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PRELIMINARY ANALYSIS OF ACCIDENTS IN A LITHIUM-COOLED SPACE NUCLEAR POWERPLANT

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Cleveland, Ohio

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16. Abstract

Reactor power, fuel, and coolant temperature responses to five types of accidents ((1) loss of coolant, (2) loss of flow, (3) ramp reactivity insertions, (4) cold lithium additions, and (5) plugging of coolant channel) occurring at 100 percent power were calculated to establish preliminary safety requirements for a uranium nitride - fueled fast reactor. Loss of coolant must be avoided, or auxiliary coolant must be provided within 380 sec to avoid melting the fuel. After losing coolant flow, natural convective cooling is inadequate, and auxiliary pumps may have to provide up to 20 percent of the design flow to prevent coolant boiling.

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SUMMARY

A uranium nitride - fueled, fast-spectrum, lithium-cooled nuclear reactor is being considered for a space nuclear powerplant. A preliminary analysis of five potential accidents occurring at 100 percent power (2.17 MW thermal) was conducted to define potential problem areas and to establish preliminary control and safety requirements. The five accidents are (1) loss of coolant, (2) loss of flow, (3) ramp reactivity insertions of 10 and 50 cents per second, (4) cold lithium additions, and (5) plugging of coolant channel.

After a loss of coolant from the reactor, heat must be removed from the fuel within about 380 seconds to prevent melting. If the fuel is not cooled, precautions must be taken to prevent the formation of a supercritical array after meltdown of the reactor. After losing coolant flow, natural convection cooling would be inadequate; however, auxiliary pumps could easily provide up to 20 percent of the design flow and prevent coolant boiling. When reactivity is ramped at 50 and 10 cents per second, the reactor must be shutdown within 2 and 8 seconds, respectively. The reactor could be shut down within 2 seconds to prevent coolant boiling. When the coolant temperature is suddenly reduced, the maximum fuel temperature rise is about one degree per degree reduction in coolant temperature. The fuel and coolant temperature rise following a plugged coolant channel are about 60° and 45° R (33 and 25 K), respectively.

INTRODUCTION

A uranium nitride - fueled, fast-spectrum, lithium-coolant nuclear reactor is being considered for use in a space nuclear powerplant. The reactor provides 2.17 megawatts (7.4×10^{6} Btu/hr) of thermal energy that could be converted to electrical energy in a separate loop, perhaps utilizing either the Brayton or Rankine thermodynamic cycle. This reactor design concept was discussed by Lahti, Lantz, and Miller (ref. 1). The purpose of this report is to present a preliminary analysis of potential accidents that might occur while the reactor is operating at 100 percent power. This analysis defines the time available after an accident to take corrective action before the reactor fails.

Five types of accidents were investigated:

(1) Loss of coolant from the core. This accident could occur if one of the coolant pipes or the reactor pressure vessel ruptured.

(2) Loss of flow. An electric power failure would cause the pumping head available from the electromagnetic pumps to suddently drop to zero and the coolant flow to decrease.

(3) Ramp reactivity insertions. If the control drums are accidentally rotated inward, reactivity would be increased, and the reactor would become supercritical.

(4) Cold lithium additions. Any reduction in coolant temperature would cause an increase in reactivity because of the negative temperature coefficient of reactivity associated with the lithium coolant. This increase in reactivity would cause an increase in reactor power and fuel temperature.

(5) Plugging of coolant channel. Excessive fuel growth, clad failure, or obstructions in the coolant inlet passage would cause a loss of coolant flow and a subsequent increase in coolant and fuel temperatures.

The accidents investigated are not unique. Many reactors would fail after a loss of coolant, loss of flow, or ramp insertion of reactivity if no corrective action were taken. Ordinarily, a safety analysis requires the determination of the time available to take corrective action before reactor failure occurs.

All accidents were investigated analytically by assuming an open-loop system; that is, variations in heat exchanger operation and secondary loop characteristics were neglected. This assumption is valid for times up to one transport time (time for a fluid particle to traverse the loop) in the lithium cooling loop. Under 100-percent flow conditions, the transport time in the loop might be between 10 and 30 seconds, depending on the length and diameter of the loop piping. The time-dependent calculations were made by use of the computer program FORE (ref. 2). This computer program has been used in the study of fast liquid-metal-cooled reactors (ref. 3), and it incorporates a cylindrical fuel pin geometry identical to that being considered in the nuclear powerplant.

The reactor and pertinent design parameters are described, followed by a discussion of the bases for conducting the accident analysis. Each of the five possible accidents is presented, and the conclusions reached as a result of these analyses are given.

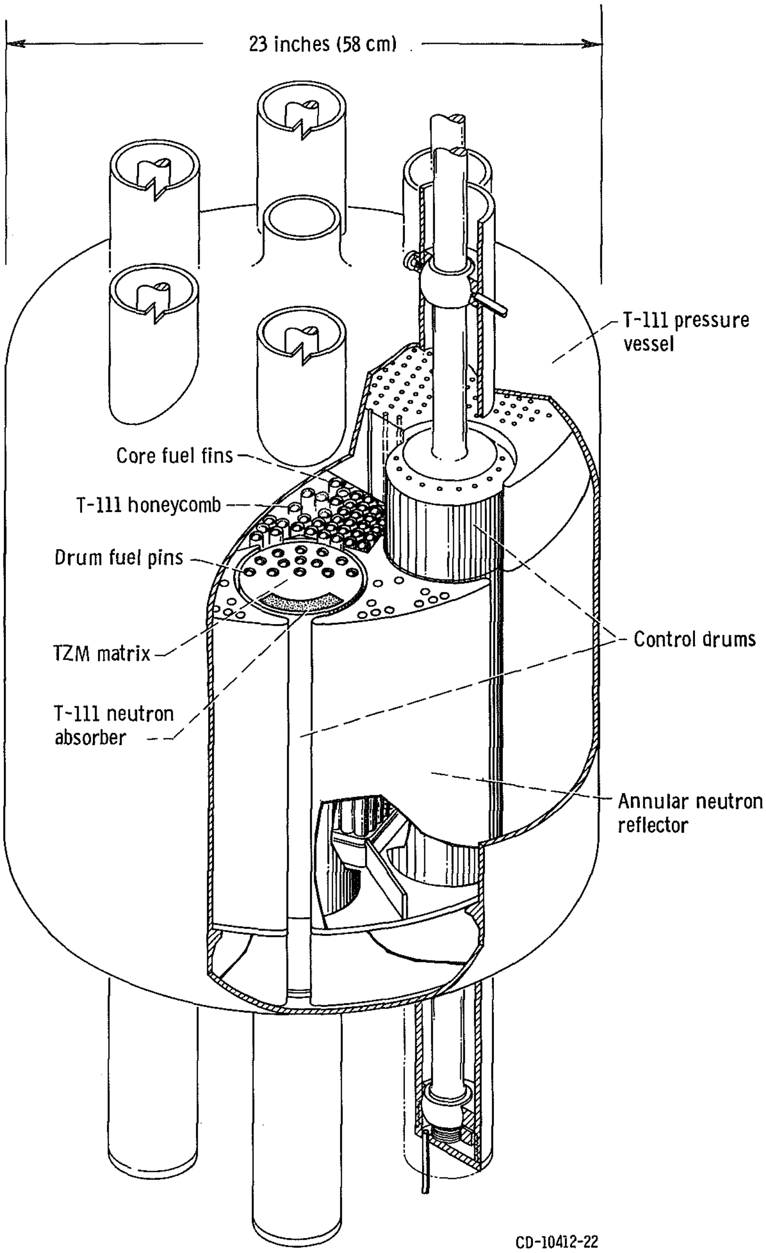


Figure 1. - Nuclear powerplant reactor.

DESCRIPTION OF REACTOR

The reactor is a uranium nitride - fueled, fast-spectrum, lithium-cooled nuclear reactor that operates at a nominal thermal power of 2.17 megawatts (7.4×10^6 Btu/hr). A sketch of the reactor is shown in figure 1. The fuel pins are placed within a T-111 (Ta-8W-2Hf) honeycomb structure. An annular neutron reflector composed of TZM (Mo-0.5Ti-0.08Zr) surrounds the fuel elements. The entire structure is surrounded by the T-111 pressure vessel. Reactivity is controlled by rotating six control drums lo-

TABLE I. - REACTOR DESIGN PARAMETERS

Dimensions	
Fuel pin length, in. (cm)	14.8(37.6)
Fuel pin outside diameter, in. (cm)	0.75(1.9)
Clad thickness, in. (cm)	0.058(0.14)
Coolant channel inside diameter, in. (cm)	0.83(2.1)
Thermal characteristics	
Reactor power, MW (Btu/hr)	2.17(7.4×10^{6})
Average heat flux, W/cm^2 (Btu/(hr)(ft^2))	38(120 000)
Power factors	
Radial	1.2
Axial	1.2
Total coolant flow, lb/sec (kg/sec)	20.7(9.4)
Coolant velocity in channel, ft/sec (m/sec)	3.8(1.2)
Coolant inlet temperature, ^{o}R (K)	
High-temperature design	2600(1415)
Low-temperature design	2100(1135)
Coolant outlet temperature, ^{o}R (K)	
High-temperature design	2700(1470)
Low-temperature design	2200(1190)
Maximum fuel temperature, ^{o}R (K)	
High-temperature design	2820(1535)
Low-temperature design	2320(1255)
Neutronics	
Neutron lifetime, sec	4.0×10^{-8}
Neutrons per fission, ν	2.52
Delayed neutron fractions	
β_1	1.719×10^{-4}
β_2	8.431×10^{-4}
β_3	2.691×10^{-3}
β_4	1.238×10^{-3}
β_5	1.402×10^{-3}
β_6	2.517×10^{-4}
β_{eff}	6.597×10^{-3}
Decay constants, sec^{-1}	
λ_1	3.88
λ_2	1.40
λ_3	0.311
λ_4	0.116
λ_5	0.0317
λ_6	0.0127

cated within the annular reflector. The matrix of each drum is TZM. Fuel pins are placed in holes drilled on one side of the drum, and an annular segment of the drum opposite the fuel pins contains a T-111 neutron absorber. Reactivity is reduced by rotating the fuel away from the core and is increased by rotating the fuel toward the core. The drum position shown in figure 1 would provide maximum reactivity.

The dimensions of a fuel assembly (fuel pin plus associated coolant) and its thermal and neutronic operating characteristics are shown in table I. The fuel pins are 3/4 inch

(1.9 cm) in diameter and 14.8 inches (37.6 cm) long. A central coaxial hole in each fuel pin serves to collect fission product gases and allows for some fuel swelling. The fuel is clad with T-111 alloy and is cooled by liquid lithium flowing through a 0.040-inch- (0.1-cm-) thick annulus surrounding the fuel pin. The total coolant mass flow rate is 20.7 pounds per second (9.4 kg/sec), and the nominal coolant velocity in the annulus surrounding the fuel pin is 3.8 feet per second (1.2 m/sec).

Two potential reactor designs are considered: a low-temperature design in which the coolant enters the reactor at 2100° R (1135 K) and exits at 2200° R (1190 K), and a high-temperature design in which the coolant enters at 2600° R (1415 K) and exits at 2700° R (1470 K). The high-temperature design would allow more efficient operation on the basis of thermodynamic considerations but may be overly optimistic on the basis of materials considerations. Two of these materials considerations are strength and chemical compatibility between the lithium and the structural materials. The two reactor designs are assumed to be identical except for the difference in temperature levels.

ANALYSIS OF ACCIDENTS

Five types of reactor accidents are reviewed: (1) loss of coolant, (2) loss of flow, (3) ramp reactivity insertions, (4) cold lithium addition, and (5) plugging of coolant channel.

In the first four accidents, the fuel and coolant temperatures and reactor power were calculated as a function of time by using the digital computer program FORE (ref. 2). Essentially no reactivity change is associated with the plugged coolant channel accident, and it is solved in closed form.

The digital computer program FORE provides a time-dependent analysis of both the heat-transfer and neutronic chacteristics of the reactor. Radial and axial temperature distributions are calculated for both the hottest and the average fuel pins in the reactor. Radial and axial power distributions must be provided as input. Reactor power is calculated by using space-indepenent neutron kinetic theory. Values of the reactor design parameters used in the calculations are summarized in table I.

Four types of reactivity feedback coefficients were used in the calculations: Doppler, coolant temperature, and radial and axial core expansion. The Doppler coefficient is assumed to be inversely proportional to the absolute fuel temperature. The values of the reactivity feedback coefficients are uncertain. Therefore, two different but typical sets of values of reactivity coefficients were selected for the analyses of the accidents. These values do not necessarily represent the extremes of values that might be expected in this reactor. The two sets of reactivity coefficients are presented as cases A and B

TABLE II. - REACTIVITY COEFFICIENTS

Coefficient	Case	
	A	B
Doppler, $T(\delta k_{eff}/\delta T)$	-0.011	-0.0028
Coolant, $\delta k_{eff}/\delta T$, $^{o}R^{-1}$ (K^{-1})	$-5.7\times10^{-6}(-1.0\times10^{-5})$	$-1.6\times10^{-6}(-2.9\times10^{-6})$
Radial expansion, $\delta k_{eff}/\delta T$, $^{o}R^{-1}$ (K^{-1})	$-2.9\times10^{-6}(-5.2\times10^{-6})$	$-2.9\times10^{-6}(-5.2\times10^{-6})$
Axial expansion, $\delta k_{eff}/\delta T$, $^{o}R^{-1}$ (K^{-1})	$-2.9\times10^{-6}(-5.2\times10^{-6})$	$-2.9\times10^{-6}(-5.2\times10^{-6})$

in table II. The smaller (closer to zero) coefficients of case B were used in the calculations of the first two accidents because they cause a slower reduction in reactor power and produce more conservative results. The larger coefficients of case A were used to calculate the cold lithium addition accident because they produce a greater rise in power and fuel temperature. Both sets of coefficients were used in the analysis of ramp reactivity insertions to illustrate their effect on the temperature and power responses.

Each accident is evaluated in terms of the maximum fuel temperature rise and maximum coolant temperature rise following the accident. Rupturing of the pressure vessel and melting of the fuel were avoided by establishing the coolant boiling point and fuel melting point as upper limits. The fuel melting point is 5620^{o} R (3090 K), and the lithium boiling point at the minimum pressure (20 psi or 13.8 N/cm^2) in the reactor is 3000^{o} R (1635 K). Limits may also be placed on fuel clad temperature, operating heat flux, and pressure vessel wall temperature to avoid undesirable situations, such as clad rupture, fuel clad burnout, and pressure vessel rupture. These limits have not been evaluated but may place greater demands on the safety circuit response times.

Loss of Coolant

If one of the coolant pipes between the pump outlet and the reactor inlet ruptures, the core might be "pumped dry" within about 0.3 second under 100-percent flow conditions. The reactor power and fuel temperature responses following this accident were calculated by assuming that no heat was removed from the fuel surface. Although it would be desirable to shut down the reactor immediately after this accident occurs, the power and temperature responses were calculated by neglecting a shutdown. Therefore, the calculated time-to-melt is shorter than would actually be expected.

The sudden loss of coolant removes sufficient reactivity to reduce the power to 18 percent of its initial value within about 20 seconds, as shown in figure 2. Once this power is reached, the reactor is assumed to be shutdown. Thereafter, the power is

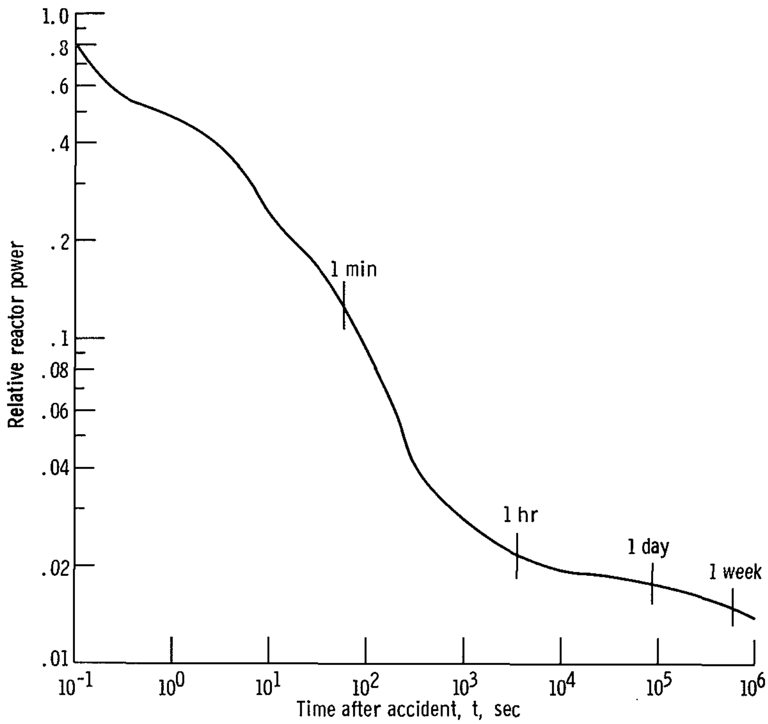


Figure 2. - Reactor power response following loss-of-coolant accident. Reactor has been operating at 100 percent power for at least 1 year, no scram.

produced by decay of fission products, fissions caused by delayed neutrons, and neutron-induced radioactivity. After 20 seconds, the reactor power continues to diminish as the radioactive fission products decay (see fig. 2). The total energy generated after shutdown relative to the initial reactor power is shown in figure 3 as a function of the time after the reactor is shutdown.

The maximum fuel temperature rise (maximum fuel temperature at any time after the accident minus the initial value of the maximum fuel temperature) is shown in figure 4 as a function of time after the accident. The first fuel pin would start to melt about 380 and 530 seconds after the initiation of the accident in the high-temperature and low-temperature designs, respectively. If the reactor is shutdown within 1 second after the accident, fuel melting would be delayed about another 80 seconds (460 and 610 sec, respectively). If the reactor could be cooled prior to this time and if the cooling system could be repaired, it might be possible to operate the reactor again. However, if the reactor is not cooled, the fuel will continue to melt.

The molten fuel must not be allowed to accumulate sufficiently to cause the reactor to become supercritical. A supercritical mass of molten fuel could cause a power excursion, vaporization of the fuel, and violent disassembly of the entire structure. Therefore, some method must be provided to avoid the formation of a supercritical array following fuel melting.

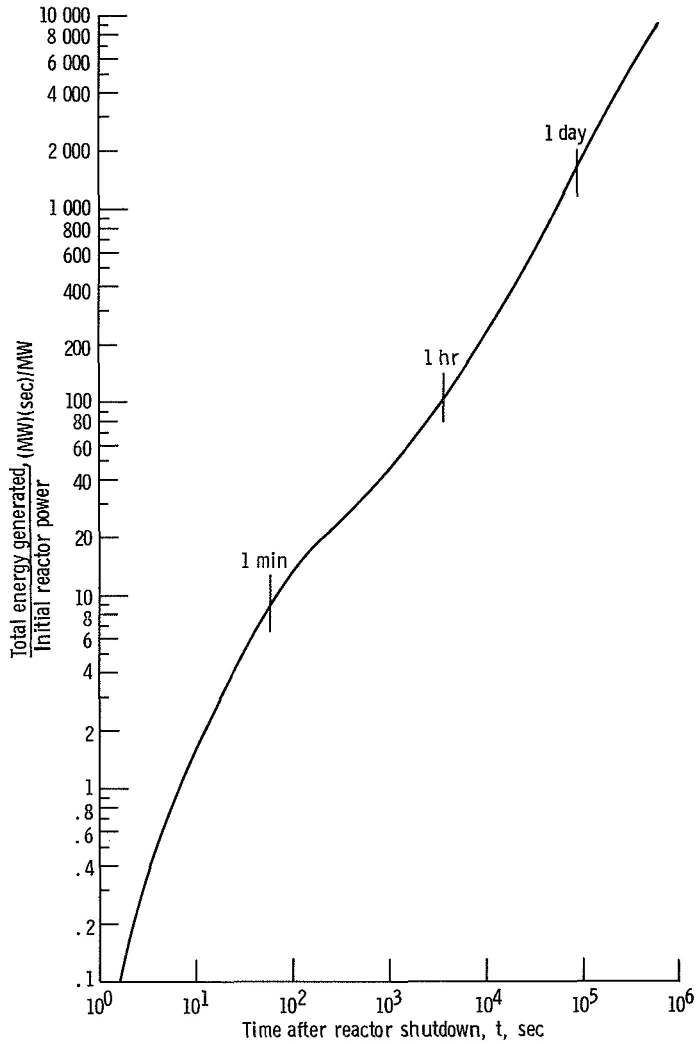


Figure 3. - Total energy generated after reactor shutdown.

Within the reactor are several potential locations where the fuel might collect to form a supercritical array. One such location is within the fuel pin itself. The fuel is designed with a central coaxial hole that collects fission product gases. During the melting process, the fuel might become sufficiently fluid to fill this hole. Because the melting point of the T-111 clad is about 260^o R (144 K) higher than the melting point of the fuel, the clad might have sufficient strength to retain the molten fuel in cylindrical form. This redistribution of fuel within the reactor might cause sufficient increase in reactivity to produce a supercritical fuel array. Several possible methods may be used to prevent a supercritical array due to fuel redistribution within the fuel pin:

(1) Add sufficient neutron absorber to the reactor to negate the reactivity increase due to fuel redistribution.

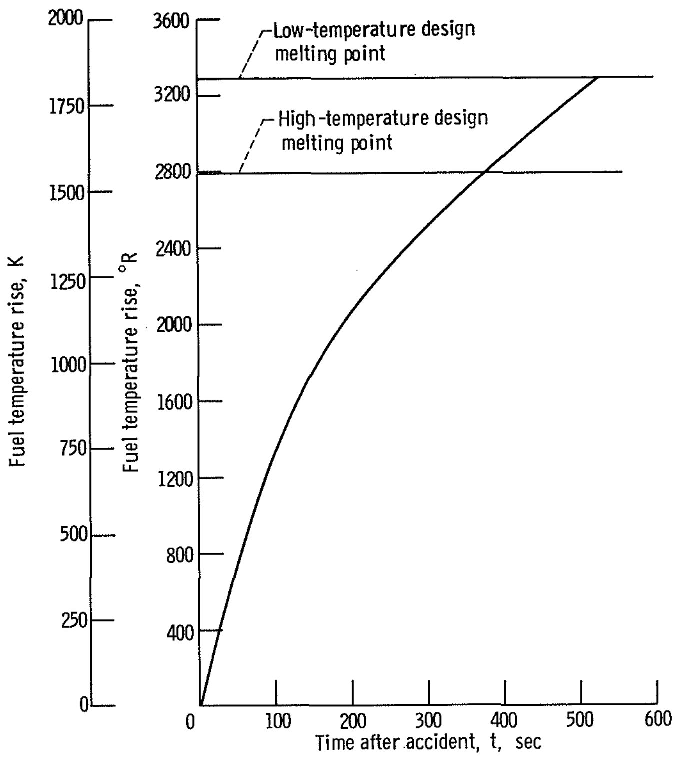


Figure 4. - Fuel temperature response following loss-of-coolant accident.

(2) Prevent a critical geometry in the pin by inserting a porous screen or membrane in the gas collection space, which would retain the fuel but would allow the fission product gases to migrate out of the fuel.

(3) Cool the fuel pins sufficiently to avoid gross fuel melting. Similar methods might be used to avoid the formation of a supercritical mass at some other location within the T-111 pressure vessel, such as in the inlet or outlet plenum.

Loss of Flow

If electrical power to the electromagnetic pumps is interrupted, the coolant flow will continue to decrease until either the pump is restarted or the thermal buoyancy in the loop is equal to the friction loss in the loop. It is assumed that natural convection can be established in the loop by locating the heat exchanger at some elevation above the reactor, providing a "cold leg" of lithium in the loop, as shown in the sketch in figure 5. In this sketch, the hot lithium enters the heat exchanger located z feet above the reactor, is cooled, and enters the electromagnetic pump. The cooler lithium is normally pumped into the reactor, heated, and returned to the heat exchanger.

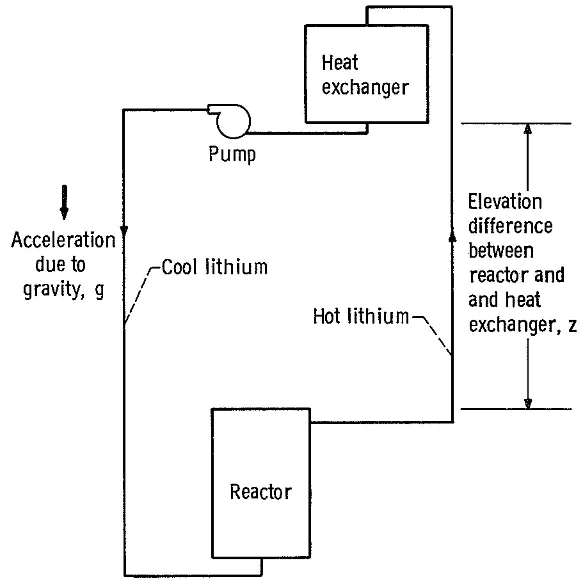


Figure 5. - Reactor cooling loop.

The coolant flow coastdown following a loss of pumping power was calculated by initially neglecting natural convection, as shown in appendix A. This assumption should be valid during the first fraction of a second of the accident if the coolant temperature rise following the accident is relatively slow. After the first fraction of a second, the flow decreases until the frictional force equals the force due to thermal buoyancy. Although the magnitude of the flow depends on the gravitational field, the flow is expected to be less than 1 percent of the design flow for most potential applications of this reactor. This accident was calculated by assuming a gravitational field producing an acceleration of about 5 feet per second squared (1.5 m/sec^2). The power and coolant temperature responses to the coolant flow coastdown were calculated by using the digital computer program FORE, which was described in the section Analysis of Accidents. Coolant inlet temperature is assumed unchanged, and heat transfer from the reactor pressure vessel is neglected.

The coolant flow, relative power, and coolant temperature rise following a loss of flow are shown in figure 6 for two situations. In the first, represented by the solid curves, no immediate action is taken following the accident (no reactor scram). In the second, represented by the dashed curves, the reactor is scrammed 1 second after the accident.

The coolant flow is reduced to less than 1 percent of its initial value in the first 0.5 second following the accident. This flow coast-down is much faster than that experienced with a free-wheeling pump because no moving components are inside the electromagnetic pump to add inertia to the fluid. The electromagnetic fields in the pump-fluid system are assumed to vanish instantaneously. As the coolant flow decreases, the

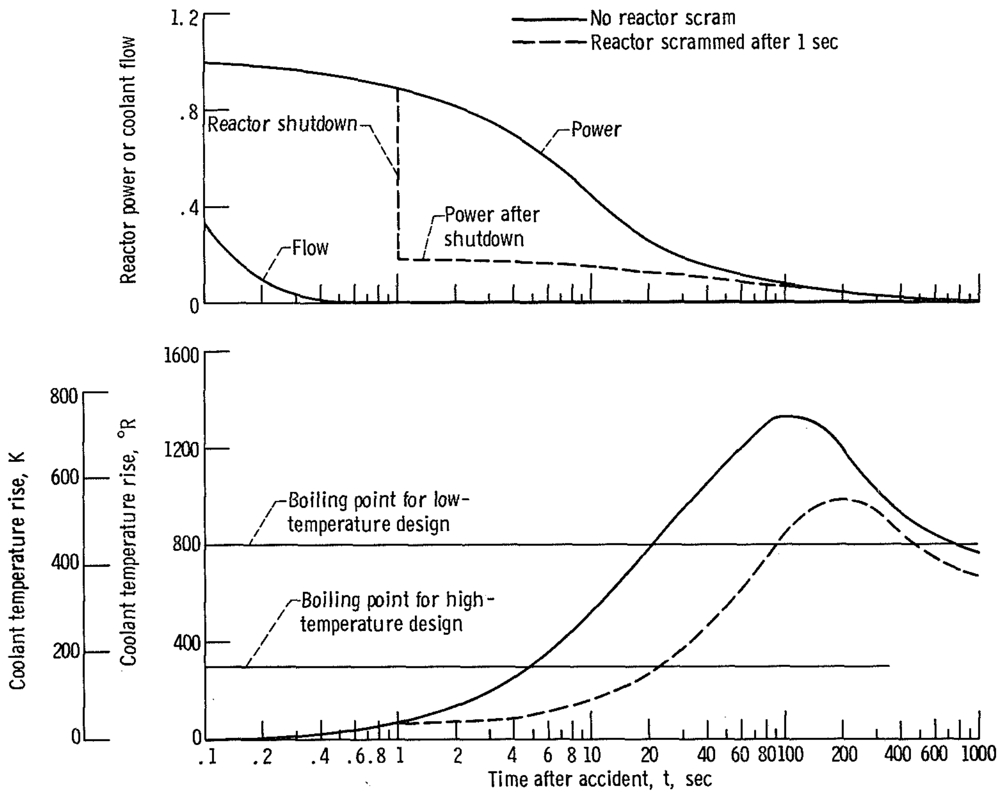


Figure 6. - Coolant flow, relative power, and coolant temperature rise following loss-of-flow accident.

coolant temperature rises and power decreases because of the negative temperature coefficient of reactivity associated with the coolant.

With no reactor scram, the power would decrease to 18 percent of its initial value in about 30 seconds. After this time, the reactor is shut down, and all the power is assumed to result from decay of fission products, fissions caused by delayed neutrons, and neutron-induced radioactivity. The coolant temperature initially increases at about 60° R per second (33 K/sec), and the rate of increase diminishes thereafter. When the flow induced by thermal buoyancy is sufficient to remove the power generated, the coolant temperature reaches a maximum and then diminishes as power decays. If boiling did not occur first, the coolant temperature would reach a maximum (about 1300° R or 720 K above the initial value) about 100 seconds after the accident. However, boiling would actually occur about 5 and 20 seconds after the accident in the high- and low-temperature reactor designs, respectively. If a reactor scram is initiated 1 second after the accident (as indicated by the dashed curves in fig. 6), coolant boiling might be postponed until about 20 and 90 seconds in the high- and low-temperature designs, respectively.

Coolant boiling could be avoided either by resuming coolant flow or by reducing the coolant temperature in the reactor. This latter method may be undesirable because of the large transport time between the heat exchanger outlet and reactor inlet. The coolant in the reactor might boil before the cooler lithium from the heat exchanger reaches the reactor. Therefore, about 20 percent of the design cooling flow must be initiated within about 5 seconds after the accident to prevent cooling boiling. Auxiliary pumps could provide 20 percent of the design flow within 5 seconds.

The maximum fuel temperature subsequent to this accident follows the coolant temperature. Therefore, coolant boiling would occur before the fuel melts.

Reactivity Addition

A control circuit may malfunction, which would allow the control drums to rotate causing reactivity to be increased. For this analysis, 2.5 percent reactivity was assumed to be available in the control drums at the time of the accident. Two rates of reactivity insertion were investigated:

(1) Ten cents per second for 37 seconds. This is the normal rate that might be expected for fine reactivity control.

(2) Fifty cents per second for 7.4 seconds. This rate was arbitrarily selected to determine the effect of a more rapid reactivity insertion.

The power, fuel temperature rise, and coolant temperature rise resulting from these reactivity insertion rates are shown in figure 7. The reactivity coefficients presented in case B (table II) were used in these calculations. The rate of reactivity insertion is assumed constant (ramp reactivity insertion) as the control drums are rotated.

When reactivity is continuously inserted at the normal rate (10¢/sec), reactor power increases nearly linearly with time until it reaches a maximum of 75 megawatts (2.6×10^{8} Btu/hr), about 37 seconds after the initiation of the accident. During the first 3 seconds, the maximum fuel temperature and coolant temperature increase less than 100° R (56 K). In the high- and low-temperature reactor designs, the fuel melts 20 and 23 seconds after the accident, respectively. The coolant temperature reaches the boiling point about 8 and 13 seconds after the accident in the high- and low-temperature designs, respectively.

If reactivity is inserted at a rate of 50 cents per second, reactor power reaches a maximum of about 86 megawatts (2.9×10^{8} Btu/hr) within about 7 seconds. At that time, not enough reactivity exists to support the power (neutron density), and reactor power decreases until it reaches a minimum value of about 70 megawatts (2.4×10^{8} Btu/hr). Within 7 seconds, the control drums have been rotated in, allowing a maximum reactivity insertion of 2.5 percent. The power gradually increases thereafter until the fuel,

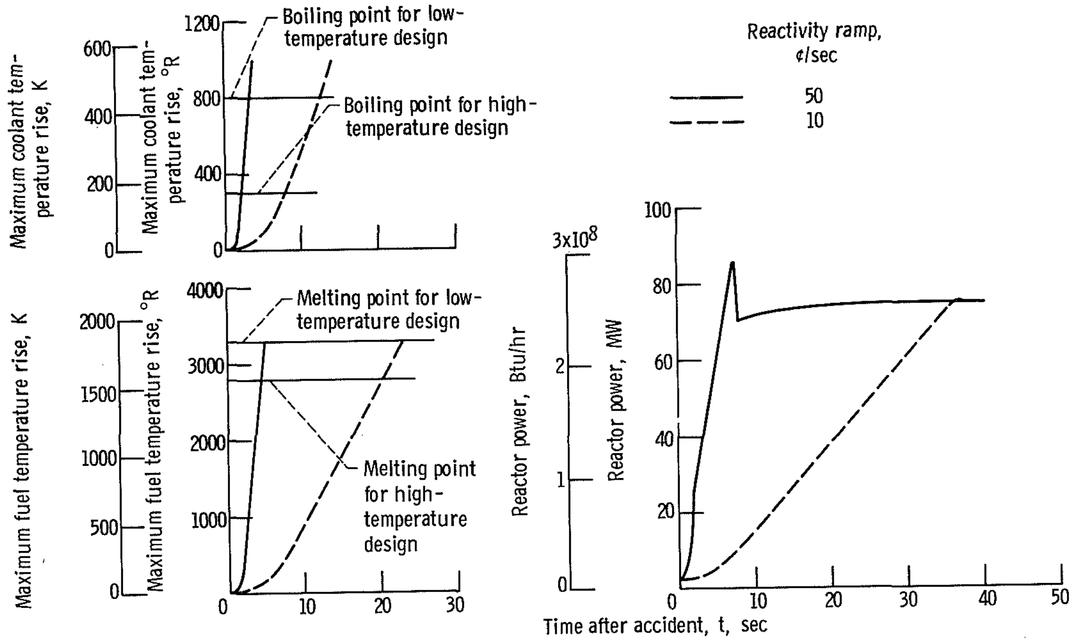


Figure 7. - Reactor power, fuel temperature, and coolant temperature resulting from insertion of 2.5 percent reactivity at constant rate.

coolant, and structure temperatures have increased sufficiently to compensate for the 2. 5-percent reactivity insertion. The power reaches about 75 megawatts (2.6×10^8 Btu/hr) after about 40 seconds.

With a reactivity insertion rate of 50 cents per second, the fuel and coolant temperatures rise more rapidly than they did with the reactivity addition rate of 10 cents per second. After about $1\frac{1}{2}$ to 2 seconds, the coolant and fuel temperatures increase at 500° and 750° R per second (280 and 420 K/sec), respectively, compared with 100° and 150° R per second (56 and 83 K/sec) experienced when reactivity was inserted at 10 cents per second. The reactor would have to be shut down within 2 and 3. 5 seconds to avoid boiling the coolant in the high-temperature and low-temperature reactor designs, respectively. Reactor safety circuits could be designed to shut the reactor down within 2 seconds. Fuel melting would occur $4\frac{1}{2}$ and 5 seconds after the accident in the high- and low-temperature designs, respectively.

The power and temperature responses are strongly dependent on the values of the temperature coefficients of reactivity. The power and temperature responses to a ramp reactivity insertion of 50 cents per second are shown in figure 8 for both sets of reactivity coefficients given in table II. The responses to the smaller and larger feedback coefficients are illustrated in figure 8 by the solid and dashed lines, respectively. The larger reactivity coefficients cause more negative reactivity for a given change in temperature, and the final steady-state powers and temperatures are lower. For example,

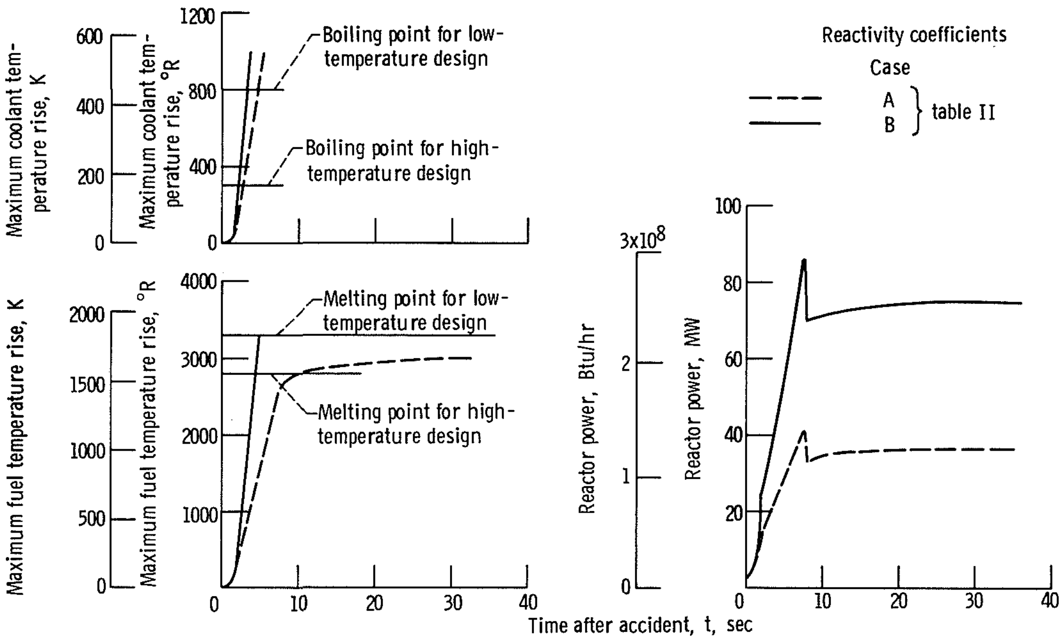


Figure 8. - Effect of reactivity coefficients on reactivity addition accident. Ramp reactivity insertion, 50 cents per second; total reactivity insertion, 2.5 percent.

with the larger reactivity coefficients, the peak power attained during this accident is 41 megawatts (1.4×10^8 Btu/hr) compared with 86 megawatts (2.9×10^8 Btu/hr) attained with the smaller coefficients. In the low-temperature reactor design, coolant boiling would be delayed about 2 seconds, but fuel melting might be avoided if the actual temperature coefficients of reactivity are as large as those in case A rather than those in case B. Conversely, if the actual temperature coefficients of reactivity are smaller than those in case B, coolant boiling and fuel melting would occur sooner.

Cold Lithium Addition

The liquid lithium in the storage tank may be cooler than the lithium in the reactor loop. If this cold lithium is accidentally added to the reactor, reactivity will increase because of the negative temperature coefficient of reactivity associated with the coolant. The fuel temperature and reactor power responses following an instantaneous insertion of cold lithium into the reactor are shown in figure 9 for a 200° R (111 K) reduction in coolant temperature. These responses were calculated by using the reactivity coefficients presented in case A (table II). The power and fuel temperature responses calculated with these reactivity coefficients are greater than would be obtained with the reactivity coefficients presented for case B (table II). The coolant inlet temperature is assumed to remain constant after the initial reduction.

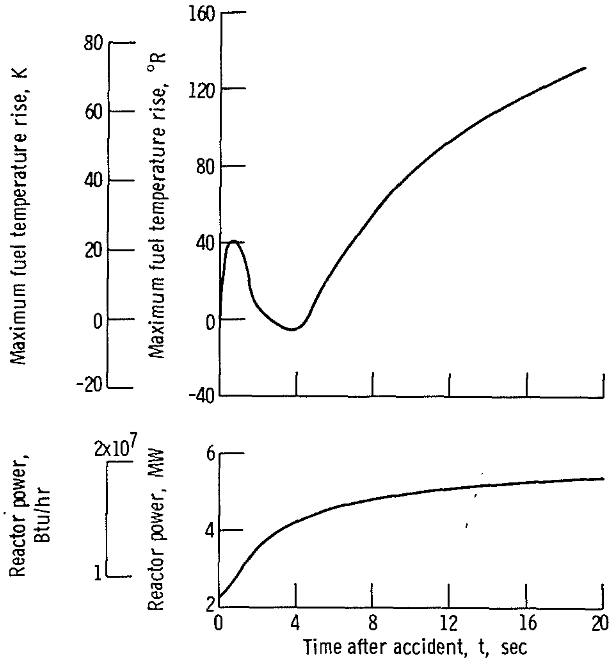
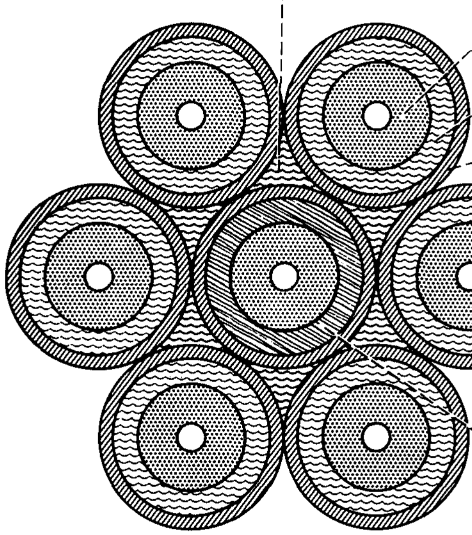


Figure 9. - Fuel temperature and reactor power responses following cold lithium accident. Coolant inlet temperature reduced 200° R (111 K); reactivity coefficients for case A (table II).

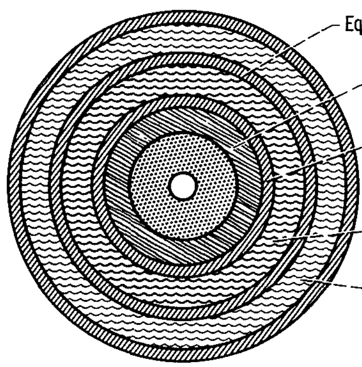
As the cooler lithium enters the reactor, reactivity is increased and reactor power rises. The initial rise in power causes the maximum fuel temperature to rise. Within about 1/2 second, the fuel temperature reaches a maximum and begins to decrease as the fuel is cooled by the colder lithium. However, the fuel temperature reaches a minimum and again begins to increase after about 4 seconds in response to the continuously rising reactor power. After about 20 seconds, the fuel temperature rise is only about 130° R (72 K). Although neither fuel temperature nor power has reached steady state after 20 seconds, the steady-state fuel temperature rise is only about one degree per degree reduction in coolant temperature.

Loss of Flow to Single Coolant Channel

Excessive fuel swelling or plugging of a coolant channel could cause a loss of coolant flow to a single fuel pin. If this loss occurred, the heat from the affected fuel pin would have to be distributed among adjacent coolant channels. The temperature of the affected fuel pin would have to increase only about 60° R (33 K) to remove this heat. The temperature rise in the fuel pin was calculated from the model shown in figure 10 by making the following assumptions:



(a) Actual geometry.



(b) Equivalent geometry for plugged channel.

Figure 10. - Model for plugged coolant channel.

(1) All the heat is redistributed among the six adjacent coolant channels.

(2) Heat is removed from the affected fuel pin surface by conduction across the stagnant lithium and across the T-111 honeycomb structure.

The temperature rise across the lithium and T-111 structure was calculated by assuming an equivalent annular region having a volume equal to the sum of the volumes of the plugged annulus, the honeycomb structure associated with the plugged channel, and six triflute regions surrounding the affected fuel pin. The inner and outer diameters of this equivalent annular region are 0.75 and 1.00 inch (1.9 and 2.5 cm), respectively. The temperature rises for the unplugged and plugged channels are shown in table III. The coolant temperature is increased by about 17° R (9 K) because of the heat redistribution among the surrounding channels. The temperature rise across the stagnant lith-

TABLE III. - COMPARISON OF TEMPERATURE RISES IN

NORMAL AND PLUGGED FUEL ASSEMBLIES

[Temperature rise due to plugged channel, 61^{o} R (33 K).]

	Fuel assembly	
	Normal	Plugged
Coolant inlet temperature, ^{o}R (K)	2100(1135)	2100(1135)
Coolant temperature rise at location of maximum temperature, ^{o}R (K)	102(57)	119(66)
Temperature rise across coolant film, ^{o}R (K)	5(3)	4(2)
Temperature rise across stagnant lithium and structure, ^{o}R (K)	---	45(25)
Temperature rise across fuel and clad, ^{o}R (K)	106(59)	106(59)
Maximum fuel temperature, ^{o}R (K)	2313(1254)	2374(1287)

ium in the plugged channel is about 45^{o} R (25 K), and the temperature rise across the coolant film in the adjacent channels is about 4^{o} R (2 K).

CONCLUSIONS

On the basis of a preliminary analysis of the five potential accidents that might occur at 100-percent power conditions in the lithium-cooled space nuclear powerplant, the following conclusions were reached:

1. If all the coolant is removed from the reactor, auxiliary cooling must be provided within 380 and 530 seconds to avoid melting any of the fuel in the high- and low-temperature reactor designs, respectively. If the fuel pins are not cooled, precautions must be taken to avoid the formation of a supercritical array following reactor meltdown.

2. Within about 5 seconds after a loss of coolant flow, 20 percent of the original coolant flow must be established to prevent coolant boiling in the high-temperature reactor design.

3. The high-temperature reactor must be shut down within 2 and 8 seconds to avoid boiling the coolant when reactivity is inserted at rates of 50 and 10 cents per second, respectively.

4. If the coolant temperature is suddenly reduced by adding cold lithium, reactivity and power increase because of the negative temperature coefficient of reactivity associated with the coolant. The maximum fuel temperature rise is about one degree per degree reduction in coolant temperature.

5. If a single coolant channel is plugged, the steady-state fuel and coolant temperature rises in the affected fuel assembly are 60° and 45° R (33 and 25 K), respectively.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 13, 1969,
120-27.

APPENDIX A

COOLANT FLOW COASTDOWN AFTER LOSS OF PUMPING POWER

The lithium coolant flow response following a complete loss of pumping power was calculated by balancing the inertia, friction, buoyancy, and pressure forces on an incompressible fluid influenced by gravitational forces (natural or artificially induced as in a spinning space station):

$$\Delta P_I = \Delta P_P + \Delta P_B + \Delta P_F$$

where the subscripts I, P, B, and F refer to inertia, pump, buoyancy, and friction, respectively.

The term ΔP_P vanishes when the pumping power is lost, and the buoyancy and friction terms can be expressed in terms of their initial values $\Delta P_{B,o}$ and $\Delta P_{F,o}$, respectively. Therefore, the force balance becomes

$$\rho l \frac{du}{dt} = \Delta P_{B,o}\left(\frac{\Delta T}{\Delta T_o}\right) - P_{F,o}\left(\frac{u}{u_o}\right)^M$$

$$\Delta P_{B,o} = -\beta g \, \Delta T_o z$$

The exponent M is between 1 and 2 depending on (1) the fraction of the frictional pressure loss due to expansion and contraction and the fraction due to "skin friction" loss and (2) the type of flow - laminar or turbulent. The coefficient is close to 1 for laminar flow with predominantly skin friction losses. Rearranging the equation gives

$$\frac{dy}{dt} = \left(\frac{\Delta P_{B,o}}{\rho l u_o} \frac{\Delta T}{\Delta T_o}\right) - \left(\frac{\Delta P_{F,o}}{\rho l u_o}\right) y^M$$

where

$$y = \frac{u}{u_o}$$

An initial friction pressure drop $\Delta P_{F,o}$ of 10 psi (6.9 N/cm^2) is allowed in 40 feet (12 m) of lithium loop. The initial driving head due to buoyancy is about 0.02 psi (0.01 N/cm^2) on the basis of the following parameters:

$$\beta = -3.5\times10^{-3}\ \text{lb/(ft}^3\text{)(}^\circ\text{R)} \qquad (-0.10\ \text{kg/(m}^3\text{)(K)})$$

$$g = 5.4\ \text{ft/sec}^2 \qquad (1.6\ \text{m/sec}^2)$$

$$z = 20\ \text{ft} \qquad (6\ \text{m})$$

$$\Delta T = 100^\circ\ \text{R} \qquad (56\ \text{K})$$

If the temperature rise ΔT is relatively slow, the pressure drop due to thermal buoyancy is much smaller than the pressure drop due to friction. Therefore,

$$\frac{dy}{dt} = -\frac{\Delta P_{F,o}}{\rho l u_o} y^M = -\alpha y^M$$

where, initially, $y = 1$. Therefore,

$$y = \left[\frac{1}{1 + (M - 1)\alpha t}\right]^{1/(M-1)} \qquad \text{when} \quad M > 1$$

and

$$y = e^{-\alpha t} \qquad \text{when} \quad M = 1$$

The relative flow is shown in figure 11 as a function of time for various values of the exponent M. The most rapid loss of flow occurs when M = 1; that is, the friction loss is entirely skin friction and the flow is laminar. This flow coastdown was assumed in the accident analysis because the fraction of the friction loss due to skin friction is unknown, and this condition yields the most conservative results.

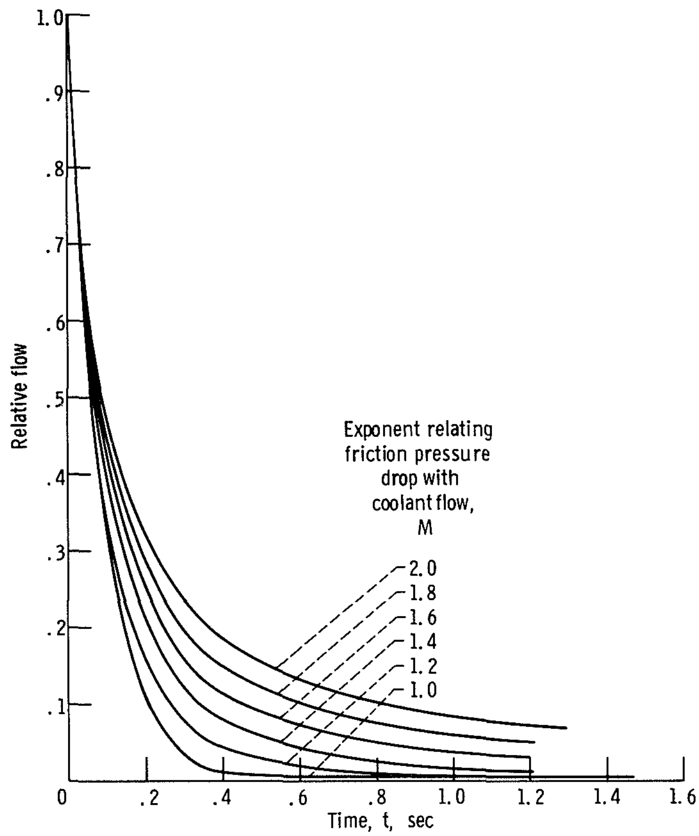


Figure 11. - Coolant flow response after loss of pumping power. $\Delta P_F = \Delta P_{F,0} y^M$.

APPENDIX B

SYMBOLS

g	acceleration due to gravity
l	length of liquid-lithium loop
M	exponent for velocity in equation for friction pressure loss
ΔP	pressure difference
ΔT	temperature difference between reactor outlet and heat exchanger outlet
t	time
u	coolant velocity
y	coolant velocity relative to initial value
z	elevation difference between reactor and heat exchanger
α	coolant flow decay constant
β	coefficient of thermal expansion for coolant or delayed neutron fraction
λ	decay constant
$\delta k_{eff}/\delta T$	temperature coefficient of reactivity
ν	neutrons per fission
ρ	coolant density

Subscripts:

B	thermal buoyancy
F	friction
I	inertia
P	pump
o	initial value

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