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THE SIMULATION OF SMALL SCALE EXPLOSION TESTS WITH THE GERMAN FLUID-STRUCTURE INTERACTION CODE ARES

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Summary

In the German licensing procedure the response of the primary containment of the fast reactor SNR-300 to a hypothetical core disruptive accident (HCDA) has to be examined in order to guarantee the integrity of the primary containment. The mechanical consequences of this accident are modeled by the Lagrangian finite difference code ARES developed by Interatom. ARES solves the equations of motion under axisymmetric conditions accounting for dynamic coupling between fluid and structures. However, ARES as well as other comparable codes contain various simplifications and, to a certain extend, also non verified hypotheses: numerical discretization, constitutive equations including uncertain material data for structures and fluid, the thin shell approximation and flow through perforated structures. Therefore, an assessment of the accuracy of the code ARES is essential when examining the integrity of the reactor vessel during an HCDA.

On the basis of a contract between the Kernforschungszentrum Karlsruhe and the UKAEA, experimental results on small scale explosion tests in water filled tanks performed in the UK are available and serve for code validation. Calculations and experimental results of four explosion tests in water-filled rigid and deformable vessels with and without internal structures are compared. The energy source is represented by a low density high explosive charge positioned on the axis of the experimental setup.

From the comparison of the calculational and experimental results for the two experiments without internal structures, it is observed that ARES slightly underestimates the impulse of the incident pressure wave, but overestimates the impulse on the roof. It is further found in the thick-walled tank test that the elastic wall deformation cannot be ignored. Comparing theoretical and experimental results of the thin tank explosion test shows that improvements in the theoretical modeling and/or in the accuracy of the input data are necessary. In the test with rigid internal and external structures a strong fluid flow through the grid plate and above the shield tank will be induced after the initial pressure wave has passed. Therefore, ARES should be capable to simulate strongly varying velocity and pressure fields. Due to the rigid shield tank an early impact of the water on the roof occurs. In a complementary test with thin shells the peak pressures at the thin walls are reduced by a factor of 1.5. Within 1.3 ms the shield tank undergoes a deformation of 10 % circumferentially with a strain rate up to 200 1/sec. The analysis shows that the deflection of the grid plate controls to a great extent the straining of the inner tank.

1. Introduction

Within the frame of the safety analysis of LMFBR's hypothetical power excursions are considered which destroy the reactor core and produce a transient loading on the internal structures, the reactor tank and roof as well as on the primary piping system. For the analysis of the mechanical consequences of this hypothetical core disruptive accident the Lagrangian finite difference code ARES ref. / 1 / developed by Interatom is primarily used in the Federal Republic of Germany. ARES as well as other comparable computer codes is based on simplified physical models describing the fluids and structures; further there are inaccuracies in the numerical procedure solving the underlying equations. These facts necessitate a systematic assessment of the theoretical model of ARES by comparison of calculational and experimental results. The UKAEA performed a series of small scale explosion tests specifically designed to provide data for use in validating the codes which were developed for explosion containment analysis ref./ 2 /. These experiments are characterized by waterfilled tanks with and without internal structures; a low density high explosive charge (LDE) is positioned on the axis of the arrangement to assure rotational symmetric conditions. The data measured are pressure and strain histories. The rationale of the experimental program is such that starting from simple configurations the complexity of the experiment is systematically increased. Thus, the theoretical model is subjected to conditions of increasing complexity and testing of separate aspects of the theoretical model is enabled.

The code validation work is performed in cooperation between KfK, GRS (Köln) and Interatom. This study presents some of the results obtained for four COVA experiments; this analysis was done by KfK and GRS.

2. Experimental setup

All experiments are characterized by short cylindrical tanks partially filled with water having an either thick- or thin-walled (40 or 1.6 mm) outer vessel. The thin-walled outer vessel is bolted to the bottom; at the top the cylinder is supported by a sliding seal allowing for axial motion. Pressure transducers are installed at bottom, wall and roof in three meridional planes as shown in fig. (1). Strain gauges are applied at the outer surface of the thin vessel. The spherical LDE-charge (56 g, PETN/Polystyrene) is positioned 220 mm above the datum line. Two groups of experimental setups are analysed. In the first pair of experiments (FT4, FT6 and the nominal identical experiment WT6, fig. 1), internal structures are not present whereas in the second pair (FT10, FT12, fig. 7) a shield tank and a perforated grid plate are installed. The shield tank is based on a perforated support annulus whereas the grid plate rests on load cell billets. The support annulus (O.D. 320 mm) as well as the grid plate (perforation ratio 16 %, thickness 8 mm) are the same for both experiments. The inner and outer tanks of FT10 are thick-walled (23 and 40 mm) cylinders. In the experiment FT12 both cylindrical tanks are thin (2.08 and 1.57 mm) and made of stainless steel EN 321. Shield tank and grid plate are also supplied with pressure and strain gauges.

3. Mathematical modeling by ARES

The geometry of the experiments is discretized by a quadrilateral finite difference mesh. For FT4 a coarse mesh (number of meshes radial 8 and axial 12), a standard mesh (11 and 17), and a fine mesh (22 and 34) are used. The water is characterized by an equation of state of

Grüneisen-type; cavitation effects are not accounted for but the fluid is not allowed to transmit tension. The pressure-volume-energy relation for the gaseous detonation products is accepted to be the JWL equation of state ref. / 2 /. The air above the water is treated as a massless, homogeneous ideal gas. Following the basic intention of the COVA experiment FT4 to test primarily hydrodynamic aspects of ARES the bottom, cylinder and roof are treated as rigid boundaries. Sliding lines are provided at the inner surface of the vessel wall.

The modeling of the experiment FT6, FT10 and FT12 differs in so far as the cylinders are allowed to deform; a thin shell theory allowing for bending (four subshells) and thickness reduction is used. The elastic-plastic constitutive equations employed are characterized by the von Mises' yield condition with isotropic hardening and the Prandtl-Reuss flow laws. Uniaxial stress strain curves obtained for the stainless steel EN 321 at various strain rates serve as a basis for the determination of the constitutive parameters; the stress strain curve used in the analysis (FT6) corresponds to a strain rate of 28 s^{-1}. Fine meshes are used for the calculation of FT6 (22 meshes radial & 34 axial) and FT10 as well as FT12 (24 & 36, fig. 8). In both experiments FT10 and FT12 also the grid plates are modeled by thin shell theory. The grid plate is assumed to be hinged at the edge. The fluid flow through the plate is described by engineering correlations for the pressure drop across the perforation.

4. Comparison of ARES predictions with experimental results

In the two experiments without internal structures (FT4, FT6 & WT6), the phenomena to be expected are as follows: After detonation of the charge, a spherical compression wave will propagate from the charge and will impinge consecutively on the bottom, water surface and cylindrical wall. This direct wave will be partially reflected from the solid boundaries as a compression wave and from the water surface as a rarefaction wave possibly producing cavitation effects in the water. Simultaneously the free surface will see an upward motion supported by the expansion of the gas bubble. At later stages water impact on the roof will occur which then produces an additional loading on the wall and bottom. A detailed analysis at bottom and wall in the experiment FT4 reveals the following general trends: The incident and first reflected wave are qualitatively predicted up to 0.7 ms (fig. 4a). However, the impulse of the direct wave up to the time of arrival of the 1. reflected wave is consistently underestimated at the bottom (fig. 2). The impulse of the wave reflected from the wall (fig. 4b) is clearly overestimated ref./ 5 /; at the wall the impulse of the direct wave is slightly overestimated. These observations can at least qualitatively be explained by the presence of some flexibility of the thick-walled cylinder in the experiment; also the pressure trace seen at the bottom (fig. 4a, 0.8-1.0 ms) is expected to be due to this effect. A larger wall thickness would have been better for the primary aim of this experiment.

Analysing the results at the roof, we find that ARES overestimates the impulse and the pressure history does not show any resemblance with the experiment. This fact does reflect in the later measurements at wall and bottom (fig. 4a, t > 2. ms). Concerning the effect of mesh sizes it is generally observed that there is only a small effect on impulse except at the roof; however, peak pressures and pressure histories are sensible to mesh variation.

Comparing the pressure and impulse records for the thin-walled experiment FT6 with those for the experiment FT4, one observes that the pressures and impulses at the cylindrical wall and the roof are greatly reduced except for the direct wave at the bottom. Further, the roof impact is delayed. The comparison of calculational (up to 2 ms) and experimental results reveals the following discrepancies: At the thin wall the approximate uniform pressure build up at later times and thus the impulse is clearly overestimated whereas the circumferential strain is underestimated in the lower 2/3rd of the vessel (fig. 5 & 6); here in the calculation the final strain is nearly reached. The ratio of the circumferential to the axial strain rate is nearly constant in the time interval 0.5 - 1.5 ms for both calculation and experiment but the ratio is about 2 in the calculation in contrast to 3 and more found in the experiment. It is conjectured that inadequate material data and multiaxial constitutive modeling are possibly responsible for the deficiencies. At the bottom the most striking difference is found in the absence of the 1st reflected pressure wave (fig. 3) in the calculational results. Qualitatively this may be due to an underestimation of the strength of the thin vessel wall at the initially higher strain rate and small strains. Also this possibly may be an indication for an insufficient modeling of the fluid-structure coupling.

In the experiments with internal structures the direct wave and the wave reflected from the shield tank propagate through the grid plate and are reflected at the bottom. Part of the direct wave is transmitted through the shield tank suffering some damping and then propagating towards the outer tank. After 0.4 ms the rarefaction wave from the water surface reaches the grid plate. These events are qualitatively modeled by ARES. From the ARES results, it is seen that the expanding gas bubble accelerates the water surfaces and produces an intensive flow around the upper edge of the shield tank and through the grid plate and support annulus. In the case of the thick-walled tank (FT10), the velocity field is primarily upward whereas in FT12 the velocity field has a strong radial component (fig. 9). The reduction of pressure pulses by plastic deformation of the thin tanks tends to lower the impulses as shown in fig. 10. In FT12 the direct wave induces an almost constant radial velocity in both inner and outer thin tank which last for about 0.5 ms. The strain rate in the shield tank varies with axial position and has a maximum of 200 s^{-1} in the lower part. As shown in fig. 11, the hoop strain of the shield tank is underestimated below charge height. Parameter calculations show that different assumptions for the diagrid support conditions have an important influence on the hoop strain in the lower part of the shield tank. As expected it is found that a stiffer restraint of the grid plate increases this hoop strain. At the outer thin tank below charge height an underestimation of the maximum hoop strain is observed.

The results obtained indicate that ARES is capable to predict qualitatively basic features. However, work is necessary to identify and understand the observed discrepancies.

Acknowledgement

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In the following figures the scales on the ordinates have been deleted due to contractual conditions.

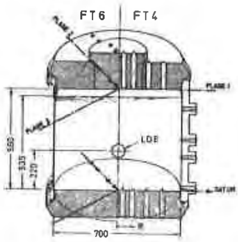

Fig 1 Experimental setup of FT6 and FT4

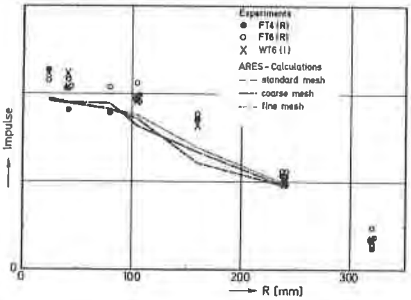

Fig 2 Impulse of direct wave bottom

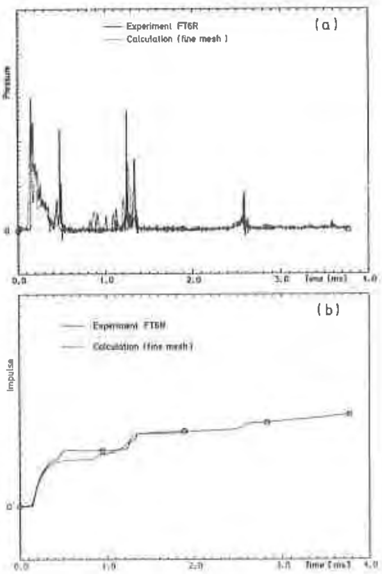

Fig 3 Pressure and impulse variations
at bottom (R=24mm); thin-walled cylinder

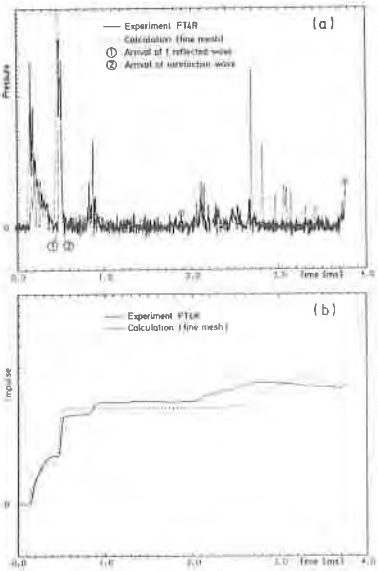

Fig. 4 Pressure and impulse variations
at bottom (R = 24mm); thick-walled cylinder

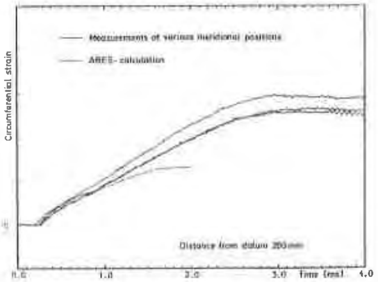

Fig 5 Strain history at outer surface of thin-walled cylinder

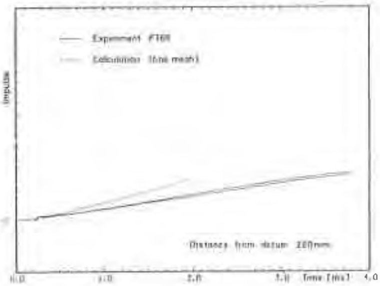

Fig 6 Impulse variation at thin-walled cylinder

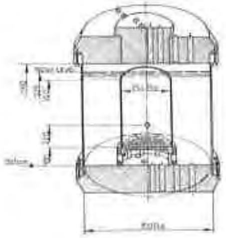

Fig 7 Experimental setup of FT12

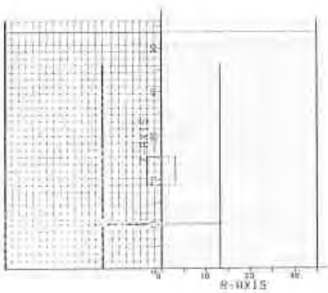

Fig 8 Initial grid for the calculations
of FT10 and FT12

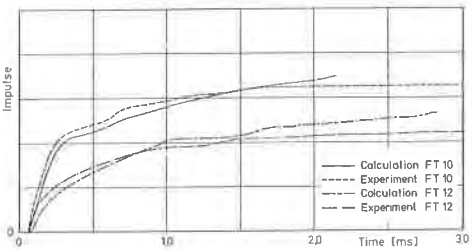

Fig 10 Impulse at the inner tank in charge height

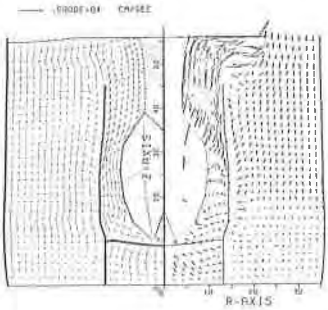

Fig 9 Grid and velocity field at 2 ms for FT12

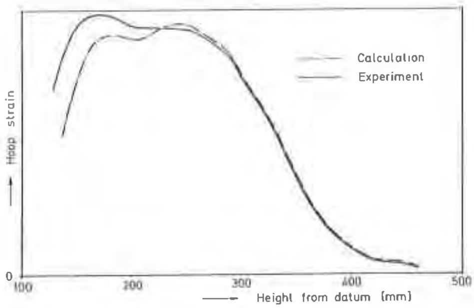

Fig 11 Hoop strain profile for the inner tank of FT12