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EMERGENCY COOLING ANALYSIS FOR THE LOSS OF COOLANT MALFUNCTION

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16. Abstract
This report examines the dynamic response of a conceptual space power fast-spectrum lithium cooled reactor to the loss of coolant malfunction and several emergency cooling concepts. The results show that, following the loss of primary coolant, the peak temperatures of the centermost 73 fuel elements can range from 2556 K (4600° R) to the region of the fuel melting point of 3122 K (5620° R) within 3600 seconds after the start of the accident. Two types of emergency aftercooling concepts were examined: (1) full core open loop cooling and (2) partial core closed loop cooling. The full core open loop concept is a one pass method of supplying lithium to the 247 fuel pins. This method can maintain fuel temperature below the 1611 K (2900° R) transient damage limit but requires a sizable 22680-kilogram (approximately 50 000-lb) auxiliary lithium supply. The second concept utilizes a redundant internal closed loop to supply lithium to only the central area of each hexagonal fuel array. By using this method and supplying lithium to only the triflute region, fuel temperatures can be held well below the transient damage limit.

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EMERGENCY COOLING ANALYSIS FOR THE LOSS OF COOLANT MALFUNCTION

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SUMMARY

This report studies the dynamic response of a conceptual space power fast-spectrum lithium cooled reactor to the loss of coolant malfunction and several emergency cooling concepts. The loss of coolant malfunction is examined using a one-dimensional heat transfer representation of the reactor core, reflector, pressure vessel, and lithium hydride-depleted uranium shield. A one-dimensional unit cell representation of the reactor centerline hexagonal fuel array was used to study the various emergency cooling concepts.

The results of the loss of coolant study show that for an emissivity of 0.2 for the T-111 clad and honeycomb structure, various axial positions along the centermost 73 fuel elements will have temperatures ranging from 2553 K (4600° R) to the region of the fuel melting temperature 3122 K (5620° R). These peak fuel temperatures are reached in about 3600 seconds after the start of the malfunction. These high fuel element temperatures, following the loss of primary coolant, strongly indicate the need for some form of emergency aftercooling.

Two types of emergency cooling were examined by this report: (1) full core open loop emergency cooling and (2) partial core closed loop emergency cooling. The full core cooling method flows emergency lithium through the entire core in an open loop, one pass operation. This concept utilized a containment vessel to maintain operating pressure throughout the accident. The partial core emergency system incorporated an internal redundant closed loop that flowed emergency lithium through only the central flow area of each hexagonal fuel array and operated independently from the primary lithium loop.

The results of this analysis showed that although the full core cooling system could adequately maintain fuel temperatures below the melting point, the amount of auxiliary lithium that would be required by the system was excessive. To aftercool a reactor that had been operating for only 1 year prior to the loss of coolant, a 4536- to 6803-kilogram (10 000- to 15 000-lb) supply of lithium would be necessary to maintain fuel temperatures below 2778 K (5000° R).

The partial emergency cooling concept, operating through the closed internal loop, was able to keep fuel element temperatures well below the fuel melting point. The results further showed that if emergency flow could be supplied to the triflute passages, the peak fuel element temperatures could be kept below an assumed transient fuel element damage limit of 1611 K (2900° R).

INTRODUCTION

In order to ensure safe and reliable operation of the conceptual space power fast-spectrum lithium cooled reactor (fig. 1), it is first necessary to identify the credible malfunctions that might occur during the operational lifetime of the reactor and then design safeguards against such accidents. Of the malfunctions studied in NASA TM X-2057 (ref. 1), the loss of primary coolant incident, with the potentially dangerous condition of a fuel meltdown, loomed as one of the most difficult accidents to counteract. The after-

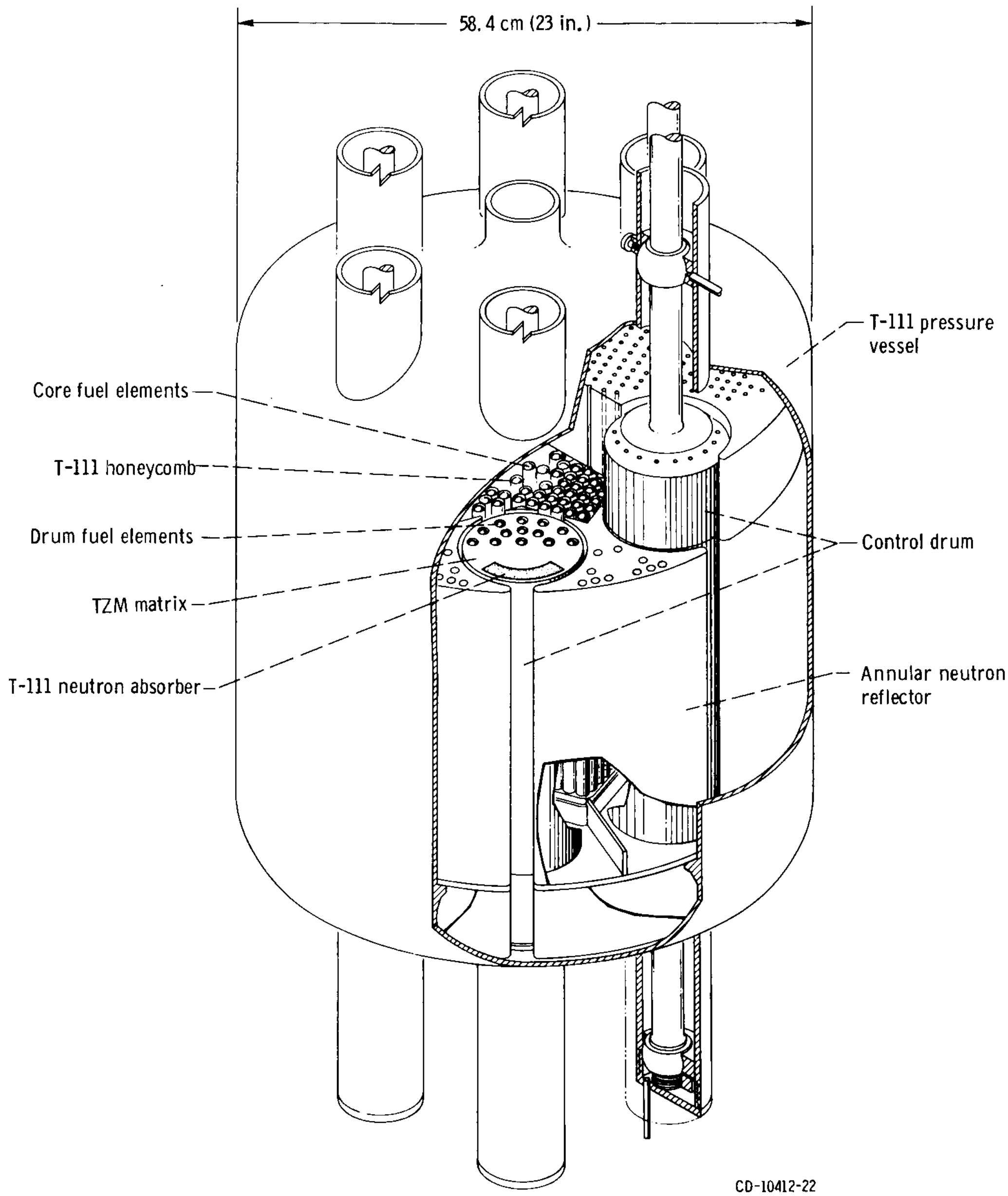


Figure 1. - Space power fast-spectrum reactor.

heat power generated by the delayed neutron fissions, fission product decay, and absorption induced radioactivity following the shutdown of the reactor, is of sufficient magnitude and longevity to drive the fuel and structural materials of the reactor core into a temperature region approaching their melting point. A fuel meltdown with the rather high uranium loading used by this reactor could result in the re-assembly of the fuel in an uncontrollable critical mass, an obviously undesirable situation.

It is, therefore, most important to determine the final fuel element temperatures resulting from this type of accident and, if these results reveal the potential for a fuel meltdown, then postulate some means of emergency cooling the reactor. The purpose of this report is then twofold: first, to investigate the loss of primary coolant accident in more detail than was presented in reference 1, and second, to examine various emergency cooling methods in an effort to determine an effective means of aftercooling the reactor core following this type accident.

In this report a one-dimensional mathematical model was used to describe the loss of primary coolant malfunction. This model represented the entire reactor core, reflector, pressure vessel, and shield as a series of concentric rings. Since the triflute region between the fuel pins (fig. 2) is difficult to simulate in one dimension, two variations on the basic configuration were necessary: (1) a model in which the triflute region was represented as solid T-111 (conduction model) and (2) a radiation model in which the triflute regions were represented by voided gaps between two T-111 rings.

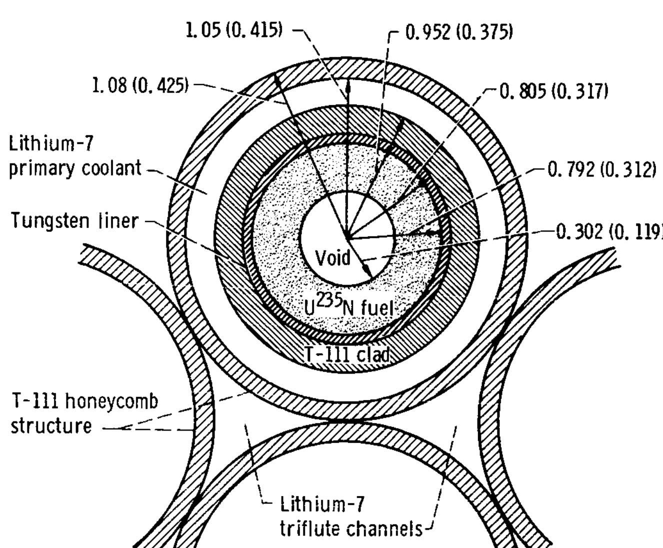


Figure 2. - Typical fuel element geometry. (All dimensions are in centimeters (in.).)

Several emergency cooling concepts will also be examined in this report; they are:

(1) Full core open loop emergency cooling
  (a) Continuous flow (flow modified)
  (b) Pulsed flow
(2) Partial core closed loop emergency cooling (hex cooling)
  (a) Central emergency channel flow
  (b) Emergency channel plus triflute channel flow
  (c) Triflute channel flow only

It is assumed, in the full core open loop emergency cooling concept, that emergency lithium flow is supplied to all 247 fuel channels of the reactor from an auxiliary lithium supply. The emergency lithium makes a single pass through the reactor in an open loop manner and is then assumed to be held within a containment vessel surrounding the reactor. Two modes of flow control are used for this analysis: (1) continuous flow, adjusted to decrease with the decreasing decay power and (2) pulsed flow - short pulses of lithium at full design flow, triggered by an arbitrarily chosen fuel element temperature limit.

The partial core closed loop emergency cooling concept assumes that only the central region of each hexagonal fuel array is available for emergency cooling (about 35 arrays in all). In this concept emergency lithium is supplied by an internal redundant emergency cooling loop. This loop would function independently of the main primary coolant loop. This type of closed cooling loop could supply emergency lithium to (1) the central coolant channel of each fuel element hexagonal array, (2) the central channel plus the triflute channels surrounding the central element, or (3) the triflute channels only. In this analysis of the partial emergency cooling concept the flow was maintained at design conditions.

DESCRIPTION OF REACTOR AND PRIMARY LOOP

The reactor design used for this analysis is similar to the one reported in reference 1. Figure 1 shows the uranium nitride fueled, fast-spectrum lithium cooled reactor. At steady-state design conditions, the reactor operates at a thermal power level of 2.17 megawatts (7.4×10^{6} Btu/hr). The fuel consists of uranium nitride (UN) enriched to 93.2 percent in the uranium-235 (U^{235}) isotope. The fuel is clad in tungsten and T-111 (tantalum - 8 percent tungsten - 2 percent hafnium) and placed in a T-111 honeycomb structure. A 0.10-centimeter- (0.040-in. -) thick coolant passage annulus exists between the honeycomb structure and the fuel pin. Figure 2 shows the basic fuel pin and honeycomb design. Of particular interest to this report are the lithium-7 triflute coolant channels.

Figure 3 shows a cross-sectional view of the conceptual space power reactor with the three fuel zones highlighted. The centermost 73 fuel elements make up the Zone I

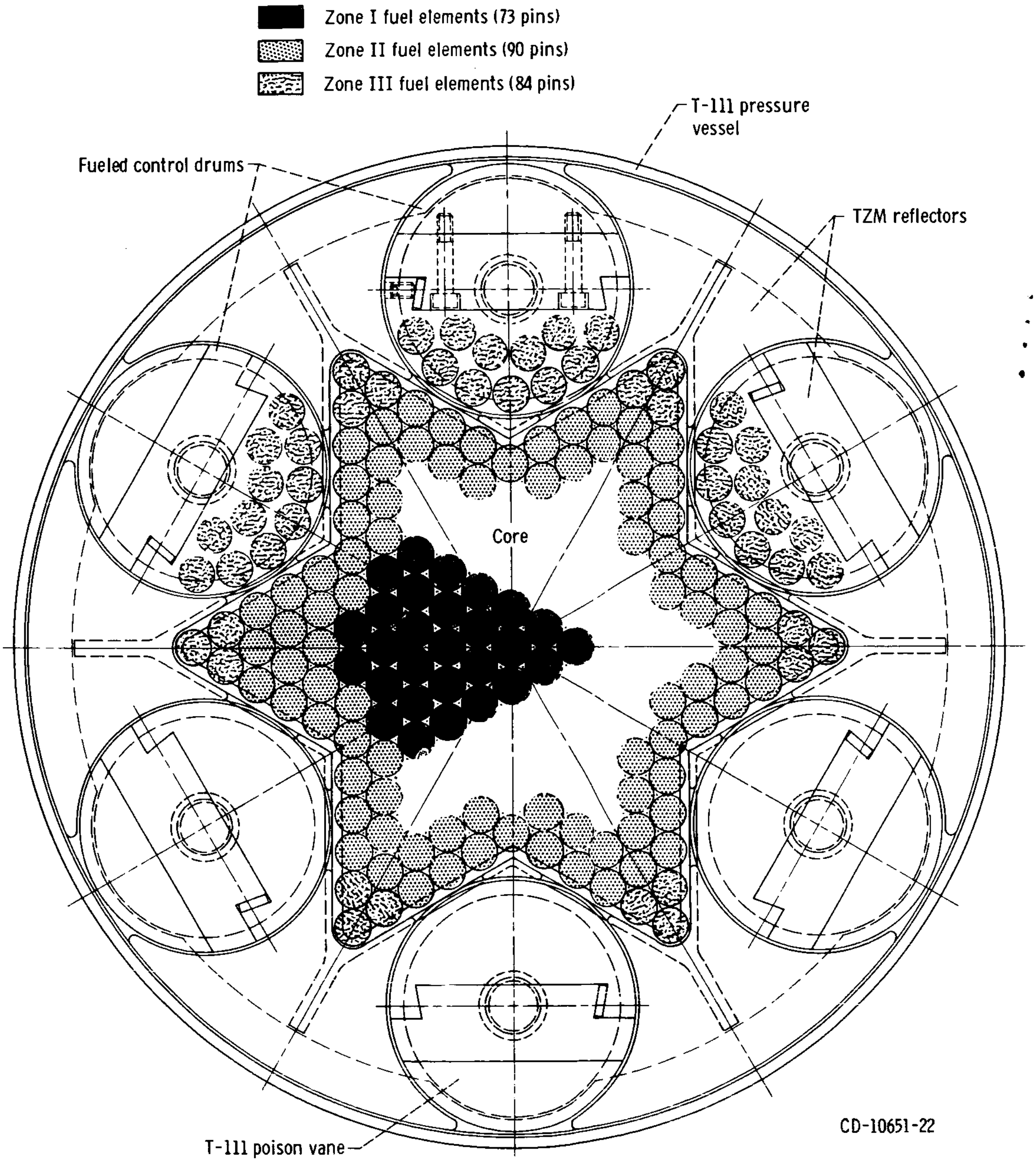


Figure 3. - Cross section of conceptual space power fast-spectrum reactor.

region; the surrounding 90 pins compose the Zone II structure; and the remaining 18 stationary core pins and 66 drum pins round out the total fuel structure of the reactor.

Figure 3 also shows the annular neutron reflector composed of TZM (molybdenum - 0.5 percent titanium - 0.08 percent zirconium) that surrounds the reactor core. Within the neutron reflector are six rotating fueled control drums. These control drums are essentially TZM, with fuel pins lining one side of the drum and a segment of T-111 that acts as a neutron poison when the fuel is revolved away from the reactor core. Reactivity control is gained by rotating the fueled control drums in such a way as to move fuel in closer to the center of the core or further away. The control drum configuration shown in figure 3 would provide maximum reactivity (normally the position at end of life).

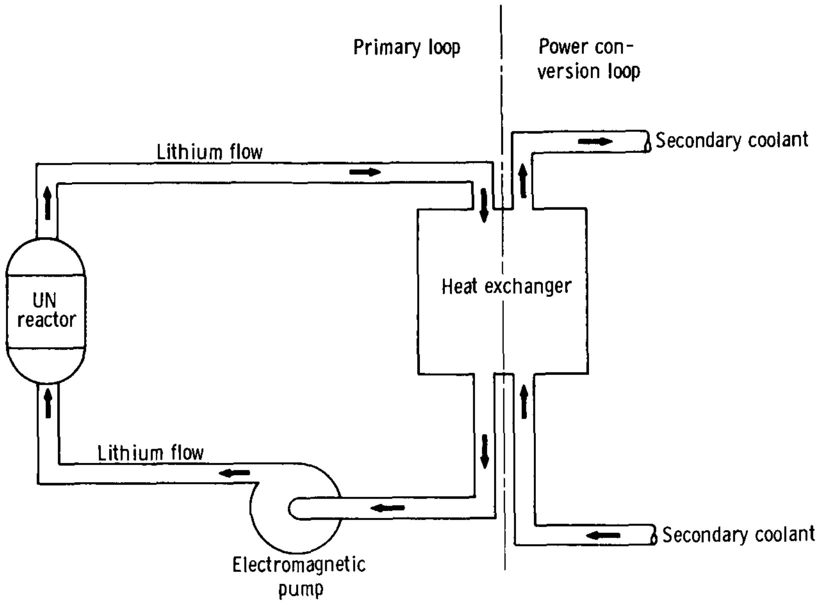


Figure 4. - Primary loop of space power fast-spectrum reactor.

The reactor core and fueled control drums are cooled by flowing liquid lithium. At steady state design conditions, the total coolant flow rate is 9.4 kilograms per second (20.7 lb/sec). The primary loop consists of the reactor electromagnetic pump and heat exchanger as shown in figure 4.

OPERATING ASSUMPTIONS AND COMPUTER PROGRAMS

In order to examine the loss of coolant malfunction and the various emergency cooling concepts in detail, it was necessary to make several operating assumptions. The following is a list of these assumptions:

(1) The reactor operated at design conditions for 1 year prior to the loss of coolant malfunction.

(2) The complete loss of primary coolant is a sufficient loss of reactivity to shut the reactor down.

(3) For the full core open loop emergency cooling concept it was assumed that the primary loop was enclosed in a containment vessel such that the normal operating pressure of 1.38×10^5 newtons per square meter (20 psi) could be maintained throughout the accident.

(4) Boiling and two-phase flow of the emergency lithium coolant was not considered in these calculations. This is a conservative approach since boiling of the flowing lithium would tend to be an aid in the dissipation of the reactor afterheat.

(5) The emergency coolant inlet temperature was maintained at the normal design operating point of 1167 K (2100° R). This could be accomplished by using heater elements on the auxiliary emergency lithium tank.

(6) A transient fuel element damage limit of 1611±56 K ($2900\pm100^\circ$ R) was used. This temperature limit is the current best estimate of the point where nitriding of the fuel element clad begins.

(7) A fuel melting point of 3122±30 K ($5620\pm54^\circ$ R) at 2.5 atmospheres of nitrogen gas (N_2) was used (ref. 2).

The computations for this study were carried out using the Continuous System Modeling Program (CSMP) of reference 3. This program is a digital computer program designed to run on the IBM 360 computer. The System/360 Continuous System Modeling Program is a problem-oriented program designed to facilitate the digital simulation of continuous processes on large scale digital machines. The program provides an application-oriented language that allows these problems to be prepared directly and simply from either a block diagram representation or a set of ordinary differential equations.

For this particular study, a series of differential equations were constructed to represent, first, the heat transfer characteristics of the entire reactor (core, reflector, pressure vessel, and shield) and, second, a unit cell that consisted of a single hexagonal array of seven fuel elements.

These heat transfer calculations were made in one dimension (radial direction). In the axial direction the fuel elements were divided into three regions or lumps. Heat conduction in the axial direction was neglected.

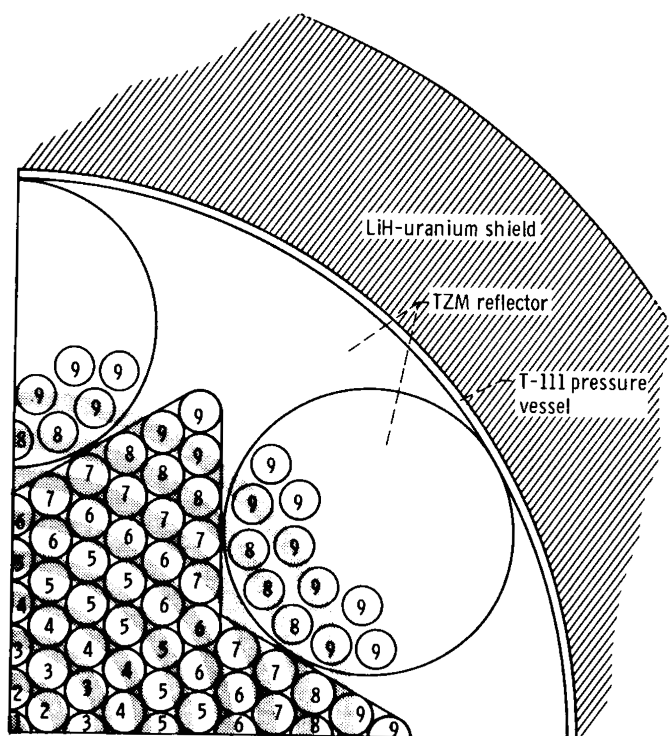
RESULTS AND DISCUSSION

Before examining the various emergency cooling concepts, it is worthwhile to present the results of the loss of coolant malfunction as calculated using the complete one-dimensional model of the reactor. This will point up the severity of the problem and hence the need for emergency cooling.

Loss of Coolant Malfunction

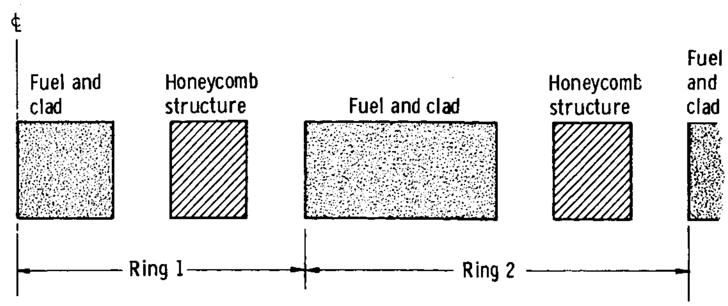
Figures 5 and 6 show the one-dimensional ring representation of the entire reactor for the conduction and radiation models, respectively. Between these two models, the heat transfer characteristics of the reactor core should be adequately represented (i. e., upper and lower bounds).

The actual fuel pin and honeycomb structure was, of necessity, simplified to the model shown in figure 6. Preliminary calculations revealed that at the reduced power levels (comparable to those produced by the afterheat processes) the tungsten liner and T-111 clad ran only about 6.0 K (10^{0} R) cooler than the fuel temperature. Since the difference in fuel and clad temperatures were so small, it was felt that there would be no

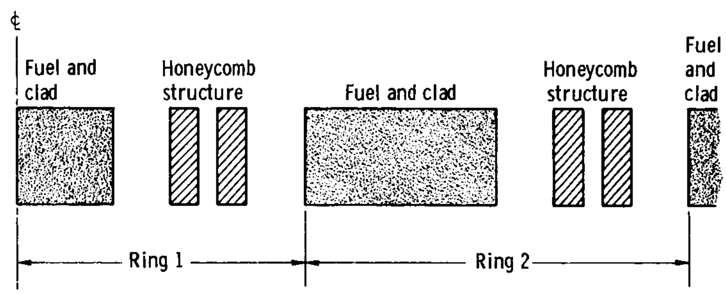


Ring number	1	2	3	4	5	6	7	8	9
Number of elements	1	6	12	18	36	36	36	36	66

Figure 5. - Ring model of space power fast-spectrum reactor.



(a) Conduction model - triflute cusps as solid T-111.



(b) Radiation model - triflute cusps as radiation gaps.

Figure 6. - Conduction and radiation ring models of space power fast-spectrum reactor.

significant loss of heat transfer information if the clad and liner were included in the fuel. Eliminating these regions from separate consideration not only simplified the equations used but sharply reduced the number of equations necessary to describe the model. In turn, these reductions resulted in a considerable savings of computer time. The power density per pin, radiating surface area, and emissivity of the fuel pin clad were however, conserved. These values are shown in appendix A. The afterheat power as a function of reactor operating time and time after shutdown is the same as that found in reference 1.

Figure 7 is a plot of fuel element temperature as a function of time after the loss of coolant malfunction. The dashed curves represent the radiation model (fig. 6(b)) while the solid curves show the results calculated using the conduction model (fig. 6(a)). The curves labeled ℄ show the fuel temperature of the centerline pin of the reactor, and those labeled Ring 5 show the temperature of those fuel elements located on the periphery of Zone I (see fig. 5). These curves therefore bound the Zone I region and indicate the response of these elements to the loss of coolant malfunction. Because of the rather high uranium loading exhibited in Zone I of the reactor, the behavior of the fuel elements in Zone I is of prime importance. Preliminary calculations (unpublished data from Wendell Mayo of Lewis Research Center) indicate that, with the proper geometrical configuration (resulting from a complete meltdown), the Zone I fuel elements alone carry a sufficiently high uranium loading to produce an uncontrollable critical mass. The data shown in fig-

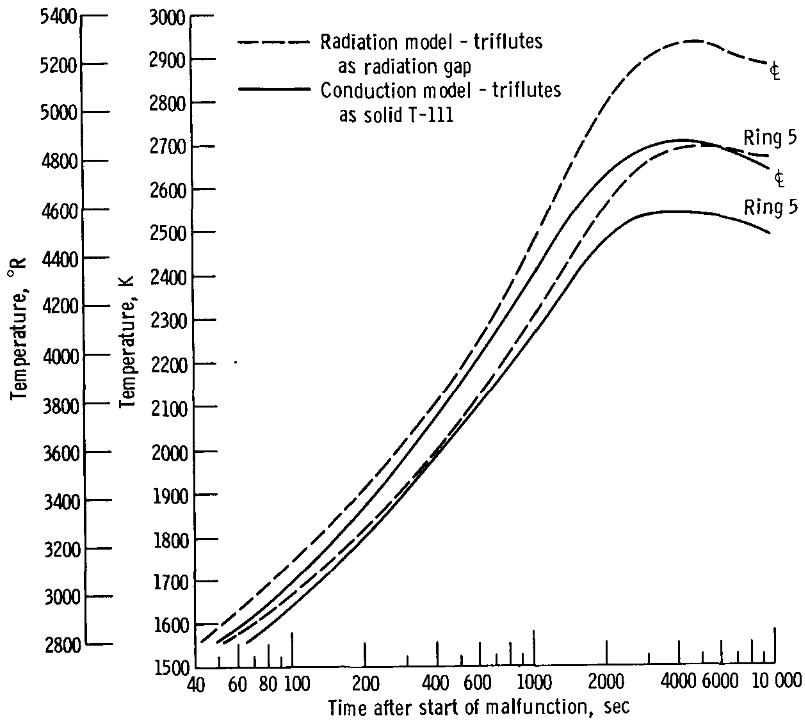


Figure 7. - Fuel temperature as a function of time after loss of primary coolant for radiation and conduction ring models of space power fast-spectrum reactor. Emissivity ϵ = 0.2; axial peaking, 1.00.

ure 7 indicate that at some average axial position (axial peaking factor = 1.00) along the fuel pin neither the radiation nor conduction model reaches the melting point 3122 K (5620° R) of the fuel. As shown, the fuel temperatures for the Zone I elements for the radiation and conduction models may range from about 2553 K (4600° R) to about 2922 K (5260° R) reaching their peak temperatures about 4000 to 5000 seconds (~1.1 and ~1.4 hr) after the loss of primary coolant.

Figure 8 shows the results of changing the axial power peaking factor. This is tantamount to moving axially along the fuel pin to the peak power point. In this case the axial peaking factor is 1.23 (ref. 4) and occurs just below midplane of the reactor core. In figure 8 we see that the radiation model shows that the centerline fuel pin will reach the melting point for UN (in about 3600 sec) while those elements on the periphery of Zone I will reach a maximum temperature of about 2833 K (5100° R) in approximately 1 hour. These same calculations indicated that several other elements composing the innermost fuel rings of Zone I were either at or approached very close to the melting point. Therefore, according to the radiation model, there was incipient melting taking place in many of the fuel pins in Zone I. The radiation model alone, however, does not accurately represent the heat transfer through the core but only presents one extreme or boundary. The conduction model presents the more optimistic results. Here the centerline fuel ele-

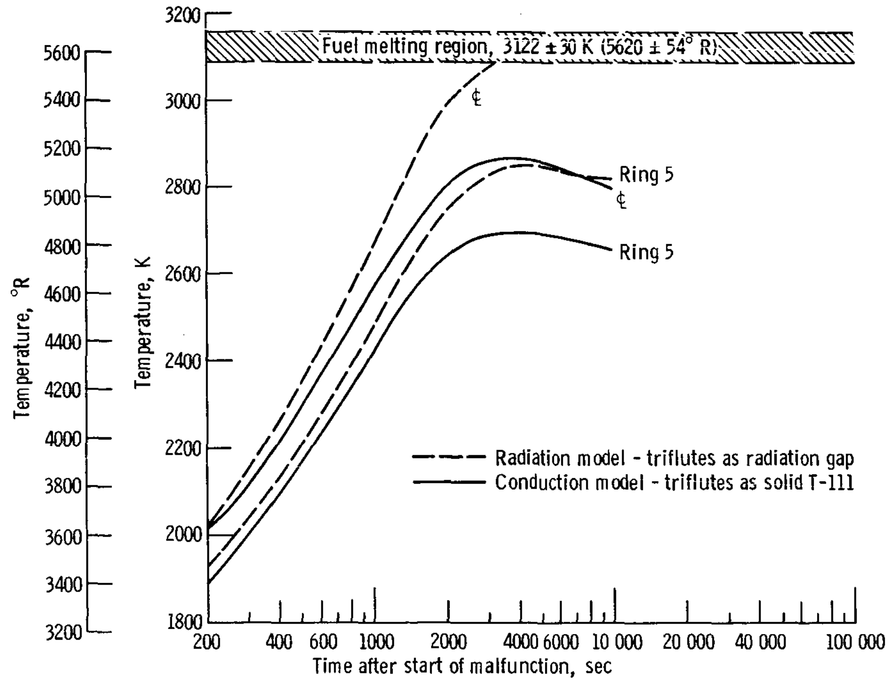


Figure 8. - Fuel temperature as a function of time after loss of primary coolant for radiation and conduction models of space power fast-spectrum reactor. Emissivity $\epsilon = 0.2$; axial peaking, 1.23.

ment temperature did not reach the melting point but peaked at about 2856 K (5140° R).

Since the actual reactor configuration lies between these two one-dimensional models, it would appear that the expected fuel element temperature exists within the bounds of these two sets of curves. Whether melting actually occurs seems, at this point, to be of secondary importance. The basic results indicated in figures 7 and 8 show that the whole of the Zone I elements are in an extremely high temperature regime and therefore could present a hazardous situation. Although the actual behavior of the fuel pins at these very high temperatures is unknown at this time, it would appear that fuel slumping and rupturing of the fuel cladding would be a distinct possibility.

In order to avoid any complications that might arise from having the reactor fuel elements at these elevated temperatures, an investigation was made of some of the possible means of emergency cooling the core.

Emergency Cooling

The purpose of an emergency cooling system should be twofold. First, the system should be capable of maintaining the fuel elements well below any temperatures where a catastrophic event might take place that would jeopardize the safety of the crew or mission. Secondly, it would be desirable (but not a necessity) for the system to have the capability of maintaining fuel element temperatures below their transient damage limit of 1611 K (2900° R). This latter capability would provide the operators of the reactor with the ability to analyze the severity of the accident and then determine if a restart of the reactor would be feasible.

Several concepts for emergency aftercooling the reactor were examined for this report. The two principal methods to be discussed here will be (1) full core open loop emergency cooling - where the entire reactor core is cooled with lithium and (2) partial core closed loop emergency cooling - where only specific fuel element flow channels are associated with the lithium flow. In both instances it is assumed that the reactor has been operating at design conditions, that is, 2.17 megawatts (7.4×10^{6} Btu/hr) for 1 year prior to the complete loss of primary coolant.

Full core open loop emergency cooling - continuous flow. - The full core emergency cooling concept requires an auxiliary lithium supply, electromagnetic pump, and a containment vessel. This particular mode of emergency cooling assumes that the lithium is supplied to the reactor in a continuous manner at a constant inlet temperature of 1167 K (2100° R). The mass flow rate of lithium was adjusted so as to decrease with the reactor decay power in such a way that the temperature drop (ΔT) across the core was maintained at approximately 56 K (100° R).

Figure 9 shows the transient response of the centerline fuel element temperature at core midplane for both immediate and delayed emergency cooling. Curve A of figure 9 shows the results of initiating emergency flow at the moment the rupture occurs. (There is no voiding of the reactor core in this case.) The control drums were assumed to initiate a shutdown at the time the rupture occurred. By introducing emergency cooling immediately, the fuel element temperature avoids a peak and instead drops rapidly with the shutdown, approaching a temperature of 1222 K (2200 R) within 50 seconds after the loss of primary lithium coolant.

Curve B of figure 9 also presents the fuel element temperature as a function of time after the malfunction. However, in this case, the control drums were assumed to remain stationary in whatever position they were in at the time of the malfunction. The reactor power decreases due only to the loss of lithium coolant.

After about 16.5 seconds the reactor has reached the shutdown level and emergency flow is then turned on. As in the preceding case, the emergency flow rate was decreased according to the decaying afterheat power. From figure 9 it should be noted that the fuel element temperature rises quite rapidly attaining a peak temperature of about 1653 K (2975° R) at the time the emergency cooling is introduced into the core (16.5 sec after the loss of primary cooling). If the primary cooling system has remained pressurized, due to a containment vessel, these fuel temperatures would come close to causing boiling

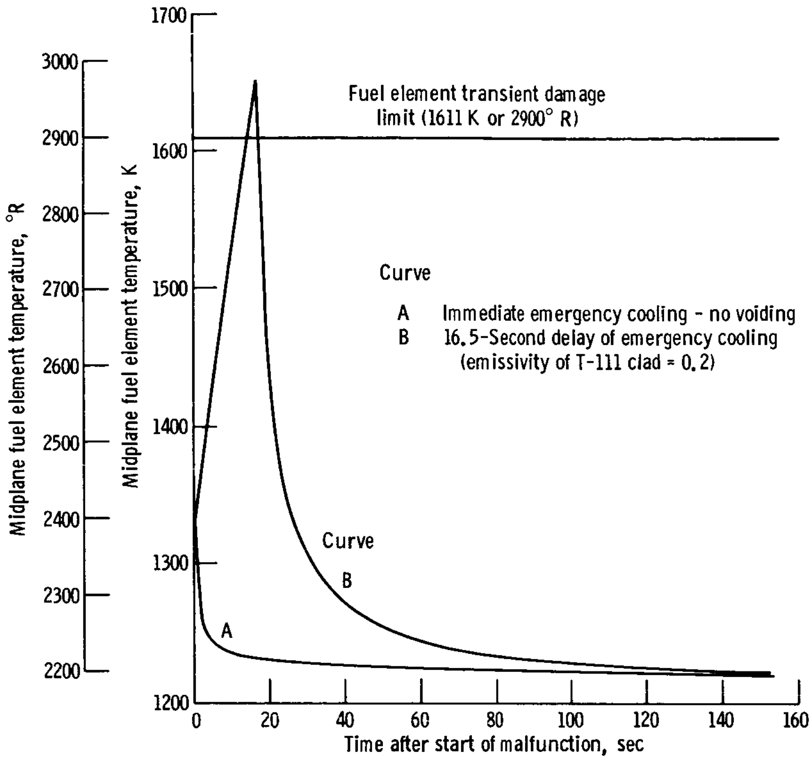


Figure 9. - Fuel temperatures as a function of time after malfunction for full core continuous flow emergency cooling.

of the emergency lithium. It would not, therefore, be prudent to delay emergency cooling beyond 16.5 seconds after the malfunction. Curves A and B of figure 9, therefore, represent the reasonable extremes in time required to get an emergency system on line.

With the primary channels voided of lithium coolant during this delay, the heat generated by the fuel must be radiated from the T-111 cladding across the flow channel gap to the honeycomb structure. The fuel element temperature is therefore quite sensitive to the value of emissivity used for the T-111 cladding. A low value of emissivity results in a faster rise in fuel element temperatures. To establish the shortest possible time available (worse case) to get an emergency cooling system on line, a low value of emissivity ($\epsilon = 0.2$) was chosen for this case. The effect of varying the emissivity value is discussed in more detail in the section Partial core closed loop emergency cooling (hex cooling).

Pulsed emergency cooling. - Another mode of emergency cooling the reactor core is to pulse the lithium coolant through the reactor core each time the fuel temperature reaches some arbitrary upper limit. For this analysis, pulsing was initiated each time the fuel element temperature reached 1667 K (3000° R). Supplementary calculations, not shown in this report, indicate that the optimum pulse length is about 8.0 seconds in duration at a mass flow rate of 0.372 kilogram per second (0.82 lb/sec) per channel (design condition). The results of pulse cooling the reactor core in this manner are shown in figure 10. This figure shows only the first three pulses necessary to cool the reactor fuel elements. The total number of pulses required to cool the fuel pins depends on (1) the final fuel element temperature desired and (2) how long the reactor had been in operation prior to the loss of coolant malfunction. From the data of figure 10 we see that the time increment between coolant pulses becomes longer as the afterheat power decays.

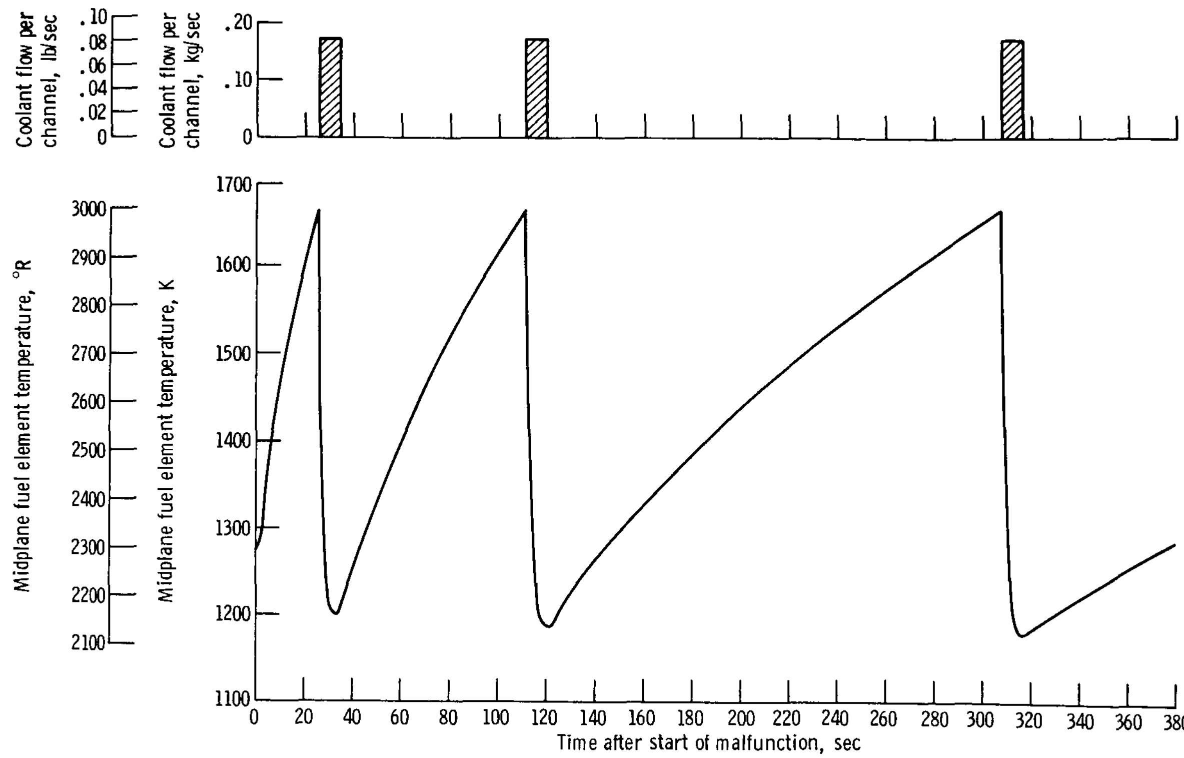


Figure 10. - Fuel element temperatures as a function of time after malfunction for cooling pulse of 8 seconds and reactor operating time of 1 year with lithium coolant inlet temperature of 1167 K (2100° R).

A major question related to both of the preceding concepts (the full core open loop - continuous and pulse cooling system) is the length of time that the emergency cooling system would be required to operate in order to adequately cool the fuel elements. This operating time is a function of (1) how long the reactor has operated prior to the loss of coolant malfunction and (2) the required final maximum fuel element temperature. Table I lists the results of a series of steady state calculations directed at determining the emergency cooling operating time for a specific final fuel element temperature. A more detailed discussion of these data is found in appendix B.

TABLE I. - REQUIRED EMERGENCY COOLING TIMES FOR VARIOUS

FINAL FUEL ELEMENT TEMPERATURES[a]

Final fuel element temperature		Emergency cooling time after -	
K	^{o}R	1 year of reactor operation	1 day of reactor operation
1611	2900	1.98×10^{7} sec ≈ 229 days	5.6×10^{4} sec ≈ 0.65 day
2222	4000	5.90×10^{6} sec = 68.3 days	1.45×10^{4} sec ≈ 0.167 day = 4 hr
2778	5000	9.8×10^{5} sec = 11.3 days	5.5×10^{3} sec ≈ 1.53 hr

[a]Data based on a constant coolant inlet temperature of 1167 K (2100^{o} R) and an 8.0-sec-long pulse flow at design flow rate of 0.372 kg/sec (0.82 lb/sec).

From table I we see that, if the reactor has been operating for 1 year prior to the loss of coolant accident, a considerable amount of time will be required to aftercool the core. For a final fuel element temperature of 1611 K (2900^{o} R) approximately 229 days of pulse cooling will be necessary. (These results are based on a constant 1167 K (2100^{o} R) lithium inlet temperature and an 8.0-second-long flow pulse at the design flow rate of 0.372 kilogram per second (0.82 lb/sec).) Pulse cooling will continue until either (1) the entire containment structure and reactor core is filled with auxiliary lithium or (2) if the containment structure is very large, until the final desired fuel temperature is reached. If it is assumed that a large containment vessel is available for this reactor, then a rough estimate of the total lithium inventory required to pulse cool for 229 days is of the order of 22 630 kilograms (50 000 lb). To cool the fuel pins such that the final peak temperature would not exceed 2778 K (5000^{o} R) would require that the emergency system pulse lithium through the core for slightly over 11 days consuming approximately 4545 to 6818 kilograms (10 000 to 15 000 lb). These results, therefore, indicate that a rather severe weight penalty (for a flight system) is associated with this type of emergency cooling.

Some savings in the total emergency lithium inventory can be realized by reducing the coolant inlet temperature. Lowering the coolant inlet temperature decreases the overall fuel element temperature at the end of the coolant pulse, thus requiring a longer time for the fuel temperatures to reach 1667 K (3000^{o} R). This obviously means fewer pulses and thus a smaller auxiliary lithium supply. The results of lowering the coolant inlet temperatures are shown in figure 11. By lowering the coolant inlet temperature to 833 K (1500^{o} R), curve B of figure 11, the time lapse between the first and second coolant pulses is significantly increased over the 1167 K (2100^{o} R) coolant inlet case. In fact, the time between pulses for curve B is more than twice that of curve A. Curve C with a

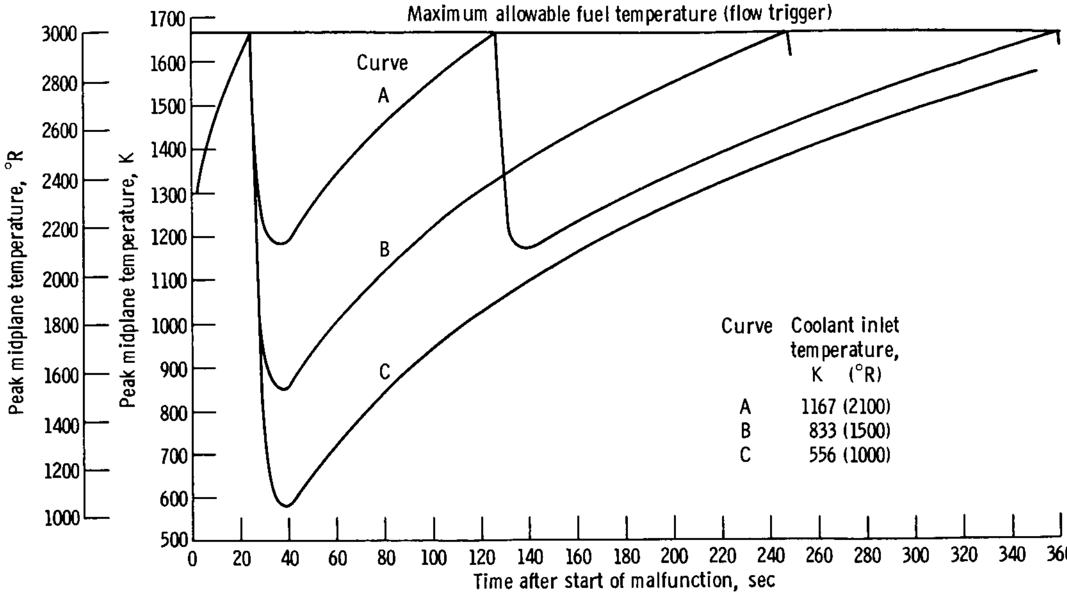


Figure 11. - Afterheat fuel temperature for lithium coolant pulses of varying inlet temperatures. Reactor operating for 1 year prior to malfunction.

556 K (1000° R) coolant inlet temperature shows an even longer time span (almost twice that of curve B) between coolant pulses. From these data we see that a considerable savings in the auxiliary lithium inventory (on the order of 50 percent or more) over the 1167 K (2100° R) case can be realized by decreasing the emergency coolant inlet temperature.

Partial core closed loop emergency cooling (hex cooling). - Because of the rather large weight penalty associated with the open loop modes of aftercooling the reactor, several closed loop concepts of emergency cooling were also examined. Throughout this study of emergency cooling concepts, the underlying and guiding principal was to arrive at a system that would be adequate for cooling the reactor and would not require a significant change of the basic core design and/or primary loop. Those changes to the reactor design that are absolutely necessary to the proper functioning of the emergency system should be minimal at best and attempt to keep fuel loading and core size of the reactor constant.

The emergency cooling concepts that will be discussed in this section of the report will all incorporate a redundant internal loop similar to the one shown in figure 12. The emergency loop will function independent of the main primary coolant loop and require a separate electromagnetic pump and heat exchanger. The heat exchanger would be tied into the secondary power conversion loop so that there would be no loss of power during normal operating conditions.

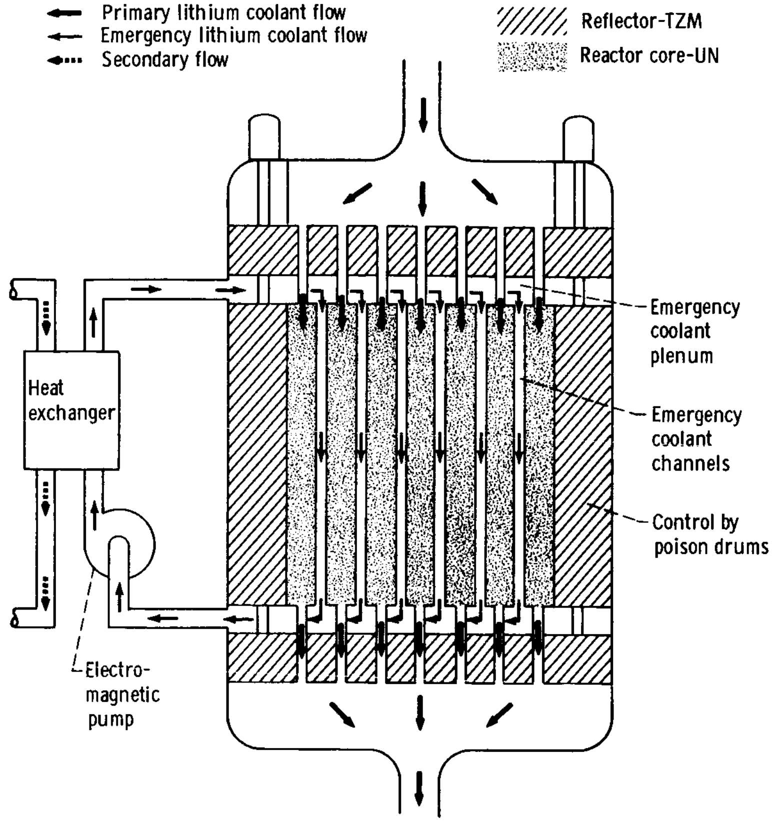


Figure 12. - Schematic of internal emergency cooling system.

Figure 12 shows the reactor and emergency coolant channels in profile. The emergency lithium coolant would enter the reactor between the top reflector and the reactor core. This region between the reflector and the reactor core would be a sealed plenum independent from the main primary flow. Flow from the emergency loop would proceed from this plenum down through those coolant channels specifically earmarked for emergency coolant into another sealed plenum at the bottom of the reactor. From this bottom plenum the emergency lithium would then exit the reactor pressure vessel and pass on to the heat exchanger. Primary flow would enter the top of the pressure vessel, pass down through the head end reflector, on through the emergency plenum via tubular extensions of the primary flow channels, past the main body of fuel elements and finally out the bottom of the reactor via similar tubular extensions. The top and bottom sealed emergency plenums, therefore, permit independent flow of the two systems within the reactor core.

Figure 13 shows a cross section of the reactor core with the specific flow channels used for emergency cooling. For this study, the central area of each hexagonal fuel array (hex cooling) was allocated for emergency cooling (this amounted to about 43 flow areas). A redundant internal loop of this type affords the capability of selecting the num-

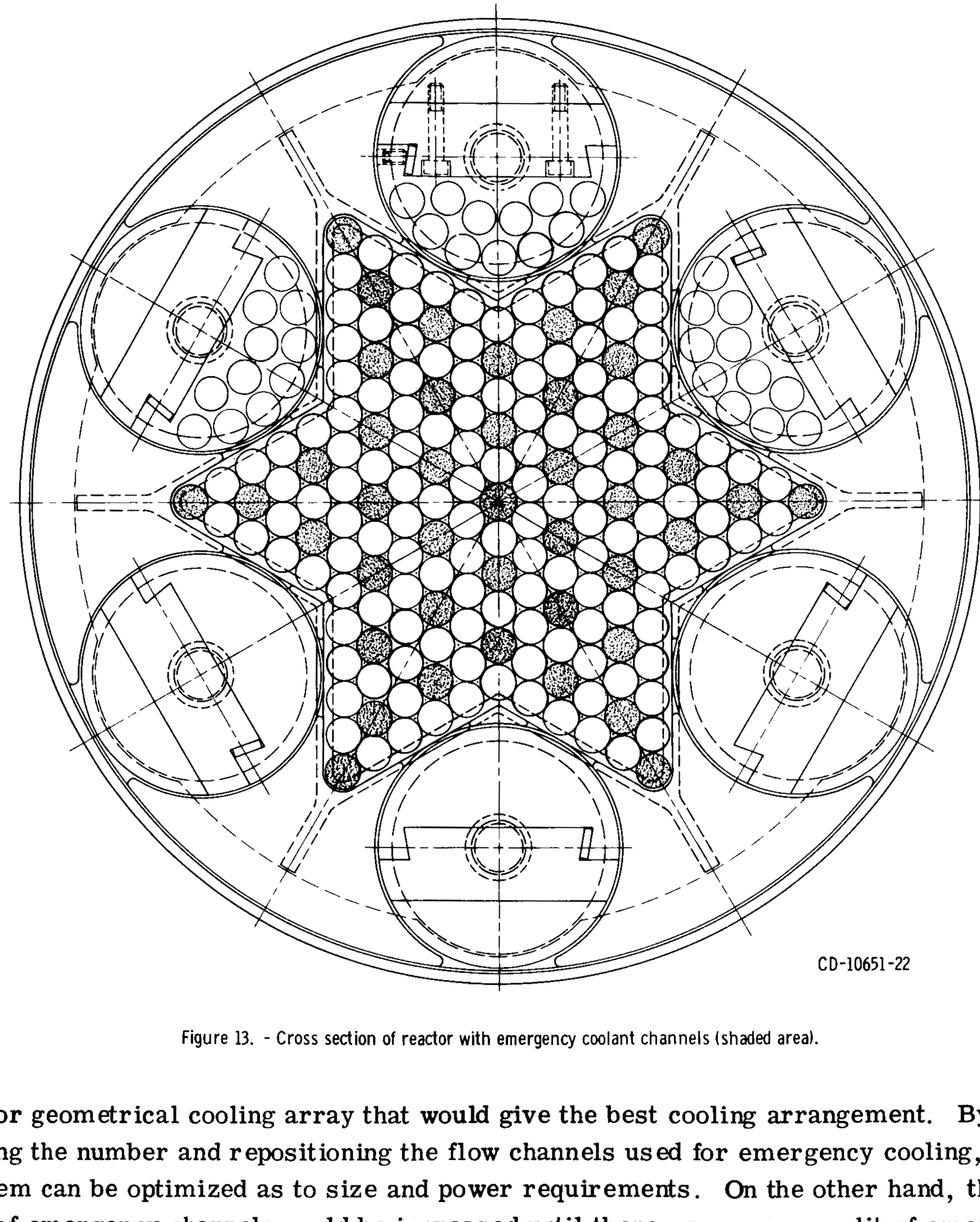


Figure 13. - Cross section of reactor with emergency coolant channels (shaded area).

ber or geometrical cooling array that would give the best cooling arrangement. By reducing the number and repositioning the flow channels used for emergency cooling, the system can be optimized as to size and power requirements. On the other hand, the number of emergency channels could be increased until there was an even split of emergency and primary flow channels - thus producing two equal and independent cooling loops. This type of redundancy in the main loop would not only be advantageous from a safety standpoint but may also be quite useful in startup, shutdown, and possibly during periods of reduced power demands.

Figure 14 is a more detailed view of a typical fuel hexagonal array. With the sur-

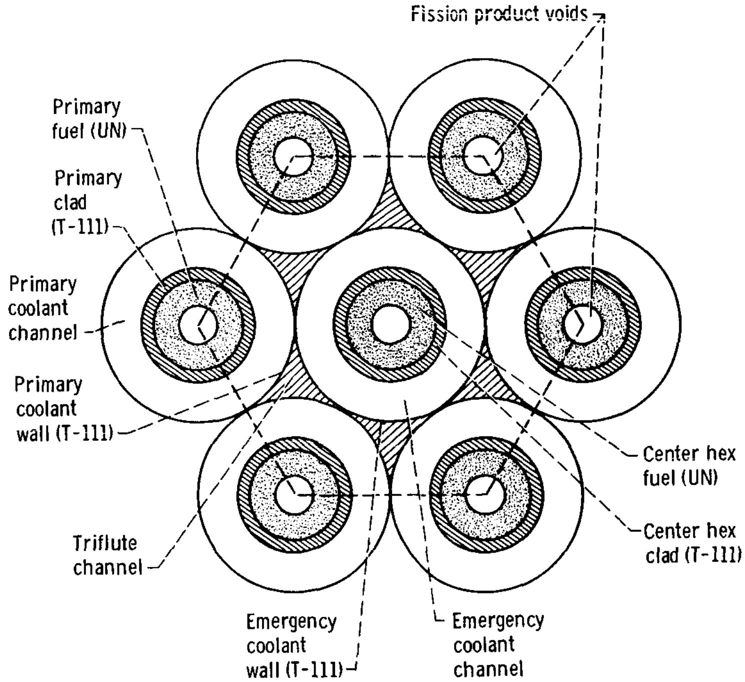


Figure 14. - Fueled hex emergency cooling array.

rounding six fuel element flow channels voided due to the loss of coolant, there remains only two flow areas available for emergency flow. These are (1) the central emergency channel and (2) the triflute region (cross-hatched area). From these two flow areas there are three combinations of emergency flow available to the system: (1) central emergency channel flow, (2) emergency channel plus triflute flow, and (3) triflute channel flow only.

Central emergency channel flow: For this analysis emergency lithium flow was supplied to only the central emergency channel. The primary coolant channels and the triflute channels were both assumed to be voided by this malfunction. The flow rate to the central emergency channel was maintained at normal design conditions (a constant 1.2 m/sec or 3.95 ft/sec). The results of these calculations are shown in figure 15. The fuel element temperature at core midplane for the six peripheral fuel pins of the central hexagonal array is given as a function of time after the loss of primary coolant. Curve A shows the fuel temperatures that were calculated with a T-111 clad and structure emissivity of 0.2. In this case the fuel temperature rises quite rapidly (about 7.0 K/sec or 12.5° R/sec) for the first 50 to 60 seconds then begins to level off and finally reaches a peak value of about 1694 K (3050° R) at about 120 seconds after the start of the malfunction. It is important to note that, under these constraints, the transient fuel element damage limit is reached in about 60 seconds and eventually is exceeded by about 83 K (150° R). Damage to the primary fuel as a result of exceeding the transient limit may be

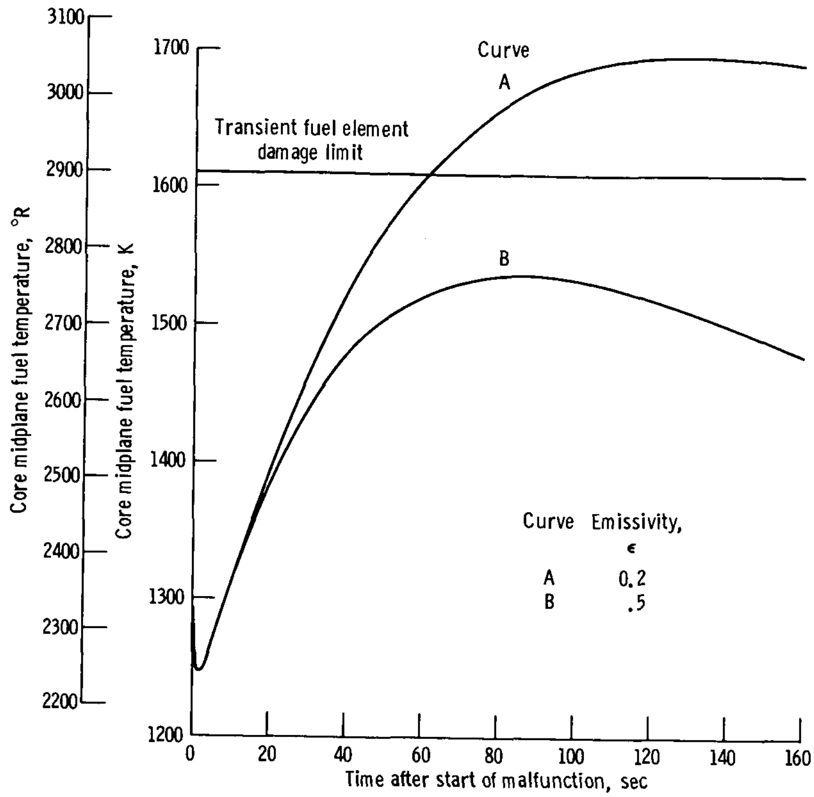


Figure 15. - Fuel element temperature at core midplane as a function of time after malfunction with flow in emergency channel only.

of such an extent that a restart of the reactor would not be possible.

Curve B, however, shows a peak temperature of only about 1542 K (2775° R), well below the transient fuel element damage limit. In this case the emissivity value used for the T-111 clad and structure was 0.5. From these data we clearly see the pronounced effect the value of emissivity has on the final results. Obviously, a high clad and structure emissivity, of the order of 0.5, is desirable.

Figure 16 is a plot of fuel element temperatures as a function of position across the fuel hexagon, starting with one of the peripheral fuel elements and moving across the hex to the central fuel pin. Figure 16 shows the temperature distribution through the hex at three times during the incident; curve A illustrates the fuel and clad temperatures with the reactor operating at normal design conditions; curve B shows the temperatures at the shutdown condition (i.e., 22 percent of design power); and curve C shows the moment the peak temperatures occur. Curve C points up the rather severe temperature gradient existing between the primary clad, primary structure, and emergency structure. These temperature gradients could be quite important in determining the feasibility of this type of emergency cooling.

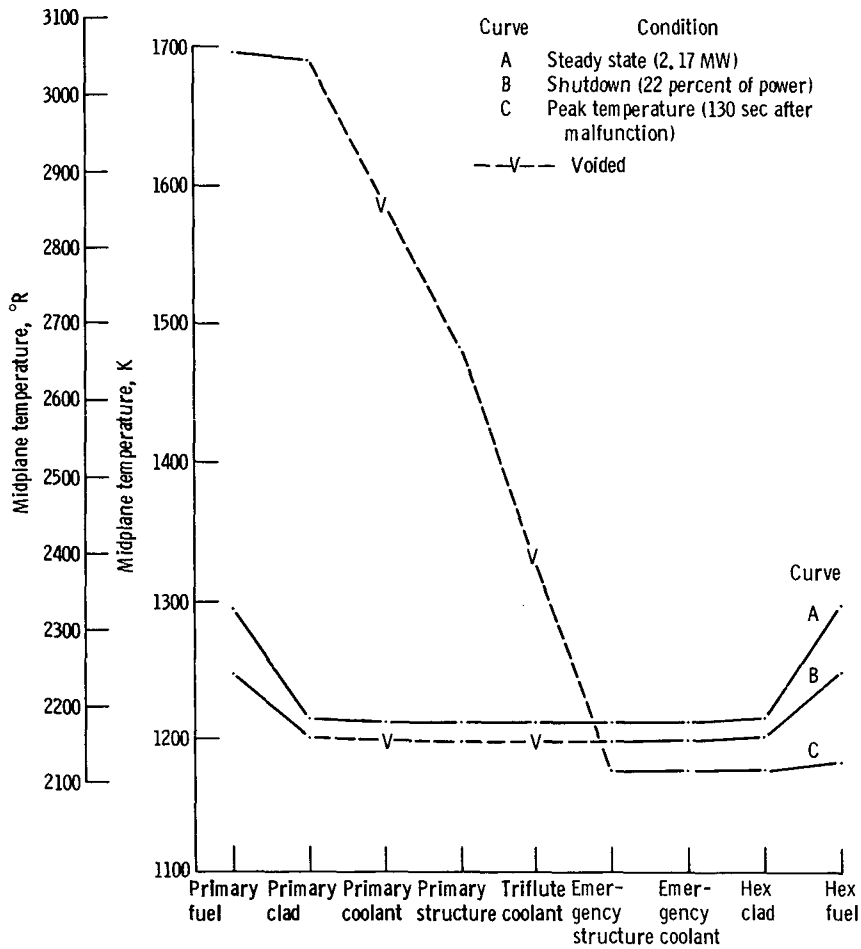


Figure 16. - Midplane temperature profile of fuel and structure for partial emergency cooling with flow in emergency channel only.

Central emergency channel plus triflute flow: For this concept emergency lithium flow is introduced into both the central emergency channel and the six triflute passages of each hexagonal fuel array in the reactor. The primary coolant channels of the six peripheral fuel pins are voided due to the loss of primary lithium coolant. The flow rate to the central emergency channel was maintained at the normal design flow rate of 1.20 meters per second (3.95 ft/sec) while the flow rate through the triflute passages were held at their design point, a constant 0.152 meter per second (0.5 ft/sec).

In figure 17, curve A shows the temperature at core midplane for the six peripheral fuel elements of the hex with an emissivity of 0.2. In this case the maximum fuel element temperatures reached about 1583 K (2850° R) in about 90 to 100 seconds after the start of the malfunction. These data show that, with this particular emergency flow configuration, the transient fuel element damage limit is not exceeded. Curve B of the same plot again points out the effect of increasing the emissivity. With an emissivity value of

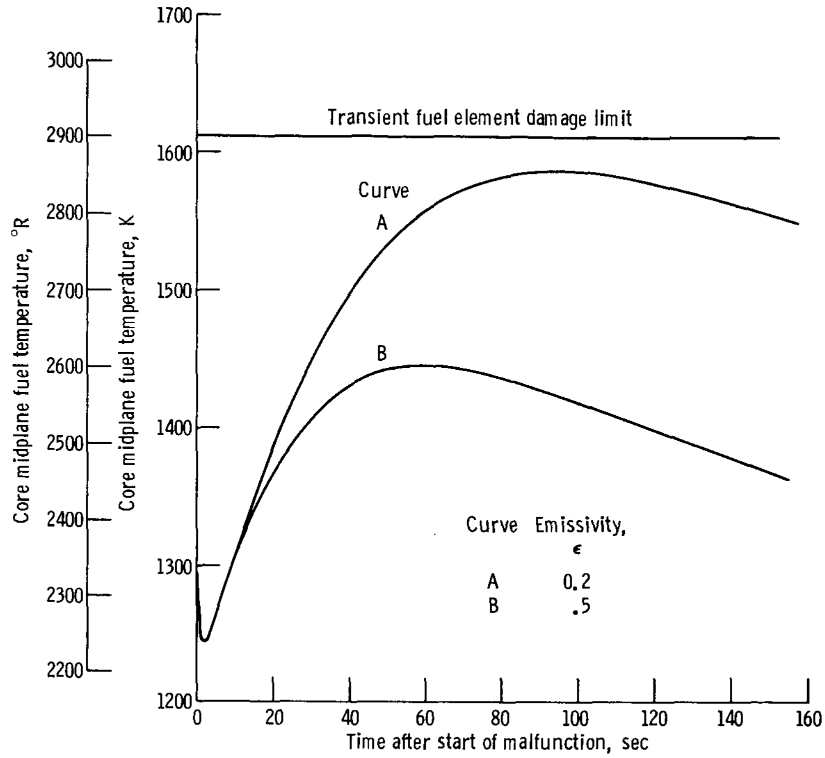


Figure 17. - Fuel element temperature at core midplane as a function of time after malfunction with flow in emergency and triflute channels only.

0.5 the fuel element temperature reached a maximum of only about 1444 K (2600° R) within 60 seconds after the loss of primary coolant.

Comparing this case of emergency lithium flow in both the central emergency channel and the triflute regions with the preceding case where flow was restricted to the central emergency channel only, we see the importance of maintaining lithium flow in the triflute passages. The fuel temperatures were lowered considerably, 111 K (200° R), by simply tying the triflute flow into the emergency flow system.

Figure 18 is another profile of the temperature distribution through the hexagonal fuel array. With lithium coolant now flowing in both the triflute and central emergency channels, the steep temperature gradient at the peak condition now exists between the primary clad and primary structure. While the peripheral fuel and clad are running at the elevated temperature conditions, the interior portion of the hex appears to remain well below normal design temperatures.

Triflute channel flow only: In this case, emergency flow is supplied to only the six triflute passages of each fuel hex of the reactor. The primary flow channels and the central emergency flow channels are both assumed to be voided due to the loss of coolant

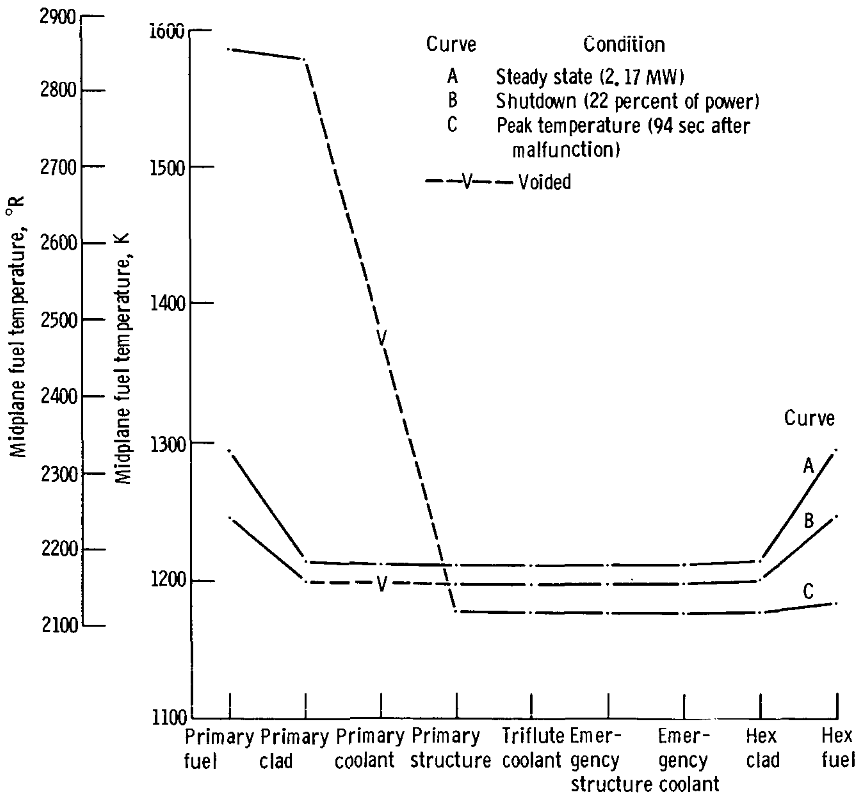


Figure 18. - Midplane temperature profile of fuel and structure for partial emergency cooling with flow in emergency and triflute channels.

malfunction. The flow rate to the triflute was maintained at the normal design flow rate of 0.152 meter per second (0.5 ft/sec).

Figure 19 shows the fuel element temperature at core midplane for the six peripheral fuel elements of the hex and the central fuel pin as well. With an emissivity for the clad and structure of 0.2 the maximum temperature calculated was about 1589 K (2860° R). This peak temperature occurred about 100 seconds after the loss of primary coolant. Curve B of this same figure again shows the effect of increasing the value of the emissivity to 0.5. A peak temperature for this case of about 1458 K (2625° R) was determined.

Comparing this case with the preceding one in which both the triflutes and the central emergency channel were used for emergency cooling, it would appear that very little cooling capability is lost by utilizing the triflute passages by themselves.

In the preceding cases the emergency flow through the various channels (central fuel and/or triflute channels) was maintained at the designed flow rate. Curve C of figure 19 shows the results of increasing the lithium flow through the triflute region to 1.20 meters per second (3.95 ft/sec). These data indicate about the same initial rise in fuel element

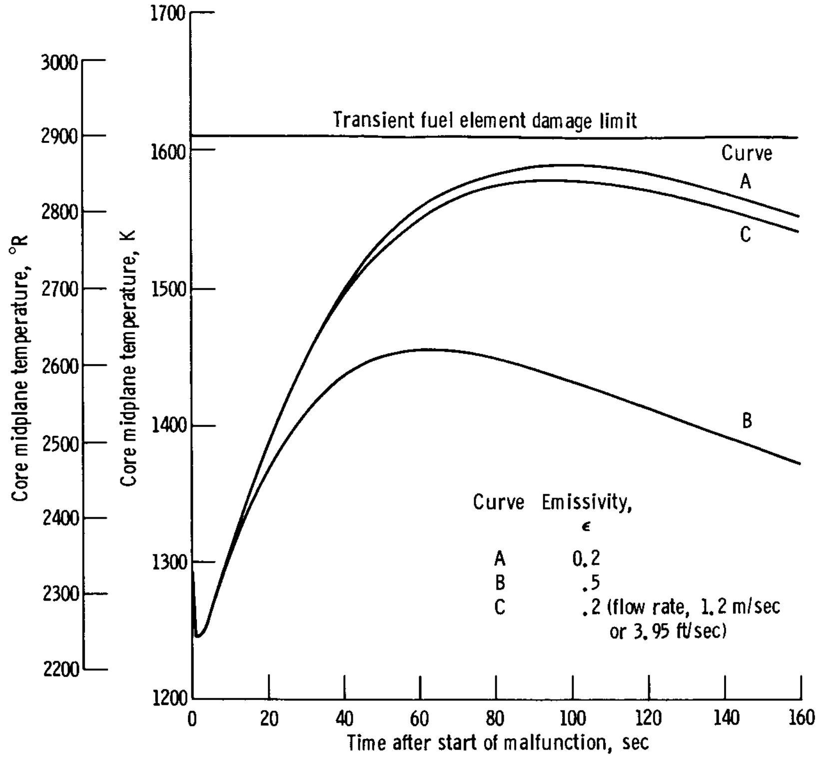


Figure 19. - Fuel element temperature at core midplane as a function of time after malfunction with flow in triflute channel only.

temperature with a final peak temperature value of about 1576 K (2840° R) for an emissivity of 0. 2. The peak fuel temperature for this case of rather high lithium flow, 1. 20 meters per second (3.95 ft/sec), differs by only about 11 K (20° R) less than 1 percent from the preceding case in which emergency flow was maintained through the triflutes at only 0. 152 meter per second (0. 5 ft/sec). From these data it would, therefore, appear that the fuel temperatures are rather insensitive to large emergency flow variations in the triflute passages.

Figure 20 shows the temperature distribution through the hex for emergency coolant in the triflute channels only. These temperatures are again shown at three time intervals through the incident: full power design conditions, shutdown, and at final peak fuel temperature. At the peak temperature condition these data show that the six peripheral fuel elements of the hex and the central fuel pin are all running at the same temperature level - 1589 K (2860° R).

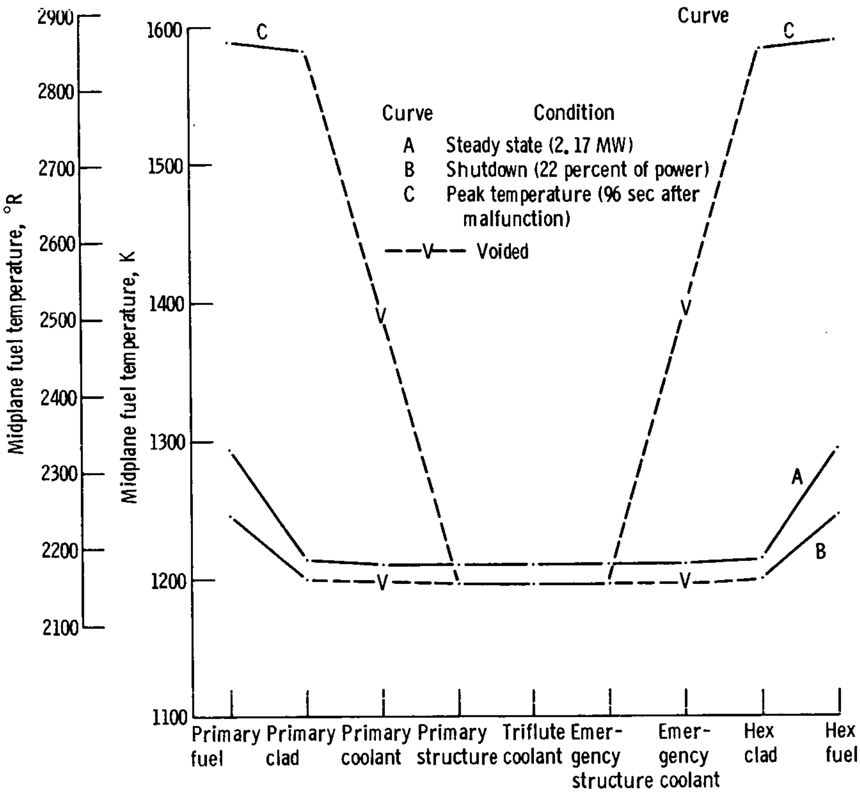


Figure 20. - Midplane temperature profile of fuel and structure for partial emergency cooling with flow in triflute channel only.

CONCLUDING REMARKS

The purpose of this report was twofold: first, to re-examine the loss of coolant malfunction in greater detail than previously reported in reference 1 and determine more closely the resulting peak fuel element temperatures and, second, to examine various emergency cooling concepts in an effort to determine an effective means of aftercooling the reactor following this type of malfunction.

A one-dimensional heat transfer analysis was made of the loss of coolant malfunction with the following results:

1. A mathematical model that represented the triflute regions of the core by radiation gaps showed that there could be localized melting axially along some of the Zone I fuel elements.

2. Both the radiation and conduction models of the reactor core showed that the fuel temperatures for the centermost Zone I elements reached or exceeded approximately 2778 K (5000° R) in about 1300 to 3600 seconds (25 min to 1 hr) after the start of the malfunction.

3. Some form of emergency aftercooling will be required if it is necessary to maintain fuel element temperatures below some arbitrary safe upper limit.

Two basic concepts of emergency cooling the conceptual space power fast-spectrum lithium cooled reactor were studied in this report: (1) full core emergency cooling with an open loop emergency supply of lithium cooling the entire core in either a continuous or pulsed mode and (2) partial core closed loop emergency cooling with emergency flow supplied to only the central region of each hexagon fuel array in any of three modes - central channel flow, central and triflute channel flow, and triflute channel flow only.

Since the full core emergency cooling concept is an open loop system, it appears to be handicapped by the necessity of having a rather large auxiliary supply of lithium available. Of the two modes of full core cooling examined even the most efficient mode, the pulse cooling method, required an auxiliary supply of as much as 4536 to 6804 kilograms (10 000 to 15 000 lb) to maintain fuel element temperatures below 2778 K (5000° R) for a reactor that had been operating for only 1 year prior to the loss of coolant malfunction.

The partial core emergency cooling concept using the internal redundant loop appears to offer considerable promise. Regardless of which of the three emergency cooling configurations used by this system, the fuel element temperatures can be kept well below their melting point - 3122 K (5620° R) - with only normal design flow rates within the emergency channels. With emergency coolant flow supplied to the triflute passage the fuel element temperatures can be kept below the transient fuel element damage limit of 1611 K (2900° R). The calculations also point out the sensitivity of the emissivity value used for the T-111 clad and honeycomb structure. Increasing the emissivity value from 0.2 to 0.5 decreased the maximum fuel element temperature by about 9 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 5, 1971,
112-27.

APPENDIX A

REACTOR PARAMETERS

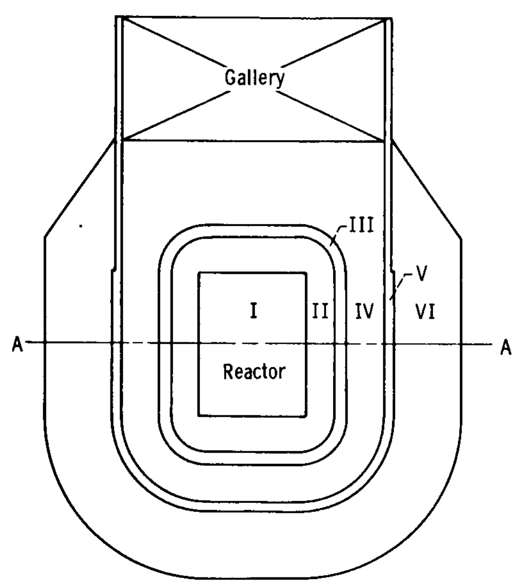
Core power, MW (Btu/hr)	2.17 (7.4×10^6)
Fuel volume, m^3 (ft^3)	0.01457 (0.515)
Core height, m (ft)	0.3758 (1.233)
Outer radius of fuel, m (ft)	0.00792 (0.026)
Outer radius of clad, m (ft)	0.00953 (0.03125)
Outer radius of coolant channel, m (ft)	0.01054 (0.03458)
Thickness of clad, m (ft)	0.00160 (0.00525)
Density of fuel, kg/m^3 (lb/ft^3)	1.429×10^3 (0.892×10^2)
Density of clad, kg/m^3 (lb/ft^3)	1.67×10^4 (1.045×10^3)
Density of lithium coolant, kg/m^3 (lb/ft^3)	4.42×10^2 (2.76×10^1)
Density of structure, kg/m^3 (lb/ft^3)	1.67×10^4 (1.045×10^3)
Melting temperature of fuel (at 2.5 atms of N_2), K (^oR)	3122±30 (5620±54)
Inlet coolant temperature, K (^oR)	1167 (2100)
Velocity of coolant in average channel, m/sec (ft/sec)	1.204 (3.95)

APPENDIX B

DECAY HEAT COOLING TIMES

In order to determine how long we must aftercool the reactor core, following a loss of coolant malfunction, it is first necessary to determine how much heat can be dissipated by the reactor core through radiation and conduction to the surrounding media. For these particular calculations it was assumed that the reactor was enclosed in a 4π biological shield similar to the configuration shown in figure 21. (This shield arrangement is similar to one of the preliminary shields proposed for the SNAP 8, ref. 5.)

Since the heat transfer calculations were one-dimensional, only a radial cross section of the shield at the reactor midplane was used (line AA). A further simplification was made. The various layers of materials (lithium hydride and depleted uranium) mak-



Region	Material	Inside diameter		Outside diameter	
		cm	in.	cm	in.
I	Reactor	------	-----	68.58	27
II	Lithium hydride	68.58	27	95.45	37.58
III	Uranium	95.45	37.58	108.33	42.65
IV	Lithium hydride	108.33	42.65	148.06	58.29
V	Uranium	148.06	58.29	155.88	61.37
VI	Lithium hydride	155.88	61.37	223.95	88.17

Figure 21. - Proposed lithium hydride-depleted uranium shield.

ing up the shield were homogenized and the thermoconductivity averaged using the following relation:

$$\Delta T_i = \frac{\overline{kA}\left(\frac{\Delta T}{\Delta R}\right)\Delta R_i}{k_i 2\pi R_i l}$$

where

ΔT_i temperature drop across i^{th} layer

$\bar{k}$ average (homogenized) shield conductivity

$\bar{A}$ average surface area

k_i thermal conductivity of i^{th} layer

ΔT total temperature drop across shield, $\Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 + \Delta T_5$

ΔR thickness (total) of shield

ΔR_i thickness of i^{th} layer

R_i radius to i^{th} layer

l length of reactor

The density of lithium hydride is 0.82 gram per cubic centimeter, while the density of uranium is 18.9 grams per cubic centimeter; the thermal conductivity of lithium hydride is 5.193 W/(m)(K) or 3.00 Btu/(hr)(ft)(^{o}R), and the thermal conductivity of uranium is 25.965 W/(m)(K) or 15.00 Btu/(hr)(ft)(^{o}R). Using the values given in the previous paragraph and those shown in figure 21, the average thermal conductivity for the shield was determined to be:

$$k_{shield} = 5.0355 \frac{W}{(m)(K)} \quad \text{or} \quad 2.909 \frac{Btu}{(hr)(ft)(^{o}R)}$$

With these data and using the computer programs HCA5 and HCA6 (private communication - programs developed by George Niederauer, NASA Lewis Research Center, Cleveland, Ohio), it was possible to calculate the steady-state centerline fuel element temperature for a range of afterheat powers and sink temperatures with the core voided of coolant.

Figure 22 is a plot of fuel temperatures as a function of afterheat power for a core voided of lithium. From these data we see that fuel element temperatures are relatively

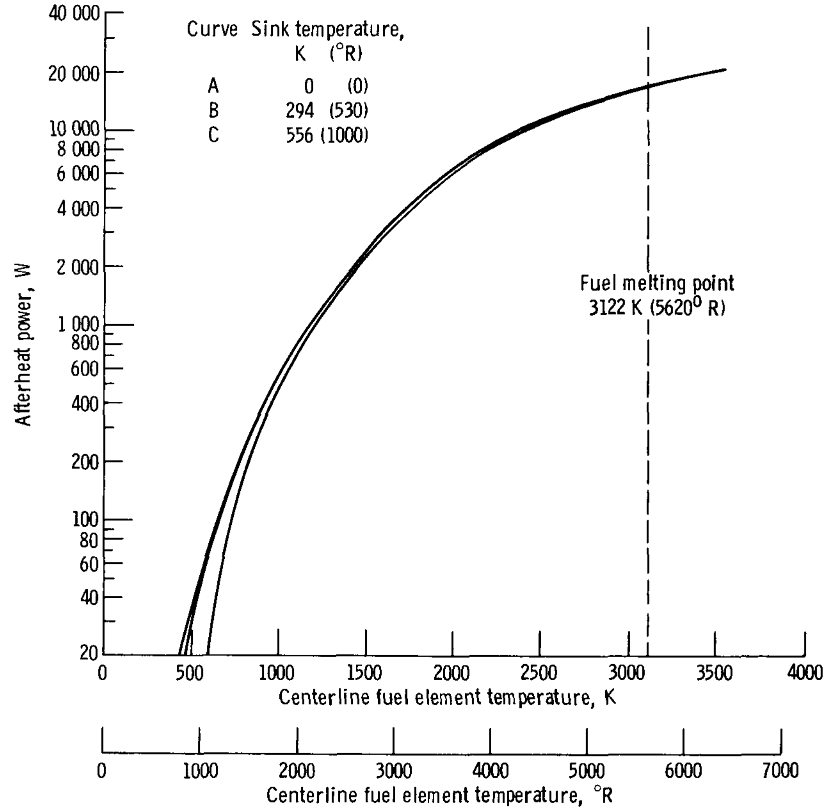


Figure 22. - Final fuel temperatures as a function of afterheat (LiH-natural uranium shield). Core voided.

insensitive to the sink temperatures outside the lithium hydride-uranium shield. With this curve one could select any desired final fuel temperature that would be considered reasonably safe and from this find the commensurate afterheat power level. From the afterheat power curves published in TM X-2057 (ref. 1) it is possible to determine the required time to reach a particular afterheat power level.

Combining these two sets of data we have the results shown in figure 23. These data show how long we must aftercool the reactor such that, following the shutdown of the emergency cooling system and with the core voided, the final fuel element temperature will not exceed a specific value. For instance, if the afterheat power (after 1 yr of operation) has finally decreased to about 14 kilowatts the emergency aftercooling system can be shutdown, thus voiding the reactor core and the resulting centerline fuel temperature will peak at about 2778 K (5000° R). A final fuel temperature of 2778 K (5000° R) would require that the core be cooled for approximately 9.8×10^{5} seconds (about 11 days). If the reactor had been operating for only 1 day prior to the malfunction, aftercooling would only be required for 5.4×10^{3} seconds (about 1.5 hr).

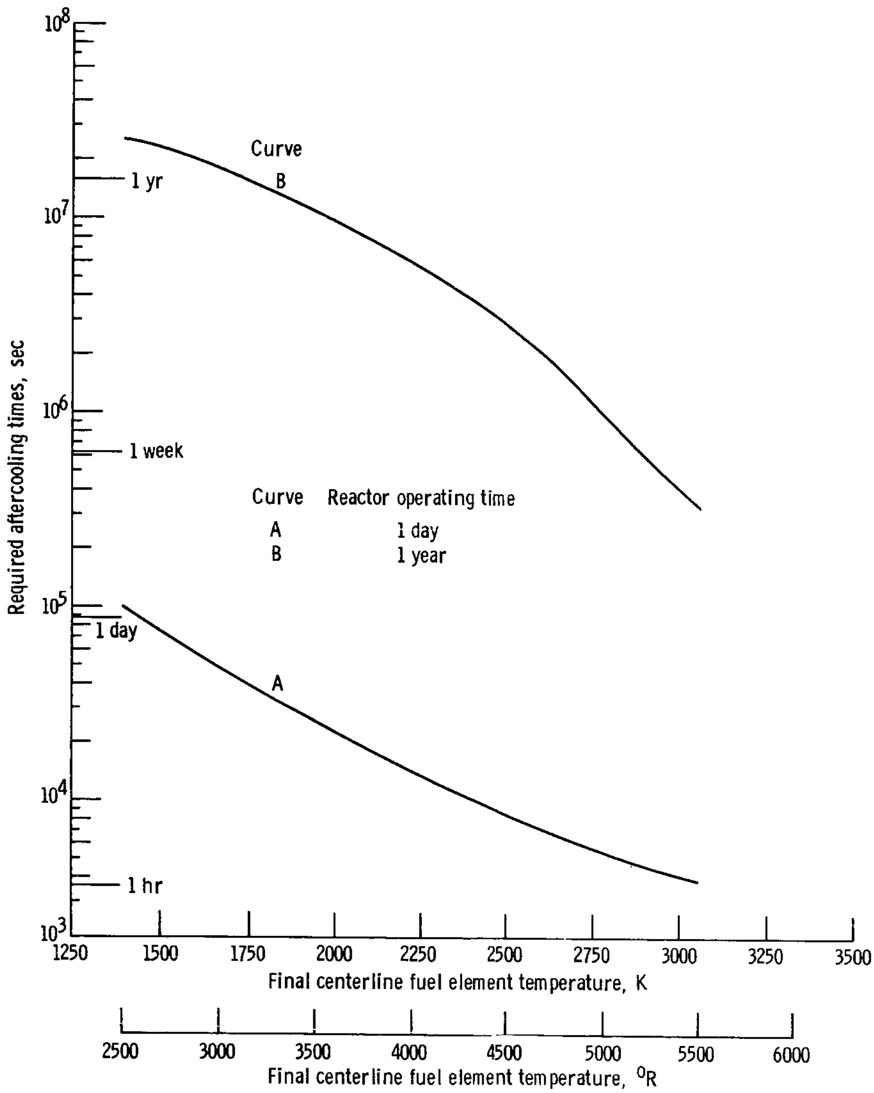


Figure 23. - Required emergency cooling time as a function of final fuel element temperature. Reactor operating times of 1 day and 1 year; core voided.

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