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AN INTEGRATED TRAC/MELPROG ANALYSIS OF CORE DAMAGE FROM A SEVERE FEEDWATER TRANSIENT IN THE OCONEE-1 PWR*

by

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SUMMARY A postulated complete loss-of-feedwater event in the Oconee-1 pressurized water reactor has been analyzed. With an initial version of the linked TRAC and MELPROG codes, we have modeled the loss-of-feedwater event from initiation to the time of complete disruption of the core, which was calculated to occur by 6800 s. The highest structure temperatures outside the vessel are on the flow path from the vessel to the pressurizer relief valve. Temperatures in excess of 1200 K could result in failure and depressurization of the primary system before vessel failure.

I. INTRODUCTION

Realistic estimates of radioactive releases in the event of a severe accident require the use of a mechanistic calculational tool that models the entire primary system of a pressurized water reactor (PWR). This tool must begin with an accident initiator and determine the entire accident sequence through fuel failure and release of radioactivity from the primary system. The TRAC/MELPROG code under joint development by Los Alamos and Sandia National Laboratories will provide such a capability. Although the current version of TRAC/MELPROG is limited by one-dimensional (1-D) fluids modeling and the lack of a fission product release, transport, and deposition model, it provides useful information about a degraded-core accident up to disruption of the core region. In this paper, we examine a calculated accident sequence involving a loss of feedwater with failure of emergency core cooling (the TMLB′ sequence) for Oconee-1. The timing and course of major in-core events such as fuel-rod heatup, cladding oxidation and melting, hydrogen production and transport, fuel disruption, debris region formation and relocation will be described. The calculation included the entire primary system so that primary-system structure and remaining water inventory would be available as a heat sink. Information about primary-system heatup that might lead to early failure and depressurization will also be discussed.

II. THE TRAC/MELPROG CODE

The initial version of the TRAC/MELPROG code has been developed by linking TRAC-PF1/MOD1 (Ref. 1), hereafter referred to as TRAC, developed by Los Alamos with the MELPROG/MOD0 (Ref. 2) code developed at Sandia and Los Alamos National Laboratories. MELPROG is coupled to TRAC to provide an integrated analysis of the behavior of core, vessel, and reactor coolant systems during severe accidents. MELPROG treats core degradation

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and loss of geometry, debris formation, core melting, attack on supporting structures, slumping, melt-water interactions, and vessel failure. TRAC models the remainder of the primary and secondary systems including trip and control actions.

The MELPROG code has been designed to predict the course of a severe accident sequence from the initiation of core damage to the stage at which the vessel fails and core materials are discharged to the containment. The principal processes to be modeled by either the current or subsequent versions of MELPROG include:

1. Vessel thermal-hydraulics and core heatup;
2. Liquefaction and melting of reactor core materials;
3. Solidification and freezing of fuel, cladding, control, and structural materials;
4. Fragmentation and relocation of liquefied and solidified materials;
5. Stressing and ablation of major structural features including core supports and pressure vessel;
6. Energy-generation processes, including decay heating and chemical oxidation;
7. Energy-transfer and mass-transport processes, including conductive, convective, and radiative heat transfer, steam explosions, and fluid flow; and
8. Associated thermochemical processes which affect the release, transport, and deposition of fission products.

The TRAC and MELPROG codes are linked together to provide an implicit numerical interface between the two codes. However, until TRAC is further generalized for core-damage problems, only liquid coolant and the vapor field can be transported through this link. Corium materials passed through the interface to TRAC from the top of the core are lost from the problem. Although aerosols and fission product vapors are transported with the vapor field, the important transport and deposition processes are currently not modeled in TRAC. Future development work planned for TRAC will remove these limitations.

III. PLANT MODEL

Oconee-1 is a Babcock and Wilcox lowered-loop PWR; the primary includes a vessel, two steam generators (SGs), two hot legs, and four cold legs. For this first application of TRAC/MELPROG, the two hot and four cold legs have been combined into a single-loop representation of the primary cooling system. A noding diagram is presented in Fig. XXIII.5-1. Also modeled were the reactor coolant pumps (RCPs), loop seals, surge line, and pressurizer with relief valves. All thermal-hydraulic (flow) elements, including the vessel, were modeled in 1-D. MELPROG/MOD0 has the capability to model the vessel's structural elements in two dimensions (2-D); this capability was used even though only a 1-D flow representation through the vessel was available. A representation of the vessel structural model is shown in Fig. XXIII.5-2. Note that the bottom of this model begins in the lower plenum below the flow distributor plate. The bottom of the vessel is not modeled; thus, this model cannot be used to calculate vessel failure. This approach was necessitated by the current limitation that the MELPROG/MOD0 core be a 1-D vertical component. In other respects, the vessel structural model is quite detailed. Structural elements modeled include the flow distributor plates, lower grid plate, lower support plate, upper tie plate, core barrel, baffle plate, formers, plenum cylinder, core support shield, and core.

IV. DISCUSSION AND RESULTS

We now proceed to review the results obtained during this first application of the linked TRAC/MELPROG code. The "front end" (TRAC-stand alone calculation) of a loss-of-feedwater transient in the Oconee-1 plant has been previously studied in detail (Refs. 3-4). After the feedwater was lost, the low-inventory, once-through SGs quickly boiled dry. With loss of secondary heat sink, the primary began to heat up and pressurize as can be seen in Fig. XXIII.5-3. The power-operated relief valve (PORV) first opened at 420 s. The core-exit temperature reached saturation at 1800 s, and boiling began in the core. The voiding history of the core is given in Fig. XXIII.5-4. Core voiding proceeded rapidly when the average liquid temperature reached saturation at approximately 3100 s. A low core water level was maintained until approximately 5000 s when draining of the SGs slowed and then ceased at 6000 s. By 3100 s, there was insufficient liquid in the core to maintain the cladding temperatures near the saturation, and cladding heatup began. The cladding temperatures for the top five levels of the core are given in Fig. XXIII.5-5. Cladding oxidation began at 4190 s when the cladding temperature exceeded 1273 K. The control-rod absorber materials are clad in stainless steel which has a melting point of 1700 K; control rods are assumed to be in equilibrium with the surrounding gas, which reached 1700 K in level 5 at 4590 s. The control rods at that level thus were assumed to fail at 4590 s. By 4600 s, the cladding temperature in level five exceeded 1850 K and the cladding oxidation rate increased rapidly. The cladding at this level began to melt by 4616 s and complete cladding melting at level five was predicted to occur by 4648 and fuel-rod breakup began. Radial structural elements (baffle plate and formers) near the top of the core began to fail by melting at 4873 s. When fuel rods disintegrated, the material entered the corium field and moved downward until it froze (if molten) or jammed (if solid), forming a debris region. The hot debris contributed to the heating of intact fuel rods, which in turn resulted in further failures. Thus, the core disruption and relocation that began near the top of the core proceeded to lower levels as the transient progressed, thereby increasing the height of the debris regions. A summary of the Oconee-1 TMLB′ event sequence is presented in Table XXIII.5-I. As can be seen in the table, all but level 1 of the core had failed by 6800 s. The calculation was ended at 6900 s because of inconsistancies and numerical difficulties that arose when additional structural failures were predicted. These numerical difficulties are expected to be corrected in the near future allowing the calculation to proceed through failure of lower core support structures.

The mass of hydrogen flowing from the core and out of the primary system is given in Fig. XXIII.5-6. The remainder of the hydrogen is within the primary system between the top of the core and the top of the hot legs. In spite of high temperature vapor flowing from the core to the PORV, the loop seals in the primary piping had sufficient water in them to block steam-hydrogen flow around the loops. The major flow path for hot gases from the core was thus through the hot leg, surge line and out the pressurizer. Pipes and structures along this path were calculated to have temperatures in excess of 1200 K; thus, failures that would lead to depressurization prior to vessel failure are possible. Although the vapor exiting the core was greater than 2000 K, the pump walls and steam generator tubes were still at the saturation temperature (625 K) corresponding to the PORV set-point pressure. High temperature failure of the pump seals and steam generator tubes would therefore not be expected up to this time in the accident.

The state of the primary system at 6900 s is as follows. The liquid content of the primary was distributed among three locations, physically separated from each other by regions filled with steam and hydrogen. First, the vessel lower plenum, and lower downcomer were filled with water. The core was vapor filled at the end of the calculation. Second, the primary side of the SG, the loop seal and pump suction contained water. However, the level of the water was below the cold-leg attachment to the RCP. Third, there was a small amount of water in the bottom of the pressurizer; this water did not drain back into the hot leg through the surge line because of countercurrent steam, and in the later stages of the transient, hydrogen flow passing through the pressurizer and out the PORV. For the computational model, the core was divided into six equal-height levels and three equal-area radial rings. The fuel pins in levels two through six and all radial rings disintegrated following complete melting of the zirconium cladding and failure of the zirconium oxide layer in the cladding. The debris resulting from pin disintegration was concentrated in levels two through four; a smaller fraction of the rubble lodged in the fuel-pin stubs remaining in core level one. The debris region consisted of a refrozen layer or crust of U-Zr-O holding up a mixture of partially molten fuel pin rubble with peak temperatures above 2800 K. Several of the structures at the outer periphery of the core had failed (levels 4-6). Specifically, the baffle plate and formers within these levels had failed by complete melting. Thus, we have obtained a first-order view into the dimensionality of damage within the vessel.

We note that the phenomena predicted with 1-D flow models do not fully describe the expected phenomena in the core region. Specifically, it is anticipated that natural-circulation phenomena will influence the course of the transient. We have completed preliminary calculations with an early MELPROG/MOD1 version that includes a 2-D flow analysis capability (Ref. 5). A strong natural-circulation flow is predicted in the upper plenum. A weaker, but still significant, natural-circulation flow penetrates into the core region, retards the rate of temperature increases in the core, and acts to delay cladding melting.

V. CONCLUSIONS

An integrated TRAC/MELPROG calculation of a TMLB′ sequence in Oconee-1 has been performed. This transient was calculated to 6900 s; at this time fuel rods throughout the core had failed. Radial structural elements had also begun to fail. Debris regions had formed in the lower areas of the core above the lower support plate.

The code version used for this analysis is limited because it is capable of performing only 1-D fluid-flow calculations. We believe that at least a 2-D flow model of the vessel is required if we are to accurately represent the phenomena occurring in the vessel after the top of the core is uncovered. A 2-D flow analysis capability is under development and will be available in 1986 when MELPROG/MOD1 is released.

REFERENCES

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3. J. F. Dearing, R. J. Henninger, and B. Nassersharif, "Dominant Accident Sequences in Oconee-1 Pressurized Water Reactor," Los Alamos National Laboratory report LA-103510-MS (NUREG/CR-4140) (April 1985).

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TABLE XXIII.5-I
OCONEE 1 TMLB′ SEQUENCE

Time (s)	Event
0	Loss-of-offsite power, total loss-of-feedwater
420	PORV first opens on high primary pressure (17.0 MPa)
1800	Boiling begins in core
3100	Cladding temperature greater than saturation temperature
4190	Cladding oxidation begins (temperature >1273 K)
4590	Control rods begin to fail (gas temperature >1700 K)
4600	Accelerated oxidation of cladding (temperature >1850 K)
4616	Cladding at hottest core level (level 5) begins to melt (temperature >2100 K)
4640	Level 5 cladding completely molten
4649	Level 5 fuel rods begin to fail (average cladding temperature >2200 K)
4727	Level 4 fuel rods begin to fail
4785	Level 6 fuel rods begin to fail
4873	Level 5 baffle plate and former fail by melting
5661	Level 3 fuel rods begin to fail
6200	Core vapor filled
6800	Level [illegible] fuel rods begin to fail
6900	End of calculation

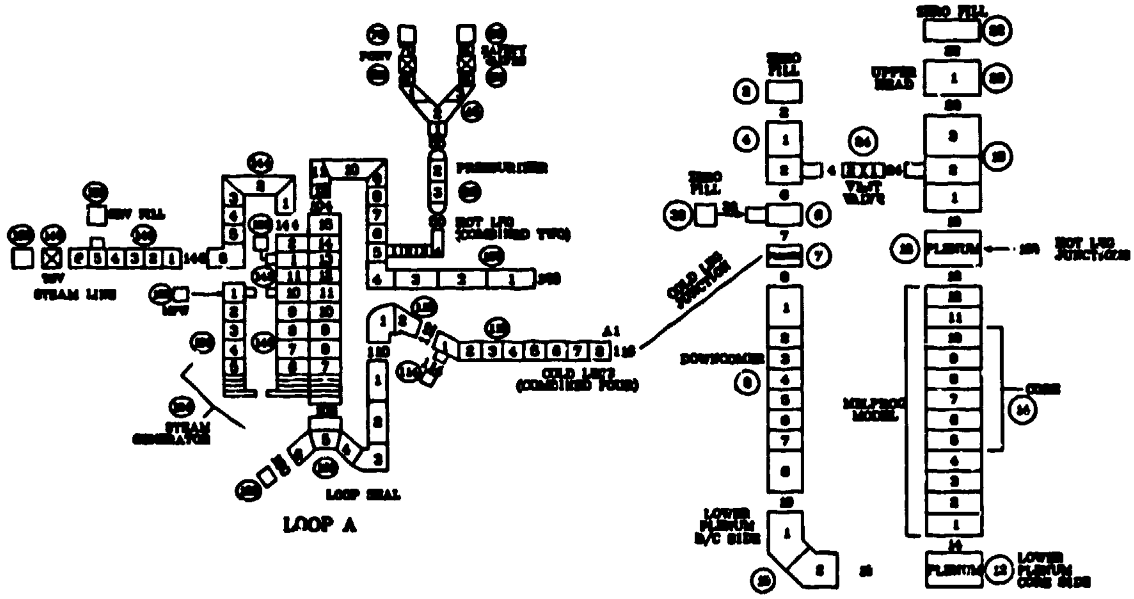

Fig. XXIII.5-1.
Oconee-1 noding diagram.

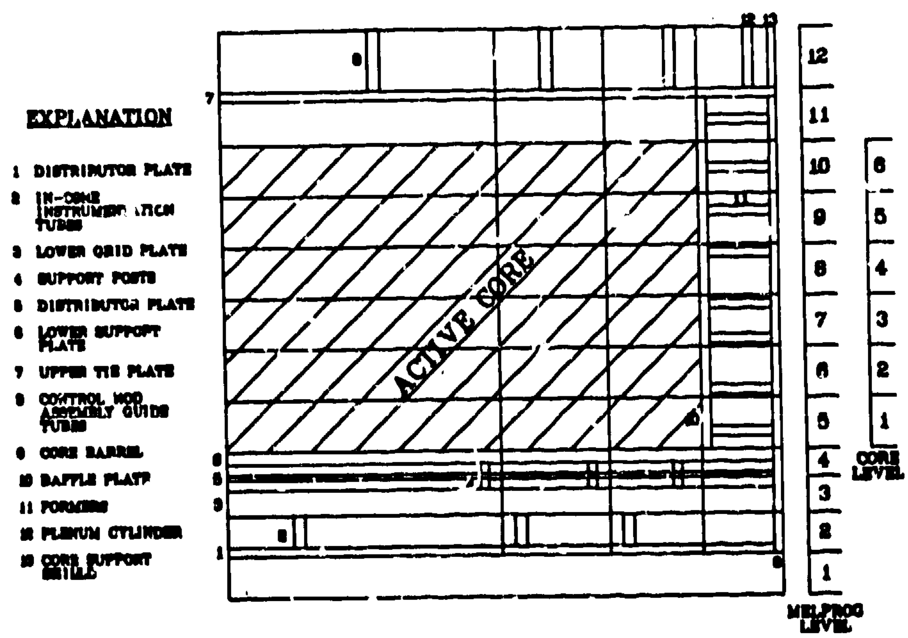

Fig. XXIII.5-2.
Vessel structural model.

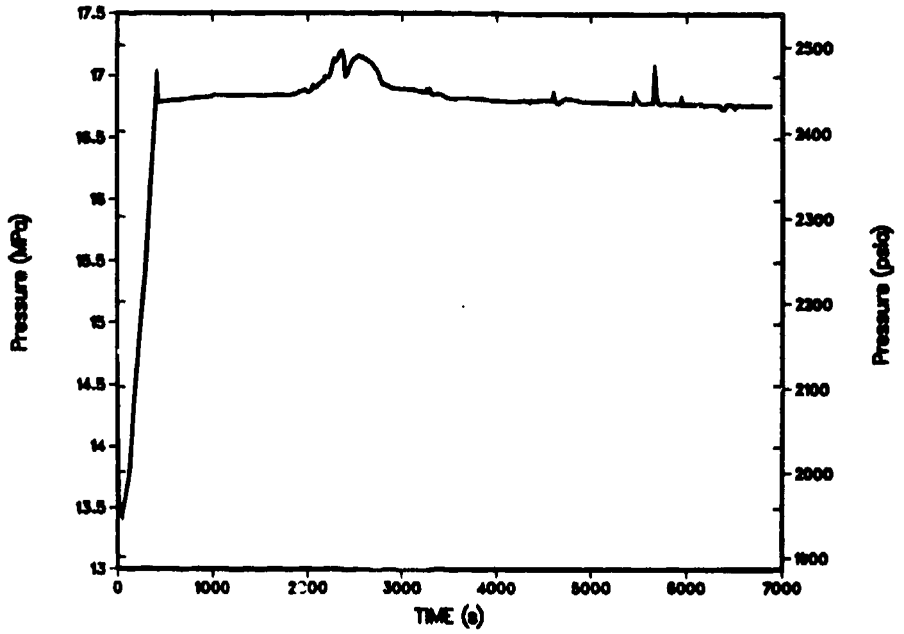

Fig. XXIII.5-3.
Primary system pressure.

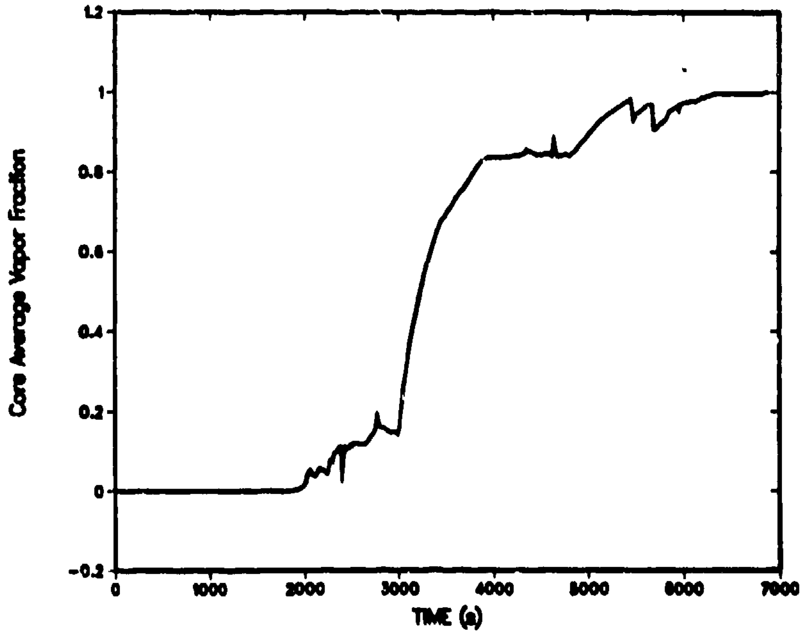

Fig. XXIII.5-4.
Core average void fraction.

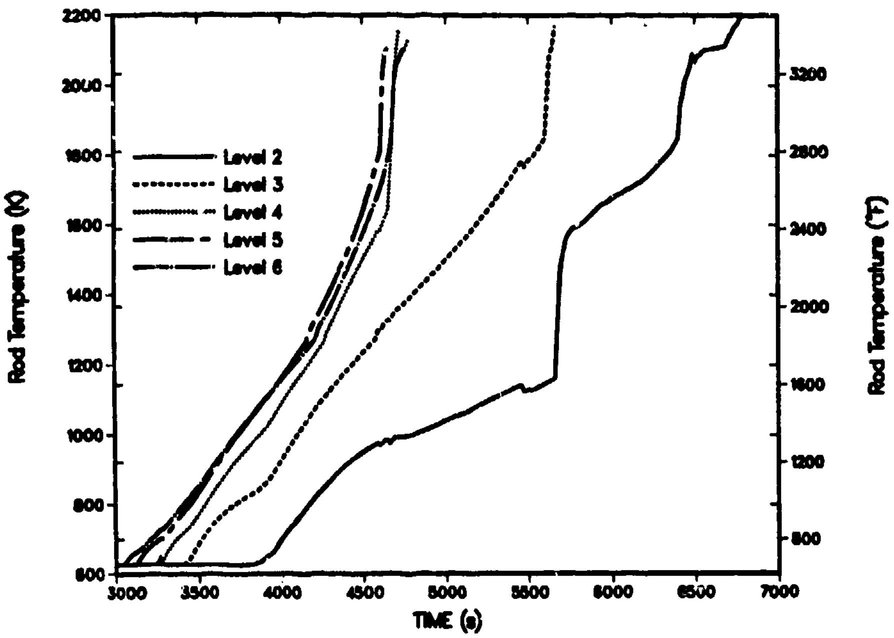

Fig. XXIII.5-5.
Peak cladding temperatures for the upper five levels of the core. Rod failure time is indicated by the end of the line.

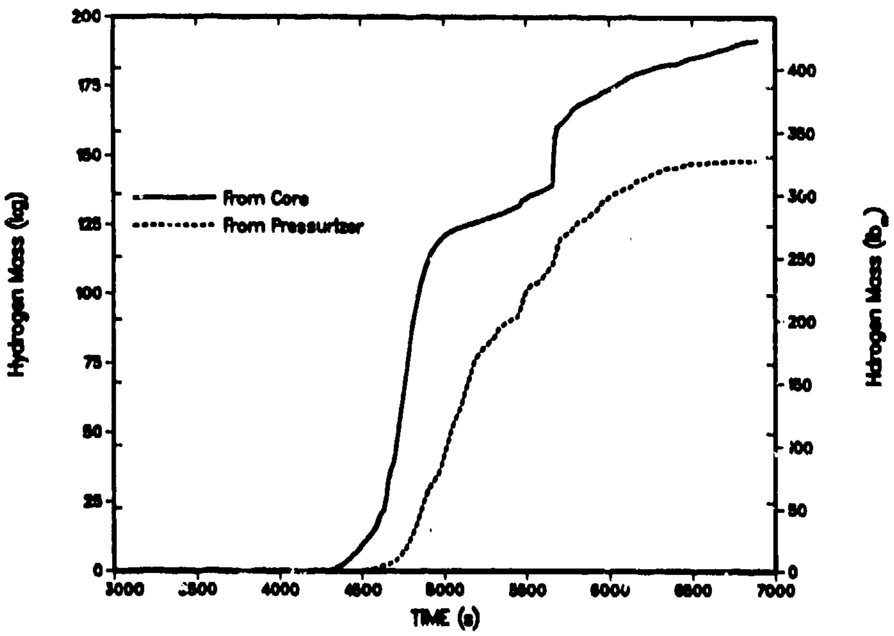

Fig. XXIII.5-6.
Mass of hydrogen flowing from core and pressurizer.