch (7.6-cm) inside diameter and the length chosen for the calculation was 100 feet (30.5 m). The length of pipe will depend on the mission. The only annular gap size investigated around the piping was 1/4 inch (0.635 cm).

The flow of gas is straight through the annular space. Heating of the reactor and piping were analyzed separately.

Governing Equations

The equations used to describe the heating of a solid by a flowing fluid are

$$V_b \rho_b C_b \frac{dT_b}{dt} = UA_{ht}(T_m - T_b) \tag{1}$$

$$V_f \rho_f C_f \frac{dT_m}{dt} = W_f C_f(T_i - T_o) - UA_{ht}(T_m - T_b) \tag{2}$$

where the subscript b refers to the solid (reactor or piping), the subscript f refers to the heating fluid, and T_m is the mean temperature of the fluid. (All symbols are defined in the appendix.)

In these equations the temperature of the reactor T_b is assumed to be independent of position. These equations are used to study the time to melt the lithium t_m as a function of gas flow rate (or pumping power). Temperature differences within the reactor axially and radially are not considered in these equations. The value of U (the overall heat-transfer coefficient) was taken as the film coefficient for the flowing gas. There

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will actually be temperature differences between the reactor surface and the interior. Hence, the true driving force for heat transfer into the reactor (e. g. , the temperature difference between the argon and the reactor surface) will be less than that which assumes an averaged uniform temperature as in these calculations. This will lead to slightly optimistic estimates of the time to melt. The smaller the radial temperature difference, the closer these approximate equations approach actual heat-transfer conditions. For the purpose of this preliminary study the results are adequate, particularly in view of the fact that radial temperature differences are purposely kept small. Also there is much conservatism built into the time-to-melt calculations since only the lithium which surrounds the control drums must be melted by the preheating system. These calculations assume that all the lithium is to be melted.

The initial temperature of the reactor T_b before the preheating operation begins or at $t = 0$ will probably depend on the mission. It is not certain that the reactor will be insulated from radiating to space nor how long after launch preheating will be started. A conservative assumption was made which assigns an initial reactor temperature of 200° R (111 K). This is approximately the temperatures recorded on the Surveyor solar panels after the onset of lunar night.

Equations (1) and (2) were used in this analysis of the two modes of heating studied in this report: the constant-heat-flux mode and the constant-inlet-temperature mode.

Constant-Heat-Flux Heating Mode

Heating and thawing of a solid cylinder does not lend itself easily to analysis, particularly when the heating fluid is a gas where the inlet- to outlet-temperature drop may be significant. The constant-heat-flux mode of thawing was investigated first because it gave a simple technique for establishing times for melting.

For this mode of heating the heating rate of the materials in the core is constant and is equal to the term $UA_{ht}(T_m - T_b)$ in equations (1) and (2). The left side of equation (1) shows how the temperature of the reactor rises as a result of this constant heat rate into it. Since the heating rate is constant and properties are assumed to be independent of temperature, the rate of temperature rise of the reactor dT_b/dt will be constant. Again, $T_m - T_b$ must be constant, and that means dT_m/dt in equation (2) must be equal to dT_b/dt, or the mean gas temperature must rise at the same rate as the reactor temperature. A comparison of the value of $V\rho C_p$ of solid and fluid showed that the value for the fluid (gas) is negligible compared to that of the solid (reactor). Hence, the heat represented by the left side of equation (2) is negligibly small compared to the left (or right) side of equation (1). For this reason the left side of equation (2) could be neglected and a balance established between the heat lost by the fluid $\left[W_f C_f(T_i - T_o)\right]$ and the heat

gained by the reactor $hA_{ht}(T_m - T)$. Thus

$$hA_{ht}(T_m - T_b) = W_f C_f (T_i - T_o) = q \qquad (3)$$

In these calculations the reactor temperature T_b was independent of axial position. A logarithmic mean temperature was used for T_m.

A flow rate was established that balanced equation (3) for particular values of T_o, T_i, and T_b, where h is a function of the flow rate. Then q was assumed to be constant for the remainder of the thawing process. That is how the constant-heat-flux mode of heating was used to analyze the melting times. The total heat required to melt the lithium in the reactor (1.78×10^5 Btu or 1.87×10^8 J) or piping (1.56×10^5 Btu or 1.64×10^8 J) per 100 feet (30.5 m) was divided by the heating rate q to obtain the time to melt.

The radial temperature difference in the reactor may be calculated from the constant-heat-flux input using the equations of Carslaw and Jaeger (ref. 2, p. 203). The initial transient in the establishment of the radial temperature profile with constant heat flux is virtually complete within minutes. Therefore, the infinite-time radial temperature profile was used throughout the calculations. Although the axial temperature distribution in the reactor is not calculated (an average temperature in the axial direction is used), the actual temperature difference in the axial direction would be less than that in the heating fluid. Therefore, the axial temperature differences in the reactor can be limited by limiting the inlet- to outlet-temperature difference in the heating fluid.

The following equations were used to calculate the heat-transfer coefficient h in the heat balance equation and the friction factor f used in the calculation of pumping power. They are from reference 3 (pp. 467 and 383, respectively).

$$h = \frac{16.6 \, C_p G^{0.8}}{(D_i)^{0.2}} \left(= \frac{0.765 \, C_p G^{0.8}}{(D_i)^{0.2}} \right)$$

and

$$f = 0.00140 + 0.125 \left(\frac{\mu}{D_i G} \right)^{0.32}$$

where

D_i equivalent inside diameter, in.; cm

G mass velocity, lb/(sec)(ft^2); kg/(sec)(m^2)

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C_p heat capacity of the gas, Btu/(lb)($^{\circ}$F); J/(g)(K)

h   heat-transfer coefficient, Btu/(hr)(ft^2)($^{\circ}$F); W/(m^2)(K)

μ/D_1G unitless Reynolds number

f   unitless Fanning friction factor

Constant-Inlet-Temperature Heating Mode

The temperature differences occurring just before melting are of major concern. Although the heat flux into the reactor was assumed to be constant during the entire heating process in the previous mode, the heat flux could initially be increased and later be reduced as melting is approached. One method of accomplishing this is by maintaining a constant inlet temperature in the heating fluid.

In order to analyze this mode, the time-dependent heat-transfer equations (eqs. (1) and (2)) were used to calculate the rise in temperature of the lithium in the reactor as a function of time with the gas inlet temperature held constant.

In order to obtain solutions for these equations, the following assumptions were made:

(1) The average or mean temperature of the gas T_m is the arithmetic average of the inlet and outlet temperatures.

(2) The lithium or reactor temperature was independent of axial position.

(3) The density of the heating fluid was constant during the heating process.

The AIROS program (ref. 4) was used for these calculations since it will solve sets of these types of equation, although it is specifically designed for solving reactor kinetics problems.

Physical Properties Used for Calculations

The physical properties used for the calculations were obtained from several sources. Table I shows the values used and the references from which they were obtained.

In the pumping power calculations, viscosity and density at the average temperature of the heating fluid were used. The other properties of the fluid were considered to be constant.

Properties of the reactor, such as heat capacity and density, were averaged with respect to the weights of the materials in the reactor. The thermal conductivity was calculated at the lithium melting point since the radial temperature difference at that

temperature is of prime importance.

In order to calculate the average thermal conductivity of the reactor, it was first divided into four concentric regions or rings. The outside ring was the T-111 pressure vessel, followed by a thin annulus of lithium as the second ring. The molybdenum reflector and control drums with the T-111 absorber made up the third ring, and the reactor core the fourth. The thermal conductivity for each ring was calculated by averaging with respect to material weight within the ring. It is the overall resistance to heat transfer from the outside of the pressure vessel to the center of the core that establishes the radial temperature difference. The resistance of each ring to heat transfer $\Delta X/kA_{ht}$ was then calculated. The sum of all the resistances is the overall resistance, and from this the overall thermal conductivity was calculated. The equations for conduction through slabs in reference 3 (p. 460) had to be converted to the cylindrical geometry of the reactor.

The material weights in the reactor together with the averaged values of the properties for the reactor appear in table II.

The total amount of heat required for heating the reactor and melting the lithium was calculated from the averaged specific heat of the reactor, the total weight of the reactor, the weight of lithium, and its heat of fusion. The values presented earlier for the heating requirement were based on an initial temperature of 200° R (111 K). The averaged heat capacity and thermal conductivity for the piping are also presented in table I, together with the weight per 100 feet (30.5 m) of the materials composing it.

RESULTS AND DISCUSSION

Constant-Heat-Flux Heating Mode

The results for the constant-heat-flux heating and thawing of the reactor coolant are presented in figures 3(a) to (c), each representing a different annular gap around the reactor. Figure 4 is a similar graph for the primary piping with an annular gap of 1/4 inch (0.635 cm). The curves show the interrelation between the radial temperature difference ΔT_r, the inlet to outlet temperature drop in the gas ΔT_g, and the pumping power requirement H_{max}.

The power required to pump the fluid H_{max} was calculated on the basis of the final temperature of the fluid. This is the maximum power requirement for the gas because the pumping power rises with the increasing temperature necessary to maintain the constant heat flux. The rising temperature decreases the density of the gas and increases its viscosity, both of which cause an increased pumping power requirement.

Once these parameters (ΔT_r, ΔT_g, and H_{max}) are selected, the abscissa shows the

initial outlet temperature of the heating fluid. The initial inlet temperature is obtained by adding the gas temperature drop to the outlet temperature. These temperatures will rise during the heating process, but the difference from inlet to outlet is constant because the flow rate and heating rate are constant.

The other parameter of interest, time to melt t_m is plotted in figures 5 and 6. This is a function only of the radial temperature difference and the initial lithium temperature.

By establishing limits on the parameters, an area may be enclosed on the graph that includes all acceptable operating points. As an example, consider figure 3(c), where the annular gap is 1/4 inch (0.635 cm) around the reactor. We can set an upper limit on the radial temperature difference of 25° R (13.9 K), and on the axial temperature difference (in these calculations the difference between inlet and outlet gas temperature) a limit of 30° R (16.6 K). The upper limit on pumping power was assumed to be 1 kilowatt for this example. The fourth limit placed on the time to melt is 24 hours. To apply this limitation, figure 5 is used. To keep the time to melt less than 24 hours, the radial temperature difference must be greater than 12° R (6.7 K) (initial reactor temperature of 200° R (111 K)). If these four boundaries are drawn on figure 3(c), they enclose the shaded area ABCD. A possible operating point would be point E where $\Delta T_g = 23^{\circ}$ R (12.8 K), $\Delta T_r = 15^{\circ}$ R (8.3 K), $H_{max} = 0.27$ kilowatt, $t_m = 20$ hours, $T_o = 254^{\circ}$ R (-206° F; 141 K), and $T_i = 277^{\circ}$ R (-183° F; 154 K).

Other values of interest in the process are the fluid flow rate W and the fluid pressure drop ΔP. In this case W = 3200 pounds per hour (0.405 kg/sec) and $\Delta P = 0.1$ psi (4.8 N/m^2).

The shaded area is much smaller for the 1/8-inch (0.317-cm) annulus under the same operating limits (fig. 3(b)). No operating points could be found for the 1/16-inch (0.159-cm) annulus (fig. 3(a)).

A curve showing the variation in pumping power for the sample case just described appears in figure 7. The initial pumping power requirement is about one-twentieth the pumping power at the lithium melting point.

The initial solid lithium (or reactor) temperature in all cases was 200° R (111 K) and the outlet gas pressure was 1 atmosphere. The initial gas inlet temperature is just a few degrees above that in the constant-heat-flux case. This very low temperature estimate is probably conservative, and any initial temperature above 200° R (111 K) will shorten the melt time. For example, in the sample case if the initial temperature of the reactor and the gas was earth ambient (about 70° F; 530° R or 295 K), the melt time would have been reduced from 20 to 10.3 hours.

Heating the lithium in the piping is considered separately from the reactor. The limits used in the example for the reactor do not produce an operating area even for the 1/4-inch (0.635-cm) annulus around the 100 feet (30.5 m) of piping. However, an oper-

ating area can be found if the limit of ΔT_g is increased to about 100° R (other parameters remaining the same). While this limit may prove to be excessive for the reactor with its complex and delicate interior, it may be adequate in the longer and simpler piping. The possibility of improving performance by other heating modes, larger annular gaps, and so forth, is discussed later (p. 12).

Constant-Inlet-Temperature Heating Mode

Results of the calculations showed that use of the constant-inlet-temperature heating mode can greatly reduce the time to melt. This can be seen in table II, where the two modes of heating are compared for a 1/8-inch (0.317-cm) annular spacing and a maximum pumping power of 3.3 kilowatts. The left side of table II shows the time to melt in the constant-heat-flux mode for the same ΔT_r as that which occurs at melting in the constant-inlet-temperature mode. Thus, for a constant inlet temperature of 860° R (487 K), the ΔT_r at melting was 17.3^O R (9.6 K) and the melt time was 4.0 hours. When a ΔT_r of 17.3^O R (9.6 K) is maintained over the entire thawing process, the time to melt is 16.5 hours as shown on the left side of the table.

When only the constant-inlet-temperature mode was considered for different inlet temperatures, it was found again as expected that the higher inlet temperatures reduced the time to melt, at the expense of increased radial temperature difference. From the right side of table II it is seen that in going from an inlet temperature of 825° to 860° R (459 to 487 K) the time to melt is reduced by a factor of about $2\frac{1}{2}$ (10.7 to 4.0 hr). But the radial temperature difference rises by a factor of about 4 (4.14^O to 17.3^O R).

Figure 8 shows the average reactor surface temperature as a function of time for various inlet temperatures in the constant-inlet-temperature mode of heating. A large fraction of the time to melt occurs with the lithium at the melting point. At the lowest inlet temperature, 825° R (459 K), the reactor is at the lithium melting point during 70 percent of the heating process.

This indicates that it may be possible to decrease the time to melt very significantly by increasing the heat flux once melting has occurred on the outside surface of the lithium. Throughout this report the radial and axial temperature differences were considered to be limiting factors. However, what is primarily of concern is the difference between the lithium melting point and the lowest temperature in the reactor (or piping) at the time melting begins. If the temperature differences at that time are within the limit imposed, all the lithium may be soft enough to extrude into the voids left on freezing without causing excessive stresses. Once that point is reached it can be assumed that an increased heat flux will not cause excessive stresses since any remaining solid will still be able to extrude into the voids.

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Thus the constant-inlet-temperature mode can decrease the time until melting begins. But a further reduction in time to melt can be obtained by raising the gas temperature (and, hence, heat flux) after melting begins without increasing the temperature difference in the solid lithium. Of course, the higher gas temperature will require a small increase in pumping power.

To make a further comparison between the two modes of heating, calculations were made for the case where the radial temperature difference at melting was the same for various constant inlet temperatures. Since ΔT_r was 10.2^O R (5.67 K) for all inlet temperatures, these cases all compare with a time to melt of 29 hours in the constant-heat-flux mode.

Figure 9 shows the average reactor temperature as a function of time for various inlet temperatures for the constant-inlet-temperature mode. In this case the higher inlet temperatures do not reduce the time to melt but increase it. This is also shown in table III, where the cases are compared in tabular form. As the inlet temperature is increased, the axial temperature difference ΔT_g also increases along with the time to melt. This occurs as a result of the reduced heat transfer (and, hence, flow rate) necessary at the higher inlet temperatures to maintain the same radial temperature differences at melting. The maximum pumping power requirement H_{max} would then be reduced at the higher inlet temperatures, as shown also in table III. The table thus shows that, if it is desired to maintain a particular radial temperature difference at melting, the time to melt and the axial temperature difference can be reduced only by lowering the inlet temperature, but this is done at the expense of a higher pumping power.

One further calculation was made comparing the constant-heat-flux and constant-inlet-temperature modes of heating. The energy requirement was calculated for the pumping of the gas during equivalent reactor thawing operations. The energy requirement in the constant-inlet-temperature mode was less than one-half that of the constant-heat-flux mode. The values of the parameters used in the calculation and the results are presented in table IV.

Figures 10 and 11 show the pumping power and energy requirements as a function of time during the melting process. The power requirement in the constant-heat-flux mode is initially lower than that of the constant-inlet-temperature case. However, because of the much longer time required for melting in the constant-heat-flux case, more energy is required to power the pump overall than in the constant-inlet-temperature mode of heating.

The comparisons made in this section are between the constant-heat-flux and constant-inlet-temperature modes of heating. The former was a conservative and mathematically expedient choice which may prove difficult to carry out in practice. This was compared with the more simply controlled constant-inlet-temperature mode of heating. Both techniques use constant gas flow rates. However, there may be other procedures

of varying temperatures and flows which could result in more effective performance of the preheating system.

Techniques for Improving System Performance

One of several techniques to improve the system performance would be to increase the heat flux once melting begins. This would shorten the time to melt beyond that obtained with the constant-inlet-temperature mode of heating. In addition, helium gas might be substituted for argon. This would cut the pumping requirement by a factor of about 10. Higher gas pressures than the 1 atmosphere used in these calculations can also reduce the pumping power. A still larger annular space than 1/4 inch (0.635 cm) might be used to meet tighter limits on temperature differences, pump power, or time.

In this study the gas was assumed to be pumped straight through the reactor annulus or the piping annulus. This could be done in one of the three ways shown in figure 12.

However, if it is found necessary to reduce axial temperature differences, the reactor or piping heating annulus could be further divided into parallel paths. This may be desirable in the piping example previously discussed, where the other limits could only be satisfied by allowing the axial temperature difference to approach 100° R (55 K).

Heating Power and Energy Requirements

Until now the only auxiliary power requirement studied has been that necessary to pump the heating fluid. This would typically be an electric power source. However, power will be required to heat the gas as it transfers its heat to the reactor or piping. The amount of this power depends primarily on the heating rate in the reactor or piping. There is also some power required to raise the gas temperature from its initial condition to its final condition when all the lithium is melted. This requires very little energy compared to the heat required in the melting and so was neglected.

The amount of energy required to heat the reactor and to melt the lithium (1.78×10^5 Btu; 52 kW-hr or 1.87×10^8 J) is about the same in the reactor and in the piping, so only the reactor will be discussed.

For the constant-heat-flux case the heating power requirement is simply $52/t_m$ kilowatts, where t_m is the time to melt. It will be constant for the whole heating process. For the operation proposed in table IV with constant heat flux, the heating power would be 52/28 or 1.8 kilowatts.

For the constant-inlet-temperature case the heating rate is initially very high, and for this same example is 27.5 kilowatts. This requirement drops off quickly to the same

1.8 kilowatts as in the constant-heat-flux case once melting begins.

The heating power requirement is much greater than the pumping power in both modes of heating. If this heating power is too high for electrical supply, some other kind of heat supply may be required to transfer heat to the gas quickly enough. The availability of heat sources for the gas may be the controlling factor in determining the mode of heating the lithium and in establishing the time to melt.

CONCLUSIONS

The calculations presented herein show that thawing of the lithium coolant can be performed using heated argon gas. Results showed that a wide operating range was available for melting the lithium in the reactor for a sample set of limits: annular gap, 1/4 inch (0.635 cm); radial temperature difference, $\Delta T_r < 25^{\circ}$ R (13.9 K); fluid temperature drop, $\Delta T_g < 30^{\circ}$ R (16.6 K); maximum power required to pump fluid, $H_{max} < 1.0$ kilowatt; time to melt, $t_m < 24$ hours. These limits are based on an initial lithium temperature of 200° R (111 K). They apply for both the constant-heat-flux and constant-inlet-temperature modes of heating.

The constant-inlet-temperature mode of heating can significantly reduce the time to melt and the energy needed to pump the fluid while maintaining the same limits on radial and axial temperature differences and on maximum pump power. For one set of limits, it was found that the melt time could be reduced by a factor of 4 and the energy requirement by a factor of 2.5 by going from constant-heat-flux heating mode to a constant-inlet-temperature heating mode.

The time to melt will ultimately depend on the availability of power and energy supplies and the limits that must be placed on radial and axial temperature differences. However, any attempt to reduce the time to melt will increase the power requirement for heating the argon. For instance, it was calculated that the initial heating power requirement for the constant-inlet-temperature case was 27.5 kilowatts compared to only 1.8 kilowatts for the comparable constant-heat-flux case (i.e., same ΔT_r and ΔT_g at melting). Of course, the heating power at melting is the same 1.8 kilowatts for both cases. If short times to melt are required, it may be necessary to supply some other heat source besides electrical power to transfer heat to the gas quickly enough.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, September 30, 1970,
            120-27.

APPENDIX - SYMBOLS

A_{ht} area for heat transfer from fluid in annular space to reactor or piping

C_b average heat capacity over reactor

C_f heat capacity of fluid

D_i equivalent internal diameter of annulus (in in. for calculation of h)

E energy required to pump fluid

f fanning friction factor

G mass velocity of heating fluid (in lb/(sec)(ft^2) for calculation of h)

H power required to pump fluid

H_{max} maximum power required to pump fluid during heating period

h film heat-transfer coefficient

ΔP fluid pressure drop

q heating rate

T_b average temperature of reactor or piping - assumed uniform in each initially and during heating and melting

T_i fluid inlet temperature

T_m average fluid temperature

T_o fluid outlet temperature

ΔT_g fluid temperature drop from inlet to outlet, $T_i - T_o$ (also assumed as measure or limit to the axial temperature difference in the lithium)

ΔT_r radial temperature difference in the lithium

t heating time

t_m time to achieve complete melting of the lithium

u overall heat-transfer coefficient

V volume

V_b volume of reactor or solid component to be heated

V_f volume of fluid in preheating system

W flow rate of heating fluid

μ viscosity of heating fluid

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ρ average density

ρ_b average density of reactor or solid component to be heated

ρ_f average density of fluid

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TABLE I. - PHYSICAL PROPERTIES OF REACTOR AND PIPING MATERIALS AND HEATING FLUID, MATERIAL WEIGHTS AND

AVERAGED REACTOR AND PIPING PROPERTIES USED IN CALCULATIONS

Material	Weight in reactor[a]		Weight per 100 ft (30.5 m) of piping[a]		Density		Heat capacity		Thermal conductivity[b]		Viscosity		Heat of fusion	
	lb	kg	lb	kg	lb/ft^3	kg/m^3	$\frac{Btu}{(lb)(°F)}$	$\frac{J}{(g)(K)}$	$\frac{Btu}{(hr)(ft)(°F)}$	$\frac{W}{(m)(K)}$	cP	$N\text{-}sec/m^2$	Btu/lb	J/g
Argon gas	----	------	----	-----	[c]0.11 (ref. 3)	1.76	0.128 (ref. 3)	0.537	----	-----	[c]0.0195 at 0° C (ref. 3)	1.95×10^{-5}	------	---
Lithium	65	29.5	141	64.0	30 (ref. 3)	481.2	1.0 (ref. 3)	4.179	26 (ref. 5)	45	-------	---------	[d]284 (ref. 8)	657
Uranium nitride	419	190.2	----	-----	895 (ref. 6)	1.435×10^4	0.045 (ref. 6)	0.189	9.4 (ref. 6)	16.3	-------	---------	------	---
Molybdenum (TZM)	2043	927.5	----	-----	624 (ref. 7)	1.00×10^4	0.066 (ref. 7)	0.277	80 (ref. 7)	139	-------	---------	------	---
T-111 (tantalum alloy)	1417	643.3	1664	755.4	1040 (ref. 7)	1.67×10^4	0.034 (ref. 7)	0.142	25 (ref. 7)	43.5	-------	---------	------	---
Average for reactor	3944	1790.6	----	-----	543	8.71×10^3	0.0677	0.283	24	41.5	-------	---------	------	---
Average for piping	----	------	1805	819.4	286	4.58×10^3	0.109	0.455	26	45	-------	---------	------	---

[a]Material weights were design values at time of report and were not published.
[b]At lithium melting point.
[c]Varies with temperature in calculation.
[d]Melting point of lithium was 354° F or 814° R (451.7 K), ref. 8.

TABLE II. - COMPARISON OF HEATING MODES AT EQUIVALENT

MAXIMUM PUMPING POWER (3.3 kW)

[Annular spacing, 1/8 in. (0.317 cm).]

Constant-heat-flux mode			Constant-inlet-temperature mode				
Radial temperature difference ΔT_r throughout melting		Time to melt, t_m, hr	Inlet temperature, T_i		Radial temperature difference ΔT_r at melting point		Time to melt, t_m, hr
°R	K		°R	K	°R	K	
4.14	2.30	70	825	459	4.14	2.30	10.7
17.3	9.63	16.5	860	487	17.3	9.63	4.0
32.3	18.0	8.9	900	500	32.3	18.0	2.7

TABLE III. - COMPARISON OF HEATING MODES AT EQUAL RADIAL

TEMPERATURE DIFFERENCES

[Annular spacing, 1/8 in. (0.317 cm).]

Constant-heat-flux mode			Constant-inlet-temperature mode							
Radial temperature difference ΔT_r throughout melting		Time to melt, t_m, hr	Inlet temperature, T_i		Radial temperature difference ΔT_r at melting point		Fluid temperature drop, ΔT_g		Power to pump fluid (maximum), H_{max}, kW	Time to melt, t_m, hr
°R	K		°R	K	°R	K	°R	K		
10.2	5.67	29	825	459	10.2	5.67	4.75	2.64	58.9	4.35
			835	465			10.1	5.62	7.4	5.05
			860	487			25.0	13.9	.63	6.60
			900	500			51.0	28.4	.092	8.40
			1000	555			123.0	68.5	.009	11.1

TABLE IV. - VALUES OF PARAMETERS USED FOR ENERGY

REQUIREMENT COMPARISON OF HEATING MODES

(REACTOR ONLY)

Parameter	Constant-heat-flux mode	Constant-inlet-temperature (860° R) mode
Radial temperature difference, ΔT_r, ^{O}R (K)	10.2 (5.67)	
Fluid temperature drop, ΔT_g, ^{O}R (K)	25 (13.9)	
Maximum power required to pump fluid, H_{max}, kW	0.62	
Flow rate of gas, W, lb/hr (kg/sec)	2037 (0.256)	
Annular gap, in. (cm)	1/8 (0.317)	
Results of calculations		
Time to melt, t_m, hr	28.8	6.6
Energy required to pump fluid, E, kW-hr (J)	8.4 (3.02×10^7)	3.4 (1.22×10^7)
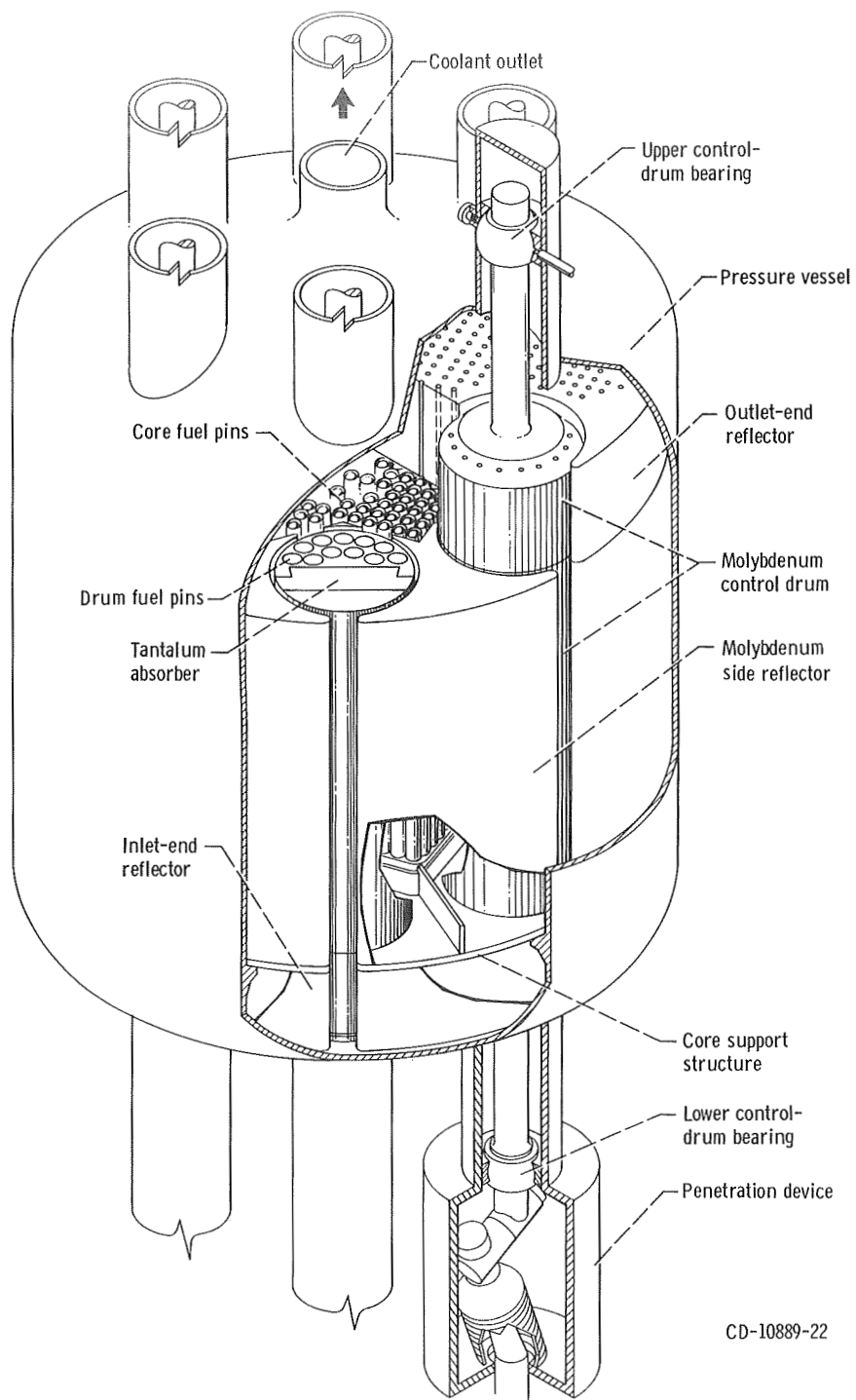
Figure 1. - Lithium-cooled fast reactor.

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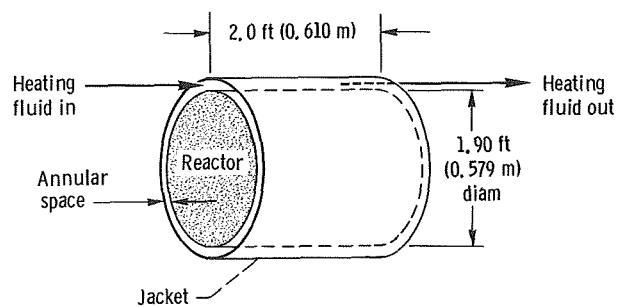
Figure 2. - Mathematical model used in calculation of reactor heating.
A similar model was used for 100 feet (30. 5 m) of 3-inch (7. 62-cm)
piping.
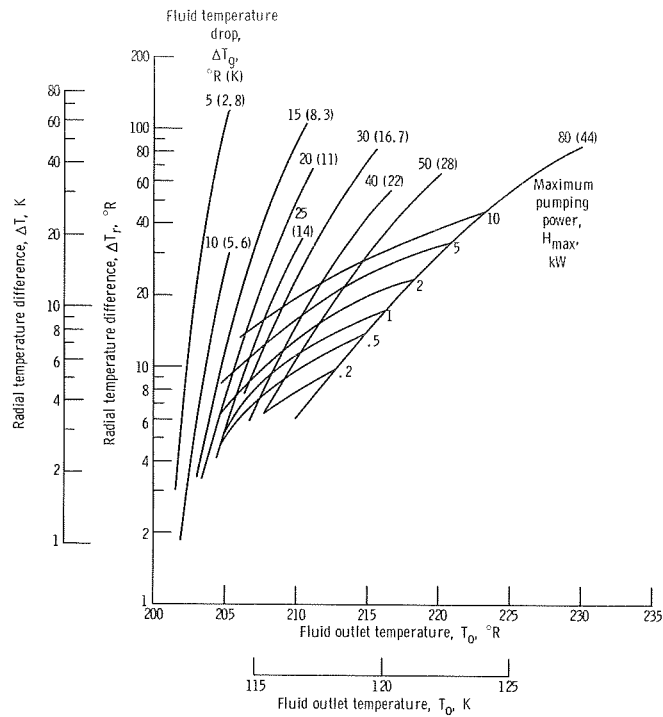
(a) Annular spacing of 1/16 inch (0.159 cm) around reactor.
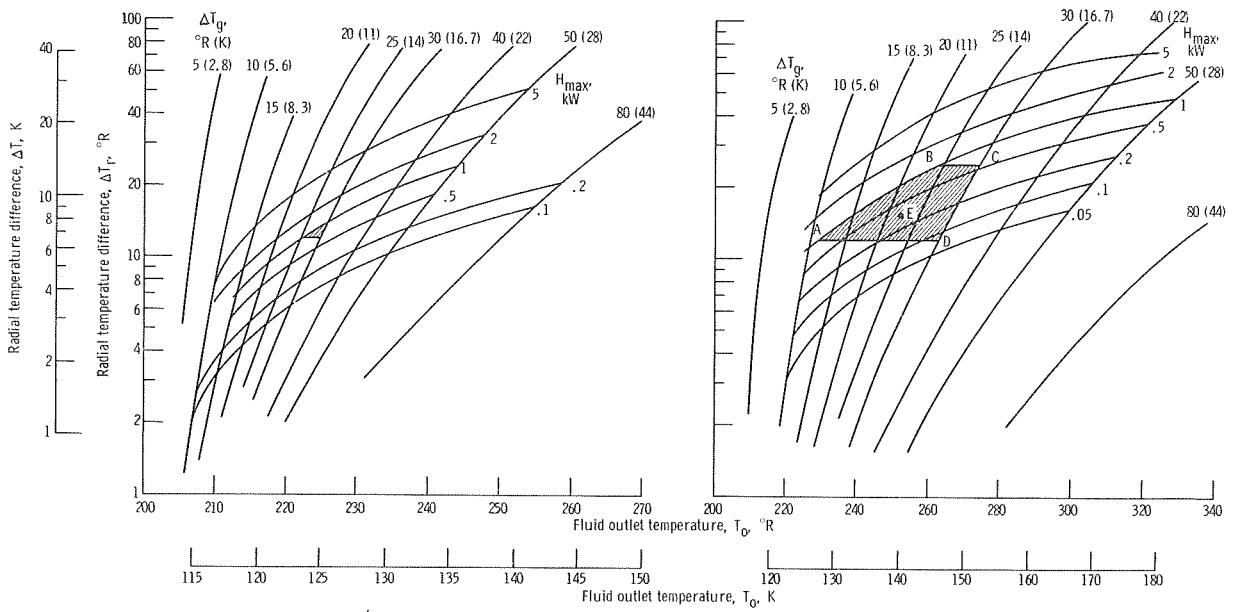
(b) Annular spacing of 1/8 inch (0.317 cm) around reactor.

(c) Annular spacing of 1/4 inch (0.635 cm) around reactor.

Figure 3. - Variation of radial temperature difference with fluid outlet temperature, temperature drop, and pumping power for three annular spacings.
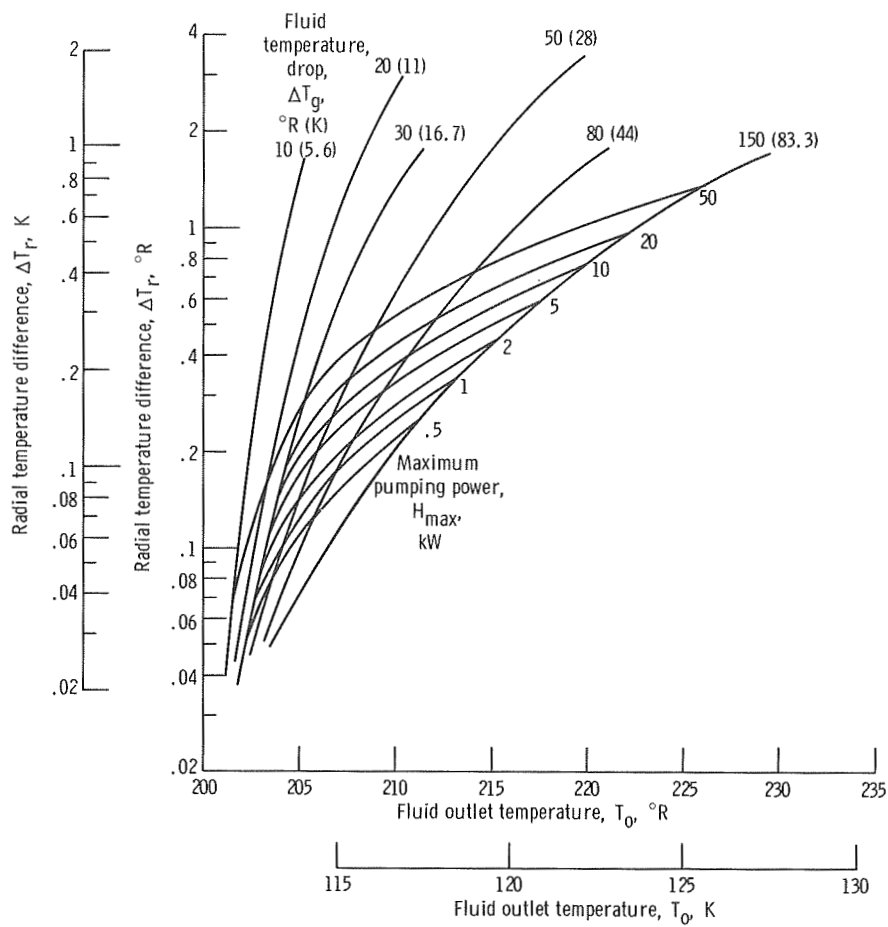
Figure 4. - Variation of radial temperature difference with fluid outlet temperature, temperature drop, and pumping power for annular spacing of 1/4 inch (0.635 cm) around piping.
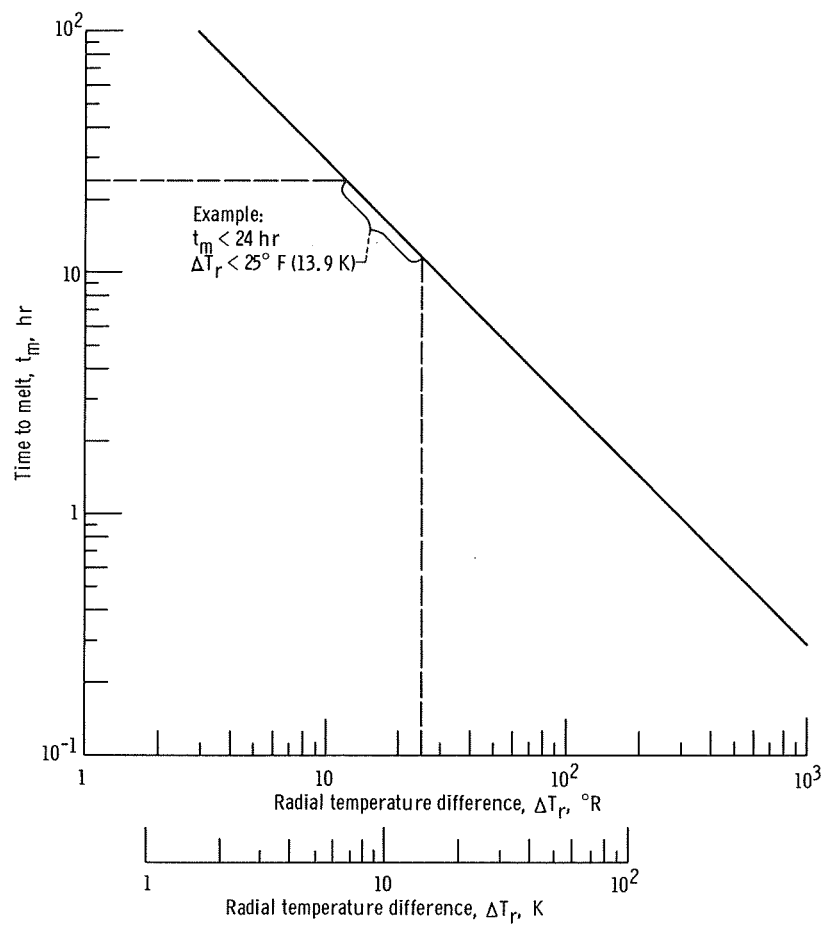
Figure 5. – Time to melt as function of radial temperature difference in reactor. Initial reactor temperature, 200° R (111 K).

Figure 7. - Pumping power variation during heating and melting of reactor lithium with constant heat flux. Fluid temperature difference, $\Delta T_g = 23°$ R (12.8 K); radial temperature difference, $\Delta T_r = 15°$ R (8.3 K). Initial temperatures: reactor, $T_b = 200°$ R (111 K); inlet, $T_i = 277°$ R (154 K); outlet, $T_o = 254°$ R (141 K).

Figure 6. - Time to melt as function of radial temperature difference in piping. Initial piping temperature, 200° F (111 K).
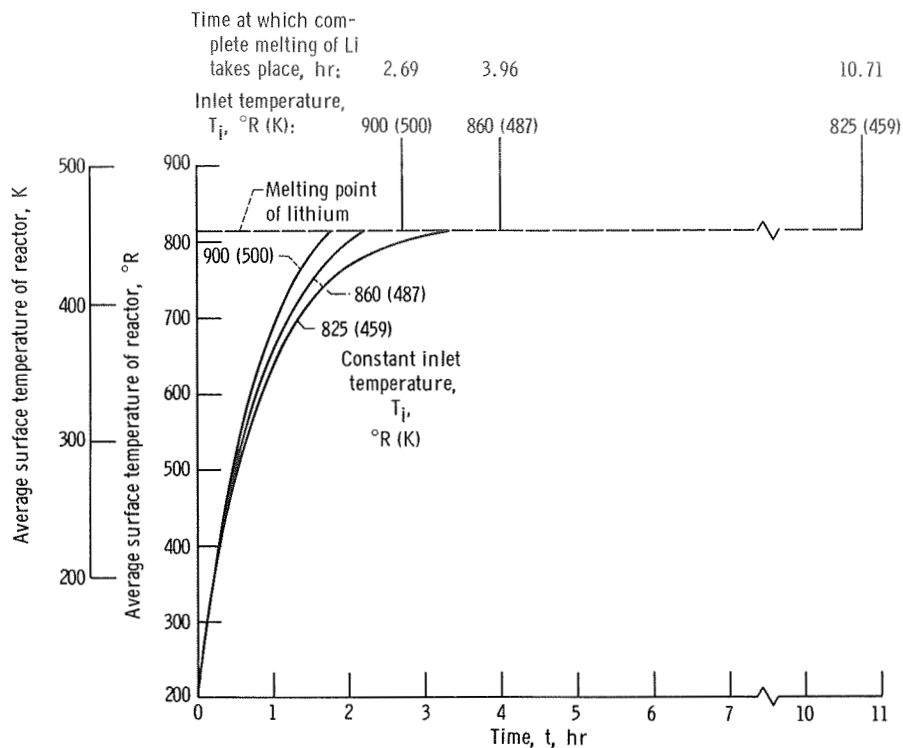
Figure 8. - Temperature rise in reactor lithium as function of heating time for various constant inlet temperatures of gas at equivalent pumping power of ~3.3 kilowatts.
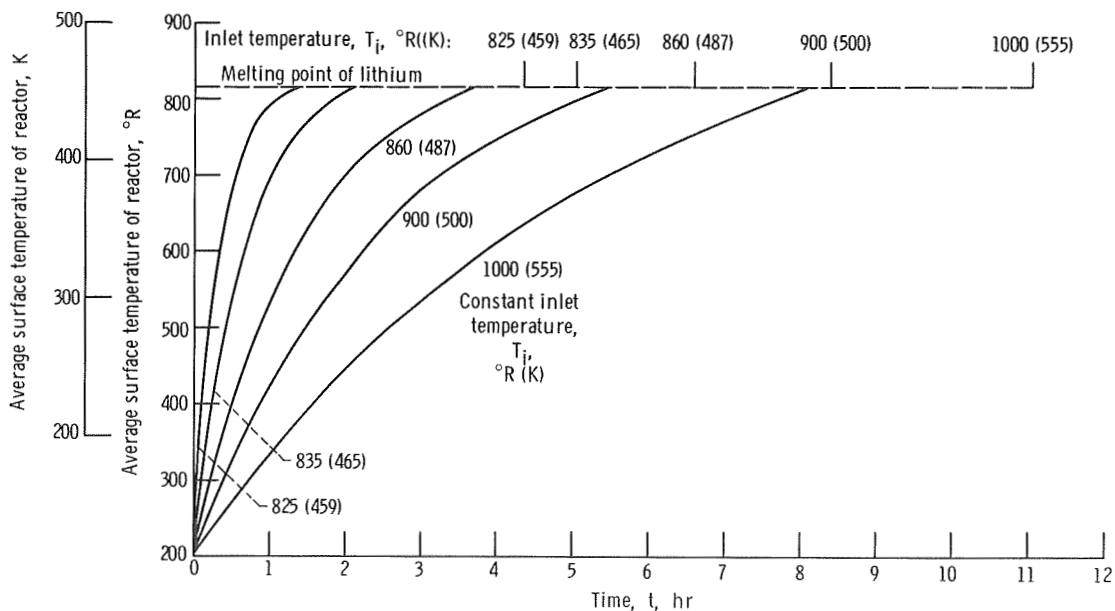
Figure 9. - Temperature rise in reactor lithium as function of heating time for various constant inlet temperatures of gas. Radial temperature difference the same in all cases, 10.2° R (5.67 K) at melting point.
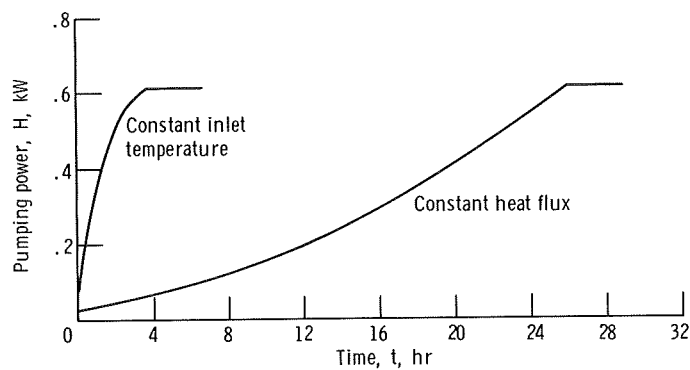
Figure 10. – Variation of pumping power requirement with heating time
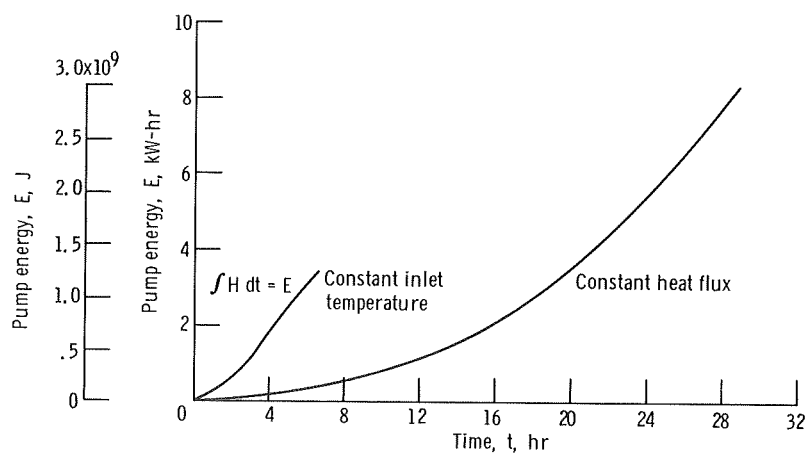for two modes of heating (see table IV for conditions).

Figure 11. – Energy required for pumping as function of heating time for two modes
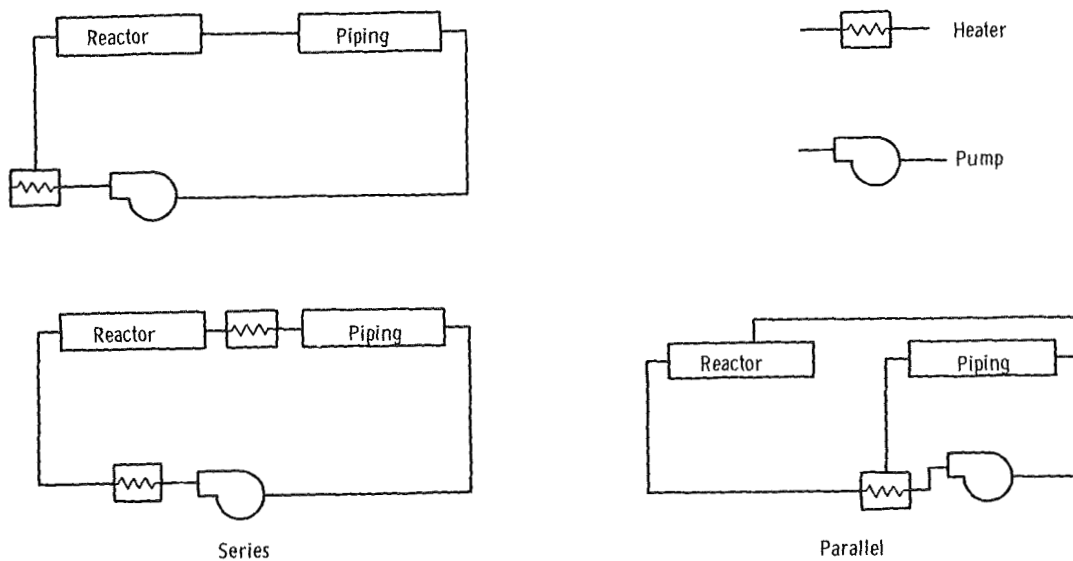of heating. (Integral of curves of fig. 9.)

Figure 12. - Variations in heating and pumping arrangements for straight-through heating fluid flow.

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