



UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

ATTACHMENT 1

APR 13 1979

MEMORANDUM FOR: Roger J. Mattson, Director, Division of Systems Safety, NRR

FROM: R. O. Meyer, Reactor Fuel Section Leader, Core Performance
Branch, Division of Systems Safety, NRR

SUBJECT: CORE DAMAGE ASSESSMENT FOR TMI-2

Attached is our assessment of the core damage at TMI-2 for use in the SER for natural circulation. It represents our independent evaluation of the facts available and of the industry/vendor/licensee analysis, which we have heard in several briefings.

An earlier estimate of fuel damage was made by Rubenstein et al, and a recent meeting was held at NRC with industry experts. Memoranda describing those evaluations are attached to this document.

A handwritten signature in cursive script, appearing to read "R. O. Meyer", is written above the typed name.

Ralph O. Meyer, Section Leader
Reactor Fuels
Core Performance Branch
Division of Systems Safety

Attachment:
As stated

cc: R. Tedesco
K. Kniel
P. Check
C. Berlinger
D. Crutchfield (FOIA File)
D. Houston
M. Tokar
V. Stello
B. Grimes
G. Knighton
J. Vogtleweide
D. Powers
PDR

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CORE DAMAGE

A. Introduction

For the usual analysis of hypothetical accidents, initial core conditions are assumed and consequences are calculated. This would involve complex thermal-hydraulic calculations and fuel behavior analyses. At Three Mile Island, however, some of the consequences are known (i.e., some information on fission product release, hydrogen generation, and instrument readings is available), so we will use "reverse engineering" as our principal method of backing out an assessment of core damage.

We start with the assumption that the core was uncovered and allowed to heat up for significant periods of time. Figure 1 shows the system pressure history for March 28, which includes three periods of significant uncover. The periods of uncover correspond approximately with the major periods when system pressure was below the saturation pressure. We will assume that the first core uncover began shortly after 92 minutes into the accident at which time excore ion chambers show a response spike corresponding to the loss of water shielding. Although the two later periods of uncover may have produced additional core damage, we will focus on the first period because decay heat was larger then and because that period produced the large radiation instrument reading (at 150 minutes) in the containment indicating major fuel damage.

Because the fuel damage to be discussed below is so extensive, we will

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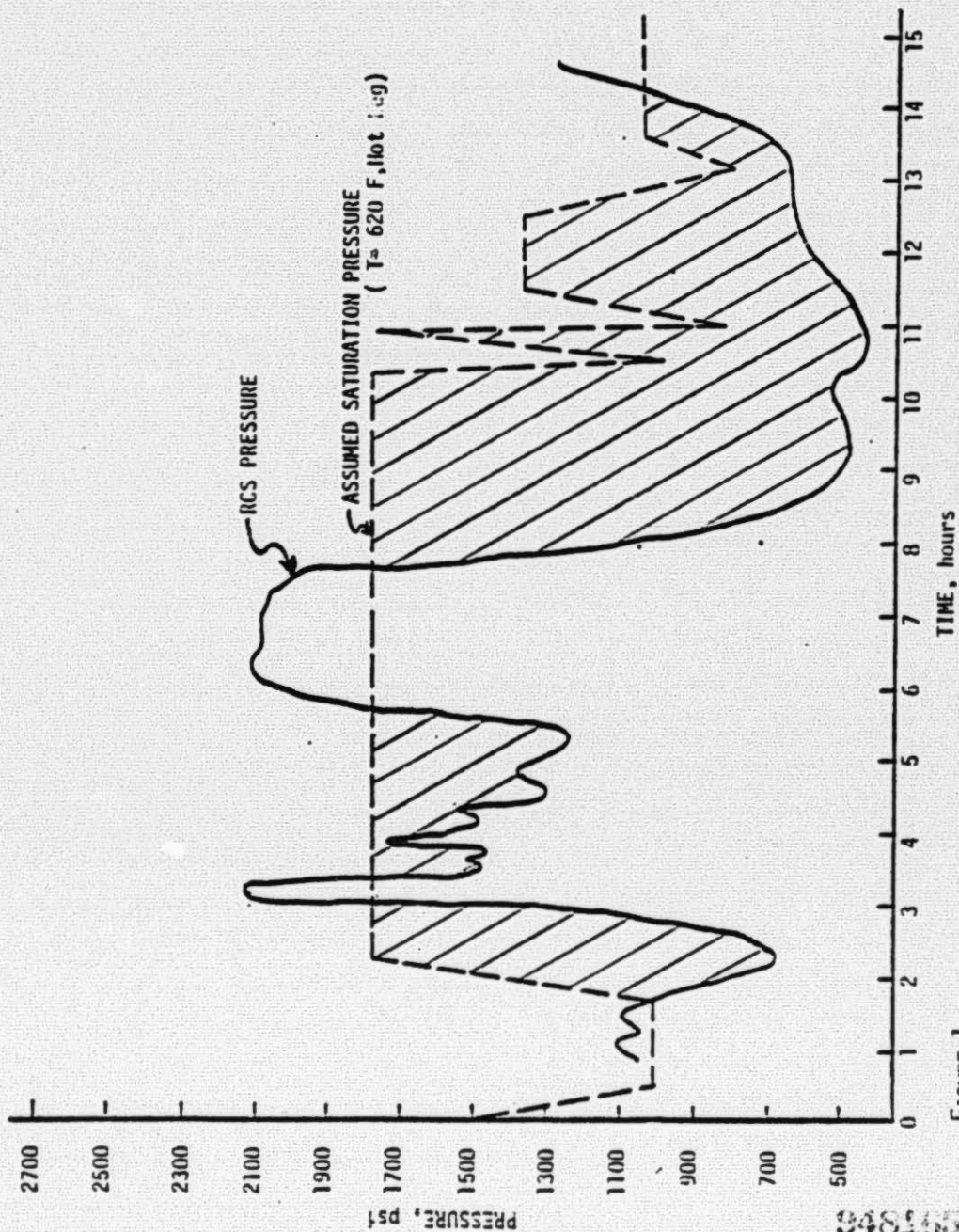


FIGURE 1.

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conclude without demonstration that virtually all of the fuel rods in the core failed in the sense of experiencing defects large enough to release gas. Furthermore, the rods probably failed by a LOCA-like ballooning-and-rupture mechanism. Because of the massive oxidation that followed, the mode of failure is probably immaterial.

As a point of reference, Table I lists melting temperatures of the various materials used in the fuel system.

B. Fuel Rods

Fission product and hydrogen measurements at TMI-2 give important clues about the condition of the fuel rods. We will deal with fission product releases first.

Air and water samples containing fission products have been analyzed. While we have analyzed both for indications of fuel conditions, we have concentrated on the Xe-133 concentration in the air sample. This isotope was selected for analysis for several reasons: (a) it is a noble gas and will not react, plate out or condense, (b) it has a relatively long half life (5.29 days) and a high production rate (6.3 atoms per 100 fissions) and therefore will be abundant thus reducing measurement errors, and (c) fission product release correlations are much better established for noble gases than for other fission products.

Bettis (BAPL) has evaluated the Xe-133 activity and concluded it is equivalent to 31% of the total core inventory. We have independently checked this calculation (but, of course, not the sample activity) and agree (31.5%).

TABLE 1. MELTING TEMPERATURES

<u>MATERIAL</u>	<u>TEMPERATURE, °C</u>	<u>TEMPERATURE, °F</u>
UO ₂	2805	5080
ZIRC-4	1850	3362
ZrO ₂	2715	4919
INCONEL 718	1260-1286	2300-2346
304 SS	1399-1421	2550-2590
Al ₂ O ₃ -B ₄ C	2030	3686
Ag-IN-Cd	800	1472
UO ₂ -Co ₂ O ₃ *	2750	4982

* Two fuel assemblies contained gadolinia test rods.

Fission products including gases are normally retained by the UO_2 pellets. A normal pellet release to the fuel rod internal voidage is only 1 or 2% (even for a successfully terminated LOCA) so that a 30% release indicates additional release from fuel pellets not just a release of the gap activity.

Fuel pellet releases are strongly dependent on temperature, and Figure 2 shows a correlation of release versus temperature for Xe-133 (from a recent ANS-5.4 draft standard). The correlation, however, is for steady-state releases and we are dealing with a transient. Further errors are possible because of kinetics changes due to oxidation to U_4O_9 or U_3O_8 . Nevertheless, it is a reasonable approximation and is consistent with recent short-time annealing experiments (private communication 4-10-79, R. A. Lorenz, ORNL) and earlier annealing work (G. W. Parker et al., ORNL-3981 - See attachment A).

Parker heated irradiated samples in a furnace for 5.5 hours. The samples had burnups ranging from trace to 4000 MWd/t (about the same as TMI-2). Parker measured releases of about 5% at 1600°C, 15% at 1800°C and 40% at 2000°C with an uncertainty of about a factor of 2 in release. These experimental releases for conditions roughly similar to TMI-2, but for different isotopes, ^{are in} fair agreement with Figure 2.

Using Figure 2 we could conclude that (a) the fuel was uniformly heated (uniform in axial and radial directions) to about 1750°C, or (b) 30% of the fuel melted while 70% remained below 1200°C, or (c) any intermediate condition existed. Because of the core uncover sequence,

Xe-133 FISSION GAS RELEASE

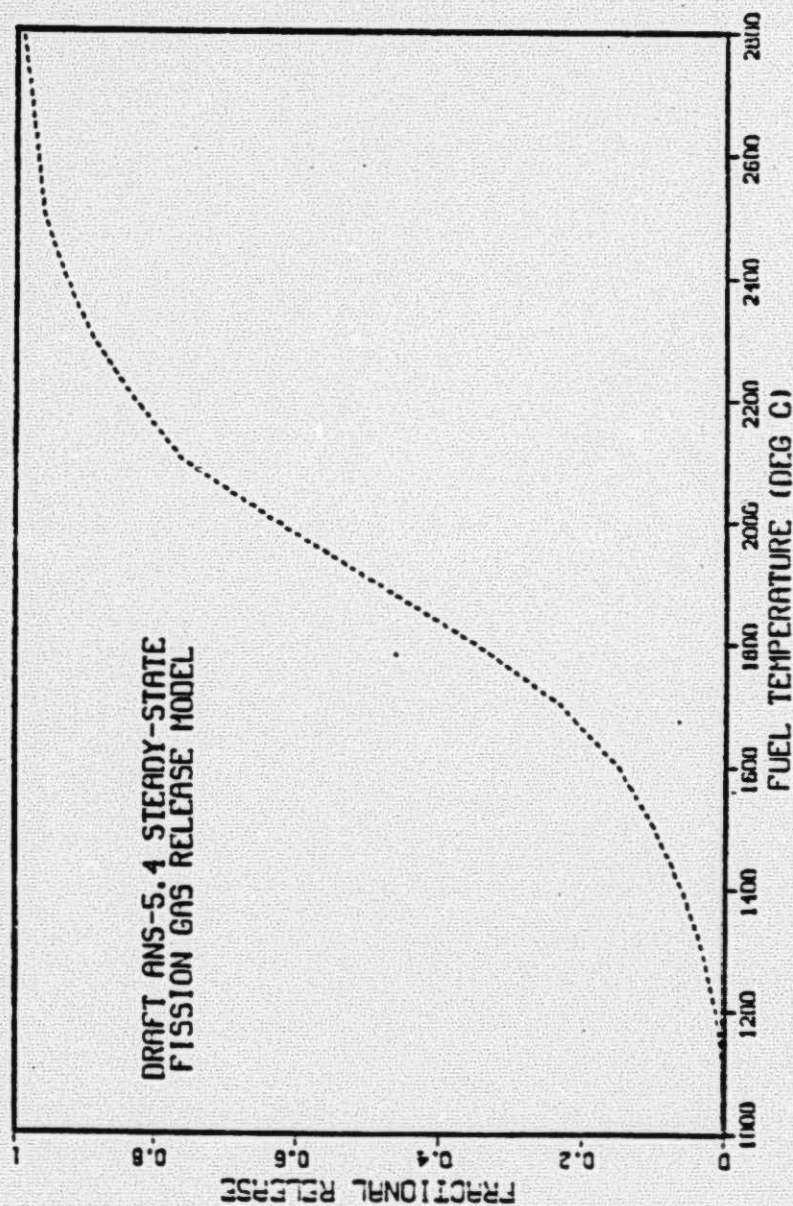


FIGURE 2.

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the fuel rods probably did not heat up uniformly in the axial direction. It is reasonable, however, to treat the fuel rods as isothermal in the radial direction because of the low heat flux. Figure 3 illustrates this point with a comparison of a full-power radial temperature profile and a decay-heat-power temperature profile.

There are physical limits on how hot the fuel can get during the periods of core uncover because the fuel rods have a large heat capacity and a low heat generation rate. If one assumes zero heat removal (this would produce the most rapid heatup rate possible) during the first period of uncover, the heatup rate is still fairly slow. Figure 4 shows the adiabatic temperature increase with time for the peak-power axial location, for the low-power ends of the rods, and for the average location. Since there must have been some heat removal thus further slowing down the temperature rise, pellet temperatures probably did not reach the melting point. Figure 5 shows the temperature changes with time for a surface heat transfer coefficient of $0.5 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$, which is a very small value.

The results on temperature distribution are, therefore, not conclusive. It is unlikely that fuel temperatures were uniform and no lower than 1750°C , and it is also unlikely that any fuel (UO_2) melting took place. The fuel, however, did get very hot compared with its normal operating temperatures.

Oxidation of Zircaloy by steam and the attendant decomposition of water provided the major source of hydrogen in the TMI-2 vessel and containment.

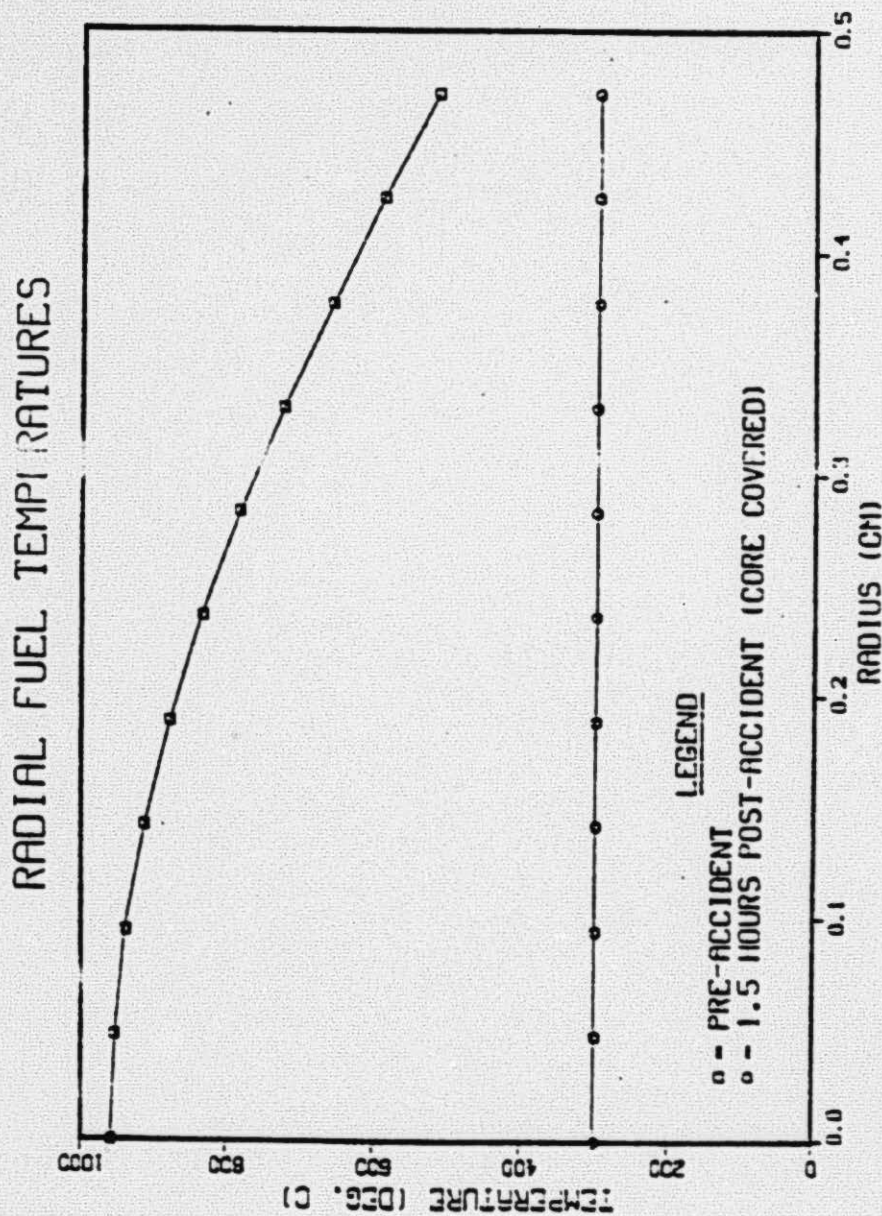


FIGURE 3.

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ADIABATIC HEATUP

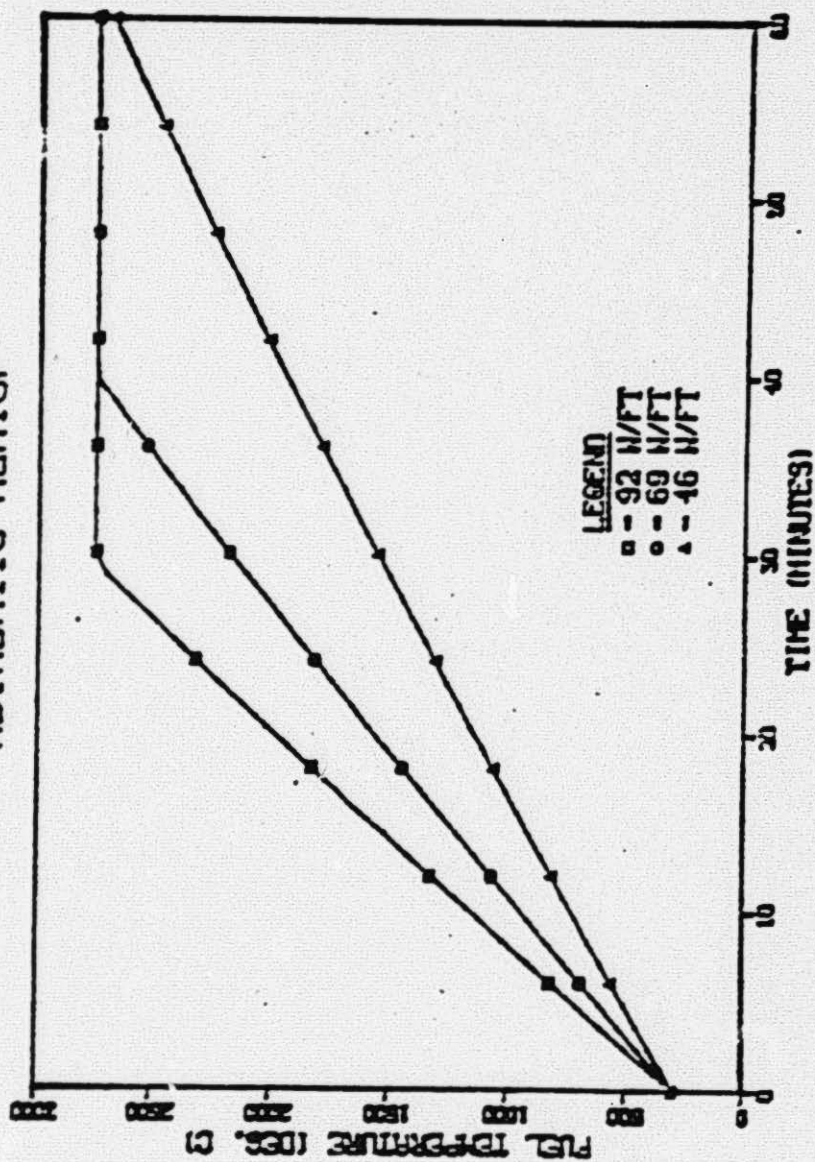


FIGURE 1,

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NEARLY ADIABATIC HEATUP

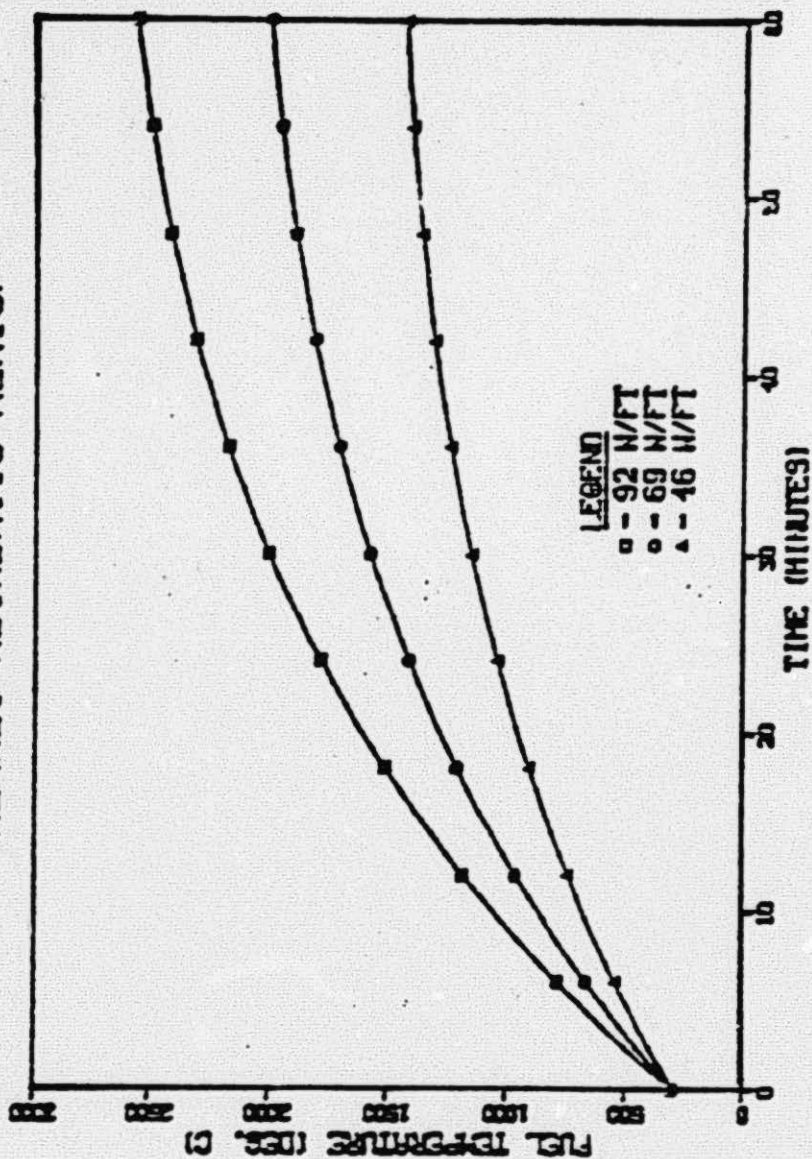


FIGURE 5.

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The Containment Systems Branch has estimated the amount of hydrogen present in the plant (Attachment B) after the periods of core uncover that caused fuel damage. They included amounts (a) consumed by the hydrogen explosion (226 lb mole), (b) remaining in containment after the explosion (80 lb mole), and (c) in the primary system bubble (76 lb mole), which was corrected for radiolysis.

Comparing the above amounts with the total amount of hydrogen that could have been produced if all of the Zircaloy in the fueled region reacted with water, we get 41%. As with the temperatures, an ambiguity exists. This could mean that (a) about 40% of the cladding wall thickness is uniformly oxidized throughout the core, or (b) 40% of the fueled region of the core has fully oxidized cladding, or (c) any intermediate condition exists.

Figure 6 shows the time required for total wall thickness oxidation as a function of temperature (Cathcart-Pawel correlation). It is clear from Figure 6 that complete oxidation is possible in cladding segments that reached temperatures of around 2000°C during the period of core uncover. It is also clear from Figure 6 that all of the cladding did not experience sustained temperatures of around 1750°C else it would all have oxidized. This is further evidence that fuel temperatures were not uniform throughout the core, and that temperatures locally were very high.

Based on early estimates by the Analysis Branch of core uncover, we will assume simplified uncover histories shown in Figures 7 and 8 for the

TOTAL OXIDATION TIME

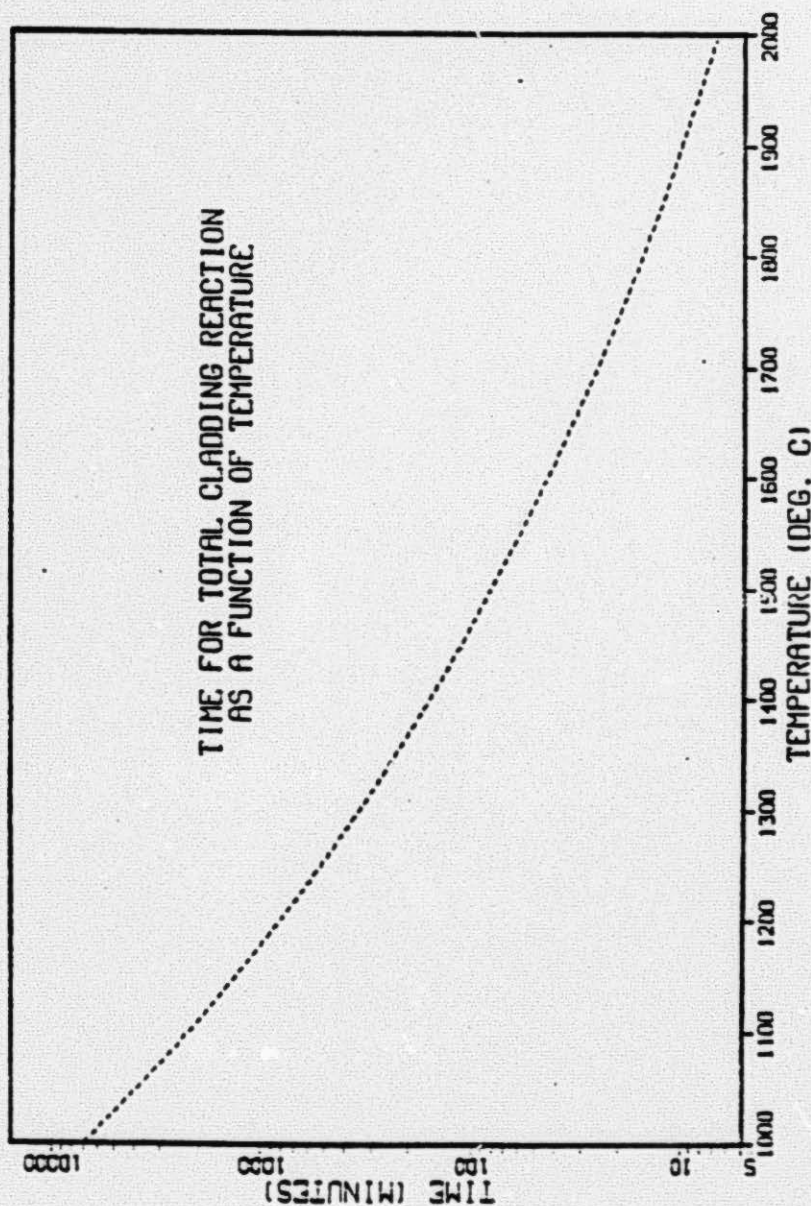


FIGURE 6.

CORE UNCOVERY - CASE 1

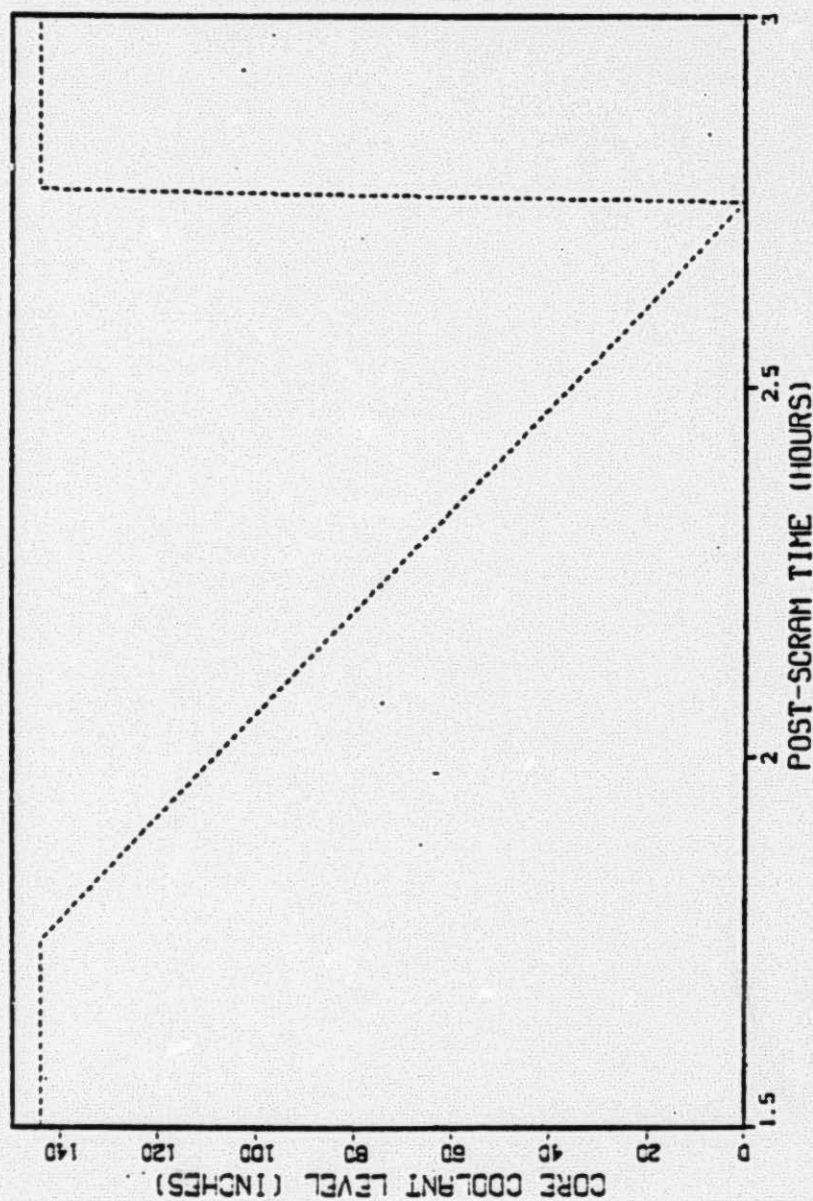


Figure 7.

CORE UNCOVERY - CASE 2

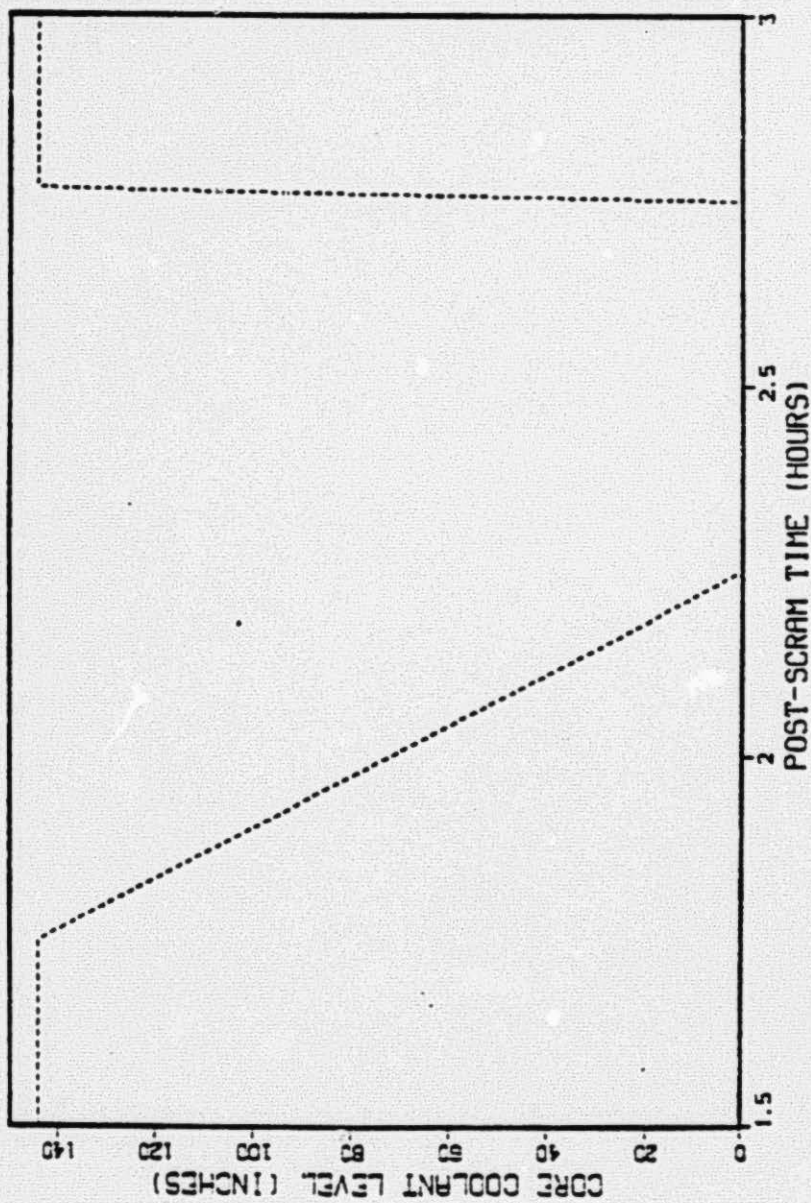


FIGURE 3.

following calculation. Fuel that is covered will be considered to be cold (i.e., no cladding oxidation). Fuel that is uncovered will be allowed to heat up; fuel that heats up will be given a heat transfer coefficient that is adjusted such that the total integrated oxidation is 40%. These calculations give the oxidation distributions shown in Figures 9 and 10, and these distributions are insensitive to many of the assumptions that were made. Figures 9 and 10 thus are more probable distributions than 100% oxidation over 40% of the core or 40% oxidation over 100% of the core.

Figure 11 is a recent best-estimate embrittlement correlation (Kassner et al., ANL) that shows high-temperature fragmentation of quenched tubes at about 30% oxidation. Using this correlation, Figures 9 and 10 indicate that a fragmented region of about 5 ft. in height exists near the top of the core. It may well be right at the top of the core as a result of simplifications in our analysis. In any event, at least 4 to 6 ft. of intact (but partially oxidized) fuel rods remain standing at the bottom of the core.

Figure 12 shows fragmented Zircaloy cladding after oxidation in a simulated-LOCA test. Kassner (ANL-78-25 and ANL-78-49 reports that at high temperatures ($> 1250^{\circ}\text{C}$) many fragments are produced whereas at lower temperature the rod may simply break into two pieces. Inasmuch as TMI-2 temperatures were higher than 1250°C and oxidation was severe, small fragments of the size shown in Figure 12 should be expected along with larger tube-like pieces.

CORE OXIDATION - CASE 1

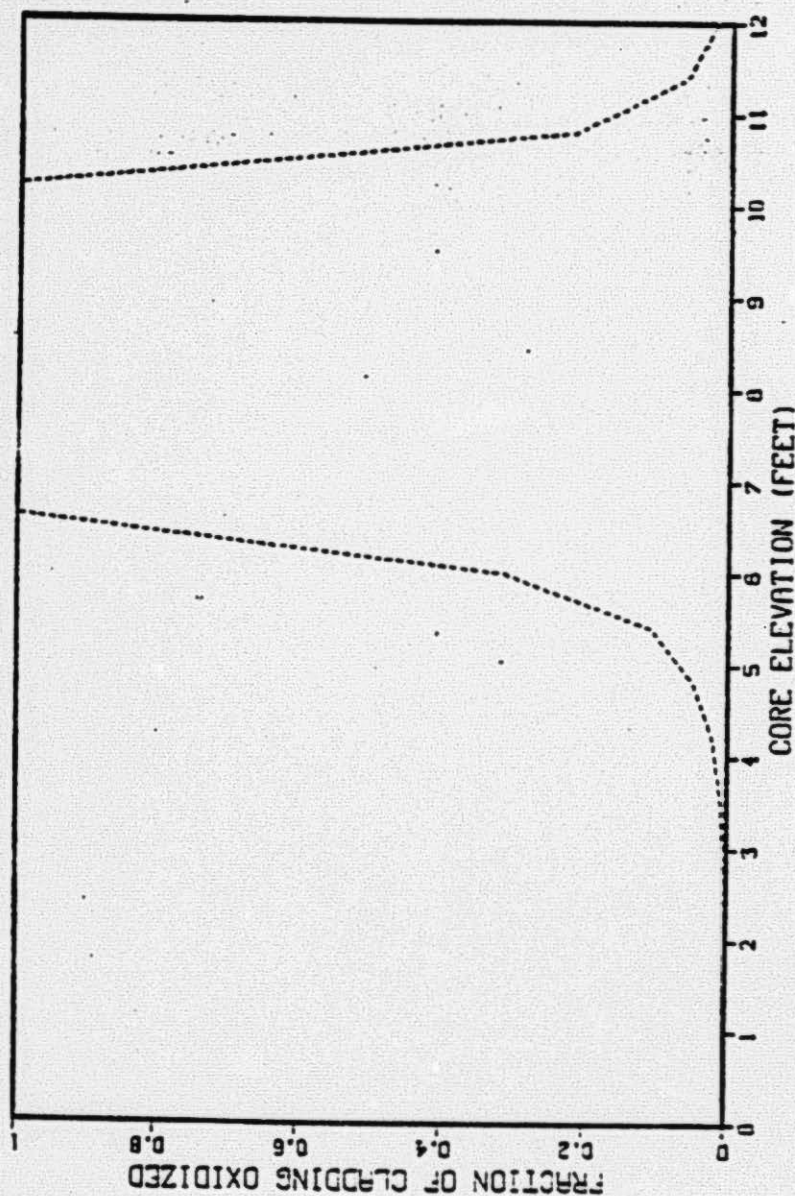


FIGURE 9.

CORE OXIDATION - CASE 2

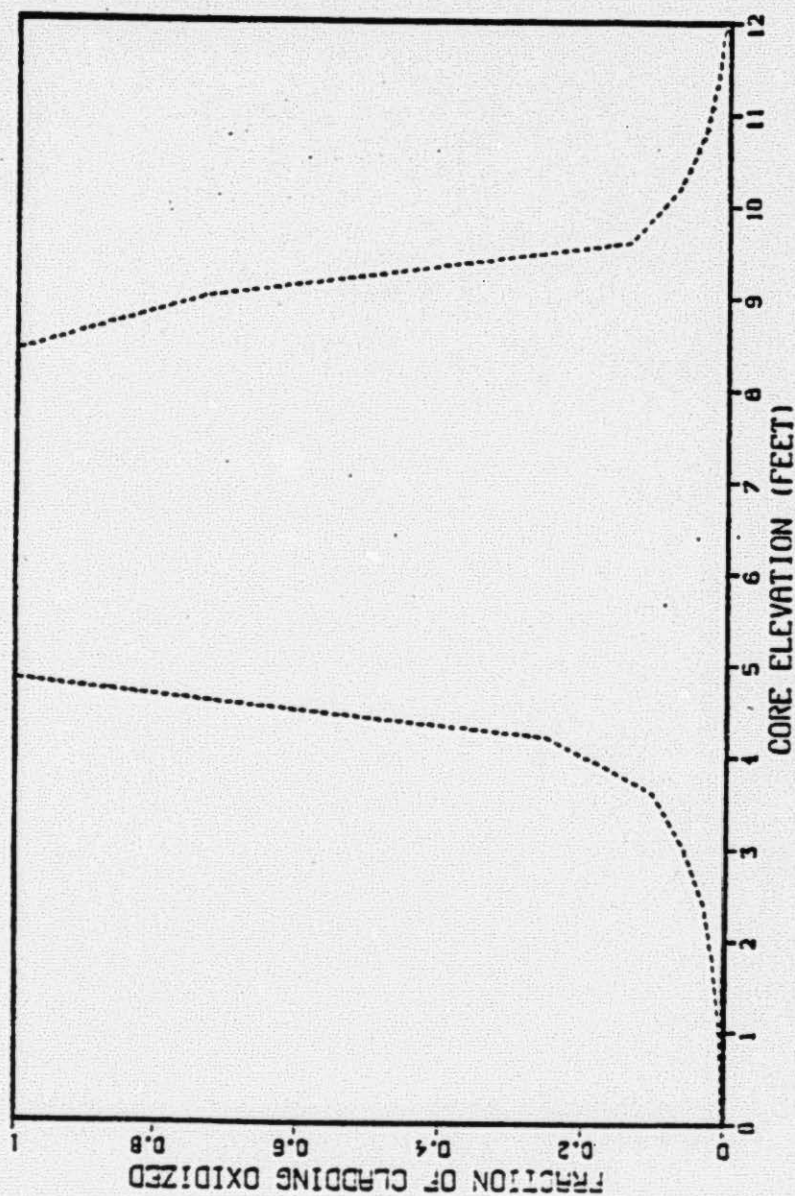


FIGURE 10.

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FAILURE MAP FOR ZIRCALOY-4 CLADDING BY THERMAL SHOCK OR NORMAL HANDLING

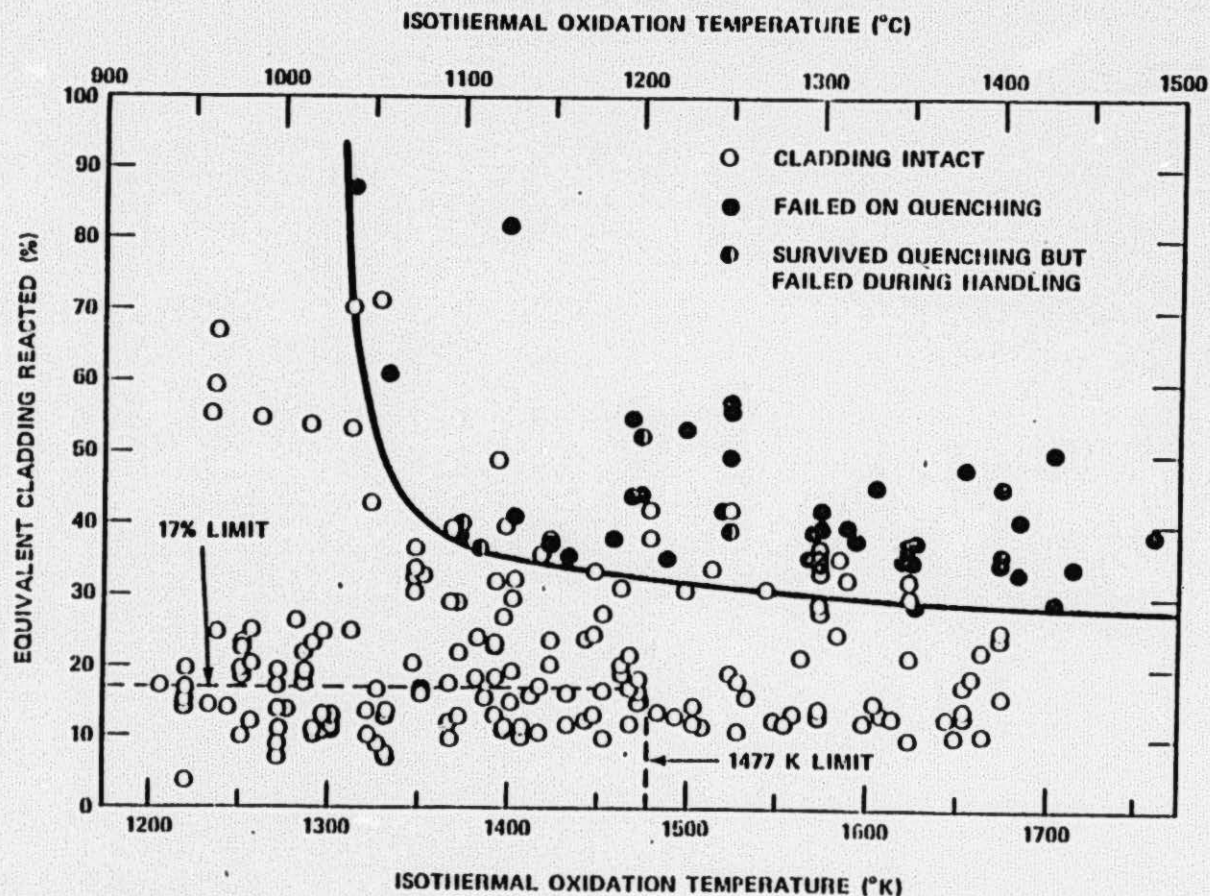


FIGURE 11.

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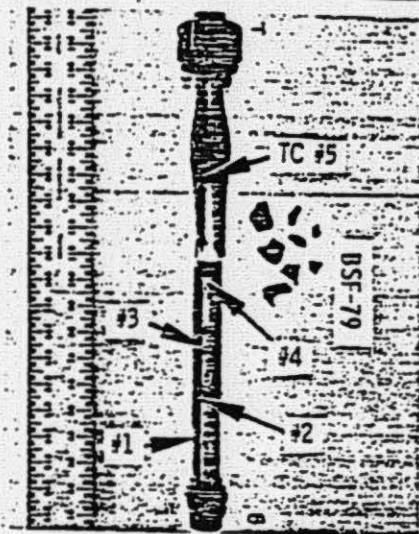


Fig. III.12

Zircaloy-4 Cladding after Thermal-shock Failure Showing Location of Thermocouples That Produced the Temperature-vs-Time Curves in Fig. III.10. ANL Neg. No. 306-78-223.

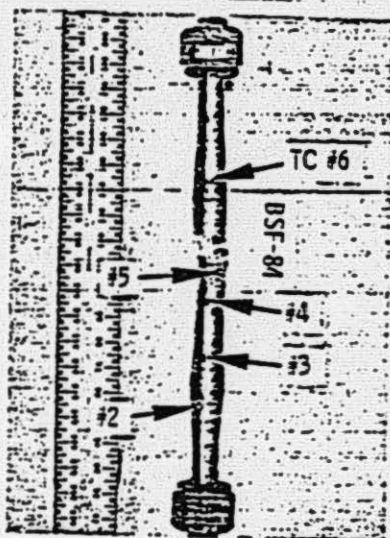


Fig. III.13

Zircaloy-4 Cladding after Thermal-shock Failure Showing Location of Thermocouples That Produced the Temperature-vs-Time Curves in Fig. III.11. ANL Neg. No. 306-78-224.

FIGURE 12.

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Fuel pellets normally crack during operation and crack healing can occur at power. Figure 13 is a typical example of a cracked pellet. Quenching during core flooding may also promote fragmenting of the pellets. Severely fragmented regions are commonly seen in fuel pellets as a result of extreme temperature conditions in test reactors. Powdered regions in fuel pellets have also been seen in some PBF tests, but these tests are characterized by very high powers (> 20 kw/ft) and very steep temperature gradients unlike the low-power uniform (radial) temperature TMI-2 fuel. Therefore we would expect the TMI-2 fuel to be in millimeter-size granules and larger pieces including whole pellets.

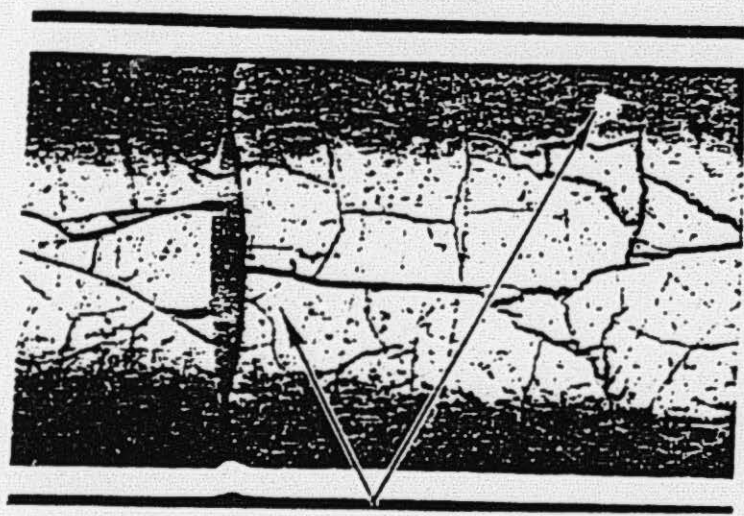
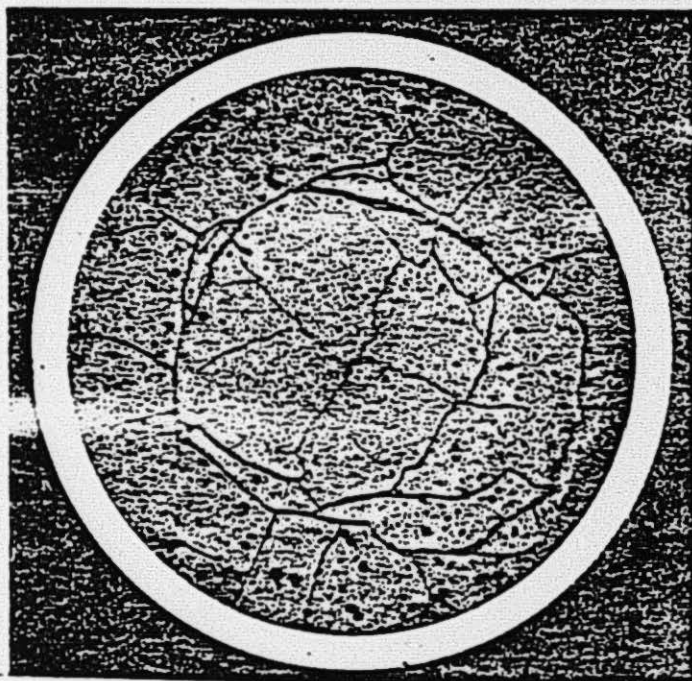
C. Unfueled Components (Control rods, guide tubes, etc.)

Figures 14 through 17 show the control rods, the burnable poison rods, the power shaping rods, and the central instrument tube. All of these rods and the instrument tube are inserted into Zircaloy guide tubes in the fuel assembly. The materials of which these components are made are indicated on the figures.

An important clue about the condition of unfueled components is provided from instrument readings. The fact that all 52 thermocouples worked throughout the accident and ^{most} continue to give credible information suggests that a central tubular structural member survived. It is tempting to conclude that all Zircaloy guide tubes also survived, but this may not be the case since the thermocouple is well protected by multiple barriers.

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FIGURE 13.

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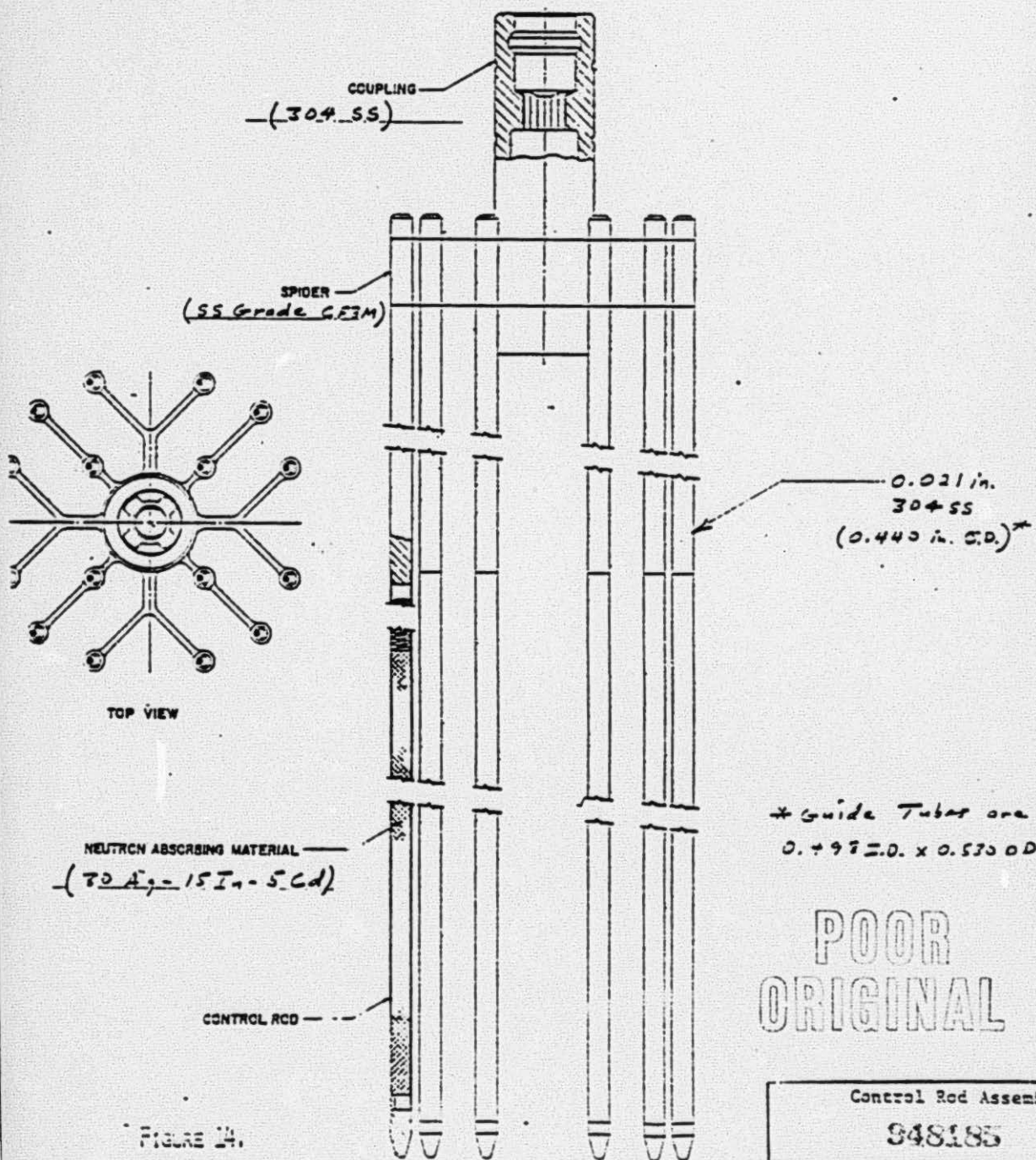


FIGURE 14.

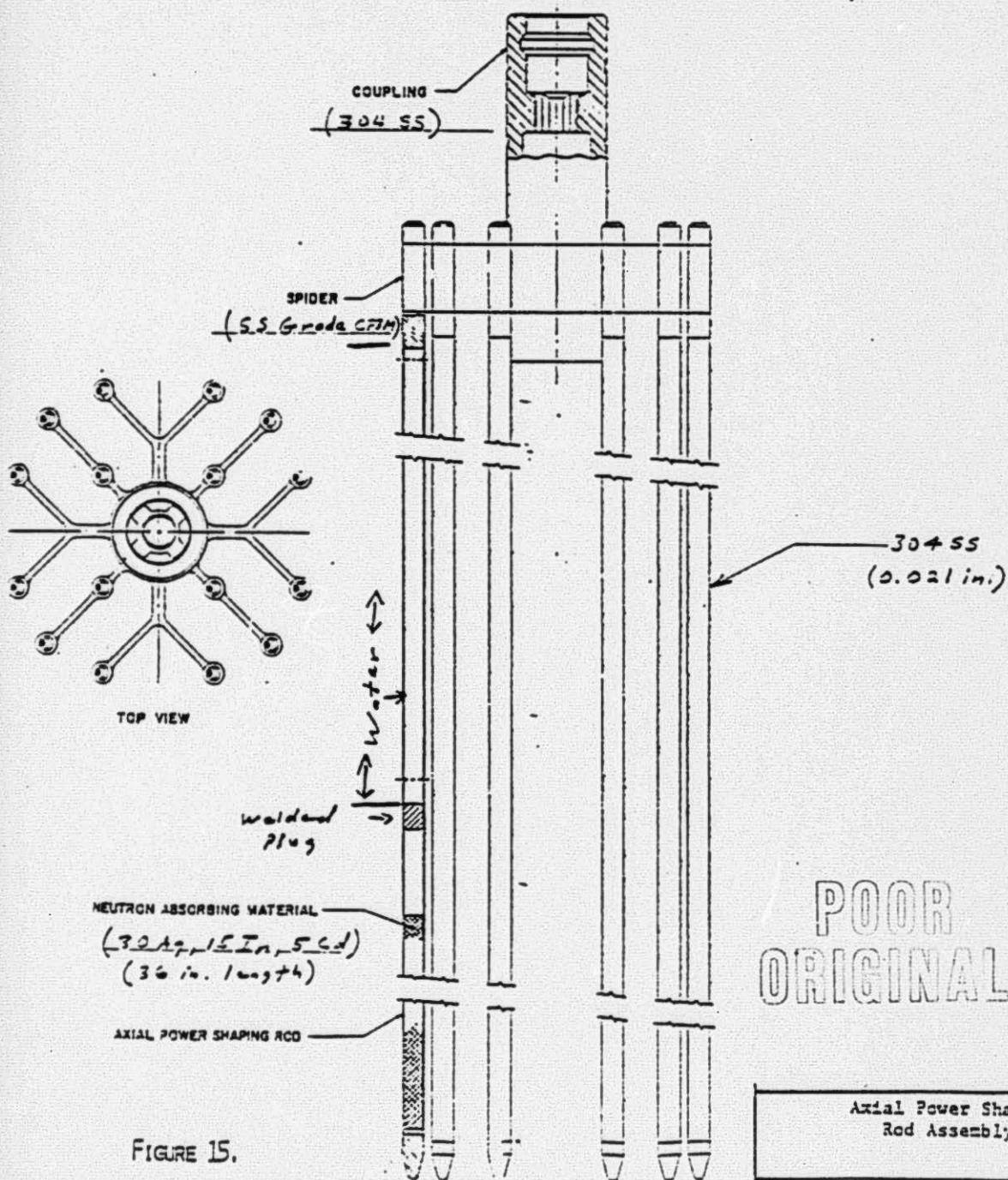


FIGURE 15.

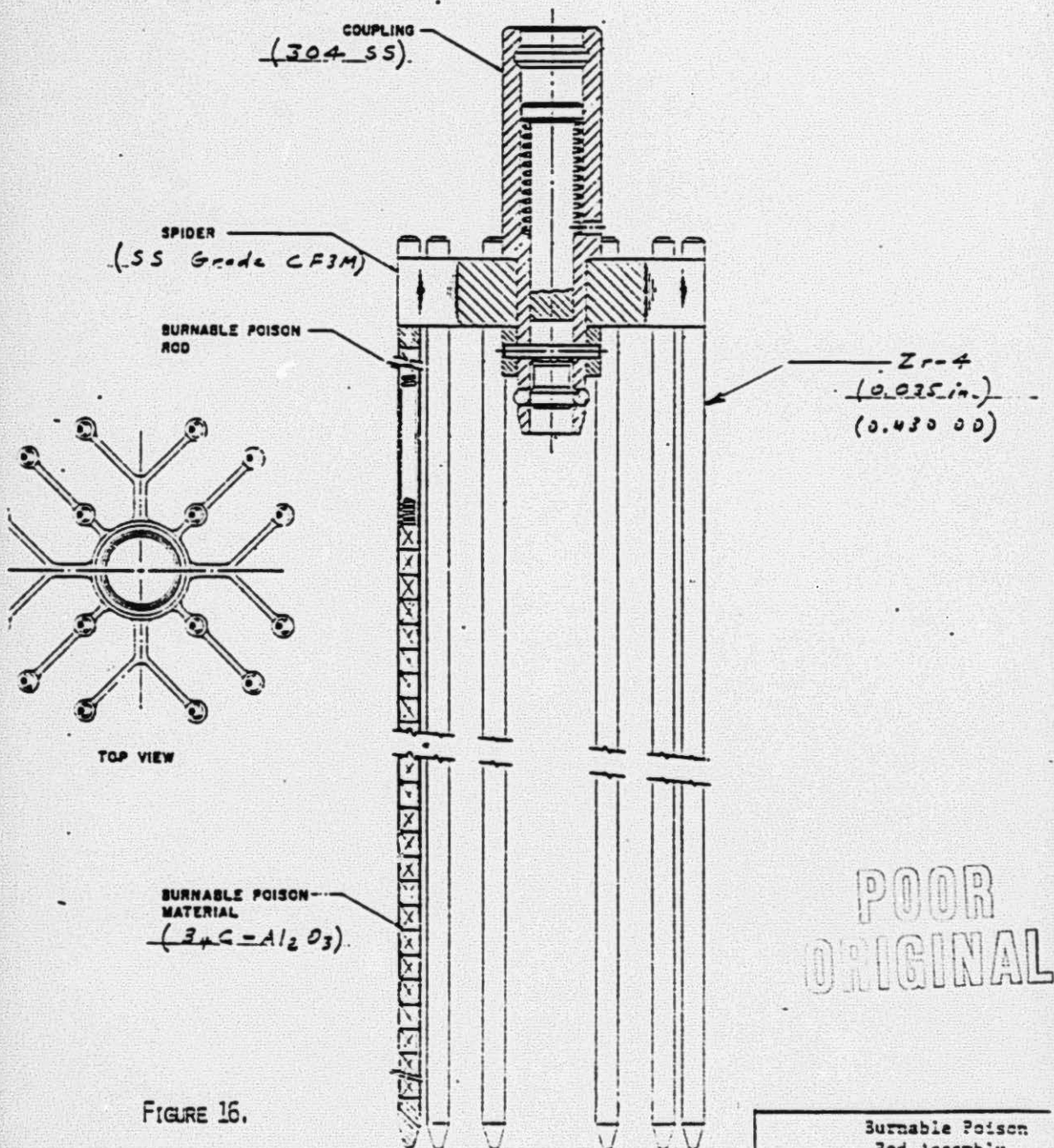


FIGURE 16.

Fixed SPND assembly cross section

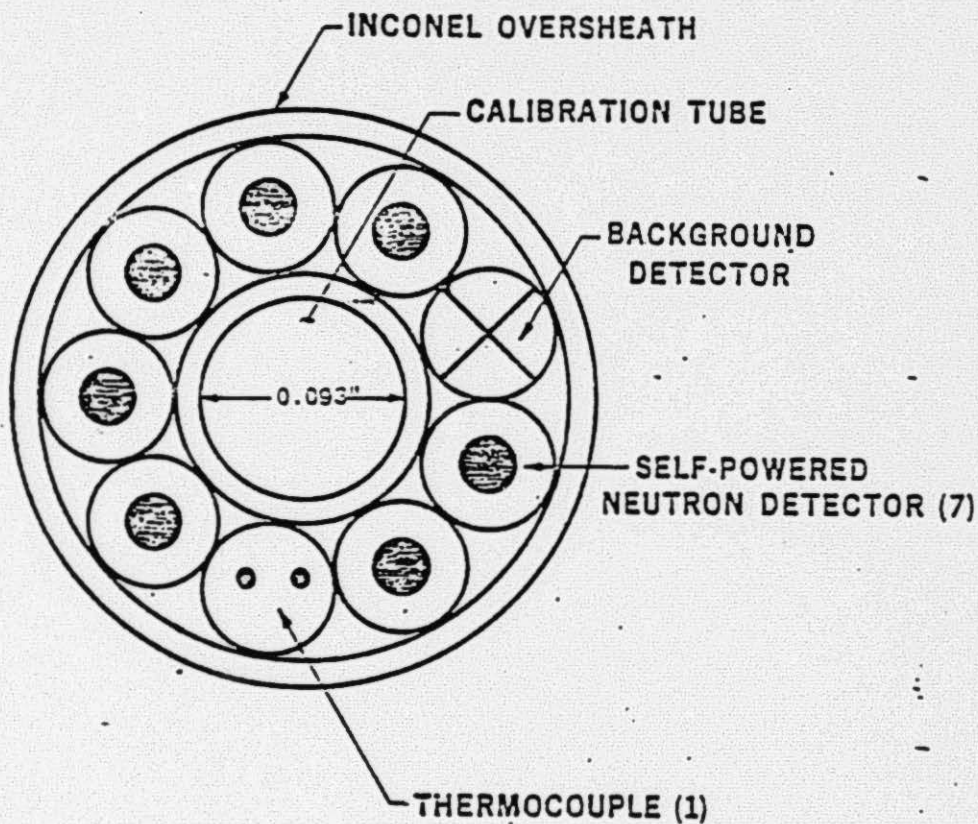


FIGURE 17.

INEL has made calculations of guide tube temperatures by parametrically varying heat transfer conditions (see Attachment C). Their results show that guide tube temperatures lag the fuel rod temperatures by only about 20°F. Babcock & Wilcox has performed similar calculations and concluded that there is a much larger spread in temperatures. We believe the INEL calculations are more nearly correct and that temperatures of unfueled components were close to fuel rod temperatures. Since fuel rod temperatures are believed to have exceeded 1750°C in the hot region of the core, then in that region (a) Ag-In-Cd and its stainless steel cladding would have melted, (b) Inconel spacer grids would have melted, (c) Zircaloy guide tubes would have oxidized, and (d) Zircaloy cladding of the burnable poison rods would have oxidized.

In the cooler parts of the core below about the 4 to 6 ft. elevation, we would expect all unfueled components to be intact, although perhaps damaged, just as the fuel rods are expected to be intact. Control rod segments could have only fallen about 3 inches if severed by melting in the hot region, and the Ag-In-Cd absorber should be in place because it is an insoluble metal. Although the burnable poison rods would also be expected to be in place, their poison is probably lost; boron is known to leach out of $B_4C-Al_2O_3$ pellets when exposed to water in a radiation environment.

D. SUMMARY

Many or all fuel rods may have ballooned and ruptured, but this mode of initial defecting is probably irrelevant in light of later more extensive damage.

In the hot upper central region of the core, fuel temperatures probably exceeded 1750°C releasing large quantities of fission products; about 30% of the total core inventory of noble gases was released.

About 40% of the Zircaloy cladding reacted with water. This region of severe oxidation was localized above the 4 to 6 ft elevation and may not have included peripheral bundles. The severely oxidized fuel probably fragmented into pieces ranging from millimeter size to whole sections of rods.

The temperature of unfueled components lagged the temperature of fuel rods by only about 20°F so that they also experienced temperatures above about 1700°C . Consequently, in the hot region of the core

Zircaloy components should have oxidized, and components with Inconel, stainless steel, and Ag-In-Cd should have melted. Because of many layers of protection, the thermocouple tubes have survived even in the damaged core region, although the outer sheath of the instrument tube may be badly damaged.

Nearly all of the broken and oxidized fuel debris should remain trapped in the upper core region because the upper end fittings have a grillage that would act as a screen. Furthermore, the compaction of fuel debris

is limited because it is fabricated with a packing fraction of about 46% and the theoretical maximum packing fraction (for a bed of spherical particles) is only about 63%. It is very likely that fuel debris are also trapped in some mixing cups (See Figure 18) contributing to non-uniform thermocouple readings.

An earlier estimate of fuel damage in TMI-2 was made at NRC by Rubenstein, Meyer, Tokar, and Johnston. That estimate is in general agreement with the present estimate although our current evaluation is more refined. A memorandum summarizing the earlier estimate is attached as Attachment D.

E. Recommendations

Reactor fuel is rugged, and it is unlikely that limits for natural circulation conditions will be related to fuel behavior. The general criterion with regard to the fuel should be that additional Zircaloy oxidation and fission gas release should be avoided.

Significant oxidation rates do not occur until 900 or 1000°C (See Figure 5). Significant fission gas releases do not occur until even higher temperatures (See Figure 2). These temperatures should be avoided in the (relatively) undamaged regions of the TMI-2 core, but these temperatures are so high that other limits will probably prevail.

By now the adiabatic heatup rate is low (See Figure 19) and ample time will be provided to detect fission gas or hydrogen releases. Therefore, on-line methods of such detection, if feasible, should give adequate

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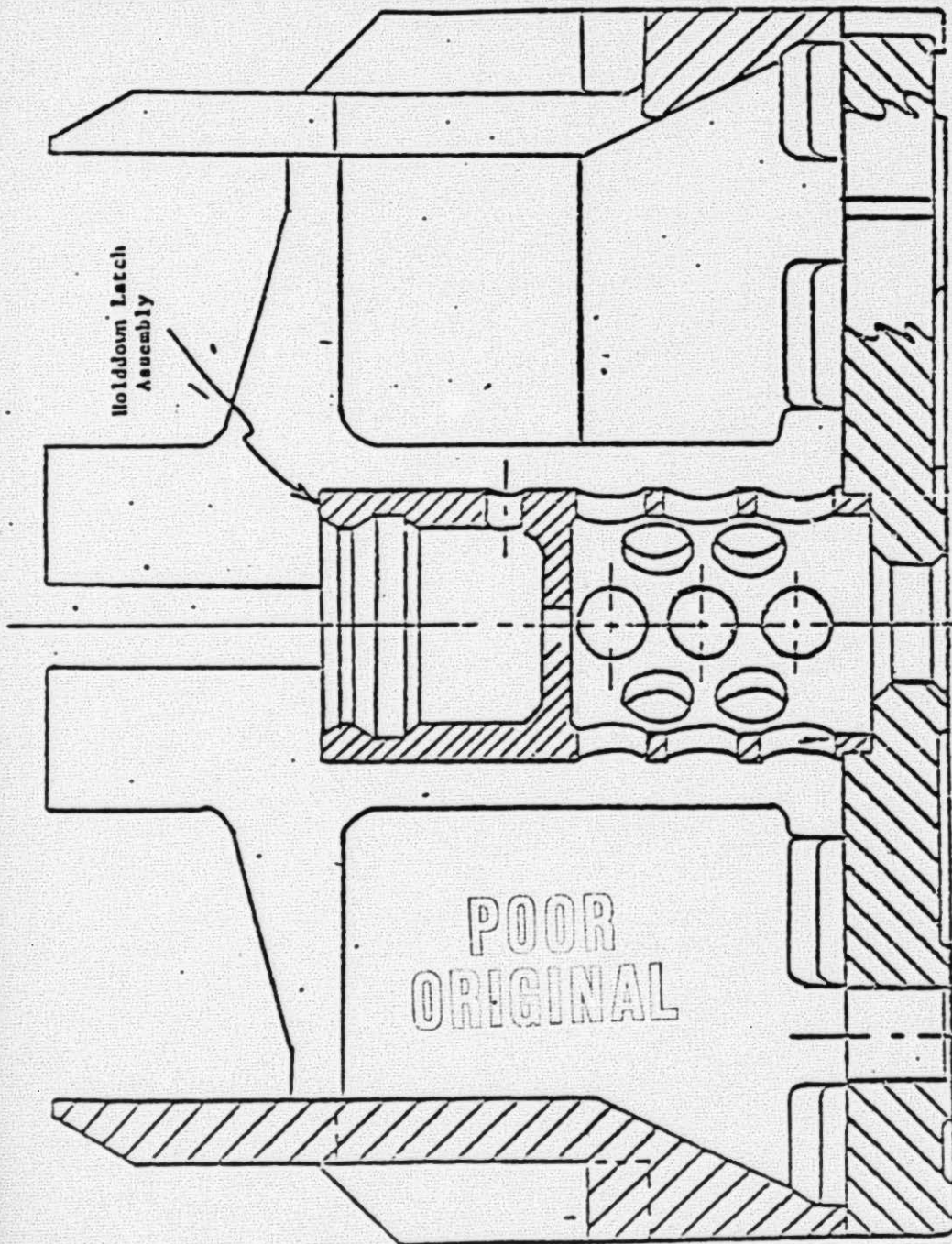
Holddown Latch
Assembly

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UPPER END FITTING AND HOLDDOWN LATCH ASSEMBLY

FIGURE 18.

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ADIABATIC HEATUP FOR APRIL 15, 1979

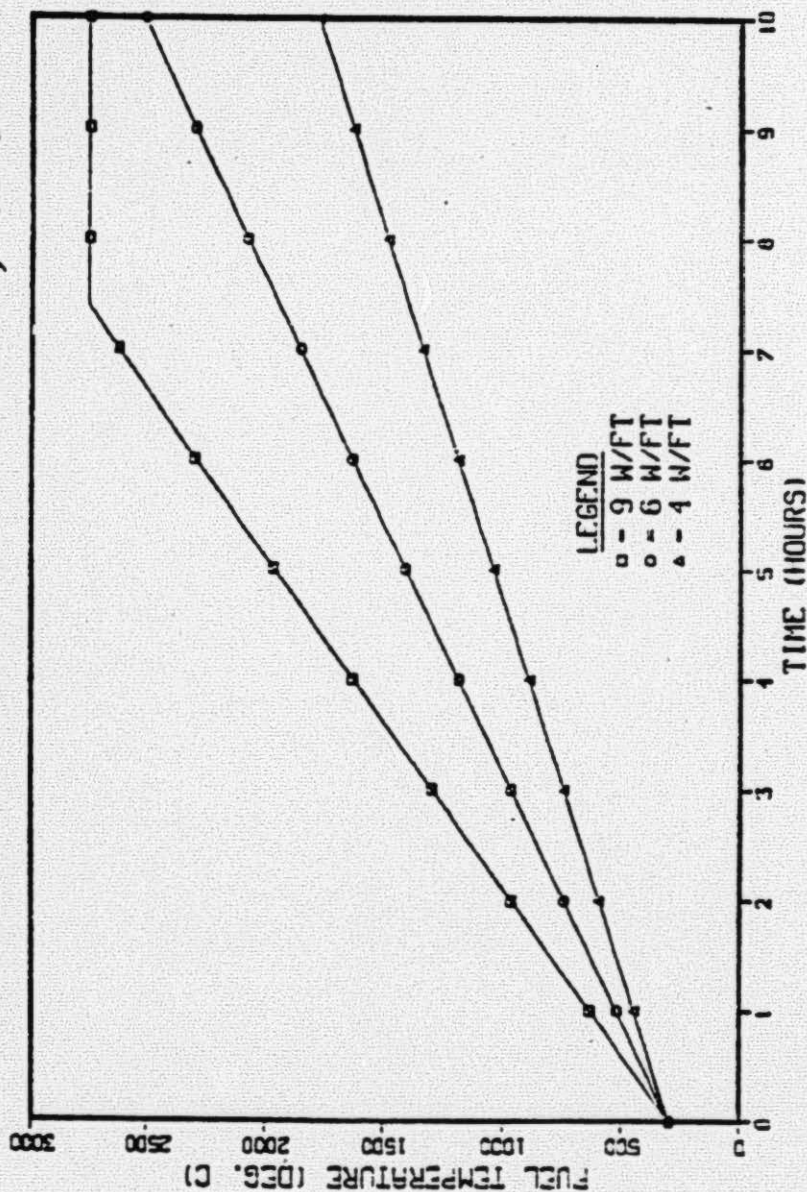


FIGURE 19.

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warning of fuel damaging conditions.

A discussion of instrument responses relevant to fuel behavior was held with a group of fuel experts from across the industry. A summary of those discussions was prepared by W. V. Johnston and is attached as Attachment E. One consensus of that group was that in-core thermocouple readings should be recorded continuously. A recommendation for such data recording was made and is attached as Attachment F.

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