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Metal Fuel Safety Performance*

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ABSTRACT

The current development of breeder reactor systems has lead to the renewed interest in metal fuels as the driver material. Modelling efforts were begun to provide a mechanistic description of the metal fuel during anticipated and hypothetical transients within the context of the SAS4A accident analysis code system. Through validation exercises using experimental results of metal fuel TREAT tests, confidence is being developed on the nature and accuracy of the modelling and implementation. Prefailure characterization, transient pin response, margins to failure, axial in-pin fuel relocation prior to cladding breach, and molten fuel relocation after cladding breach are considered. Transient time scales ranging from milliseconds to many hours can be studied with all the reactivity feedbacks evaluated.

INTRODUCTION

The current development of breeder reactor systems has lead to the renewed interest and concentration on metal fuel alloys as the driver and breeder materials. The extended operation of the EBR-II reactor and its metallic fuel to high burnup levels has provided an extensive database of operational experience. The more recent experience using EBR-II for operational transients and run beyond cladding breach experiments has provided additional confirmation of the passive safety response of these metal fueled systems. Much of the current development of these systems involves describing the plant to enhance the natural feedback systems that provide limits to the net reactivity driving the system response and even plant shutdown without the need for extensive operator evaluation, decision making, and action. Several papers at this conference present information on modelling for the evaluation of plant designs and inherent feedback systems.[1-4]

While the plant design and feedback characteristics are an important part of the overall system response, the behavior of the metal fuel itself is a crucial part of the overall development of the new reactor systems. For the oxide fueled breeder reactor systems, the SAS4A accident analysis code system[5-6] was developed to provide information on the response of the fuel and reactor core to transient scenarios. In particular, the DEFORM-4 module[7] provided the steady state characterization of the oxide fuel based on a simplified irradiation history, and then determined the transient fuel and cladding response, including the time and location of cladding breach and the initiation of the fuel motion routines. Once the fuel motion models were initiated, DEFORM-4 stopped its modelling of the pin.

With the turn to metal alloy fuels, there is a need to reconsider the methods used with the oxide fuel to assess the safety performance. Because of the differences in thermal conductivity, sodium compatibility, mechanical strength, and others, a fresh look at the modelling was undertaken. While much is known about the behavior of metal alloy fuels, there are areas where more understanding is needed before detailed phenomenological models can be built for the fuel characterization and transient behavior. However, mechanistic models are needed to extrapolate the physical phenomenon beyond the available database. In the new modelling for metal fuel safety performance, extensive use has been made of experimental data and more complicated fuel behavior codes to provide insight and direction concerning the modelling priorities.

METAL FUEL CHARACTERISTICS

One of the major differences between metal alloy fuels and the oxide fuels is the thermal conductivity. The metal fuels have a thermal conductivity that is about an order of magnitude greater. In addition, the temperature dependence is different. With the oxide, increasing temperature produces a generally decreasing thermal conductivity, while the opposite is the case with the metal alloys. As the temperature increases, the thermal conductivity also increases.

Another feature of the pin design that affects the safety performance is the use of a sodium bond with the metal fuel. Since in sodium is compatible with the metal fuel, it can be used as the fuel-cladding bond material,

providing a good heat transfer between the fuel and cladding even when the gap is large.

Both the high fuel thermal conductivity and high gap conductance lead to differences in the radial and axial thermal profiles within the fuel pin. Because of the good heat transfer characteristics, the radial temperature profile is flatter than in the oxide and the temperature drop across the fuel-cladding gap is small. Although the melting point of the metals is relatively low, the good heat transfer keeps the temperatures well below melting during normal operation. As the fuel temperatures rise during transient scenarios, the fuel conductivity increases as well, providing better heat transfer to the coolant. Those characteristics of the metal fuel and bond sodium lead to low retained heat in the fuel, a significant factor in the Loss-of-Flow (LOF) transients.

These features also affect the axial thermal profiles. The location of the maximum fuel temperature for metal fuels in steady operation and most all transients is well above the axial midplane, where the cladding is generally the weakest. This biases the failure locations toward the top of the fuel column, where the reactivity effects due to molten fuel relocation are negative. In very rapid Transient-Overpower (TOP) accidents, the location of maximum temperature moves closer to the axial centerline, but the combined effects of fuel and cladding still produces failure locations above the core midplane.

Another feature of the metal fuels is their relatively weak mechanical nature compared to the cladding and ceramics. They creep readily due to internal forces and therefore produce a much smaller component of fuel-cladding mechanical interaction.

A characteristic of the metal fuel that inhibited the early development of high burnup pins is the extensive fuel swelling early in life. However, a more complete understanding of the nature of this swelling lead to higher burnup performance when enough volume was included to allow the fuel to reach the state where significant connected porosity developed allowing fission gas release to the plenum. This eliminates early fuel-cladding mechanical interaction and the plenum pressure becomes the predominant force acting on cladding.

A phenomenon of the metal fuel pins that must be addressed is the formation of a low melting point eutectic intermetallic between the uranium and iron at the fuel-cladding interface. If transient temperatures are sufficiently high for extended periods of time, the potential exists for a thinning of the cladding with a resultant loss in containment at an earlier time than would otherwise be predicted. To develop significant cladding thinning, an abundance of molten fuel is required to drive the reaction. When zirconium is used as a component in the metal fuel alloy, this eutectic penetration is reduced. The zirconium raises the eutectic temperature and may provide a protective region on the outer fuel surface that reduces the migration of uranium to the cladding surface. While the generic features of this behavior are understood, additional information and insight is needed to be able to model this phenomenon in a mechanistic manner.

A final metal alloy fuel characteristic that may prove significant in evaluating the safety performance of metal fuels results from the thermal profiles within the pin. Because of the high axial location of the maximum fuel temperature, the possibility exists in many transient scenarios of melting through the top of the fuel and expelling molten fuel from the lower molten cavity into the plenum region above the active core, prior to cladding breach. As the molten fuel relocates axially within the cladding, a substantial negative reactive effect is generated, producing a strong shutdown effect. While this phenomenon may reduce the internal fuel integrity, the consequences to the reactor system are minimal, allowing a possible clean recovery from even severe reactor transients with a reduction in the effort and cost of plant recovery, subassembly removal, and core reloading.

In order to fully understand and predict the safety performance of metal allow fuels, these characteristics must be modelled adequately so that the effects of design changes may be determined and accident consequences studied.

TRANSIENT RESPONSE MODELLING

The consideration of inherent reactivity feedback in the new reactor system designs has changed the time scale for considering transient response from seconds to many hours. Therefore, new model development has to concern itself with computational efficiency as well as the correct representation of the important phenomena involved. DEFORM-4 provided a detailed model of the

oxide fuel during the steady state and transient fuel and cladding response up to the time of the fuel motion modelling initiation, and could be converted to use with the metal fuels with appropriate changes to the material properties. However, it was decided that the computational effort DEFORM-4 would use in extended transients was larger than was necessary for the current state of knowledge about the metal fuels. It was also a goal of the new modelling that the failure margins be continually monitored, whether SASSYS was used or SAS4A. These considerations lead to the decision to produce a new model for the metal fuels, known as DEFORM-5.

In the use of SAS4A and SASSYS to study reactor systems and their transient response, it is possible to have both oxide and metal fuel in the reactor core simultaneously, and this can be addressed through the "channel" structure of these codes. It is therefore necessary to be able to model both the oxide and metal fuel at the same time. DEFORM-5 is therefore not replacement for DEFORM-4, but a companion. DEFORM-4 would continue to be used for those channels representing oxide fueled subassemblies and DEFORM-5 would be used for the metal subassembly channels. This provides the maximum flexibility for the use of the codes.

In beginning the new modelling effort, it was also necessary to determine whether to begin with the steady state characterization of the fuel or the transient response. Because the most important information needed for the evaluation of the pin design and response involved the transient response, it was decided to begin the transient modelling first. This was also influenced by the fact that the steady state characterization could be input to the code from sibling pin information or the results of more complicated characterization codes, and the understanding from the extensive database using metal fuels in EBR-II that there was minimal fuel-cladding mechanical interaction that would influence the transient response. With the extensive interconnected porosity that develops in the metal fuel at low burnups, the plenum pressure is the primary force acting on the cladding. These factors allow the simple introduction of a steady state characterization from which to begin the transient response modelling.

In the same way, it was determined that the cladding response phenomena would take priority over the fuel response in the initial stages of the modelling efforts. The metal fuel mechanical response is dominated by the

cladding because of the relatively weak nature of the fuel compared to the cladding. Once a verified cladding response model was developed, the effort could be turned to the fuel response, while enabling the code users to perform studies, gaining valuable insight into the safety performance without waiting for the complete module. This strategy allows the most rapid introduction of the new modelling for use by the safety community. As each new modelling stage is reached, verification and validation results would be presented as well, providing a consistent validation of the modelling.

As indicated above, the DEFORM-5 module is intended for use with both the SASSYS and SAS4A code systems. Complete consistency is provided between the longer term system transients studied with SASSYS and the shorter time scale core transients studied with SAS4A. Failure margins are continuously calculated.

DEFORM-5 is also designed to continue its modelling computations even after initial cladding breach and initiation of the molten fuel motion modules. Using the results from these modules, DEFORM-5 continues to model the pin response at all unbreached axial locations. This provides total consistency between the initial cladding breach and the axial extension of the breach. As part of this effort, the possibility of eutectic thinning of the cladding from molten fuel on the outside of the pin has been incorporated within the model.

One of the other main areas of modelling for the metal fuel safety performance involves the axial relocation of molten fuel within the intact cladding. If the cladding remains intact, it is possible for the top fuel sections to melt and release the molten fuel upward. The modelling effort to represent this phenomena involves the PINACLE code module.[8] This phenomenon can introduce significant negative reactivity feedback and change the transient scenario. PINACLE is integrated with the DEFORM models and provides the molten cavity boundary conditions for DEFORM, as well as determining the amount of molten fuel relocation.

If cladding breach occurs, the LEVITATE and PLUTO2 modules are used to determine molten fuel relocation from the pin and in the coolant channels. Material property changes are made to represent the metal fuels.

CLADDING RESPONSE MODELLING

The response of the cladding to the transient involves two primary phenomena with metal fuels: (1) the strain of the cladding due to internal pressurization, and (2) the eutectic penetration and thinning of the cladding. Both are considered in DEFORM-5 and incorporated in the cladding margin to breach predictions.

Cladding Strain

The basic approach adopted for cladding strain is that developed by DiMelfi and Kramer[9,10] in their studies on plastic flow in steel cladding. The hoop stress in the cladding, σ_θ, is determined for a thin shell under internal pressure loading.

$$\sigma_\theta = (P - P_{ch}) \frac{a}{h} \tag{1}$$

where

P = Internal pressure
P_{ch} = Coolant channel pressure
a = Inner cladding radius
h = Cladding thickness

Assuming the hydrostatic loading of a thin cylindrical shell, the hoop stress is converted to an equivalent stress. This stress is then used in the flow equation developed by DiMelfi and Kramer.

$$\dot{\epsilon} = \dot{\epsilon}_{oos} \left(\frac{\sigma}{\sigma_{so}}\right)^m \exp(-Q/RT) \tag{2}$$

where

$\dot{\epsilon}$ = Equivalent strain rate
$\dot{\epsilon}_{oos}$ = Material constant
σ = Equivalent stress
σ_{so} = Saturation stress
m = Stress exponent
Q = Activation energy
T = Temperature

This formulation was chosen because it allowed the use of the same model for all cladding types of interest. Through the use of appropriate cladding parameters, SS316, D9, and HT9 can all be modelled within the DEFORM-5 context. This is also the formulation used in DEFORM-4 and therefore provides a consistency between the two complementary models.

Eutectic Penetration

The rate of eutectic penetration used is based on dip tests with iron-uranium melts and was correlated by Bauer[11], Fig. 1. The data indicate a general Arrhenius form over most temperatures with a high rate region between 1350 and 1500 K, which attributed to the breakdown a UFe_2 protective layer.

Because of the rapid nature of this penetration above 1350K, it is possible during rapid transients for the cladding temperatures to overrun this rapid penetration regime and a pointwise application of the correlation would yield inaccurate results, underestimating the cladding penetration. To accurately handle this situation and provide the maximum generality for transient study, the rate correlation is integrated numerically over the temperature change during the calculational timestep. It is assumed that the temperature change takes place linearly during the step. This formulation provides the additional advantage of providing good results over long time steps as well, an important fact in studies involving extended transients.

Cladding Breach

The determination of cladding breach, or margin to breach is based on the eutectic thinning of the cladding and the reduced ability to contain the internal pressure. Besides the eutectic thinning, the cladding wall is reduced as plastic flow takes place. Different accident scenarios and pin conditions lead to different modes of breach, whether through cladding penetration or plastic strain or a combination.

The DEFORM-5 solution method involves first determining the eutectic penetration thinning of the cladding. The new cladding thickness is then studied to determine the cladding strain. This final state is then studied to determine if breach has occurred over the time interval. If breach has not occurred, a damage fraction is calculate based on the time step and time to breach (assuming constant conditions) and this is accumulated with any

previous damage. A damage fraction of one is assumed to indicate cladding breach.

INITIAL VALIDATION OF CLADDING RESPONSE

The DEFORM-5 modelling has been applied to the TREAT experiments M2, M3, and M4[12] to determine the validity of the approach adopted. The initial plenum pressures at room temperature were provided from sibling pin data, the flow rate was taken from the experiment data, as was the power history. The plenum pressure was increased as a function of the calculated plenum temperature increase.

Table 1 shows the results compared with the experimental results for the 9 pins of those tests.[13] DEFORM-5 predicted failure in those pins that did fail and no failure in those that remained intact. The nature of the failure was also consistent with the experimental observed nature of the failure. The 2.4% burnup pin in test M4 had the greatest wall thinning ~90%, while the high burnup, 7.9%, pin in M2 had less than a 2% reduction by eutectic penetration and failed by cladding strain. The medium burnup pin, 4.4%, in M2 showed a combination of both effects.

This is consistent with the current understanding in metal fuel safety performance. The low burnup pins have a low plenum pressure and therefore require extensive cladding penetration before breach. In high burnup pins, the plenum pressure is great enough to cause strain breach if the cladding is hot enough to reduce is mechanical strength.

The state of the fuel and failure location predicted also matched the experimental observations. There was extensive melting of the fuel, 100% in the upper regions of the pin. In all cases, the failure location was at the top of the active fuel region where the cladding temperature was highest. Significant amounts of molten fuel are necessary if significant eutectic penetration of the cladding is to occur.

These initial validation exercises demonstrate that the approach adopted in the DEFORM-5 modelling of cladding response considers the most important phenomena in an appropriate manner and provide confidence in its use.

IN-PIN AXIAL EXTRUSION OF MOLTEN FUEL

With the high conductivity of the metal fuel and bond sodium, the first movement of molten fuel may not be radially through a breached cladding, but axially into an upper plenum, Fig. 2. If the transient scenario produces melting at the top of the fuel before DEFORM-5 predicts cladding breach, in pin fuel relocation occurs and is modelled with the PINACLE module of SAS4A.[14]

PINACLE models the internal molten fuel relocation and movement through the fuel top into the upper plenum. This is done with an Eulerian two-phase transient hydrodynamic model within a variable area geometry. It has been developed using the same methods and solution in the LEVITATE and PLUTO2 modules. In this manner, if a cladding breach is determined to occur with DEFORM-5, the initiation of the molten fuel relocation in the pins and coolant channel can be handled in a consistent manner. This provides a consistent treatment from fuel melting initiation through the end of the transient scenario.

The components considered by PINACLE include the molten fuel, fission gas in small bubbles constrained by surface tension, and free gas within the cavity. Currently, only a bubbly flow regime is modelled, assuming that the molten fuel and fission gas are well mixed and move with the same velocity at any given axial location.

Prior to release through the top fuel node, only limited fuel relocation occurs due to local pressure gradients. But, once the top fuel node melts, significant amounts of fuel can move axially in response to the cavity pressure, until equilibrium is reached between the molten cavity and the plenum. This can introduce a substantial negative reactivity feedback that may mitigate the accident consequences. Because of the thermal profiles, the molten cavity within the metal pins is biased toward the top of the active core region, with the top of the molten region reaching the plenum, while the bottom extends towards the core centerline and below. Movement of fuel from this region to the plenum has a large negative reactivity effect. The amount of fuel moved into the plenum depends on several characteristics of the pin. The plenum pressure will influence the equilibrium conditions that are reached, with higher plenum pressures producing smaller relocations. The plenum pressure is strongly influenced by the pin burnup, with higher burnups leading to higher plenum pressures. The burnup levels also influence the

amount of fission gas and porosity within the fuel that act as the driving force for the molten cavity.

The effect of including this phenomenon on a whole core calculation for a metal core system undergoing a 10¢/sec reactivity ramp is shown in Fig. 3. Because of the rapid nature of this phenomenon and the magnitude of the effect, a limited member of pins or subassemblies provide a large feedback on a short time scale. Also, this would occur only if other inherent feedback mechanisms did not prevent fuel melting at the top of the fuel column.

VALIDATION OF MOLTEN FUEL AXIAL RELOCATION

Experiments with both oxide and metal fuels have been analyzed with PINACLE to provide a validation database. In the M2 and M3 TREAT experiments, axial relocation was observed and modeled with PINACLE, Fig. 4. In the TS-1 and TS-2 experiments[15] with oxide fuel it was also observed and PINACLE provided a good comparison, Fig. 5. With both the oxide and metal fuels, PINACLE predictions characterized the magnitude, timing, and behavior of the aixal relocation providing confidence and validation in the modelling.

SUMMARY

The new modelling efforts undertaken to study the safety performance of the metal alloy fuels have yielded much insight into the important phenomena characteristic of the metal fuels. Initial validation efforts have been quite successful and although more needs to be done in modelling the initial stages of the fuel characterization and transient response, confidence has been developed in the models that are in place and can currently be used. The nature of the metal fuel introduces performance characteristics that help to mitigate accident consequences. These include predicted cladding breach at elevated axial locations and in-pin axial relocation of molten fuel that generally result in significant negative reactivity feedbacks. In addition, the margins to cladding breach can now be monitored continuously in an economical manner, even for extended transients. If cladding breach does occur, a consistent treatment of cladding breach margins can be continued in the remaining unbreached axial locations and include the effect of possible eutectic penetration on the outside of the cladding. Consistent, initially validated models are available for use with SAS4A and SASSYS to study the safety performance of the metal fueled systems under design.

Current efforts consist of additional validation on the ternary alloy fuels and the advanced cladding types. The effects of the ternary fuel structure is under investigation and the modelling of the fuel characterization is proceeding.

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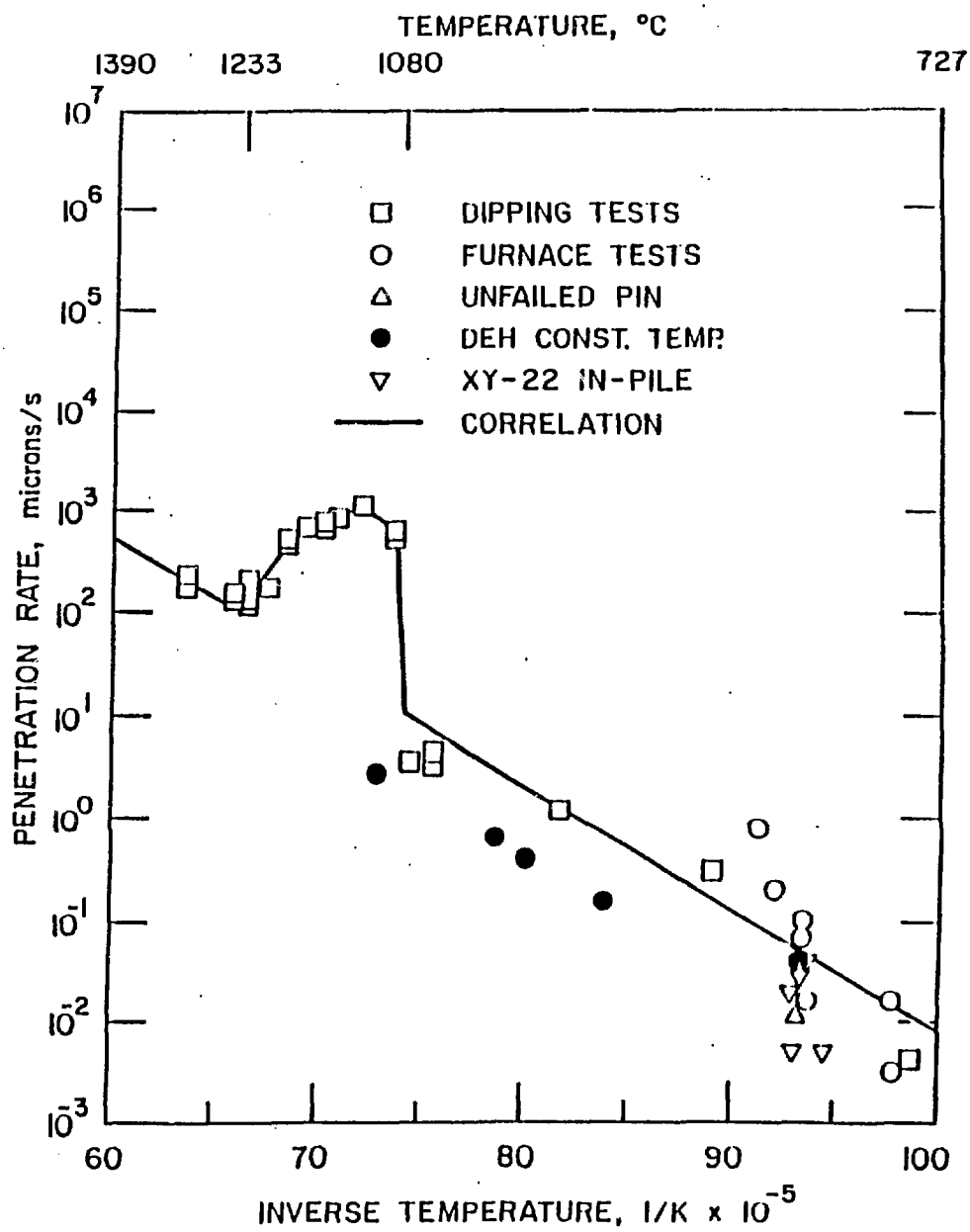
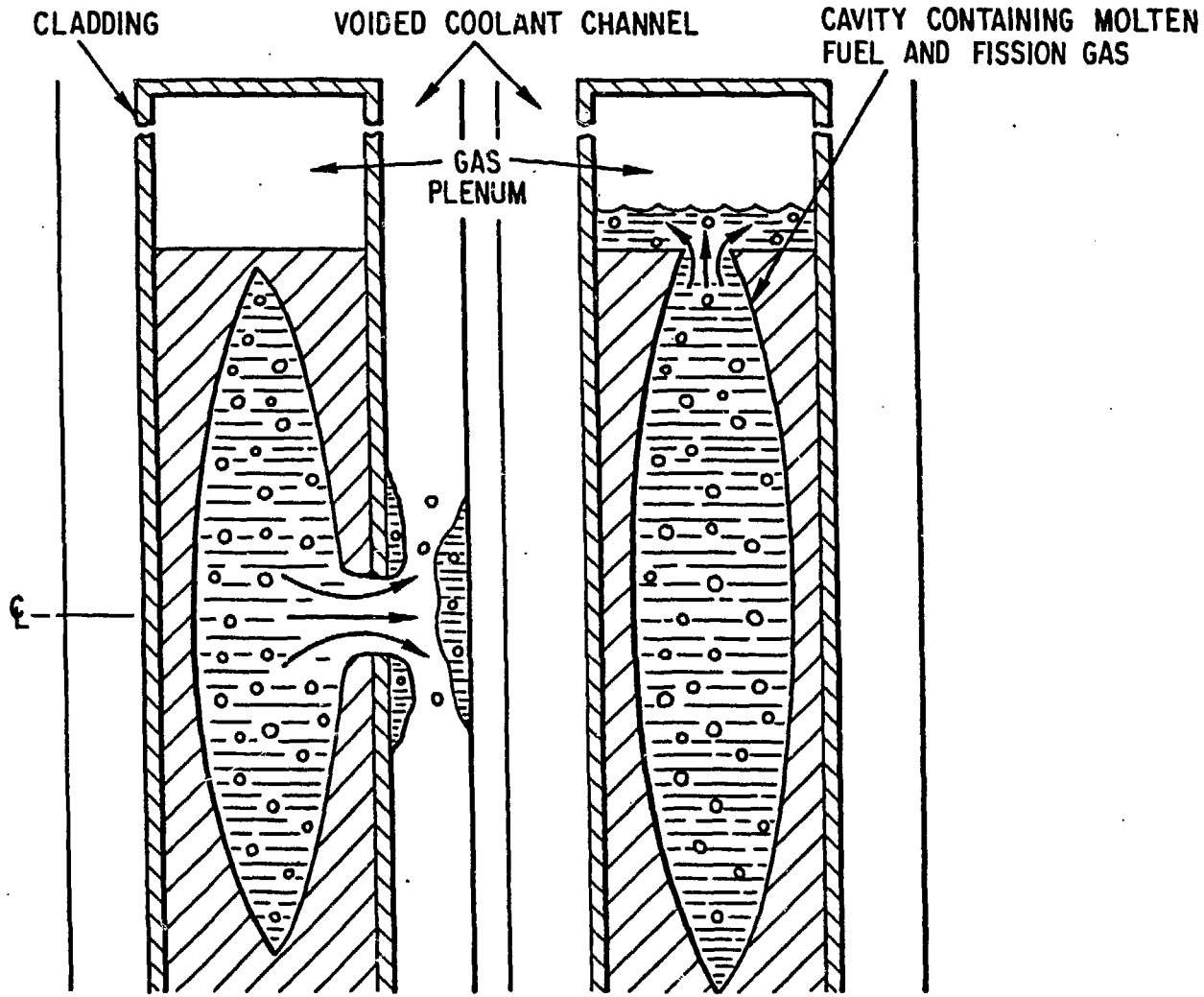
Table I
Failure Times for TREAT Tests M2, M3, M4

TREAT Test	Pin Number	Burnup (atom %)	Measured Failure Time (s)	DEFORM-5 Failure Time (s)
M2	1	0.35	No Failure	No Failure
M2	2	4.40	17.03	17.048
M2	3	7.90	17.05	17.148
M3	1	0.35	No Failure	No Failure
M3	2	4.40	No Failure	No Failure
M3	3	7.90	No Failure	No Failure
M4	1	0.00	No Failure	No Failure
M4	2	4.40	No Failure	No Failure
M4	3	2.40	14.99	14.654



Eutectic Penetration Rate

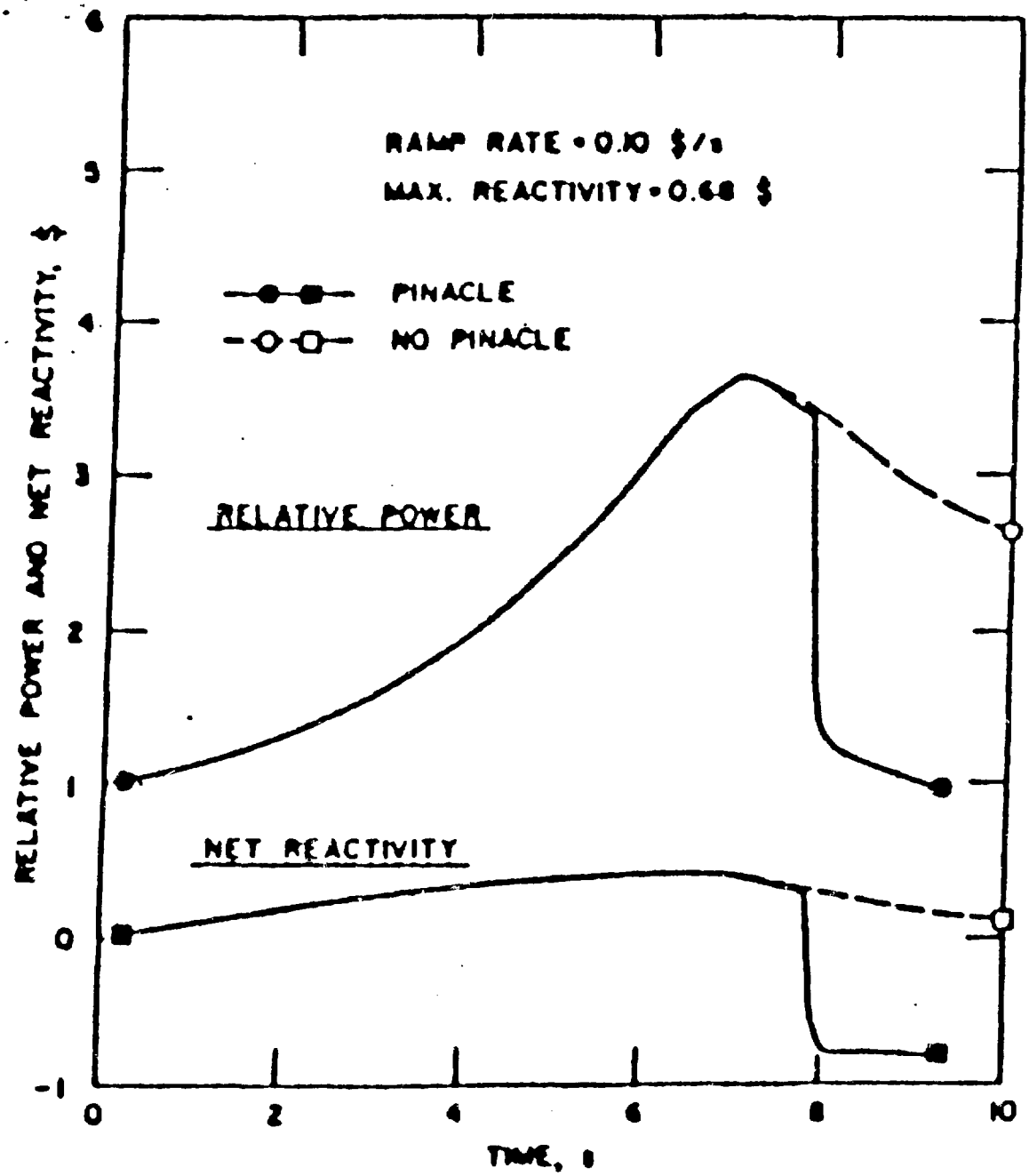
Fig 1



c. ONSET OF IN-PIN FUEL MOTION DUE TO CLADDING FAILURE

d. ONSET OF IN-PIN FUEL MOTION DUE TO CLADDING FAILURE REACHING THE TOP OF THE FUEL PIN

Fig 2



Small Metal Core TOP Analysis Resul

Fig 3

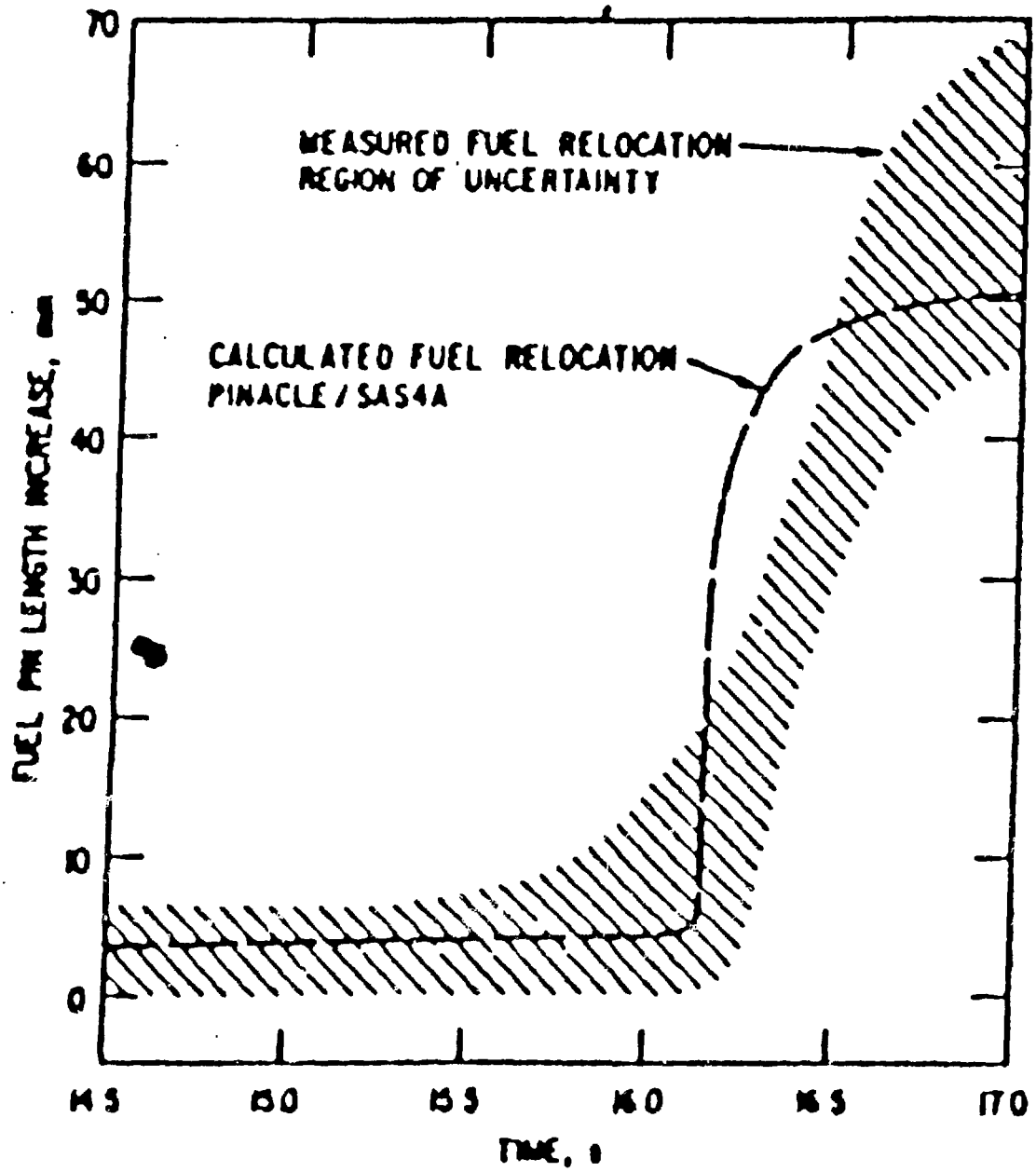
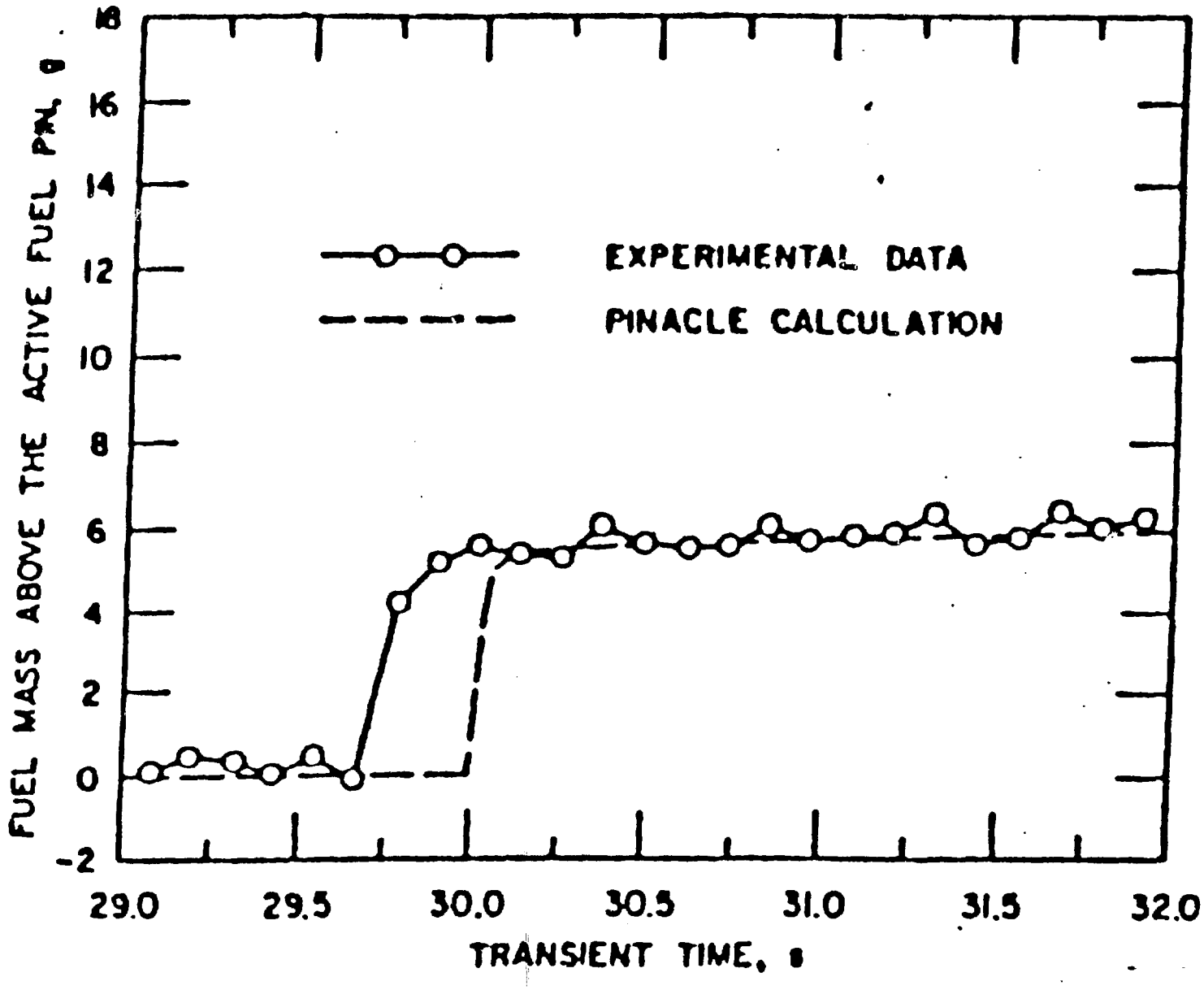


Fig 4

Fig. 5. M2 Experiment Analysis Results

Fig 5


FUEL MASS ABOVE THE ACTIVE FUEL PIN, g
18
16
14
12
10
8
6
4
2
0
-2
EXPERIMENTAL DATA
PINACLE CALCULATION
29.0
29.5
30.0
30.5
31.0
31.5
32.0
TRANSIENT TIME, s