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Estimated Amount of ^{85}Kr Available for Release from Intact Fuel Rods in the Three Mile Island Unit 2 Nuclear Power Station

R. A. Lorenz

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ESTIMATED AMOUNT OF ^{85}Kr AVAILABLE FOR RELEASE FROM INTACT FUEL RODS IN THE THREE MILE ISLAND UNIT 2 NUCLEAR POWER STATION

R. A. Lorenz

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ABSTRACT

Reactor core dismantling operations planned for the Three Mile Island Unit 2 Power Station could cause rupture of any fuel rods that might have survived the accident in a leak-tight condition. Calculations were performed in an attempt to determine the amount of ^{85}Kr that might be present in the free gaseous form in the plenum and void spaces of such fuel rods. Estimates were made of the number of fuel rods surviving intact, the temperature transient to which they were exposed, the amount of ^{85}Kr originally produced in the fuel in these rods, and the amounts released from the UO_2 matrix to the plenums both before the accident and during the accident (as a result of heatup). Since there is considerable uncertainty in these quantities, particularly the number of surviving fuel rods and the temperature transient they experienced, an analysis was made of the importance of these assumptions. Results of the analysis show that ~30 Ci of ^{85}Kr could exist in the free state in the plenums of intact rods; however, this quantity might range anywhere from 0 to 100 Ci.

1. INTRODUCTION

Reactor core dismantling operations to be conducted at the Three Mile Island Unit 2 Nuclear Power Station (TMI-2) could cause breakage of any fuel rods that might have survived the accident in a leak-tight condition. Such fuel rods would contain a certain amount of radioactive ^{85}Kr gas in the plenum and open void spaces that, in sufficient quantity, could add measurably to the radiation exposure of the working crew.[1] This report describes an attempt to determine the magnitude of the problem by using a three-step calculational sequence. First, the number of fuel rods surviving intact was estimated. Second, the total amount of ^{85}Kr produced in the fuel pellets of these rods was calculated. Finally, the fraction of krypton released from the fuel pellets into the plenum and void spaces of the rods was estimated. It is only this amount of krypton that can escape at ambient temperature if the cladding should break during future core disassembly operations.

2. ESTIMATION OF THE NUMBER OF INTACT FUEL RODS

Fuel rods can fail either by ductile rupture ("ballooning") or by brittle fracture. Ductile failure occurs when the pressure external to the cladding is sufficiently reduced that internal pressure causes expansion, or ballooning, of the Zircaloy cladding. The pressure differential required to initiate ballooning decreases as the cladding temperature rises. Brittle failure occurs when steam reacts with the Zircaloy to form a ZrO_2 layer on the reacting surface and oxygen dissolves in the underlying metal. After ~20% of the Zircaloy has reacted, the metal-oxide combination is brittle and can fracture as the result of thermal shock—induced stresses or simple mechanical stress. Hydriding can also weaken the cladding.

2.1 PREVIOUS ESTIMATES OF FUEL ROD FAILURE IN TMI-2

Four studies of the TMI-2 core heatup have included estimations of fuel rod failure.[2–5] The results of these studies are summarized in Table 1. Calculations of fuel rod temperatures that occurred in TMI-2 are especially difficult because of poorly documented changes in primary system water outflow and inflow. Because most of the calculations were concerned with temperatures in the central (hottest) portion of the core, modeling of heat losses to the core barrel was neglected or simplified. It is believed that only the outermost fuel rods could have survived in a leak-tight condition.

2.2 FUEL ROD SURVIVAL ASSUMED IN THIS STUDY

Recalculation of fuel rod temperatures was beyond the scope of this study. Instead, we assumed that the maximum number of intact fuel rods consisted of the outermost 15 circles of fuel rods around the periphery. This is approximately equivalent to a circle of complete assemblies surviving around the periphery. A cross section of the TMI-2 reactor

Table 1. Summary of predictions of fuel rod failure in TMI-2

Source	Date	Number of rods failed (% of total)
President's Commission	October 1979	>90
NRC Special Inquiry (Rogovin)	January 1980	100
LASL (NUREG/CR-1353)	June 1980	100
NSAC-24	January 1981	~100[a]

[a]"(With the possible exception of pins on the core periphery that received sufficient cooling by radiative heat transfer.)"

vessel is shown in Fig. 1. The outermost fuel rods were cooled to some extent by heat transfer to the baffle plate, core barrel, thermal shield, and reactor vessel.

Assuming that the core has a nearly circular shape, we calculated that the surviving distribution consisted of 11,220 rods (10,371 fuel rods), or ~28% of the total number of fuel rods in the core. This is a much larger percentage of unfailed fuel rods than determined in previous studies. The number assumed for the purpose of our study was not based on a heat balance or heat transfer calculation. Thus, the true number of fuel rods surviving intact may be zero, as determined in some of the previous core damage studies (Table 1).

3. AMOUNT OF ^{85}Kr PRODUCED IN THE SURVIVING RODS

The total core production of ^{85}Kr before the TMI-2 accident was calculated to be 9.68×10^4 Ci.[6] Let us assume that core disassembly takes place after a decay period of ~4 years and that the total core inventory is then 7.5×10^4 Ci. Fuel at the core periphery operated at a lower power level before the accident; therefore, the amount of ^{85}Kr produced in these fuel rods was significantly less than average. Figure 2 shows the radial power distribution obtained from NSAC-24.[5] The stairstep pattern

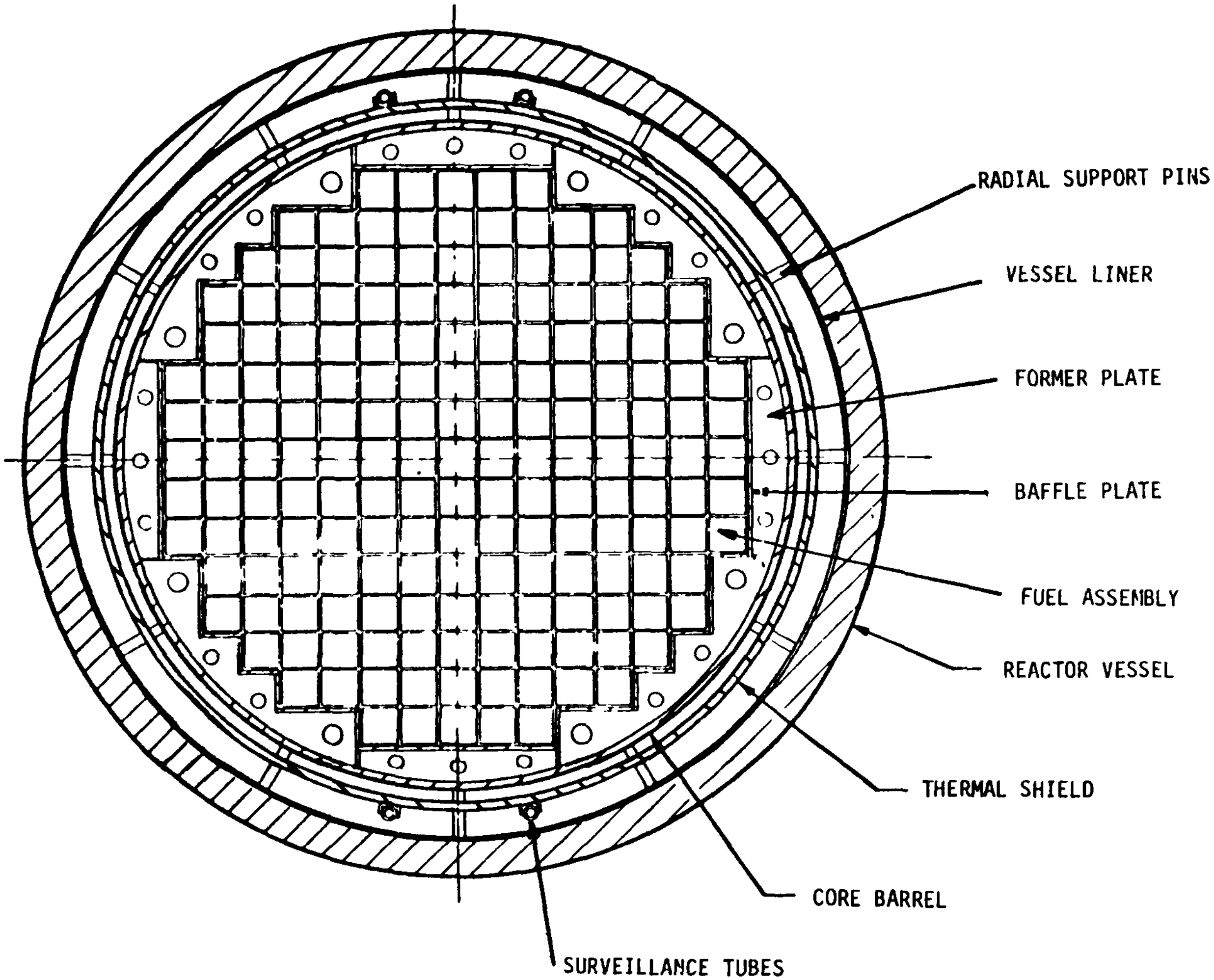

Fig. 1. Transverse cross section of TMI-2 reactor vessel and active region internals. [Reprinted by permission from Nuclear Associates International and Energy Incorporated, TMI-2 Accident Core Heat-Up Analysis, A Supplement, NSAC-25 (June 1981)]

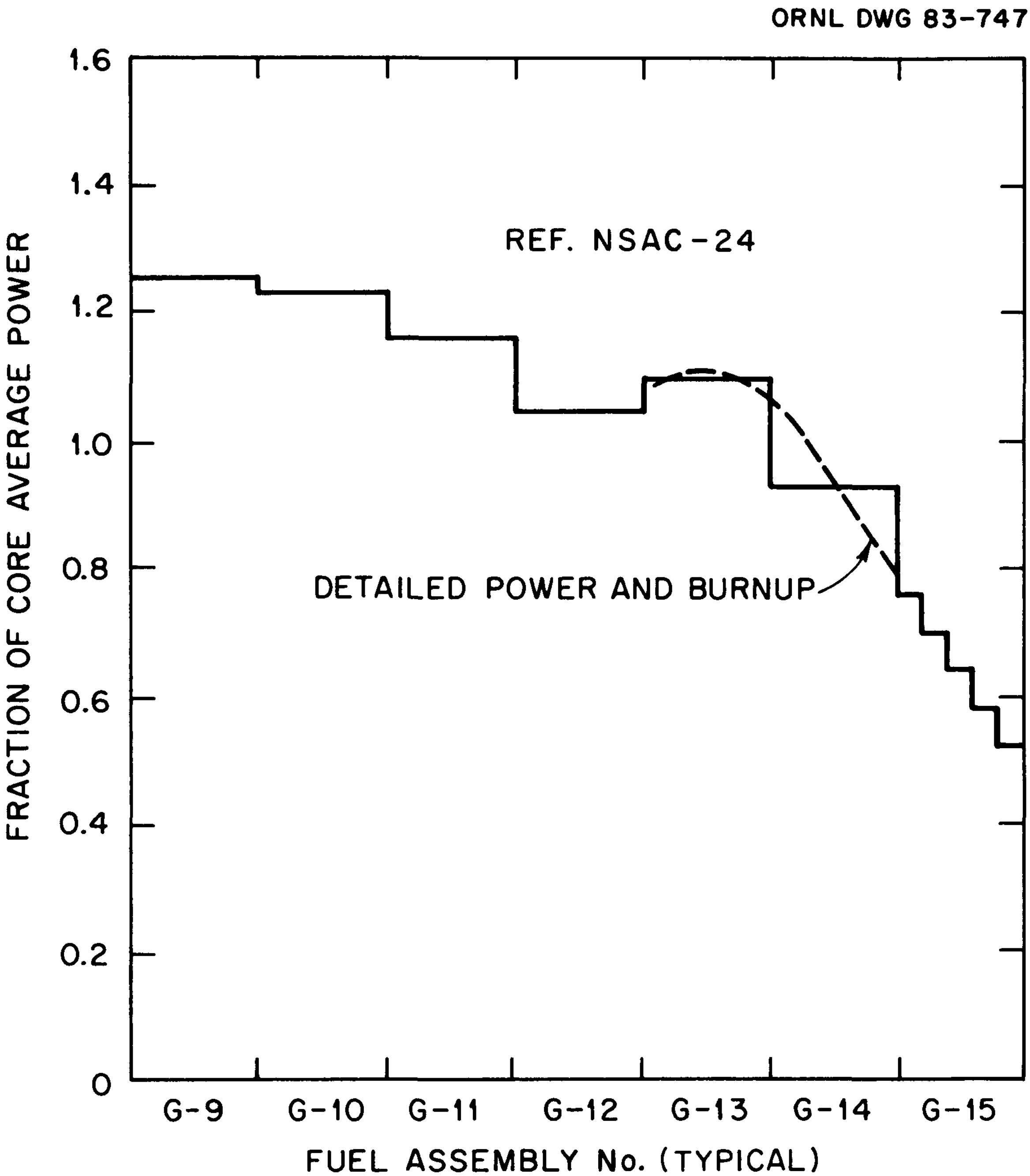

Fig. 2. Radial power and burnup distribution.

shows the detailed power (and relative burnup) distribution that we assumed for the outermost 15 circles of fuel rods. To simplify the numerical calculations, we averaged every three circles of rods together. The innermost three circles of rods operated at 76% of core average power, the next three at 70%, and so forth. Since the core periphery is nearly circular, the inner "circles" contain fewer fuel rods. These assumptions and the calculated amounts of ^{85}Kr produced in the fuel rods assumed to remain intact are summarized in Table 2.

Table 2. Amount of ^{85}Kr in possibly surviving fuel rods

Rod circle Nos.	Number of fuel rods in group	Amount of ^{85}Kr in each rod (fraction of core average rod)	Amount of ^{85}Kr in group (fraction of total initial core inventory)	
				(Ci)[a]
1–3	1,830	0.76	0.0378	2,835
4–6	1,952	0.70	0.0371	2,783
7–9	2,074	0.64	0.0361	2,708
10–12	2,196	0.58	0.0346	2,595
13–15	2,319	0.52	0.0328	2,460
Total	10,371[b]		0.1784	13,381

[a]Assumes a total ^{85}Kr inventory of 7.5×10^4 Ci after a 4-year decay period.

[b]This is equivalent to 28.17% of the total number of fuel rods in the core.

The axial power gradient that existed also had to be taken into consideration in our calculations. In this context, we divided the length of each rod into five equal parts and assumed that the power (and ^{85}Kr) generation in the segments was 18, 21, 22, 21, and 18% of the rod total from end to end.

4. RELEASE OF ^{85}Kr FROM THE FUEL PELLETS TO THE PLENUM

In case any surviving fuel rods should rupture during the TMI-2 dismantling operations, only the krypton that is currently in the free gaseous state in the plenum and connected void spaces would be released. Most of the krypton would remain bound in the UO_2 pellet matrix and could not escape unless the fuel was heated to a temperature higher than that experienced by these outer rods during the accident. Krypton present in the free state in the plenum and open voids is the sum of that which escaped from the fuel pellets during normal operation prior to the accident and that which was released as a result of core heatup during the accident.

4.1 RELEASE TO PLENUM DURING NORMAL OPERATION

The peripheral fuel rods operated at <76% of core average rod power, as discussed above. A study of fission gas release to the plenums of fuel rods operated at low heat ratings was made for the American Nuclear Society Standard ANS-5.4.[7] The model developed for low-temperature fission gas release indicated that the fractional release was directly proportional to fuel burnup. If the core average burnup at TMI-2 was 259 GJ/kg (3000 MWd/t), the burnup in circles 1–3 (Table 2) would be only 197 GJ/kg (2280 MWd/t). The ANS-5.4 model places the fission gas release to the plenum of these rods at 0.016%. Since the data base for the ANS-5.4 low-temperature release model did not include low-burnup fuel, we prefer to assume the more conservative release of 0.03% for all the peripheral rods, regardless of axial and radial variations in burnup.

4.2 RELEASE TO PLENUM DURING THE ACCIDENT

Calculation of ^{85}Kr loss from the fuel pellets as a result of heatup during the accident was more complicated. Release as the result of a temperature transient is primarily a function of the maximum temperature reached; some additional release will occur, of course, if the time at temperature is extended. Calculations for each segment of the fuel rod, or even each pellet, can be made separately. If a radial temperature gradient exists in the pellet, it can be subdivided into concentric zones so that the release from each zone is calculated according to its temperature. We assumed that the fuel and cladding temperatures were the same for the TMI-2 case. For the decay time of interest, the true pellet centerline—to—cladding temperature drop would have been of the order of 10°C. A five-step procedure is used to calculate the ^{85}Kr release: (1) select the release model, (2) estimate the maximum temperature of the surviving fuel rods using a ductile failure criterion, (3) check the maximum temperature for brittle failure, (4) determine the axial temperature profile in the hottest rods and the maximum temperature existing on the other fuel rods, and (5) calculate the ^{85}Kr release on the basis of the release model.

4.2.1 Model for Release of ^{85}Kr During the TMI-2 Core Heatup

Two sources of data[8-11] were used to obtain a krypton release model. Parker et al.[8,9] heated low-burnup UO_2 pellets, or pieces of pellets, without cladding in purified helium for 5.5 h and monitored ^{133}Xe, along with other fission product releases, from a short reirradiation. Lorenz et al.[10,11] heated, in steam, segments of H. B. Robinson PWR fuel that had been irradiated to ~2592 GJ/kg (~30,000 MWd/t). The results of these tests are plotted in Fig. 3. Three tests with BWR fuel [~1037 GJ/kg (~12,000 MWd/t)][12] heated in steam gave results similar to those obtained in the tests with H. B. Robinson fuel. Two tests with H. B. Robinson[10] and BWR[12] fuel, respectively, were performed at 1200°C in purified helium. These results agreed with those obtained in tests performed in steam. Note that the fuel in intact TMI rods would be exposed to an inert atmosphere.

The effect of time at temperature is not well known. The data for H. B. Robinson fuel (Fig. 3) indicate that time is not as important as temperature. Many tests[8] have demonstrated that a large fraction of the gas release occurs during heatup and cooldown. The 346-GJ/kg (4000-MWd/t) data of Parker et al. was chosen for the TMI-2 release model. The higher burnup and the longer heating time for these data vs the TMI-2 accident

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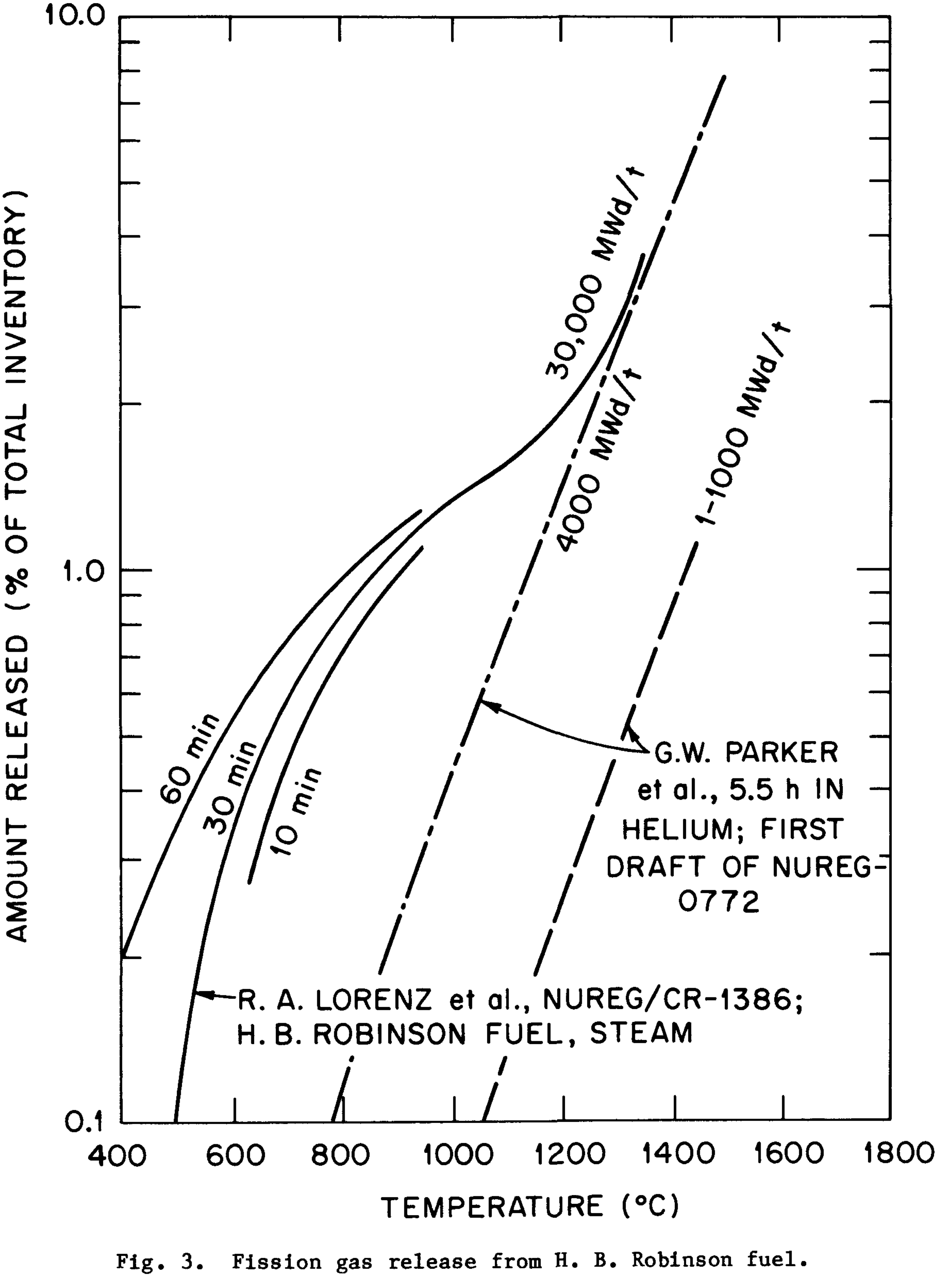

Fig. 3. Fission gas release from H. B. Robinson fuel.

data would tend to give high releases. The lack of cladding, on the other hand, would result in low releases. Some fission gas that is apparently trapped in both fuel and cladding surface layers is released with heatup.[10] The fractional releases assumed for this study are listed in Table 3.

Table 3. Fractional release of ^{85}Kr during heatup

Maximum fuel temperature (°C)	Fraction of ^{85}Kr released
1350	0.0340
1250	0.0195
1150	0.0107
1050	0.0058
950	0.0031
850	0.0017
750	0.0009
650	0.0005
550	0.0003
450	0.0001
350	0.0
300	0.0

4.2.2 Estimation of the Maximum Fuel and Cladding Temperatures Using a Ductile Failure Criterion

Previous studies[2–5,13] found that the major core heatup began at ~140 min after the start of the accident (i.e., at about the same time that the pressurizer vent block valve was closed). The pressure of the system also began increasing at this time. It is believed that most of the fuel rods ruptured by ductile failure (ballooning) in the period 145 to 155 min after the start of the accident, when the primary coolant system pressure was ~5.17 MPa (~750 psi) and the cladding temperature reached ~800°C. If the primary system pressure had remained constant, the fuel rods could not have exceeded this temperature without rupture, and the ^{85}Kr release from fuel pellets to the plenums of intact (leak-tight) rods would have been of the order of 0.1% (Fig. 3). Since the primary system pressure actually increased to >13.8 MPa (>2000 psi), some fuel rods could have been heated to much higher temperatures without ballooning. The following section examines this relationship of ductile rupture as a function of primary coolant system pressure.

4.2.2.1 Ductile Rupture Model

The ductile rupture correlation of Chapman[14] was adapted to the TMI-2 situation. He correlated the cladding temperature and pressure differential measured at the instant of rupture for PWR-size Zircaloy-4 cladding heated in steam at several heatup rates. Measurements were made both with single-rod and bundle geometries. In order to use Chapman's correlation, it was necessary to calculate the internal rod pressure at the time of maximum ballooning. (Internal pressures decrease just before rupture as a result of ballooning.) The increase in internal volume as a result of ballooning might be of the order of 15 cm^3. The average gas temperature (which controls the internal pressure) would be somewhat less than the peak temperature (which controls the ballooning and rupture) and would be strongly influenced by the plenum temperature. To simplify our calculation, we lumped these effects together and assumed that the effective gas temperature in the fuel rod was 0.8 times the peak temperature (K) with no change in internal volume. We used the ideal gas law, assuming initial pressurization with helium to be 3 MPa (30 atm) at 25°C with no additional contribution from the released fission gas. It will be seen in Sect. 4.2.5 that the amount of fission gas released to the plenum is insignificant. As an example of this calculation, the internal pressure is 0.8(800 + 273)/298 × 30 = 86.4 atm for a peak cladding temperature of 800°C. Chapman's correlation for the rupture of Zircaloy-4 tubing in steam is:

$$T = 3960 - \frac{0.024P}{1 + R/28} - \frac{10,000P}{100(1 + R/28) + 3.28P} ,$$

where

T = temperature, °C, at the point of rupture,

R = rate of temperature rise, °C/s,

P = pressure differential at instant of rupture, kPa.

The above correlation underpredicts the rupture temperature by ~20°C for fuel rods near the center of a test bundle where temperature gradients are low. We did not apply this correction since we were interested only in fuel rods near the periphery of the core where the existence of a temperature gradient is essential for their survival.

Both the pressure in the fuel rod and the pressure differential at rupture are plotted as a function of peak cladding temperature in Fig. 4. The difference in these pressures is the minimum external pressure that would prevent the failure. Since the primary coolant system pressure was measured continuously during the TMI-2 accident, we can obtain from Fig. 4 the fuel rod temperature necessary to cause ductile rupture at any time during the accident sequence.

4.2.2.2 Maximum Temperature of Intact Cladding from the Ductile Rupture Model

The coolant system pressure[3] and the data in Fig. 4 were used to construct a curve showing maximum fuel rod temperature without ductile failure for the period 8000 to 13,000 s (133 to 217 min) from the start of the accident. Previous studies[2–5] have shown that the major core heatup occurs during this time. The ductile failure curve is plotted in Fig. 5, along with curves for fuel rod heatup rates for high-power (center of core) and low-power (peripheral assemblies) fuel.[3] The locations of these heatup curves on the time scale are not known accurately because of the nature of the calculation.[3] An additional curve, identified as the 0.4°C/s curve, was drawn with the heatup slightly delayed and at a lower ramp rate to determine the maximum heatup of any fuel rod that avoided ductile rupture. There is no evidence, calculated or recorded, to show whether any fuel rods experienced such a transient. A main cooling pump that was turned on at 10,440 s (174 min) forced some water into the core, resulting in a temporary (at least) cooling of the fuel and a rapid rise in pressure. The overall cooling effect of this action on the core seems to be unknown. Injection of a high-pressure coolant, which was started at 12,000 s (200 min), reduced the core temperature as well as the system pressure.

The dotted portion of the ductile rupture curve represents the period during which the coolant system pressure was ~14.8 MPa (~2150 psi). The rupture temperature corresponding to this pressure is ~1500°C. No guideline could be found concerning heatup during this time. The curve labeled

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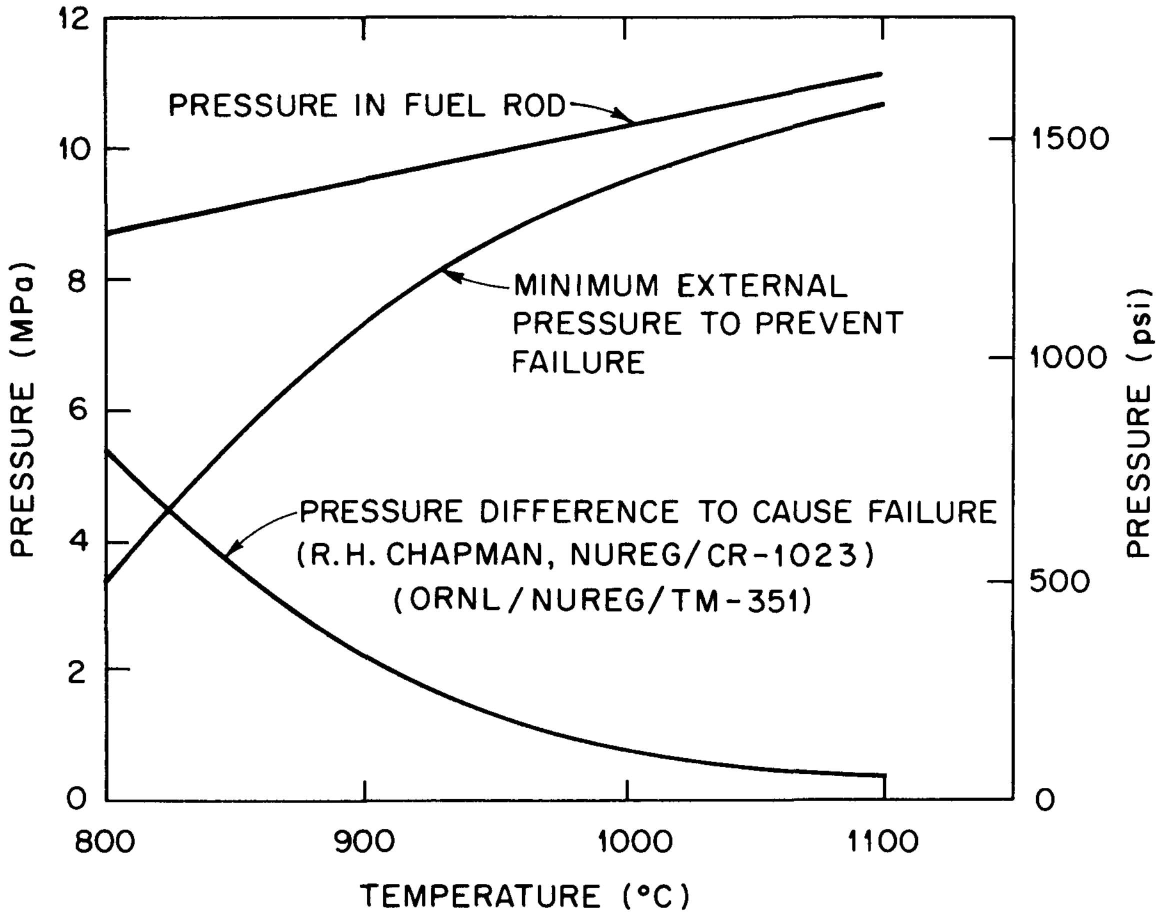

Fig. 4. Fuel rod failure by ductile rupture.

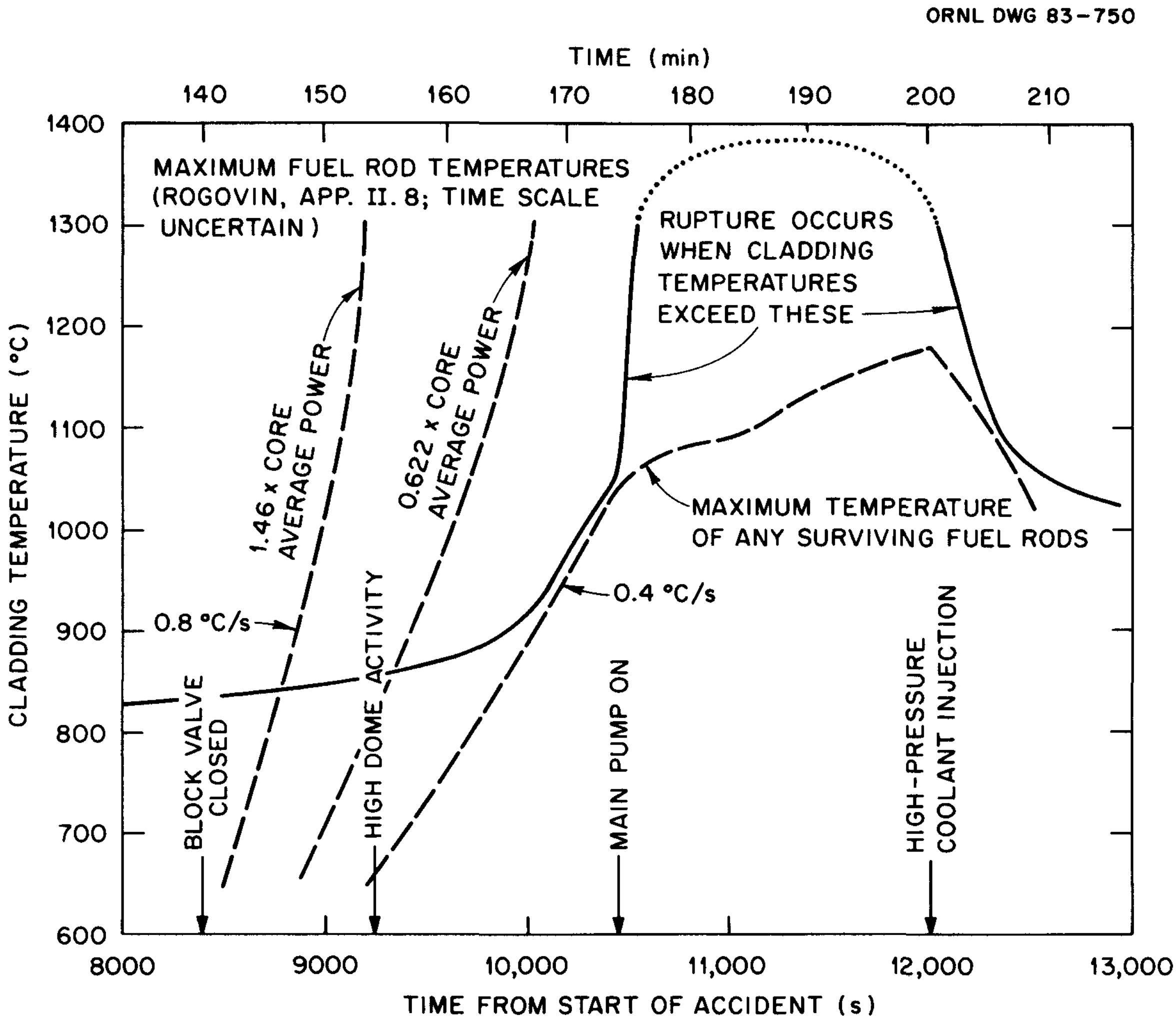

Fig. 5. Fuel rod temperatures.

0.4°C/s peaks at 1150 or 1200°C. If the 0.4°C/s heatup rate assumed for the time before 174 min was resumed after a temporary cooling period, a maximum fuel temperature of 1500°C could be approached. For this study, a maximum fuel temperature of 1150°C was chosen for the innermost three circles of fuel rods.

The pressure of the coolant system showed a considerable decrease much later [~8.27 MPa (~1200 psi) at 5 h and ~2.76 MPa (~400 psi) at 9 h]. It is presumed that the fuel rods were kept cool (below 900°C and 800°C, respectively) during these periods of low pressure. The partial oxidation of the cladding that occurred earlier would probably have allowed higher temperatures prior to ductile failure because of the strengthening effect of dissolved oxygen.

4.2.3 Maximum Temperature of Surviving Fuel Rods for Brittle Fracture

The maximum temperature of surviving fuel rods selected for the remainder of this study was 1150°C. (The maximum temperature could possibly have approached 1500°C.) To determine whether failure occurred by brittle fracture resulting from oxidation and/or hydriding, we consulted a recent comparison of in-reactor and out-of-reactor test data.[15] Several criteria have been suggested for determining the threshold of brittle failure. Many of these involve knowledge of oxygen distribution in the cladding, which cannot be predicted easily for the TMI-2 fuel rods. A simple comparison of embrittlement as a function of temperature and time of exposure obtained from ref. 15 is shown in Fig. 6. All of the test data from Argonne National Laboratory (ANL) were obtained with ruptured rods; thus, oxidation occurred both inside and outside the cladding. In this case, the oxidation, or embrittlement, rate would be approximately four times that for outside-only oxidation. No reason was given for the longer survival time in the Power Burst Facility (PBF), but apparently the "intact" rods in PBF had never ruptured; therefore, the PBF curve is essentially that for outside oxidation only. Based on this analysis, we believe that unruptured fuel rods at 1200, 1300, 1400, and 1500°C could survive exposure in steam for 35, 10, 3.5, and 1.5 min without excessive embrittlement.

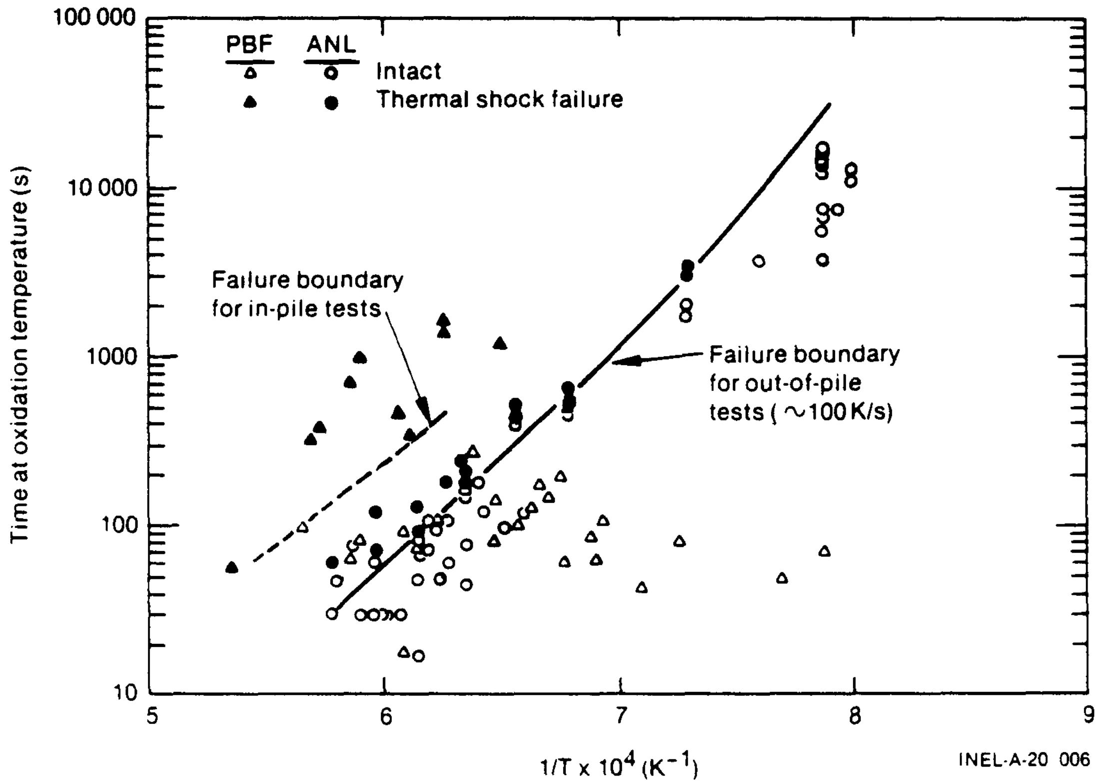

Fig. 6. Failure boundaries of thermal shock for in-pile and out-of-pile tests. Source: F. M. Haggag, Zircaloy Cladding Embrittlement Criteria: Comparison of In-Pile and Out-of-Pile Results, NUREG/CR-2757 (EGG-2123) (July 1982).

It is clear that there is no danger of embrittlement if the assumption of a maximum temperature of 1150°C is correct. The choice of a much higher maximum temperature, with its shorter allowable heating time, should probably include a reduction in the amount of fission gases released. Tests with high-burnup fuel showed that fission gas release could be rapid, supposedly because of linkage of fission gas bubbles and grain boundary separation.[11] However, these mechanisms are not likely to occur with the 197-GJ/kg- (2280-MWd/t)-burnup TMI-2 fuel under consideration.

4.2.4 Axial and Radial Temperatures in the Surviving Fuel

The fuel rods nearest the outside of the TMI-2 core will have experienced lower maximum temperatures than those at the other locations because of (1) lower heat generation in the outer rods and (2) heat loss to the core barrel and pressure vessel. Figure 7 shows the maximum fuel temperature, as determined in NSAC-24,[5] along with the much lower temperatures assumed for this study. The temperature profile shown is simply a straight line or stairstep through 1150°C at circles 1–3 and is not the result of any heat transfer investigation.

It is generally agreed that the bottoms of the fuel rods were kept reasonably cool by immersion in water during the accident. It is also commonly accepted that the highest temperatures reached were above the core centerline. Therefore, we have constructed axial temperature profiles of this type, as shown in Fig. 8. The fuel rods are divided into five lengths as described in Sect. 3. Temperature increments of 100°C are used for simplicity of calculation. The axial distribution of maximum temperatures is presented in Table 4.

4.2.5 Calculation of ^{85}Kr Release from Fuel to Plenum During the Accident Heatup

The data presented in Tables 2–4 allowed us to calculate the amount of ^{85}Kr released during the heating cycle that occurred during the accident. Detailed calculations for the fuel rods in circles 1–3 are summarized in Table 5; release calculations for all the rod groups are listed in Table 6. The total release from fuel to the plenums and open void spaces of the assumed surviving rods is ~30 Ci.

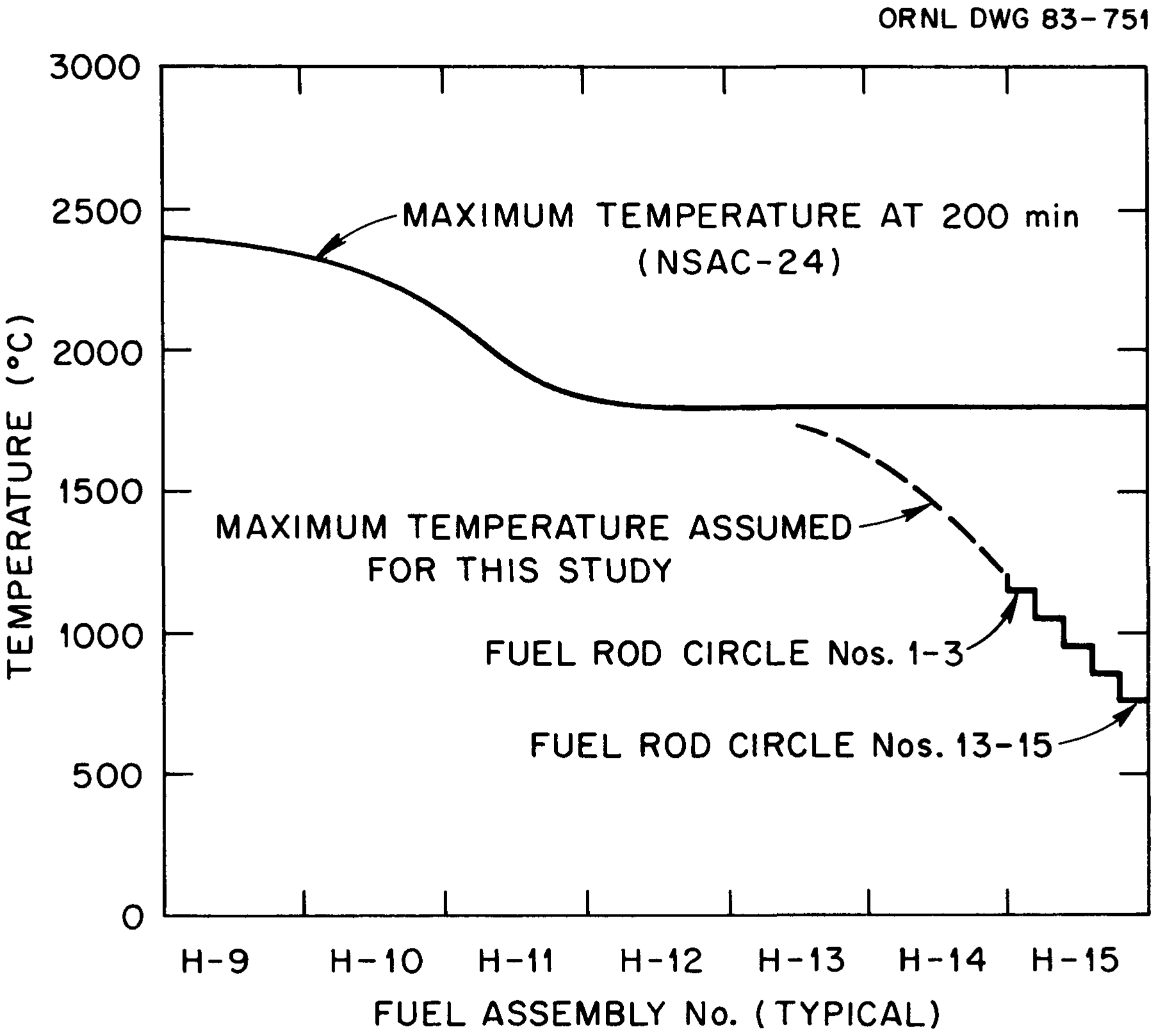

Fig. 7. Maximum temperature — radial profile.

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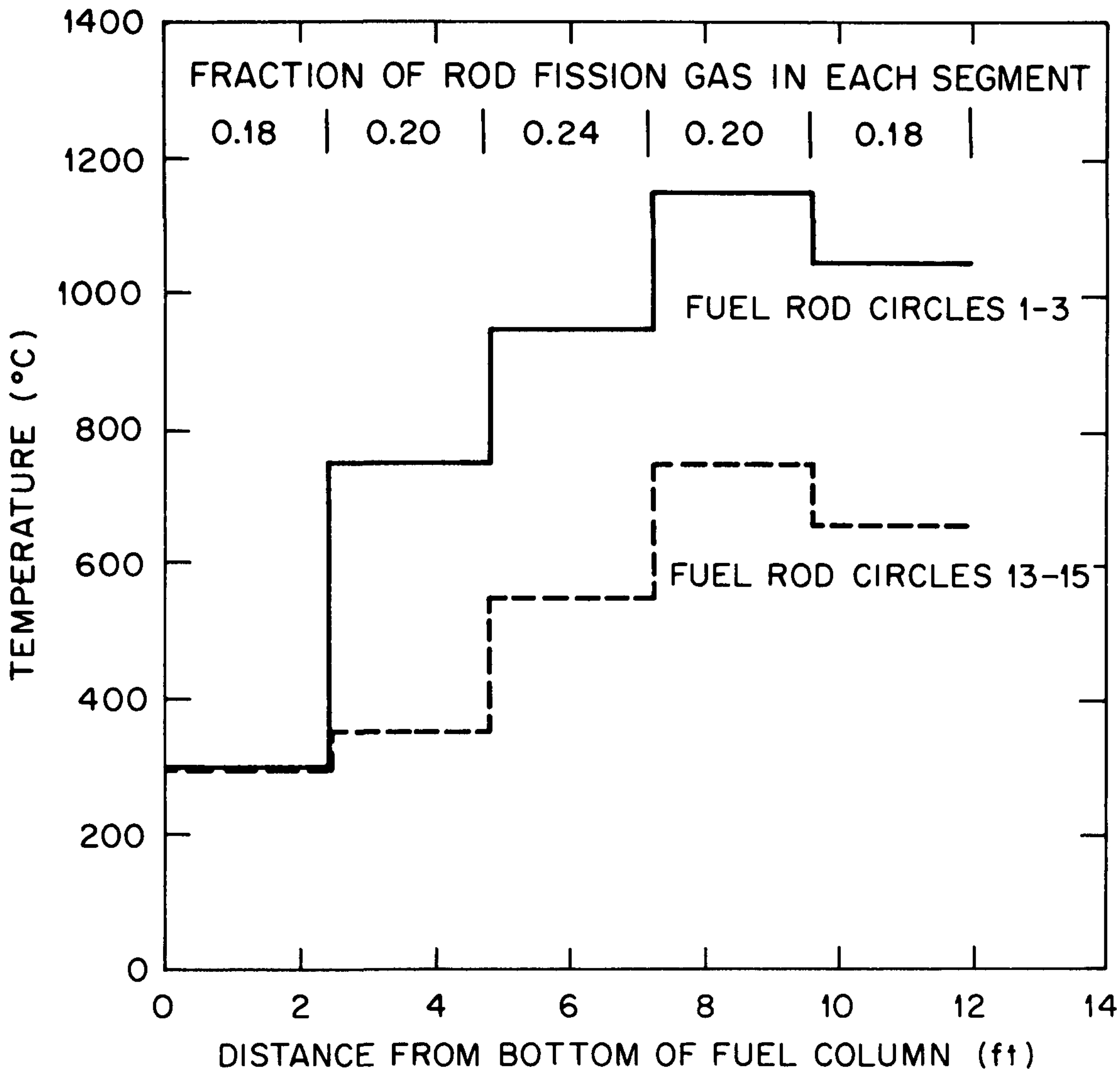

Fig. 8. Axial temperature and fission gas distributions.

Table 4. Axial distribution of maximum temperatures

Rod circle Nos.	Maximum temperature (°C) Distance from bottom of fuel column (ft) 0–2.4	2.4–4.8	4.8–7.2	7.2–9.6	9.6–12.0
1–3	300	750	950	1150	1050
4–6	300	650	850	1050	950
7–9	300	550	750	950	850
10–12	300	450	650	850	750
13–15	300	350	550	750	650

Table 5. Release of ^{85}Kr during heating of fuel rods in circles 1–3

Axial segment location (ft from bottom)	Maximum temperature of segment[a] (°C)	Fraction of rod Kr in segment	Fraction of segment inventory released from fuel[b]	Fraction of total rod inventory released from fuel
0–2.4	300	0.18	0.0	0.0
2.4–4.8	750	0.21	0.0009	0.00019
4.8–7.2	950	0.22	0.0031	0.00068
7.2–9.6	1150	0.21	0.0107	0.00225
9.6–12.0	1050	0.18	0.0058	0.00104
Total				0.00416

[a] Data taken from Fig. 8 and Table 4.
[b] Data taken from Fig. 3 and Table 3.

Table 6. Amount of free ^{85}Kr available for release

Rod circle Nos.	Amount of ^{85}Kr in group (Ci)	Amount of free ^{85}Kr available for release: Fraction of ^{85}Kr initially in group — Plenum gas	Gas from heating	Total	Activity (Ci)
1–3	2,835	0.0003	0.00416	0.00446	12.6
4–6	2,783	0.0003	0.00226	0.00256	7.1
7–9	2,708	0.0003	0.00122	0.00152	4.1
10–12	2,595	0.0003	0.00065	0.00095	2.5
13–15	2,460	0.0003	0.00035	0.00065	1.6
Total	13,381				27.9

4.2.6 Comparisons with ^{85}Kr Release in Fuel Rod Failure Tests FRF-1 and FRF-2

Fuel rod failure tests FRF-1 and FRF-2 consisted of bundles of seven 2-ft-long fuel rods that underwent loss-of-coolant accident (LOCA) type of temperature transients in flowing[16] steam. Each bundle contained one irradiated fuel rod from which the release of ^{85}Kr was measured. Fissioning in the fuel pellets was the heat source in these tests, in much the same way as fission product decay in the fuel pellets was the heat source in the lower-temperature TMI-2 fuel rods. The irradiated test rod burnups were ~56 and ~242 GJ/kg (645 and 2800 MWd/t, respectively) in the two tests. The total heating time for the fuel rod failure tests was probably less than that in the TMI-2 accident.

Table 7 gives a comparison of these test results with our calculations for the TMI-2 rods. The releases are very close and therefore add confidence to the calculation. It would not have been surprising to find as much as a factor of 4 difference in the release fractions.

Table 7. Comparison of ^{85}Kr releases calculated for TMI-2 fuel rods and measured in fuel rod failure tests

Fuel	Peak temperature (°C)	^{85}Kr release (fraction of rod inventory)
TMI-2 circles 1-3,	1150	0.00416[a]
Test FRF-2	1130-1300 for 2.5 min	0.0048
TMI-2 circles 7-9,	850	0.00152[b]
Test FRF-1	750-950 for ~3 min	0.00094

[a]Data taken from Tables 5 and 6.
[b]Data taken from Table 6.

5. COMPATIBILITY OF THIS ESTIMATE WITH THE PREVIOUS RELEASE OF ^{85}Kr FROM THE CORE

The 30 Ci of ^{85}Kr calculated to be available for release from the fuel rods assumed to survive intact is in marked contrast with the

~50,000 Ci of ^{85}Kr released from the core at the time of the accident. The question has been raised as to whether the assumptions used in this report (krypton release model, distribution of maximum temperatures, and fuel rod rupture criteria) could be extended over the remainder of the core and thereby lead us to calculate a total release from failed rods of ~50,000 Ci of ^{85}Kr. Some significant revisions would probably have to be made in our assumptions before this question can be answered affirmatively. The first of these would be an upward adjustment of the maximum temperatures shown in Fig. 7. A much higher fraction of the core needs to be >2000°C in order to obtain the total release above. This could be accomplished by raising the dashed and stairstepped portion of the ductile rupture curve in Fig. 5 by ~500°C and blending it toward 2400°C at the center. The second major revision would be to change the axial temperature profiles shown in Fig. 8 so that all of the upper three segments reach the maximum temperature. The overall effect would be to reduce the number of surviving fuel rods and to substantially increase the amount of fuel that reached a temperature exceeding 2000°C. Because of the reduction in the number of surviving fuel rods, the total amount of ^{85}Kr in their plenums available for release during core removal would not be drastically increased.

6. SENSITIVITY OF RESULTS TO CHANGES IN ASSUMPTIONS

Many assumptions were involved in making the ^{85}Kr release estimates. The importance of several of the parameters involved has been examined.

6.1 MAXIMUM TEMPERATURE

The effect of maximum temperature is given in Fig. 3. An increase of all temperatures by 100°C would increase the calculated release by a factor of ~1.8, assuming that there is no change in the number of surviving fuel rods.

6.2 UNCERTAINTY IN THE KRYPTON RELEASE RATE MODEL

The data for the high-burnup H. B. Robinson fuel represent a rather solid maximum; thus, most of the uncertainty in the krypton release model lies in the downward direction. We would estimate the possible credible range as a factor of 1.8 higher or a factor of 3 lower than the values found in our study.

6.3 NUMBER OF INTACT FUEL RODS

As a first approximation, the release of ^{85}Kr to the plenums is directly proportional to the number of circles of fuel rods estimated to remain intact in a leak-tight condition. This estimate was made by assuming that the hottest surviving fuel remains at 1150°C.

6.4 ORIGINAL PLENUM GAS INVENTORY

The plenum gas inventory at the start of the TMI-2 accident was estimated to be 0.03% of the total rod inventory, which would account for ~4 Ci of ^{85}Kr. The actual quantity of ^{85}Kr in the plenum,[3] however, could probably range anywhere from 2 to 10 Ci.

7. CONCLUSIONS

According to the assumptions used in this study, the calculated amount of ^{85}Kr available in the plenums of intact fuel rods in TMI-2 would be ~30 Ci. The greatest uncertainty is in the number of fuel rods surviving in a leak-tight condition. An examination of the parameters involved in the calculation show that the true value probably lies somewhere between 0 and 100 Ci of ^{85}Kr.

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