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INTRODUCTION

This paper describes recent work directed towards the validation of the metal fuel version of the SAS4A accident analysis code. The SAS4A code system [1] has been developed at Argonne National Laboratory for the simulation of hypothetical severe accidents in Liquid Metal-Cooled Reactors (LMR), designed to operate in a fast neutron spectrum. SAS4A was initially developed for the analysis of oxide-fueled liquid metal-cooled reactors and has played an important role in the simulation and assessment of the energetics potential for postulated severe accidents in these reactors. Due to the current interest in the metal-fueled liquid metal-cooled reactors, a metal fuel version of the SAS4A accident analysis code is being developed in the Integral Fast Reactor program at Argonne.

During such postulated accident scenarios as the unprotected (i.e. without scram) loss-of-flow and transient overpower events, a large number of interrelated physical phenomena occur during a relatively short time. These phenomena include transient heat transfer and hydrodynamic events, coolant boiling, and fuel and cladding melting and relocation. Due to strong neutronic feedbacks these events can significantly influence the reactor power history in the accident progression.

The numerical simulation of the accident sequence relies on the interaction of a large number of models describing the relevant physical phenomena. The verification and validation of the integrated code system are essential in order to establish the credibility and reliability of the results. The validation of the metal fuel version of SAS4A relies to a large extent on the simulation and analysis of integral in-pile metal fuel experiments. These experiments reproduce, under controlled conditions, the phenomenological sequence expected to occur in a postulated

accident. A series of experiments is designed to explore the changes in the accident sequence when certain parameters are varied within the range of interest. The simulation and analysis of these experiments is used to provide an early, "in-house" validation of the computer models. As the models evolve and new experiment simulations are performed the range of conditions for which the code has been tested increases. All experiment simulations are rerun periodically to verify that the code is capable of modeling correctly a wide range of situations. Eventually, the validation process is formalized by freezing a SAS4A release version and having all the experiment simulations rerun by an independent group. The paper presents the results of a recent SAS4A simulation of the M7 TREAT experiment [2].

DESCRIPTION OF THE SAS4A CODE SYSTEM

The SAS4A code has been designed to simulate in detail the events taking place in a liquid metal-cooled reactor core during a postulated severe accident. In order to simplify the simulation and reduce the computational costs the reactor core is subdivided into channels, with each channel representing a number of fuel assemblies. All the fuel assemblies in a channel are assumed to behave in an identical manner. Thus, a single fuel pin, its cladding and an associated amount of coolant and structure is taken to be representative of all the pins assigned to a particular channel.

The calculation in each channel is advanced independently. At any given time the calculation in a channel will be performed by the phenomenological module required by the accident sequence. Thus, before the onset of fuel and cladding melting and relocation the channel behavior might be simulated by the coolant dynamics or boiling models, as necessary. When the central part of the fuel begins to melt, the in-pin fuel relocation is described by the PINACLE model [3]. The mechanical response of the fuel pin cladding and cladding failure are simulated by the DEFORM-5 model [4]. Finally, if the cladding has failed and both in-pin and out-of-pin fuel relocation is expected to occur the channel behavior is described by the LEVITATE model [5]. The thermal response of

the fuel and cladding is calculated at all times by the heat transfer model. The response of the hydraulic circuit external to the core is calculated by the PRIMAR-4 model. When simulating a whole-core accident, the reactivity effects are estimated by the TSPK module, which periodically recalculates the reactivity feedback and reactor power using first order perturbation theory and point kinetics. When simulating an integral experiment, as described in this paper, the power history is input and the neutronic feedback calculation is used only as an integral measure of the fuel relocation dynamics.

M7 EXPERIMENT DESCRIPTION

The M7 experiment [2] was performed in the Transient Reactor Test Facility (TREAT) as part of the M series of experiments, designed to provide critical information regarding key safety issues for Transient Overpower (TOP) unprotected accidents in metal fuel cores. These issues include a) the potential for large negative reactivity insertion due to prefailure, in-pin molten fuel relocation, b) the overpower margin to cladding breach, and c) the potential for large negative reactivity insertion due to post-failure ex-pin and in-pin fuel relocation. The test train used in M7 was a Mark-IIIC integral loop (Fig. 1) designed to test two fuel pins simultaneously, but under separate hydraulic conditions. The TREAT fast neutron hodoscope was used to monitor the fuel relocation.

The integral loop contains the fuel test section, an Annular Linear Induction Pump (ALIP) for coolant circulation, and instrumentation. For the M7 experiment, the loop was inserted in the TREAT reactor and the fuel pins were subjected to an overpower condition characterized by full coolant flow and an exponential power rise with an 8s period.

Two fuel pins were tested in the M7 experiment. One was a ternary alloy U-Pu-Zr pin with D9 cladding irradiated to 9.8 a/o burnup. The pretest length of the ternary pin was 358 mm. The other fuel pin was a U-Zr binary alloy with HT9 cladding, irradiated to 2.9 a/o burnup. The

pretest length of the binary pin was 373 mm. The fuel pins exhibited different behavior during the experiment and they have been analyzed separately.

Baseline thermal conditions in the test fuel were selected to reflect the nominal reactor conditions. These include a peak linear power rating of 40 KW/m, a coolant inlet temperature of 630 K, and a 150 K coolant temperature rise. The power rise was rapidly terminated upon detection of cladding breach in the ternary pin. The maximum overpower level achieved was in the neighborhood of four times nominal.

ANALYSIS OF RESULTS

The metal fuel version of SAS4A was used for the analysis of the M7 experiment. Because the experiment involved two different pins, two SAS4A one-channel problems were set up and analyzed separately. The SAS4A code was used in an integrated mode, i.e., the transient was analyzed with SAS4A from beginning to end, with all decisions about the initiation of new modules being made by the code. There were several such decisions as the two fuel pins used in the experiment behaved quite differently.

The fuel disruption modules used in the analysis were PINACLE [3] describing the prefailure in-pin fuel melting and relocation, DEFORM-5 [4] describing the cladding penetration by fuel components and eventual failure, and LEVITATE [5] describing the post-failure fuel relocation both in the coolant channel and inside the fuel pin cavity. These models were used in the integrated SAS4A framework and constantly interacted with other SAS4A models, such as the fuel pin heat transfer and the single-phase coolant dynamics modules.

An important result of the SAS4A calculations is the dynamic fuel redistribution, which, in an actual reactor leads to changes in reactivity and power. Thus, this experiment analysis emphasizes the comparison between the calculated and experimentally observed fuel relocation.

In the analysis of the fuel relocation results, both computational and experimental, the relative fuel reactivity worth has been used as an integral measure of the fuel relocation. The relative fuel worth is calculated by dividing the fuel reactivity worth at any given time by the corresponding worth calculated at time zero, when the fuel is still in the original configuration. The fuel reactivity worth is a sum over all axial cells of the fuel mass in each cell multiplied by the corresponding reactivity worth per unit mass. The axial worth distribtuion used in the SAS4A calculations presented here is the same as the worth curve used in the hodoscope analysis of the experimental data [6].

The relative fuel worth based on the hodoscope measurements is shown in Figs. 3 and 5 for the two fuel pins, together with the SAS4A results. Good agreement was obtained between calculations and measurements. This agreement is observed for the analysis of both fuel pins, although the behaviors of the binary and ternary fuel pins were quite different during the M7 experiment. The binary pin exhibited rapid in-pin relocation but cladding failure did not occur. The ternary pin exhibited relatively slow prefailure in-pin fuel relocation, followed by cladding failure and rapid fuel dispersal in the coolant channel. These sequences of events were correctly described by SAS4A. The results obtained in the analysis of the two pins are described separately below.

A. Binary-Alloy Pin

1. Review of Experimental Results: No indication of cladding failure was observed during the experiment. A sudden elongation of the fuel column of about 2.7% of the pin length was observed, starting at 17.328 s, with most of the elongation occurring within 5 ms. This elongation, signaling the beginning of in-pin molten fuel relocation, led to a relative worth decrease of -1.85%.

2. Results of SAS4A Calculations: As the power level increases, the temperatures in the fuel pin begin to increase leading to the formation of a molten fuel region, originally located near the top of the

fuel pin. At 16.64 s this molten fuel region has become large enough to trigger the initiation of the in-pin fuel motion model PINACLE. Although the molten fuel in the cavity can now move, the bottled, pressurized cavity configuration allows only very small fuel movements, and thus the changes in relative fuel worth are limited. As shown in Fig. 3, the relative fuel worth remains virtually constant between the time of PINACLE initiation (point A) and the time of rapid fuel relocation onset (point B).

Prior to PINACLE initiation, the pressure in the gas plenum is calculated assuming that the fission gas can relocate freely within the fuel pin, through the open fuel porosity, leading to rapid pressure equilibration between the fuel pin and the gas plenum. After the initiation of the PINACLE model, model, the calculated pressure in the gas plenum continues to increase. However, the pressure in the molten cavity now evolves independently. The fission gas relocation model assumes that the formation of a sizeable molten fuel region will obstruct the previously open porosity paths linking the fuel pin region to the pin plenum. Thus, after the initiation of PINACLE the fission gas remaining in the solid fuel is not redistributed axially. As the molten cavity extends both axially and radially this gas becomes available for cavity pressurization. The pressures in the molten fuel region and in the pin plenum now increase at different rates, with the pressure in the molten fuel cavity increasing faster than the plenum pressure.

As the power continues to increase, there is now a competition between two possible events: a) the cladding failure due to cladding eutectic penetration and pressure loading, and b) the breach of the cavity solid top, leading to rapid molten fuel relocation above the original fuel column and cavity depressurization. Both events are tracked by SAS4A, with the cladding failure being calculated by the DEFORM-5 model and the breach of the cavity top calculated by the PINACLE model. The breach of the cavity top is predicted to occur first at 17.355 s, leading to a rapid in-pin fuel relocation above the top of the original fuel column. The physical configuration modeled by the PINACLE model at this time is illustrated in Fig. 2. The in-pin fuel relocation leads to a sudden increase in the effective pin length and an associated decrease in the

relative fuel worth. The corresponding sudden increase in the pin length was observed in the experiment to occur at 17.328 s. Both the timing of the in-pin rapid fuel relocation and the associated relative worth changes are in good agreement with the experimental results, as shown in Fig. 3.

The cladding life fraction calculated by DEFORM-5 reaches an all-time maximum value of 0.08, well below the value of 1.0 which indicates the cladding failure. The binary pin cladding never failed in the experiment and the fuel relocation remained confined within the cladding.

B. Ternary-Alloy Pin

1. Review of Experimental Results: A slow, monotonic prefailure elongation of the fuel column began at about 15 s into the transient and continued until the occurrence of cladding failure. Information from the TREAT fast-neutron hodoscope indicates that cladding failure at the top of the fuel pin occurred at 17.711 s. The timing of the failure is verified by the coolant flow reduction beginning at 17.719 s and the location of the pin failure was confirmed by post-test neutron radiography. More than one half of the fuel was ejected into the coolant channel and the ex-pin fuel motion was almost entirely upward with the fuel being dispersed downstream into a configuration that allowed continued coolability by flowing sodium [6].

2. Results of SAS4A Calculations: The power increase leads to increases in the pin pressure and temperatures. The fuel temperature increase leads to the formation of a molten fuel region, which originates near the top of the fuel pin. The in-pin fuel motion model, PINACLE, is initiated at 15.143 s, due to the beginning of fuel melting and early onset of axial in-pin fuel relocation. The breach of the cavity top occurs very early after the onset of fuel melting. This allows a continuous pressure equilibration between the expanding molten cavity and the pin plenum, achieved by gradually relocating more fuel from the cavity to the space above the fuel column. This behavior is illustrated in Fig. 5, which shows a gradual worth decrease between points B and C. The physical configuration modeled by the PINACLE model during this time is

similar to the configuration shown in Fig. 2. The cladding failure is calculated to occur at 17.713 s, in agreement with the experimental failure time of 17.711 s. This failure, which is calculated to occur at the top of the fuel pin, leads to the initiation of LEVITATE, which models both the ex-pin and in-pin fuel relocation after the cladding failure. The physical configuration modeled by the LEVITATE model is illustrated in Fig. 4.

The cladding failure leads to the ejection of molten fuel from the pin cavity into the coolant channel, causing a local depressurization in the cavity and an increase in the coolant channel pressure. The pressure gradients cause an upward acceleration of the in-pin molten fuel towards the failure location and an upward acceleration of the molten fuel in the coolant channel. Both the in-pin and ex-pin fuel motion reactivity effects are strongly negative, leading to a rapid decrease in the relative fuel worth, as shown in Fig. 5.

The calculated relative fuel worth reaches a value of 0.66 at 20 ms after cladding failure and then remains virtually unchanged. As shown in Fig. 5, the minimum relative worth based on hodoscope results is 0.74, with a more likely value corrected for the neutron flux decrease of less than 0.6. At the end of the LEVITATE calculation, at 275 ms after failure, or transient time 17.988 s, the calculated relative fuel worth has reached a value of 0.63.

As the power level decreases, the calculated pressure gradients in the pin cavity and in the coolant channel decrease sharply and the molten fuel begins to freeze. These effects lead to the leveling-off of the worth curve following the initial steep decrease. The calculated amount of fuel ejected into the coolant channel is 39.8 g, or about 52% of the original fuel pin mass. This number compares well with the experimental observation that one-half to two-thirds of the fuel was expelled from the cladding [6].

CONCLUSIONS

A detailed simulation of the M7 TREAT metal fuel experiment was performed using the metal fuel version of the SAS4A accident analysis code. This is the first integrated SAS4A metal fuel experiment simulation to cover the whole transient sequence from pin heatup and melting through in-pin fuel relocation and failure, to post-failure ex-pin and in-pin fuel relocation. The results are shown to be in good agreement with many experimentally-recorded results including timing, characteristics and magnitude of the key fuel relocation events. The fact that SAS4A was able to model quite well the very different behavior of the two fuel pins used in the experiment provides an increased degree of confidence in the SAS4A metal fuel accident analysis capabilities.

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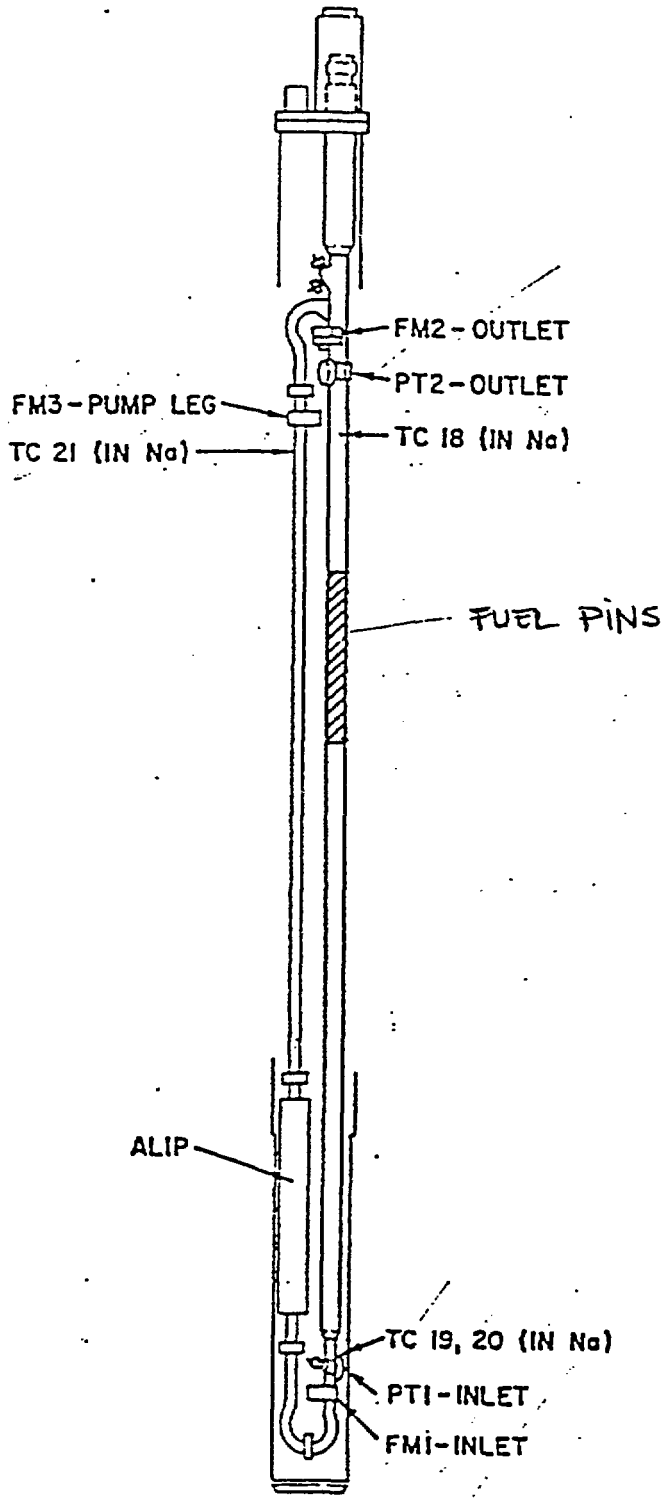

Fig 1. Experimental loop

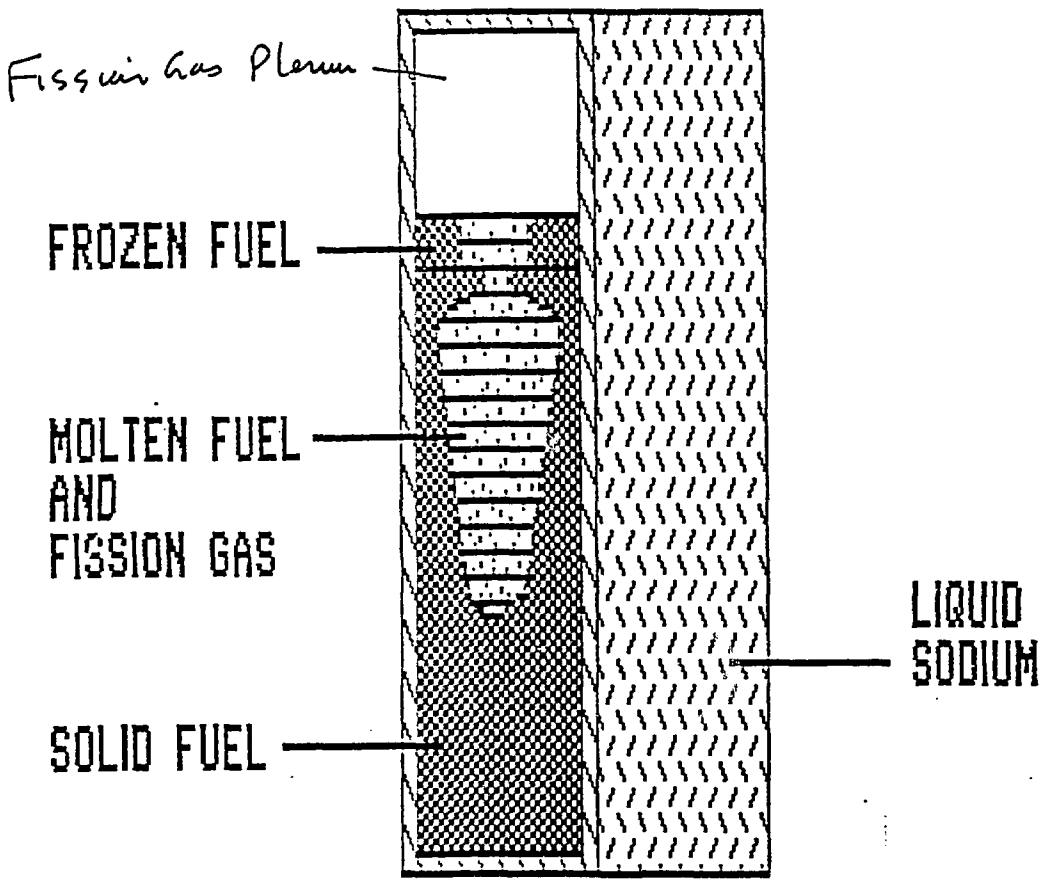

Fig 2 PINACLE configuration after the onset of in-pin fuel relocation in the binary fuel pin

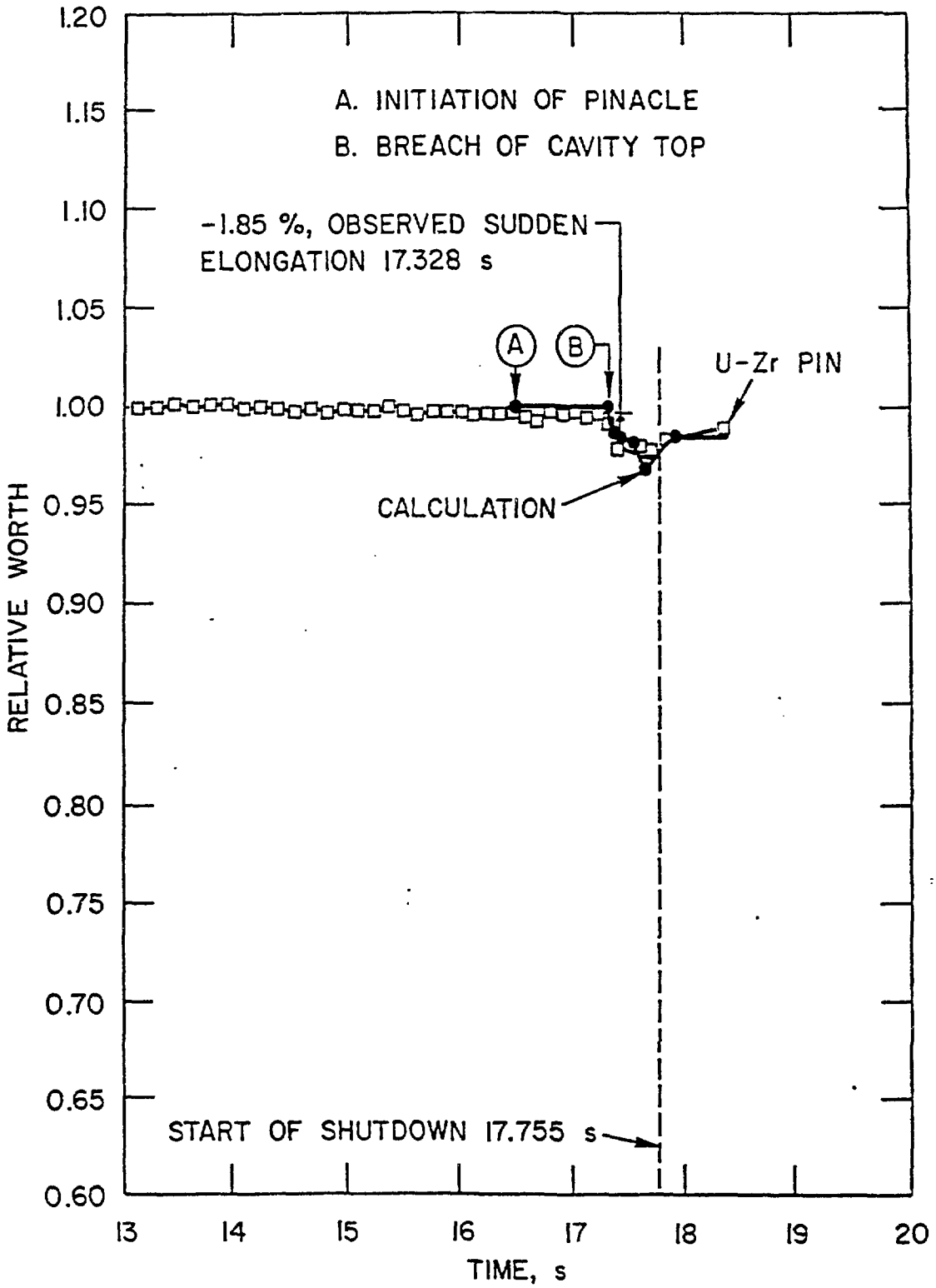

Fig. 3 Relative worth history for the binary fuel pin

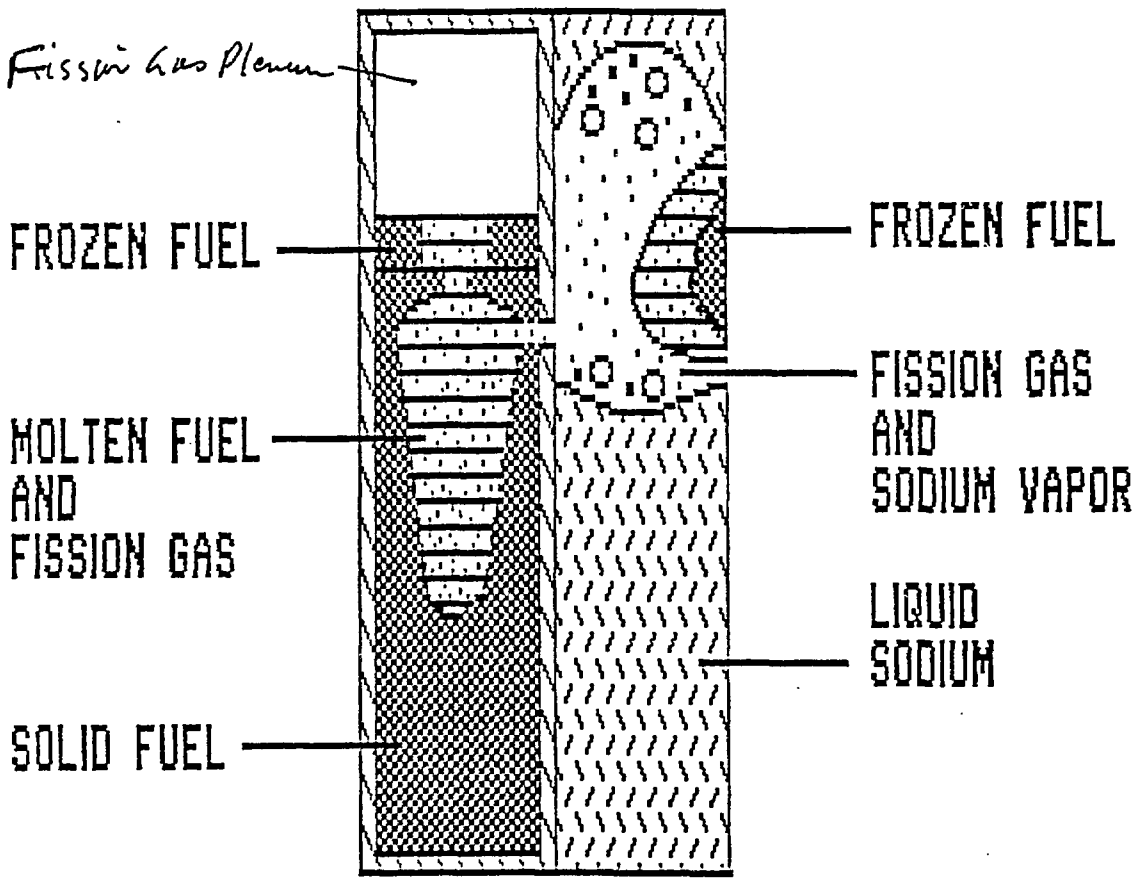

Fig 4. LEVITATE configuration after the cladding failure in the fuel pin

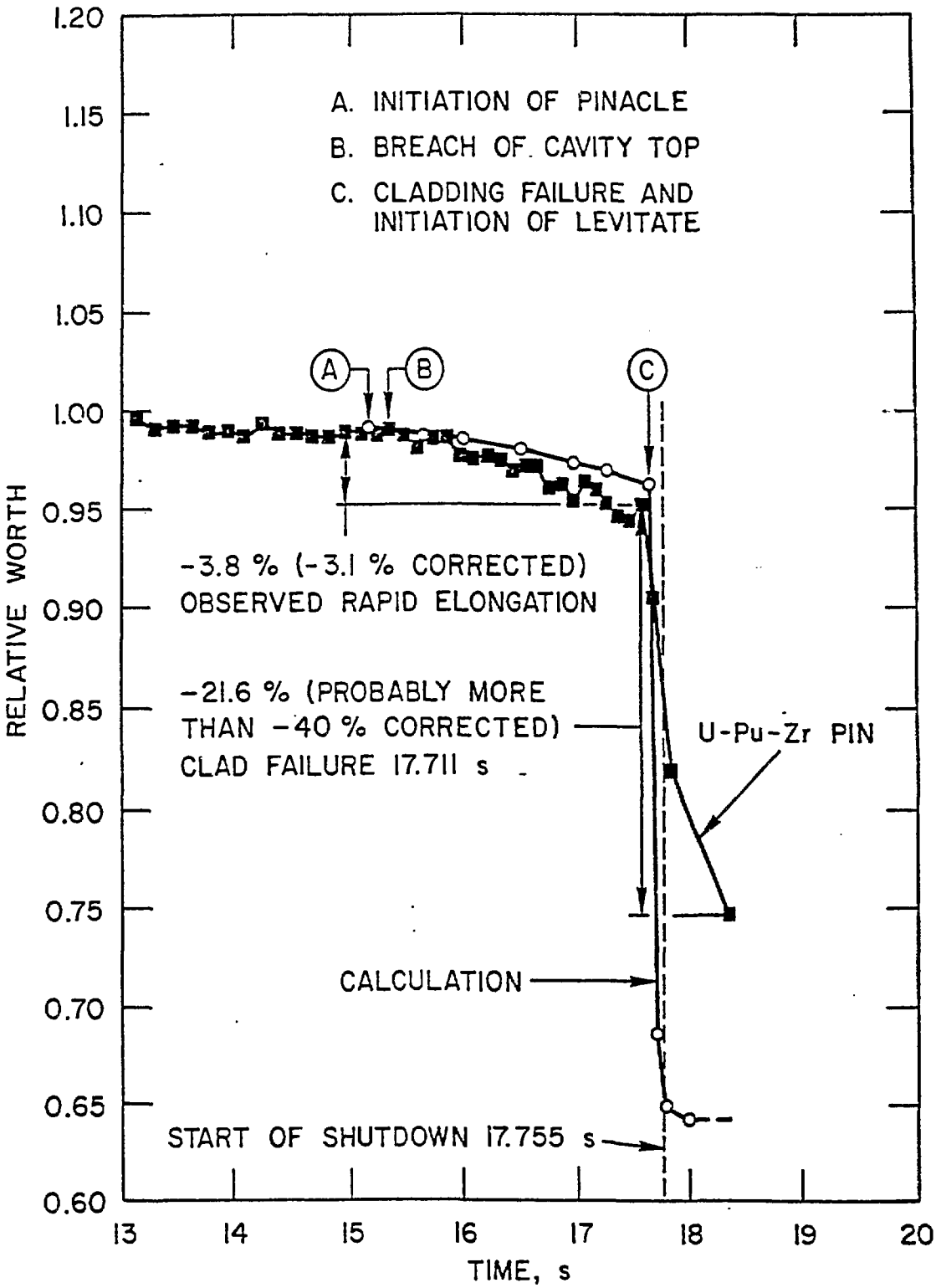

Fig 5. Relative Worth history for the ternary fuel pin