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Fuel Relocation Modeling in the SAS4A Accident Analysis Code System*

by

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The SAS4A (Ref. 1) code system has been designed for the analysis of the initial phase of Hypothetical Core Disruptive Accidents (HCDAs) up to gross melting or failure of the subassembly walls. During such postulated accident scenarios as the Loss-of-Flow (LOF) and Transient-Overpower (TOP) events, the relocation of the fuel plays a key role in determining the sequence of events and the amount of energy produced before neutronic shutdown. This paper discusses the general strategy used in modeling the various phenomena which lead to fuel relocation and presents the key fuel relocation models used in SAS4A. The implications of these models for the whole-core accident analysis as well as recent results of fuel motion experiment analyses are presented. The inherent safety aspects related to the pre-failure fuel relocation are emphasized.

INTRODUCTION

1. During both LOF and TOP postulated accidents, the mismatch between the energy generated in the fuel pin and the energy removed by the coolant leads to the overheating of the fuel pin. During the early period, fuel relocation occurs only due to the axial expansion of the solid fuel pin, which generally reduces the core reactivity. As the accident proceeds, the inside of the fuel pin begins to melt, leading to the formation of an internal cavity as shown in Fig. 1.

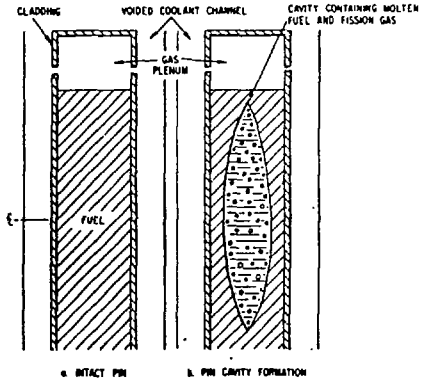

Fig. 1. Molten Fuel Cavity Formation

2. This cavity is filled with a mixture of molten fuel and fission gas and expands continuously, both radially and axially, due to continued fuel melting. The fuel-gas mixture in the cavity is pressurized due to the presence of fission gas and can move under the influence of the local pressure gradients. During this period fuel relocation occurs due to both axial extrusion of the solid fuel pin and the in-pin hydrodynamic relocation of the molten fuel. As long as the cavity maintains a bottled-up configuration the hydrodynamic fuel relocation is limited and tends to introduce a limited amount of negative reactivity.

3. As the cavity walls continue to melt there is a competition between two effects (see Fig. 2): a) First the radial extension of the cavity and cladding melting can cause the fuel pin failure. When the pin failure occurs the inner cavity is connected to the coolant channel which is at a significantly lower pressure and the molten fuel inside the pin is accelerated rapidly toward the pin failure location. This initial in-pin fuel relocation can have either a negative or positive reactivity contribution, depending on the failure location and axial failure propagation. The molten fuel is ejected into the coolant channel where it is dispersed axially. This fuel dispersal leads to a large insertion of negative reactivity and eventual neutronic shutdown of the core, and b) Second, the axial extension of the cavity can cause the cavity to reach the top of the fuel pin. When this happens the pressurized molten fuel in the cavity is connected to the lower pressure upper plenum and can relocate suddenly, leading to a large insertion of negative reactivity and possible shutdown of the core.

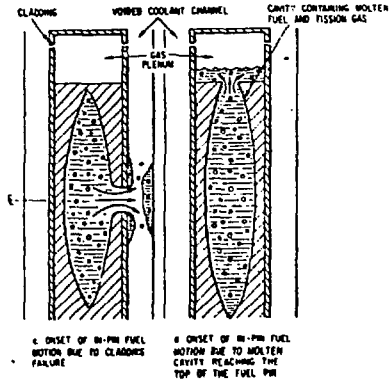

Fig. 2. Molten Fuel Relocation Initiation Modes

SAS4A FUEL RELOCATION MODELS

4. Following this chronology, the fuel relocation models in SAS4A can be grouped into two categories: models describing the fuel relocation prior to the fuel pin failure and models describing the fuel relocation after the pin failure has occurred.

5. The SAS4A models describing the fuel relocation prior to the fuel pin failure are DEFORM-4 (Ref. 2) and the recently developed PINACLE code (Ref 3). DEFORM-4 models the fuel pin mechanics and the axial expansion or contraction of the solid fuel. The PINACLE module is a transient hydrodynamic model describing the axial relocation of the molten fuel/fission-gas mixture in the pin cavity. After the pin failure has occurred, the fuel relocation is described by the LEVITATE (Ref. 4) and PLUTO2 (Ref. 5) models. LEVITATE and PLUTO2 are both Eulerian transient hydrodynamic codes. LEVITATE has been designed for the analysis of LOF initiated accidents, while PLUTO2 is used when TOP conditions are prevalent.

6. The following chapters describe the phenomenological models incorporated in the SAS4A fuel relocation modules and the influence of these models on the accident sequence of events. Results of the current validation efforts are also presented.

Solid Fuel Axial Expansion - DEFORM-4

7. In the response of a reactor system to hypothetical accident scenarios, one of the primary reactivity contributions arises from the axial expansion or contraction of the fuel relative to its initial nominal-power location. This effect is more significant for an oxide core, but even in a metal core with its relatively small thermal swings it contributes to the net reactivity level. Within the SAS4A code system, DEFORM-4 (Ref. 2) is responsible for modeling the axial expansion phenomenon and its related reactivity effects.

8. One of the prime factors that affects the magnitude, and even the sign, of the axial expansion reactivity feedback is the state of the fuel-cladding interface. Depending on the state of this interface three situations can occur: a) If the fuel is free to move within the cladding, then its response to the power temperature changes is based on its own thermal/mechanical properties and temperature changes. In this state, the cladding has no effect on the magnitude of the axial expansion; b) If, however, the fuel and cladding are bounded together through a mechanial or pressure bond, neither the fuel nor the cladding act independently. The axial expansion response in this state would be the net result of establishing a force balance between fuel and cladding. The combined system response would therefore depend on the thermal/mechanical properties of both the fuel and cladding, as well as the temperature changes in both; c) A third possibility occurs when the fuel is bonded to the cladding, but is in such a state due to high temperatures or cracking, that it has no strength. In this situation the axial expansion in controlled by the cladding and thus responds to the cladding temeprature changes. The fuel has no influence on the resultant axial expansion and reactivity. In this scenario, the cladding drags the fuel with it as it expands or contracts.

9. In DEFORM-4, all the above situations can be handled. The fuel can be assumed to expand freely, to be locked to the cladding with no strength, or locked to the cladding with a force balance solution between the fuel and cladding. In this latter case, fuel that is not in contact with the cladding and is above the highest locked interface is assumed to behave in a free fuel axial expansion manner. Because the cases a and c can be viewed as special cases of the general situation described by case b, this last approach provides the most realistic model of the various options available.

10. Besides the fuel-cladding interface condition, the axial expansion is influenced by the handling of the molten fuel region. In a generalized plane strain approach if the solution is calculated only over the solid fuel zone, the resultant reactivity will be much less than the reactivity calculated using a similar solution that includes the molten fuel region. The addition of the PINACLE model and its coupling with DEFORM-4 provides a mechanistic solution to this problem. DEFORM-4 calculates the axial expansion over the solid fuel region, but the molten cavity pressure calculated by PINACLE is also taken into account in the force balance determining the actual fuel axial expansion.

In-pin Molten fuel Relocation - PINACLE

11. The new PINACLE code (Ref. 3), which has been implemented in SAS4A Release 1.1, provides the capability to model the dynamic relocation of the in-pin molten fuel prior to cladding failure. This is a significant enhancement of the SAS4A capabilities. In the previous versions, while the post pin-failure fuel relocation was modeled in considerable detail by the LEVITATE and PLUTO2 models, the fuel relocation prior to pin failure could occur only due to axial fuel expansion.

12. The PINACLE code is an Eulerian two-phase transient hydrodynamic model describing the axial fuel relocation in a variable area geometry (see Fig. 3). It has been developed using the same computational variables and solution method as LEVITATE and PLUTO2. The compatibility of PINACLE with these two models allows SAS4A to provide a consistent treatment of the in-pin fuel relocation from melting to the end

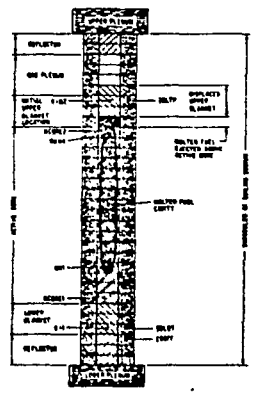

Fig. 3. Typical PINACLE Configuration

of the initiation phase. The components tracked by PINACLE are the molten fuel and two types of gas. The fission gas can exist either in the form of small bubbles, constrained by the surface tension, which do not contribute significantly to the cavity pressure, or as free gas, which pressurizes the surrounding molten fuel. The small bubbles coalesce in time and gradually become part of the free-gas field. To advance the numerical solution, PINACLE uses a staggered mesh, with the dependent variables, density, enthalpy and velocity. The density and enthalpy are defined at the center of each cell, while the velocities are defined at the cell boundaries. Only a bubbly flow regime is currently modeled, with the assumption that the molten fuel fission gas are well mixed and move with the same velocity at any given location.

13. As long as the cavity maintains a bottled up configuration, only limited fuel relocation occurs due to local pressure gradients. If the molten fuel cavity reaches the top of the active fuel column, the molten fuel can be ejected above the active fuel, displacing the upper blanket pellets which are assumed to move freely. This situation is illustrated in Fig. 3. The amount of fuel ejected above the active fuel column depends on the pressure difference driving the molten fuel and on the specific pin design, which can restrict the blanket pellet displacement.

Influence of the Pre-Pin-Failure Fuel Relocation on the whole Core accident Sequence.

14. The axial expansion of the solid fuel has a significant influence on the whole core response to accident initiatiors. As the fuel temperature increases, the fuel column tends to expand, introducing a significant amount of negative reactivity which influences the power level and the later accident sequence. For example, during a LOF in a large oxide core (Ref. 6) the reactivity contribution of the axial fuel expansion was calculated to be -1.07$. This calculation was performed using the force balance model in DEFORM-4, as described above. In a TOP scenario, the expansion reactivity will be larger than in a LOF because of the rapid temperature rise in the fuel. The faster the TOP, the more adiabatic the fuel behaves, the more rapid the temperature rise, and the greater the potential for larger axial expansion feedback. The oxide fuels, having a lower conductivity, will tend to exhibit a more adiabatic behavior during TOP events than metal fuel pins and thus have the potential for a larger axial expansion feedback. In LOF scenarios, the expansion feedback may be very small if a power reduction occurs, due to competing forces between the contracting fuel and expanding cladding.

15. The pre-failure in-pin molten fuel relocation can have a significant effect on the whole-core accident sequence of events. As the molten cavity develops the limited fuel relocation inside the cavity tends to introduce a small amount of negative reactivity. This occurs due to the relocation of small amounts of fuel from the higher temperature and pressure parts of the cavity to the lower temperature regions. In oxide fuel pins the molten cavity is located closer to the core midplane and the high temperature cavity region is closer to the high reactivity region than in metal fuel pins. Thus, the negative reactivity effect due to fuel relocation in a bottled-up configuration is more pronounced in oxide cores. Preliminary studies of a large oxide core undergoing a loss-of-flow accident (Ref. 6), indicate that the in-pin fuel relocation can introduce -0.05 $ of reactivity. The net effect of this relocation on the maximum power and on energy deposition is not significant.

16. When the molten fuel cavity extends all the way to the top of the pin prior to cladding failure, a significant and usually rapid in-pin molten fuel relocation occurs. The ejection of the molten fuel above the active fuel column can provide an important source of negative reactivity. This effect can play a particularly significant role in metal fuel cores and in oxide fuel cores subjected to a slow reactivity ramp. The metal fuel pins are more likely to benefit from this negative reactivity insertion mechanism that the oxide core, because the molten fuel cavity is biased toward the top of the pin in metal pins and thus is likely to reach the top of the pin earlier in the accident sequence.

17. Whole-core accident calculations performed with SAS4A/PINACLE analyzing a small metal fuel core indicate that signficant in-pin fuel relocation occurs both in TOP and LOF situations. In a TOP accident analysis with a 0.10 $/sec ramp, molten fuel was ejected above the pin about 1 sec prior to cladding failure in the lead channel. The negative reactivity insertion of about -1.1$ (see Fig. 4) caused the power to drop rapidly from 3 times nominal to nominal power and thus prevented cladding failure altogether. In a LOF analysis of the same core, rapid fuel relocation occurred about 0.8 sec prior to the time of cladding failure predicted without PINACLE. The rapid fuel relocation in the lead channel introduced about -1.00 $ reactivity and caused the power to drop rapidly to nominal levels. The cladding failure still occurs, but at significantly lower reactivity and power levels.

18. This calculation illustrates several interesting features of the in-pin fuel relocation effect. First, this effect appears to act as a fuse, coming into play only if other nega-

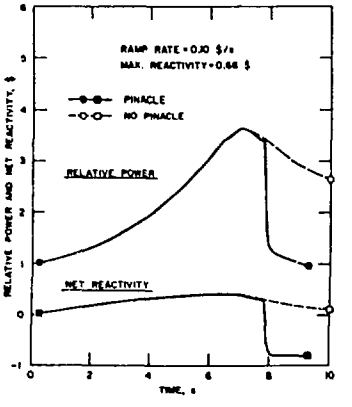

Fig. 4. Small Metal Core TOP Analysis Results

tive reactivity feedback effects are not capable of preventing the fuel pin centerline melting. Second, this effect introduces a fairly large amount of negative reactivity, about 0.10 $/ assembly, during a very short time, leading to a rapid drop in power. This means that the in-pin fuel relocation occurring in a limited number of assemblies can accommodate a large reactivity insertion and still prevent the fuel relocation in the majority of fuel assemblies in the core. This appears also to be valid for larger ramp rates, due to very rapid response of the axial fuel relocation. Thus, the in-pin fuel relocation can maintain the core integrity for most assemblies and satisfy the investment protection criterion for a large fraction of the acore even undere circumstances - where the other slower negative feedback mechanisms would fail to do so.

Pre-Failure Fuel Motion Validation

19. To validate the models incorporated in PINACLE, a comparison of computational results with experimental data is necessary. Several experiments have indicated the presence of significant pre-failure in-pin fuel relocation, both in metal and oxide fuel pins. In-pin fuel relocation was observed in the metal fuel experiments M2 and M3 (Ref 7). These experiments, conducted in the Transient Reactor Test Facility (TREAT) were performed to obtain information on the metal fuel behavior under TOP conditions. In-pin fuel relocation was also observed to occur prior to cladding failure in the oxide fuel experiments TS1 and TS2 (Ref. 8), simulating a $0.05/s TOP accident. The PINACLE model, used within the SAS4A framework, was able to predict the magnitude, timing and characteristics of the in-pin fuel relocation event in both the metal and oxide experiments (see Figs. 5 and 6).

Post-failure TOP Fuel Relocation - PLUTO2

20. PLUTO2 is the SAS4A module describing the post-pin-failure fuel relocation in unvoided or partially voided subassemblies. PLUTO2 describes both the fuel relocation and coolant the calculation, because it can treat molten voiding in these channels, until molten cladding motion begins or fuel pin breakup occurs. Beyond this time the LEVITATE Module takes over cladding motion, cladding ablation by molten fuel, and

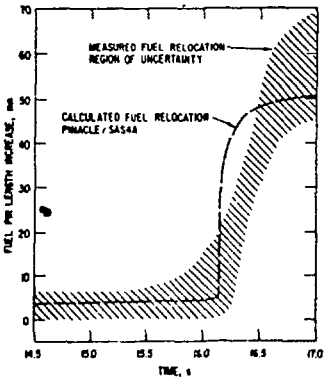

Fig. 5. M2 Experiment Analysis Results

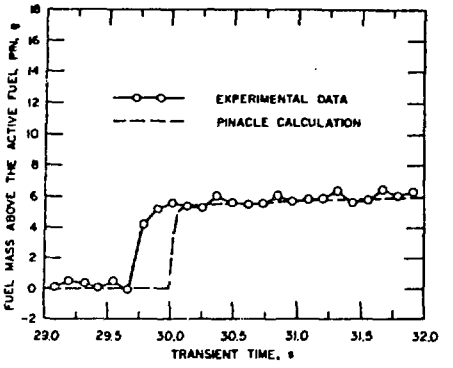

Fig. 6. TS-2 Experiment Analysis Results

fuel pin breakup. The geometry described by PLUTO2 is shown in Fig. 7.

21. PLUTO2 incorporates an in-pin hydrodynamic model which treats the flow of the fuel/fission-gas mixture as a compressible, one-dimensional flow with variable cross section. The fuel and fission-gas can be ejected into the channel at locations where cladding rupture is predicted. This ejection is governed by a pressure equilibration model, assuming pressure equilibrium between the pin cavity and the coolant channel at the rupture location.

22. An important recent development is the PLUTO2 interfacing with the PINACLE model. The molten cavity formation always preceeds the fuel pin failure and thus PINACLE is called before the initiation of PLUTO2. When PLUTO2 is initiated it continues the in-pin fuel relocation calculation using the PINACLE results as initial conditions. At the same time PLUTO2 initiates the coolant channel fuel relocation calculation. In the coolant channel, a one-dimensional two-fluid hydrodynamic model is used to heat the flows of fuel and sodium/fission gas mixture. The fuel can be in particulate, partially or fully annular, or a bubbly flow regime. The particulate flow regime is used when significant amounts of liquid sodium and molten fuel are present at the same location, leading to the fragmentation of the molten fuel ejected in the channel. This situation occurs early after PLUTO2 initiation. As the sodium voided region

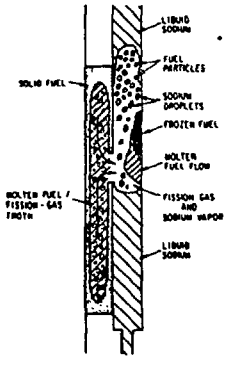

Fig. 7. Typical PLUTO2 Configuration

develops, the molten fuel is ejected in partially voided regions of the channel and the continuous fuel flow regimes, annular or bubbly, are used (Ref. 9). Eventually, when cladding melting begins or fuel vapor pressure becomes relevant, control of the calculation is transferred to LEVITATE, where the continuous flow regimes are predominant.

Post-Failure LOF Fuel Relocation - LEVITATE

23. The LEVITATE model (Ref. 4) describes the physical processes that occur in a subassembly during a loss-of-flow (LOF) accident. LEVITATE can be initiated at the time of fuel pin failure in a voided or partially voided channel or can be called to continue the PLUTO2 calculations in previously unvoided channels where the cladding begins to melt. LEVITATE models the fuel assembly in a one-dimensional geometry, assuming that all the pins in the subassembly behave coherently. Three basic thermal-hydraulic models are used to describe each subassembly: a) the hydrodynamic model describing the fuel pin cavity, which contains liquid fuel and fission gas, b) the hydrodynamic model describing the coolant channel, bounded by the outside cladding surface and the hexcan wall, and c) the heat transfer and melting/freezing model describing the solid fuel pin stubs, which separate the coolant channel from the pin cavity. A typical LEVITATE configuration illustrating the code capabilities is presented in Fig. 8. LEVITATE describes a large spectrum of physical phenomena

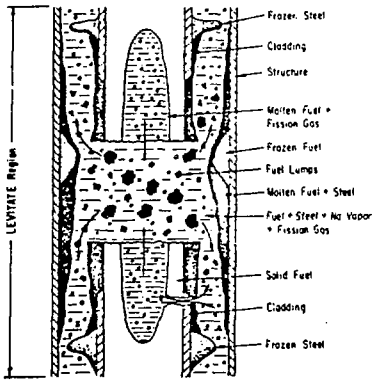

Fig. 8. Typical LEVITATE Configuration

such as fuel pin melting and disruption, cladding ablation, continuous fuel-steel flow regimes, fuel-steel freezing and plug formation and a tight coupling with the sodium slug dynamics. LEVITATE also describes fuel chunk formation and relocation, fuel ejection from the pin cavity into the channel and cladding rip propagation. The components which are tracked by LEVITATE are: a) liquid fuel and steel, b) solid fuel and steel and c) liquid sodium, sodium vapor, fuel vapor, steel vapor and fission gas. LEVITATE calculates three velocity fields, associated with the 3 component groups listed above. However, a separate mass balance is maintained for each of the nine components listed. The local flow regime and geometry determine the momentum and energy transfer between various components. Mass exchange between various components can occur due to melting, freezing, vaporization or condensation.

INFLUENCE OF THE POST-PIN-FAILURE FUEL RELOCATION ON THE WHOLE CORE ACCIDENT SEQUENCE

24. When the cladding failure occurs, the cavity is connected to the coolant channel and a local drop in the cavity pressure occurs. This lower pressure causes the molten fuel in the cavity to the accelerated towards the failure location and then ejected into the channel. Once in the channel, the hot molten fuel generates higher local pressures and is accelerated towards the core perisphery. The net reactivity effect of the post-failure fuel relocation is thus the result of two competing effects: a) the in-pin fuel motion, which moves the fuel towards the failure location and b) the coolant channel fuel motion which moves the fuel away from the failure location. The failure location and subsequent axial failure propagation play a very important role in determining the fuel reactivity effect. When the failure location is close to the core center, as it usually happens in oxide cores subject to a LOF or a fast ramp TOP, the in-pin motion tends to introduce positive reactivity, while the channel dispersive fuel motion introduces negative reactivity. In the early stages of the initiating phase, the positive reactivity effect of the in-pin motion can dominate, leading to a temporary positive reactivity insertion.

25. Rapid axial fuel failure propagation, which can occur when a long section cladding is near melting at the time of failure, can significantly reduce this initial positive reactivity addition by reducing the in-pin fuel relocation toward the failure location. This reactivity behavior, exhibiting a temporary positive reactivity contribution followed by rapid fuel dispersal and negative reactivity insertion was observed in a number of oxide fuel experiments, both LOF and TOP and is examplified by the LO7 experiment described below.

26. When the failure location is close to the top of the core, however, the situation is changed. Because the in-pin fuel motion accelerates the fuel towards the low worth regions, and the channel motion remains predominantly dispersive and biased towards the top of the core, there is no positive reactivity contribution due to post-failure fuel motion. Both the in-pin and channel fuel motion introduce negative fuel reactivity and contribute to the neutronic shutdown. This negative reactivity insertion due to post-failure fuel motion was observed in metal fuel TOP experiments M2 (Ref. 7). Because of the temperature profiles characteristic for metal fuel pins, the failure location in metal cores is biased towards the top of the pin and tends to occur at the very top in a large number of accident scenarios. In general, the failure location in metal cores will be considerably higher than in oxide cores, for similar accident conditions, leading to a more favorable negative reactivity effect due to post-failure fuel relocation.

Post Failure Fuel Motion Validation

27. Analysis of a number of TREAT experiments has been undertaken with PLUTO2 and LEVITATE

either separately or as an integral part of SAS4A with excellent results, (Refs. 10, 11, 12, 1). The level of agreement for both the timing and extent of fuel motion and the approximate reactivity worth is good and this gives a high degree of confidence in the phenomenology embodied in the codes.

28. An experiment recently analyzed with SAS4A is the LO7 PFR/TREAT experiment (Ref. 12). This is an excellent test of code performance as it covers the full range of conditions described by PLUTO2 and LEVITATE. LO7 is a fast ramp TUCOP simulation where fuel pin failure occurs at midplane and for about 10 ms the fuel relocation is dominated by the in-pin fuel motion. Since the failure site is at midplane, this leads to a momentary positive increase in reactivity caused by in pin fuel relocation towards the failure site. The ejected fuel contacts the sodium, vaporizing it and fragmenting into fuel droplets. These are swept up and down along with the void interfaces. Additional fuel leaving the failed pins moves in an annular flow along the flow tube and cladding. This fuel melts the cladding and extends the breach from an initial length of 0.091 m (one tenth of the fuel column) to 0.455 m. The pin bundle is then predicted to disrupt, and a transition is made from PLUTO2 to LEVITATE. The results are summarized in Fig. 9 which compares the hodoscope data in the form of relative worth, and the SAS4A calculated worth including the effect of fuel leaving the hodoscope field of view, (Refs. 11, 12).

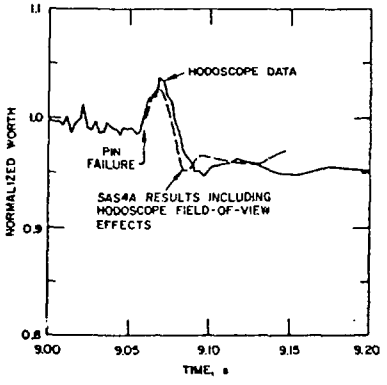

Fig. 9. LO7 Experiment Analysis Results

CONCLUSIONS

29. Significant progress was achieved in the development and validation of SAS4A fuel relocation models. Recent development efforts have concentrated on the modeling of resulted in-pin fuel relocation and have resulted in the introduction of the new modules PINACLE and DEFORM-4. These modules have been designed to handle both metal and oxide fuel pins. The validation effort has continued, concentrating also on the pre-failure stage of the accident. The integrated SAS4A code system has been used successfully in the analysis of the metal fuel tests M2 and M3 and the oxide fuel tests TS-1 and TS-2. The analysis of the LO7 LOF test, including the post-failure fuel relocation, was also completed successfully.

30. The current modeling and validation activities continue to be centered on the sequence of events occurring prior to fuel pin failure and emphasize the inherent safety characteristics of the core. Particular attention is devoted to the development of new modeling capabilities for the metal fuel cores.

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