Discussion of Code Predictions for COVA Experiments

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Summary

The computer codes ARES, ASTARTE and SEURBNUK have been developed within the European community for the analysis of the mechanical consequences of a hypothetical core disruptive accident in a fast reactor. ARES was developed in Germany by Interatom, ASTARTE was developed in the UK and SEURBNUK was jointly developed by the UKAEA and JRC Ispra. ARES and ASTARTE are Lagrangian codes whereas SEURBNUK is an Eulerian code. All three codes use finite difference formulations to solve the equations of motion accounting for dynamic coupling between a compressible fluid and thin flexible structures under axisymmetric conditions. These codes and other comparable codes contain non-verified simplifications and assumptions. Therefore, an extensive model assessment has been made in recent years by comparing code predictions with small scale explosion test results provided by the COVA experiments. The COVA experiments were jointly performed by the UK and JRC Ispra. These experiments progress from simple bare assemblies to tests incorporating the main axisymmetric features of loop and pool reactor designs with one new feature introduced at a time. The vessels were partly filled with water leaving an air gap above the water surface. An energy release was provided by a low density explosive (LDE) positioned on the axis.

This paper briefly describes the main results and trends found in the comparison of the calculated and measured results in terms of loads on structures and thin vessel deformations. Several noteworthy discrepancies are indicated that are qualitatively consistent for various experiments and are common to all three codes. In this paper possible explanations for an underestimate of thin vessel deformations are discussed including: (I) uncertainties in the standard uniaxial dynamic material data and (II) the wall thickness, (III) modelling of the boundary conditions for thin shells, (IV) influence of mesh size, (V) uncertainties in the equation of state for the detonation gases, (VI) deficiencies in the elastic-plastic constitutive equations, particularly under oscillatory stress variations (acoustic softening). These various hypotheses were assessed on the basis of parametric calculations and additional experimental evidence. In the discussion it is demonstrated that the simpler conjectures (I)-(IV) are inadequate to explain the discrepancies in thin vessel deformations and that uncertainties in the equation of state for the charge do not provide a satisfactory explanation. The acoustic softening hypotheses is presented but further investigation is needed before a final assessment of this effect can be made.

1. Introduction

In recent years an extensive assessment of the fast reactor containment codes ARES [1], ASTARTE [2] and SEURBNUK [3] has been made by comparing code predictions against data from the small scale COVA experiments [4-7]. These experiments include assemblies with thick and thin structures and cylindrical and hemispherical vessels; emphasis in this paper is made on the results for experiments with cylindrical vessels (Fig. 1). Experiments with thick walled structures (e.g. Fig. 1a & b) provide measured data for the validation of hydrodynamic aspects of the codes and generally an acceptable level of agreement between calculation and measurement is obtained for the impulse histories at the floor and wall of the vessels. The main features of the pressure histories are calculated but some details are not reproduced. The largest discrepancies in the pressures histories are observed at the roof both for the Lagrangian and the Eulerian codes. There is generally a trend to overstimate the impulses at the roof at later times; the largest overestimate of about 50 % being observed for a long vessel test (Fig. 1b).

Experiments with thin structures (e.g. Fig. 1c & d) provide data for the assessment of the structural mechanics aspects of the codes in conjunction with the hydrodynamics and the modelling of the fluid structure coupling. Again the largest discrepancies in the pressure histories are observed at the roof. At the thin walls the calculated impulse histories and average pressures are within or close to the experimental scatter band (Fig. 2a). However, the form of the pressure histories, expecially the high frequency (10 ~ 50 kHz) oscillations (Fig. 2b & c) are not adequately reproduced by the calculations.

The calculated final hoop strain profiles are generally in qualitative agreement though the codes systematically underestimate the hoop straining over the lower and mid regions of the vessels that occurs following the charge detonation, and overestimate a second phase of straining that occurs near the roof after fluid impact on the roof (Fig. 3). The underestimate at charge height amounts to ~30 - 40 % relative strain; a similar discrepancy is observed for thin internal vessels.

The measured axial strains are clearly less than the hoop strains for the cylindrical vessels; the code predictions are in qualitative, and generally, in quantitative agreement. Thus the ratio of axial to hoop straining for an external cylindrical vessel is overestimated [6, 7].

These results are qualitatively consistent for various experiments and are common to all three codes. The discrepancies are not unique to the COVA program, a similar underestimate of hoop strain has been observed in studies elsewhere, for example, the APRICOT exercise [8, and Ref. 8 therein].

2. Discussion of Discrepancies in Thin Vessel Deformation

It is likely that the various discrepancies in the deformations of the thin cylindrical vessels need different explanations. The overestimate of the hoop strain near the roof is possibly due to the overestimate of average pressures at the roof after fluid impact on the roof which results in an increased loading on the vessel in this area. This is observed for both the ARES and SEURBNUK calculations for the short vessel tests (WT6/FT6). Furthermore, for this test, the vessel is accommodated in a sliding seal at the top (Fig. 1c) and it is reasonable to expect some friction in this seal after fluid impact on the roof which would constrain the axial motion of the shell in the experiment. However, these causes cannot explain the underestimate of the hoop straining in the lower part of the vessel that occurs before fluid impact. This was demonstrated in an additional experiment WTO with no air gap and with the sliding seal replaced by a clamped end condition. In this case the hoop strains were underestimated over the whole length of the shell (Fig. 4). The observed underestimate of the hoop strains in the cylindrical vessels initiated various parametric calculations and analyses.

2.1 Sensitivity Studies for Uniaxial Material Data, Wall Thickness, End Conditions and Mesh Sizes

Time independent elastic-plastic constitutive equations were used in the various computer codes. However, the stainless steel EN321 from which the thin vessels were fabricated exhibits a strain-rate sensitivity (Fig. 7). To account for this effect a representative uniaxial stress-strain curve was chosen according to the measured average rate of hoop straining (20-30 s^{-1}). For the short (WT6/FT6) and long (WT8/IT7) vessel tests (Fig. 1c & 1d) calculations with reduced ("soft") and enhanced ("hard") stress-strain curves (Fig. 7) were performed. This parametric range is clearly larger than the actual observed spread of the experimental data at a fixed strain-rate. The final calculated hoop strain levels are enhanced with the "soft" data but are still significantly less than the experimental levels at the charge height (Fig. 3 & 5). A comparison of the impulse histories at the wall obtained with ARES for WT6/FT6 shows a reduction of the impulses in the mid-region of the wall when the flow stress is decreased; furthermore, with the soft data the calculated impulses are markedly lower than the measured impulses. Thus, further manipulation of the uniaxial data to obtain agreement between hoop strains at the mid and lower regions of the vessel would increase the disagreement between the calculated and measured impulses and average pressures at the thin vessel.

Calculations with ASTARTE and ARES using a reduced wall thickness of ~ 6 %, consistent with tolerances in thin sheet fabrication, show that the sensitivity of the hoop strain profile to thickness variation is moderate.

The choice and numerical modelling of the lower end condition of the outer vessel does influence the hoop and axial strains but only in a limited region above the floor (≤ 175 mm); the mid-region is not appreciably affected (Fig. 6).

It was suggested that the cause of the discrepancies in the axial to hoop strain ratios might be due to friction in the sliding seal: friction is ignored in the calculations. Strain measurements made on the sliding seal in one test at Ispra /¯9_7 indicate that any frictional force at the seal is negligible before fluid impact on the roof. However, the discrepancies in the strain ratios are observed during the first phase of straining, before fluid impact occurs: thus the hypothesis does not explain the discrepancy in the strain ratio.

Coarse and fine mesh sizes (e.g. 3.0 and 1.5 cm for WT6) were applied in ASTARTE and ARES /¯10_7 calculations. The strain predictions are rather insensitive to this variation, though details in pressure histories are significantly affected.

It is evident that these simple suggestions are insufficient to explain the underestimate of the hoop strains. Other more subtle hypotheses have been raised; among these are suggestions concerning possible uncertainties in the parameters for the equation of state characterising the LDE charge detonation gases and inadequacies in the elastic-plastic constitutive equations.

2.2 Influence of Possible Uncertainties in the Equation of State for the Detonation Gases

Instead of the complete equation of state ("Jones-Wilkins-Lee" form) the so called "constant volume burn" ("CVB") adiabat was used in the COVA calculations. Among other criteria the parameters of the CVB adiabat were determined from non-COVA type "cylinder tests", and "box tests" in which LDE spheres were fired in large boxes filled with water. Although the COVA results have not led to any direct evidence to suspect the validity of these equations, it was conceived that possibly the pressure in the gas bubble was incorrectly predicted at large expansion volumes. This conjecture is based on the fact that the "cylinder tests" and "box tests" cover only expansion ratios of the detonation gases up to about 7 and 25 respectively. However, in the COVA tests with thin vessels final expansion ratios of more than 100 were obtained.

A first sensitivity study related to variations of single parameters ($\leq$ 25 % relative to the standard adiabat) in the CVB adiabat indicated that agreement between the calculated and measured strains could not be obtained: the underestimate of hoop strain persisted.

In a second study larger more arbitrary variations in the expansion adiabat were allowed (Fig. 8). Calculations performed for WTO showed that raising the level of the standard adiabat at expansion volume ratios greater than $v/v_o = 10$ did not provide a significant increase in the hoop strain. A marked increase in the pressure level at earlier expansion times was also required to increase the straining: one such adiabat is illustrated in Fig. 8 (adiabat A). With this adiabat, though agreement in the hoop strain history at charge height is obtained (Fig. 10a), as expected, the initial floor and roof impulses are markedly overestimated (Fig. 9a). These observations were confirmed in calculations with the same adiabat for two other situations, namely COVA tests WT6 and FT4 (short rigid vessel). A further calculation was performed for WTO with an adiabat formed by raising the pressure level of the standard adiabat at a volume expansion of $v/v_o = 4$ (adiabat B, Fig. 8), well within the range of expansion volumes covered by the "cylinder tests". Reasonable agreement in the hoop strain history (Fig. 10b) at charge height is obtained; but though the impulse for the initial pressure pulse is relatively invariant compared to the results with the standard adiabat, the impulse at later times is grossly overestimated at the floor (Fig. 9b), roof and wall.

In summary, even larger more arbitrary variations in the adiabat did not generate a consistent agreement in strains as well as loads. It is concluded that uncertainties in the charge parameters, within the context of its characterisation, cannot explain the discrepancies in hoop strain.

2.3 Discussion of Some Possible Inadequacies of the Elastic-Plastic Constitutive Equations

It has been recognized that the underestimate of hoop strains in the cylindrical vessels is not accompanied by a general trend to underestimate the impulses and time averaged pressures when the standard adiabat is used (Fig. 2a). However, it is noted that none of the codes is capable to reproduce the high frequency oscillatory component of the pressure observed at the thin vessels. Several experimental studies have been performed to investigate the origin of this oscillatory form. Comparative tests of the acceleration sensitivity, response under large strains, signal distortion due to storage of the data on magnetic tape /¯9_7 show that these oscillations cannot be attributed to the peculiar response properties of the pressure transducers and the recording system. Other experiments illustrate that the pressure oscillations are also present at positions in the free water near the thin wall /¯9_7.

Assuming the measured pressure history is real and inertial effects are not dominant oscillating stresses will be induced in the thin vessels. Oscillating stresses are indeed obtained with ARES. However, it was found for a simplified ring model that the mass inertia allows only rather small stress oscillations.

When searching for a mechanism which would produce more plastic strain under oscillatory stress conditions it was suggested that the elastic-plastic constitutive equations used in the codes are deficient in modelling unloading and reloading processes as well as neutral stress changes: they are assumed to be perfectly elastic. It was conjectured that - in contrast to presently used plasticity models - plastic strains were generated during such processes in the actual experiment; these plastic strains might be small but they could accumulate during stress cycling.

This constitutive conjecture was motivated by phenomena of cyclic strain accumulation (e.g. hysteresis loop shift) under uniaxial and multiaxial cyclic stress conditions observed at low (< 1000 Hz) frequencies. A literature survey /¯11_7 on the influence of ultrasonic cyclic stressing on the plastic behavior revealed that ultrasonic oscillations superposed on the monotonically increasing uniaxial stress during a tensile or compression test leads to a significant reduction of the mean stress necessary to maintain the prescribed average rate of deformation (Fig. 11). This phenomenon - the Blaha effect - has been observed for various metals and temperatures including stainless steel at room temperature /¯12_7. Similarly it was observed that insonation enhances the rate of deformation in a constant load type test /¯13_7, but experimental data appear to be rather sparse. The explanation of these acoustic softening phenomena is still a matter of controversy. Three models have been suggested /¯14_7. (a) The "linear elastic superposition mechanism" is based on classical isothermal plasticity and is abel to explain part of the Blaha effect at relatively low stress amplitudes but not the softening in a constant load test. (b) The "localized heating conjecture" suggests that heating due to internal friction takes place in regions around dislocations when ultrasonic stress waves propagate through the metal; thus the mobility of the dislocations is increased so that they are movable at a much lower resolved shear stress than required at the measured (average) specimen temperature. However, in cases where no marked increase in the average temperature is observed the model remains a subject of controversy. (c) The "nonlinear viscous superposition model" is based on an isothermal nonlinear viscous constitutive model. It has the capability to explain partially both the Blaha effect and the increase in deformation observed in a test with constant mean stress.

In summary, there is experimental evidence that the application of ultrasound to constant load and constant rate tests may lead to softening phenomena. Two theories using the models (b) and (c) could possibly serve to understand qualitatively part of the COVA discrepancies. However, it should be noted that the strain rate and duration of the insonation tests in the survey /¯11_7 do not correspond to those observed in the COVA tests.

3. Conclusions

From the sensitivity studies for uniaxial material data, wall thickness, end conditions and mesh sizes it is concluded that neither of these quantities is a sound basis for an explanation of the general trend to underestimate the hoop strains. Further, relatively large arbitrary variations in the equation of state for the charge detonation gases do not produce a consistent agreement between strains as well as loads. It is concluded that uncertainties in the charge parameters, within the context of its characterisation, cannot explain the straining discrepancy. The experimentally observed phenomenon of acoustic softening at ultrasonic frequencies, which is not incorporated in the presently used plasticity models, is qualitatively in the right direction. However, the existence of this effect is not certain at test conditions typical for COVA situations; further experimental studies are necessary. On the other hand it is presently uncertain that oscillating stresses of sufficient magnitude are present in the thin vessels of the actual COVA experiments. It is recommended not only to follow this line of reasoning but also to evaluate the quality of the elastic-plastic constitutive equations under bidimensional dynamic conditions. Furthermore, the effect of the form of the calculated pressure loading on the vessel deformation should be studied; in particular the influence of the initial pressure pulse on the initial acceleration and on the subsequent straining should be evaluated.

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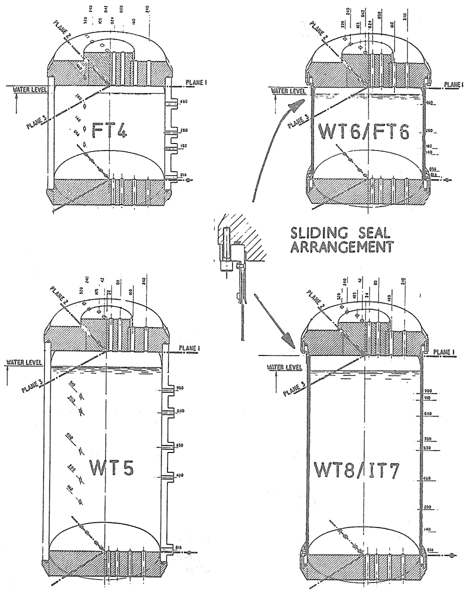

Fig.1 Selected experimental arrangements

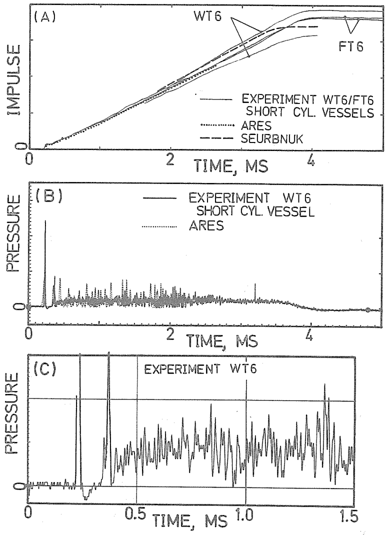

Fig.2 Impulse & pressure histories at a thin wall 182 mm above floor

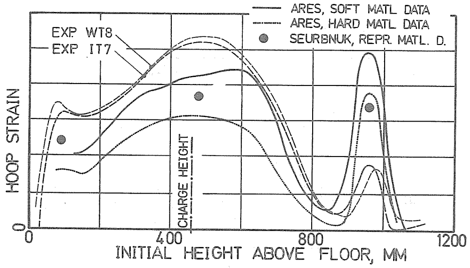

Fig.3 Final hoop strain profiles for long cylindrical vessels

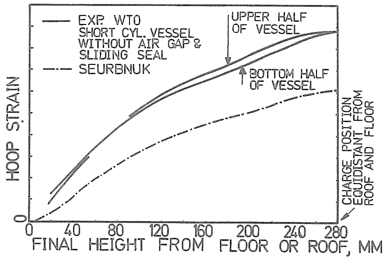

Fig.4 Final hoop strain profiles for experiment WT0

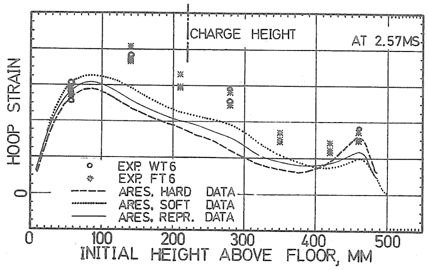

Fig.5 Sensitivity of calculated hoop strain profiles to variations in material data

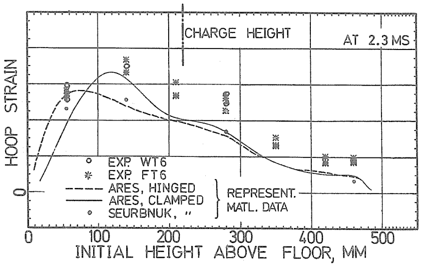

Fig.6 Sensitivity of calculated hoop strain profiles to variations in vessel end condition

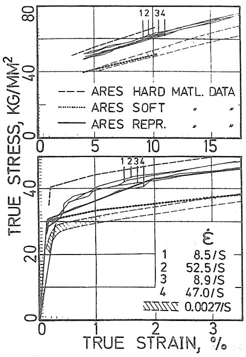

Fig.7 Stress-strain data for the WT6/FT6 cylinder material (EN321) and representations used in ARES

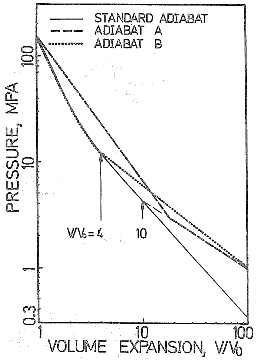

Fig.8 Adiabats of the charge detonation gases used in sensitivity studies

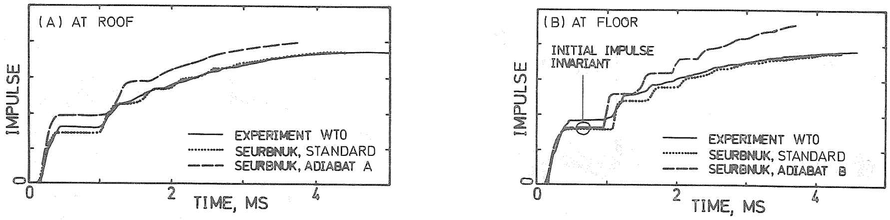

Fig.9 Sensitivity of impulse histories to variations in charge adiabat

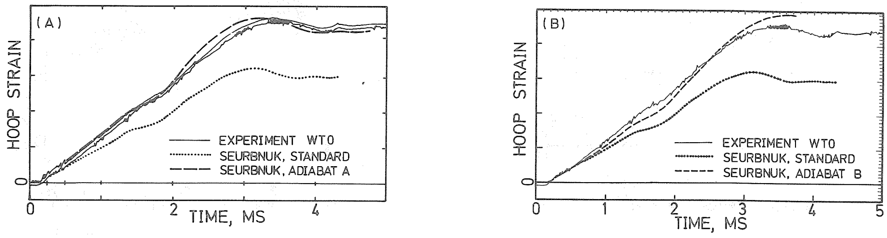

Fig.10 Sensitivity of hoop strain histories to variations in charge adiabat at charge height

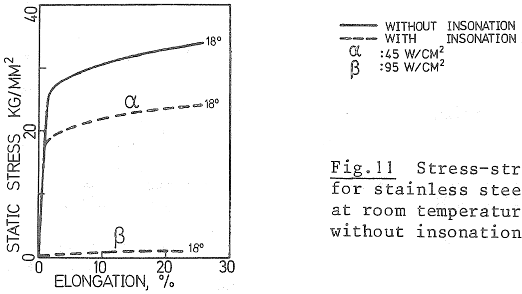

Fig.11 Stress-strain curves for stainless steel (type 302) at room temperature with and without insonation; from [12]