A Review of the EPRI Hydroloads Program

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Abstract
For a large, rapid, close-to-the-vessel break of a pressurized water reactor (PWR) inlet pipe, hydrodynamic loads in the primary system were speculated by the U.S. Nuclear Regulatory Commission (NRC) to have licensing significance during the subcooled portions of a hypothetical loss-of-coolant accident (LOCA). The analytical methods which are used to analyze hydroloads for licensing submittals rely on one-dimensional modeling techniques and require significant engineering judgment to couple the internal structures, such as the core support barrel, and the adjacent fluid. These analysis methods are expected to overestimate the acceleration and impact forces on primary system components.

EPRI-sponsored research [1] provides a three-dimensional, fluid-structure interaction methodology for realistically calculating the transient loads on the vessel, core support barrel, and core during the subcooled portion of a hypothetical LOCA. The methodology was developed in a stepwise fashion and directed toward the adaptation, assessment, and application of the methodology. The hydrodynamics computer program is the STEALTH code [2]. The structural computer program is the WHAMSE code [3]. A smaller and faster version of STEALTH called STEALTH-HYDRO was used, which henceforth will be referred to as STEALTH.

Methodology enhancements were made in a stepwise fashion (1D, 2D, then 3D). The modified computer programs were then assessed by comparing calculated results with analytical solutions and experimental data. The calculated results compared favorably with the analytical and experimental results. Furthermore, the calculation of HDR tests V31.3 and V32 proved to be valuable for understanding the fundamental mechanics of fluid-structure interaction in large-scale systems during subcooled blowdown. The final stage of the EPRI program was to apply the coupled, 3D fluid-structure interaction methodology to the calculation of the hydrodynamic loads in a modified HDR model having a dynamic axially distributed core.

EPRI's fluid-structure interaction program has resulted in state-of-the-art technology which can be applied to both nuclear licensing and engineering problems without the significant engineering judgment required of less sophisticated methods. Realistic loads can be obtained to quantify conservatism in current licensing approaches.
1. Introduction

During a large, rapid, close-to-the-vessel break of a PWR inlet pipe, the hydrodynamic loads in the primary system, that were speculated by the NRC to have licensing significance during the subcooled portions of a hypothetical LOCA, are caused by pressure differences across the core, the core barrel, and across the vessel. These forces result in axial loads on the fuel bundle and on the tie plate, lateral loads on the fuel bundle, and loads on the vessel and foundation tie plates. The questions raised by the NRC in 1976 and 1977 related to the safety significance of these loads. EPRI began research in 1977 to provide a coupled, three-dimensional (3D), nonlinear methodology to be used in the event that licensing methods could not be developed to adequately handle the problem. The EPRI approach was to be realistic and not conservative. EPRI used a matrix approach, with 1D, 2D, and 3D methodologies being developed sequentially in a stepwise fashion based on past EPRI-funded research. Each step began with adaptation or development of the 1D, 2D or 3D methodology, followed by analytical and experimental assessment, and model studies (as appropriate).

The NRC and the utility owners group have, by the act of working on the asymmetric loads issue, effectively removed it from NRC’s problem list. The NRC is now considering leak-before-break based on experimental work funded by a utility owners group. This has reduced the concern for rapid pipe breaks in the primary system. Additionally, probabilistic risk assessment techniques have shown that large rapid breaks are not risk contributors. Thus, from an NRC and therefore industry perspective, asymmetric loads now has a low priority.

2. Adaptation of Computer Codes

The methodology was based on prior EPRI technical developments [4]. STEALTH [2] is an explicit, finite difference, nonlinear continuum mechanics computer code available in one-, two-, and three-dimensional (1D, 2D, and 3D) versions. WHAMSE [3] is an explicit, finite element, nonlinear structural computer code available in 2D and 3D versions. WHAMSE has a beam element, a triangular plate element, and a rigid linkage. The STEALTH computer code was streamlined to a hydrodynamic version, which henceforth will be referred to as STEALTH. The developmental effort progressed from 1D to 2D to 3D, using STEALTH for the analysis of the fluid response and WHAMSE for the analysis of the structural response. Additional methodology enhancements included the fluid-structure coupling between STEALTH and WHAMSE, fluid-fluid coupling with control volumes, and obstacle zones to preclude fluid movement through areas containing structure.

The fluid grid-to-fluid grid coupling or "valve" control volume [1,5] was developed to transfer information between adjacent STEALTH fluid grids. This model is also the basis for the "orifice" control volume model used for discharge from pipes. The "orifice" model is the "valve" model with one side of the "valve" degenerated to a time-dependent pressure boundary condition.

The "valve" model connects upstream and downstream fluid grids. It consists of a 1D model based on isentropic expansion, with the wave equation and conservation laws relating the upstream and downstream variables. The "valve" model allows the user to set the cross-sectional area or uses the minimum area of the upstream and downstream fluid grids, with choking handled by setting the "valve" pressure to the critical pressures, and a vena contracta model for proper flow conditions.
The obstacle model prevents flow within a fluid grid. The motion on the surface of the obstacle zone are modeled by STEALTH grid points, which slip freely on the surface and around the corners of the obstacle. The only constraints are the kinematic boundary conditions show in Figure 1.

The fluid-structure coupling algorithm [1,6] allows the structure to "feel" the fluid through a set of external forces and external masses, while the fluid "sees" the structure in the form of a kinematic wall constraint. This coupling is termed "weak" and is correct when the fluid, which is the softer medium, can flow over the stiffer structure.

A subcycling algorithm was developed to allow the structure, with its smaller stable time step, to subcycle along with the first row of fluid zones. Subcycling reduces computing time. It can also improve accuracy by allowing the grids to be integrated using time steps closer to their respective maximum stable time steps, resulting in smaller diffusion of sharp waves in the fluid calculation.

For the 3D methodology, a mixed phase equation of state for water was added. WHAMSE was streamlined and a hinge model added for beam elements.

3. Model Studies
To check STEALTH 1D, a straight pipe decompression problem was run [1] with various length-to-orifice ratios. The magnitude and velocity of the first decompression wave were compared to the analytic solution as follows:

<table>
<thead>
<tr>
<th>Pipe-to-Orifice Area Ratio</th>
<th>Pressure STEALTH</th>
<th>Pressure Acoustic Theory</th>
<th>Velocity STEALTH</th>
<th>Velocity Acoustic Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/1</td>
<td>10.04 MPA</td>
<td>10.05 MPA</td>
<td>3.336 m/s</td>
<td>3.331 m/s</td>
</tr>
<tr>
<td>10/1</td>
<td>10.46 MPA</td>
<td>10.46 MPA</td>
<td>3.054 m/s</td>
<td>3.049 m/s</td>
</tr>
<tr>
<td>20/1</td>
<td>11.27 MPA</td>
<td>11.26 MPA</td>
<td>2.513 m/s</td>
<td>2.510 m/s</td>
</tr>
</tbody>
</table>

The analytical solution did not consider fluid compressibility. Comparisons to acoustic theory were also made for a two-area pipe decompression and decompression from a tee. To check out STEALTH 2D, it was compared to the two-area pipe problem. Coupled STEALTH/WHAMSE 2D was used to do "slice" studies of blowdowns from an HDR geometry [7,8,9,10]. The HDR is a large-scale German LWR used for various tests. LOCA blowdown tests in HDR will be discussed later.

The HDR "slice" studies, as shown in Figure 2, was the first evidence the EPRI program achieved on the effect of fluid-structure interaction. Surface plots, such as the one shown in Figure 3 were useful in interpreting physical phenomena revealed in the 2D and 3D computer codes.

4. Experimental Assessment of the Methodology
The major emphasis in this program was to evaluate the methodology, which was developed, by comparing it to experimental data. The Semiscale test 711 was calculated with 1D, 2D and 3D versions of the STEALTH computer code. Figure 4 shows the Semiscale 711 geometry and the instrumentation locations. Figure 5 is the comparison of the data to the 1D calculations of the vessel blowdown. Figure 6 is the comparison to the 2D STEALTH calculations. 3D STEALTH/
WHAMSE comparisons to data are shown in Figure 7. This exercise caused us to learn that the Semiscale 711 downcomer was hollow and filled with desert sand. This made it difficult if not impossible to characterize the fluid-structure interaction that was present in the experiment. 2D WHAMSE was tested by comparison to an impulsively loaded ring problem as shown in Figure 8. The couple STEALTH/WHAMSE 2D and 3D were tested with the Hirt problem [11]. The Hirt problem consists of a circular steel ring placed between two concentric regions of liquid water. Initially the ring is at rest, but the liquid regions are at different pressures. Since a zero tangential velocity boundary condition is specified at both ends of the steel ring, only radial motion occurs, and the motion of the ring is confined to the breathing mode because of symmetry. The period of the steel ring calculated with STEALTH/WHAMSE 2D was 0.692 ms; compared with the analytical result of 0.664 ms, and the STEALTH/WHAMSE 3D result of 0.678 ms. The STEALTH/WHAMSE 2D calculated amplitude was $2.385 \times 10^{-5} \text{m}$ compared to the theoretical value of $2.372 \times 10^{-5} \text{m}$, with STEALTH/WHAMSE 3D giving $2.400 \times 10^{-5} \text{m}$.

The Semiscale 704 experiment was similar to 711 except the vessel had no internals. This experiment was chosen to qualify 3D STEALTH and Semiscale 704 data is compared to STEALTH 3D calculated results in Figure 9.

To qualify WHAMSE 3D, it was used to calculate a statically loaded square flat plate for which theoretical solutions are given [12]. Comparison of theoretical and calculated results are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Displacement plate center (m)</th>
<th>Stress plate center (Pa)</th>
<th>Stress edge center (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>$-5.265 \times 10^{-4}$</td>
<td>$-5.971 \times 10^{6}$</td>
<td>$1.3265 \times 10^{7}$</td>
</tr>
<tr>
<td>WHAMSE 5x5 model</td>
<td>$-5.460 \times 10^{-4}$</td>
<td>$-6.592 \times 10^{6}$</td>
<td>$1.1129 \times 10^{7}$</td>
</tr>
<tr>
<td>WHAMSE 10x10 model</td>
<td>$-5.321 \times 10^{-4}$</td>
<td>$-6.516 \times 10^{6}$</td>
<td>$1.2184 \times 10^{7}$</td>
</tr>
</tbody>
</table>

Another problem used to test WHAMSE 3D was a cylindrical panel subjected to an explosive load [12]. The panel spans an angle of 120° with a radius of 0.0746 m, a length of 0.319 m, and a thickness of 0.00318 in. The material model assumed an elastic, perfect-plastic behavior. The displacement time history at the center of the panel is compared with the measured data in Figure 10.

The most demanding experiments conducted for testing fluid-structure interaction during LOCA blowdown have been conducted in Germany. One such test is the Battelle-Frankfort test RS-16B DWR 5. Figure 11 shows a comparison of experimental data and calculations of pressure done with STEALTH/WHAMSE 3D [1,13]. One calculation was done with a rigid core barrel and the other with a flexible barrel. Note that the calculation done with a flexible core barrel compares better with the data. This experiment was not typical of commercial LWRs, since the vessel radius was small relative to vessel length. However, this experiment did have strain data (Figure 12) which compared favorably with the calculations and qualified the methodology to predict fluid-structure interaction (FSI). The most demanding test of the coupled
methodology was in predicting the blowdown experiments done in the German HDR facility. The large HDR geometry is representative of commercial LWRs. EPRI has done calculations of tests V31.1 and V32 [1,13,14]. Figure 13 shows the HDR geometry and Figure 14 shows a typical model used for representing the HDR geometry. Figures 15 and 16 show typical comparison of pressure data and calculational results for HDR tests V31.1 and V32, respectively. Figures 17 and 18 show comparison of representative strain data and calculational results for V31.1 and V32, respectively. The HDR test results comparisons are presented in more detail in paper B6/8 [15].

5. Dynamic Core Calculation

The developed 3D methodology has recently been put through an application exercise. Since the HDR geometry was well understood, it was used as the basis for a calculation with an axially distributed core, as opposed to the mass ring at the bottom of the core barrel in the actual HDR tests. An actual reactor core is axially distributed compared to being concentrated in a mass ring at the base of the core barrel. One outcome of this exercise was that the fluid dynamics was essentially the same as was seen in HDR experiments V31.1. A detailed discussion of this effort is presented in paper B6/7 [16].

6. Conclusions

The component computer codes, STEALTH and WHAMSE, gave good results when compared to theoretical problems and experimental data. The coupled 2D and 3D fluid-structure interaction (FSI) methodology gave good agreement between calculated results and experimental data in which FSI is important. A major goal and a major advantage of the STEALTH/WHAMSE computer program is that it is user-oriented and highly versatile in modeling reactor systems.

The calculations of LOCA test RS-16B DWR5 and HDR LOCA hydroloads tests V31.1 and V32 display the influence of FSI on the hydrodynamic response in a vessel during subcooled blowdown. The HDR tests in particular were well characterized. The effects observed in the tests and the calculations were: the reduced velocity of the pressure wave because of the flexibility of the core barrel, the transmission of decompression waves through the core barrel into the core region, the initial kickback of the bottom of the core barrel away from the exit nozzle, the hoop mode of expansion of the core barrel at the exit nozzle level, ovaling of the core barrel, and barrel shortening or Poisson effect as the barrel expands in the hoop mode.

The flexibility of the core barrel, and the fact that the decompression wave travels about five times faster in the core barrel than in the fluid, result in smaller loads across the core barrel than if the barrel were assumed rigid. This is a positive statement for the safety of large PWRs during a rapid close-to-the-vessel double-ended-cold-leg-break. The good agreement with the RS-16B DWR5 and HDR test V31.1 and V32 experiments demonstrate the capability of STEALTH/WHAMSE to calculate FSI effects, and to do it well. STEALTH/WHAMSE was qualified with LOCA hydroloads in mind, but its development was such that it is flexible and applicable to other FSI problems not just LOCA hydroloads.
References


[10] Versuchsröstkoll Blowdown-Versuch Nr. 32, PHDR-Arbeitsbereich Nr. 3.275/82.


Figure 1. Schematic of the oscillating zones and the special grid points associated with these zones that are used in STEALTH/3D.

Figure 2. Snapshot at 3.0 ns showing the pressure in the HDB 2D vessel with a flexible core support barrel. The dot density in the upper portion of the figure is proportional to the local pressure. The curve labeled Path ABCDE represents the pressure along the blowdown nozzle and around the annulus. The curve labeled Path ABCDE represents the pressure along the blowdown nozzle and across the vessel.

Figure 3. Surface plot of pressure vs distance around the annulus (Path ABCD) vs time for the HDB 2D vessel with a flexible core support barrel, 1 m nozzle, and 2 ms orifice opening time.

Figure 4. Scheme of the vessel used for semicircular Test 711. Dimensions are in metric. P1, P2, P3, P7, and P8 indicate transducer locations.

Figure 5. Comparison of STEALTH/3D base case calculation results to Semicircular Test 711 data.
Figure 6. Comparison of STEALTH-HYDRO 10/20 base case calculational results to Sericsula Test 711 data.

Figure 7. Pressure time histories from the 39 STEALTH-HYDRO calculation of test 711 with a stainless steel design. Transducer locations shown on the insert: (a) transducer P1, (b) transducer P2, (c) transducer P7, and (d) transducer P9.

Initial Velocity - 10.1 m/s

2.1 m/s

5.0 m/s

10.5 m/s

3.2 m/s

4.4 m/s

3.9 m/s

Figure 8a. Accuracy and initial value conditions for the positively loaded ring problem.

Reflection of pipe in [mm]

0.0

0.1

0.6

1.5

3.0

Time (sec)

Figure 8b. Comparison of WAMS 30 calculational results to experimental data from the positively loaded ring problem.

Figure 9. Pressure time histories from the STEALTH-HYDRO calculation of test 711. The transducer locations shown on the insert: (a) transducer P1, (b) transducer P2, (c) transducer P9, and (d) transducer P9.
Figure 10. Comparison of SMILE 3D calculation results to experimental data for the explosively-loaded, cylindrical panel.

Figure 11. Pressure-time history comparison of the test data with the calculation for the SMILE 3D simulation. The data is the actual measured pressure at the designated points.

Figure 12. Comparison of the calculated and measured displacements for the cylindrical panel for the different loadings.

Figure 13. Schematic of the test setup and configuration with labeled components.

14a. STEALTH 3D finite element model.
14b. SMILE 3D core barrel model.

Figure 14. 3D STEALTH and SMILE models used in this test P92 calculation.
Figure 14. Pressure-time history comparison of the H3R test V2P experimental data and the STEALTH/WAVE 3D Calculations: in the dome container at the blowdown nozzle level 1, in the dome container at the blowdown nozzle level 2, in the dome container at the blowdown nozzle level 3, and differential pressure across the core barrel at the blowdown nozzle level 4.