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In the PFR/TREAT experiments the fast neutron hodoscope has provided experimental data on post-failure material movement during Transient Overpower and Transient Under-Cooled Overpower events. Analyses of selected experiments have been done, using SIMMER-II and SAS4A, to validate these codes. Full results of these analyses are presented in the paper. The general conclusion that can be drawn from the analyses that have been made so far is that the hodoscope is providing data which has appropriate resolution in time and space and that the computer models which are being used by the USDOE and the UKAEA provide good representations of fuel redistribution.

INTRODUCTION

A prime objective of PFR/TREAT experiments has been to obtain data on pre- and post-failure material movement, principally that of fuel and sodium coolant, for validation of computer models of reactivity changes during hypothetical whole-core accidents. Specifically, experiments on 7-pin clusters of prototypic reactor fuel hae been selected for comparisons of code calculations with transient test data. Such test results include coolant flow, pressure, and temprature measured at the bundle inlet and outlet as well as structure temperatures measured along the pin bundle wall. An especially valuable feature of the PFR/TREAT experiments has been the ability of the fast neutron hodoscope to measure fuel motion. Hodoscope fuel motion measurements can be displayed in the form of two dimensional spatial distributions of fuel in time or spatially integrated for convenient comparisons with codes or evaluations of fuel worth. Details of the hodoscope and the analysis of hodoscope data are given in Reference 1.

To date, material motion in four PFR/TREAT tests have been analyzed and the results of computations and experiment compared. The UK has analyzed the high ramp rate Transient Over-Power (TOP) test LO1 and LO2 with the SIMMER II

code, and the US has analyzed the low ramp rate TOP L03 and the high ramp rate Transient Under-Cooled Over Power (TUCOP) test L07 with the SAS4A code. SAS4A analyses of three additional TUCOP tests of lower ramp rate: L04, L05, and L06 are currently underway. This paper presents results from analyses of the four tests L01, L02, L03, and L07. Because of its paramount importance of reactivity worth, computation of fuel motion and its comparison with hodoscope results during the transient and final results from Post-Test Examination (PTE) will be emphasized.

The SIMMER II (Ref. 2) and SAS4A (Ref. 3) codes, whose results are discussed here, span a broad range of modeling concepts, and in a very real sense complement one another. SAS4A envisions material motion taking place in an essentially intact pin bundle geometry; so its domain of usefulness extends through initial stages of core disruption. On the other hand, SIMMER II computes motions of core materials when in a more homogenized state, and its strengths emerge later on during the transition phase of the accident sequence.

All large computer codes written to analyze accidents in large plants tend to model averaged behavior of clusters and many pins and have great difficulty in explicitly modeling geometry and boundary conditions of small-scale experiments. By design, the 7-pin bundles tested were intended to simulate much larger assemblies, and non-prototypic features to small-scale were kept to a minimum. Thus, the ability of averaged calculations to successfully analyze material movement in the present experiments not only serves to validate the code which performed them but also support the relevance of the experiments to material movement in full-scale plants.

All of the PFR/TREAT tests discussed here simulate initiating phases of accidents; so SAS4A modeling should be most appropriate to experiment analysis, and good agreement is essential to SAS4A validation. By contrast, SIMMER II analyses of entire tests are far more ambitious, and much more qualitative agreement of calculations with experiments would be considered satisfactory for partial validation of models whose principal application lies in the transition phase.

SIMMER II ANALYSIS

The analyses of postfailure material motion that have been carried out with the SIMMER II code at Winfrith were done not only to understand phenomena occurring in particular tests but also to assess the capabilities of the code. The application of the SIMMER II code usually involves the preliminary use of another code to determine the initial conditions, from reactor steady state, for example. In the PFR/TREAT tests, the limitations of the TREAT facility leave insufficient time to establish a genuine steady state before the power transient. The SIMMER II code has therefore been used to compute the whole of the TREAT transient. The simple geometric representation of the test loop and the single phase conditions throughout most of the test in LO1 and LO2 allowed this approach to be adopted without excessive use of computer time.

A one-dimensional SIMMER II model was developed for LO1 and LO2 to model axial material motion with a minimum of complication. Initially only the test leg of the TREAT loop from the lower bend to the upper return tee was modeled using an array of 56 axial cells. One radial mesh cell in the SIMMER II model can represent (on average) fuel, cladding, sodium, and the fluted tube. The radial boundary, assumed to be adiabatic, is taken to be the outside of the fluted tube and so heat capacities and losses beyond the boundary are not included in this one-dimensional calculation.

LO2 ANALYSIS

In SIMMER II there is no mechanistic prediction of clad failire but, "breakup" of fuel is initiated at a preset value of fuel enthalpy, (or melt fraction). The average molten fuel fraction for the axial mid-plane was calculated by FRAX to be $\simeq 0.7$ at failure time for LO2 and the failure was mechanical. This value was then used in the SIMMER II analyses of LO2. It was found that a good match to the sodium outlet temperature could be obtained with a heat transfer coefficient of 2750 $W/m^2 \cdot K$. However, this led to a calculated fuel break-up time which is significantly later than the experimental observation based on flowmeter and pressure transducer disturbances. A lower heat transfer coefficient, 1375 $W/m^2 \cdot K$, gave better agreement on the failure time, but the sodium outlet temperature match was not as good as the

previous one. For postfailure calculations it was considered more important to match the melt fraction than the sodium temperature. A melt fraction of 0.7 and an effective heat transfer coefficient of 1375 $W/m^2 \cdot K$ were therefore adopted as the best compromise for the SIMMER II calculation for L02. It is not to be expected that these values of effective heat transfer coefficient would be consistent with those used in the L01 calculation, since they are used here to "tune" the calculation of break up to an earlier failure caused by a different mechanism.

Since L02 was performed with pre-irradiated fuel while L01 was done with fresh fuel, it was necessary to introduce fission gas into the SIMMER II model for L02. The quantity of retained fission gas was calculated and divided equally between intragranular gas and intergranular gas. However, there is no representation in SIMMER II of fission gas previously released from the fuel that could subsequently be involved in the fuel dispersal. To take some account of this reservoir, the total gas in SIMMER II has been doubled (to approximately the theoretical maximun produced) and the extra gas was added to the intragranular component. For simplicity, the gas was assumed to be distributed uniformly in the axial direction.

The scenario of events which occur after fuel failure, according to the SIMMER II calculations, is the following. At failure the fuel has melted in the vicinity of the midplane but the cladding has not yet melted. Sodium boiling has occurred where the sodium has come in contact with the molten fuel. At 0.11 s after failure, fuel melting extends beyond the region of the midplane and some of the once-molten fuel has now refrozen into solid particles which have spread out beyond their original position in the fuel. Some of the heat loss from the fuel has melted the cladding and this exists as molten steel with a little refrozen into solid particles. The boiling region has extended, and sodium vapor pressure exceeds the fission gas pressure. The fission gas in the vapor field has spread beyond the position of the fuel, mainly toward the outlet. At 0.19 s after failure, a significant quantity of fuel has melted and a greater proportion of the melted fuel is in the form of solid particles with less remaining as liquid, the solid particles have moved further from the center. Of the cladding that has melted, a small amount of steel has refrozen onto the fluted tube, and some has refrozen into solid particles. Sodium voidage extends over a longer length and produces a higher sodium vapor pressure in the middle of the fuel length. The fission gas, which is concentrated at the ends of the fuel, has also increased its

pressure. At 0.43 s after failure the fuel has stopped melting, the power having fallen to a negligible level. All the melted fuel has refrozen; some is in the form of solid particles which have spread well beyond the original fissile length; the remainder is refrozen solid in the middle of the fuelled length. The fluted tube has melted where the liquid fuel has refrozen on it. The cladding has melted over most of the original fuel length and is still in the form of molten steel; it has not moved very far axially. The fission gas has collected at the end of the fuelled length but is at a lower pressure than before, while the sodum vapor pressure has increased due to continuing fuel coolant interaction.

LO1 ANALYSIS

In the SIMMER II analyses of LO1 two cases, each with a different heat transfer coefficient, were analyzed. In the two cases considered different values of fuel enthalpy were assumed so that breakup at the observed failure time with each of the effective heat transfer coefficients would be ensured. Thus, break up at liquidus was associated with a heat transfer coefficient of 5500 W/m^2K, and break up at a melt fraction of 0.4 with a heat transfer coefficient of 11,000 W/m^2K. These values reflect, for example, changes that might be expected in the fuel-cladding gap resistance. The effect of the change in heat transfer coefficient was observed by comparing experiment and analysis values for outlet sodium temperatures and the inlet and outlet flow rates. The outlet temperature rise was better matched by the higher heat transfer coefficient, although for both cases the results from the analyses rose slower than did the experiment. The most significant difference between the two cases was seen on inlet flow; there, an initial flow increase with the lower coefficient and a flow decrease with the higher coefficient suggested that an intermediate value would probably give the best match to the constant flow observed in the test. With respect to the outlet flow, the difference between the two cases is only apparent in the timing and magnitude of the flow excursion. From detailed fuel modeling calculations using the FRAX code, it has been found that a lower value of the fuel melt fraction, i.e., 0.8, would be more consistent with the initiation of cladding failure in LO1. The resulting SIMMER II calculations are similar to those described for LO2.

COMPARISON WITH HODOSCOPE DATA

The single measure which best summarizes the agreement, or lack of it, between theory and experiment as well as characterizing the nature of the fuel motion is the relative worth. To obtain this, the time-dependent fuel mass distribution is weighted with a typical reactor worth distribution and thus it is representative of the reactivity effects of the fuel motion if it had occurred in a reactor. Figure 1 shows the worth history for LO1 based on the hodoscope results; it also shows the worth history based on the SIMMER II calculations. The results from the case with the higher heat transfer coefficient at fuel break-up agree better with the hodoscope results.

Axial distributions of fuel mass obtained from the SIMMER II calculations have been compared with preliminary hodoscope results of fuel motion. For LO1, the overall effect observed with the hodoscope is one of net fuel losses from the third quarter of the fuel column (Z/L = 0.5 to 0.75), and accumulations of fuel just above the top of the fuelled length. The net losses in that region amount to about 30 to 40% of the fuel cross-section by the end of the transient. The accumulation above the fuelled length is of roughly equivalent mass.

Preliminary hodoscope results from LO2 have also been compared with appropriate SIMMER II results. Towards the end of the LO2 transient, the hodoscope results show a general loss of mass from the bottom two thirds of the fuelled length, with a small accumulation just below the original fuel position and a larger accumulation at, and just above the top of the original fuel. SIMMER II results show the fuel losses to be roughly symmetrical about the center, with movement of fuel material away from the center and accumulated at the two ends of the fuelled length. Note that this is a natural consequence of the SIMMER II failure model when the axial power profile is symmetrical. Axial fuel distributions derived from hodoscope data at ~300 ms after fuel failured are compared with those calculated with SIMMER II in Fig. 2. This figure shows that the rather symmetrical distribution calculated by SIMMER II has a large accumulation at the bottom of the fuelled length than was obtained from the analysis of the hodoscope data.

COMPARISON WITH PTE

The present SIMMER II model does not continue the calculations as far as the final resolidified state because it does not include heat losses to the adiabatic insert and the loop wall which contribute to the refreezing of the molten materials after the power burst. The significance of these difference can be evaluated by a comparison of the distribution of materials at the termination of the calculations with the findings of the posttest examination.

In the PTE for LO1, fuel disruption was extensive and complete over the upper two-thirds of the fuel zone. This is consistent with the fuel distribution at the termination of the calculations; at that time the fuel is calculated to be intact for the bottom 0.1 or 0.2 m, above which it is in the form of solid particles with a small amount of molten liquid. According to the PTE, the cladding failed from 0.3 m below midplane to above the top of the fuelled length. At the termination of the calculation the cladding was calculated to be melted from the bottom of the fuel column to just below the top of the fuel. The flow tube was observed to have failed over nearly the same length. The PTE showed upper and lower metal blockages; the lower blockage filled a grid spacer 0.3 m below midplane while the upper blockage was a complete blockage nearly 0.1 m thick above the top of the fuel. The calculations show accumulations of liquid steel in the bottom and top quarters of the fuelled length, the largest at the top. On solidification these could easily account for the observed blockages.

In the PTE for LO2, it was found that fuel disruption was extensive and complete for the upper three quarters of the fuel zone. In SIMMER II calculations there was fuel disruption over three quarters of the fuel length, centered about the axial midplane. Cladding failure was observed from near the bottom of the fuel to above the highest point of the intact fuel length. Cladding failure was calculated to occur over nearly the whole of the original fuelled length. The PTE shows the flow tube failed from about quarter height to above the top of the fuel. In the calculations, the flow tube failure occurred from about quarter height to a point just below the top of the original fuel. Upper and lower metal blockages were also observed in the PTE, the lower from near the bottom of the fuel to about quarter height, and the upper just above the top of the fuelled length.

The most significant difference between the experiments is the presence of fission gas in LO2. This increases the pressure developed at fuel failure which therefore occurs at a lower melt fraction, and maintains a higher pressure over a longer length of the failed fuel in LO2 than in LO1. Nevertheless, it can be seen from the PTE that there are no significant differences in the extent of fuel disruption and metal blockages between LO1 and LO2. This characteristic is also apparent from the final material distributions calculated by SIMMER II for these two tests.

In both LO1 and LO2, SIMMER II calculations indicate fuel movements away from midplane towards the ends of the fissile length. In the case of LO1, the movements calculated with SIMMER II agree with those observed with the hodoscope, but in LO2 the SIMMER II results show a uniform dispersal of the fuel whereas the hodoscope results show larger fuel accumulations above the fuelled length than below the fuelled length.

SAS4A ANALYSIS

Analyses have been performed with SAS4A for the low ramp rate TOP Test LO3 and the high ramp rate TUCOP Test LO7. The analysis for LO7 is described first.

Fuel failure analysis is carried out within SAS4A by using a model of the average pin bundle at the end of the flattop portion of the transient ans subjecting this to the transient seen by the hottest pin. However, for the fuel motion analysis, it is not the hottest pin but the average bundle that must be considered. It was found that the failure time difference between the hottest pin and average pin is not very significant for fuel motion. For example, for LO7 it is only ~10 ms even when the effects of fuel impingement are not taken into account. Furthermore, six of the seven pins lie in the average-to-hot range, with the central pin power being considerably depressed. Thus all six outer pins (containing all the fuel that is molten at failure time) can be expected to fail within a few ms of each other. The Moorhead meltthrough model (Ref. 4) gave an accurate determination of time and location of failure; fuel motion was initiated in SAS4A by requiring all seven average pins to fail at the failure time and location (Z/L = 05-0.6) predicted and observed. This gave an artificial coherency to the initial

stages of fuel motion, but the overall effect should be small. One check on this effect is that a hot-pin calculation (i.e., seven hot pins failing simultaneously) produces results analogous to the average pin case.

The validation of SAS4A, especially in the areas of fuel pin failure and post-failure fuel motion, is almost completely based on the analysis of in-pile experiments, particularly those performed in TREAT. Analysis of the PFR/TREAT series of experiments using SAS4A not only supplements and clarifies the data, but also help define areas where the modeling is inadequate and should be improved. If a consistent prediction of the results of these experiments can be made without specifically tailoring the code input to reproduce the observed results, then a high degree of credibility will be achieve when the code is used for reactor design or licensing studies.

Following this validation approach, the strategy behind the L03 and L07 analyses has been to model the loop used for the experiments within the framework of the standard version of the SAS4A code and see if the code can accurately reproduce the results of the experiments. The fuel motion modules in SAS4A, PLUTO2 and LEVIATE, required many input parameters. In order to properly test the code, only those values recommended in the SAS4A documentation were used, with one exception concerned with flow regimes at the PLUTO/LEVITATE transition. Exactly the same input was used for both the L03 and L07 analyses, which is valuable check on the applicability of PLUTO2.

In addition to the failure and fuel-motion comparisons, the DEFORM-IV module was used to characterize the pre-irradiated fuel used in the tests. Using recommended mixed-oxide fuel parameters and an approximation to the actual operating history, good agreement was calculated for peak burnup, fission gas production and release, porosity and fuel-clad gap as measured in sibling pins.

L07 ANALYSIS

At the time of pin failure, the average pin in L07 is calculated to have a molten fuel fraction of 84% at the failure site, Z/L=0.55, with a gas pressure of 10.3 MPa. The boiling region extends only from Z/L=0.95 to 1.0; therefore when the code enters the PLUTO2 module, fuel is ejected into liquid sodium and fragments into particles assumed to be of radius 250 μm. Use of

smaller particle sizes gave poor descriptions of events. The rapid heat transfer associated with this causes the coolant to be accelerated upwards and downwards, collapsing the vapor bubble in the boiling region. Conditions in the loop offer more resistance to downward voiding, so the fuel and coolant are more likely to be swept upwards.

Initially the fuel motion towards the failure site within the pin dominates, and there is an accumulation of fuel at the midplane, as observed by the hodoscope. This fuel is rapidly dispersed as the fuel-coolant interaction drives the coolant slugs towards the ends of the channel, carrying fuel droplets with them and creating a voided region around the failure site. After the initial expulsion, the fuel that is ejected from the pin enters a voided region and flows as a film on the fuel pins and structure. By 19 ms after failure, the cladding in the calculational node above the original failure site, Z/L=0.6 to 0.7, has been heated to melting by the annular fuel flow and the breach is extended. At 30 ms past failure, it extends further to Z/L=0.8 to 0.9, and at 41 ms to Z/L=0.4 to 0.5. This last extension of the breach coincides with the transition to the LEVITATE module. Figure 3 give a time history of mass distributions calculated with SAS4A while Fig. 4 shows the observed distributions observed with the hodoscope. Comparison indicates excellent agreement on the nature of the fuel motion, i.e., momentary accumulation near midplane followed by dispersal. Figure 5 shows the worth history for L07 based on hodoscope data; it also shows two worth histories based on the SAS4A results. One, labelled SAS4A WORTH, is based solely on the mass distribution calculated with SAS4A. The other, labelled ADJUSTED WORTH, is adjusted to account for material which leaves the field-of-view of the hodoscope. It is recognized that material does leave the hodoscope field of view; however it is difficult to take this into account in a straight-forward manner in the preliminary hodoscope data analysis. Agreement between the data and the ADJUSTED WORTH curve are excellent, showing that 1) the field of view effects are important in reconciling observation and prediction, and 2) that the hodoscope results can underestimate the extent of the fuel sweepout if the field-of-view correction is not taken into account.

A "hot-pin" case was run to test the validity of the assumptions for initial conditions at failure. In this case the pin is hotter and thus has a higher pressure at failure. It was found that the results for the initial

dispersal are essentially the same but that there is slightly more accumulation. This shows that the fuel motion results are not a sensitive function of the transient energy and also that the average pin concept is adequate for describing the general features of the fuel motion. However, the flow and pressure calculations following failure do not agree with the data in the hot pin case. Using the average pin representation, the timing and magnitude of pressure pulses and flow oscillations are calculated quite well. The hot pin case produces oscillations that are to much too large and too frequent, indicating that the average pin case is the better overall choice.

In summary, the overall picture that emerges for L07 is as follows. Fuel pin failure occurs with a pin pressure of about 10 MPa (average), and for about 10 ms the ejection of fuel is dominated by the internal gas pressure. Since the failure site is at midplane, this leads to a momentary positive increase in reactivity. The ejected fuel contacts the sodium, vaporizes it and fragments into particles of 250-μm radius. These are swept up and down along with the void interfaces. Additional fuel leaves the failed pins and moves in an annular flow along the flow tube and pins. This fuel melts the cladding and extends the breach from an initially assumed 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 to LEVITATE. No flow tube failure was observed, nor it is predicted until much later in the transient, so comparisons to the experiment are still meaningful. One effect that is not included in the calculations is that of the spacer grids. These are important freezing surfaces. While their presence will not noticeably affect the fuel worth history, they could be important in considerations of blockage formation.

L03 ANALYSIS

The low ramp rate TOP Test L03 was analyzed in a similar manner. The overall picture that emerged from that analysis is the following. Fuel pin failure occurred at about 10 MPa in the L03 fuel pins and for 10 ms or so the pressure dominated the motion of fuel. Fuel contacted sodium, vaporized it and fragmented it into drops of 250-μm radius. These were swept up and down with the void interfaces. Subsequently, fuel which left the failed pins moved as an annular flow upon the flow tube and pins in the vapor region and froze

in cooler regions. After 35 ms the pressure in the fuel pins fell to the loop pressure and the ejection was essentially over. The net effect of the motion was dispersive. At about 50 ms the remaining pins failed leading to a further fuel motion event (not modeled here). When experimental comparisons are possible the agreement is good.

Figure 6 compares the hodoscope results and the SAS4A results for L03. It is clear that the fuel motion is dispersive and that SAS4A provides an excellent simulation of this first phase of the fuel motion, particularly the initial gradient. When some of the details of the hodoscope worth data are examined in Fig. 6, it is noted that well into the dispersal, at 13.6 s, there is a slight gain that might be more than an experimental fluctuation; this gain is not present in worth calculated with SAS4A. This apparent gain correlates with mass leaving the hodoscope field-of-view and furthermore SAS4A predicts mass to be leaving at this time.

CONCLUSIONS

The comparisons presented here show that the PFR/TREAT experiments have provided valuable data which have been used not only for validation, but also the development and refinement of the accident analysis codes SIMMER II and SAS4A. The major features of the four experiments presented in this report are calculated very well, and in the SAS4A analyses many of the details are also reproduced. Further analysis of the PFR/TREAT series will be used to expand the validation data base for these codes and increase the confidence level when these codes are used for the calculation of hypothetical whole-core accidents.

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