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FUEL DAMAGE ESTIMATES FOR THE TMI-2 REACTOR*

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ABSTRACT

A best-estimate postaccident analysis of the TMI-2 reactor system was made with the TRAC code. Based on these results, an assessment of the extent of damage to the TMI-2 reactor core was made; and several alternative event sequences and their consequences were investigated. Our results indicate that although no significant fuel melting occurred, large regions of cladding were severely oxidized and clad melting and relocation took place in the central region of the core, above the midplane elevation. In the alternative event sequences, the timeliness of the initiation of HPI flow in preventing large scale fuel melting is examined.

INTRODUCTION

A best-estimate analysis of the first three hours of the TMI-2 accident has been performed with the TRAC code and is reported in detail in References 1, 2, and 3. The analysis out to that point indicated that while the zircaloy cladding sustained considerable damage (rupture, oxidation, and embrittlement), no melting of fuel occurred (excluding eutectic formation). Beyond that point in the accident sequence, there exists considerable uncertainty in the actual thermal-hydraulic conditions (make-up flow vs letdown flow). In addition, certain modeling limitations in the TRAC code (lack of treatment of noncondensible gases in the vapor field equations and the absence of a core flow blockage model) to raise questions about the quantitative validity of a TRAC calculation beyond that point. Therefore, to make an estimate of possible core damage during the time from 10800 s - 12600 s in the accident (the most critical period for core damage), engineering judgment has been used to supplement the TRAC calculation and extrapolate to the time at which the high-pressure injection (HPI) was reinitiated at full flow conditions. A discussion of the effects of TRAC modeling deficiencies and system make-up flow is also included. Finally, an extension of the TRAC calculation, despite its limitations, to cover two alternative accident sequences is included. These variations are:

1. The pilot-operated-relief-valve (PORV) is not opened from 11520 s - 11820 s,

2. The HPI flow is not initiated at 12000 s.

*Work performed under the auspices of the U. S. Nuclear Regulatory Commission

ESTIMATE OF CORE DAMAGE

At the point where the TRAC calculation of the TMI-2 accident was terminated,[2] the core region immediately above the midplane was approaching a heat-up rate of several degrees per second due to decay heating and the zircaloy cladding reacting with steam, the latter effect predominating. Extensive ballooning and rupture of the cladding had occurred across most of the core radius (with the possible exception of some peripheral fuel assemblies),[3] resulting in a relatively uniform increase in flow resistances across the upper core elevation (about 2.6 - 3.3 m, see Fig. 1) due to the blockages formed. The axial temperature profile had also shifted such that the region immediately above the core midplane was the hot spot. This shift reflected the influence of the axial power profile and the onset of the zircaloy-water reaction, once the core liquid level dropped below the midplane. The occurrence of severe ballooning and rupture of the cladding at a higher elevation, earlier in time (about 9200 s), was due to the boil-down of the core liquid inventory, causing peak core temperatures to occur initially at the highest core elevations, see Fig. 2.

To extrapolate the TRAC calculation beyond 10800 s the fuel-cladding heat-up rates were computed at each level until the opening of the PORV. For the hot-core region (level 5, 2.09 - 2.61 m) this resulted in the melting point of zircaloy, approximately 2100 K, being exceeded. At this juncture the continuation of the TRAC calculation becomes totally unrealistic because the core modeling does not include material motion. Since a significant fraction of the cladding is oxidized, about 50 per cent at this level, the molten zircaloy is prevented from draining by this oxide "crucible." Experimental evidence[4,5] indicates that the presence of an oxidized layer of cladding can contain the molten cladding at temperatures from 2200 - 2500 K. The temperature at which this sheath fails has been experimentally correlated to increase in proportion to the fraction of cladding oxidized. In Fig. 2, which is a plot of the axial core temperature profiles, the slope of the level 5 curve is changed to the adiabatic heat-up rate, about 0.75 K/s,[6] at 2300 K (the levels correspond to the Fig. 1 noding diagram). This is based on the assumption of failure of the oxide sheath, which allows the unoxidized molten zircaloy to drain and removes the oxide reaction heat source. In the subsequent period until the opening of the PORV, the fuel reaches a temperature of about 2500 K at this level. In this same period the levels immediately above (levels 6 and 7, Fig. 1) reach temperatures of about 2000 and 1700 K, respectively. The temperatures in the lower core regions follow saturation values below the water level and approach values estimated for level 6 above the water level (about 1.2 m at 11520 s).

To estimate the effect of the opening of the PORV during the period from 11520 s - 11820 s the heat rejection through the PORV to the containment by escaping steam (about 15 kg/s) has been compared to the decay heating of the core (about 25 MW). These values are of the same order of magnitude. In addition, the opening of the PORV would induce turbulent steam convection in the upper core, as steam was generated at lower elevations. This core boiling rate can be related to the relief valve flow rate by the ratio of enthalpy of the exhausted steam to the latent heat of vaporization of water in the core. Therefore, it was predicted that the core temperature excursion was terminated during the period the relief valve was opened. In Fig. 3 the hottest core region is shown to remain at a constant temperature, approximately 2500 K.

At 11820 s, with the closing of the PORV, the temperature of the core hot zone returns to an adiabatic heat-up rate. The levels above the hot zone are predicted to return to a heat-up rate slightly higher than their adiabatic values. The loss of liquid from the core during the time the PORV was opened is likely to have reduced the steaming rate of the core and result in some steam starvation of the oxidation reaction at these higher elevations. At 12000 s, with the HPI reinitiated to rated flow, the core is quickly quenched to saturation temperatures. The cooling rate during the quenching is esimated at 5 K/s, based on classical film boiling heat transfer rates. When fuel rod temperatures drop below the minimum film boiling temperature (about 800 K), the final quench to saturation temperature is very rapid (about 4 s).

Figure 3 is an illustration of the maximum core damage sustained during the first 3 hours and 30 minutes of the accident. The lower fourth of the core remained intact, since the lowest core water level during this period was approximately 1 m. The region immediately above (about 1 - 1.3 m) underwent some oxidation of the cladding during the period when the water level was the lowest (9500 s - 11000 s). In the region just below the core midplane it is expected that substantial blockages from freezing of UO_2-Zr eutectic and zircaloy cladding and debris from quench induced fragmentation of oxidized cladding and fuel will have formed. This would be consistent with available experimental evidence on meltdown behavior of light-water reactor cores.[4,5] In the region extending 1 m above the core midplane severe fuel damage is predicted to have occurred. Besides the UO_2-Zr eutectic and molten zircaloy which would have drained to lower regions, the zircaloy-oxide and fuel remaining underwent brittle fracture during the quenching period; however, the exact disposition of the core material is difficult to estimate. The region from 3 m - 3.3 m was where severe ballooning and rupture of the cladding occurred earlier in the accident (about 9500 s). This zone is predicted to have been severely oxidized, embrittled, and possibly fragmented upon quenching. The uppermost elevation of the core (3.3 - 3.6 m) and the peripheral assemblies above the water level underwent cladding oxidation.

MODELING AND SYSTEM UNCERTAINITES

The preceding discussion of core damage estimates for the TMI-2 core is regarded as pessimistic and is subject to several uncertainties. Three key modeling and system condition uncertainties have been identified as having a strong bearing on the estimates presented in the preceding sections. These are: (1) loop flow conditions, (2) make-up flow rates, and (3) fuel-cladding blockages and relocation. The TRAC code prediction out to 10800 s indicated a steady "refluxing" of core-generated steam through the loops. In other words, steam from the core was condensed in the steam generators (and in the pressurizer as the system pressurized) and drained to the loop seals. Paradoxically, this flow would be expected to provide some cooling of the upper core; however, it also insured a sufficient supply of steam to drive the cladding oxidation reaction, resulting in faster rising temperatures than in the case of no cooling (see the analysis of limiting oxidation rates in Ref. 6). The evolution of hydrogen from the oxidation reaction introduces a noncondensible gas component in the steam environment in the loops. This noncondensible is expected to collect in the upper elevations of the system, particularly in the "candy-cane" of the hot legs, impeding the refluxing of core-generated steam, hence resulting in partial steam starvation of the oxidation reaction and lower temperatures. Inclusion of a noncondensible gas component in the vapor field equations is planned for a future TRAC code version to better address this issue.

The net make-up flow to the system is an important variable. Based on an EPRI communication,[7] it appears that after the block valve on the pressurizer relief line was shut at 8280 s the letdown flow was reduced. A net make-up flow (about 50 gpm vs an assumed value of zero) was then available to the primary system. However, this flow rate is quite small (comparable to a reflood rate of less than 1 mm/s) and, for the heat generation rates in the core, is not sufficient to significantly alter the core thermal transient. The importance of marginal make-up flow rates is in determining the liquid level in the core, which limits the extent of core damage.

Blockage formation and the mechanics of material relocation in light-water reactor cores are phenomena that presently are little understood. In the previously cited references to relevant experiments, results indicate that when molten zircaloy is contained in contact with the uranium dioxide fuel pellets, the fuel can be partially dissolved (20 - 50 per cent[5]) by formation of a eutectic alloy with the molten cladding. Since this mechanism takes place at the melting point of zircaloy, it means that fuel motion is possible at almost 1000 K below its melting point. This phenomenon is estimated to have occurred in TMI-2, as the calculated conditions coincide with conditions of these experiments. Figure 3 shows that significant fuel-cladding blockages formed by this phenomenon may be found slightly below the core midplane. This is the most difficult part of the accident sequence to predict as the results are dependent on rate processes.

ALTERNATIVE EVENT SEQUENCES

Two alternative event sequences were examined: (1) the PORV is not opened at 11520 s and (2) HPI flow is not initiated at 12000 s. If the PORV is not opened at 11520 s the fuel rod temperature is estimated to continue rising at the adiabatic rate until HPI initiation at 12000 s. The peak temperature attained is about 2800 K, see Fig. 2. While no fuel melting is predicted for an average rod, some localized melting might occur. If the HPI flow was not reinitiated at 12000 s, the temperature is estimated to continue rising at the adiabatic rate. The melting point of fuel (about 3000 K) would be reached at 12500 s. At the decay power level of the core it would take another 1000 s, approximately, to supply the latent heat of fusion to completely melt the material in the hot region. While outside the scope of this paper, it should be mentioned that the presence of molten core material does not imply catastrophic failure of the reactor vessel, particularly if water is present in the lower plenum of the vessel, as was the case at TMI-2.

CONCLUSION

An estimate of maximum damage to the TMI-2 core was made based on a TRAC code calculation of the first three hours of the accident, supplemented by extrapolation to the time of reinitiation of HPI flow. These results indicate, that although core temperatures remained below the melting point of uranium dioxide, severe core damage was sustained and some fuel-cladding was relocated due to eutectic formation and quench induced fragmentation. In the alternative event sequences investigated it was estimated that failure to reinitiate full HPI flow at 12000 s would have resulted in the onset of fuel melting within approximately 1000 s. Results of this study indicate there is a need for further light-water reactor core meltdown experiments and mechanistic analysis tools to evaluate these categories of accidents.

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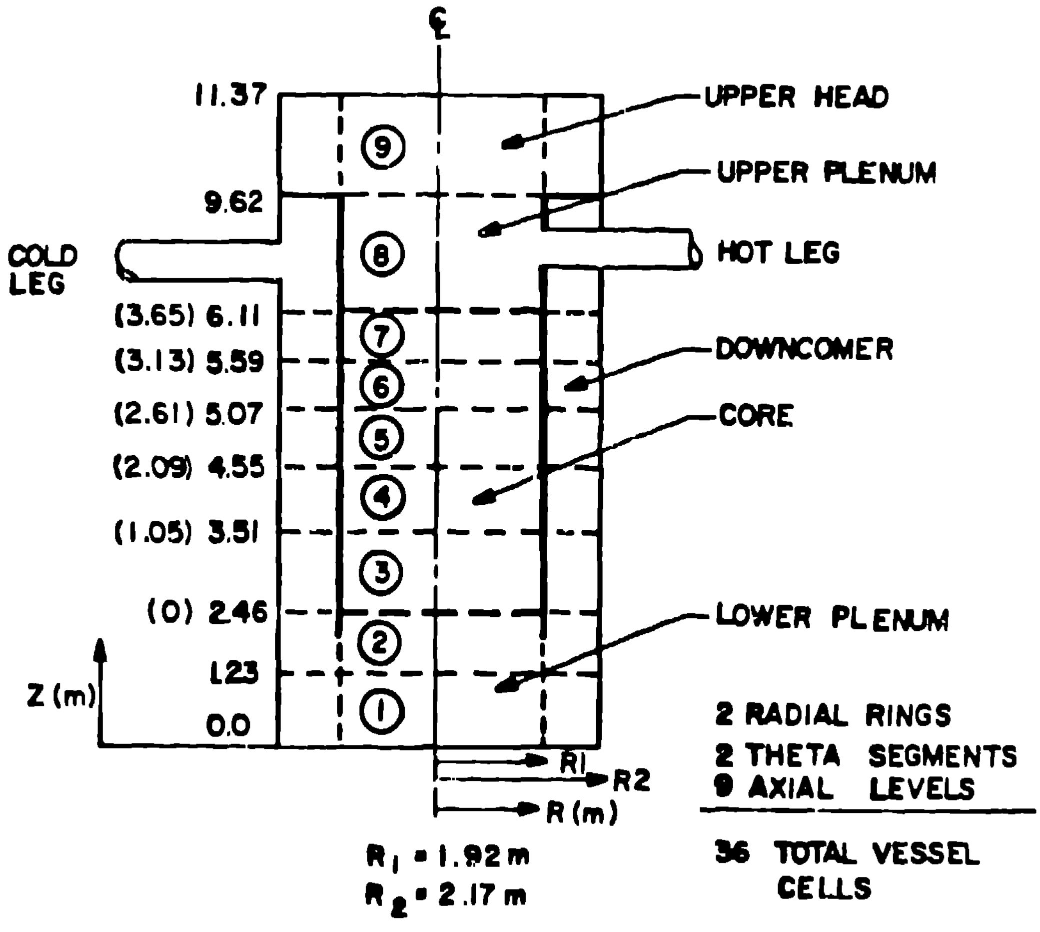

Fig. 1 - TRAC noding of TMI-2 reactor vessel.

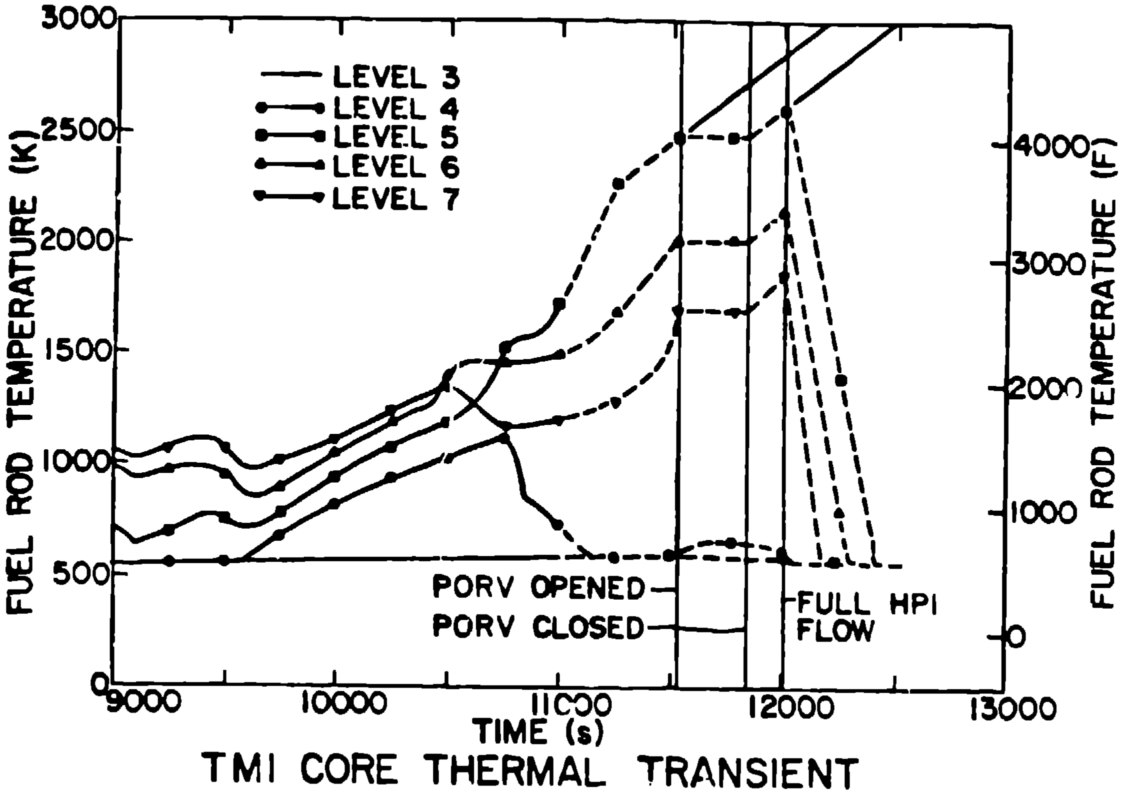

Fig. 2 - Estimate of TMI-2 core axial temperature profile.

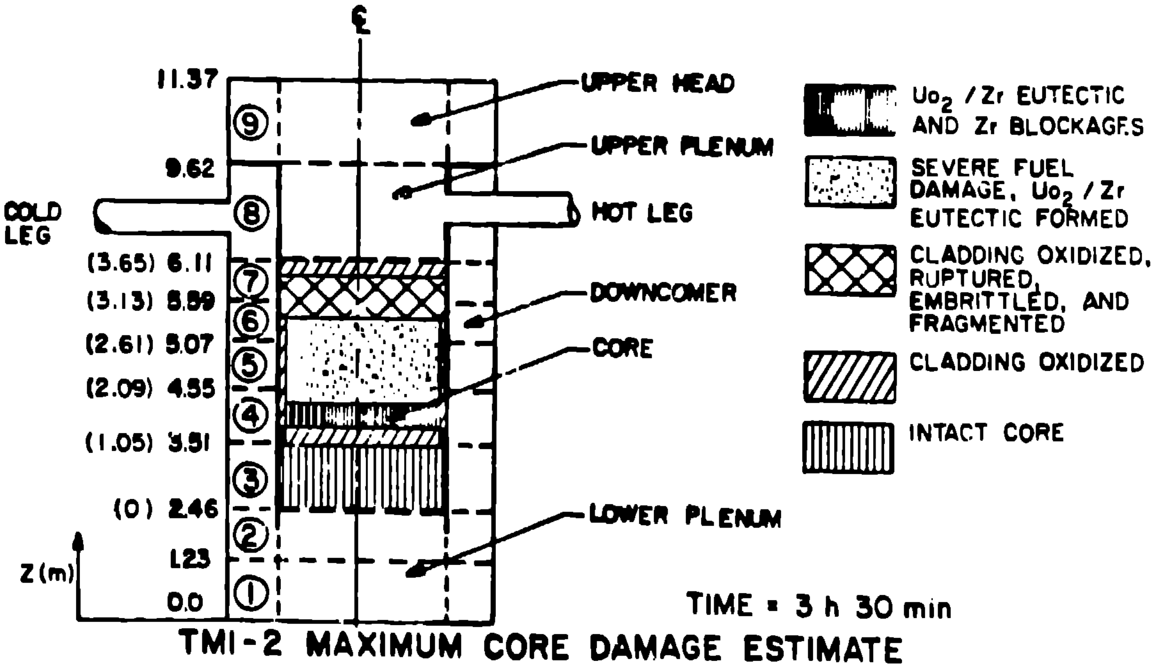

Fig. 3 - Estimate of TMI-2 maximum core damage.