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SIMMER-II Analysis of SRI Postdisassembly Expansion Experiments

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SIMMER-II ANALYSIS OF
SRI POSTDISASSEMBLY EXPANSION EXPERIMENTS

by

Terry F. Bott and C. R. Bell

ABSTRACT

Calculations of simulated postdisassembly expansions with SIMMER-II are compared to experimental data. The main features of the fluid motion are reproduced accurately. Good agreement is achieved for the important parameters of kinetic energy and impulse imparted to the vessel head. The most important calculated results are shown to be relatively insensitive to numerical modeling variations and uncertainties in many physical parameters. The geometric configuration of the upper internal structures is shown to affect significantly the vessel head impact energy and impulse.

I. INTRODUCTION

An important aspect of the liquid-metal fast-breeder reactor (LMFBR) hypothetical core-disruptive accident (HCDA) is the expansion of the vapor generated in the postdisassembly disrupted core into the upper plenum. This expansion is expected to result in pressure-driven impact of the upper core sodium on the vessel head. It is important to determine the energy and impulse delivered to the head under the range of conditions postulated for the HCDA to assess the structural integrity of the vessel following such an event.

The calculation of post-disassembly expansion in an HCDA is a nonequilibrium, multiphase, multicomponent, thermal hydraulic problem. The SIMMER-II computer program¹ can perform such a calculation, using basic thermal hydraulic field equations supplemented by general exchange functions for mass, momentum, and energy transfer. Such calculations must be verified by comparison with appropriate experimental data, however. Experimental conditions approaching those found in an HCDA are very difficult to achieve, so simulated post-disassembly tests are utilized in the assessment procedure.

A. SRI Experiments

Stanford Research Institute, International (SRI), using a gas-water system in a scale model, clear acrylic vessel, performed a set of postdisassembly expansion (PDE) experiments in 1978. A schematic of the experimental apparatus is shown in Fig. 1. This experiment was designed to provide data on the effect of upper core structures (UCS) and upper internal structures (UIS) on the expansion of a gas bubble into a liquid plenum. Measurements included maximum head pressure, upper plenum liquid pool surface displacement and pressures at various points in the vessel. From these direct measurements, head impulse, maximum slug kinetic energy, and slug impact time were derived. A visual record of the tests was preserved by high-speed photography. The experimental measurements are enumerated in Table I.

The expansion pressure source was simulated by high-pressure, room-temperature nitrogen. The cover gas was simulated by nitrogen at atmospheric pressure and the sodium pool by room-temperature water. The entire vessel was 1/30 Clinch River Breeder Reactor (CRBR) linear scale. The UCS was simulated by an 11.4-cm-diam circular plate with 139 holes. The cross-sectional area of each hole was scaled to the area of an empty subassembly duct, producing a total flow area of 16.25 cm^2 . The UIS was simulated by a 9.8-cm-diam circular plate at 1/30 CRBR linear scale with nineteen 0.80-cm-diam holes and

ten 0.84-cm-diam holes for a total flow area of 14.95 cm². The UIS was supported by four columns sufficiently strong to prevent any permanent deformation.

An explosively actuated sliding-door mechanism was designed for introducing the source pressure into the upper core. This apparatus provided an opening time of about one-tenth the expansion time of the bubble in the vessel (230 μ s). The door opening time was measured for each test with a photodiode device. An extensive description of the apparatus and results is given in Ref. 2.

B. Purpose

The purpose of this work was twofold: 1) to report comparisons of SIMMER-II calculations with the SRI UIS-UCS experiments and 2) to report sensitivity studies of several parameters important in the SIMMER-II calculations. The comparisons will provide a solid starting point for SIMMER-II extrapolations to systems beyond the reach of experimental apparatus, but of interest to safety analysts. The sensitivity study will provide an indication of the effects of data uncertainties on the extrapolations.

C. SRI Apparatus Modeling.

A calculational mesh in two-dimensional, right cylindrical geometry with azimuthal symmetry was used to represent the SRI vessel. Eight radial and forty axial cells were used, with fourteen geometric regions. A schematic of the calculational mesh is given in Fig. 2, with important structural regions indicated. The axial and radial mesh spacings were varied to allow accurate modeling of structure. The axial mesh spacing was also reduced in the cover gas region to allow better modeling of the cover gas compression. Coarse noding in the cover gas would lead to unrealistic early transitions to single-phase liquid without proper compression of the gas.

The sliding doors used in the experimental apparatus to introduce the source pressure into the vessel were modeled as solid fuel in the area above the source (with water properties in the liquid phase) and solid subassembly can wall in the area of the door guides (Fig. 1). The opening of the doors was simulated by internal heating in the doors, leading to melting and axial flow through the area above the source and failure of the can wall, allowing radial gas expansion to fill the area evacuated in the door guides. The

opening rate was determined by the rate and radial distribution of the heat generation.

To account for the elasticity of the acrylic vessel, the effective compressibility of the water was increased. An effective sonic velocity for the water was calculated by including the bulk expansion of the vessel. This led to a sonic velocity of 919.58 m/s for the liquid. The single-phase-transition void fraction was also reduced from its customary value of 0.05 to 0.03 to allow maximum compression of the cover gas before single-phase conditions were encountered.

II. EXPERIMENTAL COMPARISONS

Four base cases were calculated to assess the four geometries modeled in the test program: 1) no structure, 2) UCS only, 3) UIS only, and 4) UCS and UIS.

A. Summary of Experimental Comparisons

Comparisons of calculations with data are meaningful only if the reproducibility of the data is demonstrated. For the current set of tests Ref. 2 cites reproducibility of 3% for bubble surface displacements, 10% for peak pressures, 9% for lower core pressure and 3% for vessel cover plate impact time. These values provide an indication of the uncertainty in initial conditions and hence the band of results to which the SIMMER-II calculations with nominal conditions should be compared.

The results of these base-case calculations are summarized in Table II. Most of the calculated results are in good agreement with the experimental values. The only significant discrepancies are in the impact pressure and impact kinetic energy for test D-004, a test with both UCS and UIS installed. The uncertainty in the experimental value of the kinetic energy is large, so this discrepancy is probably not as significant as would be major discrepancies in directly measured quantities (for example, impact time or vessel head pressure.) The experimental kinetic energy values are derived from pool surface displacement measurements. All the liquid above the top of the upper core is assumed to move at the velocity of the pool surface. Visual records of the bubble expansion show that the lower surface of the pool is concave upward. The bubble-pool interface velocity exceeds the pool surface velocity, so the velocity of some liquid must exceed the pool surface velocity. Because the kinetic energy depends on the square of the velocity

and directly on mass, the slug-motion approximation used in determining the pool's kinetic energy probably provides a lower bound.

Detailed comparisons of base-case calculations with data are presented in the following sections.

B. Comparison with Test D-006 (No Upper Structure)

The pressure traces at sensors P1-4 and P6-8 for test D-006 are plotted with the SIMMER-II calculated pressures in Figs. 3-9. Transducer P5 did not function for test D-006. The location of these transducers is shown in Fig. 1. In Fig. 3 the slight difference between the modeled and actual door-opening rates is reflected in the discrepancy between the calculated and measured slopes of the initial pressure drop for sensor P1. The calculated pressures follow the data well for longer times and eventually reach nearly the same final value. Comparisons with transducer P2 (Fig. 4) are similar to those for P1.

For sensors P3 and P4 (Figs. 5 and 6) the calculated pressure maxima are high and slightly early (partially due to imprecision in the door-opening model). The basic trend is calculated correctly, but the frequency of the pressure waves is too low in the calculation. The data indicate more damping than was calculated by SIMMER-II. This may be partly caused by gas leaks in the apparatus, but is primarily a result of highly nonequilibrium expansion caused by multi-dimensional and local dissipative effects that are on a scale not represented in the SIMMER-II hydrodynamics models. The calculated equilibration pressure is higher than the experimental value. The measured value is also well below the values measured by transducers lower in the apparatus. The pressure comparisons for P6 and P7, located in the cover plate are shown in Figs. 7 and 8. In general, the calculations agree with the data, but pressure pulse magnitudes and timing are off, especially at later times. In the data the frequency of the pulses slowly decreases, and their magnitude rapidly decreases, indicating strong attenuation of the disturbance. The calculations indicate a weaker attenuation and a constant frequency. Again the measured equilibration pressure is below the equilibration pressure calculated by SIMMER-II.

Transducer P8 (Fig. 9) was designed to measure the pressure in the pool during bubble expansion. Again the calculation follows the general trend of the data, but the initial pressure rise is a little early due to the

door-opening model and pressure oscillations are overpredicted. The calculated equilibrium pressure is higher than the measured value.

Figures 10 and 11 compare measured pool-surface displacement with calculated values for two transducers. The calculated values were estimated from the liquid fraction in the mesh cells and thus have a resolution of at best one cell length (0.36 centimeters in the region of estimation.) The comparison shows good prediction of the pool motion.

Figure 12, contour plots of the vapor volume fraction, provides a good indication of the calculated flow pattern. In these plots the source bubble expands through the upper core and enters the pool region (1.8 ms). From 2.3 to 3.4 ms the bubble expands in a nearly spherical manner but with slightly enhanced axial growth. Lateral expansion begins near the equatorial plane of the nearly spherical bubble at around 3.4 ms, as the cover gas is highly compressed. The peak pressure occurs just after 3.5 ms. This plot shows that most of the cover gas was lost in the calculation because of single-phase compression. In SIMMER-II, noncondensable gas is lost permanently in a cell that reaches single-phase conditions, such as the cover gas cells in this calculation. After 3.6 ms a series of periodic compression and rarefaction waves are predicted to move through the tube until the calculation is ended at about 8.0 ms.

The experimental sequence shown in Fig. 13 is taken from Ref. 2. SIMMER-II does not predict the vortex (created by convection of the upper core viscous sublayer into the pool) or postimpact cavitation, but the basic elements of the flow are predicted.

C. Comparison with Test D-003 (UCS only)

Data from four pressure transducers were recorded for Test D-003 (with UCS only). One transducer (P2) was in the source vessel (simulated lower core). The pressure trace at this location is compared with the SIMMER-II calculation in Fig. 14. The modeling of the door opening is not exact, and the equilibration pressure calculated by SIMMER-II is a little high, but the overall agreement is very good.

Three sensors measured cover plate pressure. Sensor P5 was located at the center of the cover plate. The data and calculation for the pressure at this location are compared in Fig. 15. The agreement is excellent for the first pressure peak, with the data showing a slightly higher value than was calculated. Later peaks are overestimated by the calculation and eventually

become out of phase with the data. For this location, the calculated second pressure peak is actually higher than the initial impact pressure. Similar behavior is noted in Fig. 16, comparing calculated pressures with the data from sensor P6, which is located in the cover plate about half-way radially between the cover plate centerline and the plate edge. Finally, sensor P7, located near the outer edge of the cover plate, is compared with data in Fig. 17. The calculated pressure pulse widths are greater than those measured and occur a little later, but agree very well with the data in amplitude. The second pressure maxima calculated with SIMMER-II are higher than the initial ones. This appears to be the result of the liquid accumulating preferentially along the centerline of the pool. This results in low void fractions above the bubble and high pressures when the reflected pulse again impacts the cover plate.

Figures 18 and 19 compare surface displacement measurements with SIMMER-II calculations. The agreement is excellent and indicates good simulation of the hydrodynamics for this bubble-pool interaction.

D. Comparison with Test D-004 (UIS and UCS)

Only four sets of pressure data are available for test D-004. SIMMER-II calculations, shown with P2 data in Fig. 20, exhibit good simulation of the door opening and follow the data trend well, except for the overprediction of equilibration pressure. Figure 21 compares calculated and measured pressures at the center of the cover plate (P5). The calculations predict a later and higher initial impact pressure than the data and tend to overestimate later peaks. Again the calculated final equilibration pressure is higher than the measured value. Figures 22 and 23 are comparisons for sensors P6 and P7, also in the cover plate, but farther from the centerline. Trends similar to those noted for P5 are seen. With both the UIS and UCS in place, the expanding bubble tends to move through the UIS-UCS gap, leading to considerable acceleration of the pool near its edges. Because of this gap flow, the highest peak pressure is calculated nearer the plate edge. The data exhibit a higher initial peak at the plate center, however.

The surface displacement comparisons are given in Figs. 24 and 25. The calculated pool-surface movement agrees well with the measured data, even for the complex flow patterns induced by the extensive structures present in this test.

Void fraction contour plots are exhibited in Fig. 26. These plots clearly illustrate the effect of the UIS on the flow development. The plots for 1.2 to 2.3 ms show the early expansion of the bubble into the UCS. At 2.3 ms the bubble has encountered the UIS and flow through the gap is beginning. By about 2.8 ms there is considerable gap flow. From 3.3 to 3.8 ms expansion through the UIS and the gap continue with penetration into the pool at about 3.8 ms. Plots for 3.9 to 4.5 ms illustrate the nearly vertical expansion of the bubble in the upper pool, with lateral expansion beginning near the impact time of 4.4 ms.

The experimental sequence is shown in Fig. 27. The main qualitative difference to note is the greater lateral expansion in the test photographs than was calculated by SIMMER.

E. Comparison with Test D-005 (with UIS only)

Pressure plots for the sensors used in test D-005 are compared with SIMMER-II calculated pressures in Figs. 28-33. Again, the pressures calculated for the lower core (Figs. 28-29) indicate the accuracy of the door-opening model in SIMMER-II. The calculated pressure does follow the data quite well, but a higher final pressure is calculated by SIMMER-II, again suggesting a gas leak in the apparatus and/or highly nonequilibrium expansion.

Figure 30 exhibits the comparison for sensor P4 near the top of the upper core. The agreement is generally excellent, but the final calculated pressure is somewhat above the data. A few pressure spikes are seen as the bubble expands through the upper core near 2 ms, but the overall agreement is close.

Figures 31-32 illustrate the pressure trace comparison for transducers P6 and P7 located on the cover plate. The peak heights are very close for sensor P7, but overpredicted for P6. This may be explained by the radial cover gas flow calculated by SIMMER-II. Transducer P7 is located farther from the plate centerline than P6. SIMMER-II calculated preferential liquid flow in the center of the core, which pushed the cover gas rapidly outward. This led to higher single-phase pressures nearer the centerline of the top plate, and explains the overprediction of pressures near the plate center.

Pressure sensor P8 is compared with calculated pressures in Fig. 33. This sensor was located on a probe extending to within about 1 cm of the top of the UIS. The calculated pressures are close to the data and the overall trend is well represented. An interesting feature of this comparison is the

peak pressure at about 4 ms. This is apparently a reflection of the impact peak on the plate at about this time. The pulse propagation time calculated by SIMMER is very close to the experimental value, but the peak pressure is overpredicted. Figures 33-35 show pressures at the same axial location (P8) but at progressively greater radial positions (radial nodes 1, 2 and 3 respectively). A strong radial pressure gradient is noted in the SIMMER-II calculation, apparently because the centerline nodes are more nearly pure liquid, and higher pressures occur nearer the centerline.

Finally, Fig. 36 compares the calculated SIMMER-II pressure trace about halfway through the UIS with the measured pressure above the UIS (P8). Here the throttling effect of the UIS is clearly indicated by the greatly attenuated pressures above the UIS. The highly oscillatory conditions when the bubble enters the UIS are also illustrated.

Figures 37-39 compare calculated and measured water surface displacement for the three sensors used in test D-005. The SIMMER results lie well within the data scatter and indicate excellent simulation of the pool-bubble interaction.

III. SENSITIVITY STUDIES

The sensitivity of SIMMER-II calculations to uncertainties in physical parameters or variations in numerical control parameters is important in determining the extrapolative capabilities of the program. If the calculation shows great sensitivity to a physical parameter that has considerable uncertainty in a system of interest, SIMMER-II calculations will be of less value. Likewise, if perturbations in numerical controls lead to significant variations in results, extrapolative calculations will be questionable.

Another value in sensitivity studies with SIMMER-II is the relative ease with which the effects of variations in test conditions may be investigated. Once the fidelity of the calculations has been established through experimental comparisons with the available experiments, variations in initial test conditions can be rapidly explored with reasonable certainty of continued fidelity. Changing input and rerunning the computer program is much faster, cheaper, and easier than rerunning the experiments.

For these reasons, the sensitivity of the calculations to a number of parameters was examined by varying the values and noting changes in the

results. These parameter variations and their effects are discussed individually.

A. Effect of Mesh Cell Spacing. To solve the fluid-dynamics field equations with a finite-difference approximation, it is necessary to model a physical system with a spatial grid. Such a model must, of necessity, result in some loss of accuracy in spatial distributions of mass, energy and momentum due to lumping within nodes. This inaccuracy can often be reduced by finer mesh spacing, so the mesh dimension is closer to the scale of the physical phenomena. A finer mesh also allows more accurate representation of structures.

There are important numerical constraints on the mesh spacing, however. Computational effort increases with the number of mesh cells, and the maximum allowable computational time step, determined by the Courant stability limit for the semi-implicit finite-difference equations, decreases directly with mesh dimensions. The optimum mesh grid for computation must balance computational effort with fidelity of results. The purpose of this noding study was to determine the effects of noding on the calculation to estimate the numerical uncertainty introduced into the calculation as a result of the mesh size chosen for the bulk of the analyses.

The base-case mesh size was 8 radial and 40 axial nodes, a total of 320 nodes. Calculations were also made with 14 radial and 70 axial (980 total nodes).

These calculations are compared in Table III. This table shows the rates of altered-to-base-case calculations for parameters of interest. It is clear from this comparison that decreasing the size of the nodes does not significantly affect any of the parameters. Only the cover gas region is significantly affected by decreasing node size. Decreased node size allows greater compression of the cover gas before single-phase conditions are encountered. More expansion energy is used compressing the cover gas, thus lowering the kinetic energy of the liquid slug upon impact. The maximum pressure is also lower.

B. Single-Phase Transition Void Fraction. When the void fraction in a cell is below an input transition value, single-phase compressibility is calculated for that cell. The single-phase compressibility is very low, so small additions of mass to the cell result in very high pressures, and great resistance to further mass addition. The value of the single-phase void

fraction can affect significantly the compression of the cover gas during liquid slug impact on the cover plate. The smaller the single-phase transition value, the greater the compression of the cover gas will be before single-phase conditions are reached.

Table IV illustrates the effect of changes in the transition value. Reducing the value results in somewhat lower kinetic energy for the liquid pool but in a much higher peak cover-plate pressure. The higher peak pressure is caused by the direct dependence of the single-phase compressibility on the transition void fraction. A decrease in this value leads to a decrease in compressibility, hence resulting in a higher pressure when single-phase conditions are reached. This purely numerical artifice does not greatly affect the kinetic energy or cover-plate-impulse calculations. These two parameters are most important in determining vessel loading and are not very sensitive to the single-phase treatment.

C. Liquid Sonic Velocity. In the SIMMER-II pressure formulation, single-phase liquid pressures are determined from the inverse of the effective mixture liquid compressibility. The liquid compressibility is calculated from the effective liquid sonic velocity. Therefore, variations in the liquid sonic velocity will affect single-phase pressure calculations in the same manner as single-phase transition void fraction variations.

The sonic velocity used in the base-case calculation took into account the elasticity of the acrylic vessel. Using elasticity parameters supplied by SRI and a standard expansion formula for a cylinder, an effective liquid compressibility was calculated based on the sonic velocity of water at the test temperature. This calculation produced a sonic velocity of 919.58 m/s as compared to a value of 1498.0 m/s for pure water at this temperature.

Table V illustrates the effect of sonic velocity on the calculated results. The kinetic energy and impulse of the slug are not sensitive to sonic velocity variations. The main sensitivity lies in the peak cover plate pressure. This demonstrates that a good effective single-phase liquid compressibility is necessary for good peak pressure calculations, but considerable uncertainty in this parameter does not affect significantly the impulse or slug kinetic energy that determines vessel head loading.

D. Source Pressure. The effect of variations in source pressure on calculated results should be roughly predictable from ideal gas calculations. The SIMMER-II base-case calculations were approximately isentropic because

interphase heat transfer was not included (interphase momentum transfer was included, however). Based on isentropic ideal gas expansion, the maximum kinetic energy of the slug should vary directly with the initial pressures. This is seen to be the case for all SIMMER-II calculations. These results, shown in Table VI, indicate good agreement with expected variations for changes in source pressure.

E. Heat Transfer. Heat-transfer effects were not included in the base-case calculations. When heat transfer between the gas and liquid is modeled, the results are only slightly affected as shown in Table VII. The kinetic energy and peak pressure are decreased slightly because of the increased work required to compress the cover gas when heat losses occur. The reason for these variations may be visualized by examining an ideal gas. The ideal gas isothermal compressibility, a limiting case of high heat transfer, is given by

$$K_T = - \left(\frac{V}{P} \right) ,$$

whereas the adiabatic compressibility is

$$K_S = - \frac{1}{\gamma} \left(\frac{V}{P} \right) .$$

Because γ is greater than one,

$$|K_T| > |K_S| .$$

The adiabatic case should be "stiffer," leading to higher peak pressures. Comparing work done by adiabatic and isothermal expansions, we see that more work is done in the isothermal case, so the kinetic energy should be smaller. These trends are seen in the results of Table VII.

F. Upper Core - UIS Gap.

The test vessel was constructed to provide an adjustable circumferential gap between the top of the upper core and the bottom edge of the UIS. In the tests the gap was set to provide a lateral flow area based on that resulting from UIS displacement in previous structural response experiments.³ This nominal gap size was used in the base-case comparison calculations. In the sensitivity studies the gap size was varied from no gap to double the nominal gap size to investigate the effect of this geometric parameter.

The UIS is very effective in attenuating the effects of the bubble expansion on the cover plate. The gap allows flow to bypass the UIS, so an increase in gap size results in an increase in cover plate impulse, energy and peak pressure and a shorter time to impact. A decrease in the gap size has the opposite effect. This is illustrated in Table VIII. This table illustrates that altering the gap size has the greatest effect on the impulse. The calculation also shows a greater sensitivity to decreasing the gap size below its nominal size than to increasing it. Apparently, even if the gap is significantly increased from its nominal size the bypass flow is still redirected through a narrow path with considerable momentum losses, so that some minimum attenuation is still achieved even with a wide gap. If the gap size is decreased, however, more flow is directed through the highly dissipative UIS and marked reductions occur in the momentum of the slug.

G. Cover Gas Properties

The base-case calculations modeled the cover gas as an ideal gas with the properties of nitrogen at one atmosphere. Several variations on this calculation were completed (see Table IX).

A very low density cover gas was modeled to approximate a void. This calculation produced higher kinetic energy and a greater impulse to the cover plate. A condensable water vapor cover gas was also modeled. No significant variations in the calculations resulted from this variation.

H. Liquid - Gas Friction

The effects of variations in the liquid-gas momentum exchange parameters were studied in two ways: 1) the interfacial area was varied, and 2) a direct multiplier was applied to the momentum exchange function. These results are presented in Table X. Drag effects are seen to be relatively unimportant in determining cover plate response. This is a reassuring result, because the SIMMER constitutive equations use only a droplet flow regime, so interfacial transport is highly dependent on droplet size criteria that are highly uncertain.

IV. CONCLUSIONS

A preliminary assessment of SIMMER-II PDE modeling was performed through comparison with SRI simulated PDE experiments. The hydrodynamics modeling in SIMMER-II accurately reproduced the pressure, impulse, kinetic energy and pool displacement data for all the tests. The calculated flow patterns showed the

main features noted in the tests, but obviously did not reproduce effects (such as vorticity and cavitation) for which SIMMER-II has no models.

Sensitivity of the SIMMER-II calculations was investigated for a number of numerical and physical parameters. Numerical modeling was found to be of secondary importance in determining cover-plate impulse and the impact kinetic energy of the slug. An accurate sonic velocity is necessary to reproduce cover-plate pressure measurements, however. Interphase drag and heat transfer were found to be of minor importance. Reasonable variations in the cover gas properties did not affect the results greatly. The UIS-UCS circumferential gap size was a major factor in determining cover-plate loading in those cases with UIS present.

Based on these comparisons, the SIMMER-II code appears to be capable of modeling the important hydraulic phenomena that determine the interaction of expanding fuel with a sodium pool. Further work should be performed to assess the ability of SIMMER-II to model the thermal effects of the PDE.

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3. C. M. Romander and D. J. Cagliostro, "Experimental Simulation of a Hypothetical Core Disruptive Accident in 1/20-Scale Models of the Clinch River Breeder Reactor," Technical Report 4, SRI Project PYU-3929, SRI International, Menlo Park, CA (October 1978).

TABLE I
MEASURED PARAMETERS IN SRI
HCDA BUBBLE EXPANSION EXPERIMENTS

Initial conditions:
 Lower core pressure
 Lower core temperature
 Cover gas gap
 Transient measurements:
 Sliding door opening time
 Lower core pressure
 Upper core pressure
 Pressure in the pool and bubble
 Water surface displacement
 Vessel cover pressure
 High-speed photography of the bubble expansion

TABLE II
SUMMARY OF MEASURED AND CALCULATED
VALUES FOR IMPORTANT PARAMETERS^a

Test Number	Structure Present	Impact Time (ms)	Impact Pressure (MPa)	Impact Kinetic Energy (kJ)	Impulse of First Slug Impact Pulse (N·s)
D-006	None	2.33 (2.16)	32.9 (32.8)	2.45 (2.46)	357. (296.)
D-003	UCS	2.69 (2.51)	25.6 (28.2)	2.12 (2.42)	312. (264.)
D-005	UIS	3.00 (2.75)	23.0 (20.4)	1.65 (0.85)	235. (192.)
D-004	UCS UIS	3.20 (2.84)	32.4 (17.0)	1.58 (0.61)	204. (178.)

^aFigures in parentheses are experimental results.

TABLE III
SENSITIVITY OF SIMMER-II SRI CALCULATION TO NODING

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N.s)</u>
980 Nodes	None	1.04	0.91	0.96	1.08

TABLE IV
SENSITIVITY OF SIMMER-II SRI CALCULATIONS
TO SINGLE-PHASE CUTOFF VOID FRACTION

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N.s)</u>
Reduce cutoff To 0.01	None	1.0	1.81	0.96	1.03
Increase cutoff to 0.05	None	0.99	0.83	1.01	1.01

TABLE V
SENSITIVITY OF SIMMER-II SRI CALCULATIONS
TO LIQUID SONIC VELOCITY

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N.s)</u>
Increase sonic velocity by 63%	None	1.0	1.49	0.94	0.93
Increase sonic velocity by 30%	None	1.0	1.13	0.94	0.95

TABLE VI
SENSITIVITY OF SIMMER-II SRI CALCULATIONS
TO UPPER CORE PRESSURE

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N.s)</u>
Reduce press by 50%	None	1.07	0.73	0.47	0.65
Reduce press by 80%	None	1.86	0.34	0.19	0.47
Reduce press by 50%	UIS	1.29	0.68	0.47	0.57
Reduce press by 80%	UIS	1.88	0.20	0.18	0.31

TABLE VII
SENSITIVITY OF SIMMER-II SRI CALCULATIONS
TO GAS-LIQUID HEAT TRANSFER

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N.s)</u>
Heat transfer included	None	1.0	0.87	0.93	1.03

TABLE VIII
SENSITIVITY OF SIMMER-II SRI CALCULATIONS
TO UIS-UPPER CORE GAP SIZE

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N.s)</u>
NO gap nominal	UIS	1.29	0.58	0.76	0.25
1/2 gap nominal	UIS	1.29	0.56	0.76	0.30
2 x Gap	UIS	0.89	1.03	1.26	1.13

TABLE IX
SENSITIVITY OF SIMMER-II SRI CALCULATIONS
TO COVER GAS PROPERTIES

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N·s)</u>
Condensable cover gas	None	1.06	0.84	1.05	0.95
Low-density cover gas with $\gamma = 1.0$	None	1.06	0.85	1.08	0.96
Low-density monatomic cover gas ($\gamma = 1.67$)	None	1.06	0.85	1.06	0.95

TABLE X
SENSITIVITY OF SIMMER-II SRI CALCULATIONS TO
INTERFACIAL DRAG

<u>Parameter Variation</u>	<u>Structure Present</u>	<u>Ratio of Altered Value to Base-Case Value</u>			
		<u>Impact Time (ms)</u>	<u>Impact Pressure (MPa)</u>	<u>Impact Kinetic Energy (kJ)</u>	<u>Vessel Head Impulse (N·s)</u>
Increase drag by factor of 10	None	1.0	0.85	1.01	0.98
Decrease drag by factor of 10	None	0.99	0.87	1.0	0.98

Fig. 1.
SRI experimental apparatus.

Fig. 2.
SIMMER-II model of SRI apparatus.

Fig. 3.
Measured pressure from sensor P1
compared with SIMMER-II calculation
for test D-006.

Fig. 4.
Measured pressure from sensor P2
compared with SIMMER-II calculation
for test D-006.

Fig. 5.
Measured pressure from sensor P3
compared with SIMMER-II calculation
for test D-006.

Fig. 6.
Measured pressure from sensor P4
compared with SIMMER-II calculation
for test D-006.

Fig. 7.
Measured pressure from sensor P6
compared with SIMMER-II calculation
for test D-006.

Fig. 8.
Measured pressure from sensor P7
compared with SIMMER-II calculation
for test D-006.

Fig. 9.
Measured pressure from sensor P8
compared with SIMMER-II calculation
for test D-006.

Fig. 10.
Measured water surface displacement
from sensor 3929-17 compared with
calculated value for test D-006.

Fig. 11.
Measured water surface displacement
from sensor WS1 compared with
calculated value for test D-006.

Fig. 12.
Calculated vapor volume fraction contour plots for test D-006.

Fig. 12. (cont)
Calculated vapor volume fraction contour plots for test D-006.

$t = 1.195$ msec from detonation
 $\Delta t = 0.0$ msec
 Doors begin to open

$t = 1.786$ msec
 $\Delta t = 0.591$ msec
 Vortex appears at core
 barrel opening

$t = 1.984$ msec
 $\Delta t = 0.789$ msec
 Vortex grows

$t = 2.182$ msec
 $\Delta t = 0.987$ msec
 Bubble emerges into pool

$t = 2.282$ msec
 $\Delta t = 1.087$ msec
 Bubble continues to emerge

$t = 2.480$ msec
 $\Delta t = 1.285$ msec
 Bubble engulfs vortex

$t = 2.778$ msec
 $\Delta t = 1.583$ msec
 Bubble continues to grow and
 reaches pool pressure transducer

$t = 3.075$ msec
 $\Delta t = 1.880$ msec

$t = 3.373$ msec
 $\Delta t = 2.178$ msec
 Slug impact at $t = 3.35$ msec

$t = 4.067$ msec
 $\Delta t = 2.872$ msec
 Post impact cavitation

Fig. 13.
 Photographic record of test D-006.

Fig. 14.
Measured pressure from sensor P2
compared with SIMMER-II calculation
for test D-003.

Fig. 15.
Measured pressure from sensor P5
compared with SIMMER-II calculation
for test D-003.

Fig. 16.
Measured pressure from sensor P6
compared with SIMMER-II calculation
for test D-003.

Fig. 17.
Measured pressure from sensor P7
compared with SIMMER-II calculation
for test D-003.

Fig. 18.
Measured water surface displacement
from sensor 3929-17 compared with
calculated value for test D-003.

Fig. 19.
Measured water surface displacement
from sensor WS1 compared with
calculated value for test D-003.

Fig. 20.
Measured pressure from sensor P2
compared with SIMMER-II calculation
for test D-004.

Fig. 21.
Measured pressure from sensor P5
compared with SIMMER-II calculation
for test D-004.

Fig. 22.
Measured pressure from sensor P6 compared with SIMMER-II calculation for test D-004.

Fig. 23.
Measured pressure from sensor P7 compared with SIMMER-II calculation for test D-004.

Fig. 24.
Measured water surface displacement from sensor 3929-17 compared with calculated value for test D-004.

Fig. 25.
Measured water surface displacement from sensor WS1 compared with calculated value for test D-004.

Fig. 26.
Calculated vapor volume fraction contour plots for test D-004.

3.4 ms

3.6 ms

3.8 ms

3.9 ms

Fig. 26. (cont)
Calculated vapor volume fraction contour plots for test D-004.

Fig. 26. (cont)
Calculated vapor volume fraction contour plots for test D-004.

$t = 1.19 \text{ msec from detonation}$
 $\Delta t = 0.0 \text{ msec}$
 Doors begin to open

$t = 1.812 \text{ msec}$
 $\Delta t = 0.622 \text{ msec}$
 Vortices appear at core barrel opening

$t = 2.114 \text{ msec}$
 $\Delta t = 0.924 \text{ msec}$
 Vortices appear at top of upper internal structure

$t = 2.416 \text{ msec}$
 $\Delta t = 1.226 \text{ msec}$
 Bubble grows

$t = 2.718 \text{ msec}$
 $\Delta t = 1.528 \text{ msec}$

$t = 3.020 \text{ msec}$
 $\Delta t = 1.830 \text{ msec}$

$t = 3.322 \text{ msec}$
 $\Delta t = 2.132 \text{ msec}$

$t = 3.623 \text{ msec}$
 $\Delta t = 2.433 \text{ msec}$
 Bubble reaches vessel wall

$t = 4.026 \text{ msec}$
 $\Delta t = 2.836 \text{ msec}$
 Slug impact at $t = 4.03 \text{ msec}$

$t = 4.831 \text{ msec}$
 $\Delta t = 3.641 \text{ msec}$
 Post impact bubble growth

Fig. 27.
 Photographic record of test D-004.

Fig. 28.
Measured pressure from sensor P1
compared with SIMMER-II calculation
for test D-005.

Fig. 29.
Measured pressure from sensor P2
compared with SIMMER-II calculation
for test D-005.

Fig. 30.
Measured pressure from sensor P4
compared with SIMMER-II calculation
for test D-005.

Fig. 31.
Measured pressure from sensor P6
compared with SIMMER-II calculation
for test D-005.

Fig. 32.

Measured pressure from sensor P7 compared with SIMMER-II calculation for test D-005.

Fig. 33.

Measured pressure from sensor P8 compared with SIMMER-II calculation for test D-005.

Fig. 34.

Pressure calculated at the second radial node compared with measured value at the same axial location at the centerline (P8).

Fig. 35.

Pressure calculated at the third radial node compared with measured value at the same axial location at the centerline (P8).

Fig. 36.
Pressure calculated half-way through
the UIS compared with the value
measured above the UIS (P8).

Fig. 37.
Measured water surface displacement
from sensor 3929-17 compared with
calculated value for test D-005.

Fig. 38.
Measured water surface displacement
from sensor WS1 compared with
calculated value for test D-005.

Fig. 39.
Measured water surface displacement
from sensor WS2 compared with
calculated value for test D-005.