THE COMPUTER CODE SEURBNUK-2 FOR FAST REACTOR EXPLOSION CONTAINMENT SAFETY STUDIES

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SUMMARY

The paper describes the theory and capabilities of the SEURBNUK-2 fluid flow code developed by JRC Ispra and AWRE Aldermaston for use in containment analysis for fast reactor explosion containment studies. It is a 2D Eulerian code and is a major extension of the SURBOUM code developed earlier by Belgonucléaire and Aldermaston. SEURBNUK-2 has a full thin shell treatment for tanks of arbitrary shape and is able to include the effects of compressibility of the fluid.

To introduce the effects of compressibility into the code, viscosity and diffusion are neglected and a purely implicit time centred difference scheme adopted. Results are presented from a SEURBNUK calculation for the Ispra test shot 114 of the expansion of a Belgonucléaire charge in an overstrong water filled vessel. Comparisons are made both with experimental results and with calculations done on the 2D Lagrangian codes REXCO-H and ASTARTE-2.

Thin shells are treated by a full bending theory and may be of general shape. Their positions in the program are given by a series of Lagrangian marker particles which are allowed to move through the fixed Eulerian fluid grid as the shells deform. The shells are divided into a number of sublayers each of which is assumed to behave as a perfectly plastic material but with a different yield stress. This so called mechanical sublayer model has been shown to be a realistic model of actual materials behaviour.

A thin external deforming cylindrial tank is chosen for the first test of this model, though in this case the fluid was assumed incompressible. The geometry chosen is the same as that used by Belgonucléaire in their experiment 32 (SMiRT-3 Paper 3/5). The problem has already been studied by REXCO and SURBOUM VD8 (SMiRT-3 Paper 3/3 and the SEURBNUK results are compared with both experiment and these calculations.

Comparisons have been made of the effect of using a full bending theory for the tank as opposed to a simple membrane treatment. It is shown that the inclusion of bending terms does not alter the ultimate strains significantly but it does lead to much smoother results for the values of the stress components in the wall.

Results are also presented for calculations on a U-shaped tank containing fluid with a cover gas simulating a bare primary tank. Three different calculations have been done involving rigid and flexible tanks and an incompressible and compressible treatment for the water. These are:

(A) water treated as incompressible, rigid outer tank,
(B) water treated as incompressible, flexible outer tank,
(C) water treated as compressible, flexible outer tank.

Comparisons are made between the three solutions both as regards final tank shape and energy distributions.

1. INTRODUCTION

The SEURBNUK-2 code has been developed jointly by JRC Ispra and AWRE Aldermaston for use in containment analysis for fast reactor safety studies. It is a major extension of the SURBOUM code developed earlier by Belgonucleaire and Aldermaston, which in turn was based on the Marker and Cell (MAC) code [1]. In the Marker and Cell method the motion of a two dimensional incompressible fluid, which may have a free surface, is solved using an Eulerian approach whereby the fluid moves through a fixed grid of mesh lines with velocity and pressure as the basic variables. Massless particles are distributed throughout the fluid and move with it but their sole use is to determine which cells contain fluid.

The numerical procedures adopted in SEURBNUK to solve the basic hydrodynamic equations are similar to the ICE procedure [2] which itself is an extension of the MAC method. In this the non linear partial differential equations are solved by an implicit finite difference technique which advances the solution in a series of time steps. SEURBNUK-2 has a full thin shell treatment for tanks of arbitrary shape and includes the effects of compressibility of the fluid. A feature of SEURBNUK is that the equations of motion for the thin shells are solved quite separately from those for the fluid and the time step for the fluid flow calculation is an integral multiple of that for calculating the shell motion. The interaction of the shell with the fluid is then considered as a modification to the coefficients in the implicit pressure equations, the modification naturally depending on the behaviour of the thin shell section within the fluid cell.

Containment analysis for any hypothetical excursion in a fast reactor is inherently a three dimensional problem but many aspects may be examined to good approximation with a two dimensional analysis such as is possible with SEURBNUK-2. The code is limited to dealing with the motion of a fluid with two free surfaces in an axisymmetric geometry. One free surface is in contact with a cover gas and the other encloses a gas bubble representing the hypothetical explosion products. The thin internal or external shells may be of arbitrary axisymmetric shape and may develop large deformations. This has been made possible by the considerable attention given to the logic of the programme to allow these shells to be placed in general positions within the mesh and to move through the mesh in quite a general way. In general applications of the code the fluid may contain additional rigid structures though in the applications of the code referred to here it is assumed that there are no structures within the main fluid body.

Sections 2 to 8 describe the basic equations, treatment of boundary conditions, free surfaces and thin shells. Later sections discuss the results of calculations with the code on hypothetical excursions within both cylindrical and U shaped tanks. For the former comparisons are made with experimental results in order to show that the code is giving correct answers though for the latter there are no experimental results for comparison and it is necessary to accept plausible answers. In the case of the U shaped tank comparisons are made between the results for rigid and deformable tanks and for compressible or incompressible modelling of the fluid.

2. BASIC EQUATIONS WITHIN THE FLUID

The equations to be satisfied by the fluid are the continuum mechanics conservation equations of mass, momentum and energy in cylindrical co-ordinates which, neglecting viscosity and mass diffusion may be written

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial(r\rho u)}{\partial r} + \frac{\partial(\rho v)}{\partial z} = 0 \quad (1)$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{1}{r}\frac{\partial(r\rho u^2)}{\partial r} + \frac{\partial(\rho uv)}{\partial z} = -\frac{\partial p}{\partial r} \quad (2)$$

$$\frac{\partial \rho v}{\partial t} + \frac{1}{r}\frac{\partial(\rho ruv)}{\partial r} + \frac{\partial(\rho v^2)}{\partial z} = -\frac{\partial p}{\partial z} + \rho g \quad (3)$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{1}{r}\frac{\partial\{ru(\rho E + p)\}}{\partial r} + \frac{\partial\{v(\rho E + p)\}}{\partial z} = \rho v g \quad (4)$$

where ρ, u, v, p, E, g are the density, radial and axial velocities, pressure, total energy/unit mass and axial gravitational acceleration (positive) respectively. The total energy/unit mass, E, may be written

$$E = I + \frac{1}{2}(u^2 + v^2) \quad (5)$$

where I is the internal energy per unit mass. To complete the equations we have an equation of state relating the pressure to the density and internal energy

$$p = p(\rho, I) \ . \quad (6)$$

For many physical problems the changes of state may be considered to a good approximation as adiabatic and in the initial applications reported here the energy equation and equation of state are replaced by a simpler relation

$$\frac{dp}{d\rho} = 1/c \quad (7)$$

where c is related to the sound speed. If for instance we use the adiabatic form of

$$p = a_1(\zeta - 1) + a_2(\zeta - 1)|\zeta - 1| + \rho_o(\gamma - 1)\zeta I \quad (8)$$

where $\zeta = \rho/\rho_o$ and ρ_o is a reference density, then

$$1/c = \{(a_1 - a_2)\zeta^\gamma + \frac{a_2'}{2-\gamma}\left[2\zeta^2 - \gamma\zeta^\gamma\right]\}/\rho \quad (9)$$

where $a_2' = \pm a_2$ according as $\zeta \gtrless 1$. For an incompressible fluid c is zero.

3. THE DIFFERENCE EQUATIONS WITHIN THE FLUID

The differential equations are solved by a finite difference procedure similar to the ICE method [2] in which an interlaced network of dependent variables is introduced as shown in figure 1. Instead of using the velocities as dependent variables it is convenient to use the momenta ρu and ρv. The latter are defined at the centre of the mesh sides as shown in figure 1 whilst the pressure, density and energy are defined at the mesh centres. Time and space derivatives are approximated by first order advanced and central differences respectively.

At the beginning of each time step, we know the solution everywhere. To find the advanced time quantities we first eliminate $(\rho u)^{n+1}$ and $(\rho v)^{n+1}$ from the difference equations to obtain an implicit equation for the pressure which may be written

$$p^{n+1}_{i,j} = A_1\, p^{n+1}_{i-1,j} + A_2\, p^{n+1}_{i,j-1} + A_3\, p^{n+1}_{i+1,j} + A_4\, p^{n+1}_{i,j+1} + R^n_{i,j} \quad (10)$$

where

$$A_1 = r_{i-\frac{1}{2}}/(Dr_i\,\Delta r^2) \qquad A_2 = A_4 = 1/(D\Delta z^2) \qquad A_3 = r_{i+\frac{1}{2}}/(Dr_i\,\Delta r^2) \quad (11)$$

$$R_{i,j} = \Delta r\left[A_1\,\xi_{i-\frac{1}{2},j} - A_3\,\xi_{i+\frac{1}{2},j}\right] + \Delta z\left[A_2\,\eta_{i,j-\frac{1}{2}} - A_4\,\eta_{i,j+\frac{1}{2}}\right] \quad (12)$$

$$+ c_{i,j}\,p_{i,j}/(D\Delta t^2) + \frac{\Delta r}{\Delta t}\left[A_1(\rho u)_{i-\frac{1}{2},j} - A_3(\rho u)_{i+\frac{1}{2},j}\right] + \frac{\Delta z}{\Delta t}\left[A_2(\rho v)_{i,j-\frac{1}{2}} - A_4(\rho v)_{i,j+\frac{1}{2}}\right]$$

and

$$D = 2/\Delta r^2 + 2/\Delta z^2 + c^n_{i,j}/(\Delta t)^2 \ . \quad (13)$$

In these equations the convection terms ξ and η are given by

$$\xi = - \left\{ \frac{1}{r} \frac{\partial(r\rho u^2)}{\partial r} + \frac{\partial(\rho uv)}{\partial z} \right\} \qquad \eta = - \left\{ \frac{1}{r} \frac{\partial(\rho ruv)}{\partial r} + \frac{\partial(\rho v^2)}{\partial z} - \rho g \right\}. \qquad (14)$$

In the case when the fluid is incompressible we set $c^n_{i,j}$ zero in the above formulae.

Equation (10) is solved by iteration but in problems where the fluid is treated as incompressible the rate of convergence is very slow and in consequence an over-relaxation process is adopted.

A feature of SEURBNUK is that rigid wall boundary conditions and the interaction of the thin shells with the fluid are both considered using a modified form of the pressure equation (10). This avoids difficulties such as the evaluation of the convection terms ξ and η (14) at the boundaries and leads to a much simpler formulation. It is contrary to what is done in MAC, ICE and early versions of SURBOUM II.

4. BOUNDARY CONDITION FOR A RIGID WALL COINCIDENT WITH THE MESH

The fluid velocity (and consequently momentum) normal to the wall is restrained to be zero, but in the tangential direction there is a free-slip condition. Since the face of a grid wall is coincident with the grid line the boundary condition applied is either

$$(\rho u)_{i+\frac{1}{2},j} = 0 \quad \text{or} \quad (\rho v)_{i,j+\frac{1}{2}} = 0 \qquad (15)$$

for suitable (i,j). In the pressure equation (10) this leads to the appropriate coefficient A_1 to A_4, on the edge of the fluid cell adjacent to the rigid wall cell, being set zero.

5. TREATMENT OF FREE SURFACE INTERFACES

In a typical SEURBNUK problem there will be two free-surfaces between gas and fluid. One is between the gas bubble containing the explosion products and the reactor fluid while the other is between the fluid and the cover gas. The pressure within each gaseous region is assumed to be uniform and is found from either a pressure-time or a pressure-volume relationship. These interfaces are represented by a series of massless marker particles (typically three per Eulerian mesh) which are moved with a velocity obtained by linear interpolation from the local velocity field.

The boundary condition applied at the cover gas free surface is that the pressure at this interface is equal to the cover gas pressure. Assuming that the interface is roughly horizontal, the pressures at the centres of the fluid cells next to the cover gas (cover gas surface cells) are found by quadratically or linearly interpolating between the pressures at this interface and within the fluid in the direction parallel to the axis of symmetry. Thus in these boundary cells (which are at least half full of fluid) we do not use the standard pressure equation (10). The density of the fluid is obtained from the equation of state.

In order to calculate the convection terms near the free surface, it is useful to extend the momentum field beyond the region where it is calculated using the momentum equation (2). This is done using the continuity equation (1) with the neglect of time variations in the density to calculate the radial momentum, and by linear extrapolation parallel to the axis of symmetry for the axial momentum. If three values of momenta are required in a cell, all three are determined by linear extrapolation in the appropriate directions.

The boundary condition applied at the bubble surface is that the pressure at this interface is equal to the bubble pressure. Thus, pressures at the centres of cells adjacent to the bubble (bubble surface cells) are found by linear or quadratic interpolation between the pressures at this interface and within the fluid, in a direction roughly normal to the bubble surface. As previously, we use continuity in momentum with neglect of density changes, and linear extrapolation to extend the momentum field. Note that in bubble surface cells their centres lie within the fluid. The density is obtained from the pressure using the equation of state.

6. TREATMENT OF THIN SHELLS

Thin shells are treated by a full bending theory and may be of general shape. They may be either (a) within the fluid (internal tanks) or (b) external tanks containing the fluid. Fluids can slip past the shells but at the shell surface must have the same normal component of displacement as the shell. The thin shell in SEURBNUK is represented by a set of adjoining frustra of cones with boundary particles at the joins of the cones. These particles have half the mass of the frustrum on its left plus half the mass segment on its right.

We express the equations of motion for the shell in terms of a curvilinear co-ordinate system (s,ϕ,θ) as shown in figure 2(a): s is a distance along the meridian, ϕ the angle of the tangent plane to the local radial vector and θ an angular co-ordinate of the meridional plane. For shells of revolution under rotationally symmetric loadings the only forces acting on a typical element are N_ϕ, N_θ and Q together with moments M_ϕ, M_θ as shown in figure 2(b).

By considering the forces and couples on a shell element in the normal and tangential directions, (Krauss [3] equation 2.71) we obtain the following equations of motion

$$\rho_w h \frac{du}{dt} = - F_n \sin\phi + F_t \cos\phi \tag{16}$$

$$\rho_w h \frac{dv}{dt} = - F_n \cos\phi + F_t \sin\phi - g\,\rho_w h \tag{17}$$

where the non-body forces on the shell are

$$F_n = \frac{1}{r}\frac{d}{ds}(rQ) - (N_\phi \chi_\phi + N_\theta \chi_\theta) + P_L - P_R \tag{18}$$

per unit area normal to the shell and

$$F_t = \frac{1}{r}\frac{d}{ds}(rN_\phi) + Q\chi_\phi - \frac{N_\theta \cos\phi}{r} \tag{19}$$

per unit area tangential to the shell with the shear force per unit area (Q) given by

$$rQ = \frac{d}{ds}(rM_\phi) - M_\theta \cos\phi \tag{20}$$

where $\chi_\phi = d\phi/ds$, $\chi_\theta = \sin\phi/r$ are the curvatures of the shell. In these equations p_L and p_R are the pressures on the left and right hand sides of the shell, h its thickness and ρ_w its density. It is assumed that the principal strains e_ϕ, e_θ vary linearly through the thickness, i.e.

$$e_\Omega = \varepsilon_\Omega + y\,\chi_\Omega \qquad \Omega = \phi,\theta \tag{21}$$

and y is the perpendicular distance from the mid-surface of the shell.

We assume that the principal stress in the shell normal to its mid-surface is small and take it to be zero. Then the forces and couples per unit length are related to the principal stresses σ_ϕ and σ_θ

$$N_\Omega = \int \sigma_\Omega(y)\,dy \qquad M_\Omega = \int y\sigma_\Omega(s)\,dy \qquad \Omega = \phi,\theta \tag{22}$$

The shell wall is divided into layers with each layer having individual values of $\sigma_\phi,\sigma_\theta$ which are integrated numerically to give the forces and couples.

The shell is allowed to deform both elastically and elastoplastically. The criterion for an elastic deformation is $f(\sigma_\theta,\sigma_\phi) < Y$ where

$$f^2(\sigma_\theta,\sigma_\phi) = \sigma_\theta^2 + \sigma_\phi^2 - \sigma_\theta\,\sigma_\phi \tag{23}$$

the von Mises condition. The changes in stress in an elastic deformation are related to the changes in strain by Hooke's law, that is

$$\begin{pmatrix} \Delta\sigma_\theta \\ \Delta\sigma_\phi \end{pmatrix} = \frac{E}{1-\nu^2} \begin{pmatrix} 1 & \nu \\ \nu & 1 \end{pmatrix} \begin{pmatrix} \Delta\varepsilon_\theta \\ \Delta\varepsilon_\phi \end{pmatrix} . \tag{24}$$

The changes in stress in a plastic deformation are related to the changes in strain by the Reuss flow rule which gives

$$\begin{pmatrix} \Delta\sigma_\theta \\ \Delta\sigma_\phi \end{pmatrix} = \frac{E}{C^2 - 2C + 1} \begin{pmatrix} 1 & C \\ C & C^2 \end{pmatrix} \begin{pmatrix} \Delta\varepsilon_\theta \\ \Delta\varepsilon_\phi \end{pmatrix} \tag{25}$$

where $C = (2\sigma_\theta - \sigma_\phi)/(\sigma_\theta - 2\sigma_\phi)$. In any given deformation, the deformation is assumed elastic with the changes in stress given by (24). If however the yield criterion $f(\sigma_\theta,\sigma_\phi) \lesssim Y$ is not satisfied at the end of the deformation, then the deformation is split into an elastic deformation followed by a plastic deformation. The elastic deformation is given by (24) with strain changes reduced proportionately so that $f(\sigma_\theta,\sigma_\phi) = Y$ exactly at the end of elastic deformation. The stress changes in the remainder of the deformation are then given by (25). Work hardening has been introduced by means of the mechanical sublayer model.

To overcome instabilities in the thin shell equations, all forces and momenta except the longitudinal force are evaluated in terms of the stresses at the particle positions using full bending theory; the longitudinal force N_ϕ is evaluated from stresses calculated, using membrane theory, at the middle of the segments. Several types of end conditions can be applied to the thin shells in SEURBNUK-2. These are applied by suitably restraining the points of the wall where necessary, and where necessary imposing specified forces or couples near the end.

7. MOVEMENT OF THIN SHELLS

Cells containing part of a thin elastoplastic shell are normally designated as 'thin shell boundary cells' and may contain one or two different volumes of fluid, depending on whether the thin shell forms part of an external or internal tank. There are several criteria which such a boundary cell must satisfy, the main one being that at least one quarter of the volume of the cell should contain fluid. If all the criteria cannot be satisfied the boundary condition becomes effective via a neighbouring cell. Within a boundary cell free slip conditions are assumed at the shell interface i.e. the displacement of the fluid (or fluids) normal to the thin shell is constrained to be equal to the displacement of the thin shell normal to itself while the fluid velocity component tangential to the shell is unrestricted. The use in the boundary condition of normal displacement rather than normal component of velocity ensures that the shell and fluid(s) remain together even when different time steps are used to compute their motions.

Values of the momenta on any face of such a boundary cell which cannot be obtained by application of the momentum equations are obtained by continuity or simple extrapolation and values on the shell boundary are obtained by linear interpolation within the cell. The fluid pressure acting on the shell is obtained by linear interpolation in the pressure field in a direction approximately normal to the shell. For an internal tank there are fluid pressures on both sides of the shell and in fact pressures and momenta are doubly defined in such a boundary cell.

The boundary conditions at the shell are applied directly through the momentum continuity equations for the boundary cell so that the conditions eventually appear as modifications to the pressure equation (10). This ensures that the pressure field obtained is consistent with the applied conditions and that the movements of fluids and thin tanks have the correct mutual dependence on each other.

8. COMPUTATIONAL PROCEDURE

The fluid, cover gas, bubble and tanks are initially assumed to be stationary with zero strain and stress in the tanks. The density of the fluid is assumed uniform and equal to the standard (incompressible) value. In a compressible calculation the pressure, internal energy and total energy are assumed to be zero everywhere, whereas in an incompressible calculation, the initial pressure distribution is assigned a combination of the hydrostatic pressure and the pressure around the bubble; (this aids the convergence during the first time step). The bubble and cover gas are assigned pressures in exactly the same manner at all time steps.

Referring to the description in section 3, prior to iterating on the pressure field to obtain the new pressures using equation (10) one must first calculate the convection terms ξ, η from equation (14), then calculate D, the coefficients A_1 to A_4 and the source term R from equations (12). New momenta and densities are calculated and thence a new velocity field. Although it is not essential to the calculation this is a convenient time to derive the new total and internal energies for the meshes using a difference form of (4).

Using the new velocities the free surface boundary particles are moved to give the new configuration. Again using the new values of the pressure in the fluid cells a subsidiary calculation is done to compute the motion of the thin shells. Because of stability problems the time step for this is much less than a reasonable sized fluid time step and accordingly (16) to (19) can be solved over the fluid time step in several substeps.

The stability time step for the shell, δt, is

$$\delta t < \frac{2}{3}\,\Delta s \sqrt{\frac{\rho_W(1-\nu^2)}{E}}\ \min\left(1, \frac{\sqrt{3}}{2}\frac{\Delta s}{h}\right) .$$

The fluid step must be chosen so that the fluid does not cross more than one mesh in a time step, that is

$$\Delta t < \min\left(\frac{\Delta r}{|u|_{max}}, \frac{\Delta z}{|v|_{max}}\right) .$$

For a compressible fluid the time step should not be chosen much larger than the Courant value if significant diffusion is to be avoided.

The boundary of the fluid is traversed and the Eulerian boundary cells are selected using the appropriate criterion for bubble boundary cells, cover gas boundary cells, rigid grid boundary cells and thin shell boundary cells. If a cell contains a boundary but does not satisfy the criteria then it is treated with an appropriate neighbouring cell, and is not included in the calculation in the next time step. An internal thin shell can cause boundary cells for the fluids on each side to be generated in the same Eulerian cell. Care is taken that each of the two boundary cells is connected to the appropriate fluid cells.

At this stage all the fluid cells are labelled as to their type, and initial values of density, momentum, total energy are inserted into 'new' cells, that is boundary cells, which were not previously fluid cells. Momenta are found by extrapolation and continuity, density and total energy from an appropriate neighbouring cell.

9. CALCULATION OF AN EXPLOSION IN AN OVERSTRONG TANK

The Ispra experiment no. 114 [5] examined the ignition of a 1.6 kg Belgonucleaire pyrotechnic charge in an overstrong cylindrical tank containing water. Figure 3 shows the initial geometry; pressure gauges are mounted at positions 1 and 2. A comparison is made of results from experiment, SEURBNUK-2 and the 2-D Lagrangian code REXCO-H [5].

A tabular pressure-volume relationship was used for the gas bubble as given in table 19.1, intermediate and extrapolated values were found using a log-log interpolation.

Table 9.1. Pressure-volume relation for the gas bubble

Pressure (MPa)	41.1	26.3	18.2	15.2	12.4	10.9	6.55	4.4	3.05	2.35
Relative volume	1.0	1.72	2.37	3.13	4.11	5.18	8.93	13.90	20.90	27.80

For all calculations it was assumed that the initial pressure and volume were 41.1 MPa and 1.43 litres respectively. For the REXCO-H calculation it was assumed that the behaviour of the water is described by an equation of state of the form represented by 2.8 with $a_1 = 2.2$ GPa and $\gamma - 1 = 0.28$. The cover gas was assumed to give a zero pressure condition in all cases.

The number of uniform Eulerian cells used in the SEURBNUK-2 calculation was 10 radially and 30 axially and this was similar to the number of Lagrangian cells (12 × 31) in the REXCO-H calculation. The bubble was assumed to be spherical in SEURBNUK-2 but cylindrical in the other code. The time step for SEURBNUK-2 was fixed at 5 μs, whereas in REXCO-H it was chosen automatically from the stability criterion and was normally between 1 and 2 μs.

The results of the pressure-time histories at the pressure gauge positions 1 and 2 are given in figures 4 and 5 for SEURBNUK-2, REXCO-H and experiment. The waveforms for SEURBNUK-2 calculation are much smoother than either the REXCO-H or experimental ones and at late times the peak pressures decay more rapidly, both effects being expected since in Eulerian codes the numerical technique automatically tends to produce damping of the solution. The agreement between SEURBNUK-2 and REXCO-H is quite good, the waves get out of phase at late times, but this may not be entirely due to the different wave speeds since the initial charge configurations were different. The experimental curve is similar to the initial pressure pulses obtained by all codes but different thereafter.

10. CALCULATION ON A THIN CYLINDRICAL TANK

SEURBNUK-2 has been tested on a thin cylindrical tank with the same geometry, explosive and material properties used by Belgonucleaire in their experiment no. 32 [4,5]. As this problem has already been calculated with REXCO-HEP and ICECO [6] there are experimental and calculational results available for comparison to validate SEURBNUK. In addition, because SEURBNUK has a full bending theory treatment of thin shells, it is possible to investigate differences arising from using bending or a pure membrane treatment. For this SEURBNUK calculation the fluid has been taken as incompressible as it was believed that for this experiment compressibility effects would not be significant: this was subsequently verified.

The left-hand side of figure 6 shows the initial configuration, with fluid at a density of 10^3 kg m^{-3}. For the cover gas, the pressure, p is related to the volume, v, by a van der Waals equation

$$p = - a(v_o/v)^2 + p_o v_o^{\gamma}/(v - bv_o)^{\gamma}, \quad a = 1.725\ 10^{-4}\ \text{MPa}, \quad b = 1.146\ 10^{-3}, \quad \gamma = 1.4, \quad (26)$$

v_o is the initial volume and an initial pressure of p_o = 0.101 MPa has been assumed. Table 10.1 gives the bubble pressure as a function of volume appropriate to the charge.

Table 10.1. Bubble Pressure Versus Volume

Volume, litres	0.796	1.46	1.73	2.32	3.09	4.02	5.07	20.6
Pressure, MPa	100	42.7	38.1	27.9	19.9	11.2	7.14	1.00

It has been assumed that the steel tank is 4 mm thick has a density 7.8 × 10^3 kg m^{-3}, Youngs modulus 264 GPa and Poisson's ratio 1/3. Three calculations have been done with different tank properties:-

(a) A membrane theory, together with a perfectly plastic model.

(b) A bending theory with four layers, still with a perfectly plastic model.

(c) A bending theory with two layers and a strain hardening model.

For all three calculations, a von Mises yield condition has been used with a yield stress of 441 MPa. For (c), strain hardening of the von Mises yield stress has been included to model the uniaxial bilinear stress-strain relation of reference [4] with a hardening modulus of 301 MPa. It is believed that (c) represents the most realistic calculation.

The outer tank deforms plastically before a final elastic oscillation and figure 6 shows the resultant configuration for the third calculation (c), together with the experimental REXCO-HEP and ICECO results from reference [6]. The REXCO-HEP results were obtained with a yield stress of 436 MPa, corresponding to a yield strain of 0.214% instead of 0.167% in the SEURBNUK calculation. It is believed [5] that differences in the material properties such as the above do not significantly affect the results. Figure 7 shows the radial wall deformations as functions of time at the charge height and at the lower end of the vessel as calculated with SEURBNUK superimposed on the results taken from reference [6]. As mentioned above, the SEURBNUK and REXCO results agree well at the charge height. However, the displacement at the lower end of the vessel is smaller than we would expect from the impulse calculated, which is comparable with that from REXCO. Overall, there are no significant differences between any of the calculations or experimental results.

Although only the results from the calculation (c) are shown, the results from (a) and (b) only differed by about 1%. The addition of bending moments for this calculation did not alter the results significantly. It did, however, lead to much smoother results for the value of the stress components in the wall. Figure 8 shows a comparison of the circumferential stress around the wall at three times for calculations (a) and (c), with and without bending showing the smoothing effect of the former.

11. CALCULATIONS ON A U-SHAPED TANK

A comparison of the results of three calculations involving a cylindrical tank with a hemispherical bottom are presented. The tank contains water, a cover gas and a high pressure gas bubble immersed in the water. The essential differences between the three calculations are in the treatment of the water and the tank;

run a - the water is incompressible and the tank is rigid,

run b - the water is incompressible and the tank is flexible,

run c - the water is compressible and the tank is flexible.

The initial geometry of the tank is given in figure 9(a). It is assumed that at the top there is a free hinge. A uniform Eulerian mesh of 20 mm × 20 mm has been used with 101 particles to represent the tank shell. For the fluid, which is assumed to be inviscid and of initial density 10^3 kg m^{-3}, a time step of 5 μs has been used, whereas for the flexible shell, a smaller time step of 0.5 μs has been chosen. The treatment of the cover gas is similar to that referred to in section 9, and an adiabatic law is assumed for the gas bubble with $p = 39.3(v_o/v)^{0.832}$ MPa.

Since the use of bending moments did not significantly affect the results for the deforming cylindrical tank calculation a membrane theory has been adopted. A non-work hardening model of the tank has been used, as given in section 10 for calculation (c). The thickness of the tank was 5.1 mm.

In the calculation with a rigid tank, the bubble expands and forces the liquid up towards the roof but, as can be seen from figure 9(b), when the wall is deformable, the bubble expansion also produces a permanent bulge in the tank. From table 11.1, comparing (a) with (b) we see that this expansion absorbs 24% of the energy from the bubble, but leads to a reduction of only 6% in the velocity of impact of the top surface. The time before impact is increased by 11%. From the table we can see that introducing a deforming tank does not

Table 11.1. Comparison of Quantities at Roof Impact Time

	(a) Rigid tank incompressible	(b) Deformable tank incompressible	(c) Deformable tank compressible
Time, (ms)	2.08	2.330	2.455
Free surface velocity (centre), ms^{-1}	128.8	119.5	122.2
Free surface velocity (outside), ms^{-1}	107.01	100.1	97.78
Work done by the bubble, kJ	236	241	247
Work done on the cover gas, kJ	7.7	7.5	9.1
Fluid kinetic energy, kJ	226	171	168
Wall internal energy, kJ	-	63.2	70.0
Wall kinetic energy, kJ	-	0.13	0.09

significantly affect the work done on the cover gas. Compressibility leads to a further slight delay in roof impact but its effect is not significant. The insignificant effect of compressibility is confirmed by figure 10 which shows the strain in the tank wall at charge height for calculations with compressible and incompressible fluids.

12. CONCLUSION

The SEURBNUK-2 code contains three significant extensions of the earlier SURBOUM code

(a) compressibility of the fluid,

(b) thin shells of arbitrary shape,

and (c) simplification of the treatment of rigid wall boundary conditions and the interaction of thin shells on the fluid.

Compressibility of the fluid is treated in a similar way to that used in ICE and from the manner in which the equations are formulated it is a simple matter to change from a compressible to an incompressible treatment. A novel feature of SEURBNUK is in the simple treatment of rigid wall boundary conditions through modifications to the coefficients in the basic pressure equation. This idea has been successfully extended to treating the interaction of the thin shells on the fluid. Thin internal and external shells of arbitrary shape are included in SEURBNUK and because of the extensive logic in the programme these are allowed to have quite a general motion through the Eulerian mesh.

The results of section 9 for the Belgonucleaire shot 114, where the effects of compressibility are important, show that the SEURBNUK-2 treatment of compressibility is essentially correct. In comparison with Lagrangian codes it is found that sharp gradients in the solution are smoothed out more because of the diffusion associated with the difference scheme.

Because of this feature it has been found unnecessary to introduce the usual artificial viscosity terms into SEURBNUK-2 when shocks are present.

From the results of section 10 on calculations for a thin deformable outer cylindrical tank it can be seen that SEURBNUK-2 is giving answers which are in broad agreement with both experimental results and independent calculations. Although in the problems considered to date the addition of bending does not seem to affect the results significantly, it does have the advantage of giving much smoother computer stresses in the walls of the tank.

There are no experimental results for comparison, but the ability of the code to calculate U-shaped tanks and obtain plausible answers has been demonstrated. For tanks of the dimensions given here, it would appear that a significant percentage (25%) of the energy of the bubble can be absorbed by the tank in strain energy.

To sum up, for the simpler geometrical configuration SEURBNUK-2 gives results which agree reasonably well with experiment and independent solutions and even for more complicated systems the results look plausible. The COVA series of experiments [7] will provide a fuller validation under a wide range of reactor-type configurations.

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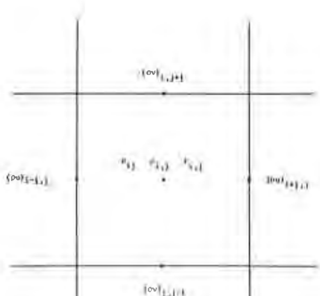


Fig 1. Placement of field variables in SEURBNUK

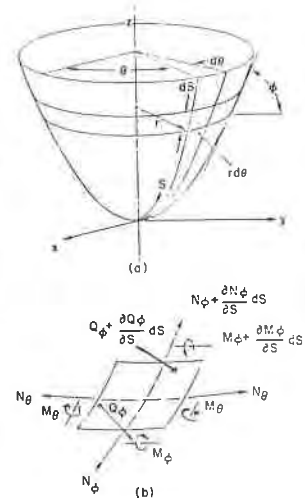


Fig 2. Nomenclature for a shell of revolution

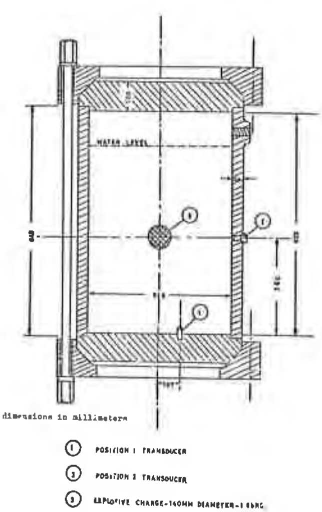


Fig 3. Overstrong vessel for Belgonucleaire experiment 114

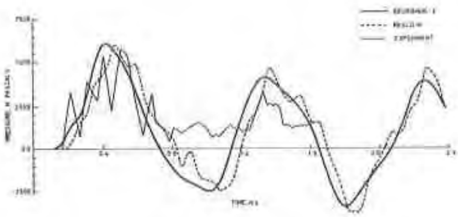


Fig 4. Pressure time history at 100 mm radius on the floor for the Belgonucleaire experiment 114

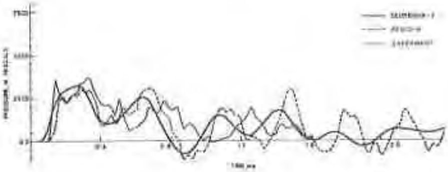


Fig 5. Pressure time history on the wall at charge height for the Belgonucleaire experiment 114

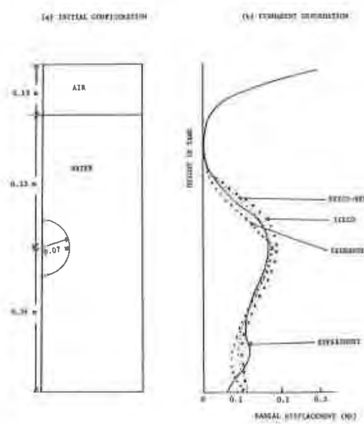


Fig 6. Comparisons of results for Belgonucleaire experiment 32

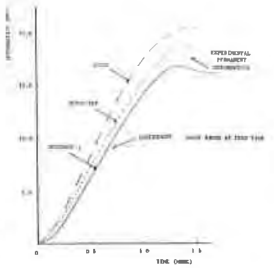


Fig 7a. Vessel deformation at the charge height of 360 mm

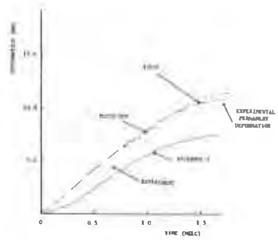


Fig 7b. Vessel deformation at the lower end at a height of 40 mm

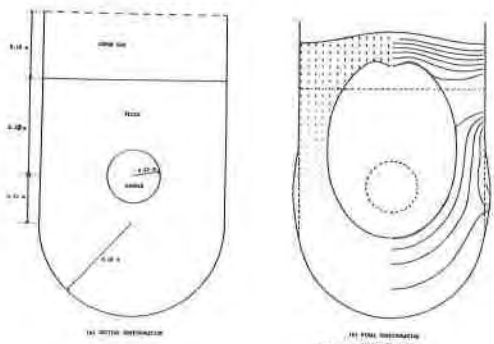
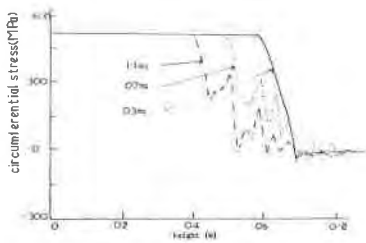
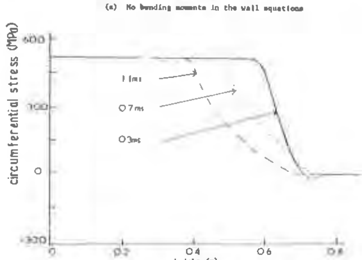


Fig 9. Initial and final configurations for a U-shaped tank



(a) No bending moments in the wall equations



(b) Bending moments in the wall equations

Fig 8. Comparison of the circumferential stress in the shell with and without bending moments in the treatment of the shell

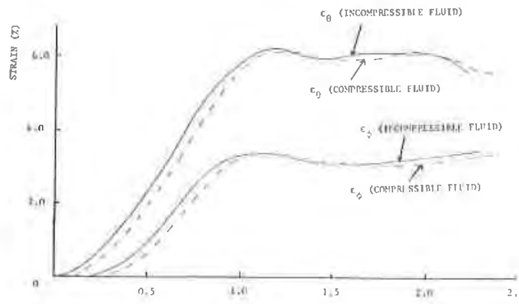


Fig 10. Strains at charge height for U-shaped tank with compressible and incompressible fluid