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FUEL RELOCATION MODELING IN THE SAS4A ACCIDENT ANALYSIS CODE SYSTEM*

by

A. M. Tentner and K. J. Miles
Reactor Analysis and Safety Division
Argonne National Laboratory
Argonne, Illinois 60439

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SAS4A [1] is a new code system which has been designed for analyzing 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 also presented.

During both the 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 reduces the core reactivity (Fig. 1a). As the accident proceeds, the inside of the fuel pin begins to melt, leading to the formation of an internal cavity. 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 fuel vapor and can move under the influence of the local pressure gradients. The general effect of the in-pin fuel motion is to reduce the core reactivity but the magnitude of this effect depends on the cavity configuration, as explained later. During this period, fuel relocation occurs

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due to both the axial expansion of the solid fuel pin and the in-pin hydrodynamic relocation of the molten fuel (Fig. 1b). As the cavity walls continue to melt and the cladding temperature approaches the melting point, the continued pressurization of the cavity leads to fuel pin failure. Due to the fuel-pin failure, 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. The molten fuel is ejected into the coolant channel where it is dispersed axially (Fig. 1c). This fuel dispersal leads to a large insertion of negative reactivity and is responsible for the neutronic shutdown of the core.

Following this chronology, the fuel relocation models in SAS4A can be grouped into two categories:

1. Models describing the fuel relocation prior to the fuel pin failure and
2. Models describing the fuel relocation after the pin failure has occurred

The SAS4A models describing the fuel relocation prior to the fuel pin failure are DEFORM-III [2] and the recently developed PINACLE [3] code. DEFORM-III models the fuel pin mechanics and calculates the axial fuel relocation. This fuel relocation is due to (1) expansion or contraction based on fuel density changes in response to temperature changes, (2) expansion or contraction based on the changes in the mechanical state of the fuel (e.g., boundary conditions), and (3) expansion or contraction due to volume changes caused by the volatile and solid fission products. The third mechanism, generally referred to as extrusion, has only recently been modeled in DEFORM-III [4]. This mechanism is particularly effective in metal fuels where a phase change leads to a significant weakening of the fuel. This weak fuel allows extensive creep and bubble expansion to occur, leading to axial fuel expansion and negative reactivity insertion.

The PINACLE module, which has been completed recently, is an Eulerian transient hydrodynammic model describing the axial relocation of the molten fuel-fission gas mixture in the pin cavity. This model is active prior to the occurrence of the fuel pin failure and interacts closely with the pin mechanics module, DEFORM-III, by providing the cavity pressures used in DEFORM-III as boundary conditions. The PINACLE model has been developed for the metal fuel version of the SAS code. The calculations indicate that pre-failure in-pin fuel motion can play a significant role in metal fuel cores, due to the formation of a molten region which extends all the way to the top of the pin and can allow significant in-pin molten fuel relocation prior to cladding failure. PINACLE has also been coupled to the oxide fuel SAS version. The negative reactivity effect of the prefailure in-pin fuel motion is significantly smaller in oxide cores than in metal fuel cores because the molten cavity in the oxide fuel pins generally does not extend to the top of the pins and thus maintains a pressurized-bottle configuration, which allows only a limited axial fuel relocation.

After the pin failure has occurred, the fuel relocation is described by the LEVITATE [5] and PLUTO2 [6] models. LEVITATE is an Eulerian transient hydrodynamic code that has been designed for the analysis of Loss-of-Flow accident situations, while PLUTO2 is used where transient overpower conditions are prevalent. Both codes model the in-pin and the out-of-pin fuel motion, and their results have ben shown to be in good agreement with the experimental data in a number of experiment analyses, such as L6, L7, L07 for LEVITATE and L8, H6, AX1 for PLUTO2. These codes incorporate sophisticated models such as fuel freezing, fuel flow regimes, and a tight coupling with the sodium slug dynamics which were not modeled in the older SAS3D whole core Accident Analysis Code. LEVITATE also models the in-pin fuel motion during LOF accidents, cladding ablation, and fuel/steel mixing. It is shown that the net reactivity effect of the early fuel relocation is determined to a large extent by the balance between the in-pin fuel relocation, which generally tends to have a compactive character, and the fuel relocation in the coolant channel, which has a dispersive character and tends to reduce the core reactivity. The location and timing of the initial fuel failure, as well as the fuel pin failure propagation, directly influence the balance between the in-pin and out-of-pin fuel motion and play an important role in determining the sequence of events and the energetics of the postulated accident. Historically, the initial fuel pin failure criterion used in SAS4A was the local fuel melt fraction. This criterion predicts well the time of failure, as shown by comparisons with the experimental data. It does not predict very well the failure location but it provides a conservative estimate, as it will always predict the failure to occur near the center of the core. This model also has the disadvantage that is inconsistent with the mechanistic axial failure propagation models used in LEVITATE and PLUTO2. These models, which become operational after the fuel pin failure, use a pressure burst criterion to define the local cladding failure. A recent addition to the SAS4A code is a mechanistic model for the prediction of the initial pin failure. This model, which is similar to the model used in the fuel motion modules, shows that while in voided channels the failure occurs around the traditional fuel melt fraction of 0.5, the melt fraction reached at failure can be significantly higher in channels where the presence of liquid sodium causes the cladding to remain relatively cold and thus stronger. This effect increases the incoherency between different channels and will tend to reduce the maximum power level and energy deposition before neutronic shutdown. This effect is counterbalanced, however, by the fact that the axial pin failure propagation proceeds slower than before, due to consistency between the initial failure and failure propagation models. The influence of the new failure models on the whole-core accident sequence is analyzed and illustrated by results obtained within the framework of the Whole-Core Accident Analysis (WAC) international exercise.

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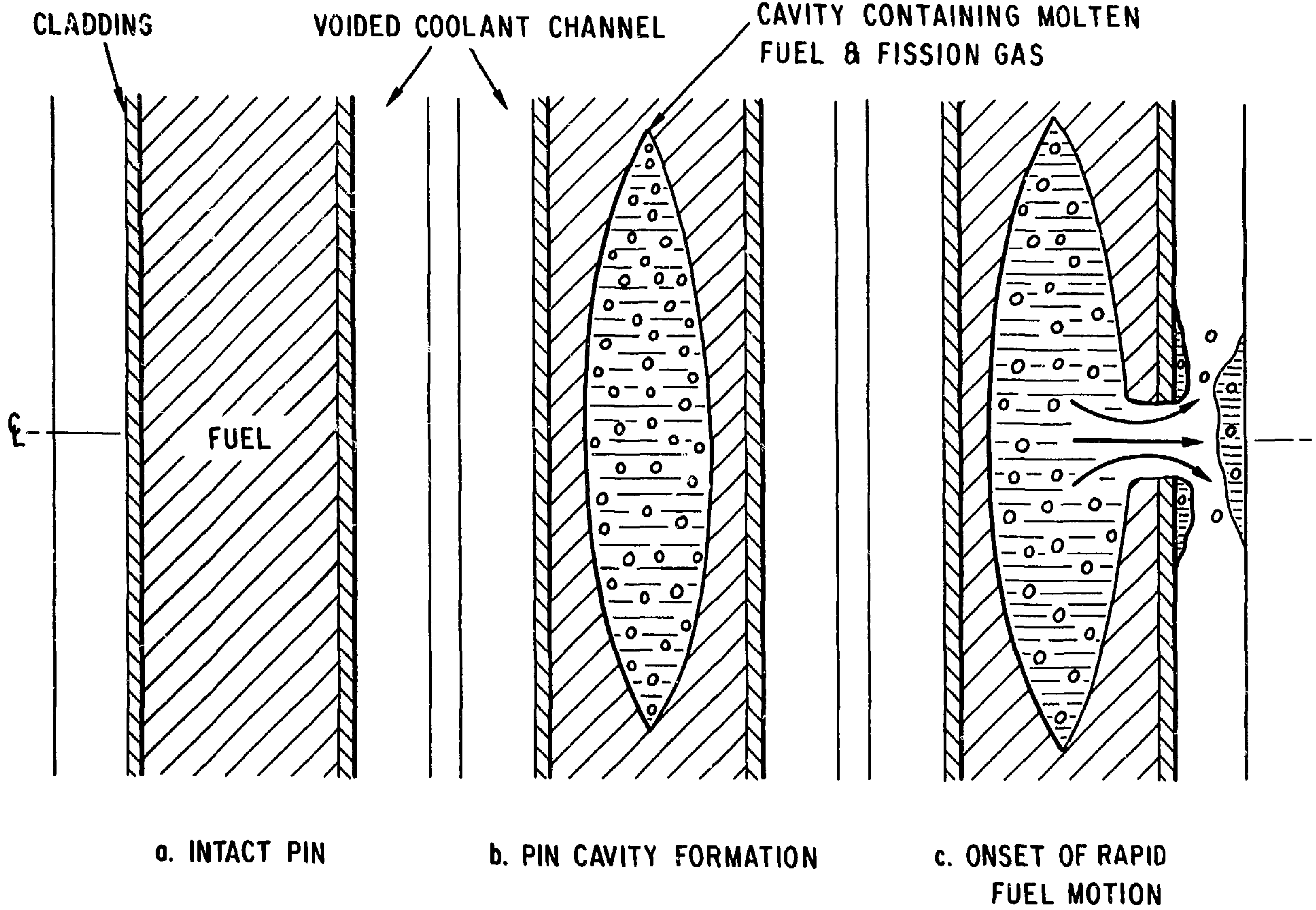

Fig. 1. Models of Fuel Relocation at Various Stages of a Hypothetical Accident