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THERMOHYDRAULICS IN A HIGH-TEMPERATURE GAS-COOLED REACTOR PRESTRESSED-CONCRETE REACTOR VESSEL DURING UNRESTRICTED CORE-HEATUP ACCIDENTS *

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INTRODUCTION

The hypothetical accident considered for siting considerations in High Temperature Gas-Cooled Reactors (HTGR) is the so called Unrestricted Core Heatup Accident (UCHA), in which all forced circulation is lost at initiation, and none of the auxiliary cooling loops can be started.

The result is a gradual slow core heatup, extending over days. Whether the liner cooling system (LCS) operates during this time is of crucial importance. If it does not, the resulting concrete decomposition of the prestressed concrete reactor vessel (PCRV) will ultimately cause containment building (CB) failure after about 6 to 10 days.

The primary objective of the work described here was to establish for such accident conditions the core temperatures and approximate fuel failure rates, to check for potential thermal barrier failures, and to follow the PCRV concrete temperatures, as well as PCRV gas releases from concrete decomposition.

The work was done for the General Atomic Corporation "Base Line Zero" reactor[1] of 2240 MW(th). Most results apply at least qualitatively also to other large HTGR steam cycle designs.

SYSTEM DESCRIPTION

A brief system description of a typical large HTGR was given in the preceding paper.[2] A schematic of the thermal barrier which plays a crucial role during long term UCHA sequences is shown in Figure 1. The cover plates are typically of carbon steel in the upper plenum, and most of the side walls. If they or their anchors fail due to excessives temperatures, the thermal insulation can fall away, exposing the steel liner to direct radiation from hot reflectors or side shields. The cooling tubes are welded to the liner -- 1 in or 1 1/4 in, schedule 40 pipes -- and are embedded in the PCRV concrete.

ACCIDENT DESCRIPTION

UCHA transients generally begin with loss of all forced circulation (LOFC) and scram. Furthermore, none of the core auxiliary cooling system (CACS) loops can be started. Initially the primary loop will heatup with the pressure increasing, and leading to depressurization after a few hours. The early phases of UCHA scenarios up to depressurization were considered in the preceeding paper.[2] This paper considers the long term accident sequences in which forced circulation could not be restored prior to the maximum time for restoration of forced circulation (MTRC) which amounts typically to about 12 hr. All transients analyzed here assumed LOFC at scram, i.e., no prior cooldown, closing of the main loop isolation valves and virtually no bypass flow through the side cavities. There are two major classes of scenarios that can be encountered.

1. In case of the LCS functioning, but with the primary system depressurizing a few hours into the accident, the core will heat up and temperatures will peak at about 6500°F at about 100 hr. Significant fuel failures will occur between about 20 and 150 hr, with corresponding fission product releases into the CB. Some thermal coverplate failures will occur, but the LCS can ultimately remove the decay heat leading to safe cooldown so that liner and PCRV integrity are maintained. The CB does not fail, and the fission product release remains limited.

2. In the event that the LCS does not function -- or fails during the accident -- the thermal barrier and the liner will fail, resulting in PCRV concrete degradation and decomposition with large masses of H_2O and CO_2 being released from the concrete. Some of these gases can react with the core graphite, forming water gas and CO. The release of these gases into the CB can ultimately lead to CB failure from deflagration burning or overpressurization after 6 to 10 days with significant fission product releases.

METHOD OF ANALYSIS

The long term UCHA analyses were conducted using a modified version of the CORCON code.[3] Details of the modifications are given in Appendix A of

Reference 4. Subsequent to primary loop depressurization the core heat transport by convection is very minor, and in-core conduction as well as radiation between the core and the thermal barrier dominate. The code solves the two-dimensional transient conduction equation for the core and reflectors in a cylindrical coordinate system with symmetry around the axis; i.e., in "r, z" coordinates. The code permits the joining of blocks of solid having intermediate gaps and allows for non-linearities in material properties. Heat transfer across the gaps is generally by conduction and one-dimensional radiation. At the high core temperatures of this accident, radiation through the coolant holes becomes essential. This effect is treated in modifying the axial thermal conductivities of the core as described in Section D.3 of Reference 5.

Typically, the core cavity is nodalized into about 400 core nodes and a total of about 800 solid nodes, including reflectors, side shields and thermal barrier with numerous gaps, for example at the side shields. In cases of the LCS not operating, about 700 concrete nodes are added, accounting for the heatup of about 18 ft of PCRV concrete on top, 8 ft on the sides and 1.5 ft on the bottom, assuming adiabatic planes at the outside boundary.

Across both plena, two-dimensional radiation between the surfaces of the reflectors, the side walls, and the thermal barriers is modeled. In our modifications of the code, the nodalization of the two-dimensional radiation models for the upper and lower plena were extended to 47 nodes in the upper plenum and 45 in the lower plenum. The radiation heat fluxes were solved iteratively with the reflector surface temperatures facing the plena. The axial temperature gradients in the top reflector region are sufficiently large that the use of reflector surface temperatures rather than nodal average temperatures in the radiation computations is very essential. The code, in its original and revised version, computes and uses surface temperatures at all radiation boundaries. The current upper plenum radiation model is conservative in that it disregards the control rod assemblies in the center of the upper plenum, which would reduce the radiation from the hottest regions in the center of the plenum element surface to the most damage susceptible haunch region.

Side thermal barrier failure proved to be an essential aspect of the long-term UCHA transients. The Base Line Zero design uses a set of four side shields of carbon steel, each 1-in. thick, with intermediate gaps between the side reflectors and the side thermal barrier. Heat transfer across this set of side shields and gaps is by conduction and radiation. To maintain efficient code running times, each axial section of the four side shields was modeled as one node with the composite radial heat transfer resistance being obtained from a curve fit to the results of a free standing separate model of four shields with corresponding internal radiation and conduction heat transfer. The curve fit was found to give temperatures within ± 5% of those from the detailed shield model over the temperature range of 1000 to 3000F.

The spatial and temporal decay heat distributions within the core were computed from a version of the SORS code.[7] The total decay heat curve for a typical case is given in Figure 2. In some code applications, to simulate the effect of decay heat reduction due to fission products having left the core, an arbitrary decay heat reduction was applied, assuming a 30% reduction in core decay heat between 100 and 240 hr, as indicated in Figure 2.

The initial input data were introduced in sets of uniform temperatures for various regions of the PCRV. Correspondingly, some of the initial transient over the first few hours is a response to these simplified inputs. By introducing a more detailed set of input data, this can be avoided. However, the simplified initial input data caused no noticeable effect on the long-term transient. Therefore, they were used, and some of the very early transient responses should be disregarded.

CODE APPLICATION AND RESULTS

UCHA Transient with Functioning Liner Cooling Water System

In the first "Base Case" to be considered, the liner cooling water system (LCS) was assumed to function during the entire UCHA transient, extending over 10 days.

In this case, the thermal barrier failure limits -- the maximum cover plate temperature before failure occurs -- were those previously suggested by GA6, with 1800F for the upper plenum refueling region and 1500F for the upper plenum haunch region, as well as 1800F at the upper plenum side walls and 2000F at the core barrel side walls. This case also did not allow for any decay heat reductions after fission products begin to leave the core. The thermal response of the system under these conditions is shown in Figures 3 through 6.

The peak active core temperature reaches 6600F at about 120 hr and slowly decreases thereafter (Figure 3). The average active core temperature peaks at 140 hr at 4800F. Significant fuel failures occur at about 4500F but fuel failure is not a function of temperature alone but also of the accumulative effect of time integral over temperature. Figure 4 shows the fraction of the active core exceeding 4500F. This value is not a fuel failure model, but it can be considered as a qualitative guide to the amount of fuel failures and the time range in which they occur. Thus, fuel failures should be expected to begin before 20 hr, and at 100 hr about half of the fuel may have failed. However, with the LCS operating, average core temperatures peak at 140 hr, and only about 60% of the fuel is expected to fail ultimately. Even at the above core temperatures, core geometry would be preserved since the side-restraint temperatures do not reach the melting point of steel.

Thermal barrier temperatures are shown in Figure 5. Frame (a) shows that the top surface of the plenum elements on top of the reflector will reach about 1850F at about 120 hr. At that time, the innermost ring of the haunch-region coverplates reaches about 1500F and fails by the above failure criterion. Failure of top thermal barrier components was simulated in the computer calculation by removing the coverplates and the kaowool from the top thermal barrier and redepositing them on top of the plenum elements or the side reflectors at their corresponding radial positions. As failures occur, significant peak heat fluxes into the failed region of the barrier will arise, where parts of the water-cooled liner are now directly exposed to radiation from the top reflector plenum elements. Due to this increase in heat flux to the failed region, the temperatures in the remaining parts of the upper plenum decreases slightly.

The side wall thermal barrier temperatures behave similar to those of the upper plenum (Frame (b) of Figure 5). As the hottest region, at the midheight of the core, reaches 2000F, coverplate failure occurs. At that time the coverplate and the insulation are assumed to fall off and disappear into the lower plenum. (In terms of the model, they are being removed from the system.) The side thermal barrier temperatures also show a slight decrease subsequent to failures.

The essential effect of thermal barrier failures is that the increased heat flux into the failed regions effectively limits the thermal barrier temperatures approximately to those values at which the first failures occur. After some failures in the top and side thermal barriers, between 120 and 160 hr, the temperatures begin to decline. In total, 17% of the top thermal barrier and 19% of the side thermal barrier failed during this transient. Separate localized and more detailed LCS analyses have shown that LCS failures due to boiling at the hot spots of the failed regions is not expected and that the LCS can effect safe cooldown under all reasonably expected peak load conditions.

The core and system heat fluxes of Figure 6 show that the heat flow out of the active core exceeds the decay heat after 150 hr, permitting the beginning of safe cooldown. For the total core cavity, this condition is reached at about 160 hr as the second series of side thermal barrier failures occurs.

To summarize, this case was characterized by a few top and side thermal barrier failures, which resulted in limiting the thermal barrier temperatures, thus avoiding further failures. Although significant fuel failures must be expected under such conditions for the time period of about 20 to 150 hr, the core temperatures peak around 120 to 140 hr, and beyond 160 hr the heat transfer to the LCS exceeds the remaining decay heat. Thus, with the LCS operating, significant damage to the core will occur, however, the liner integrity is maintained. Although fission products will escape into the CB, no CB failures occur, thus avoiding the major potential fission product releases associated with CB failure.

The currently used thermal barrier failure criteria may be conservative. To estimate the effect of higher failure limits, a case was considered with all failure limits raised above the expected thermal barrier temperatures, thus eliminating all failures. The core temperatures for this case remained close to the Base Case and the amount of fuel failure also reached about the same level of about 60% at 125 hr.

The thermal barrier temperatures (Figure 7) are significantly different for this case. The top head coverplates reach a peak temperature of 1780F in the refueling region and 1740F in the haunch region at about 200 hr, with a very slow decrease in temperature at longer times. The side thermal barrier cover-plates reach a maximum of about 2240F at the midheight of the core at about 240 hr. The thermal barrier heat fluxes peak at about 240 hr for the side thermal barrier (4000 Btu/ft^2-hr) and at 200 hr for the top thermal barrier (3700 Btu/ft^2-hr), with the total heat flow to the LCS exceeding the total decay heat after 210 hr, leading to a gradual, safe cooldown.

The essential conclusion from this case is that to eliminate all coverplate failures, failure limits of 1800F for the top head coverplates and of 2300F for the side coverplates would be required. (There is some conservatism in these numbers, inasmuch as the reduction in radiant heat transfer due to the control rod units in the upper plenum was neglected, and the effect of decay heat reduction due to fission product escape from the core was not included.)

Neither of the above cases allowed for reduced decay heat with fission product escape from the core. Therefore, an arbitrary reduction in decay heat between 100 and 240 hr was introduced for a third case, as indicated in the dotted branch of Figure 2. Compared to the Base Case, the core temperatures for this case case were about 500F lower at 240 hr, with about 300F lower temperatures in the top reflectors and about 100F lower temperatures in the side reflectors. The fraction of the active core reaching the fuel failure region of 4500F was only slightly lower than with full decay heat (0.55 vs 0.60).

With the assumed decay heat reduction, only one set of thermal barrier failures was encountered at the top, and one at the side, both at about 120 hr, effectively limiting the thermal barrier temperatures. The component heat flows showed that net heat loss from the active core now occurred at 110 hr, while the heat flow to the LCS exceeded total decay heat after about 145 hr.

Thus, when including the effect of reduced decay heat due to fission product escape from the core, some thermal barrier failures are still likely to occur, at about the same time. However, there are only about half as many failures, and the resulting peak heat fluxes to the liner were significantly lower. The amount of failed fuel remained about the same as in the base case. A 26% reduction in decay heat may be more than can be expected with 55% fuel failure, and, the actual accident scenario might be expected to lie between the above two cases.

UCHA Transients Without Functioning Liner Cooling Water System

A series of cases in which the LCS was not started or failed during the UCHA transient, are described here. These cases were also followed for 10 days.

In the Base Case to be considered, the decay heat followed the base curve of Figure 2, i.e., no decay heat reduction was allowed for escaping fission products. The results are shown in Figures 8 through 14.

The core temperatures are given in Figure 8. The maximum temperatures reach a peak of 6700F at about 180 hr. However, active core average temperatures and reflector temperatures are still rising at 240 hr. Figure 9 shows that fuel failure now begins a few hours earlier than in the case with the LCS operating, and the fraction of the core exceeding fuel failure temperature levels of 4500F is above 90% at 240 hr, and still increasing. Thus, essentially all fuel will fail.

The thermal barrier temperatures are shown in Figure 10. Without LCS protection, massive failures occur. Top failures begin at 65 hr, and side failures at 80 hr. The whole top barrier has failed at 100 hr and the last side barrier failures are at 140 hr. Exposure of the liner will no longer result in sharp temperature drops. As the insulation drops away, the non-cooled liner will rapidly rise in temperature, resulting in heatup of the concrete behind the liner. Beyond the failure point, the liner will continue to heat up, reaching the melting point of carbon steel (2650F) at about 150 hr at the top reflectors.

The early phases of this case also establish another important parameter: namely the maximum time up to which LCS could be restored. In the Fort St. Vrain Safety Analysis Report (Appendix D), a maximum coolant tube temperature of 1500F is accepted on a design basis as a criterion for this time.[5] The liner and coolant temperatures prior to thermal barrier failure are much lower. A very safe criterion would be to consider first thermal barrier failure as the time up to which LCS can be restored. This occurs at about 65 hr. Thus, LCS operation must be restored within 65 hr to avoid the damaging consequences of UCHA with failed LCS. The less conservative criterion of 1500F tube temperatures would be reached only a few hours later.

At the side shield, the steel melting temperature is reached in places at 130 hr. Inasmuch as our current model does not remove the side shield and side thermal barrier as they reach the melting temperature, the analysis beyond this point has some further uncertainty. In reality, the side shield and liner would disappear, exposing concrete directly to the side reflectors, thus accelerating the concrete heatup and degradation. Keeping these thermal resistances in the system is not strictly correct, and our models should be improved. However, the side shield thermal resistances are relatively small at these high temperatures, and the error is minor with respect to other uncertainties involved, like, for instance, the calculation of concrete heatup.

As the side shields and side restraints melt, an annular gap of about 12 in. could open up around the permanent side reflectors. Possible dislocation of some of the side reflector and core blocks would now become a distinct possibility, but it is doubtful whether there is enough room available for any collapse of the fuel element columns which are of 14-in. key width and 31-in. high.

In the top thermal barrier, the kaowool insulation and the steel coverplates were assumed to fall onto the plenum elements of the top reflectors when failures occurred. The melting of the plenum element steel canisters and of the coverplate and liner would again not be too significant. However, the kaowool insulation melts at 3200F, and its disappearance at those temperatures would permit an increase in top reflector heat fluxes. This point is reached at the center line at about 170 hr and should effect, at 240 hr about 70% of the active core cross section. This means that top head concrete degradation could proceed more rapidly if the melting of kaowool would have been considered at times beyond 170 hr.

Some of the component heat flows are shown in Figure 11. Over the 10-day period shown, the heat accumulation in the active core, as well as in the total core, remains positive, with average temperatures rising and a continuous heat flow of about 2.5 MW going into the PCRV concrete.

As the PCRV concrete heats up, it will undergo several physical and chemical reactions. Concrete composition and chemical structure vary considerably from plant to plant depending on raw material sources.[8,9]

The two gases released in large quantities as the concrete is heated up are water vapor and carbon dioxide. Most of the water in the concrete is physically bound and is released at low temperatures, below 400F. The chemically bound water is given off at higher temperatures, mostly below 1200F. The CO_2 is released in the decarbonization of limestone, most of which occurs in a narrow temperature range around 1650F.

In assessing the PCRV concrete gas releases, the following data were used for the H_2O and CO_2 content of concrete:[9]

	Quantity (lb/ft^3)	Release Temperature (^oF)
Physically bound water	8.11	90 - 250
Chemically bound water	3.74	250 - 1110
Total water	11.85	
Carbon dioxide	39.6	1600 - 1650

As the concrete heats up and its moisture is vaporized, some of the water will be released into the core cavity, but some of it will be flowing through the porous concrete into colder regions of the PCRV, with a pressure peak in the concrete. A complete analysis of this flow process[10] was not possible within the scope of the current work. Therefore, in a simplified approach, we computed the total water released from heated up concrete, which would include the water entering the core cavity, as well as the water being driven away through the concrete as it is being heated up. It was then assumed that the water from those regions of the concrete which exceed 600F (corresponding to a saturation pressure of 1500 psi) would enter the core cavity. This generally amounted to about one half of the total water released. The total gas masses released into the core cavity will have a significant effect on estimates for CB overpressurization and more refined modeling is clearly desirable, but further uncertainties in the water-gas reaction to be discussed below will be even more significant.

The progressive heatup of the PCRV is shown in the isotherms of Figure 12. Late in the transient, significant portions of the PCRV will have all the water vaporized. Actually only a small fraction of the concrete is above its melting temperature of 2400F and should thus have been assumed to change location, if the model would have considered melting properly. Cracking and spalling of concrete above 1500F might also cause chunks to fall away and expose more concrete. The isotherms further show that most of the concrete damage would occur on the sides, primarily due to the kaowool on top of the top reflectors restricting heat flow to the top head for much of the time.

The fractions of the PCRV concrete included in the model,[a] which have been heated beyond 1650F (CO_2 release), 1110F (all H_2O released), and 250F (physically-bound water released) are shown in Figure 13. At 240 hr, only 6% of all concrete included in the model reached the point for decomposition of limestone. About 12% of the concrete has released its water, while about 60% of the concrete remained below 250F.

With these concrete temperatures and the above described gas release models, the gas masses shown in Figure 14 will be released into the PCRV. Comparing the total helium inventory of 25,000 lb to almost 300,000 lb each of H_2O and CO_2 that have been released into the core cavity at 240 hr, these gases will dominate the PCRV atmosphere after about 100 hr. Since they are not transparent to radiation, gas radiation will occur in the upper plenum and side shield areas, reducing heat transfer rates, perhaps compensating somewhat for the previously discussed practice of not removing the melting steel and kaowool components from the model.

Previous analyses[6] have not considered any water ingress into the core cavity until the liner reached a temperature of 2000F. Following thermal barrier failure, concrete degradation in the vicinity of the liner cooling pipes will begin very soon after liner failure. Inasmuch as the vapor pressures in those areas can exert significant pressures on the back of the liner, possibly separating it from the concrete,[b], earlier failures could be possible. The time of liner failure and initiation of gas ingress is not too significant. It certainly will be before the beginning of CO_2 release at 85 hr, at which time the liner temperatures reach about 2000F at the side and 1750F at the top. That means that the early H_2O release shown in Figure 16 cannot enter the core cavity and water ingress begins only when the liner fails, at about 70 to 85 hr.

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[a] PCRV portions further away from the core, in particular on the outside of the side cavities, were not included in the current analysis.

[b] The Fort St. Vrain SAR[5] explains the design limit for the LCS water pressure as the pressure that could not cause liner/concrete separation in case of tube failures. This pressure corresponds to a saturation temperature of about 280F.

A very important effect of these gas releases is the potential chemical reaction between concrete decomposition gases and core graphite:

$H_2O + C = H_2 + CO$

$CO_2 + C = 2CO$

in which 2 moles of gas are formed for each reacting mole of concrete decomposition gas. This endothermic reaction has a negligible effect on core temperatures. The sensible heat to heatup the gases is also relatively minor and was not included in the model. However, the additional mass of gases going into the CB atmosphere with the potential for combustion in the CB is very significant.

During the period from 140 hr to 240 hr, the side shields and side restraints will no longer be present, and a 12-in. gap around the core will be filled with relatively cool H_2O and CO_2. If the core coolant passages were open, a significant natural circulation flow through the core of the order of 8000 to 20,000 lb/hr was found to be possible. Comparing this to a water ingress rate of about 2000 lb/hr, it is clear that large parts of the incoming H_2O could react. However, debris on top of the core as well as at the sides will block large parts of this coolant flow. Thus, debris distribution and even potential core block dislocations will control the amount of gas circulation through the core and the amount of water gas and CO that can be formed. The effect of these PCRV gas releases into the CB with its potential failure due to overpressurization or due to deflagration burning will be the subject of a separate paper. However, it should be stated here for completeness, that the gas releases from the PCRV for this base case combined with several assumptions on the CB atmosphere evolution resulted in a prediction of CB failure due to overpressurization of about 240 hrs and a possible -- but much less probable -- failure from deflagration burning at around 140 to 160 hrs.

With the massive fuel failures occurring in this base case without LCS, and with significant gas flows from the PCRV to the CB atmosphere, fission product release from the core should result in some further decay heat reduction. To assess this effect, a second case without functioning LCS was investigated, using the reduced decay heat curve of Figure 2. The core temperatures for this run were significantly lower with the maximum core temperature at 240 hr is now being only 5900F, and the active core average temperature 4800F. The fraction of the core reaching the assumed fuel failure level of 4500F is reduced from 0.92 at 240 hr to 0.68, i.e., the effect of fission products escaping from the core will be to reduce active core temperatures sufficiently to cause significantly less fuel failures. While 26% of the total decay heat was was assumed to be removed from the core at 240 hr in this case, this would amount to 38% of the failed fuel and may, therefore, be too large a reduction. The actual progression of an accident without LCS may lie between these two cases.

Since the thermal barrier heat flows are minimally affected by the reduced decay heat levels, the concrete heatup and the subsequent releases of H_2O and CO_2 were almost identical to those obtained with full decay heat.

Thus, fission products escaping from the core will lower the core temperature and reduce the fraction of fuel failed, but there is not much effect on the PCRV heatup. The potential for CB failure will therefore remain essentially unaffected.

Another case to be considered is that in which the LCS functions initially, but fails during the transient. The case used here as the starting point for such a transient is the original base case with functioning LCS. Following the first set of thermal barrier failures, it was assumed that the LCS failed for some reason at 140 hr and service could not be restored. The transient was continued for 200 hr beyond this failure point. The results showed that if the LCS fails during a UCHA transient, then the consequences of an accident without any LCS will be reached, but at a later time. In the current case, 140 hr of LCS operation brought a delay of about 60 to 80 hr before a comparable accident severity was reached.

SUMMARY AND CONCLUSIONS

A thermal analysis of the long term heatup of an HTGR core cavity and the surrounding PCRV has been conducted, with and without operating liner cooling system. In particular, during the late phases of UCHA sequences without functioning LCS, melting of components and debris accumulation occur and some of the current model assumptions should be revised and refined in the future.

The current results show that with functioning LCS, significant core damage will occur with about 60% of the fuel failing and with some thermal barrier failures. However, the thermal liner remains intact and the PCRV is protected. The LCS can turn around the core heatup after 140 to 200 hr and effect safe cooldoown without CB failure.

The time available to restore LCS operation if it initially fails, for instance due to station blackout, is about 60 hrs.

If the LCS does not function, or fails during the accident, the core heatup will continue with temperatures still rising after 10 days. The thermal barrier and the liner will fail, resulting in PCRV concrete decomposition and concrete gas releases. These gases, after partly reacting with the core graphite will ultimately lead to CB failure from deflagration burning or overpressurization after 6 to 10 days.

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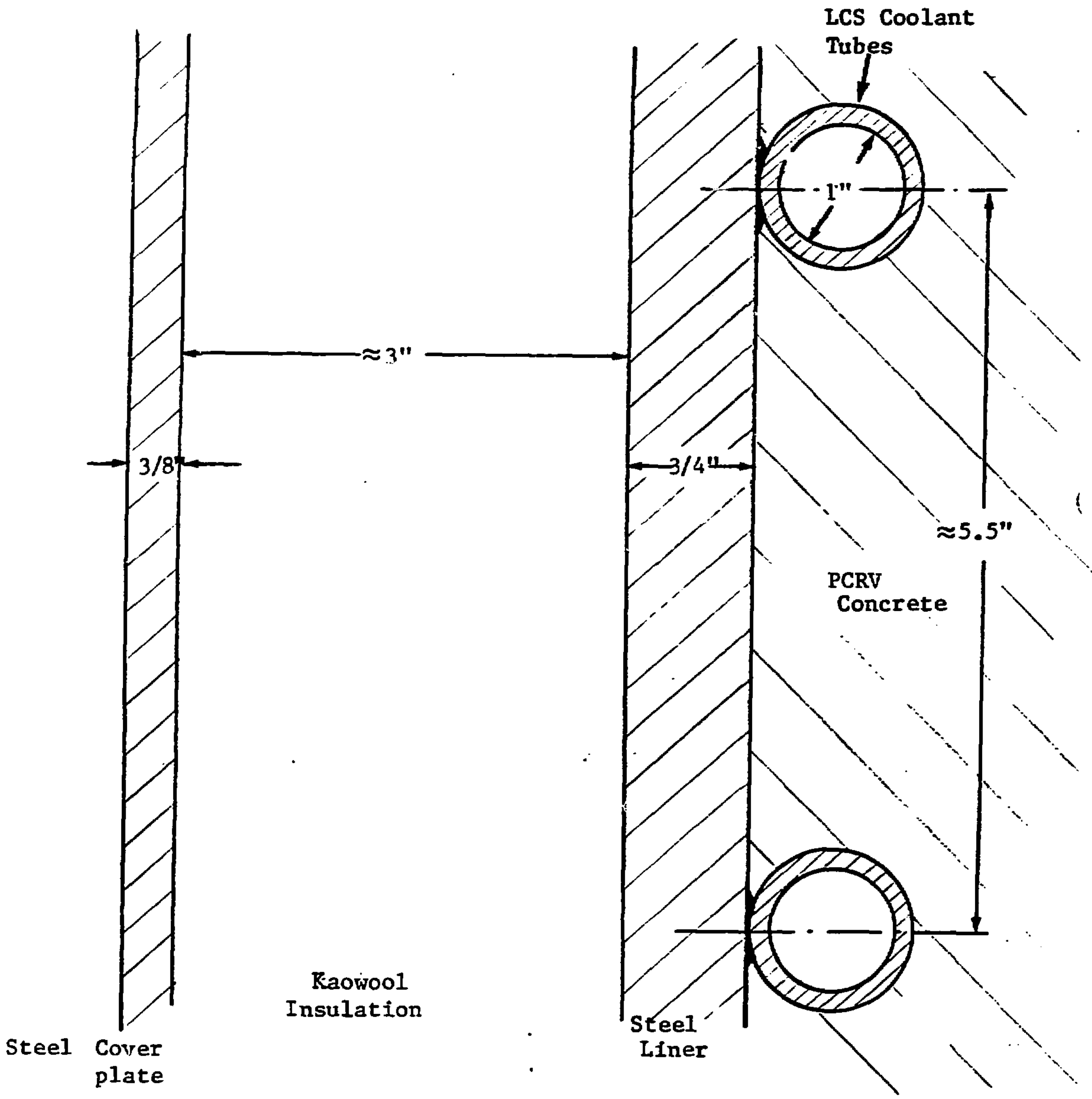


Figure 1. Schematic of Thermal Barrier Design with Typical Dimensions.

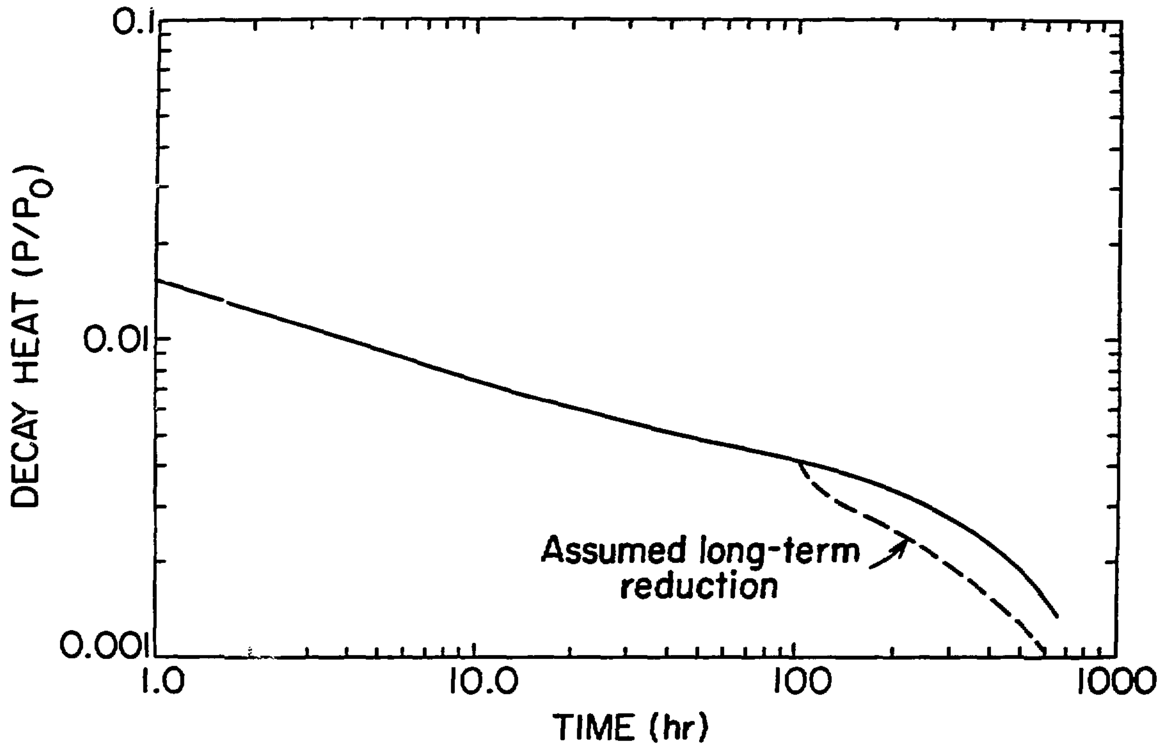


Figure 2. Total core decay heat as fraction of full power during long-term UCHA transients with optional long-term decay heat reduction due to fission products leaving core.

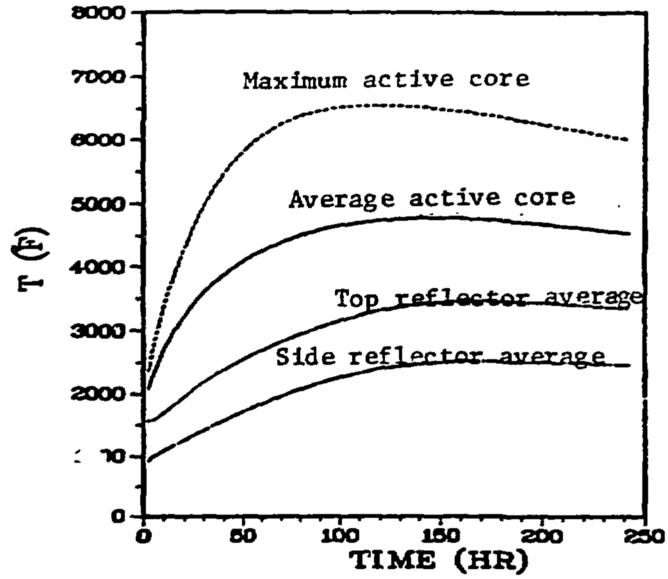


Figure 3. Core temperatures (T) during UCHA with operating LCS; no decay heat reduction as fission products escape; standard thermal barrier failure limits.

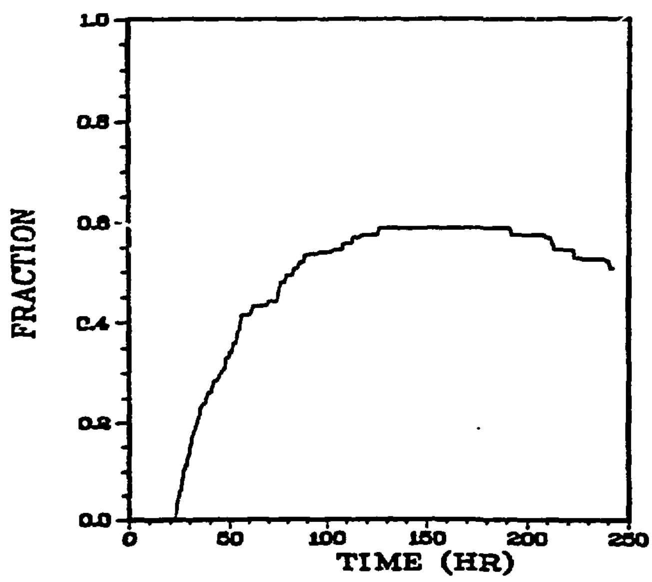
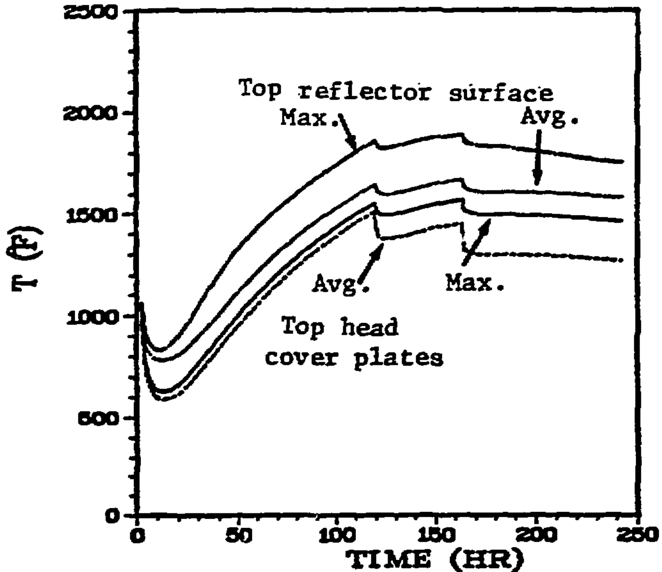
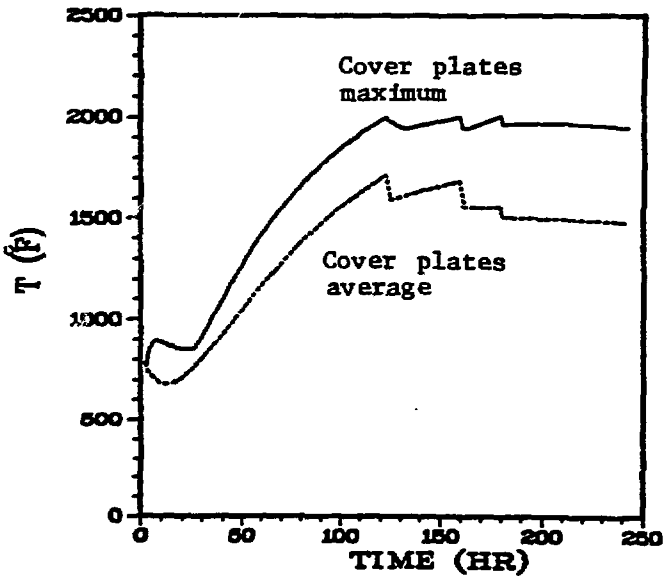


Figure 4. Fraction of active core exceeding temperature of 4500°F during UCHA with operating LCS; no decay heat reduction as fission products escape; standard thermal barrier failure limits.

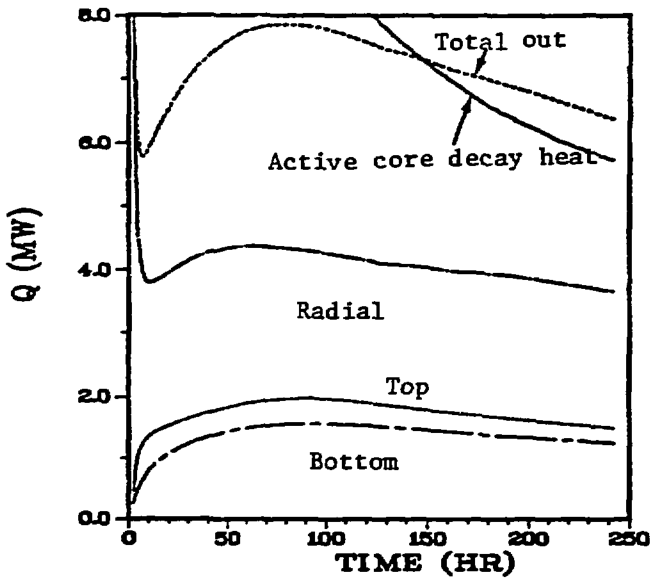


(a) Top thermal barrier

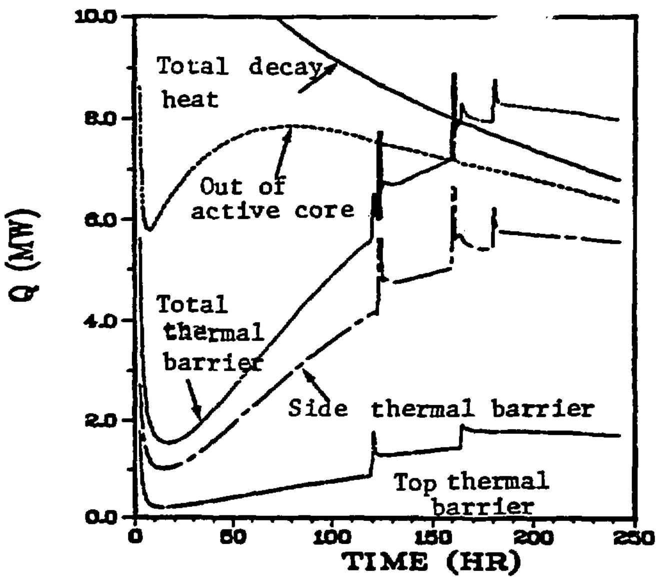


(b) Side thermal barrier

Figure 5. Thermal barrier temperature (T) during UCHA with operating LCS; no decay heat reduction as fission products escape; standard thermal barrier failure limits.



(a) Active core.



(b) System.

Figure 6. Component heat flows (Q) during UCHA with operating LCS; no decay heat reduction as fission products escape; standard thermal barrier failure limits.

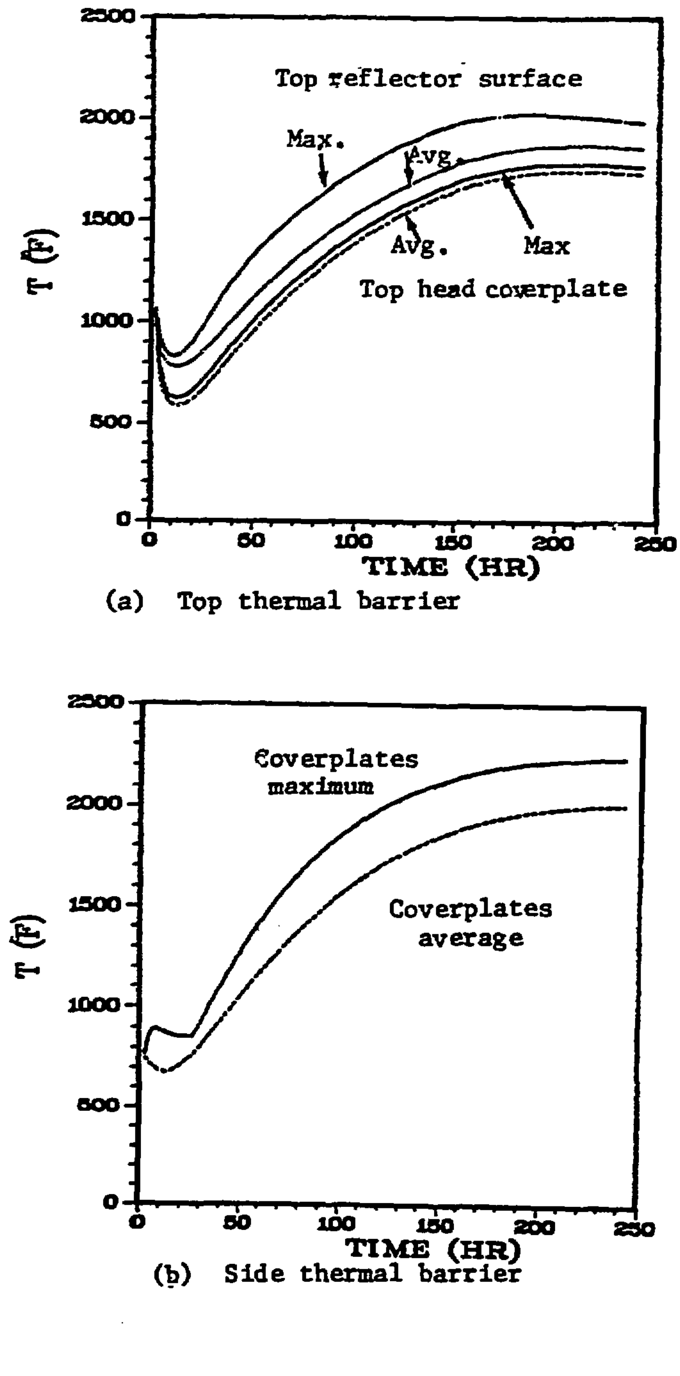


Figure 7. Thermal barrier temperatures (T) during UCHA with operating LCS; no decay heat reduction as fission products escape; thermal barrier failure limits raised.

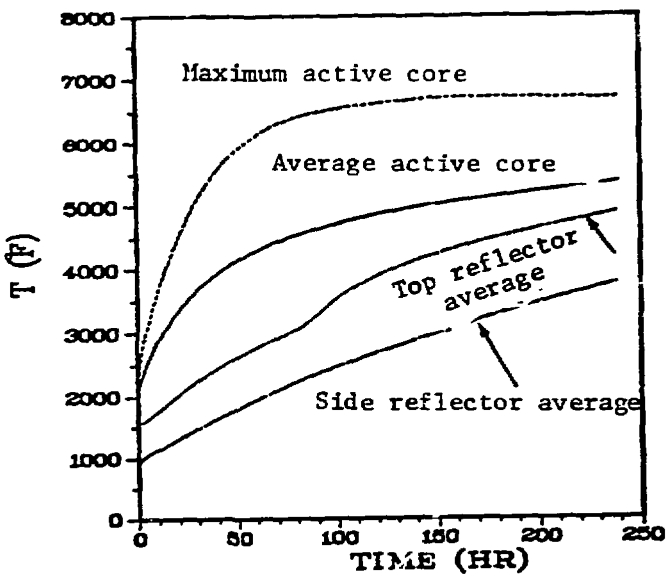


Figure 8. Core temperatures (T) during UCHA without LCS operation; no decay heat reduction as fission products escape.

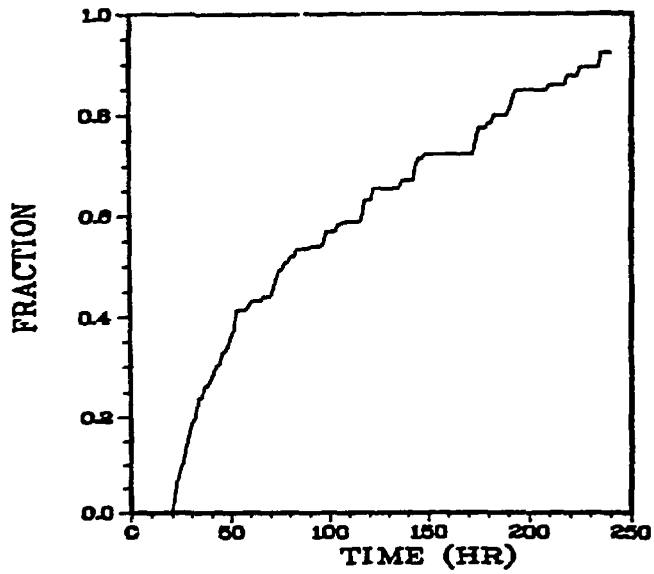
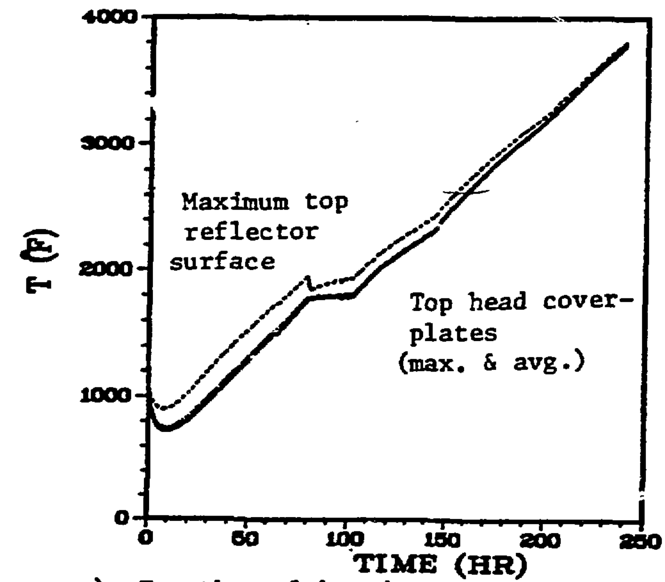
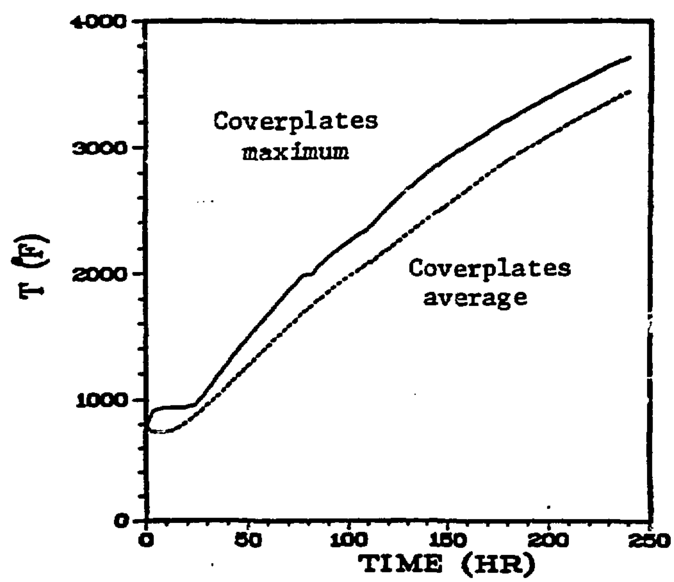


Figure 9. Fraction of active core exceeding temperature of 4500 F during UCHA without LCS operation; no decay heat reduction as fission products escape.

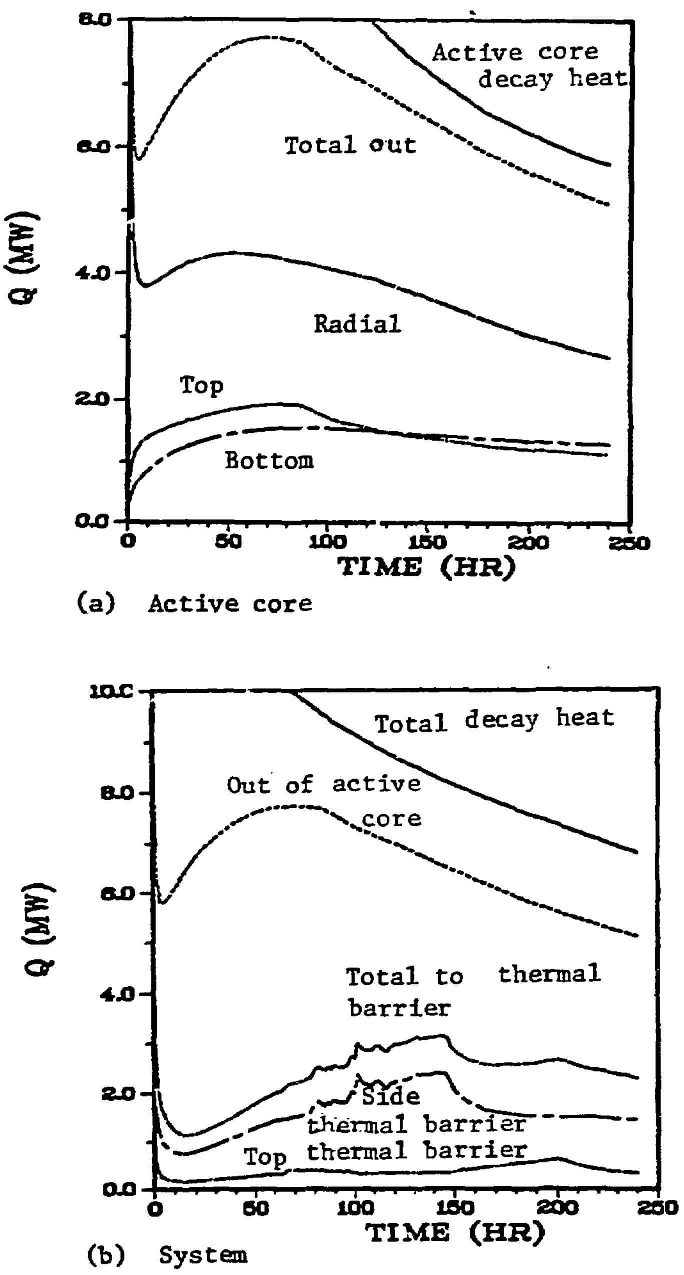


(a) Top thermal barrier



(b) Side thermal barrier

Figure 10. Thermal barrier temperatures (T) during UCHA without LCS operation; no decay heat reduction as fission products escape.



(a) Active core

(b) System

Figure 11. Component heat flows (Q) during UCHA without LCS operation; no decay heat reduction as fission products escape.

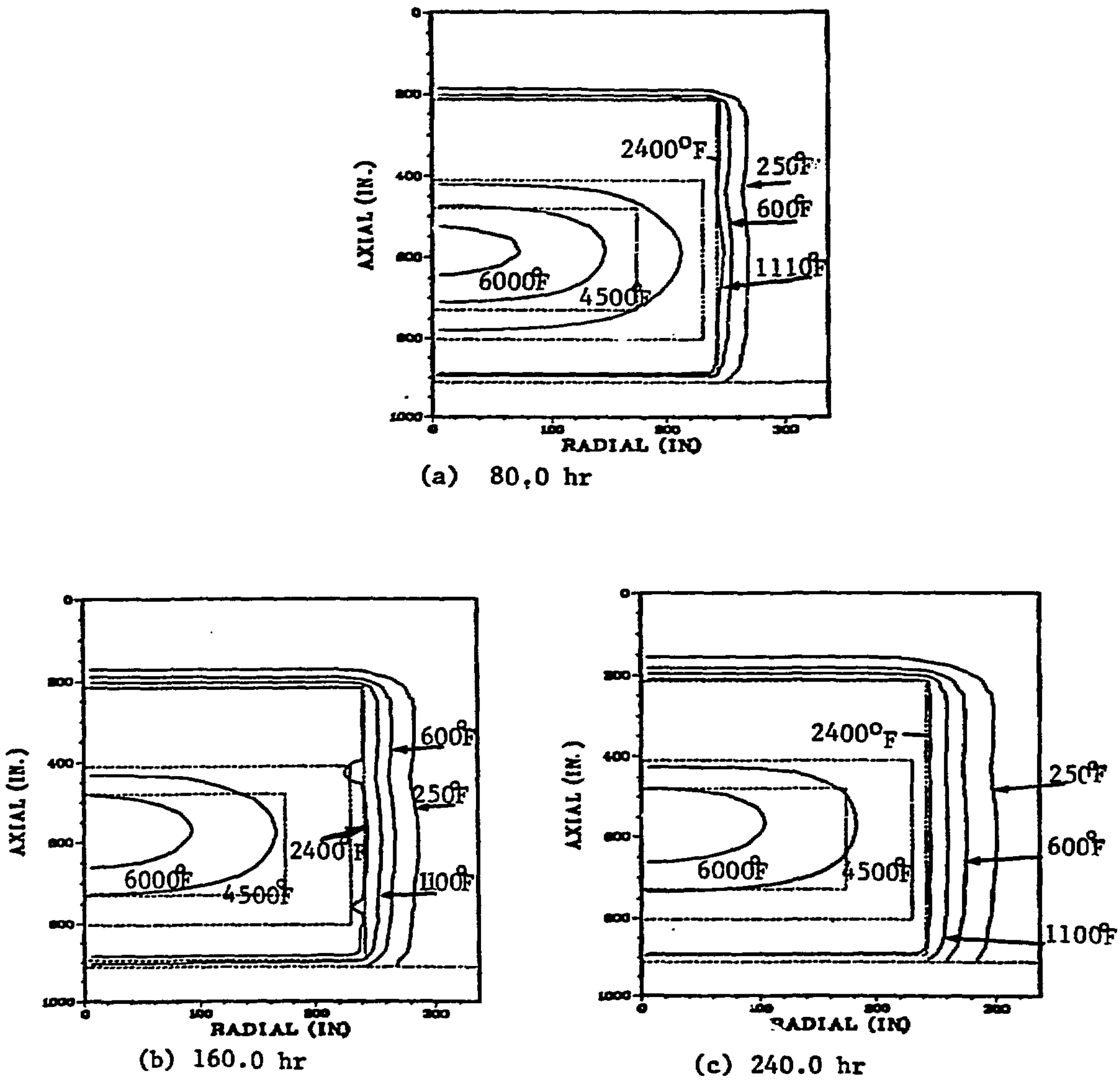


Figure 12. Isotherms of core and PCRV during UCHA without LCS operation; no decay heat reduction as fission products escape.

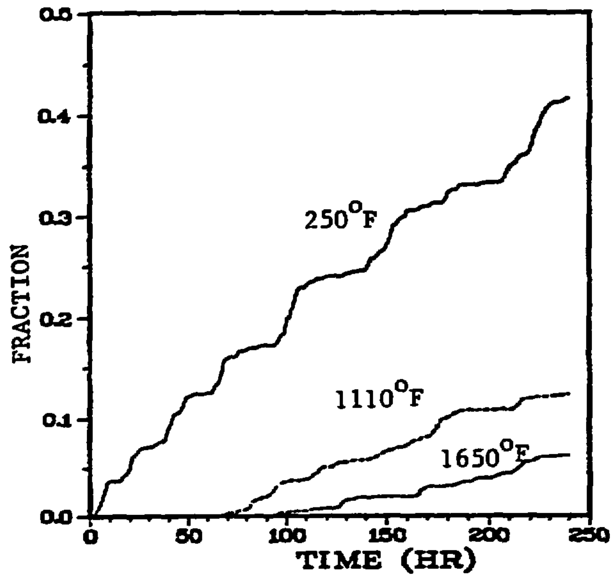


Figure 13. . Fractions of concrete above various temperature levels during UCHA without LCS operation; no decay heat reduction as fission products escape.

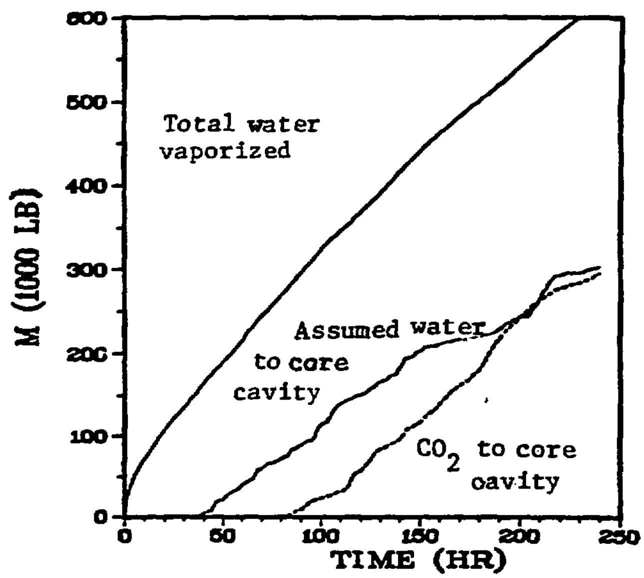


Figure 14. Total gas mass (M) released from PCRV concrete during UCHA without LCS operation; no decay heat reduction as fission products escape.