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A REVIEW OF THE SIMMER-II ANALYSES OF LIQUID-METAL-COOLED FAST BREEDER REACTOR CORE-DISRUPTIVE ACCIDENT FUEL ESCAPE

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ABSTRACT

Early fuel removal from the active core of a liquid-metal-cooled fast breeder reactor undergoing a core-disruptive accident may reduce the potential for large energetics resulting from recriticalities. This paper presents a review of analyses with the SIMMER-II computer program of the effectiveness of possible fuel escape paths. Where possible, how SIMMER-II compares with or is validated against experiments that simulated the escape paths also is discussed.

INTRODUCTION

Although excluded from the design basis, core-melt accidents in liquid-metal-cooled fast breeder reactors (LMFBRs) have claimed a prominent role in licensing. Clearly, the probability of such events, which are more commonly known as core-disruptive accidents (CDAs), is very low. However, in the LMFBR case, configurations of higher reactivity are possible as meltdown and loss of the original core geometry occur. Thus, the theoretical possibility of achieving very high temperatures and pressures with direct and potentially severe consequences on the containment barriers gives rise to an LMFBR generic safety issue--that of "energetics."

Fuel removal from the active-core driver regions during postulated CDAs in LMFBRs is of primary importance in determining the ultimate accident termination mode and its severity in terms of energetics. Earlier SIMMER-II calculations of the meltdown phase of such accidents in heterogeneous cores(1) have shown that a propensity for fuel slumping produces a dynamic system response characterized by a series of prompt- or near prompt-critical power bursts. Similar considerations for the Clinch River Breeder Reactor (CRBR) have indicated that fuel compaction is a primary path to significant energetics.(2) The number and severity of such recriticalities are related directly to the availability of mobile fuel in the active core.

Early fuel losses can eliminate or moderate recriticalities. The fundamental prerequisites for timely dispersal of fuel are the availability of fuel escape paths, the ability of core materials to move through these paths, the existence of pressure gradients to provide the required rates, and sufficient fuel reservoir volume outside the active core. Fuel escape paths may be found in the subassembly pin bundles and the intersubassembly gaps. Steel (cladding or subassembly wall) boundaries exist for both kinds of paths; hence, as a minimum, the escaping molten fuel (or fuel/steel mixture) would be exposed to approximately 1000 K lower temperatures (the difference between the fuel and steel melting points) at these boundaries. As a consequence of this strong cooling environment, the effectiveness of these paths in allowing the required fuel removal must be assessed against the potential for refreezing and plugging during this dispersal process.

The SIMMER-II (S_n, Implicit, Multifield, Multicomponent, Eulerian, Recriticality) computer program(3) was developed to perform accident sequence calculations. Its development resulted from recognizing the importance of quantifying the phenomena occurring during the transition phase and the importance of using experimentally supported correlations dependent on local conditions for the mass, momentum, and energy transfer occurring in fast reactor accidents. It is the purpose of this paper to present a review of SIMMER-II analyses of the effectiveness of possible fuel escape paths and a review of experiment analyses that have been performed to test the SIMMER-II approach.

From these analyses, it was concluded that the porosity represented by the extension of escape paths beyond the active core was easily sufficient to accommodate 40% of the core volume (the approximate amount necessary to prevent further recriticalities) and because available paths increase with disruption, large-scale disruption with a sustained high fuel inventory in the core would be difficult to maintain. Thus, the disruption sequence and associated neutronic response appear to have a damped character (mild recriticalities) as a result of the fuel removal processes, at least for heterogeneous cores, and large containment-threatening energetics appear to be unlikely.

SIMMER-II ANALYSES

Available Paths for Fuel Removal

A fuel removal path is characterized by its size, general availability, and associated reservoir size. The first available fuel removal paths are the normal coolant-flow passages from the active core into the upper and lower axial blankets. Cladding blockages and fuel freezing and plugging in those axial blanket passages may limit the effectiveness of these paths to all discharges but those with superheated fuel at the leading edge. However, if the freezing and plugging process effectively ablates the cladding, the two axial blankets could accommodate about 70% of the core fuel.

The second paths for early fuel removal are through the internal and radial blanket subassembly gaps (Fig. 1). For timely and substantial gap fuel removal, the reservoirs for fuel deposition must be large and available. Of these reservoirs, the lower axial blanket gaps can hold about 10% of the driver fuel, and the gaps of the radial blanket can hold about 10%. In addition, a very large volume is available in the radial reflector region such that it can accommodate sufficient fuel for permanent subcriticality.

The final fuel removal paths are the control rod subassemblies. If the gaps cannot remove the necessary amount of fuel, there may be

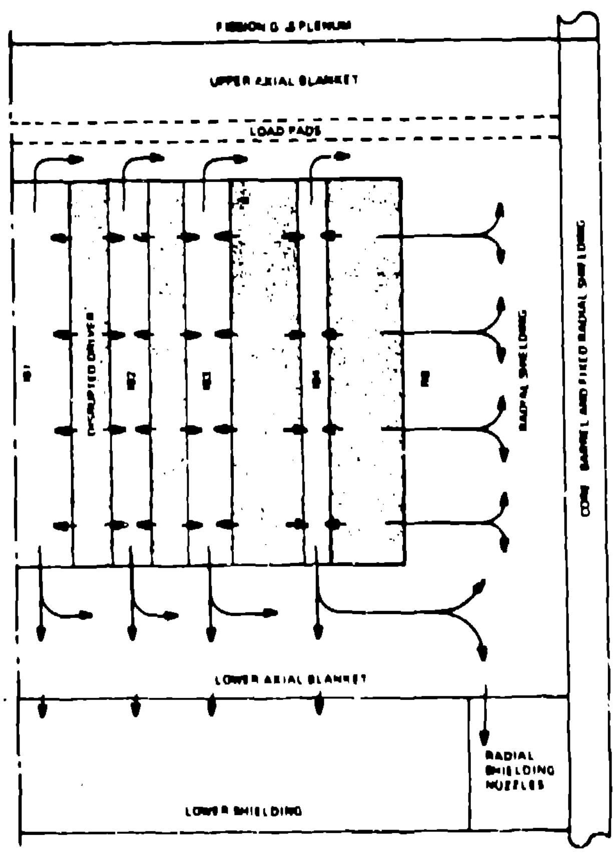

Fig. 1. Intersubassembly gap fuel removal paths.

sufficient heat flux to the walls of some primary control subassemblies to cause them to fail and thus provide additional fuel escape paths. Just the volume below the partially withdrawn control rods could accommodate more than 10% of core driver fuel without requiring fuel flow through the inlet orifices.

Therefore, we can conclude that reservoir capacity is not a problem because the porosity represented by voided coolant channels, intersubassembly gaps, and withdrawn control rods is large and because the volume necessary to accommodate approximately 40% of the core is small. The available paths to access this capacity increase with disruption such that large-scale disruption with sustained high inventory in the core would be difficult to maintain.

Types of Flows Analyzed with SIMMER-II

Two of the fundamental prerequisites for timely dispersal of fuel, the availability of escape paths and reservoir capacity, generally are satisfied in most LMFBR designs. We now consider a third prerequisite, the ability of fuel and steel to move through the available paths. In particular, we evaluate the effectiveness of the various escape paths as modeled and analyzed using the SIMMER-II code.

The first set of SIMMER-II calculations modeled a CRBR subassembly from the active core midplane to the top of the fission gas plenum and was used to investigate the fuel removal potential through CRBR pin bundles.(2) The treatment of the extremely complicated interactive fluid flow and heat transfer associated with steel melting and fuel freezing was based on a generalized model. This model was validated against the available prototypic-material experimental data to be described later. Generally, the figure of merit considered in assessing freezing and plugging models is fuel penetration distance. The calculated penetration distance vs pressure is shown in Fig. 2. A penetration of about 0.35 m corresponds to complete removal of nearly one-half the subassembly contents. The calculated fuel removal potential for a discharge following a power burst during the early subassembly disruption phase also is shown in Fig. 2. The core material was assumed to be a mixture of cladding steel and fuel that was 50% solid and 50% liquid. The steel and fuel were brought into thermal equilibrium at the fuel melting point. The discharge was driven by power bursts of different magnitudes with a representative CRBR axial power shape. Thus, small bursts produced low discharge pressures and had particulates at the leading edge. The cladding steel was assumed to be distributed physically on a scale for rapid heating by the fuel (in less than 0.2 s) and therefore was the pressurizing material. The correspondence between burst energy in full-power-seconds (FPS) and steel vapor pressure can be seen in Fig. 2. The calculations suggest that substantial fuel removal can be expected for a wide variety of conditions if the pin bundles are unblocked initially.

In the second set, SIMMER-II calculations were performed to determine the discharge characteristics of fuel/steel mixtures through intersubassembly gaps. The first study(4) involved a

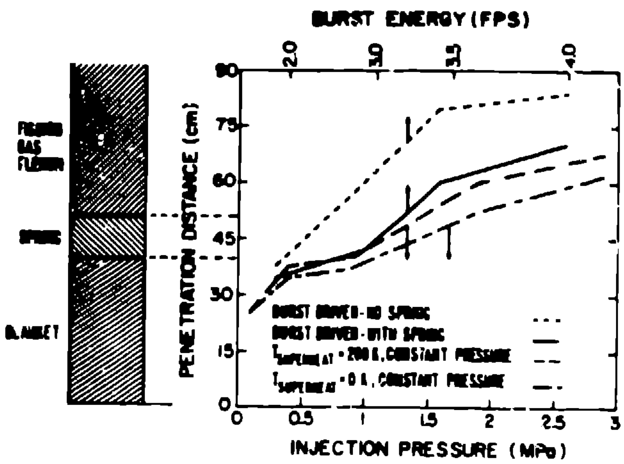

Fig. 2. Fuel penetration distances in pin bundles for various assumptions and conditions.

whole-core simulation with a disrupted outer annular driver containing a slumped pool of molten fuel and steel at 3100 K. The region inside the annular core region was modeled as a nonparticipating "filler" region for convenience. The lower axial blanket region below the pool was treated as an intersubassembly gap region (considered to be a two-dimensional "porous" region with the intersubassembly gaps being the porosity and the pin bundle being blocked completely with steel). The radial blanket and reflector surrounding these regions also were treated as a gap region, as was the subassembly region below the core. A leak path for the sodium initially in the gaps was provided at the top of the radial blanket region to simulate the small clearances between the subassembly load pads. A second leak path was provided at the lower boundary to simulate the imperfect seating of the subassemblies in the core support plate. The problem setup for this analysis is shown in Fig. 3. Melt-through failure of subassembly duct walls separating the core pool from the radial blanket gap region initiated the flow of pool material into the radial gaps. Before this, some flow into the lower gap region occurred. As pool material (consisting of 25% fuel particles, 25% liquid steel, and 50% liquid fuel at the time of wall failure) began moving into the radial blanket gaps, some liquid fuel partially froze on the structure, but most froze into particles as a result of slurry cooling. The particles were able to penetrate far into the gap region. In particular, the fuel mass in the slumped core had decreased 33% by 3 s after wall failure. This was sufficient to decrease significantly the probability of further recriticality. This potential for fuel removal depends on the various heat-transfer processes that are occurring simultaneously. These processes affect the amounts and timing of fuel particle and fuel crust formation, sodium interaction and vaporization, and the opening of flow passages. This set of calculations indicated a strong potential for whole-core fuel removal into the gaps surrounding the core even without strong neutronic bursts to provide the pressure.

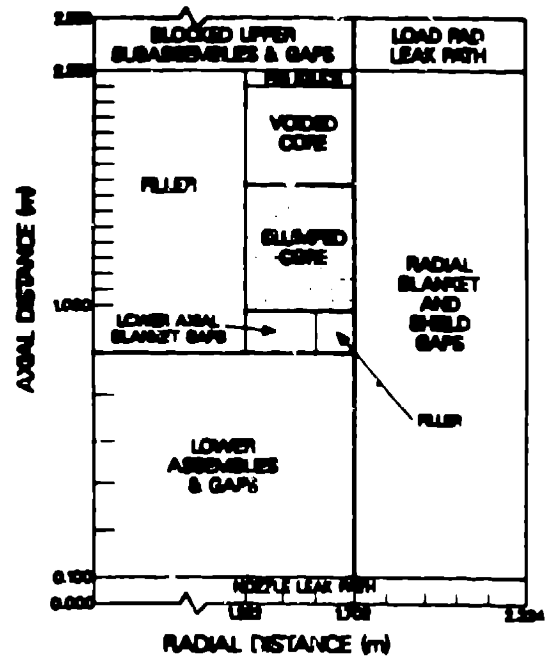

Fig. 3. Calculational model for the whole core analysis of fuel removal through intersubassembly gaps. Tic marks indicate the radial and axial meshes.

Extensive calculations also were made for fuel removal through the inner blanket intersubassembly gaps for the CRBR heterogeneous core under the conditions of an unprotected loss-of-flow accident.(5) A small load pad region within the upper axial blanket was included. The load pads are part of the core restraint system in CRBR and effectively reduce the local flow area to less than 1% of the nominal gap area. The lower and radial system boundaries were assumed closed; the only way for materials to leave the system was through the narrow load-pad gaps above the core. Calculations also were performed with the load pads removed. The dominant discharge limitation was shown to come from the narrow load-pad gaps as they progressively closed from freezing of core materials; when the load pad effects were deleted, the achievable discharge fraction was more than tripled. Parenthetically, these calculations point out the desirability of nonrestricting load pads. These results show that the in-core gaps can be an effective avenue for early fuel removal.

To study further the physics of the core material discharge through gap channels and to gain confidence in the fuel removal prediction, we performed a large set of calculations with SIMMER-II using slab geometry and fuel and fuel/steel mixtures under a variety of conditions.(2) The analysis was oriented toward the fuel discharge through the gaps between internal blankets because they are important as early removal paths as indicated above. Calculations of the fuel removal capability for different situations are shown in Fig. 4. The areas under the curves represent the mass removed through a 0.5-m-long

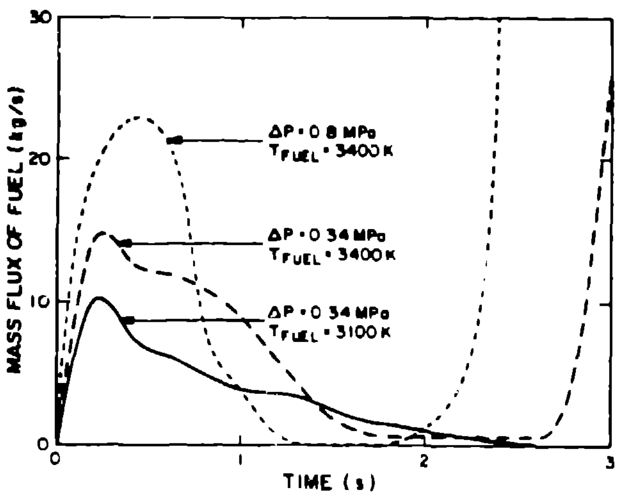

Fig. 4. Gap channel fuel removal transients for various conditions.

channel with a lateral extent equal to one side or flat of the hex subassembly. The injection in these cases was fuel only. The effect of superheat was to increase throughput initially because of delayed crust growth. The wall ablated and introduced large quantities of liquid steel into the stream, which reduced the fuel throughput until it was transported out of the channel. The throughput then increased rapidly because the ablating wall had been removed and the flow area increased. Increased pressure produced higher throughput initially, more rapid wall ablation, and a quicker return to high flow. A typical fuel removal quantity for the superheat cases was approximately 15 kg/gap, occurring within approximately 1 s, even if the later flow re-establishment was neglected. Given the large number of internal blanket gaps in a typical heterogeneous core, an important fraction of the core inventory could be removed in this way.

The final fuel removal paths considered were the control rod subassemblies.(6) They are cold relative to the disrupted core and are protected by residual sodium flow. To evaluate this fuel removal possibility, SIMMER-II was used to model a primary control rod (PCA) subassembly with a surrounding annular pool region that represented six neighboring disrupted driver subassemblies. The problem setup for this analysis is shown in Fig. 5. Successively imposed power bursts caused this disrupted pool of molten fuel, molten steel, and sodium vapor to be in a sloshing mode. SIMMER-II then calculated the response of the control subassembly to this sloshing pool. The control subassembly contained an unvoided control rod assembly encased in an inner duct wall that could be moved axially relative to the subassembly outer duct wall during normal operation. Between these two walls was a bypass that, in normal operation, carried 39% of the control subassembly coolant flow. Melt-through failure of the outer subassembly duct wall separating the disrupted core material from the control rod assembly initiated the flow of pool material into

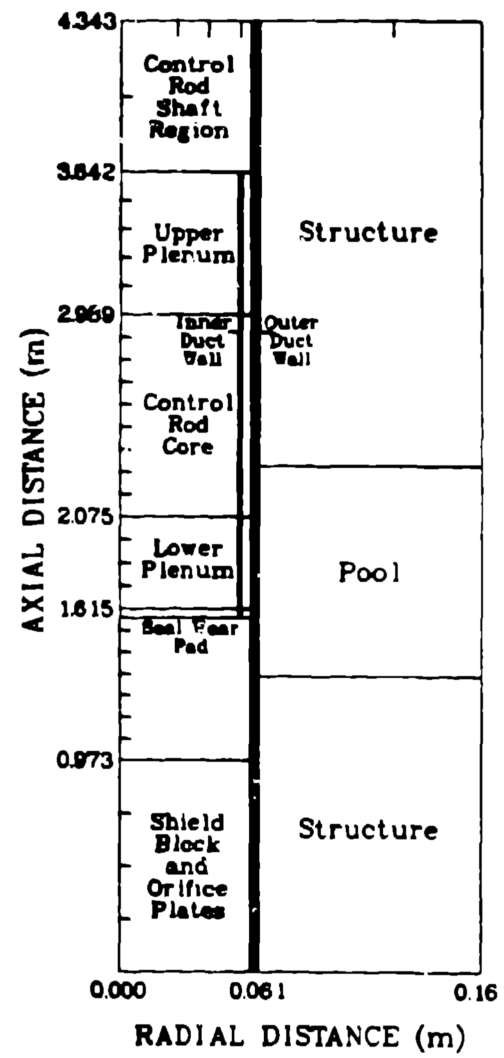

Fig. 5. Geometrical representation of the control subassembly and its surroundings. Tic marks indicate the radial and axial meshes.

the voided bypass region. The hot fuel was able to flow in both axial directions.

Two cases that differed only by the disrupted-pool state at melt-through were calculated: (a) the pool was at 0.64 MPa and 3510 K for Case 1 and (b) the pool was at 3.05 MPa and 4290 K for Case 2. In Case 1, particle blockages formed in the upper bypass so that the early fuel escape path was downward toward the shield block and orifice plates. However, the resulting fuel-coolant interactions produced pressure gradients of sufficient magnitude to force fuel and steel up into the pin bundle of the control-rod assembly. This induced melting of much of the cladding and inner wall and provided a favorable fuel escape path. Of the 55% of fuel removed from the six melted subassemblies, 75% flowed out the top. In Case 2, the initial pool pressure and temperature were sufficient to avoid severe blockages; the upward direction provided the least restraint to flow from the beginning. For this case, 92% of the fuel was removed from the six melted subassemblies with 87% of this going out the top. The results indicated that fuel escape from a severely disrupted core through primary control subassemblies may indeed be an important contribution toward limiting further recriticalities.

We can conclude from all these analyses that fuel will be removed readily through the paths represented by voided coolant channels, intersubassembly gaps, and withdrawn control rods. Thus, because the reservoir capacity is available and the available paths to access this capacity increase with disruption, large-scale disruption with sustained high inventory in the core would be difficult to maintain. Therefore, the potential for large ramp rate events associated with high-inventory whole-core sloshing of the fuel will be decreased greatly.

SIMMER-II TESTING OF FUEL REMOVAL

SIMMER-II model predictions important in fuel removal analysis were compared with experimental data. These comparisons are discussed below.

Argonne National Laboratory (ANL) Pin-Bundle Experiments

SIMMER-II calculations for a range of freezing and plugging tests were compared with experimental data.(7) They were important for validating the complex modeling of the molten material flow into the axial blankets of the driver subassemblies with associated freezing and plugging in the pin bundle geometry. The complexity arises because fuel solidifies at a temperature more than 1000 K higher than the melting point of steel. The fact that steel substrate melting may occur during the fuel freezing process may indicate destruction of insulating fuel crusts and hence greater freezing and plugging potential. This behavior transforms a straightforward heat-transfer calculation into an extremely complicated interactive fluid flow and heat-transfer problem. A generalized multiphase, multicomponent flow and heat-transfer model included in SIMMER-II attempts to account for these complications.

The most important data currently available for validating the model in pin-bundle geometry is that of Spencer.(8) The test setup used a thermite injector attached to a seven-pin rod bundle containing prototype CRBR axial blanket pins; it was modeled as a two-dimensional cylinder using SIMMER-II. Five calculations were performed to test different model assumptions. With one exception, the fuel flow stopped in all cases between 0.30 and 0.45 m, which is about the length of the axial blanket pellet region. Large steel blockages were formed downstream of the fuel in all cases. Some particulate fuel was blown downstream into the fission gas plenum region before the steel blockage formed. As the fuel entered the test section, the cladding rapidly ablated and entrained into the flowing stream. The entrained steel cooled the fuel in a bulk freezing mode and produced a steel-fuel particle slurry. The bulk temperature of the slurry decreased as it flowed sluggishly downstream. The steel froze on the walls at a downstream location, generally at a simulated spring retainer location where the wall heat capacity was high. Even a partial occlusion by steel freezing acted as a blockage in that the particulate slurry had a very difficult time flowing through it. Table I lists these tests and summarizes the results of calculations.

Gap Experiments

At the present time, there are only a few experiments of fuel injection into gap channels. Of these, the GAP3 and 4 experiments performed at ANL(9) are of interest because of their prototypicality and low injection pressures. The test results are somewhat suprising in that they produced short penetrations, 0.1 to 0.3 m, in an environment that was expected to be controlled by conduction-controlled freezing.

These experiments were analyzed with SIMMER-II to seek an understanding of the data as well as for validating it.(2) Straightforward application of SIMMER-II led to penetrations of greater than 0.3 m. To cause earlier flow stoppage, the effective viscosity of the stream had to be greatly enhanced by the particulate fraction in the flow. To get agreement with the GAP3 experiment, it had to be assumed that the injected stream initially contained 5% by volume of particles. GAP4 may not have had these particles because of the reduced waiting time between the thermite reaction and the initiation of the flow; the predicted behavior using this model agreed well with this test. Although a unique match to these experiments is not possible because the conditions in the leading edge of the discharge cannot be determined, the model does suggest plausible explanations for both results without major model adjustment.

Control Rod Experiments

Recently, experiments(10) were performed at ANL with the objective of simulating a midplane fuel injection into a nonvoided fully withdrawn PCA containing stagnant sodium to represent the meltdown phase of a CDA in an LMFBR. Their test section, mounted in the CAMEL II sodium-flow loop at ANL, was designed to match both steady-state and transient hydraulic behavior of a PCA. It contained a large open inlet pipe that simulated the fully withdrawn PCA region. Above this was a transition to a reduced-area exit pipe that simulated the absorber pin-bundle and bypass region. A 2.54-cm-diam fuel-injection port was in the side wall just below the transition. Molten fuel from a thermite reaction at 3470 K was driven into the test section with compressed argon gas. The sodium in the test section was at 773 K. To determine the subsequent fluid dynamics and fuel relocation, measurements relating to flow, pressure, and void fraction were made along the test section. Two tests were performed; in the first, C6, the fuel was injected with an initial argon driver pressure of 0.63 MPa; the second, C7, had a driver pressure of 0.31 MPa.

SIMMER-II calculations of the C6 and C7 tests were performed at the same time as these experiments.(11) These calculations and the preliminary analysis were done with no *a priori*

TABLE I

COMPARISON OF EXPERIMENTAL AND CALCULATED RESULTS FOR SPENCER'S TEST (USING NONEQUILIBRIUM FREEZING MODEL)

	Test Conditions			Penetration	
Test No.	Injection Pressure (MPa)	Cladding Temperature (K)	Thermite Mass (kg)	SIMMER-II (m)	Data (m)
1	6.6	1173.0	0.5	0.45	0.43
2	5.5	873.0	0.5	0.30	0.43
3	2.5	573.0	2.0	0.35	0.34
4	3.7	573.0	2.0	0.37	0.41
5	5.0[a]	1173.0	2.0	1.40	1.40

[a]Estimated

knowledge of the experimental results (the one exception was that it was known that about half of the injector fuel inventory of 4 kg was injected). The only information furnished by ANL was that necessary to set up the SIMMER-II calculations. It included (a) the geometries of the test section, CAMEL II loop, and injector system; (b) the fuel and coolant temperatures at the injection time; (c) the steady-state pressure drops; (d) the pressure history of the argon driver gas in the thermite injector; and (e) the steady-state and the initial transient sodium flows. The analysis model is shown in Fig. 6.

Typically, the calculations showed fuel flowing from the fuel injector tank and down through the injector tube and melting through the diaphragm at the point of injection into the test section. There was then a fuel-coolant interaction (FCI) that reversed the flow of the fuel in the injector tube and sloshed molten fuel to the upper part of the fuel injector tank. A little less than half the fuel inventory froze as crust on the tank walls. The remaining fuel then was driven back through the injector tube to the test section. Because the original FCI had caused voiding in the test section in the neighborhood of the injection point, fuel was relatively free to enter the test section.

The SIMMER-II calculations were made in cylindrical coordinates with azimuthal symmetry. However, the experiments did not have this symmetry because of the injector. Thus, a comparison of the fine details of the experimental and calculated results is not appropriate in general. However, comparisons of the overall results showed that, in most instances, SIMMER-II did a remarkable job. The comparisons showed that the SIMMER-II calculations were reasonable for (a) predicting the amount of fuel injected into the test section, (b) tracking the liquid-void interfaces both up and down the test section, (c) predicting the test-section total mass flows at any time during the injection, and (d) explaining the qualitative behavior of the FCIs.

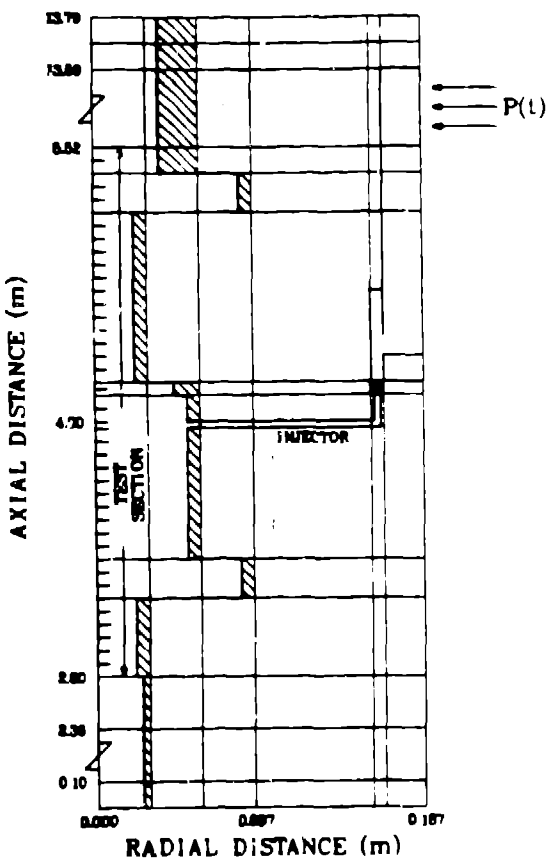

Fig. 6. SIMMER-II calculational model for the analysis of CAMEL-II tests C6 and C7.

SUMMARY

The technology base for assessing molten fuel removal from disrupting cores during CDAs in LMFBRs is currently sufficient for evaluating general accident behavior and energetic potentials. High precision is not obtainable because of the extreme complexity of the coupled, nonlinear assessment problem, but high precision is not required. Credible assessment of the behavioral trends and uncertainties is the primary focus of CDA analyses. The SIMMER-II code with its comprehensive but simplistic modeling, which has been tested against experimental data, provides this credible assessment capability.

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