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AUTHOR(S): P. K. Mast
T. R. Wehner
J. R. Ireland

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los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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ANALYSIS OF EARLY CORE DAMAGE AT THREE MILE ISLAND

by

P. K. Mast

T. R. Wehner

J. R. Ireland*

Energy Division

Los Alamos Scientific Laboratory

University of California

Los Alamos, NM 87545 USA

INTRODUCTION

Los Alamos Scientific Laboratory reactor safety groups have performed a detailed mechanistic analysis of a best-estimate composite sequence of events[1,2] for the March 28, 1979 accident at the Three Mile Island - unit 2 (TMI-2) nuclear reactor. This paper deals with one aspect of that study; the core response to the calculated thermal hydraulic transient, including an estimate of likely core damage, for the first 3.5 h of the accident, the time including the first core uncovering. The specific phenomena considered include

(1) cladding ballooning prior to rupture;

(2) cladding rupture;

(3) cladding oxidation including the effects of hydrogen evolution; cladding swelling, and cladding embrittlement;

(4) possible cladding and fuel fragmentation; and

(5) possible cladding and fuel melting.

The core response/damage calculations for the first 11 050 s (3:04 h) of the accident were based on the primary-system thermal-hydraulic response[3] obtained using the Transient Reactor Analysis Code (TRAC).[4] However,

*Work performed under the auspices of the US Nuclear Regulatory Commission and the US Department of Energy.

because TRAC was developed primarily to analyze shorter-time-scale loss-of-coolant accidents, certain limitations in the code could impact this analysis. These limitations include no allowance for deformed channel geometry in the core thermal-hydraulic analysis, and the omission of the effects of noncondensible gases (hydrogen, for example) on the system pressure and steam condensation rates. Despite these limitations, the TRAC results agreed very well with measured system parameters during the first 3 h.

Calculations of core response to 3.5 h, the time of the first reflood, were based on extrapolations[5] of these TRAC results, taking into account possible molten cladding relocation and hence, oxidation heat source relocation. The pin temperatures and system pressure used for the core response/damage calculations are shown in Fig. 1 and Fig. 2, respectively. The TRAC-calculated results are represented as solid lines and the extrapolated results as dashed lines.

CLADDING BALLOONING AND RUPTURE

TMI-2 instrumentation data[1] and the TRAC analysis[3] both indicate excessive pin temperatures (Fig. 1) and below-normal operating system pressure (Fig. 2) during the accident. For the prepressurized TMI-2 fuel pins, these conditions are likely to have led to cladding ballooning and rupture as the first manifestation of core damage.

The time of fuel pin rupture during the TMI-2 accident was estimated from the calculated cladding hoop stress and the TRAC-calculated cladding temperature. Two independent failure criteria were used; the first was based on the failure-stress correlation given in MATPRO-11,[6] and the other on a linear life-fraction-rule criterion[7] derived from an analysis of Chalk River Zircaloy stress-rupture data.[8]

The thin-cylindrical-shell stress equations were used to determine the cladding hoop stress as a function of the pin gas pressure (calculated using the ideal gas law) and the system pressure (obtained from TRAC analysis[3]). Because of uncertainties in the initial (steady-state) gas pressure and in the pin internal void volume during the transient, the analysis was performed for initial (room temperature) pressures ranging from 2.5 MPa to 4.2 MPa (3.0 MPa is the room-temperature fill-gas pressure).[9]

The results of these analyses are shown in Table I. Failure is calculated to occur at a fractional axial height of 0.85 to 1.00 at about 9 500 s (2:40 h). The uncertainty in the initial pressure leads to an uncertainty of ± 750 s (0:13 h) in the calculated failure time. Because of the coarse core nodalization used in the TRAC analysis, the radial variation in cladding failure time was calculated to be small. The calculated failure time is consistent with the observed sharp increase in radiation-monitor readings in the containment-building dome at 9 300 s (2:35 h).[2] This excellent agreement reinforces confidence in the TRAC calculations to that point.

The strain at failure was estimated using the failure-strain correlation from MATPRO-11.[10] For a failure temperature of 1 000 K, this correlation predicts a total (uniform plus local) ballooning strain of 80%. While this may be an overestimate, only a 30% strain is required to cause rod-to-rod contact in the TMI-2 assembly which has a 1.3 square-pitch-to-diameter ratio.

CLADDING OXIDATION: HYDROGEN EVOLUTION AND SWELLING

Oxidation of the Zircaloy cladding from the metal-steam reaction was calculated using the Cathcart isothermal parabolic rate equations from MATPRO-11.[11] Because of prolonged high cladding temperatures, these rate equations must be extrapolated beyond the time and temperature range of the available data.

Analysis of the axially-dependent TRAC-calculated cladding temperatures indicates that substantial oxidation occurred at a fractional axial height of 0.6 to 0.9. The oxidation should not have been severely inhibited by steam depletion as indicated by the TRAC-calculated steam velocities. At the hottest axial location, the outer third of the cladding thickness is calculated to oxidize before the onset of cladding melting. This amount of oxidation would generate 130 kg of hydrogen (core-wide). For a typical TRAC-calculated upper-plenum temperature of 1 200 K and pressure of 10 MPa, this mass of hydrogen would occupy about 65 m^3, which is equivalent to the volume of the vessel upper head plus part of the upper plenum. High thermocouple readings between 4 and 5 h into the accident indicate possible continued hydrogen generation.

Upon oxidation, Zircaloy undergoes a 50% volumetric expansion. Because the inner part of the cladding was unoxidized and hence, unaffected by such swelling, the cladding outside diameter increase is only 2%. Thus, the decrease in coolant-channel cross-sectional flow area caused by oxidation was insignificant, and the fuel-bundle coolability was only affected by cladding ballooning.

POSSIBLE CLADDING AND FUEL DISRUPTION

Reflood by the high-pressure injection system at 12 000 s (3:20 h), following prolonged elevated core temperatures, may have induced cladding and fuel fragmentation. The likelihood of unoxidized cladding fragmentation was investigated by comparing the calculated cladding thermal stress with a temperature-dependent failure stress.[6] The maximum thermal-shock temperature drop across the cladding, estimated using Kantorovich profiles,[12] was 120 K. Using this value, the maximum circumferential stress was calculated to be 7.2 MPa, well below the failure stress of unoxidized Zircaloy at temperatures below 1 500 K.[5] Thus, it is unlikely that fragmentation occurred in the unoxidized cladding.

The Zircaloy oxidation reaction, however, causes the cladding to become very brittle. Experiments[13] indicate that the likelihood of thermal-stress-induced fragmentation increases following high-temperature oxidation. Comparison of these experimental results with the TRAC-calculated cladding thermal conditions indicates that the cladding over a 0.5 m length of the TMI-2 core may have embrittled and failed. Thereafter, the bared hot fuel, even more brittle than the cladding, probably fragmented also.

The TRAC-calculated cladding temperatures (Fig. 1) also indicate that cladding, but not fuel, melting occurred. This calculated severe core disruption implies a significant effect on the local coolability of the core, which is consistent with the observed large core-wide variation of thermocouple readings at the core outlet at 4 to 5 h into the accident.[1]

CONCLUSION

These analyses indicate that extensive core damage occurred during the first uncovering of the core during the TMI-2 accident. Calculations based on temperatures extrapolated beyond the onset of core disruption are somewhat speculative. However, the good agreement between the calculated core response and available instrumentation data gives confidence in this detailed mechanistic analysis.

TABLE I

VARIATION IN PIN FAILURE TIME WITH INITIAL ROD PRESSURE

Initial Rod Pressure (MPa)	Failure Time: Peak Power Rod (s) (h)	Failure Time: Average Power Rod (s) (h)
2.5	9 237 (2:34)	10 230 (2:50)
3.0	8 840 (2:27)	9 195 (2:33)
3.5	8 679 (2:25)	8 872 (2:28)
4.0	8 614 (2:24)	8 743 (2:26)
4.2	8 582 (2:23)	8 711 (2:25)

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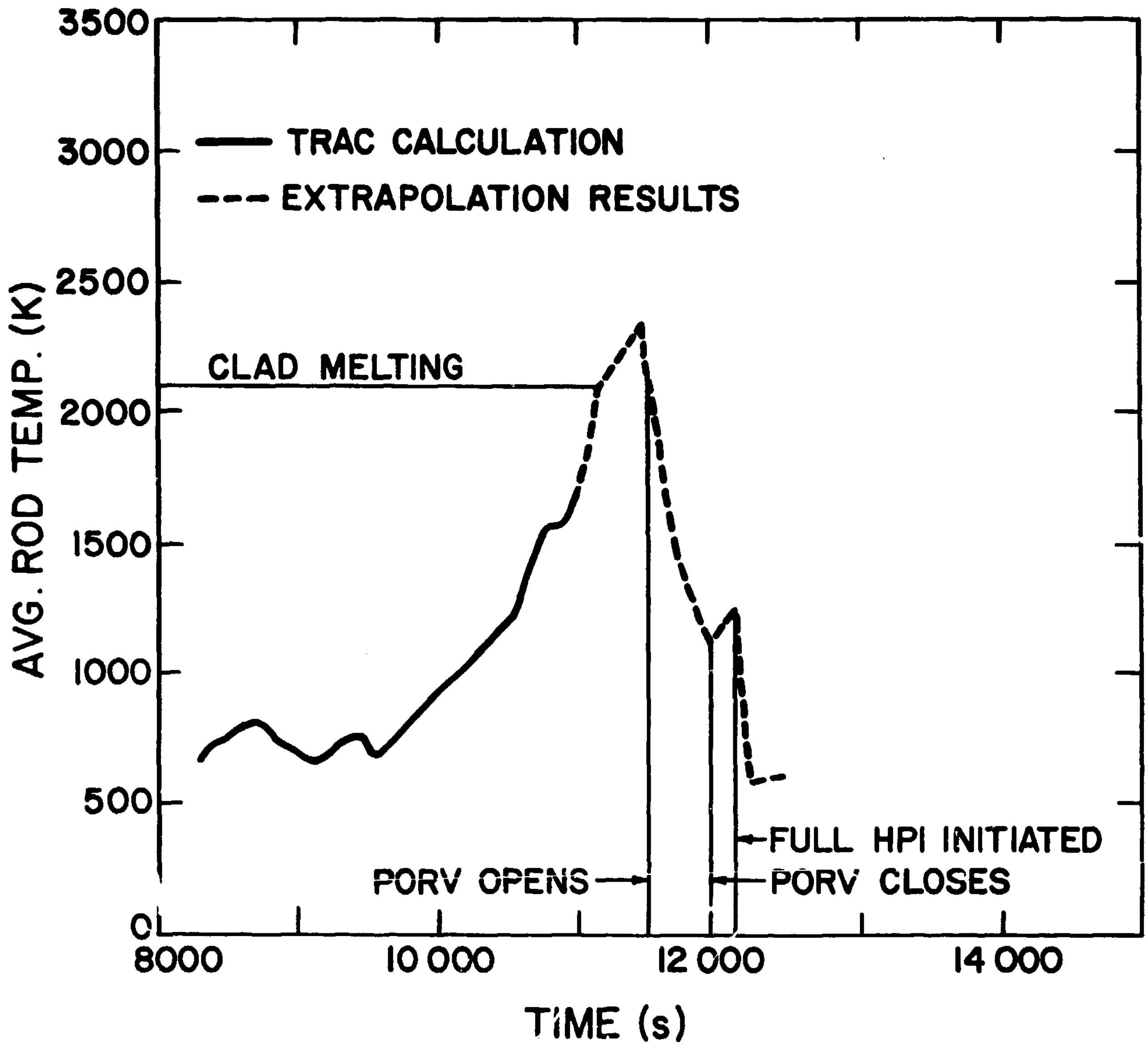
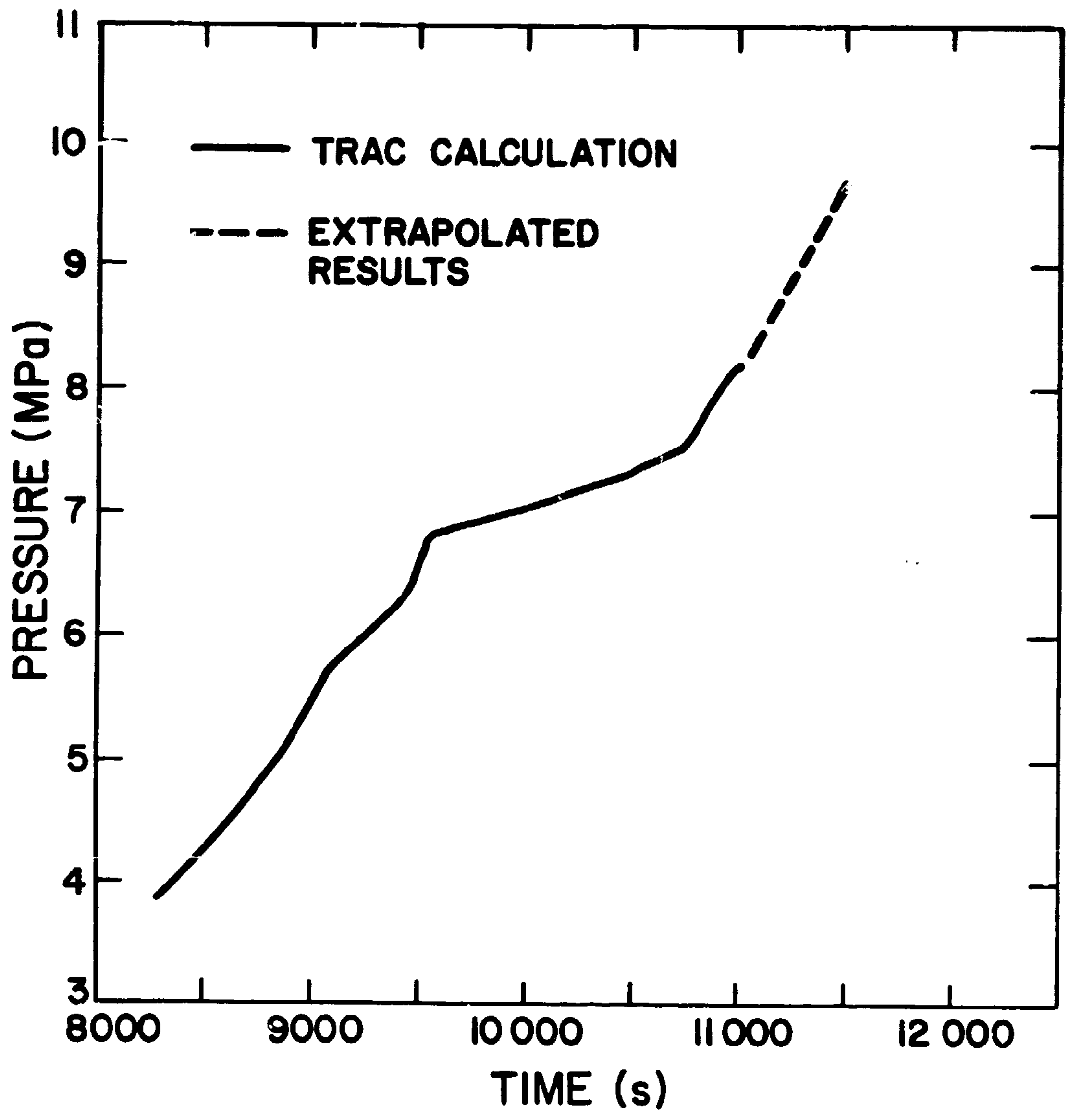
FIGURE CAPTIONS

1. Cladding temperaztures used in core/response damage calculations.

2. System pressure used in core/response damage calculations.



TRAC CALCULATION
EXTRAPOLATION RESULTS
CLAD MELTING
AVG. ROD TEMP. (K)
3500
3000
2500
2000
1500
1000
500
0
8000
10 000
12 000
14 000
TIME (s)
PORV OPENS
FULL HPI INITIATED
PORV CLOSES



TRAC CALCULATION
EXTRAPOLATED RESULTS
PRESSURE (MPa)
11
10
9
8
7
6
5
4
3
8000
9000
10 000
11 000
12 000
TIME (s)