Cavitation Effects in LMFBR Containment Loading -- A Sensitivity Study

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SUMMARY

The motivation for and design of a sensitivity study into the effects of bulk cavitation of the coolant upon predicted roof loadings and vessel wall loadings and deformations are presented. The study is designed to cover simple and sophisticated models of cavitation in various geometries and with two types of energy source to represent both an explosion charge and the lower pressure expansion behaviour expected in a real core disruptive accident. Effects of change of scale (from reactor to model), of coolant tensile strength, of reactor aspect ratio and design (presence or absence of an internal tank) and of reactor structural resistance (rigid or deforming outer tank) are all examined in order to provide a quantitative answer to the question "how and to what extent does dynamic cavitation affect the containment loading process?".

1. Introduction

The loading of the LMFBR primary envelope during the post-disassembly phase of a core disruptive accident is now a fairly well-understood process, at least by comparison with the very complex chain of events which preceeds it /1/. Work done by the expanding core material is transformed to a large extent into strain energy of the reactor structure via the coolant in a highly involved fluid-structure interaction process. Understanding has been built up on the basis of model testing and code development /2/, the objective being to demonstrate that no part of the containment envelope suffers more than some prescribed strain or loading for a specified energy release. In making the demonstration the main remaining problems are the existance of constructive interference between pressure waves tending to produce high local strains and the possible difficulties in scaling up model test results to real reactors due to rate-dependent material properties /3/.

It is now some five years since the author pointed out that one physical process resulting in both rate-dependent material properties and in variations in wave-speeds which could affect the location and extent of constructive interference was bulk cavitation of the reactor coolant /4/. This cavitation is produced by the negative pressures resulting from the reflection of pressure waves of suitable profile at free surfaces or deformable structures and consists of numerous small nearly empty bubbles within the coolant mass which grow or shrink under the influence of the local fluid pressure field. The propagation speed of a pressure wave is drastically reduced as it enters a region of cavitated liquid /5/ and some of its energy is absorbed in collapsing the bubbles. Both processes are a priori of importance for containment loading and both are very poorly modelled by the "p-min" device customarily introduced into containment codes in which calculated coolant pressures below some pre-assigned negative value p-min are simply replaced by p=p-min and the calculation allowed to proceed. Subsequent publications /6, 7, 8/ have given details of a more realistic cavitation model which simulates the local dynamics of cavitation bubbles, of its coupling to a Lagrangian containment code, and of the application of the combination to some containment problems (model tests). "Validation" applications to purpose-built cavitation experiments have also been described /9/. What has been lacking up to now however is a quantitative assessment of how cavitation affects containment loading and to what extent based on comparison calculations under a realistic range of circumstances, i.e. a sensitivity study. This paper sets out the considerations behind the design of such a study and supplies a test matrix of calculations to cover the influences of length scale (reactors vs models), coolant purity and tensile strength, geometry (short and long tanks, rigid or deformable walls, absence or presence of an internal tank), energy source (explosive source vs "realistic" expanding core) and crude vs sophisticated cavitation models upon the roof loadings and vessel wall loadings and strains. It is intended to present the results and conclusions of this sensitivity study orally at the Conference.

2. Some theoretical considerations

This section contains remarks on the energy absorbing power of cavitation, on scaling effects, on the selection of a "reactor" energy source for comparison with a low-density

explosive in the sensitivity calculations, on the coupled fluid-structures code used in the calculations, on the way in which cavitation is incorporated into the code and on the code facilities for handling a "reactor" energy source.

We begin by considering the energy-absorbing power of bulk cavitation. As Fig. 1 shows, work done upon a fixed mass of liquid in expanding it sufficiently to initiate cavitation and later recompressing it is converted irreversibly into heat via the cavitation bubbles. We wish to estimate the magnitude of the consequent dissipation of mechanical work and to compare it with typical CDA energy releases and experimentally determined strain energies absorbed by structures. As Fig. 1 indicates, the excess pressure needed to collapse cavitation bubbles at even rather high rates is significantly lower than the negative pressures necessary to force them to grow at the same rates, and consequently most of the irrecoverable work done on the system is done during the expansion phase. A very simplified analysis of the expansion phase is given below, based on the equations of ref. /8/.

Assume that the liquid originally of specific volume v is subject to a constant expansion rate of x/sec. The liquid pressure falls initially but is then driven up again as the cavitation bubbles begin to expand. These bubbles eventually expand at such a rate as to maintain an almost zero liquid pressure so that the p. V diagram follows the path BC of Fig. 1 and no more irrecoverable energy storage takes place. The differential equations corresponding to this process are

$$\dot{p} = -\rho_o a^2 (x - 4\pi\rho_o N R^2 \dot{R}) \qquad (2.1)$$

$$\dot{R}^2 = -\frac{2}{3\rho_o} p \qquad (2.2)$$

with conditions at the initiation of cavitation (point B)

$$p = p_{cav} < 0; \quad R = 0, \quad t = 0. \qquad (2.3)$$

(2.2) is a very simplified form of the Rayleigh-Plesset equation suitable for the later stages of bubble expansion. The specific energy may be written as

$$e = -\int_{\rho_0^{-1}}^{v_{cav}} p \, dv \quad - \int_0^\infty \rho_o^{-1} x \, p \, dt \qquad (2.4)$$

in which the first integral represents work done in expanding the liquid to specific volume v_{cav} (i. e. along the path AB). The differential equations and the energy equation may be solved numerically for given x and N, and indicative results for water with p_{cav}=-1.125MPa, N = 10000/kg are given below. V. F. is the % void fraction at point C t_c the time taken to reach point C (approximate value).

$x(s^{-1})$	sp. energy absorbtion (J/kg)	V. F. (%)	t_c (/us)
21.6	0.44	0.02	9.3
220	3.9	0.33	15
2200	151	4.7	22

The energy absorbtion thus rises very sharply with expansion rate, and the timescale of the absorbtion process is short. A sharp-fronted tension wave will suffer more dissipation than a more gradual application of tension. Examination of the equations also shows that for fixed expansion rates a higher value of N (i.e. "dirtier" liquid) loads to lower energy absorbtion. This apparent paradox stems from the fact that in physical rather than artificial situations the expansion rate is limited by the corresponding tensions induced in the liquid, and such tensions are lower for higher values of N. The overall effect of changing N is thus the outcome of opposing tendencies and must be examined case by case.

We now compare the specific energy figures given above with other specific energies in the containment problem. A cursory examination of the energy releases of "design basis accidents" and of coolant masses in various designs yields mean specific energy figures of 150 - 300 J/kg of coolant. The mean specific energy absorbtion of primary tank structures is for comparison of the order of several KJ/kg, and these figures when set beside those for cavitation effects demonstrate that on the scale of the complete reactor or model the mitigating effect of cavitation is negligible.

This is not however the whole story. The main concern of containment studies is with FSI mechanisms which may concentrate stresses and strains in localized and possibly vulnerable portions of the primary envelope, and two such mechanisms are acknowledged to be roof impact and the constructive interference of pressure waves (e.g. around the inner tank). As remarked in the introduction, in both of these mechanisms cavitation can play a significant part by virtue of the fact that wave-speeds are drastically affected by the presence of cavitation /5/. Zones of constructive interference or the process of roof impact may thus be altered by cavitation in ways which are difficult to predict a priori since they involve the whole primary geometry and are history-dependent. The only reasonable approach to evaluating the safety-related influence of cavitation appears to be the sensitivity study.

We now turn to the question of comparison between model tests and reactors. Scaling between models and reactors has been treated repeatedly elsewhere /3/. If one adheres to the now traditional velocity scaling and is prepared to ignore rate-dependent material properties then model strains and roof impact pressures translate unchanged to the reactor, while impulses must be multiplied by the scaling factor. In this study the strain-rate dependence of the structures has been ignored and it is only the rate-dependence of cavitation which is of interest. Fortunately, as was explained in /6/, unless one is concerned with the first few nanoseconds of the bubble expansion process one may confidently apply a very simple scaling law viz: a model simulates the cavitation behaviour of the reactor identically under the usual velocity scaling transformation if the concentration of cavitation sites in the model exceeds that in the reactor by the cube of the scaling factor. Briefly, reduced-scale models require a relatively dirtier coolant. The consequence of this law for the sensitivity study is that it is not necessary to perform calculations for various sizes of models to examine the relative influence of cavitation. A single length scale will serve for all calculations with a fixed geometry, with comparisons between cavitation effects in models and in reactors of various sizes being obtained by varying N.

After this brief mention of scaling we may now consider the energy source. Model tests of e.g. the COVA programme /10/ employ a low-density explosive as driving source, with a peak surface pressure of about 300 MPa and a relatively rapid fall-off in the pressure with volume. It seems to be the general consensus that in the real reactor the initial pressures would be much lower and the fall-off of pressure with volume less pronounced. Since cavitation is a rate-dependent phenomenon it was thought advisable in this sensitivity study to examine the containment response both to LDE and to such a "realistic" energy source, and to facilitate comparison it was decided to fix the parameters of this latter type of source in such a way that the total energy release upon expansion to 200 volumes was the same for both sources. The figure of 200 was based on the calculated maximum volume of the charge gases in a COVA experiment (IT9) with a single long round-bottomed deformable tank /11/. This volume corresponds to about 2.7 times the original cover-gas volume.

For the "realistic" source a polytropic law was chosen with an exponent of 0.7 and an initial pressure of 19.9 MPa. The energy release on expansion to 200 volumes of such a source is calculated to be 259 MJ/initial m^3. The code chosen for the execution of the sensitivity study was the Lagrangian finite difference coupled fluids-structures code ASTARTE-4 /12/ developed by AWRE Aldermaston. As has previously been described /4,5,7/ this code has been adapted to include the SIMON equation of state module which calculates the dynamics of the cavitation bubbles for each hydrodynamic F.D. cell and evaluates the liquid pressures as a function of local specific volume and dilatation rate which the main code then uses to drive the hydrodynamics and structural dynamics forward another timestep. The combined ASTARTE/SIMON has been applied to some purpose-designed dynamic cavitation experiments and has had considerable success in predicting their outcomes /9/. In addition to an equation of state for the liquid (here supplied by SIMON) ASTARTE also needs an equation of state for the energy source. The JWL equation employed for the LDE charge /11/ is already incorporated by the code designers, and by a fortunate coincidence it was found that a polytropic law such as that assumed for the "realistic" source had also been included in the guise of the "simple 2-D equation".

$$p = a_1 \mu + a_2 \mu |\mu| + E (b_o + b_1 \mu) \qquad (2.5)$$

where $\mu = (\text{rel. vol.})^{-1} - 1$; $E = \rho_o x$ specific energy. It is merely necessary to set the input parameters $a_o = a, = 0$; $b_o = b_1 = -0.3$, $E(t=0) = -6.6333_{10} - 4$ Mbar. The use of negative internal energies does not seem to disturb the operation of the code.

Returning to the code as a whole, it was decided that since the interest of the study was in hydrodynamic effects the structural side of the calculations should be made as simple as possible. The steel of which the vessels are composed was assumed to be insensitive to strain-rate, although a realistic trilinear (σ - ϵ) curve was maintained in the interests of verisimilitude.

Membrane theory was employed for the shells to cut down calculational expense without sacrificing too much accuracy, while FD discretisation of shells was kept fairly fine to bring out any local stress concentration effects.

3. The model geometries and the test matrix

In the selection of test cases preference was given to simplified models over real reactors because real reactors are very complex, are non-axisymmetric and are often constructed of materials with unpublished properties. Furthermore one may for models be guided by experimental results in the selection of calculational parameters (mesh size, total run time, etc.) while for reactors experimental results are not generally available. Within the domain of models it was decided to include both low and high aspect ratio tanks corresponding to pool and loop designs, and to include a variety of configurations with rigid or flexible walls and without or with internal tanks. Mention has already been made of the options available regarding the energy source and effective scale as reflected in the cavitation parameters.

The experimental geometries selected are "IT3.5", a short tank experiment with rigid walls, IT5, the same configuration in a long tank, IT7, a set-up like IT5 but with a deformable wall free to move at the upper end within a sliding collar, IT10 (like IT3.5 but with a rigid inner tank) and IT11 which is a version of IT10 with deformable outer wall. Fig. 2 shows the geometries discretized for the calculations. In the choice of cavitation parameters one is rather hampered by the lack of good data for reactor sodium or model water. The calculations with the well-known p-min cavitation "model" used a p-min of zero which seems to have become standard practice /2/ while for the calculations using SIMON p_{cav} values of -0.5 and -2.5 MPa were employed which span the range of current guesses /9/. The number-density of cavitation sites N was set at 5000/kg in the reactor, i.e. rather higher than the value for ultrapure water deduced in /9/. Using scaling factors of 6 and 20 and the scaling laws mentioned in section 2 the corresponding N values in the model should be $1.08_{10}6$ and $4_{10}7$ respectively. Values of N in real models are more likely to be around 5000/kg. The values of N finally chosen for the study were N = 5000/kg, N = 500000/kg, N = $50_{10}6$/kg. The calculation test matrix based on the considerations given in this section is provided as Fig. 3. It contains 70 calculations, which would result in a very expensive sensitivity study even with present-day computing costs. To reduce the overall cost of the study a limited selection has been made from Fig. 3 in a way which takes full account of the information from one test in choosing the next. The basis and outcome of this heuristic selection process will be explained orally at the Conference.

4. Choice of significant output variables

The outcome of the calculation of a single experiment with a typical containment code is a set of perhaps 100 graphs of pressures, impulses and strains as functions of time plus plots of the pressure and velocity fields at various epochs . In a sensitivity study it is necessary to extract from this mass of data some "critical parameters" for comparison between cases. Taking into account the remarks in section 2 concerning the expected effects of cavitation and current notions of the most challenging features of containment loading for the design engineer it was decided to select the following outputs for intercomparison:

a) The impulse and pressure histories on the roof at radii corresponding to 23% and 69% of the radius of the roof structure. Where an inner tank is present the two points are inboard and outboard respectively of the inner tank.

b) The final radial deformation profile of the primary tank where available. Where the tank is treated as rigid the impulse histories at levels above the tank base of 50% and 82% of the tank height were selected.

c) Where an inner tank was present, the impulse history at charge height on the inner wall of this tank.

In the analysis of the values of these output parameters as functions of the input parameters indicated in the test matrix, the procedure is strictly one of intercomparison between calculations with no attempt to compare the outcomes with experimental results where these are available. (At Ispra IT3. 5 is a fictitious experiment and IT10 has yet to be performed.) The reason for this is that comparison of calculation with experiment introduces a whole collection of distracting difficulties associated with the degree of sophistication of the containment code rather than with cavitation processes. Examples are that calculations may not always proceed far enough to simulate the experiment in its entirety (mesh tangling problems), that experimental information may not always be complete (especially as regards material properties), that strain-rate effects for steels have been neglected in the calculations, and that some models present in the code for e.g. flow over the lip of an inner tank and flow of the cover gas during roof impact are currently rather unsophisticated and possibly subject to systematic errors. The modelling considerations just mentioned are the subject of code validation compaigns /2/ and are best omitted from a restricted study such as the present one.

5. Conclusions

Results and conclusions will be presented orally.

REFERENCES

/1/ T.G. Theofanous, "Multiphase Transients with Coolant and Core Materials in LMFBR Core Disruptive Accident Energetics Evaluations", NUREG/CR-0224 (July 1978).

/2/ K.C. Kendall and A. Benuzzi, "The COVA Programme - Validation of the Fast Reactor Containment Code SEURBNUK", Nuc. Eng. and Desn.57, 79-105 (1980).

/3/ R. Staniforth, "Experimental Modelling of Hypothetical Core Disruptive Accidents", Nuc. Eng. and Desn. 55, 225-33 (1979).

/4/ A.V. Jones, "The Mitigating Effect of Coolant Cavitation in the Response of LMFBR Containment to a Whole-Core Accident", Proc. Int. Meeting on Fast Reactor Safety and Related Physics, Chicago, USA (Oct. 5-8, 1976), CONF-761001, 1354.

/5/ L. Van Wijngaarden, Ann. Rev. Fluid Mech. 4 (1972), 369.

/6/ A.V. Jones, "Bulk Coolant Cavitation in LMFBR Containment Loading Following a Whole-Core Explosion", 4th Int. Conf. on Structural Mechanics in Reactor Technology, San Francisco, USA (August 15-19, 1977).

/7/ A.V. Jones, "The Calculation of the Propagation of Tension and Recompaction Waves", in: Proc. Colloq. The Response of Liquids to Dynamic Tension, Ispra September 27th, 1977. EUR 6046en(1978).

/8/ A.V. Jones, "Coolant Cavitation in Dynamic Containment Loading", Nuc. Eng. and Desn. 55, 197-206 (1979).

/9/ A.V. Jones, "Validation of a Cavitation Model and its Application to Containment Loading Experiments", 5th Int. Conf. on Structural Mechanics in Reactor Technology, Berlin, 13-17 August, 1979 (Paper E 2/6).

/10/ N.E. Hoskin, M.J. Lancefield, "The COVA Programme for the Validation of Computer Codes for Fast Reactor Containment Studies", Nuc. Eng. and Desn., 46 17-46 (1978).

/11/ A.V. Jones, JRC Ispra internal document.

/12/ N.E. Hoskin, M. W.S. Mawbey, N.J.M. Rees, Proc. Int. Conf. on Engineering of Fast Reactors for Safe and Reliable Operation (Karlsruhe 1972). p. 1084.

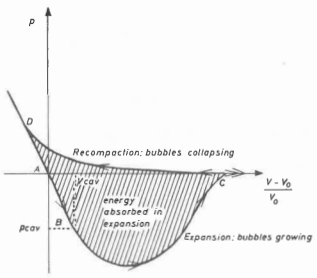

Fig. 1 Energy absorbtion during cavitation and recompaction

	N(kg-1)	Pmin. G	Pcav = -0.5 MPa			Pcav = -2.5 MPa			SOURCE			GEOMETRY	
		-	$5\,10^3$	$5\,10^5$	$5\,10^7$	$5\,10^3$	$5\,10^5$	$5\,10^7$	oz LDE	rel. vol (10^{-4})	rel. height	aspect ratio	%cover gas
IT 3.5	LDE core								2	9.46	0.393	1.6	4.46
IT 5	LDE core								4	9.46	0.437	3.2	7.59
IT 7	LDE core								4	9.46	0.437	3.2	7.59
IT 10	LDE core								2	9.46	0.393	1.6	4.46
IT 11	LDE core								2	9.46	0.393	1.6	4.46

Fig. 3 The grand test matrix

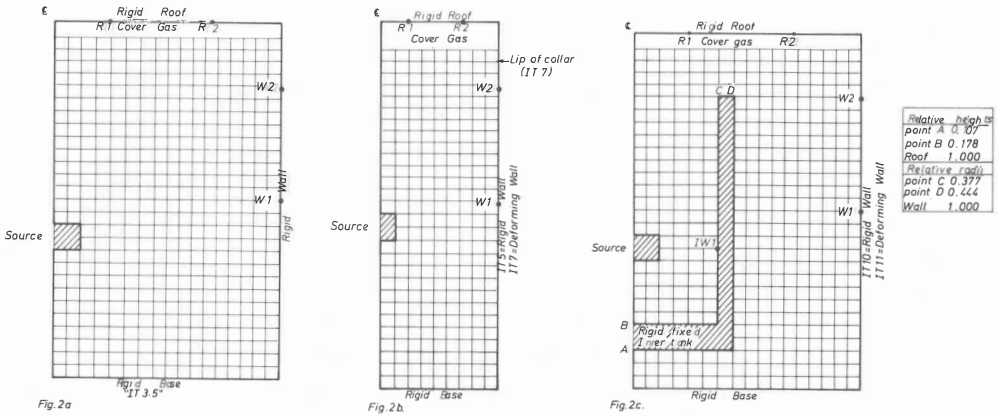

Fig. 2 Geometries and discretizations of test cases