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SAS VALIDATION AND ANALYSIS OF IN-PILE TUCOP EXPERIMENTS

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ABSTRACT

The validation of the SAS4A accident analysis code centers on its capability to calculate the wide range of tests performed in the TREAT (Transient Reactor Test Facility) in-pile experiments program. This paper presents the SAS4A analysis of a simulated TUCOP (Transient-Under-Cooled-Over-Power) experiment using seven full-length PFR mixed oxide fuel pins in a flowing sodium loop. Calculations agree well with measured thermal-hydraulic, pin failure time and post-failure fuel motion data. The extent of the agreement confirms the validity of the models used in the SAS4A code to describe TUCOP accidents.

INTRODUCTION

The SAS4A code (1) is the latest in the series of SAS reactor accident analysis codes. Historically, the code has been used mostly for the analysis of hypothetical whole-core accidents. While the code has been used previously to analyze in-pile experiments, such analyses required some modifications for the modeling of a single, closed-loop system such as the TREAT loop. These modifications were necessary because the key modules were not fully integrated in the SAS4A code system. These early analyses were useful in the validation of individual SAS4A modules such as PLUTO2 (2) or LEVITATE (3), but did not address the validation of the integrated system. In addition, the early models did provide information about the nature of the tests, filling in details not available from the data.

Part of the validation of the current release version of SAS4A centers on the capability to calculate the wide range of tests which are performed in the TREAT in-pile experiments program. Some of these experiments are designed to simulate those accidents which the SAS code is used to model. Only when the analysis code can consistently predict the results of such experiments without being modified specifically to match the measured results will the code attain a high degree of credibility for full-scale reactor accident calculations.

The strategy behind the L07 analysis and validation has been to model the Mark-IIIC loop used for the experiment within the framework of the SAS4A code, use the recommended or default values of as many input variables as possible, and see if the code can accurately reproduce the results of the experiment. While earlier TUCOP tests have been analyzed with earlier versions of the SAS code, the L07 analysis is the first to use the release version of SAS4A without special modifications, using recommended input variables whenever possible. The PRIMAR-4 thermal-hydraulics model is used to compute the loop characteristics during the test.

THE L07 EXPERIMENT

The L07 experiment (4) was a 7-pin test using full-length, bottom-plenum Prototype Fast Reactor (PFR) fuel pins, irradiated to an average burnup of 3.5 at-%, in an Argonne National Laboratory (ANL) Mark-IIIC flowing sodium loop. The pin bundle was supported by grids along its entire length, and had an active fuel height of 0.914 m. The goals of this test included investigation of pin failure with colder cladding than previous tests into a coolant channel that was just beginning to void, and to look for evidence of any tendency for escaping fuel to accumulate around the failure site as the sharpness of the power burst increases. This test was designed to reach a peak power about 40 times nominal, thus extending the maximum power range investigated previously in the L6 and L7 loss-of-flow experiments (5), where maximum power was 10-20 times nominal.

The transient power profile for L07 consis-

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ted of a 3.72-s long flattop, followed by burst initiation at 8.4 s (Fig. 1). The burst consisted of a 440-ms period for 480 ms, then a 50-ms period until the transient control rod T-1 was full-out, reaching a peak TREAT power of 3010 MW at 9.053 s. The total energy released during the transient was 867 MJ.

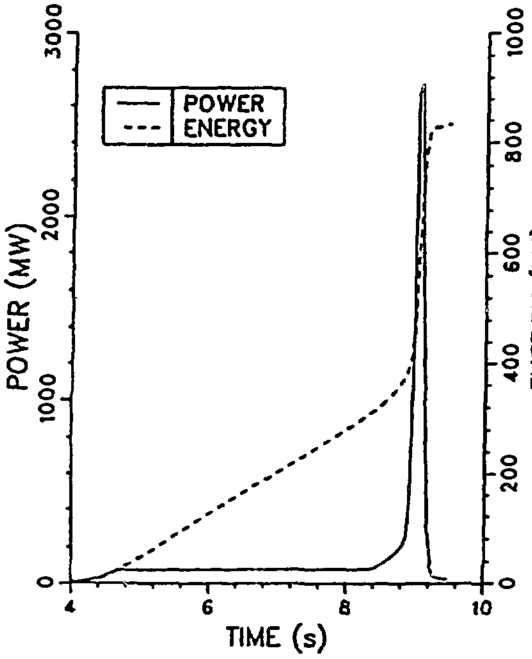

Figure 1. Power and Energy Profiles for the L07 final transient.

CALCULATIONAL APPROACH

The model for the experimental loop consists of basically two parts -- the test train or fuel bearing section, and the rest of the loop. Figure 2 shows the model of the Mark-IIIC loop used for the L07 test, simplified to match the requirements of the code. Accurate flow areas, hydraulic diameters and lengths are input for each element. The electromagnetic pump is included as a "dummy" element because the current model in the code does not adequately represent the pump in the loop. Given the inlet temperature and flow rate as a function of time along with the initial loop pressure and pressure drop coefficients around the loop, the PRIMAR-4 part of SAS4A calculates conditions throughout the loop.

The test-pin section is modelled in SAS4A as a representative single pin, and under this constraint, some care must be taken to specify the correct number of pins that are assumed to fail initially. The COBRA-PI code (6) is used to model a multi-pin, possibly asymmetric fuel bundle. COBRA analysis can determine the existence of local boiling in one or more subchannels that can lead to early failure of one or more pins in the bundle, and the SAS4A failure scenario can be adjusted accordingly. For L07, boiling was just beginning at failure time and all seven pins were taken to fail at the same time, consistent with experimental data that did not indicate separate pin failure events.

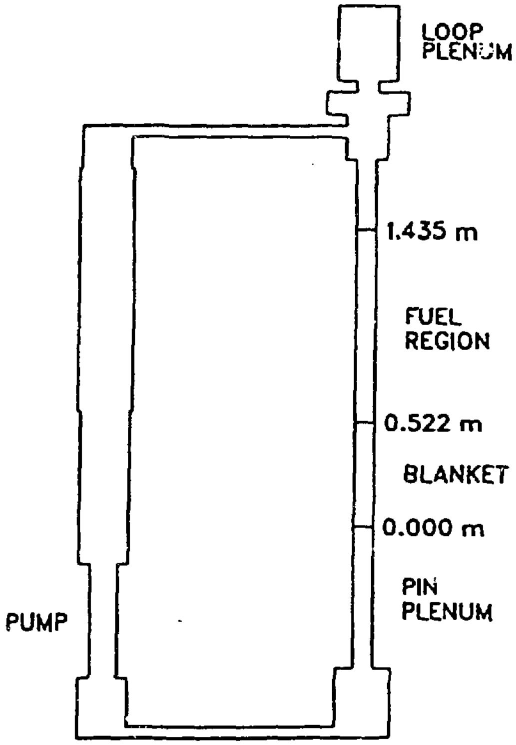

Figure 2. SAS4A Model of the L07 TREAT Loop.

PRE-FAILURE RESULTS

The short duration of the final TOP simulation provides only a partial test of the code's capability to calculate long-term flow conditions around the loop. To further test the code, the L07 heat balance transient was also calculated. The heat balance was a reactor run at low, near constant power for 20 s. The main purpose of the heat balance is to verify fuel power coupling factors and to check operation of the loop instrumentation, but also serves to verify a near steady state calculation. The pins and loop are the same as that used in the final transient, and accordingly the loop model within the code is the same.

The pre-irradiation in PFR was modelled within the limitations of SAS4A as two high-power reactor runs with a complete shutdown after each. The steady state DEFORM-IV calculations closely matched peak burnup, porosity, fission gas production and release, and the fuel-clad gap near the center of the pins as determined from sibling pin examinations. Calculated peak temperatures also approximately matched PFR conditions.

Figure 3 compares calculated temperatures with data for thermocouple locations at the fuel midplane and in the pin extender region above the upper breeder during the heat balance. Figure 4 shows similar data for the pre-failure part of the final L07 transient. The agreement with both sets of data is generally good, but calculated temperatures are somewhat higher than the data. This may reflect the location of the thermocouples on the outside of the flowtube wall or problem with fuel/clad gap conductance. Pre-failure inlet and outlet pressures and flow rates are accurately calculated by the code.

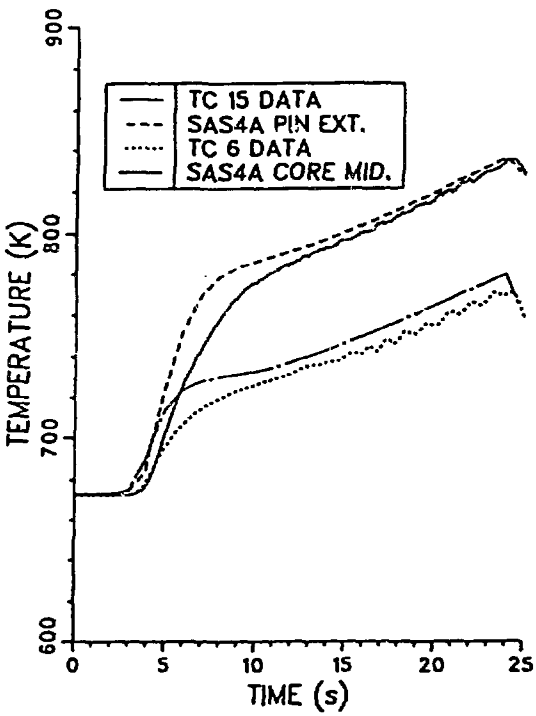

Figure 3. Temperature Calculations and Data for the L07 Heat Balance Run.

POST-FAILURE RESULTS

By design, no boiling or pin failure occurs during the heat balance run described above. However, during analysis of the final transient, the TOP simulation, calculations continue through boiling and pin failure. While a completely mechanistic prediction of failure time and location was not yet operational in SAS4A, a good result can be obtained by keying on the molten fuel fraction at any given node. Specifying failure when the areal melt fraction of any node reaches a value of 0.55, the failure time is predicted to within a few milliseconds of the actual event as determined from the data, at a time correspinding to 9.059 s on Fig. 1. This melt fraction criterion was determined from earlier experimental analyses.

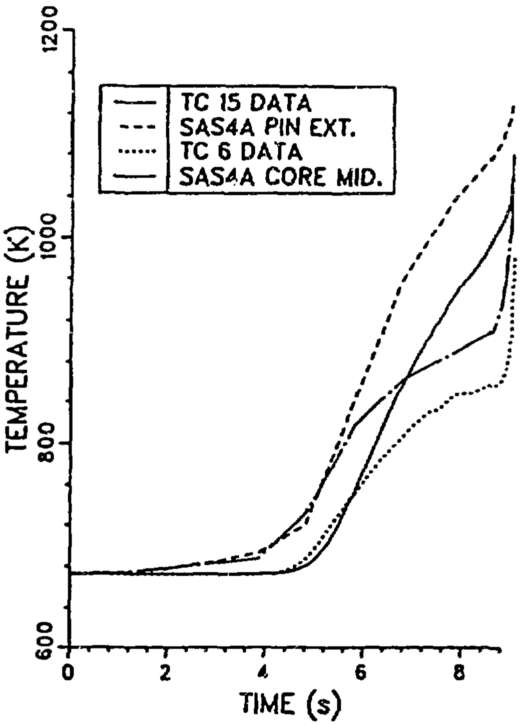

Figure 4. Temperature Calculations and Data for the L07 Final Transient.

Following failure prediction, subsequent fuel motion and channel conditions are compared to the data. The L07 fuel pins failed into a coolant channel just beginning to boil, so the PLUTO2 module was used initially to calculate post-failure fuel motion in the non-voided channel. At about 51 ms after pin failure, control is transferred to LEVITATE, to continue the calculation in a nearly voided channel. Transition between the two modules occurs with no discontinuities. Pin failure occurs shortly after peak power. Because the early runs to establish the failure time used the melt fraction criterion, the hottest node at x/L=0.55 was the calculated failure site. Initially, the clad fails at only one node and fuel is ejected into the channel, then transported mostly upwards in a particulate flow regime. As the transient continues, the rip extends, first upwards then downwards. Fuel ejection continues with partial or fully annular flow becoming predominant. At 60 ms after failure, pin disruption occurs over five nodes (46 cm) and the switch is made to LEVITATE. From this point on, pin disruption continues and fuel is slowly ejected from the pin with annular flow predominating.

Figure 5 compares the test train inlet and outlet flow rates after failure with calculated results, and Fig. 6 compares the inlet and outlet pressures. Figure 7 compares measured and calculated inlet and outlet flow rates. Agreement in general is quite good, with some overprediction of the inlet and outlet flow and pressure oscillations possibly caused by bubble formation and collapse instability.

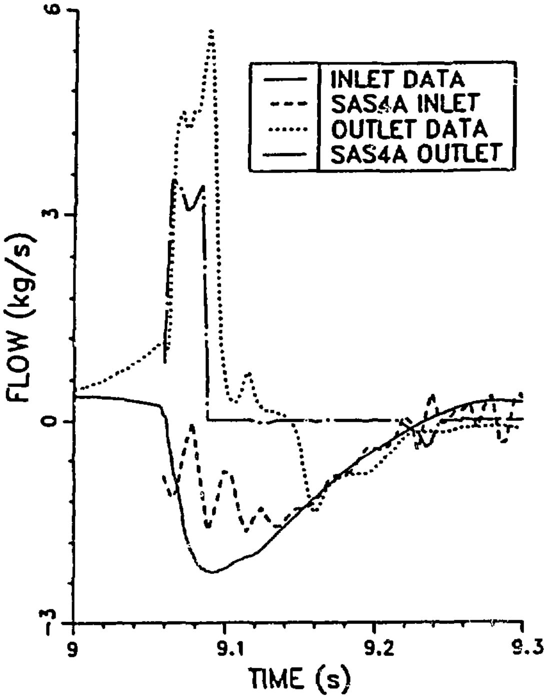

Figure 5. Post-failure Data and Calculations of L07 Inlet and Outlet Flow Rates.

Calculated fuel motion can be compared with the hodoscope (6) data taken during the transient, keeping in mind the data analysis normalization techniques and the limitations of the code. Figure 7 summarizes the post-failure fuel motion calculated by SAS4A. One method of comparing the fuel motion data to calculations is to consider the equivalent fuel worth as a function of time, as shown in Fig. 8. The dispersive nature of the fuel motion is clearly calculated. Agreement between hodoscope fuel motion data and the calculations is qualitatively good, but localized details often do not match. SAS4A does not currently treat grid spacers, so their effect on fuel freezing is not modelled. The deviations after about 9.1 s may arise from many things, including the manner used in hodoscope data analysis to treat fuel which has left the field of view, and the lack of grid spacers in the calculational model. When a correction is applied to the SAS4A results for fuel leaving the hodoscope field of view (the same correction used in hodoscope analysis), a dramatic change

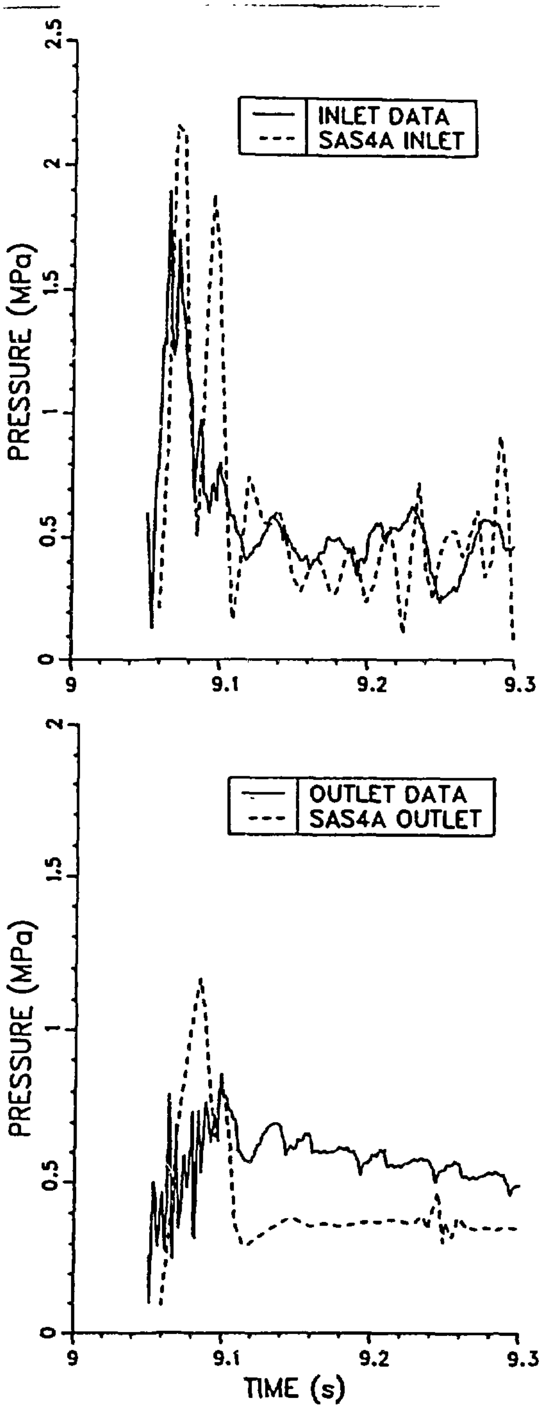

Figure 6. Data and Calculations of Post-Failure L07 Inlet (top) and Outlet (bottom) Pressures.

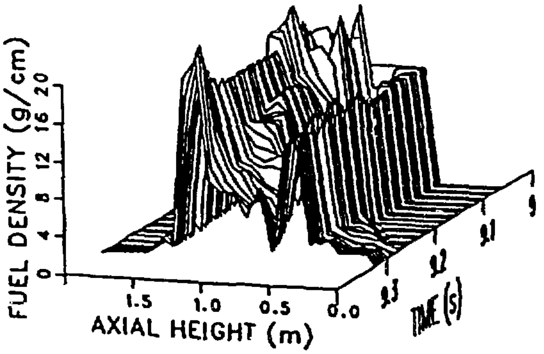

Figure 7. Post-failure Fuel Motion Calculated by SAS4A for L07.

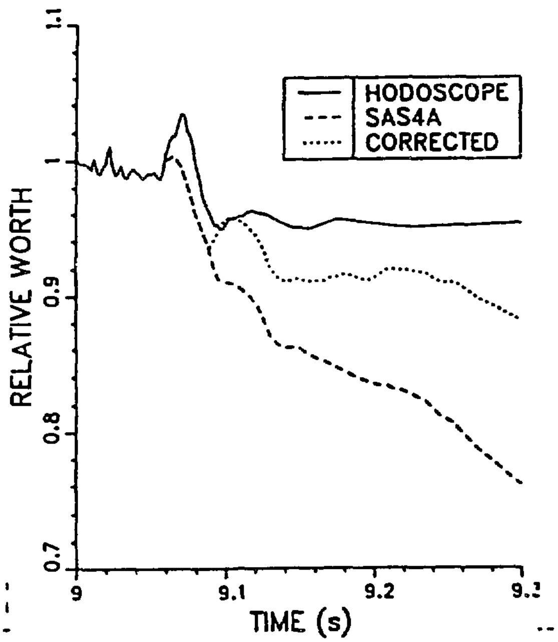

Figure 8. Equivalent Fuel Worth Curves from Hodoscope Data and SAS4A Calculations for L07.

is made to the worth curve as shown in the curve labelled "SAS4A CORRECTED" in Fig. 8. The agreement with the data now becomes very good, and indicates that the non-normalized SAS4A worth curve is a good representation of the true event, more dispersive than indicated by the worth curve drawn from the hodoscope data.

SUMMARY

The SAS4A analyses of the TUCOP test described here provide very good agreement with the measured data, both thermal-hydraulic and fuel motion. The extent of the agreement confirms the validity of the models used in the code for treating fuel pin failure into both voided and non-voided coolant channels. Inclusion of grid spacers in the models is necessary for correct treatment of fuel freezing after failure. In-pile tests using wire-wrapped pins are needed in order to test the code for such systems and thus validate its use for prototypical U. S. LMFBR designs.

The work presented here represents the first steps in validating the models in the release version of SAS4A for TUCOP accidents through the use of in-pile experiments for comparisons. The SAS4A analyses have been performed using recommended values for the input parameters, not fitting the results to the observations. Good agreement for the thermal responses of the entire loop have been found in the period up to pin failure. This gives a high degree of confidence in the basic thermal-hydraulic modeling in SAS4A. Using observed times of pin failure to initiate fuel motion, good agreement is again found with the measured data up to the pint in time where the grids significantly influence the behavior of the fuel. Thus the basic modeling in PLUTO and LEVITATE is also supported.

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