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LWR FUEL ROD BEHAVIOR OBSERVED DURING POSTULATED ACCIDENT CONDITIONS: A COMPARISON OF FRAP-T CALCULATED AND PBF EXPERIMENTAL RESULTS [a]

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ABSTRACT

Light water reactor (LWR) fuel rod behavior during transient experiments conducted in the Power Burst Facility is reviewed. The experiments examined simulated hypothetical reactivity initiated accidents (RIA) and power-cooling-mismatch (PCM) events. Fuel rod behavior calculated by the Fuel Rod Analysis Program-Transient (FRAP-T) is compared with the test data. Important physical phenomena observed during the tests and not presently incorporated into the FRAP-T code are: (a) fuel swelling in the radial direction due to fission gas effects, (b) UO_2-zircaloy chemical interaction, and (c) loss of UO_2 grain boundary strength and fuel powdering. Additional models needed in FRAP-T to reflect the fuel behavior observed during the two types of transients are cladding thickness variation during an RIA, molten fuel movement and possible cladding-molten fuel thermal interaction during a PCM event, and in the case of breached rods, the effects of hydrogen pickup on cladding embrittlement.

INTRODUCTION

LWR fuel rod behavior during various hypothetical off-normal and accident conditions is being studied in the Power Burst Facility (PBF). These irradiation experiments are part of the Nuclear Regulatory Commissions (NRC) Safety Research Program and emphasize the physical phenomena, failure thresholds, and damage mechanisms which occur during selected design basis accidents. The performance of the Fuel Rod Analysis Program - Transient (FRAP-T) which calculates thermal, mechanical, and chemical interaction behavior of fuel rods during off-normal and accident conditions in an LWR is evaluated based on the test results. The fuel behavior phenomena and the code calculations, as applied to various transients, are compared and assessed here from an experimenter's point of view. The purpose of the review is to identify possible modifications and additions to the models in the current computer code to better reflect the experimental evidence. Two types of accident conditions are reviewed:
(a) reactivity initiated accidents (RIA), and
(b) power-cooling-mismatch (PCM) events.

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Reactivity Initiated Accidents

LWR type fuel rods were subjected to peak fuel enthalpies of 185 to 285 cal/g during the PBF RIA Test Series starting at hot-startup conditions typical of a commercial boiling water reactor. The failure threshold of previously irradiated fuel rods, up to a burnup of 4.6 GWd/t, was identified to be approximately 140 cal/g UO_2. The failure mechanism was brittle rupture or tearing of the cladding due to deformations at high strain rates caused by pellet-cladding mechanical interaction. Departure from nucleate boiling has no influence on this damage mechanism. The failure threshold of previously unirradiated rods was found to be between 225 and 250 cal/g UO_2, with the failure mechanism being brittle fracture of oxidized and deformed cladding. Flow blockage was observed at a fuel enthalpy of 285 cal/g UO_2. This enthalpy is similar to the NRC guideline (280 cal/g UO_2) for loss of coolable geometry.

At high enthalpies, the rods failed with severe cracking and crumbling of fuel and embrittled cladding. Significant wall thickness variations were observed in the cladding of fuel rods subjected to 225 to 285 cal/g UO_2. Regions of cladding thinning and thickening from about 60 to 170%, respectively (Figure 1), of original thicknesses were observed.[1] Such gross wall thickening and thinning was associated with partial or total melting of cladding at enthalpies of 225 cal/g UO_2 and above[2] and was apparently assisted by variations in the local coolant pressure associated with the rapid heating of the coolant during the power burst due to neutron and gamma heating of the coolant. Uniform oxidized layers of oxygen stabilized alpha zircaloy and zirconium oxide, developed around the circumference of both the inside and outside surfaces of the cladding. The oxidized inner layer resulted from the fuel-zircaloy reaction, and the outer layer from the zircaloy-water reaction. The thinned regions of the cladding were often fully oxidized. The oxidation rate was noted to increase significantly for temperatures above 1800 K.

The fuel in the unirradiated rods experienced fuel grain boundary separation and consequent fuel powdering due to the thermal stresses caused during quenching from the film boiling operation.[3] A considerable amount of the fuel powder washed out upon fuel fracture. The rods with burnup of 4.6 GWd/b experienced fission product induced swelling of molten or nearly molten fuel which resulted in cladding rupture and complete blockage of coolant flow shrouds at enthalpies of about 285 cal/g UO_2 as shown in Figure 2.

Fuel temperatures in the RIA tests were generally well calculated by the FRAP-T code;[a] however, the code undercalculated the severity of the mechanical deformation and breakup of the fuel rods at high energy depositions.

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a. FRAP-T, MOD-004, Version 5/2/78, EG&G Idaho, Inc., Configuration Control Number H00372IB.

The important phenomena observed during RIA experiments in the PBF that are not presently modeled in FRAP-T include:

1. Fuel swelling due to fission gas and volatile fission product coalescence, release, and expansion (which strongly influences rod diametral deformation and the potential for coolant flow blockage);

2. Cladding thickness variation and the UO_2-zircaloy chemical interaction and oxidation (which together lower the failure threshold);

3. More realistic zircaloy-water reaction kinetics at higher temperatures up to 2100 K (the oxidation rate at temperatures above 1800 K is believed to be much higher than calculated by the existing Cathcart model[4]);and

4. Loss of UO_2 grain boundary strength (needed to calculate the amount of powdered fuel available for flow blockage).

Power-Cooling-Mismatch Event

The PBF tests simulating PCM events showed that fuel rods can operate in a film boiling condition and incur considerable damage without failure. The severity of the rod damage is primarily dependent on the power level, cladding temperature, and duration of high temperature operation. At temperatures above 920 K, cladding damage included cladding collapse and waisting.[5] For long periods of film boiling with cladding temperatures above 1200 K, oxygen embrittlement was observed from both the cladding-water and cladding-fuel chemical reactions.[6] The PBF in-pile test rod failures support Pawel's failure criteria.[7] However, additional room temperature cladding embrittlement, from a combined effect of hydrogen and oxygen, occurred with cladding hydrogen concentrations as low as 300 ppm in the prior beta material.[8] Hydriding contributed to embrittlement only in rods that had failed prior to or during film boiling and was probably the result of the presence of stagnant steam conditions inside the fuel rod.

Fuel damage included fuel swelling, molten fuel relocation, and grain boundary separation. Modest fuel swelling was observed in previously unirradiated rods due to thermal effects. However, fuel swelling occurred in preirradiated rods to a somewhat larger extent due to the additional effects of retained fission gas. Fuel swelling neither resulted in rod failure nor significantly affected the behavior of rods with burnups ranging up to 17,000 MWd/t during a PCM test. Fuel restructuring occurred within the film boiling zone after the formation of a central void within the high density, molten fuel (Figure 3). Equiaxed grain growth was observed around the region of previously molten fuel, with the grain size decreasing toward the pellet exterior. Fuel grain boundary separation (powdering) during quenching from film boiling operation occurred in both fresh and previously irradiated fuel.

Molten fuel contact with the cladding as a result of molten fuel relocation, with the potential for cladding melting, was observed. However, cladding melting did not occur in the few PBF tests in which molten fuel contacted the cladding.

Peak cladding temperatures calculated by FRAP-T matched the posttest estimated values very well (Figure 4) for the periods of film boiling operation, but the calculated fuel centerline temperatures were somewhat higher. The calculated temperature drops across the cladding at high power levels were much smaller than those observed during film boiling. The calculated rod elongation during film boiling followed the measured values relatively well (although 18% lower) as a function of time for rods that did not balloon. To more completely simulate the behavior of an LWR fuel rod during a PCM event, inclusion of the following phenomena, not currently modeled in FRAP-T, should be considered.

1. Fuel swelling in irradiated rods due to fission gas bubbles trapped at grain boundaries and in molten fuel (needed for calculation of diametral expansion of high burnup fuels during film boiling operation);

2. Central void formation during film boiling (needed to better calculate fuel temperature distributions);

3. Molten fuel movement, fuel freezing, and cladding thermal interaction (necessary to estimate the potential for cladding melting upon molten fuel contact);

4. UO_2-zircaloy chemical interaction and oxygen diffusion (necessary to calculate the degree to which it increases cladding embrittlement);

5. Loss of UO_2 grain boundary strength and fuel powdering (needed to calculate the potential for such phenomena to cause coolant flow blockages); and

6. Effects of hydrogen pickup on cladding embrittlement in the case of defective or breached rods (needed to calculate the failure thresholds for such rods).

On the basis of the observed phenomena, the following modifications to the existing FRAP-T models are also suggested. Pawel's room-temperature cladding embrittlement criteria, or the Chung and Kassner criteria[9] based on oxygen content in the beta zircaloy, should be adopted to properly account for posttest handling fractures. The increased degradation of cladding conductivity with increased oxidation should be modeled to better reflect the observed larger temperature drops across the cladding.[10]

REFERENCES

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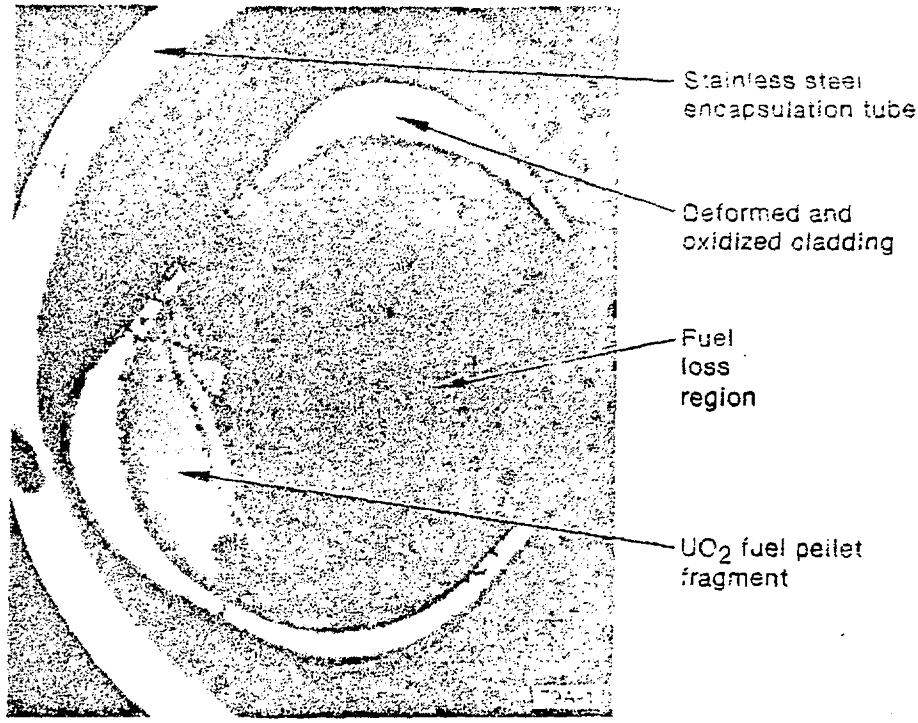

Figure 1. Test RIA-ST-1 fuel rod cladding near the peak flux location (0.35 m from the bottom of the rod).

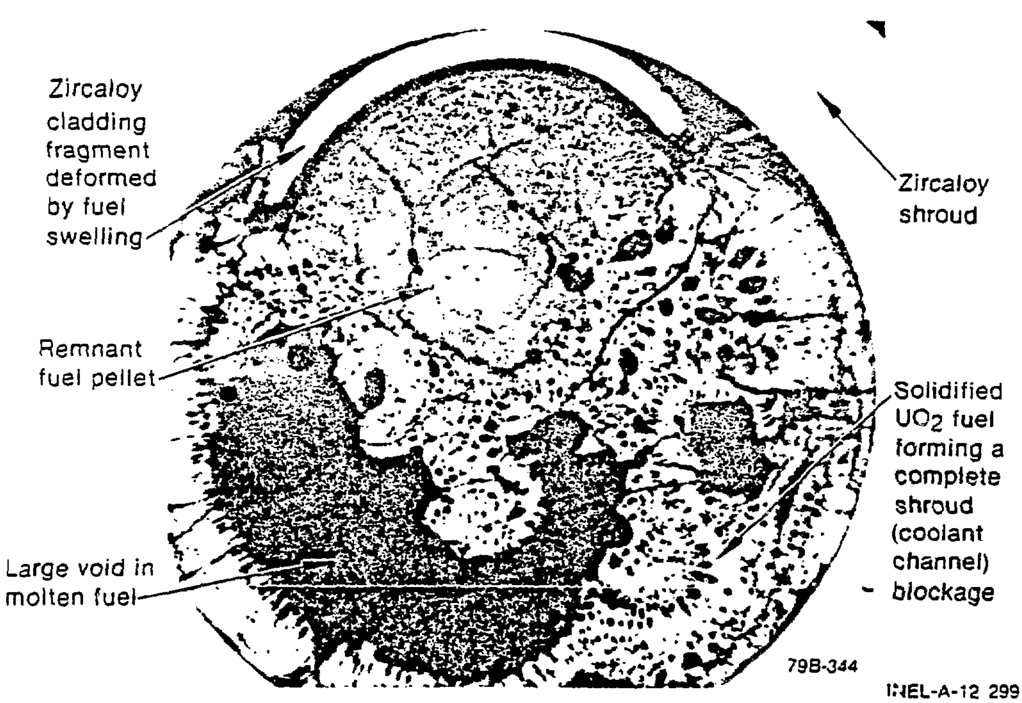

Figure 2. Ground and polished cross section of Rod 801-1 showing fuel, cladding, and shroud near the peak power elevation (Test RIA 1-1).

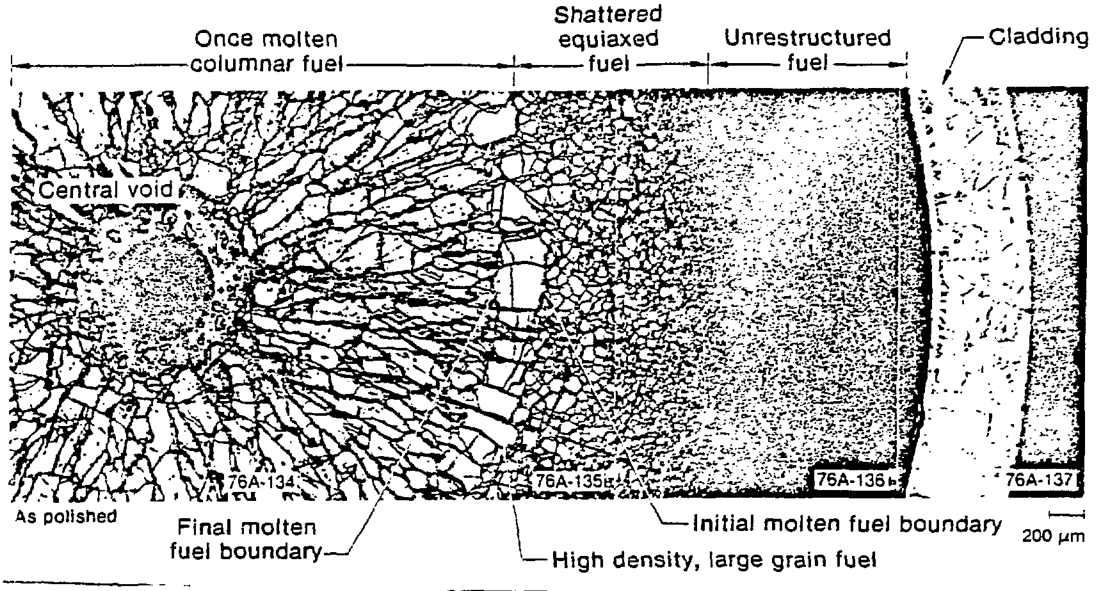

Figure 3. Transverse section showing typical fuel microstructure across a fuel pellet from the film-boiling zone. Sample from the unirradiated fuel Rod IE-001, following the IE scoping Test 1.

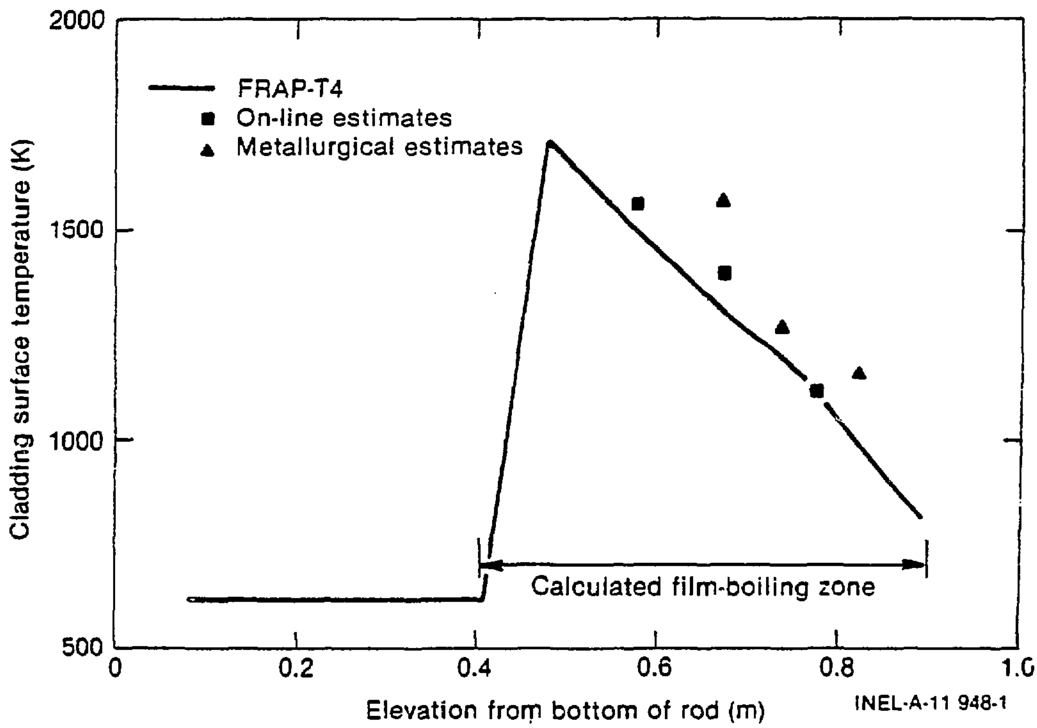

Figure 4. Axial cladding surface temperature profile calculated by FRAP-T4 and measured cladding peak temperatures for the initial film boiling period Test PCM-1.

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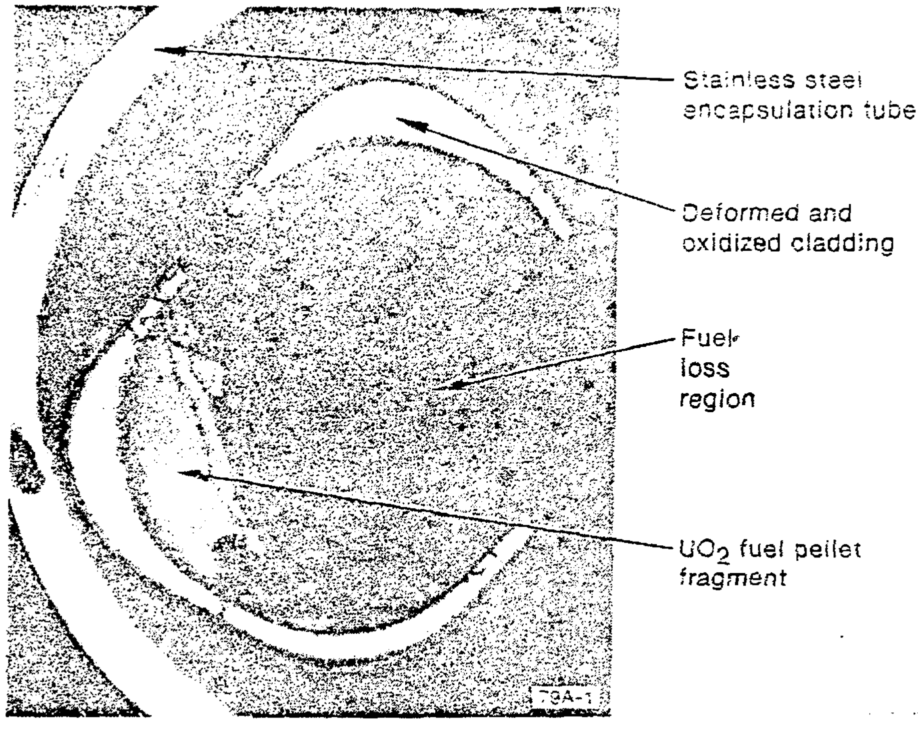

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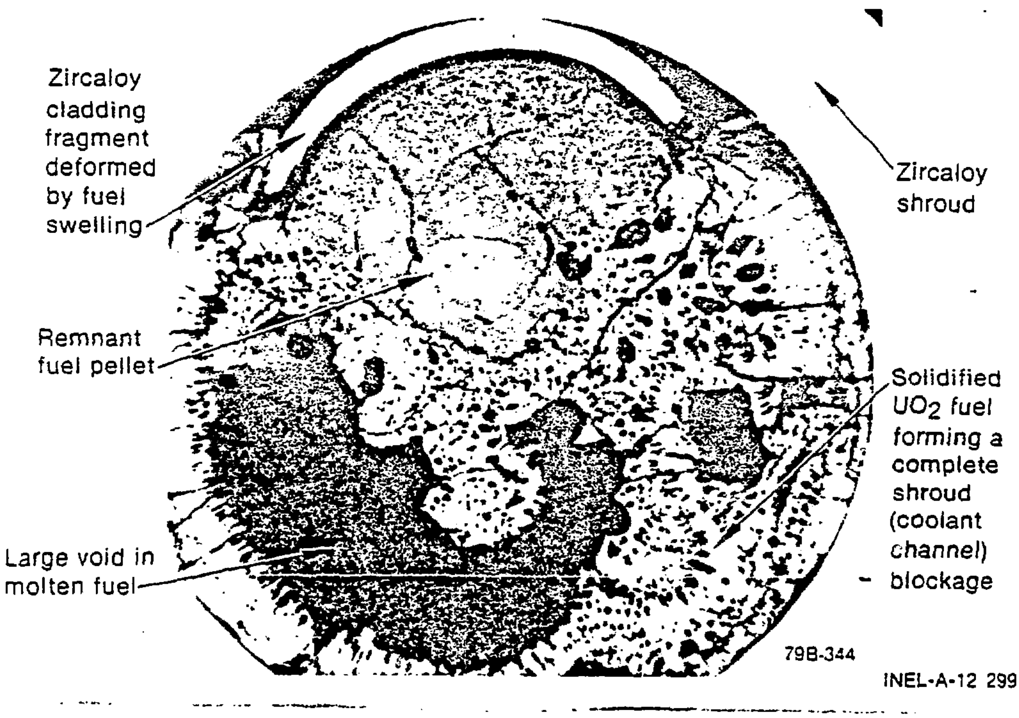

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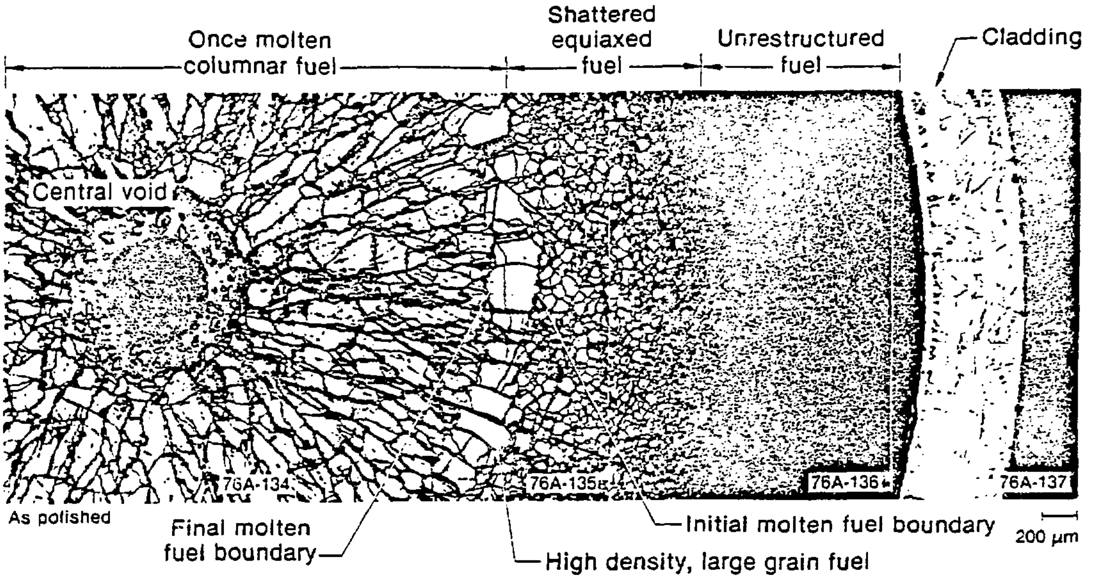

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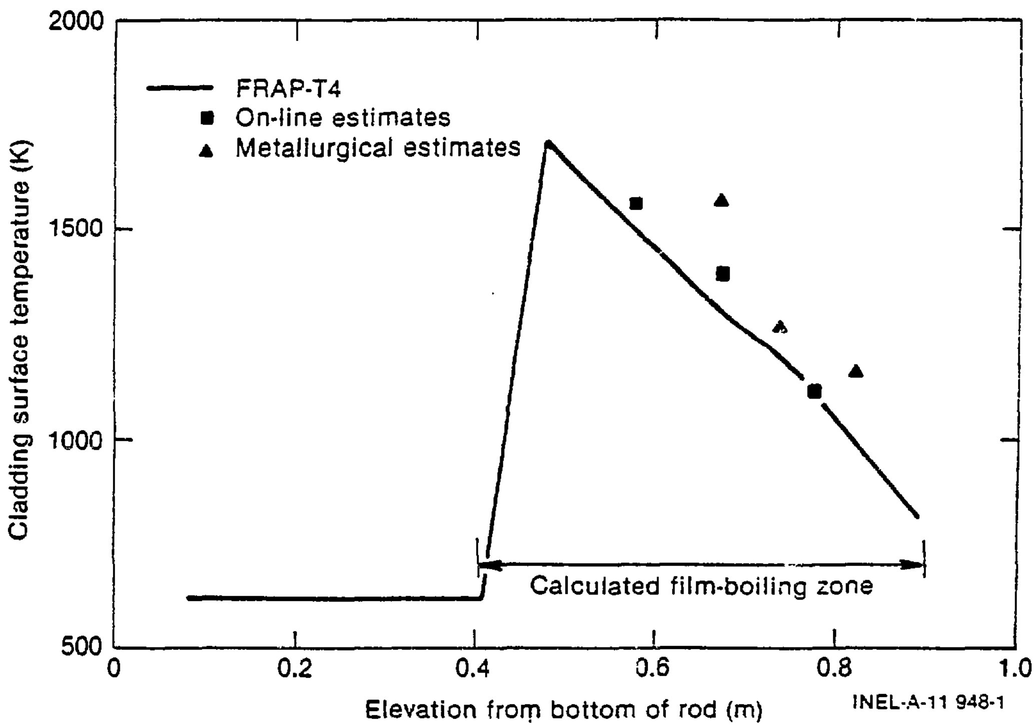

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