

Sensitivity of LMFBR Containment Response to the Parameters of a HCDA Situation

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ABSTRACT

A synthesis of a lot of theoretical and experimental results is presented pointing out the sensitivity of some selected results to important parameters. A sensitivity study is defined for a real reactor size lay-out, which is now in progress ; a first result of the reference case is given.

1. INTRODUCTION

The consequences of a Hypothetical Core Disruptive Accident (HCDA) on a Liquid Metal Fast Breeder Reactor (LMFBR) containment were analyzed under various aspects in a lot of publications, namely in the previous SMIRT conferences. Experiments and associated calculations performed up to now provided much information on the influences of some parameters of such an accident and enabled the validation of the computer codes.

Much has been learned about the sensitivity to some parameters, but referring essentially to the results of explosion tests in small-size mock-ups and to calculations related to specific conditions for various reactor designs. A sensitivity study at reactor scale has been undertaken for a typical reactor lay-out by the CONT Working Group (subgroup of the Fast Reactor Safety Working Group of the Commission of European Communities).

The first part of this paper presents a tentative synthesis of the currently available theoretical and experimental results showing the sensitivity to some parameters. The second part defines the reactor lay-out to be used for the sensitivity study and gives preliminary results concerning the reference case from that study.

2. REVIEW OF THE SENSITIVITY TO THE MAIN PARAMETERS

Many reference documents were assessed [1] under CEC study contract and this has enabled trends to be deduced.

The investigated parameters can be classified into five groups, according to the relation to (a) calculation mesh and techniques, (b) fluid characteristics, (c) core bubble features, (d) structures, and (e) roof impact. There are also computer code aspects (3D/2D/1D, Eulerian/Lagrangian), but they are beyond the scope of this paper.

On the other hand, the main calculation or experimental results used as sensitivity criteria in the studies can be pointed out according to their frequency of use. They represent two main classes of phenomena : roof impact consequences and vessel deformation.

For loop or pool LMFBR, the most interesting loading parameters are not all the same ; even for one reactor type, specific design effects are possible.

The roof impulse is often the most useful result ; the vessel strain is considered at essentially two different levels : upper bulge and other maximum deflection points. The pressure on the roof is used as input to structure computer codes to check the strength of the roof and the supports ; in that respect, the displacements of roof and bottom structures are of interest. The distribution of energy in the various components has also been widely investigated. Other auxiliary results are the impulse on walls, some characteristic times (roof impact initiation, pressure pulses, maximum displacements, etc), cover gas behaviour, stresses and load forces as well as mesh distortion and other problems related to the computer codes.

Table I attempts to summarize the main results of the available parametric studies, gathering the significant qualitative influences of a series of 18 parameters on a selection of 12 results. For some cases, a clearly different behaviour is pointed out for small geometry tests and reactor size model calculations, because the chemical explosives used in scaled-down mock-ups do not accurately simulate an actual reactor HCDA. The criteria to evaluate the level of the influences (weak/medium/strong) refer to a relative evaluation for a typical parameter, but cannot be compared with each other i.e., the relative qualification is only valid inside a line of the table.

The main influences are summarized hereafter for the five groups of parameters :

- (a) - The fluid mesh size in computer code has a weak effect on the calculated roof impulse, but is significant for pressure histories ; a coarse mesh delays the roof impact.
 - The amplitude of the peak pressures can vary significantly according to the mesh regularization technique in Lagrangian codes.
 - Some Lagrangian code instabilities may be controlled by the use of an artificial pseudo-viscosity, but it must be cautiously selected to limit energy losses or internal energy accumulation in some fluid meshes and too much attenuation of mechanical loading.
- (b) - The fluid equation-of-state has a negligible influence.
 - The cavitation phenomena are important and should be considered. A pressure "cut-off" model is often used with P_{min} near zero.
 - There is a large influence of cavitation on the roof impulse for initial bubble pressures higher than 40 MPa, typical of mock-up experiments, but its importance is small for pressures lower than about 20 MPa, typical of reactor size models.
 - Sodium induces faster phenomena in comparison with water. Simple geometry calculations conclude that the sodium reduces slightly the impulse for a fixed roof, while other reactor size calculations show that using water results in lower central roof impulse at the late stage.
- (c) - Smooth, nearly spherical shape of the bubble makes the calculation easier ; an automatic "reshaping" can improve energy and mass balances, but tends to increase the roof impulse.
 - An increase of the bubble initial pressure below 10 MPa (typical of reactor cases) increases the roof mean impulse, while when it is above 20 MPa (more typical of simple mock-up geometries), the roof mean impulse slightly decreases.
 - The bubble equation-of-state has an important influence on the results. A slower explosive induces more energy absorption in a deformable roof, and less energy absorption in walls as well as a smaller extension of the wall upper bulge. With a rigid roof, there are opposite influences : the wall absorbs more energy and the upper bulge is greater. For the slow explosives, the fraction of energy release during the transient is smaller due to the primary containment reaction.
 - The excursion energy is a less sensitive parameter than the previous one. A reduction by a factor two for instance delays the roof impact and induces a lower roof impulse, but does not affect the roof pull down load of the walls, due to plastic deformations which limit the force transmission. The final energy distribution between wall, roof and bottom remains similar.

- (d) - For elastic materials, large differences in vessel shell modelling have no big influence ; for elastic-perfectly plastic ones, significant discrepancies are produced by slight model changes. A better agreement with experiments like COVA [2] was obtained with a deformable shell modelling for thin inner vessels and an elastic response model for the thick ones.
 - A decrease of the thickness of thin primary tanks reduces the roof impulse and the energy absorbed in the tank is slightly increased. The deformation axial profile changes : it is quasi-symmetrical for the thinner case while for a thicker one it is localized in the upper part and the deformation occurs essentially after fluid impact.
 - An increase of the strength of the bottom or roof causes more energy absorption by the walls and, generally, an extension of the wall upper bulge, but no systematic increase of the outer wall maximum displacement.
 - The presence of internal structures above the core delays the roof impact and reduces the roof impulse. On the other hand, the presence of radial inner structures reduces the impact delay and increases the central roof impulse. Inner structures generally absorb energy, reduce the outer vessel loading and the rate of energy release.
 - Specific experiments [3] simulating 3D aspects showed that non homogeneous radial structures do not result in large asymmetry of vessel strain or roof pressures.
 - The strain rate effect on the stress-strain law is mainly important for lateral wall deformations and roof impulse. Stiffer walls generally show reduced final hoop strain and increased impulse on the wall.
 - The modelling of porous materials and perforated structures has a medium effect on the impulses on the vessel components. Only the fluid motion around these structures is quite different.
- (e) - In simple geometry models, when the liquid slug height above the bubble is larger, the free surface becomes more sloped, the velocity radial distribution is less homogeneous and the mean impulse on the roof increases (for a given slug radius).
 - The height of the cover gas gap has no significant effect on roof impulse and wall strain in reactor conditions, due to the large gap size. For very small gaps in simple geometry tests, it is different : a gap height increase reduces the roof impulse and spreads out more widely the wall upper bulge.
 - Some problems remain for the "after impact" scenario in some designs, they refer namely to the simulation of the cover gas leakages at roof-wall junction, fluid peeling-off model from roof and also the leakages at plug seals.

3. SENSITIVITY STUDY AT REACTOR SCALE

Thanks to previously obtained similar results with different computer codes, a sensitivity study on a real reactor size model can be undertaken to evidence the importance of some specific parameters under reasonably realistic conditions and to evaluate the uncertainty level of some calculation results.

The study is restricted to a simplified model of a pool-type reactor. The lay-out is given on Fig. 1. The selection of parameters to be varied includes the six following ones : (a) energy content, (b) initial pressure of the bubble, (c) cover gas gap height, (d) roof mass, (e) steel yield stress for the shells and (f) steel plastic modulus for the shells.

Table II summarizes the selected reference values and the proposed variation range.

The energy content of the bubble and the initial pressure are essential features. The low γ -value (0.75) for the pseudo-adiabatic expansion reflects the behaviour of nuclear accidents.

The energy release strongly depends on the quasi-steady pressure which prevails after full expansion of the bubble. The energy release down to 1 bar is usually not achievable due to the limited available space inside the vessel. For the reference initial conditions (600 MJ, 10 MPa), the order of magnitude of the effective work released should be about 300 to 350 MJ.

The variation of the cover gas gap height is suggested to analyze the effect of the liquid slug height above the bubble in real reactor size conditions.

The reference case will consider a fixed rigid roof. Nevertheless, some sensitivity calculations could simulate a movable roof and a hold-down clamping system. In that respect, it is interesting to consider the sensitivity to the roof weight.

The internals proposed are oversimplified and the coupling of these with the outer vessel is not modelled realistically, but the approach will show the enhancement of the axial load when an inner vessel is modelled.

Standard mechanical properties of steel are used with a plastic modulus equal 2 % of the elastic modulus. As the plastic behaviour of steel is thought to have a large effect on the results, the plastic modulus should be varied in a reasonable range (+ 50 %). Sodium properties are defined for 500 °C. Cover gas is at 1 atmosphere initial pressure and follows an adiabatic equation of state. The parameter P_{min} refers to the cavitation model.

A sensitivity analysis procedure is necessary to reduce the total number of calculations. The proposed study considers the sensitivity of some integral and final results of the accident calculations to input parameters taking no time dependency into account. It intends to apply a non-linear methodology using first- and second-order coefficients in a polynomial development of the responses. This method was applied for some parameters of the Low Density Explosive equation-of-state related to the COVA tests [4]. For 6 input parameters, the procedure requires a minimum of 28 calculations instead of 64 for a systematic two-level analysis. A specific sequence of parameter variation will be followed.

A preliminary reference calculation was run by UKAEA to check the coherence of the reference data set.

A set of preliminary results obtained by the JRC/Ispra using the SEURBNUK code is presented on Fig. 1, till 250 ms (the fluid time step is 10^{-4} sec ; the step number is indicated for each plot). The evolution of the pressure field and the fluid motion appear clearly up to the beginning of fluid collapse. Roof impact occurs after 116 ms. Maximum cover gas pressure (~ 2.5 MPa) occurs at 140 ms. More detailed results will be described at the Conference.

REFERENCES

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- [2] C. ALBERTINI et al.,
The JRC-COVA Programme - Final Report,
EUR 8705-EN (1983).
- [3] J.A. BASSINDALE et al.,
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Paper E1/1 - 7th SMIRT Conference (1983).
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JRC Technical Note (1982).

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RESULT PARAMETER	ROOF IMPULSE	ROOF PRESSURE	ROOF DISPLA- CEMENT	BOTTOM DISPLA- CEMENT	WALL STRAIN (BUBBLE)	WALL UPPER BULGE	WALL IMPULSE	BOTTOM ENERGY	ROOF ENERGY	WALL ENERGY	ENERGY RELEASE	IMPACT TIME DELAY
FLUID MESH SIZE	W	M		M	M							M+
REZONING	W	M										
PSEUDO-VISCOSITY	M-	S						M(6)				
FLUID E.O.S.	=	=	=									
CAVITATION MODEL	S / W				M							
BUBBLE MODEL	M											
BUBBLE INITIAL PRESSURE	W- / W+											-
BUBBLE E.O.S. (SLOWER)	S+		S+	+	= ?	{ - + (3)		+	+	{ - + (3)	-	+
EXCURSION ENERGY	M+		M+	+		{ = ?		+	+	+		-
SHELL MODEL					{ M (4) S (5)							
PRIMARY TANK STRENGTH	+				M -					M -		-
STRENGTH OF BOTTOM OR ROOF	+				{ = or +	{ + or =		=	-	+		
INTERNAL STRUCTURE PRESENCE	- (1) + (2)			+ ?	-			=	-	-		+ (1) - (2)
SODIUM (INSTEAD OF WATER)	W- / W+		M -	=	=			=	=	=		-
STRESS/STRAIN LAW (HARDER)	S			S	S -		+					
POROUS MATERIAL MODEL	M				M							
LIQUID SLUG HEIGHT ABOVE BUBBLE	+											+
COVER GAS HEIGHT :												
{ SMALL	-		=	=	-			=	=	=		+
{ LARGE	W				W							+

LEGEND

W Weak influence.
M Medium influence.
S Strong influence.
= Practically no influence.
- Decreases } when the parametric feature increases.
+ Increases }
/ Separates the influences detected on small geometry tanks (left) from those obtained in reactor size models.

blank No information available

- (1) If Above Core Structure.
(2) If Radial Internal Structures.
(3) If Rigid Roof.
(4) For Elastic Material.
(5) For Elasto-Plastic Material.
(6) Influence on energy balance

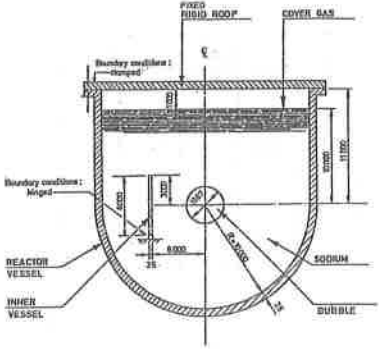
TABLE I - Main Isolated Results of Available Parametric Studies

- TABLE II -
Selected Parameters with Their Variation Range

Parameter Name	Preferred Value	Range	
Energy Content of the Bubble (MJ)	600	200	1000
Initial Pressure of the Bubble (MPa)	10	5	15
Cover Gas Gap Height (m)	1	0.5	1.5
Roof Mass (tons/m ²)	10	5	15
Steel Yield Stress (MPa)	105	70	140
Steel Plastic Modulus (GPa)	3	1.5	4.5

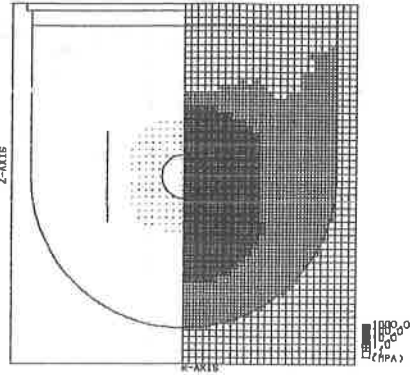
Fixed Parameters

Pseudo-adiabatic constant of the bubble : 0.75
Sodium temperature (°C) : 500
Initial cover gas pressure (MPa) : 0.1
Adiabatic constant of cover gas : 1.6
Sodium minimum pressure (P_{min}) : 0

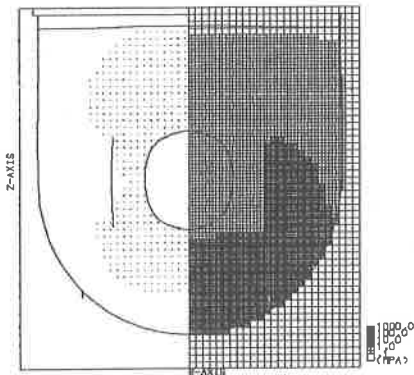


TYPICAL POOL TYPE LMFBR

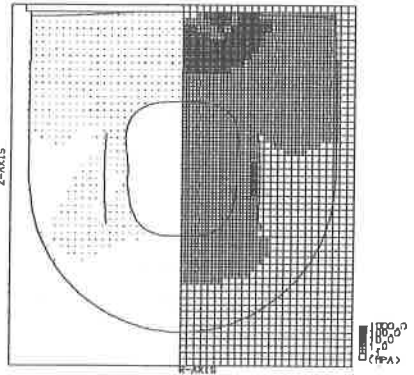
Fig. 1



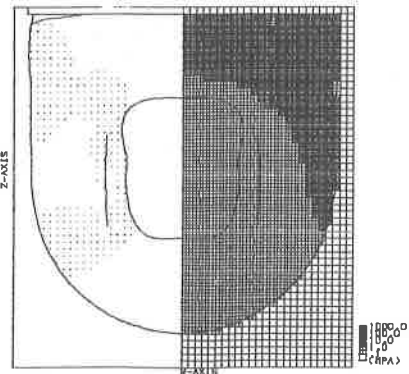
EEC4 HFR (HYPOTHETICAL FAST REACTOR)
STEP NUMBER 100 TIME (MICROSECS) 9999.0



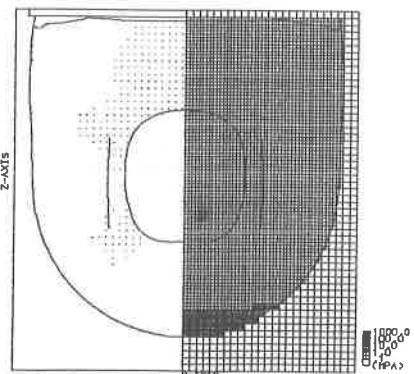
EEC4 HFR (HYPOTHETICAL FAST REACTOR)
STEP NUMBER 300 TIME (MICROSECS) 49999.1



EEC4 HFR (HYPOTHETICAL FAST REACTOR)
STEP NUMBER 1201 TIME (MICROSECS) 99999.9



EEC4 HFR (HYPOTHETICAL FAST REACTOR)
STEP NUMBER 1601 TIME (MICROSECS) 99999.9



EEC4 HFR (HYPOTHETICAL FAST REACTOR)
STEP NUMBER 2401 TIME (MICROSECS) 99999.9