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AUTHOR(S): W. R. Bohl

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los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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SOME RECRITICALITY STUDIES WITH SIMMER-II

W. R. Bohl

Energy Division
Los Alamos Scientific Laboratory
University of California
Los Alamos, NM 87545 USA

ABSTRACT

The SIMMER-II code was applied to the problem of evaluating the potential for recriticality in an LMFBR HCDA. The phenomenology examined was based on the post SAS3D behavior in a CRBR LOF accident. The SIMMER-II results were found to be sensitive to the development of fuel blockages. If blockages were formed close to the core, the core-disruption phase of the accident generally involved prompt-critical transients. This behavior resulted from the significant energy required following SAS3D termination to raise the average steel temperature to saturation conditions; also material deposition near heat sinks eliminated condensation surfaces and induced core pressurization and fuel collapse. Excessive ramp rates (greater than \$100/s) were judged to be unlikely, but improved knowledge and calculational treatments of the applicable phenomenology would be desirable.

INTRODUCTION

A loss-of-flow (LOF) hypothetical core-disruptive accident (HCDA) in liquid metal fast breeder reactor LMFBR designs considered recently in the United States might be expected to proceed into some type of initial power burst(s) caused mainly by sodium voiding and/or fuel slumping. This initial transient history will generally cause significant disruption of pin geometry; however, it may not result in sufficient fuel dispersal to terminate the possibility of recriticality.[1,2] Varying opinions have been advanced concerning the potential for recriticality[1-4] in evaluation of HCDA consequences. This paper discusses insights obtained from the SIMMER-II code on the neutronic and fluid-dynamic behavior of the reactor during core disruption.

The SIMMER-II code[5] calculates the coupled hydrodynamics, thermodynamics, and neutronics of disrupted LMFBR core geometry in a two-

dimensional framework. Initial conditions either can come from calculations or plausibility arguments. Because consistent calculations past initial fuel disruption have not been performed previously, an examination is made of SIMMER-II results obtained using the SAS3D code to calculate initial conditions. The resulting insights are integrated into existing knowledge on core disruption in LMFBRs for construction of additional SIMMER-II cases. The dominant features of these SIMMER-II calculations are then related to the recriticality issue.

SIMMER INITIAL CONDITIONS

Initial conditions for SIMMER-II were first obtained from a 10-channel Clinch River Breeder Reactor (CRBR) SAS3D calculation, with input provided by Argonne National Laboratory.[6] This case was similar to the end-of-equilibrium cycle calculations reported by Ferguson.[7] Boiling starts at 11.75 s. Three neutronic bursts are observed (see Fig. 1). Beyond the first power burst from sodium voiding, the calculated development of the accident is dominated by the influence of fission gas on fuel motion. The input assumptions result both in fairly rapid release of fission gas at high power and in considerable slip of fission gas relative to moving fuel. Recent experimental evidence[8] suggests that under CRBR LOF conditions these assumptions on fission-gas-induced fuel motion overpredict early fuel mobility. However, unless such changes in irradiated fuel phenomenology lead to an early energetic disassembly, the uncertainties in a continued mechanistic calculation are believed to dominate the uncertainties introduced by inaccuracies in SAS3D modeling.

The transition from SAS3D to SIMMER-II was performed at 15.70 s, between the second and third power bursts. At this point, the core sodium has been removed through voiding, steel vapor is beginning to form in the peak subassemblies, and much of the fuel pin structure has been destroyed.

The SIMMER-II hydrodynamics mesh is shown in Fig. 2. The neutronics mesh was similar, although extra mesh subdivisions were made in the blankets to calculate better flux gradients; also, the neutronics mesh was terminated 0.762 m into the fission gas plenum for reasons of economy. The assignment of SAS3D channels into SIMMER rings was made by examining all the SAS3D channels that occupy a given ring and selecting the one channel that most typifies that ring.

The neutronics algorithm used in these SIMMER-II calculations was time-dependent diffusion theory using the quasistatic solution method.[9] Nine energy group cross sections were collapsed from a standard 50-group LASL library using a typical fast reactor spectrum.[10] Consistency between SIMMER-II and the SAS3D power profiles was not possible because of the SAS3D point kinetics treatment and the two-dimensional SIMMER-II mesh. These consistency problems and the desire to minimize computation time in such exploratory calculations prompted the assignment of all fertile fuel material to the U-238 isotope and all fissile fuel material to the Pu-239 isotope. Outer control rods were eliminated because a ring of control material was judged to distort the hydrodynamics far more than it would help the neutronics modeling. The elimination of these control rods did lead to a fuel excess. An adjustment in the fuel neutronic number densities was made to compensate for the extra fuel.

INITIAL SIMMER CALCULATIONS

The initial SIMMER-II run indicated immediate neutronic termination of the accident from interaction of hot core material and liquid sodium at the lower core boundary. Such an interaction has two effects. First, there is upward fuel dispersal because of sodium vapor generation. Second, the liquid sodium subsequently retreats, allowing downward removal of core material. To cushion these interactions, voided nodes containing fission gas were placed in the blanket between the liquid sodium and the hot core material. The resulting reactivity history is shown in Fig. 3. Initially, there is some fuel dispersal due to steel vapor pressures, and some fuel compaction due to slumping. However, because blockages do not form, fuel is eventually removed from the core vicinity. A third case eliminated the fuel-sodium interactions completely by assuming that, in addition to the extra voided nodes, both momentum fields (liquid and vapor) saw infinite-structure frictional resistance in the second blanket node, starting 0.07 m below the core. In this case, a disassembly very similar to the SAS3D case was calculated. A fourth case increased liquid-to-structure friction in this blanket node by only a finite amount (three orders of magnitude). Although such a partial blockage limits the magnitude of the power burst, sodium that had leaked through interacted with the postburst melted core fuel to result in apparently permanent core dispersal.

A SIMMER-II CALCULATION WITH BLOCKAGES

The initial calculations indicate three problems. First, available LOF experiment evidence suggests that the interfacial interaction calculated between fuel and sodium at the core/blanket interface is too strong.[11] Second, the purely conductive freezing model yields difficulties in the formation of complete blockages. Current understanding of LOF phenomenology[12] suggests that blockages should form. Third, the final two cases suggest that interfacial interaction problems should be resolved with local conditions determining the motion restraints, if a plausible calculation is to be produced. A change in the SIMMER-II numerical procedures was found to significantly reduce the severity of these problems.

The minimal reformulation used defines the Reynolds number in the liquid-to-structure drag relationship by

$$Re = \sum_m \left(\frac{\bar{\rho}_{\ell m} |v_\ell| D_h}{\alpha_{\ell m} \mu_m} \right) , \qquad (1)$$

where $\bar{\rho}_{\ell m}$ is the macroscopic liquid density for component m, v_ℓ is the liquid field superficial velocity, D_h is the node hydraulic diameter, $\alpha_{\ell m}$ is the volume fraction for liquid component m, μ_m is the viscosity for liquid component m, and m is summed over all the liquid density components. This redefinition of the Reynolds number allows viscosity to be defined for the solid fuel particles that exist in the SIMMER-II liquid momentum field. The value chosen for particle viscosity was 100 Pa·s

outside the active core, in the blanket, the fission gas plenum, and in control rod regions. This change was applied to the case with the extra voided nodes initially between the liquid sodium and fuel. The resulting power and reactivity traces for this case are shown in Fig. 4. Following the first power burst a "blockage" forms in both axial blankets. Below the blockage a voided region begins to develop, with the majority of the fuel slowly and incoherently collecting in the bottom of the core. At about 2.15 s, a dispersal event occurs from can wall failure. Recompaction follows, and a mild, subprompt critical burst develops at 3.50 s. This burst and the resulting fuel-to-steel heat transfer sends material upward and to the radial periphery of the core. Movement downward and radially inward then develops, which is assisted by failure of the can wall in the control rod channel at the core midplane. The resulting disassembly burst has a reactivity insertion ramp rate at prompt critical of about \$70/s, and peak fuel temperatures reach 5670 K. Fuel blockages are melted and massive core dispersal results.

DEVELOPING A BOILING POOL

Three events may be exaggerated in the previous case. First, the initial burst may be overpredicted because of early excessive fuel mobility. Second, depressurization following can wall failure is obviously too coherent. Third, the final disassembly is augmented by the center control-channel vapor sink. The question can be asked as to whether a boiling pool could develop if events occurred more slowly. For example, fission-gas-induced fuel swelling might be expected to retard initial fuel motion. To simulate such a possibility, a "jamming" algorithm was implemented in the SIMMER-II particle viscosity treatment. In this algorithm, the particle viscosity was assumed to be the product of two factors, an input constant and a packing fraction multiplier, μ_p, where

$$\mu_p = \frac{1}{\max\left[\left(1 - C\,\frac{\alpha_{\ell p}}{1 - \alpha_s}\right),\ 10^{-10}\right]} \quad , \tag{2}$$

with $\alpha_{\ell p}$ = the particle volume fraction, α_s = the structure volume fraction, C = the inverse of the maximum packing fraction (input). The values chosen were 1 Pa s for the input particle viscosity and 0.3 for the maximum packing fraction. These values appear to reproduce reasonably well fuel penetration lengths in thermite injection experiments analyzed by Henninger.[13]

By adding these changes to the previous case, high concentrations of fuel particles stay jammed in place in the core until can wall melting occurs. Fuel melting is required to release any particle jams that occur in regions with fabricated fuel. Consequently, no initial power burst occurs and the power declines to about 10% of the nominal value for many seconds. Fuel settling takes place essentially in a step fashion (see Fig. 5). The more active phase of the transient begins at about 20.5 s as the net reactivity slowly increases to delayed critical and melting begins in those fuel pins with retained fission gas. This causes a perturbation

in fuel motion, eventually leading to a prompt critical burst with a ramp rate of about \$10/s. Additional fission gas released during this burst rapidly causes local fuel dispersal, but the resulting fuel "sloshing" leads to recompaction and prompt criticality at \$20/s. This burst expels enough fuel into the fission gas plenum to render the system at least temporarily subcritical. The liquid fuel-steel mixture remaining in the core is at 3300-3400 K. It develops a sloshing motion related to the dependence of liquid-vapor momentum transfer on the local void fraction. The further development of this scenario would best be determined using techniques other than those in SIMMER-II. Fuel recompaction, if it occurs, is likely either to develop slowly and/or be accompanied by significant structural motion.

A BOILING POOL CALCULATION

It might be speculated that the SIMMER-II termination of the above cases is too violent; a so-called "boiling pool" might form without a prompt critical excursion. There are two possible outcomes of such an occurrence -- either the pool can disperse by a two-phase blow down through blockage meltout or by means of a neutronic burst. Blockage meltout requires a stable pool. To examine this question with SIMMER-II, a pool stability problem was postulated with a fuel-steel pool initially at 3300 K, as is shown in Fig. 6. Blockages were placed in both the lower and upper axial blankets to limit the degree of achievable subcriticality. Appreciable heat sinks were present along the sides and in the axial blanket region. The power and reactivity traces for this case are shown in Fig. 7. The "pool" does have significant dispersive potential. However, the flow of material to condensing surfaces is so strong that the material in nodes adjacent to the large heat sinks becomes single phase. This eliminates the condensation nodes and the pool now begins to pressurize and collapse. Eventually, enough material collects to produce a prompt critical burst. Because of modeling and other uncertainties, the details of this behavior are speculative. However, the formation of insulating crusts may also significantly retard vapor condensation. Crust formation in this regime is not modeled by SIMMER-II because the bulk fuel temperature is above the melting point.

A limited parametric study was performed to better examine such molten core behavior. The study suggested that if vapor condensation sinks were removed, fuel collapse would occur eventually with widely varying flow-regime and heat-transfer assumptions. For example, to simulate a bubbly-flow regime, the previous problem was rerun with the liquid-vapor drag coefficient increased by two orders of magnitude and liquid-fuel to liquid-steel heat transfer increased by a factor of 50. The calculation was accelerated by input elimination of the heat transfer to the blankets and pool boundaries. Initially, the power gradient led to a pressure gradient dispersing the fuel. However, at 10% nominal power, recompaction began and a prompt-critical burst occurred before the redeveloping pressure gradient could reverse the motion. Consequently, in contrast to fuel dispersal arguments by Fauske,[3] this study suggests that if blockages develop close to the core such that fuel escape paths do not exist, a prompt-critical burst may be inevitable.

POSTULATED RECRITICALITY SITUATIONS

Many imaginative situations can be investigated here. Unfortunately, results are highly dependent on the conditions assumed. A gravity collapse of disintegrating blockage depends on the amount of falling fuel and the degree of core subcriticality. Pressure-driven recompaction adds the additional variables of the magnitude of the driving forces and the duration and location of their action. Unless an understanding both of expected accident event sequences and associated phenomenology is used to attack such problems, postulated recriticality situations seem artificial. Three examples can be used to illustrate the speculative character of such events.

First, a model problem was constructed to calculate the consequences of postulated core compaction from fission gas, released late from the fission gas plena in lower-power subassemblies after a mild neutronic burst. Results were highly dependent on the amount of gas assumed to be present. A small amount of gas had the simple effect of imparting a small initial velocity to the liquid. A larger amount of gas induced a significant wave of compacting fuel. In one case, a ramp rate of $250/s was attained at prompt critical when a 2-MPa initial driving pressure was allowed to act on the annulus comprising 20% of the core area.

Second, liquid sodium can be postulated to mix with expanding fuel resulting in core recompaction. It should be emphasized that this phenomenology is not to be expected in a CRBR LOF sequence, where expanding core materials are calculated to form a highly dispersed spray before interaction with sodium. This is similar to the situation simulated by Henry in the upper plenum injection tests.[14] However, SIMMER-II can be modified to calculate phenomenology where fuel (1) is driven by mild pressures, (2) contacts sodium in a slug mode, and (3) has a small time delay before rapid heat transfer commences, without satisfying the criteria for a true vapor explosion. Fuel recompaction at velocities of between 5 to 10 m/s are not unreasonable in this case.

Third, the tendency of molten core pools to compact rather than disperse can be exploited utilizing the "sloshing modes" of a two-dimensional pool. A vapor source at the top along the centerline of a dispersed fuel-steel pool initially will cause a diagonal "slosh" of material to the sides of the pool and thereby increase neutron leakage. The dense fuel will then flow down the outer boundary and collect at the bottom of the pool with readily obtainable reactivity insertion rates on the order of several hundred dollars per second.

CONCLUSIONS AND DISCUSSION

The SIMMER-II calculations on the core-disruption phase of an HCDA indicate a large dependence on the quantity of fuel remaining in or near the reactor core. Loss of sufficient fuel precludes recriticality. Blockage formation and meltout processes thus are important. Nominal SIMMER-II calculations do not lead to the formation of complete fuel blockages. Consequently, neutronic shutdown is observed. Current experimental evidence on fuel freezing and plugging suggests that blockages should form. If ad hoc assumptions are inserted into SIMMER-II to simu-

late expected fuel blockage formation, recriticality events are calculated. Material flow from the colder regions covers vapor condensation surfaces, and core pressurization and fuel collapse can occur under various situations if the core power level is low.

The SIMMER-II calculations suggest that excessive ramp rates (greater than $100/s) are rather unlikely. First, fuel collapse is both expected and calculated to be significantly incoherent as long as can walls restrict radial fuel motion. Delays in melting can walls may result in fuel axial penetration and fuel losses from the core vicinity. Second, only moderate reactivity insertion rates were observed in this study using SAS3D calculated conditions as input. This is true despite the two-dimensional SIMMER-II format that exaggerates coherence in fuel relocation. SIMMER-II generally predicts a strong tendency for core material to collect on the cold outer periphery from condensation and power-induced pressure gradients. Such material then drains down the outer periphery and fills the system with a coherent radially inward motion. Third, expected mitigating mechanisms exist that are not in current models. For example, SIMMER-II does not simulate a fall in of solid blanket pellets and the subsequent dilution of the fuel-steel mixture.

It is not possible to bound rigorously the degree of possible accident energetics when arbitrary recriticality situations are postulated. This situation is further complicated by the existence of burst-augmenting mechanisms that are not in current models, such as escape of volatile neutron precursors and a collapse of unclad fuel pellets. Obviously, further insight and knowledge into the treatment of the applicable phenomenology is desirable so that the likelihood of recriticality situations can be well established. For the present, events involving recriticality cannot be ruled out.

ACKNOWLEDGMENTS

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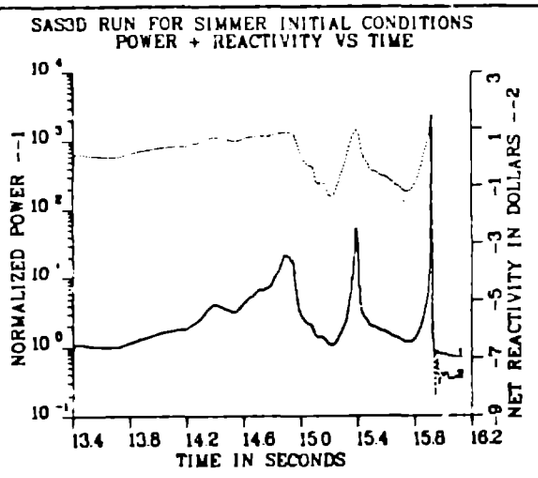
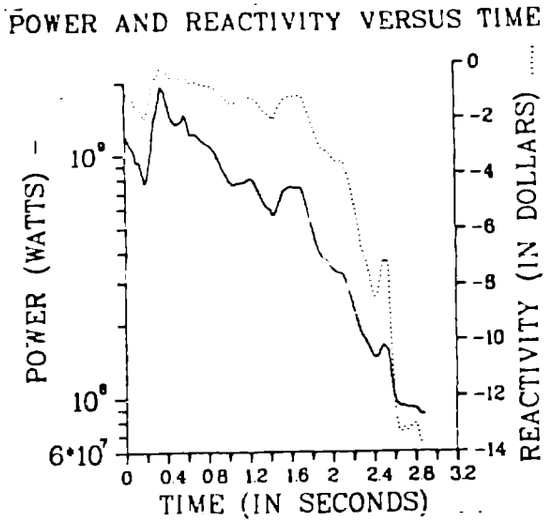
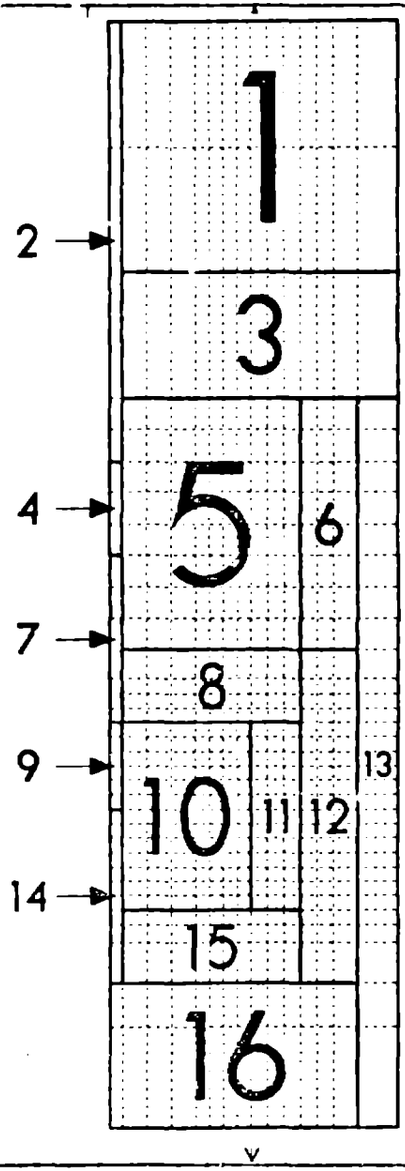
FIGURE CAPTIONS

1. SAS3D run for initial conditions.
2. Mesh and region setup for SIMMER-II calculations.
3. Typical SIMMER-II results when blockages do not form.
4. SIMMER-II results with an increased particle viscosity.
5. SIMMER-II results with the addition of a jamming model.
6. Core and axial blanket SIMMER-II setup for the pool stability case.
7. Typical SIMMER-II results in the pool stability case.







1. ABOVE CORE STRUCTURE
2. REGION ABOVE CONTROL ROD
3. SODIUM GAP
4. UPPER BLANKET CONTROL ROD
5. CORE FISSION GAS PLENUM
6. BLANKET FISSION GAS PLENUM
7. B4C REGION CONTROL ROD
8. UPPER AXIAL BLANKET
9. LOWER BLANKET CONTROL ROD
10. INNER CORE
11. OUTER CORE
12. RADIAL BLANKET
13. RADIAL SHIELD
14. SPACE BELOW CONTROL ROD
15. LOWER AXIAL BLANKET
16. LOWER SHIELD

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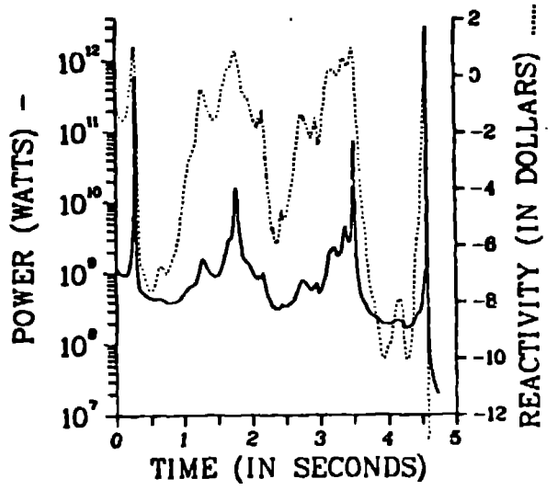

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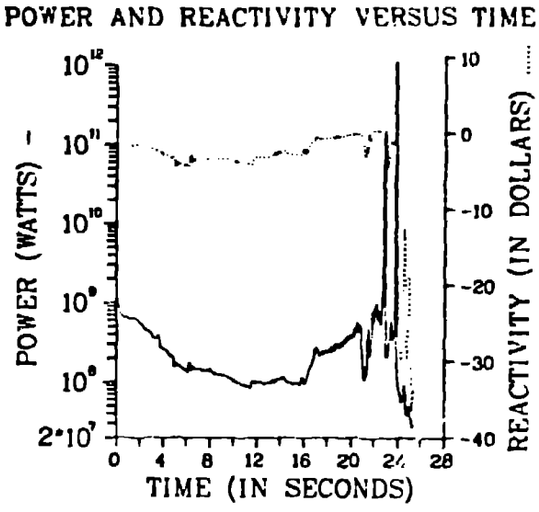

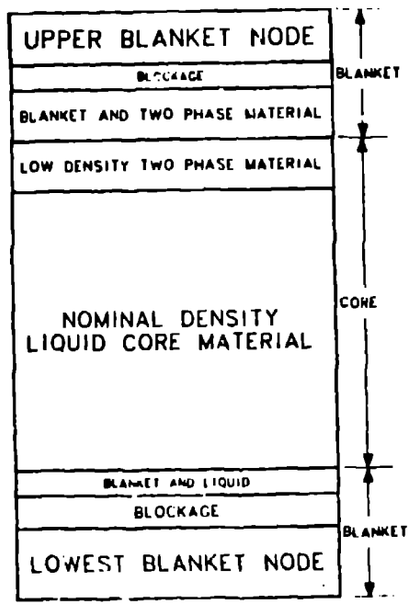

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