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COOLANT BOILING IN THE BEGINNING-OF-LIFE CORE DURING OVERPOWER EXCURSIONS

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A hypothetical unprotected transient overpower accident (TOP) in the fresh and near fresh LMFBR core may involve coolant boiling prior to cladding failure for relatively slow transients--say on the order of 50¢ to 3$/sec. Indeed, coolant boiling on the cladding surface is a possible failure mechanism postulated for overpower transients. The scope of this paper is not to provide a definitive statement on failure, or post-failure occurences, but to access the implications of bulk boiling if boiling initiation preceeds failure, when the pumps are fully operational.

SLIDE 1

SLIDE 1 provides an outline of the topics that will be covered. First, the Beginning-of-life core will be defined. Next, the salient features of the analytical model will be summarized. This includes modifications to the MELT-III code for BOL analysis. Further, a means to represent the core hydrodynamics with a manageable system of equations is presented. Uncertainties in the fuel failure mechanism for fresh and near fresh fuel, is beyond the scope of this paper. To the extent that time of fuel failure is pertinent, it will appear as a parametric quantity.

Next, the specific characterization of the boiling phenomenon within the context of the current version of MELT is discussed. Finally, the initial aspects of the fuel-coolant interaction process in a previously voided region is considered.

Attention is focused here on the beginning-of-life (BOL) core. Whereas fission gases are absent in a fresh fuel, the BOL core would have experienced an effective full power operation of a couple days. The fission gas produced is small, but may be significant.

SLIDE 2

The mixed oxide fuel will have reached sintering temperature so restructuring of the microstructure will have occurred. SLIDE 2 illustrates the calculated radial densification of fuel typical of irradiated and of BOL cores.

It is of fundamental importance that low burnup cores experience greater melting prior to cladding failure. Thereby, more molten fuel is available to be released initially. Indeed, the absence of a large continuous fission gas source to provide a long term driving force leads to a relatively shorter squirt duration.

The computational tool utilized to study the BOL core was the MELT-III neutronics, thermal hydraulics computer program. The primary modifications made to MELT-III for this analysis are outlined on the next two slides. (SLIDES 3 and 4).

Boiling initiation and growth in the coolant is based upon the bulk coolant temperature reaching local saturation conditions. Two models are used to describe vaporization within the bubble: 1) the standard FCI package, and 2) the pure boiling package. As with the FCI voiding model, only one bubble may exist within the channel at a time, and the thermodynamic features of the bubble are homogeneous.

SLIDE 3

To the standard MELT-III energy balance around the bubble was added sodium sensible heat and superheat terms. Superheat is usually specified as zero or near zero. The essence of the boiling model is in the recasting of the numerics and logic in order to attain numerical stability, conservation of mass and energy, and timely sequencing of events in the iterative algorithm. Essentially then, the MELT-III boiling model is nearly identical to the fully documented fuel-coolant interaction bubble model.

SLIDE 4

For calcualtions involving fuel vapor, the total pressure at failure was computed as the sum of fuel vapor pressure and partial pressures of fission and fill gases. The fuel vapor pressure is predicted from a temperature dependent relation of Menzies. The fuel vapor is assumed to adiabatically expand into the coolant channel with negligible replacement from molten surfaces.

A liquid film was presumed to remain on the clad wall after voiding. The film was approximated by a spatially uniform and stationary region within the bubble. The film serves as a thermal resistance between clad surface and saturated bubble as well as storing energy. The effects of latent heat of vaporization, though absent from the film model, are included in the acceleration of liquid slugs using the standard MELT-III voiding scheme. The film thickness and heat transfer coefficient are constant until dryout. The time to dryout, measured from bubble initiation, is user specified. After dryout, film thickness and heat transfer coefficients are reduced to small values.

The hydrodynamic and nuclear model used in this analysis is the following: First, the coolant flow was presumed to be maintained. Subassemblies possessing similar characteristics were then lumped together in order to reduce the computational effort in a manner simlar to that described by Waltar and Wilburn earlier in this session. Subassembly lumping relied on similarities in boiling sequence and power level. Analysis was based upon a 4-channel model which simulated the complete core transient. Subassemblies that boiled were subdivided to account for non-simultaneous boiling in all regions of that subassembly (Channels 1 and 2 in SLIDE 5).

SLIDE 5

SLIDE 5 illustrates this noncoherency phenomenon for a reactivity insertion rate of 50¢/sec. Non-coherency in voiding across a subassembly follows from the fact that superheat is small and the coolant temperature is not uniform radially across any subassembly as exhibited by the difference in the temperature between Channels 1 and 2.

SLIDE 6

In order to present the nature of the bulk boiling phenomena predicted by the current version of MELT, it is instructive to first consider the case where cladding failure is suppressed. SLIDE 6 illustrates the voiding pattern for a 0.05¢/sec ramp rate. It is noted that whole channel voiding is never established, i.e., the flow pattern is that of single bubbles percolating off the top of the core.

It is observed in SLIDE 6 that the top of the core (node 24) does not experience noticeable cooling due to the intermittent flushing of the site with subcooled liquid. This is because this site is also the point of bubble initiation and bubbles are seldom absent. Above and below this site, the expected intermittent cooling is predicted.

SLIDE 7

SLIDE 8

SLIDES 7, 8, and 9 provide a three-dimensional perspective of the transition from the boiling domain into the fuel-coolant interaction domain. SLIDE 7 illustrates the generally well behaved thermodynamic nature of the boiling domain up to the fuel failure. SLIDE 8 shows the difference in spatial variation of the coolant temperature along the channel for both the boiling and FCI domains. The vertical lines orthogonal to the channel axis enclose the core region.

SLIDE 9

SLIDE 9 emphasizes the conditions after fuel failure. The fuel-coolant interaction region is characterized by rapid pressurization and flow reversal. The pressure drop across the core eventually corrects the flow reversal. The disturbance in the coolant is convected upstream. Depressurization is rapid with the expanding bubble establishing a uniformity in coolant temperature until bubble collapse or bubble expulsion from the channel.

SLIDE 10

The concentration of fission gas, sodium vapor, liquid fuel, and liquid sodium in a typical bulk boiling to FCI transition is illustrated in SLIDE 10. Note the plot is semi-log in order to display the low fuel and fission gas concentrations.

The bulk boiling region is predicted to have a high liquid content. This feature serves to emphasize that the bubble domain might be regarded more as a collection of bubbles rather than a single physical bubble. After the transition of the bubble into an FCI Zone, the sodium vapor content becomes dominant at the expense of the liquid sodium. Eventually, the high quality bubble pictured in SLIDE 9 is swept from the core. An alternative scenario is for the FCI zone to fill with sodium liquid with subsequent collapse specified by MELT.

SLIDE 11

SLIDE 11 illustrates the influence of initial voiding and, thereby, fuel motion for a relatively weak FCI as predicted by MELT-III. The selection of a weak FCI serves to dramatize the expected upper limit of the phenomenon. In the absence of a voided region, energy from the FCI process would be required to open a void. The attendant pressurization limits initial fuel squirting for this case to about 3/4 the amount associated with squirting into a voided region. Later in the transient the two cases become quite similar.

SLIDE 12

As shown in SLIDE 12, the consideration of fuel vapor pressure increases the amount of fuel initially squirted into the voided region. Though the vapor pressure is only a small fraction of the total pressure at the time of failure the number of moles of vapor is relatively substantial. As time into the FCI increases, the fuel vapor becomes less important.

SLIDE 13

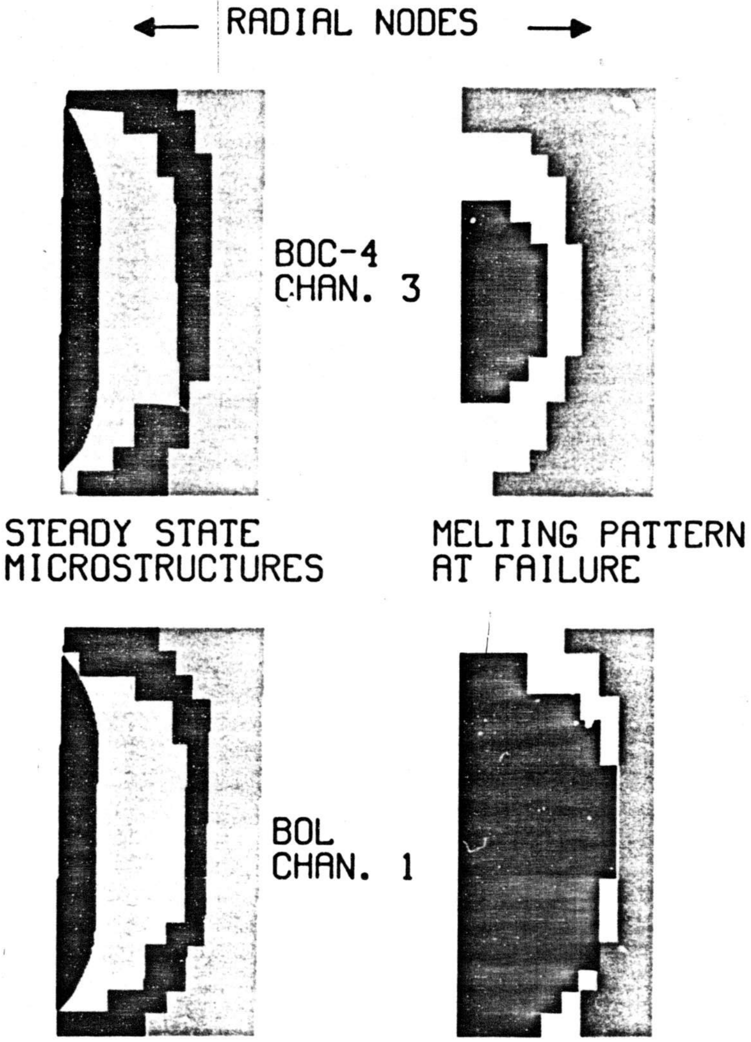
SLIDE 13 illustrates the feature that the peak coolant temperature and, hence, bubble initiation site is closer to the core center for higher reactivity insertion rates. Above around 3$/sec failure is expected to preceed boiling. Thus boiling initiation would be limited to the upper third of the core. Additionally, more rapid reactivity insertion rates will increase the peak core power. However, the amount of fuel squirted increases substantially so the fuel motion feedback generally tends to enhance neutronic shutdown. Finally, more subassemblies boil prior to neutronic shutdown for higher ramp rates.

In conclusion, the following key points have been made concerning the boiling phenomenon in the BOL core:

- Fully developed bulk boiling is not attained.
- The failure site is in the upper third of the core if boiling preceeds failure.
- Fuel vapor pressure may be an important factor in initial fuel squirting.
- Boiling does not necessarily imply an increase in hypothetical transient overpower accident severity.

COOLANT BOILING IN THE BOL CORE DURING OVERPOWER EXCURSIONS

- The BOL Core
- Calculational model
  - MELT-III
  - Hydrodynamic
  - Fuel failure
- Nature of boiling
- Post-boiling fuel squirting
- Conclusions

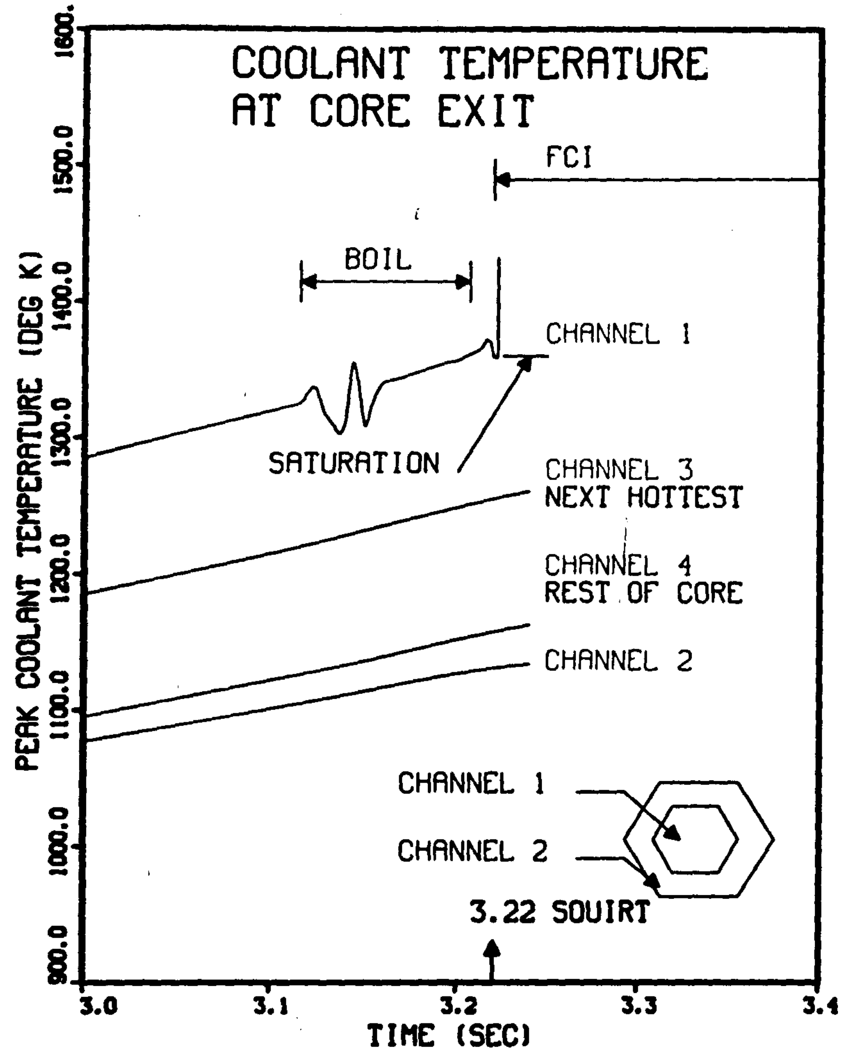


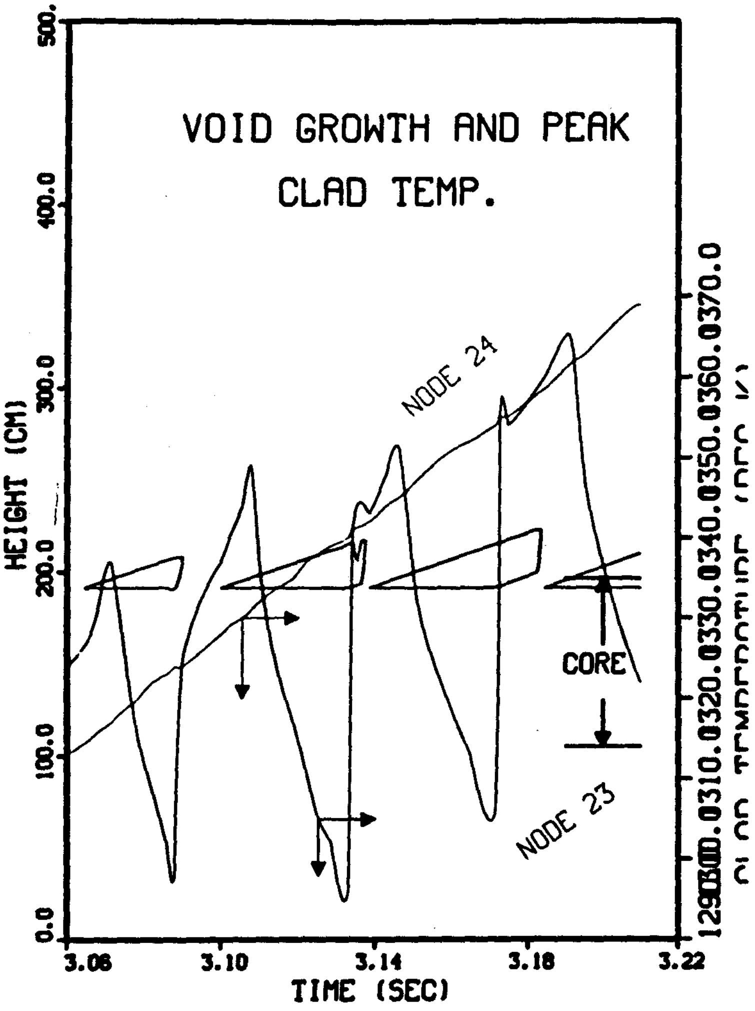
COMPARISON OF FUEL MELTING PATTERNS
AT TIME OF FIRST CHANNEL FAILURE

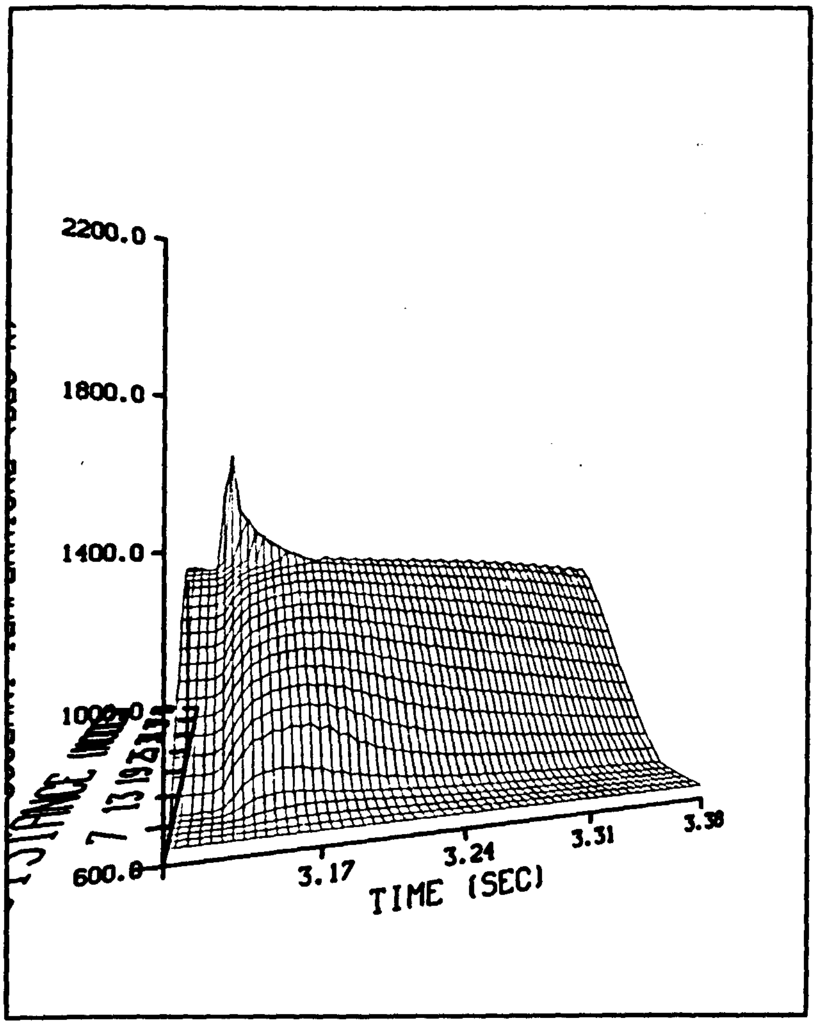
MELT-III MODIFICATIONS

- Bulk boiling
    - Local saturation
    - Single bubble
    - NA sensible heat
    - Superheat
    - Numerics

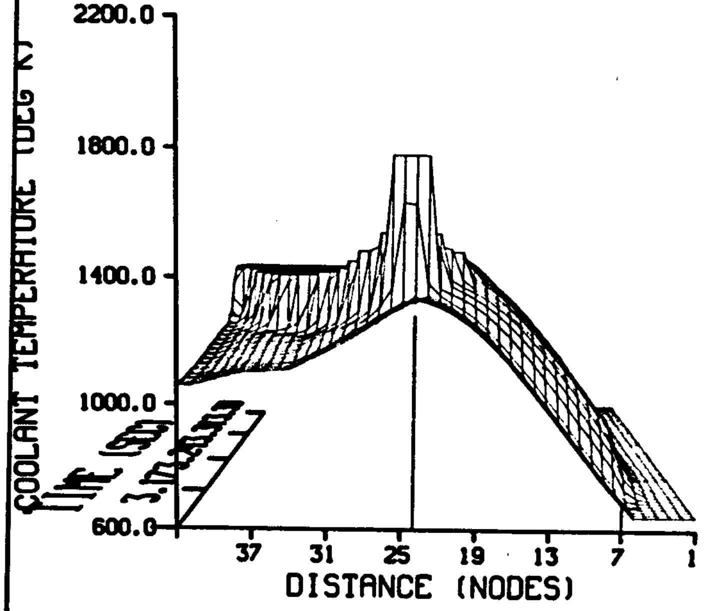
- Fuel vapor pressure
- Film model
    - Stationary
    - Resistance
    - Energy storage
    - Dryout time


COOLANT TEMPERATURE
AT CORE EXIT
FCI
BOIL
CHANNEL 1
SATURATION
CHANNEL 3
NEXT HOTTEST
CHANNEL 4
REST OF CORE
CHANNEL 2
CHANNEL 1
CHANNEL 2
3.22 SQUIRT
PEAK COOLANT TEMPERATURE (DEG K)
900.0
1000.0
1100.0
1200.0
1300.0
1400.0
1500.0
1600.
TIME (SEC)
3.0
3.1
3.2
3.3
3.4

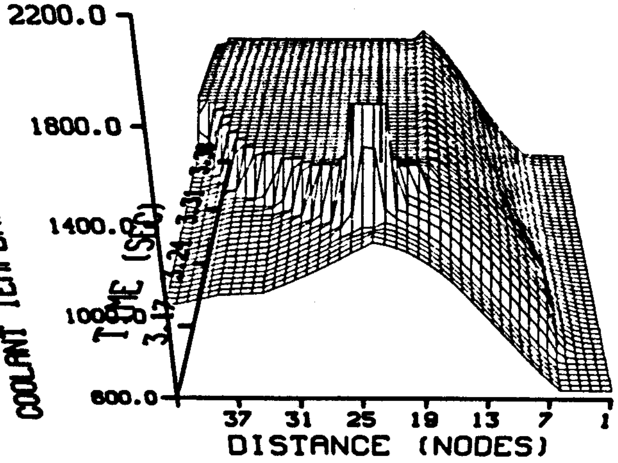

VOID GROWTH AND PEAK
CLAD TEMP.
HEIGHT (CM)
0.0
100.0
200.0
300.0
400.0
500.
TIME (SEC)
3.06
3.10
3.14
3.18
3.22
1290.0
1300.0
1310.0
1320.0
1330.0
1340.0
1350.0
1360.0
1370.0
NODE 24
NODE 23
CORE



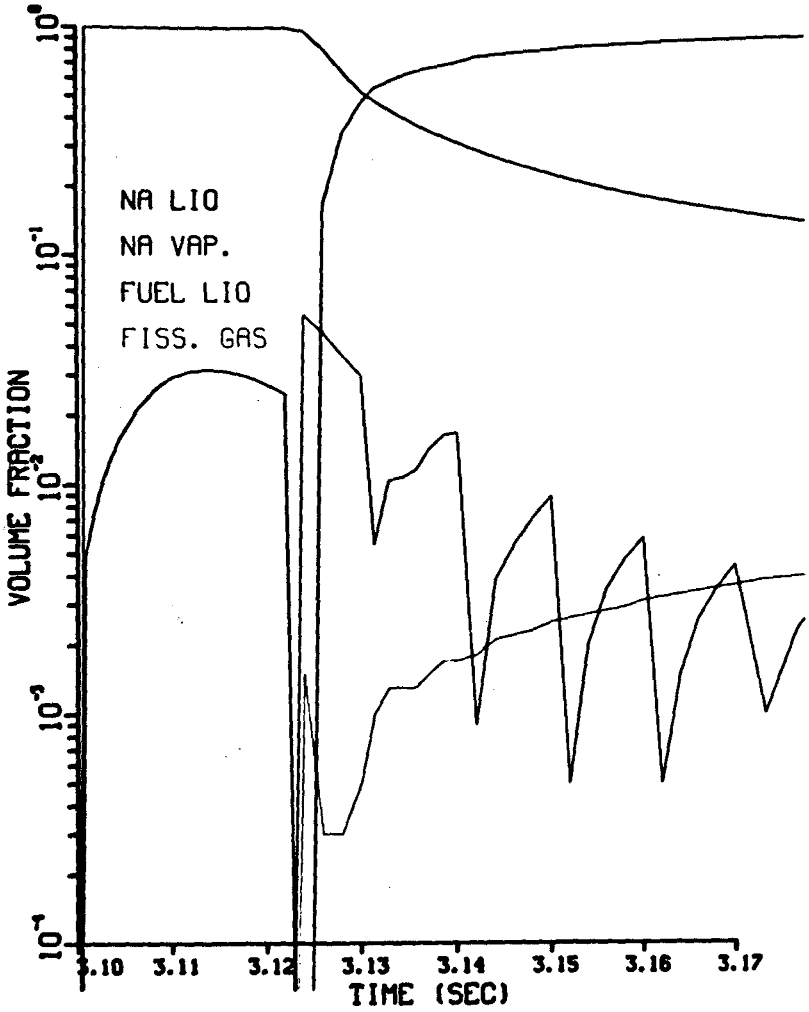
SLIDE 7


COOLANT TEMPERATURE (DEG K)
2200.0
1800.0
1400.0
1000.0
600.0
TIME (SEC)
37
31
25
19
13
7
1
DISTANCE (NODES)

SLIDE 8

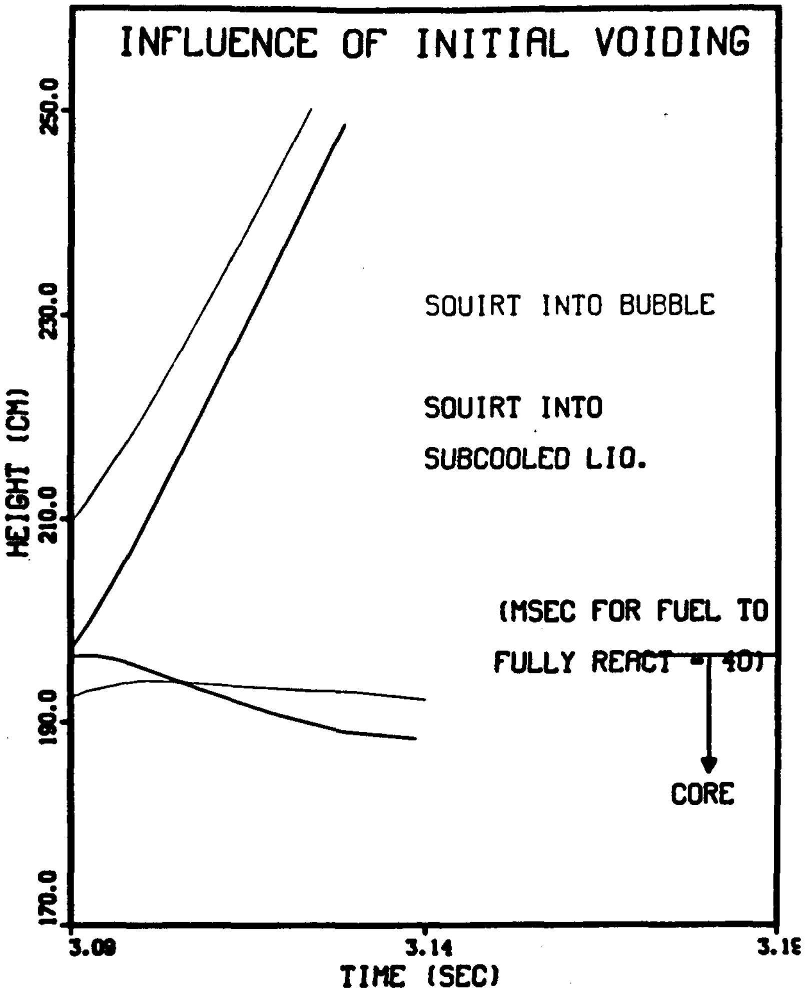

2200.0
1800.0
1400.0
1000.0
600.0
COOLANT TEMPERATURE
TIME (SEC)
3.17
3.24
3.31
37
31
25
19
13
7
1
DISTANCE (NODES)

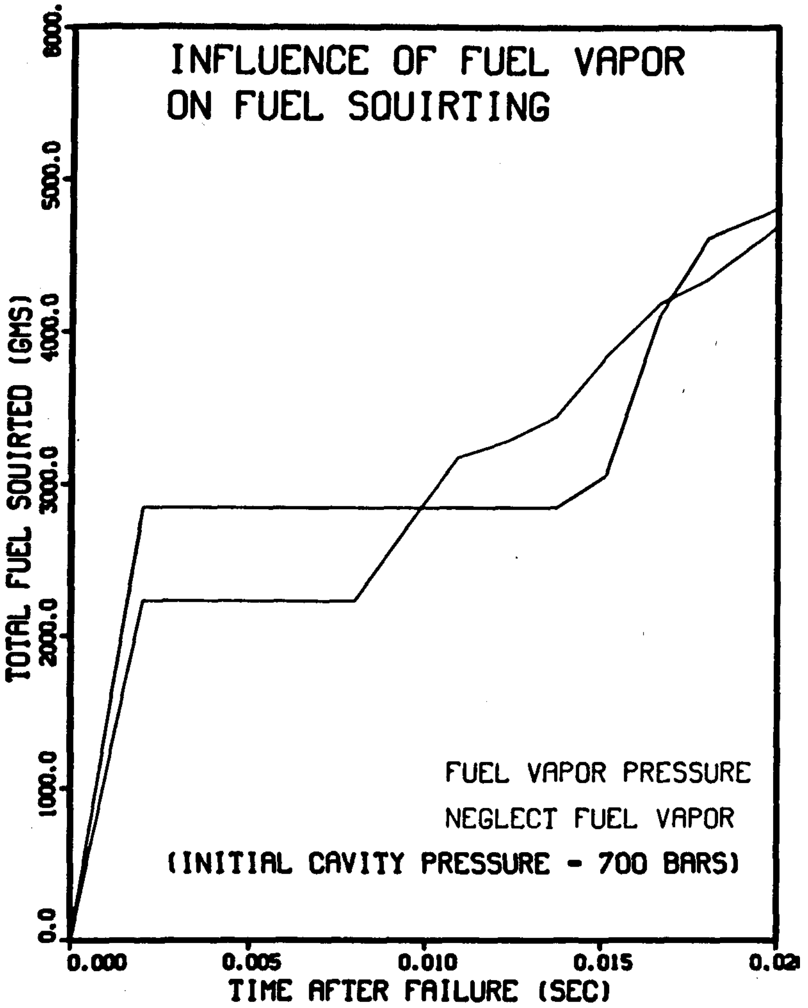
SLIDE 9

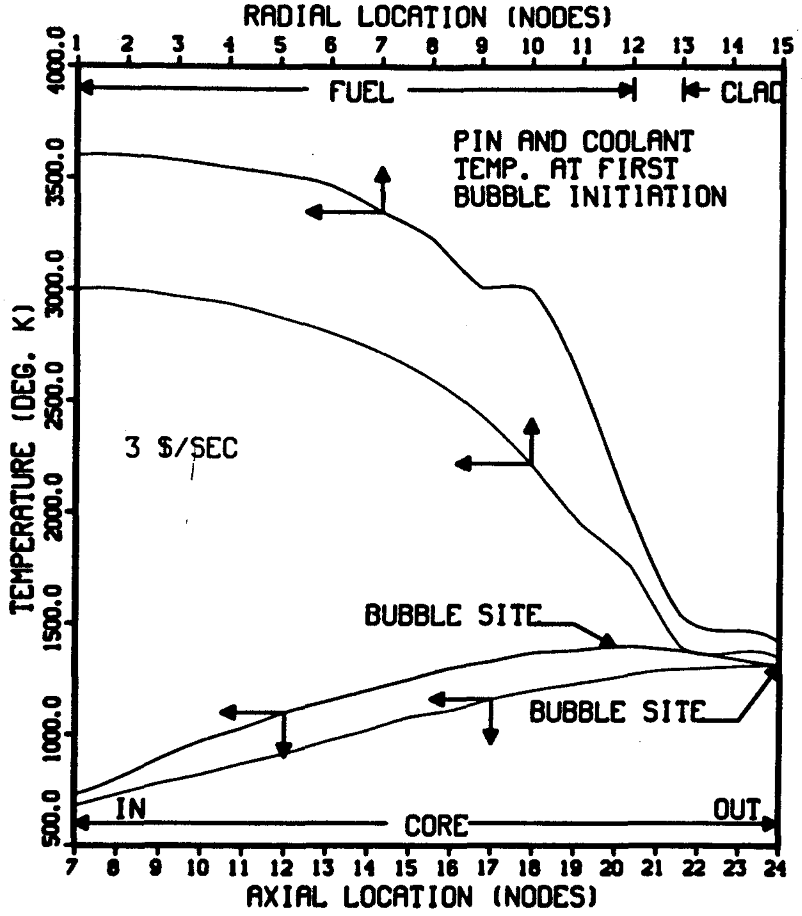


NA LIQ
NA VAP.
FUEL LIQ
FISS. GAS
VOLUME FRACTION
10^0
10^-1
10^-2
10^-3
10^-4
3.10
3.11
3.12
3.13
3.14
3.15
3.16
3.17
TIME (SEC)

SLIDE 10


INFLUENCE OF INITIAL VOIDING
SQUIRT INTO BUBBLE
SQUIRT INTO
SUBCOOLED LIQ.
(MSEC FOR FUEL TO
FULLY REACT = 40)
CORE
HEIGHT (CM)
250.0
230.0
210.0
190.0
170.0
3.08
3.14
3.18
TIME (SEC)


INFLUENCE OF FUEL VAPOR
ON FUEL SQUIRTING
FUEL VAPOR PRESSURE
NEGLECT FUEL VAPOR
(INITIAL CAVITY PRESSURE - 700 BARS)
TOTAL FUEL SQUIRTED (GMS)
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.
TIME AFTER FAILURE (SEC)
0.000
0.005
0.010
0.015
0.02


RADIAL LOCATION (NODES)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
FUEL
CLAD
PIN AND COOLANT TEMP. AT FIRST BUBBLE INITIATION
3 $/SEC
BUBBLE SITE
BUBBLE SITE
IN
CORE
OUT
TEMPERATURE (DEG. K)
4000.0
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
AXIAL LOCATION (NODES)

CONCLUSIONS

- No fully developed boiling
- Boiling initiation site in upper third of core
- Importance of fuel vapor
- Boiling does not necessarily imply an increase in TOP hypothetical accident severity