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CHARGE DEVELOPMENT AND ANALYSIS OF RECENT UK EXPERIMENTS IN THE COVA MODEL TEST PROGRAMME

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SUMMARY

The COVA programme of small scale experiments consists of a two pronged attack on the provision of high quality accurate data for validating explosion containment codes. One series of tests is being carried out within the UK while a parallel but complementary programme of experiments is being carried out at JRC, Ispra in a UK-JRC collaboration which ensures that all components, charges, etc. are being developed within the UK and at JRC, Ispra.

The rationale of this test programme has been discussed at the International Meeting on Fast Reactor Safety and Related Physics, Chicago, 1976, and results of the first tests at the three participating sites have been published to provide a benchmark problem for basic code validation (UKAEA-TRG 2909 (R/X); Euratom JRC Ispra EE/01/76). Analysis of the experiments is a continuous process as the data accumulate. A parallel paper at this conference discusses the results arising from the analysis of bare charge, rigid-walled model tests. This paper examines some effects arising from the inclusion in the model geometries of either thin or over strong outer tanks, of hemispherical or right cylindrical bases or of simple internals.

The main energy source for the COVA programme is a low pressure high explosive which has been especially developed by the UK for use in model test series. The paper describes the characterisation of this low density explosive which is based on a PETN/polystyrene mix expanded, under strictly controlled heating, to form self supporting charges of various sizes. This characterisation, involving the analysis of cylinder tests and underwater firings of bare spheres, shows that the explosive performs in a reproducible manner in both dry and wet environments. The development of a JWL equation of state will be illustrated and discussed.

The explosion containment codes being developed within the UK are the 2-D Lagrangian code ASTARTE-3 and the 2-D Eulerian code SEURBNUK-2, the latter being currently developed jointly with JRC, Ispra. Both codes are able to deal with transient compressible flow in deformable primary containment tanks, with various geometries of internal components, depending upon the limitations of Lagrangian or Eulerian concepts and the current state of the development of both codes.

For the bare tank experiments the ASTARTE code can be used to predict the entire history of impulse loading due to the fluid flow and some typical comparisons are given for experiments with thin outer tanks. The treatment in the code of the boundary condition at the ends of the tank can have a significant effect on the agreement between calculation and experiment and the effects are illustrated.

The presence of even simple internal components causes large distortions of the fluid flow pattern and Lagrangian codes become less suitable for use in predicting the complete loading history. The Eulerian code SEURBNUK-2 is being developed for this purpose and results are presented using this code for an experiment which includes a rigid internal overstrong cylinder. Comparisons are made with the corresponding ASTARTE calculation and with experiment.

1. INTRODUCTION

The UKAEA and the Joint Research Centre Ispra are engaged in a collaborative experimental programme carrying out a series of small scale well instrumented tests aimed at providing high quality data of the stresses, strains and loads occurring when a well characterised energy source is released within a fluid in a containment vessel. In the UK the data are being used to validate the explosion containment codes ASTARTE and SEURBNUK. The former is being developed by the UK and the latter by the UK in collaboration with JRC Ispra.

In an earlier paper [1] the rationale of the COVA (Code Validation) programme has been discussed and some of the results from the first three tests involving Comp B high explosive energy sources described. After the early benchmark experiments [2] the COVA tests have used a low density explosive (LDE) developed specially by the UKAEA for the series. The UK COVA programme is now about half complete and has involved thick and thin bare tanks in a number of geometrical configurations while recent experiments have included a variety of internal cylindrical tanks and diagrid structures (see figure 1). A companion paper [3] at this conference describes the validation of the hydrodynamic codes for simple bare tank geometries for both Comp B and LDE charges. The objective of this paper is to describe the characterization of the specially developed LDE source and to present some of the preliminary analysis and calculations with ASTARTE and SEURBNUK of the more recent COVA experiments involving thin tanks or internals.

2. DEVELOPMENT OF LDE ENERGY SOURCE

The feasibility of producing UK high explosive charges of low density was considered initially because such a low density explosive was predicted to produce stress levels which would be within the range of those thought to be achievable by UO_2 vapour expansions of interest. However at the same time it could be expected to satisfy two basic conditions. These were that:-

(a) Being a high explosive, its behaviour would be reproducible from test to test and would be independent of the geometry of the test, and

(b) Its behaviour could be characterised by the procedure developed for more conventional explosives so that its performance could be predicted separately from and preliminary to, its use in either the COVA test sequence or in the CFR scale model tests.

A considerable amount of information exists on the manufacture and performance of low density explosives. Most of those investigated in the past used pentaerythritol tetranitrate (PETN) because it had several desirable properties:- (a) it could be prepared in high purity in powdered form, (b) it could be pressed into handleable charges over a wide density range, (c) because of its high oxygen content its detonation products should be almost all gaseous and (d) it had a very low failure diameter.

It is not possible to form pure PETN powder charges of density less than about 0.25 g cm^{-3}. However, by using low density fillers, foaming agents or precipitating PETN into porous materials, the effective explosive densities could be reduced to values as low as 0.025 g cm^{-3} and even such a low density composition could produce high order detonation. Detonation pressures for low density explosives have been determined directly for pure PETN for densities down to 0.25 g cm^{-3}, the lowest pressure measured being 500 MPa. However, to achieve the pressure level required in the COVA tests it was necessary to extrapolate to lower densities and after reviewing the tested methods, the approach of Archibald [4] was followed in which PETN powder was mixed with partly-expanded polystyrene beads and then heated to further expand the beads to give a self-supporting assembly of any desired shape.

3. DETERMINATION OF EQUATION OF STATE PARAMETERS

In order to calculate the performance of this explosive, it is necessary to have an accurate description of the pressure-volume-energy relation (ie, an equation of state) of the detonation products. The JWL form [5] of equation of state is currently thought to be the one most suitable to describe the behaviour of detonation products at low pressures. It is, therefore, natural to use this form of equation to describe the behaviour of LDE since pressure levels will be low throughout the expansion of the products. We define the adiabats of the JWL form as

$$p = Ae^{-R_1V} + Be^{-R_2V} + CV^{-(1+W)} , \qquad \ldots (3.1)$$

where p is pressure, and V is relative volume (v/v_o). A, B, C, R_1, R_2 and W are constants, requiring determination by considering information on the explosive's physical properties and the dynamic behaviour of its products in simple integral experiments which are amenable to analysis. The full (pressure-volume-energy) relationship corresponding to (3.1) may be written, if E is now the internal energy per unit volume at normal density, in the form

$$p = A\left(1 - \frac{W}{R_1V}\right)e^{-R_1V} + B\left(1 - \frac{W}{R_2V}\right)e^{-R_2V} + \frac{W}{V}(E - E_1) , \qquad \ldots (3.2)$$

where

$$E_1 = A\left(\frac{1}{W} - \frac{1}{R_1}\right)e^{-R_1} + B\left(\frac{1}{W} - \frac{1}{R_2}\right)e^{-R_2} . \qquad \ldots (3.3)$$

The energy is considered here in a scale such that E = 0 in the undetonated state ($p = 0, V = 1$).

The standard procedure for high explosives of normal densities is to obtain the detonation pressure, p_{CJ}, from experiments in which metal plates of different thicknesses are accelerated by slabs of explosive and an extrapolation is made to zero thickness of the metal. For the case of LDE, where the value of p_{CJ} is much lower, this method is not sufficiently accurate. In fact, it was concluded that no direct determination of p_{CJ} was likely to be successful. Conditions at the CJ state, and hence a value of p_{CJ}, were therefore, derived from examination of other data on low density explosives. In particular calculations at Aldermaston using a BKW code, assuming that the polystyrene was chemically inert but absorbed heat (its specific heat coefficient c_p being assumed constant) gave a value of detonation velocity very close to that measured experimentally and also a value of Γ_{CJ}, the adiabatic exponent at the CJ point of 2.0. Using this value, and measured values ρ_o and D the detonation pressure p_{CJ} was determined from

$$p_{CJ} = \rho_o D^2/(\Gamma_{CJ} + 1) \qquad \ldots (3.4)$$

This provided a value of p_{CJ} = 360 MPa.

In order to determine the remaining parameters required to specify the JWL equation of state, a series of cylinder tests has been performed at Aldermaston. In order to confirm the parameters obtained in this way, additional experiments involving LDE spheres in water have been carried out at AWRE, Foulness and at AEE, Winfrith. Both types of experiments were chosen because the resulting configurations had certain simplifications which permitted relatively simple and unambiguous interpretation of the results.

3.1 Aluminium cylinder tests

The standard cylinder test, in routine use at several laboratories, comprises a 30.5 cm long close tolerance copper tube of 2.54 cm internal diameter and 0.26 cm wall thickness, containing the explosive composition under investigation. The charge is initiated at one end by a 2.54 cm diameter explosive plane wave lens. The consequent radial expansion of the outer surface of the cylinder is recorded as a function of time. Because of the low power of the PETN/polystyrene composite explosive, it was necessary to modify the standard cylinder test in two respects. In order to obtain an adequate radial expansion of the detonation products over the time of interest, the 0.26 cm thick copper tube was replaced by a lighter 0.2 cm thick EIC aluminium tube. Also, in order to avoid overdriving the low power composition, the plane wave lens was removed and initiation was made directly from a Mk 3 eht detonator placed in contact with the explosive.

3.2 Analysis of experimental data

Values of the constants A, B, C, R_1, R_2 and W in the JWL equation of state were obtained by carrying out ASTARTE calculations on the cylinder test geometry, varying the constants judiciously to achieve good agreement between experiment and calculation when the final set of values were obtained. The accuracy of the results was checked by repeating the calculations to examine the effect of mesh size, shear strength of the aluminium and end boundary conditions. In all cases the effects were minor. The agreement between calculation and experiment for one of the cylinder tests (the experimental data has four sets, testing repeatability and symmetry) is shown in figure 2 and seen to be good.

In order to verify that this equation of state was valid in other geometries and that the explosive was performing as predicted in an underwater environment, data was examined from experiments in which spherical charges were detonated underwater in large wooden cubical boxes and in overstrong cylindrical metal tanks. In both types of experiments pressure measurements were made on the boundaries and in the water itself. The agreement between calculation and experiment was again good. Additionally, examination of pressure records at in-fluid gauge positions for different size charges showed that results scaled well with charge size. Thus non-scalable effects, such as heat transfer, turbulence etc were not significant in the underwater expansion of LDE spherical charges.

The equation of state constants defined by the above calculations were:-

$$\left.\begin{array}{lllll} \rho_o = 0.27\ \mathrm{g\ cm^{-3}} & D = 0.2\ \mathrm{cm}\ \mu\mathrm{s}^{-1}, & \Gamma_{CJ} = 2, & E_o = 0.006\ \mathrm{Mbcc\ cm^{-3}}\ . & \\ A = 0.17039\ \mathrm{Mb} & B = 0.011595\ \mathrm{Mb}, & R_1 = 9.0, & R_2 = 2.4, & W = 0.1. \end{array}\right\} \quad \ldots (3.5)$$

Although a value of E_o, the energy per initial cubic centimetre, is given above this must be treated with caution. This is equivalent to the total work done by the explosive in expanding to infinite volume. However because of the slow rate of transfer of mechanical energy from the detonation products of LDE to their surroundings (a characteristic similar to that for a UO_2 vapour explosion), this ultimate value has little relevance in a finite sized model system in which the detonation gases can only expand by a finite amount. Conversely tests which can only cover relatively small volume expansions (20-30) cannot be expected to precisely define the magnitude of the ultimate energy release. In any case for analysis of the COVA experiments it is not necessary to define 'a priori' the magnitude of energy transfer to be expected and it is sufficient to know the equation of state of the detonation products. For scale model tests it may be necessary to define an energy equivalence, although there are also difficulties in defining limits of a UO_2 vapour expansion.

4. PRELIMINARY ANALYSIS OF RECENT COVA EXPERIMENTS

The COVA programme consists of a series of experiments chosen to validate the various material models and facilities of the containment analysis computer codes. It starts with simple bare tanks and graduates to configurations with internals which are fairly realistic models of reactors. Arising from this graded programme comes the ability to assess independently of any commercial design or calculation the effect of significant features and individual components.

One can, for example, assess the effect on the roof loadings of using tank aspect ratios appropriate to loop or pool designs. From among the data in figure 3 we can compare the roof impulses for two overstrong tanks of lengths 560 and 1120 mm respectively, both of radius 350 mm, with the same LDE charge and air gaps of 25 and 85 mm respectively. It can be seen that the roof impulse for the long tank is ∿ 50% more than that for the short tank. Increasing the air gap by a factor two in the long tank experiment produces the not unexpected result that the roof impulse is only marginally reduced, by ∿ 10%. When the HE (Comp B) charge was used measured roof impulses in the short tank were similar to those obtained with the LDE charge but roof impulses were not increased significantly when the Comp B charge was used in the long tank geometry.

The potential relieving effect on roof loadings of a deformable outer containment is clearly seen when the thick outer tank is replaced by a thin one. The roof impulses reduce by ∿ 50% in short tank geometry although a final impulse is difficult to determine in these cases (as indicated by the hatched band in figure 3). When the thin tank has a hemispherical base roof impulses are only marginally increased, (mainly near the axis by a later pressure pulse that does not occur in the cylindrical tank experiment). Introducing an internal tank has a gun barrel effect on the flow of fluid inside this inner tank giving significant increases in impulse in this area but even the impulses on the outer region of the roof are increased from the values in the corresponding bare tank experiments due to the directional effect of the internal structure.

These broad impulse variations hide sharp and major differences in the recorded pressure profiles on the roof. These differences are illustrated in figure 4 which compares the roof records at different radii from long and short tank experiments using the LDE charge. In long bare tank experiments with large air gaps the pressure record is generally a single, comparatively smoothly varying pulse with impact occurring at approximately the same time across the roof (± 200 μsec)(see upper figure of figure 4). In the short bare tank experiments (middle figure), where the charge is closer to the free surface, the air gap is smaller and reflected waves from the wall do not contribute so much to the free surface velocity, the surface is generally domed with roof impact on the axis occurring up to 1 msec before that for the fluid close to the wall. As a result the initial pressure pulse is often followed by a second major pulse that has been reflected from the wall. A clearly defined reflected wave does not occur, of course, if the outer tank is deformable and more complex pressure profiles arise if an HE (Comp B) charge is used, as in the early benchmark experiments [2], or if internal structures are included. The presence of a thick internal tank completely eliminates the initial pressure wave at large radii and the initial wave is followed instead by a plane slug type impact at much later times. This is clearly seen in the lower figure of figure 4 and it is apparent that the flow pattern in experiments with and without an internal tank is quite different.

From the above, somewhat superficial, review of roof pressures and impulses it should be apparent that detailed study of the whole series of COVA experiments provides valuable insight into the different flow processes that might take place in reactor configurations.

5. VALIDATION OF ASTARTE

The period immediately following an energy release is characterized by energy distribution through wave propagation and is calculable by traditional Lagrangian finite difference treatments. Examples of such codes are REXCO (ANL), ARES (INTERATOM) and ASTARTE (UKAEA). A companion paper [3], already referred to, illustrates the use of ASTARTE, REXCO-H and ARES on bare rigid tank experiments in the COVA series. This review is extended to later experiments, highlighting the main conclusions that have been drawn from comparisons of ASTARTE predictions and experimental results so far.

For the short tank experiments which constitute the bulk of the first half of the UK COVA programme ASTARTE is generally able to reproduce all the important hydrodynamic features. Predicted impulses on floor, walls and roof are accurate to within approximately ± 20% and this is true also for the early phases of experiments with internal structures before severe distortion of the Lagrangian mesh results from significant fluid flows. Notwithstanding this good overall agreement there is a clear and consistent tendency for ASTARTE to overestimate by significant amounts ($\sim$ 50%) the impulse arising from pressure waves that have been reflected from the containing walls. This effect, described in detail in reference 3, contributes to larger errors in predicted floor impulses in long tank experiments where these reflected waves contribute a larger proportion of the total impulse.

One of the most consistent features of calculations by Lagrangian codes such as ASTARTE is their apparent inability to predict representative roof pressure profiles. For each experiment ASTARTE predicts a series of pressure spikes bearing very little resemblance to any of the measured profiles. The spikes occur as the fluid impacts the roof and are thought to be due to numerical effects associated with the finite mesh, aggravated by spurious density restrictions introduced by an equation of state for water that cannot adequately model the behaviour of water in tension. They can be reduced by careful imposition of mesh regularisation techniques or other palliatives. Recent analysis has shown the importance of including a cover gas explicitly in the calculations because in long tank experiments the cover gas plays a dominant role, sometimes actually preventing roof impact. With the gas modelled explicitly (ie not as a void) ASTARTE can reproduce the smooth measured pressures which arise from compression of the cover gas. The motion of a thin outer tank is similar to that of a free surface and instead of following the smoothly varying measured pressure (corresponding to the yield pressure of the tank) ASTARTE again predicts a series of unrealistic pressure spikes reminiscent of those predicted on the roof. These, also, appear to be due to shortcomings in the model for water and can be improved dramatically by mesh regularisation techniques without significantly affecting the hydrodynamics of the system. Of course it is preferable to remove the cause of these problems rather than treat the symptoms and basic studies of the numerical methods and the equations of state for water are underway.

The inclusion of thin shells of revolution within the framework of two dimensional unsteady hydrodynamic codes is a topic which has received attention in the last few years. For external shells of arbitrary, axisymmetric shape a full thin shell theory with bending moments has been developed in ASTARTE with the fluid allowed to slip freely over the shell. Early calculations indicated that the end boundary conditions can have a significant effect over the whole length of the tank and a variety of boundary conditions have been included to model, as closely as possible, the configurations in the COVA experiments. The full thin shell treatment is being extended to internal shells which are treated, at present, by membrane theory without fluid and shell nodes being decoupled.

Maximum hoop strains in the region of 5-10% are generally achieved with tensile longitudinal strains when the vessel is fixed at the top (as in the hemispherical tanks) and compressive longitudinal strains if there is a sliding seal at the top to allow the tank to move freely downwards (as in the cylindrical tanks). ASTARTE is able to reproduce both hoop and longitudinal strain profiles (see figure 5) although there are quantitative differences that have not yet been conclusively ascribed to either the thin shell model or the material data. The analysis performed so far has indicated that an improved representation of strain rate hardening effects is required if accurate strain predictions are to be achieved at the comparatively high strain rates ($\sim$ 25 sec^{-1}) experienced in the COVA tests.

Measured and predicted pressures on diagrid structures have been in good agreement ($\sim$ + 10%) during the early part of recent experiments but excessive loads (3-5 MN, as predicted by ASTARTE) put load cells under the diagrid into permanent yield so that no direct comparison of loads is yet available.

6. SEURBNUK AND ASTARTE CALCULATIONS FOR COVA EXPERIMENTS WITH INTERNAL STRUCTURES

Although ASTARTE predictions of impulse for a number of recent COVA experiments with internal structures have been in good agreement with measurement (± 20%) during the first 1-2 msec the calculations are not reliable during the later phases of the experiments for a number of reasons:-

(1) severe mesh distortion which occurs because of shear flow around the ends of internal tanks

(2) difficulties in adequately modelling fluid flow along internal tanks by decoupling fluid and shell nodes by slide line techniques or internal boundary conditions

(3) difficulties in adequately modelling thick internal structures with material strength without prohibitively increasing the cost of calculations

(4) the absence of a treatment of flow through perforated structures (eg diagrids, dip plates) and shield arrays.

It is to deal with difficulties of this type that the Eulerian code SEURBNUK-2 was developed, as the Eulerian approach avoids the problem of mesh distortion though it has the disadvantage of requiring special attention at interfaces and free surfaces. It is described in detail in a companion paper at this conference [6].

Figure 6 shows the development of a SEURBNUK calculation for the COVA experiment shown in figure 1(d), having a thick open ended cylinder suspended in the water in an overstrong cylindrical tank. The calculation has been taken to 3 ms, by which time the bubble has reached its maximum volume and is beginning to collapse downwards at the top. The impulse comparisons shown in figure 7 indicate that predictions agree well with measurement until near the end of the calculation where the predicted values are over estimates. The reasons for this over estimation are being investigated and other code developments will further enhance the ability of SEURBNUK to produce reliable estimates for COVA; a treatment of flow through porous structures is being introduced to deal with perforated structures (eg diagrids, dip plates), and an improved equation of state for cavitating water is being incorporated.

7. CONCLUSION

The main self supporting charge for the COVA series of experiments is the LDE and the paper has described how a standard JWL equation of state has been derived. This characterization involved both cylinder and underwater firings which demonstrated that the charge performed in a reproducible manner in both dry and wet environments.

Data from the tests so far have shown that it is possible to vary both the magnitude of roof impulses (by a factor of about three) and the character of the roof impact process by suitable choice of test geometry. It is thus possible to examine in depth different features of the codes by concentrating on appropriate experiments.

So far code validation has concentrated on the Lagrangian code ASTARTE which is expected to be used for the initial wave propagation phase of COVA calculations and reactor containment studies. It has been indicated that ASTARTE can reproduce the main hydrodynamic features for bare tank COVA experiments, predicting impulses to within ± 20% in most cases, and this applies also for the early stages of experiments with simple internal structures. However, a number of shortcomings in current methods and data have been highlighted during the ASTARTE validation programme. These include unresolved errors in predicting the impulse in reflected pressure waves and difficulties in predicting pressure profiles on roofs and on thin deforming tanks. Considerable advances have been made in calculating the deformation of thin external walls but although strain profiles are being reproduced there are still quantitative differences between measured and predicted strains. Current development effort on ASTARTE is devoted to a parallel improvement in the calculation of internal thin shell deformations.

The limitations of Lagrangian concepts were emphasised when internal structures were introduced into the COVA experiments. The Eulerian code SEURBNUK has been developed recently to overcome these problems and preliminary results from a SEURBNUK calculation on a COVA experiment with thick inner and outer tanks have been presented to demonstrate that SEURBNUK can deal with problems having high shear flows; initial results for the early stages (2-3 msec) of the calculation are in good agreement with experimental results.

Work will continue to analyse these, and later, COVA experiments in detail and thus validate the codes in order to gain confidence in their use to study containment in fast reactor designs.

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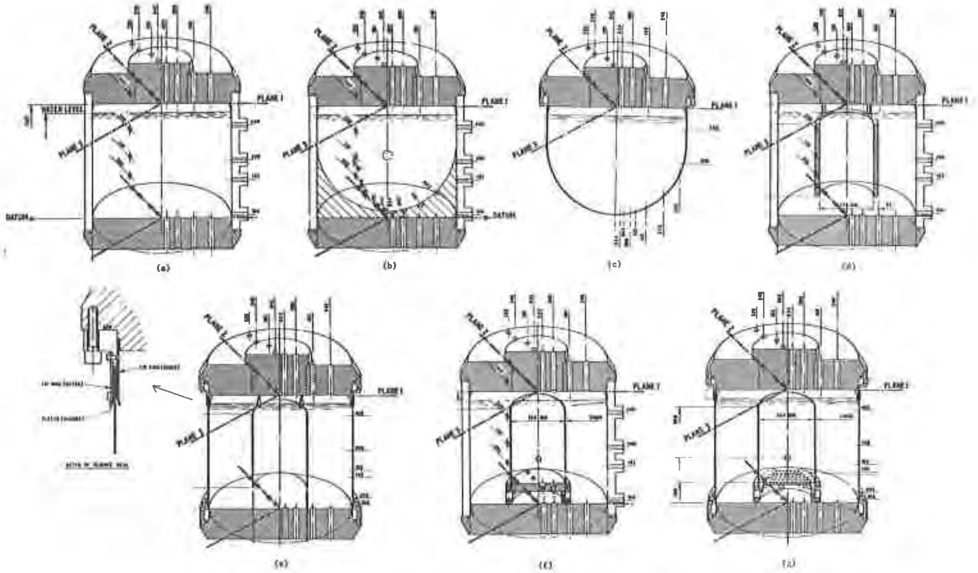


FIGURE 1 CONFIGURATIONS OF VARIOUS COVA SHORT TANK EXPERIMENTS

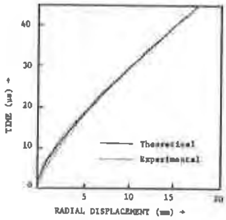


FIGURE 2

CALCULATED AND MEASURED RADIAL DISPLACEMENT - TIME PROFILE FOR LDE CYLINDER TEST

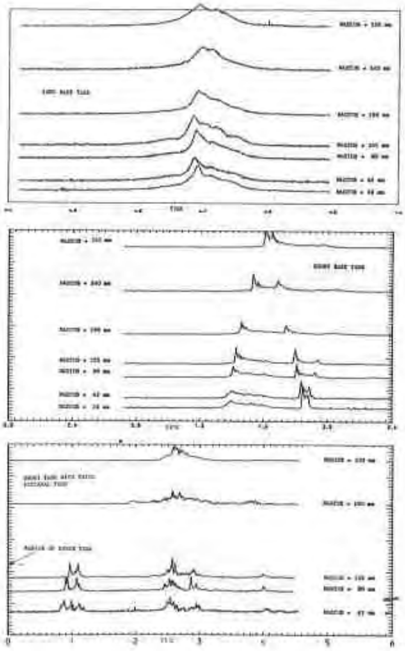


FIGURE 4 PRESSURE SUMMARY RECORDS ON ROOF FOR THREE TYPES OF COVA EXPERIMENT

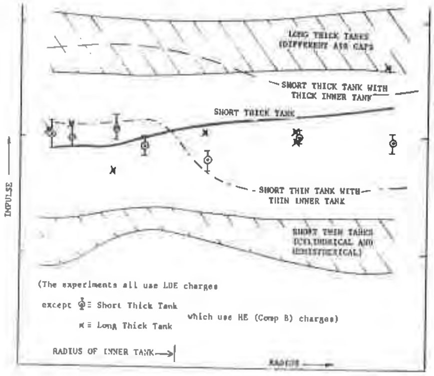
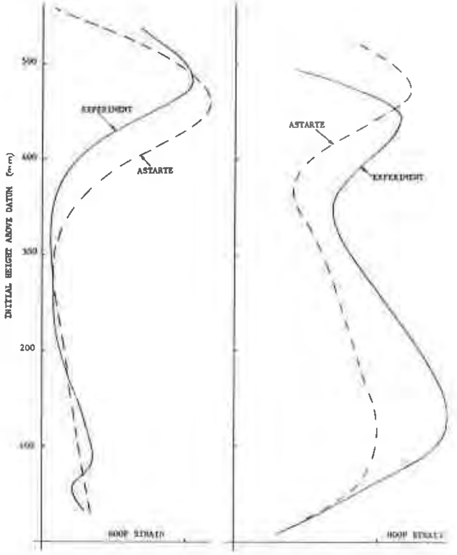


FIGURE 3 ROOF IMPULSE VARIATIONS IN COVA EXPERIMENTS



HEMISPHERICAL VESSEL
(FIXED AT TOP)

CYLINDRICAL VESSEL
(SLIDING SEAL AT TOP)

FIGURE 5

COMPARISON OF PREDICTED AND MEASURED HOOP STRAINS

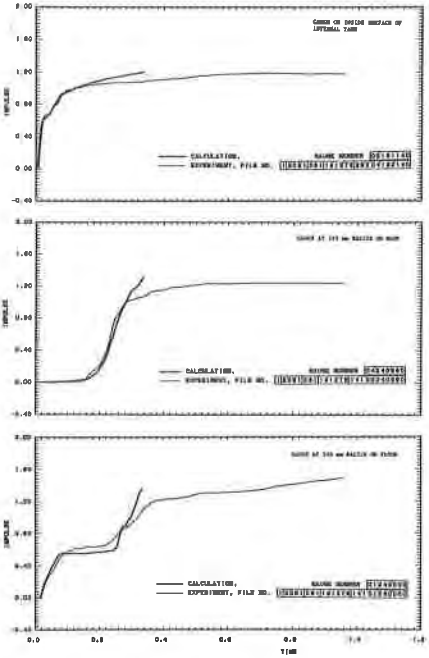
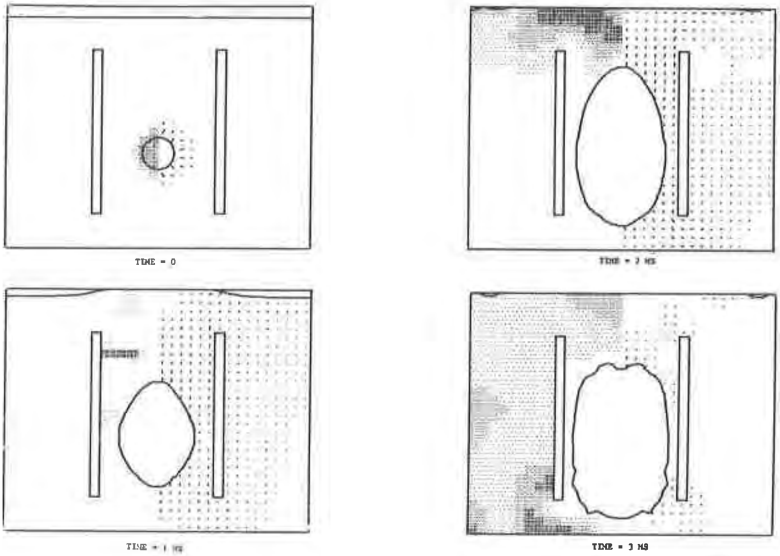


FIGURE 7

COMPARISON OF MEASURED AND
PREDICTED (SEURBNUK) IMPULSES FOR
COVA TEST WITH THICK INTERNAL TANK



TIME = 0

TIME = 2 MS

TIME = 1 MS

TIME = 3 MS

FIGURE 6 SEURBNUK CALCULATION AT
FOUR DISTINCT TIMES FOR COVA TEST
WITH THICK INTERNAL TANK