ANALYSIS OF AN HCDA IN A FAST REACTOR WITH A MULTIPHASE AND MULTICOMPONENT BEHAVIOR LAW

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ABSTRACT

With the CEA/DMT PLEXUS program, HCDA behavior can be analyzed in an LMFBR using a 3-component multiphase model. Coupling between phenomena enables a comprehensive survey to be obtained in a single run. An application is presented for an SPX type reactor, for three different loadings.

1. INTRODUCTION

Fast breeder reactor safety requirements include analysis of hypothetical core disruptive accident (HCDA) consequences. This accident causes core meltdown and the formation of a high pressure gas bubble which thrusts the sodium upwards, compressing and ejecting the argon cover gas, so that the sodium eventually impacts the roof slab. The path followed by the bubble and the sodium is modified by the internals and the associated fluid structure couplings, thereby significantly altering repercussions on the vessel and slab.

First encouraging experiments, using PLEXUS with available resources (1), confirmed the advantage of developing a 3-component, two-phase behavior law to model the internal fluids, thereby obtaining a comprehensive view of the interconnected phenomena. This project was subsequently implemented and presented at the SMIRT 11 (2). Finally, many tests and validations (3) have evidenced the code's suitability for analysis of this type of accident. PLEXUS is currently a reference code in France for LMFBR safety studies.

With a view to demonstrating the possibilities of PLEXUS for complex structure calculations, we here present an application to a Superphenix-type reactor, with three different energy scenarios.

2. MODELLING PRINCIPLES

2.1 Mesh

Since the accident is assumed to occur in mid-core, an axisymmetrical representation is used. An overall diagram is given in Figure 1. The obstacles, the two vessels and the cylindrical shells are modelled using thin shell theory, the roof slab is meshed as solid elements, as is the 3-component mixture (argon, sodium, reaction gas) filling the main vessel. The space between the main and safety vessels is nitrogen-filled (Figure 2).


2.2 Structures

Owing to its important safety function, the slab has been modelled in considerable detail, featuring the large and small rotating plugs (GBT, PBT), the core cover plug (BCC) and the support ring. These various sub-structures are linked by shell rings, the stiffness of which was determined to ensure the realistic behavior of the assembly. In addition, added masses model structures resting on the slab.

Sub-structures inside the vessel, such as the diaphragm, the core support plate and ring, the inner vessel and inner shell are represented by equivalent shells. The lateral neutron shielding assemblies are modelled as a single shell ring, without circumferential resistance, encircling the diaphragm. The external thermal shield is represented as added thickness to the main vessel.

2.3 Fluids

All space between these structures is fluid-filled. Initially, argon occupies the upper area and sodium the rest of the main vessel, except for a small spherical region occupied by the reaction gases. All these fluid elements are of the ALE type and coupled to the structures, whether these are immersed in the fluid or in contact on only one side.

2.4 Materials

The behavior of all the shell modelled structures is of the isotropic Von Mises type. The solid roof slab structures remain linear. Except for the nitrogen in the space between the vessels, which is a perfect gas, all fluids are modelled using a single 3-component, two-phase equation of state (2). In a given element, the phases are in mechanical equilibrium (same pressure) and the components identified by their concentration. As the calculation proceeds, flux between the elements modifies local concentrations and thereby behavior.

2.5 Loadings

Three cases are considered, differing only by the behavior of the gas in the bubble. The volume of the bubble is consistently 4 m³, but in the first two cases, the gas undergoes a polytropic transformation (PVⁿ = constant), without exchanging heat with the sodium or argon (ADCR material). In the third case, the gas undergoes an adiabatic transformation and follows a JWL equation of state, linking pressure P, density and internal energy e (ADCRJ material)

\[
P = A \left(1 - \frac{W}{R_1 V}\right) \exp(-R_1 V) + B \left(1 - \frac{W}{R_2 V}\right) \exp(-R_2 V) + \frac{W_e}{V}
\]

The behavior of the gas in the bubble was established by the safety authorities (Figure 3), taking into account the dynamics of the chemical reaction, which is not instantaneous. This explains the pressure peak followed by a letdown corresponding to bubble expansion.

However, since such behavior cannot be replicated with a polytropic law, we have maintained the maximum pressure (155 bar) and adjusted the exponent to obtain approximately the required energy release: 250 MJ for case 1 and 800 MJ for case 2. This means that energy released before the bubble reaches maximum pressure is disregarded in favor of that due to the expansion following the pressure peak. With such a simple polytropic law, n < 1 exponents have to be used, since there is energy input during the expansion.
For case 3, a JWL equation of state is used, where better adjustment can be achieved owing to a larger number of parameters. The energy release in this case is also in the vicinity of 800 MJ.

3. RESULTS

In all three cases, the calculations were carried out through to 500 ms, at which time practically all the energy released had been absorbed. Each case was processed in a single run for 2 hours of CPU time on an IBM RS6000/540 workstation. To facilitate comparison, main results for all three cases are given in Table 1.

3.1 Case 1: 250 MJ

Most of the energy is released from the bubble in less than 100 ms, the kinetic energy starts decreasing at 50 ms and the structure deformation energy, after a first increment to 56 MJ at 100 ms, rises to about 90 MJ after 200 ms, due to substantial deformation of the inner vessel following impact on the heat shield.

At 50 ms, the core cover plug and lateral neutron shielding are severely deformed. At 100 ms, the entire lower part of the main vessel, the core support plate and the diagrid drop by 10 to 15 cm, entailing substantial deformation of inner vessel structures. Deformations in the upper part of the vessel are observed at about 200 ms and by 300 ms (Figure 4), the situation has stabilized and the residual deformation pattern is practically reached. The gas concentrations obtained at the end of the calculation (500 ms) are shown in Figure 5.

Stresses in the roof slab remain below 25 MPa and maximum argon blanket pressure beneath the slab (about 14 bar) is reached around 110 ms. The main vessel is severely deformed (2.3%), but the safety vessel fulfills its functions, since it remains elastic.

3.2 Case 2: 800 MJ

Far more energy is absorbed by the structures, with the peak occurring later, but the energy distribution is similar to that in case 1, as is the sequencing of the phenomena. The argon is far more compressed towards the walls (Figures 6 and 7). Roof slab stressing is doubled (52 MPa at 150 ms). The main vessel is highly deformed (10%), but the safety vessel remains practically elastic.

3.3 Case 3: 800 MJ

The explosion is far more violent and the energy release faster giving a different distribution. The structures nearest to the explosion absorb more energy than in case 2, thus protecting the main vessel. The core cover plug is highly deformed with considerable risk of buckling (Figures 8 and 9).

4. CONCLUSIONS

The PLEXUS program provided a means of assessing maximum load areas and detailed component behavior and deformation patterns and of checking roof slab resistance and safety vessel integrity for an SPX type breeder. Containment integrity was thus confirmed even under the most penalizing conditions. The code also readily accommodated energy release and reaction speed variations.
These fluid-structure coupling calculations were performed in one run and at reasonable cost. The flexibility of PLEXUS enabled development of complex JWL equations of state under optimum conditions.

5. REFERENCES


Table 1. Comparison

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<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
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<tr>
<td>Bubble volume (m³)</td>
<td>3.955</td>
<td>3.955</td>
<td>3.955</td>
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<tr>
<td>Initial pressure (bars)</td>
<td>155</td>
<td>155</td>
<td>3000</td>
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<td>n exponent (in PVn)</td>
<td>0.9</td>
<td>0.6</td>
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<td>Mechanical energy released (MJ)</td>
<td>258</td>
<td>768</td>
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<td>Structure deformation energy (MJ)</td>
<td>90</td>
<td>425</td>
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<td>main vessel (MJ)</td>
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<td>280</td>
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<td>core cover plug (MJ)</td>
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<td>diagrid (MJ)</td>
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<td>roof slab (MJ)</td>
<td>1.5</td>
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<td>internal neutron shielding (MJ)</td>
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<td>Main vessel residual indentation (cm)</td>
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<td>Maximum slab deflection (cm)</td>
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<td>4.5</td>
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<td>Final vessel pressure (bar)</td>
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<td>Increase in vessel volume (m³)</td>
<td>60</td>
<td>240</td>
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FIGURE 1: SCHEMA

FIGURE 2: MESH

FIGURE 3: P Versus V for the bubble

FIGURE 4: Energy répartition