Main Results of Activities Performed by the CEC LMFBR Containment Expert Group

W. Balz
Commission of the European Communities, Brussels, Belgium
J. Dufresne
CEA-FAR, Fontenay-aux-Roses, France

1. Introduction

The Commission of the European Communities (CEC) is conducting since many years activities in the nuclear field which are essentially related to nuclear safety. These activities are in line with the EURATOM Treaty and reply to Council resolutions by which the Commission was asked to prepare the harmonisation of safety criteria in the member States of the European Community.

This paper refers to an activity which the CEC performed during 1975-87 in the frame of the Fast Reactor Safety Working Group, a subgroup of the Fast Reactor Coordinating Committee which was set up in 1970 by the Council of Ministers with the mandate to stimulate coordination and cooperation in the field of fast reactors. It also shortly describes the prospectives of containment issues for the design of future reactors.

The Safety Working Group identified problems related to the integrity of the primary containment of fast reactors as an area in which a Community action would be particularly appropriate. It therefore decided to set up in 1975 a Containment Expert Group (CONT) with the mandate to contribute to outstanding containment problems on a Community level. This group had members from all EC countries involved in fast ractor development, i.e. representatives from research organisations, industry and licensing authorities.

As at that time core disruptive accidents were still considered as a design basis for fast reactors, the mechanical behaviour of the reactor tank under severe accident conditions was the main task of the group. Later the group's mandate was extended to include mechanical aspects of local sub-assembly accidents.

The CONT group also undertook some exploratory studies on phenomena related to the radiological source term, i.e. the formation and behaviour of sodium aerosols in the secondary containment following a sodium fire.

2. Primary Containment Studies

These activities fall under two main headings : 1) code validation, 2) code comparison and sensitivity analysis. In parallel a number of actions were carried out which are related to specific modelling problems, especially of fluid structure interaction.

2.1. Code Validation (COVA) (ref.1)

COde VAlidation (COVA) activities were carried out in national programmes and at the JRC-Ispra. The JRC COVA programme was followed more closely as the CONT group had an advisory function for the execution of this programme. The group also maintained close contacts with COVA activities performed in national research centres and discussed specific problems of containment modelling under severe accident conditions. The Commission supported these activities by a number of study contracts which were concluded with experts or national research organisations.

The rationale of the COVA programme is presented in fig.1. The objective was to provide data for the validation of computer codes that can be used to determine the response of the primary containment, i.e. the reactor tank, in the event of a hypothetical core disruptive accident (HCDA). A series of small scale model experiments were performed in national laboratories and at the JRC-Ispra. Phenomena of interest in this context are pressure wave propagation, coolant roof impact, fluid flow through obstacles and porous structures and elastic-plastic deformations.

The test series started with simple experiments consisting in rigid cylindrical tanks partially filled with water. The complexity was increased to reproduce the most relevant axisymetric features of both pool and loop reactor designs such as: deformable primary tanks, inner tanks of variable thickness and shapes, diagrids, neutron shields, dip plates and deflector plates.

Analysis of the predicted roof loading indicated that computed roof pressures were often quite different from the measured profiles. The calculated impulses were in good agreement with experimental values of the short vessel tests where the cover gas gap is small but they were generally higher for the long vessel tests where the gas gap is larger.

Differences between experimentally measured and computed strains in deformable vessels were observed. The final shape of the deformable vessel was usually well predicted and the overall behaviour of the axial strains was also well reproduced but the predicted hoop strains were usually low by about 25-35 % (relative strain) in the lower part of the vessel and sometimes significantly high in the upper part of the vessel.

Concerning the roof loadings, recent investigations indicate that pressure wave propagation in the cover gas and the junction between roof and tank can explain a significant part of the discrepancies observed. With reference to the strain discrepancies, this problem has not been completely explained. More recent studies have provided the evidence that the LDE (Low Density Explosive) equation of state was not correctly described.

From the COVA programme resulted suggestions for further research in a number of areas such as the theoretical treatment of fluid structure interactions, multiphase flow and material behaviour. Recommendations for further experimental investigations were made with regard to dynamic material behaviour and roof impact characterization.

2.2. CODE COMPARISON AND SENSITIVITY ANALYSIS

In 1983 when it was felt that the code development was sufficiently advanced the CONT group performed a comparative evaluation of containment codes available in the European Community. It included a critical analysis of the codes from the modelling point of view, benchmark calculations for a typical reactor case and a sensitivity analysis for the main parameters.

Code modelling comparison (ref.2)

The codes compared were: ASTARTE4, CASSIOPEE, PISCES, SEURBNUK, SEURBNUK/EURDYN and SIRIUS. Their characteristics are given in table 1.

The main features of the codes can be summarised as follows. The modelling approach in the various codes is rather similar. Rezoning facilities are included in all Lagrangian codes. Fluid structure interaction in particular on the roof structures was a subject of much development. Internal structures can be treated by all codes as well as porous structures.

The numerical treatments are also very similar in all codes. The equations solved are: conservation of mass, momentum and energy together with equations of state for materials, particularly fluids. None of the codes consider viscosity terms in the Navier-Stokes flow equation, although some numerical viscosity terms are added in Lagrangian schemes to aid stability. No thermal effects are modelled. Regions where this may not be true (within the core bubble) are accounted for in an uncoupled fashion in separate calculations defining bubble characteristics.

Benchmark calculations (ref.3)

The reactor lay-out for which the benchmark calculations were made is given in fig. 2. A pool type reactor has been chosen the details of which allowed a comparison of the most representative calculational results. The scale was representative for a large 1200 MWe reactor.

The reactor roof is represented by a rigid plate fixed to the ground and the top part of the reactor vessel is clamped to the roof. The effects of the internal structures have been schematically taken into account by the inclusion of a stainless steel cylindrical inner tank surrounding the core region. The lower part of this cylinder is fixed in vertical direction, but is free to move radially. Expanding fuel vapour as a core bubble was modeled by a polytropic equation of state. It was considered as an appropriate representation of a HCDA characterized by an energy release of 600 MJ and a core bubble expanding from an initial pressure of 10 MPa to a final quasi static pressure of 0.1 MPa. These assumptions were judged acceptable by the CEC Whole Core Accident Code (WAC) expert group, which has the mandate to investigate problems of severe accident analysis.

Table 2 summarizes the numerical results. The impulse history is illustrated in fig.3. Fig.4 shows the final shape of the main vessel predicted by all computer codes. The results must be evaluated taking into account the relevant differences between codes in discretisation and modelling (table 1), e.g.: membrane or full bending thin shell for the structural description, isotropic or mechanical sublayer to represent the strain hardening effects, gas bag or continuum for the cover gas and core bubble description.

It is difficult, if not impossible, to analyse separately the combined effects of these differences on the calculated results and to explain clearly the discrepancies in all the cases.

Except some results, e.g. the final axial displacements of the vessel nadir, the calculated values were in reasonable agreement. The spread of the scalar responses evaluated in terms of standard deviations ranges from 2% to 12% which has to be considered satisfactorily. It can therefore be said that all the computer codes have demonstrated an almost equivalent predictive capability.

Sensitivity Analysis (ref.4)

The analysis was performed with the code SEURBNUK/EURDYN for the same reactor layout as had been used for the benchmark exercise with the exception that the roof structure was represented by an elastic-plastic plate retained by an elastic-plastic hold-down system.

In order to limit the computer runs, the number of input parameters was limited to six, which were judged as most relevant with regard to their influence on the results, to cover existing physical uncertainties and different reactor design features. The parameters considered are listed in table 3 together with their nominal values and their range of variation. The range of variation of the parameters has been chosen according to the uncertainties of the actual value by engineering judgement.

The calculated results show that the code predictions do not exhibit pathological behaviour. Most important parameters are, in the order: the bubble energy, the plastic modulus of the vessel stainless steel, the cover gas gap and the yield stress of the vessel stainless steel. Most important response variations obtained from the parameter variation are: the maximum roof displacement, the maximum cover gas pressure, the roof impact time and the maximum strain energy of the outer vessel.

In general, the responses have shown a low sensitivity to the prescribed input parameter variations which is a reassuring outcome.

3. Other activities

Sodium Aerosols

Aerosols which might have formed in a sodium fire as consequence of a leak in the primary tank are a potential carrier of radioactivity. Their behaviour, in particular their deposition in the reactor building, prior to a possible release into the environment is of prime importance for the assessment of the radiological consequences of a severe fast reactor accident.

Two studies were undertaken: a comparison of codes and of aerosol measurement techniques.

The code comparison (ref.5) started from an analysis of the assumptions made with regard to the physical modelling and the mathematical treatment. In a second step calculations were performed for a reference case and also for several cases in which the parameters which deemed to be important or not well known were varied over a certain range. The codes used in this exercise were: ABC-INTG(Japan), AEROSIM(UK), AEROSOLS/A2 and B1 (both F) and PARDISEKO (D).

Generally speaking, the differences between the calculated results are minor (a factor of 2). The parameters that have a marked influence on the results were: collision factor and collision effectiveness, dynamic form factor.

More recently pretest calculations were performed for a sodium fire in a 400 m^3 vessel (CEA-Cadarache). The results from the different codes were in good agreement. As the fire did not produce aerosols at the rate foreseen, the calculations are presently repeated.

In an experiment (FAUNA facility at KfK) the various measurement techniques commonly used to characterise aerosols (impactors, spectrometers, sedimentation batteries, thermal precipitators, laser photometers, etc.) were compared (ref.6). The different methods were used simultaneously in five tests. It was concluded that the measurements of the mean diameters of the sodium aerosol particles and the standard deviations differed by 20% and 50% respectively.

4. Primary containment of future projects

In the current discussions on the safety approach to be applied to the next European fast reactor project (EFR = European Fast Reactor) which is jointly developed by several EC countries the design basis for the primary containment is a main issue.

Amongst other the energy release to be taken into account is a matter of discussion. The calculations of the primary containment behaviour under accident conditions will probably be performed with the code SEURBNUK which was developed and validated in the frame of the COVA activities. This code provides results which compare well with those of other containment codes.

5. Concluding remarks

During more than 10 years the CONT group has made a valuable contribution to the activities performed in the European Community in the field of primary containment loading and response.

These activities comprised also collaboration with non-Community countries, e.g. the USA in the APRICOT exercise and Japan for the aerosol code comparison.

The Commission appreciated very much the sucess of the CONT group which is the fruit of an effective collaboration between all members. This collaboration was characterised by an open exchange of information and the willingness to solve jointly open problems in the field of containment behaviour.

The CONT group was dissolved in 1987 after it had fulfilled its mandate. It was concluded that the codes existing in the EC countries to evaluate the behaviour of the containment under HCDA conditions had reached a state which allowed to answer satisfactorily the questions arising from fast reactor safety analysis. It has to be kept in mind that the determination of the containment behaviour constitutes only one element of severe accident analysis. Other elements are: the energy source term, the radioactivity release and the post accident heat removal. For a well balanced accident analysis it is necessary that the analytical tools used for the description of the various phenomena occuring during an accident have the same state of development and provide results with a comparable accuracy. From this point of view one can conclude that the containment codes available are not the weakest in the package of analytical tools.

The Commission sees in the achievements made by the CONT group an important contribution to fast reactor safety and to the harmonisation of the safety approach in the member states, a task which the Council assigned to the Commission.

REFERENCES

(1) C. ALBERTINI, ET AL.
"The JRC - COVA Programme, Final Report"
EUR 8705 EN

(2) V. WASHBY
"Comparison of the Containment Codes used in the Benchmark Exercise from modelling and numerical Treatment point of view".
EUR 11306 EN

(3) A. BENUZZI
"Comparison of different LMFBR primary containment codes applied to a benchmark problem"
EUR 10638 EN

(4) A. BENUZZI, S. MERLINI, A. YERKESS
"Sensitivity analysis of SEURBNUK/EURDYN predictions concerning a LMFBR primary containment problem"
EUR 10429 EN

(5) I.H. DUNBAR, J. FERMANDJIAN
"Comparison of Sodium Aerosol Codes"
EUR 9172 EN

(6) W. CHERDRON, C. HASSA, S. JORDAN, W. LINDNER ET AL.
"Intercomparison test of various aerosol measurement techniques"
EUR 9203 EN

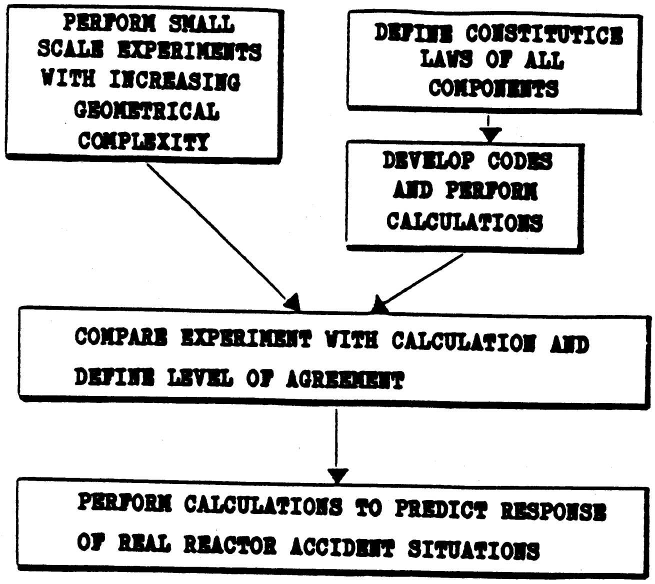

FIGURE 1 COVA APPROACH

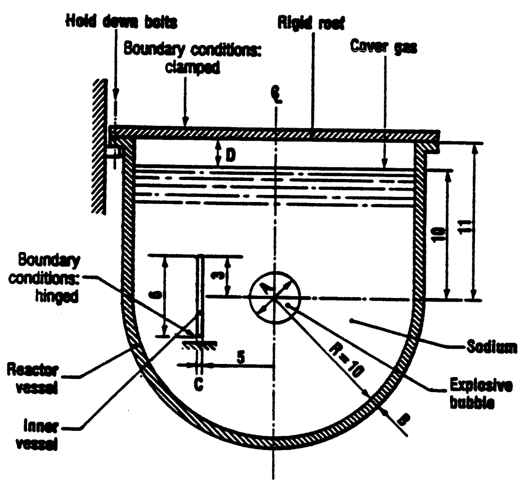

FIGURE 2

TYPICAL POOL TYPE LMFBR
FOR
«CONT» BENCHMARK CALCULATIONS
(Dimensions in meters)

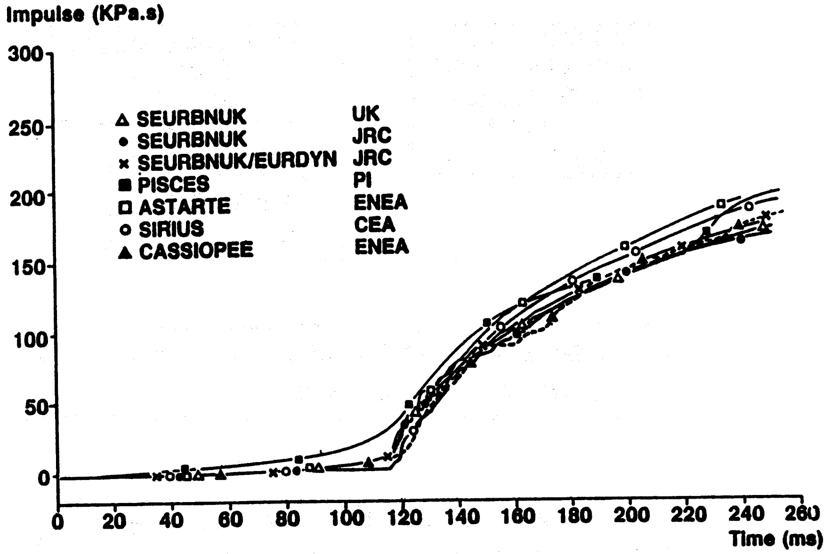

FIGURE 3 **CENTRAL ROOF IMPULSE VS. TIME**

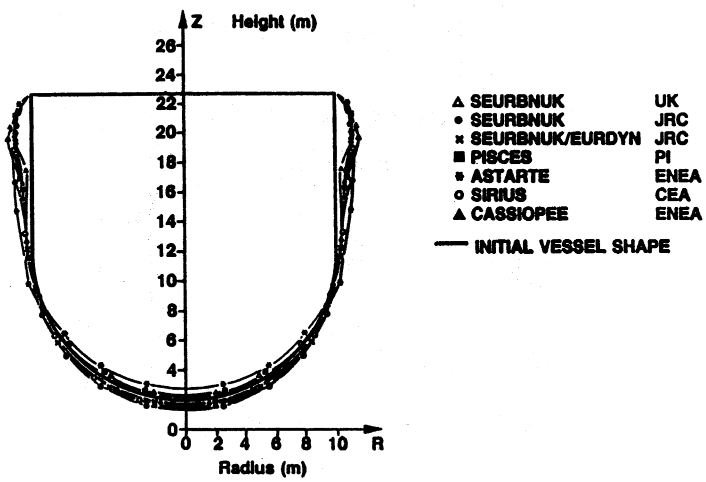

FIGURE 4 **FINAL VESSEL SHAPE**
(Deformations magnified by a factor 5)

COMPUTER CODE	ASTARTE-4B	CASSIOPEE	PISCES-2DELK	SEURBNUK	SEURBNUK	SEURBNUK/ EURDYN	SIRIUS
ORIGIN	UKAEA	CEA	PI	UKAEA-JRC	UKAEA-JRC	UKAEA-JRC	CEA
CALCULATOR	ENEA-BOLOGNA	ENEA-BOLOGNA	PI-GOUDA	UKAEA-RISLEY	JRC-ISPRA	JRC-ISPRA	CEA-CADARACHE
FLUID							
Model	Compressible/ Inviscid	Compressible/ Inviscid	Compressible/ Inviscid	Compressible/ Inviscid	Compressible/ Inviscid	Compressible/ Inviscid	Compressible/ Inviscid
Discretisation	FD	FD	FD	FD	FD	FD	FD
Description	Lagrangian	Euler/Lagrange	Euler/Lagrange	Eulerian	Eulerian	Eulerian	Lagrangian
Time integration	Explicit	Explicit	Explicit	Implicit	Implicit	Implicit	Explicit
Number of cells	22×39=858	18×30=540	21×44=924	26×55=1430	26×55=1430	26×55=1430	8×26=208
Time step (*)	16 - 6	35	55	100	100	100	60
STRUCTURE							
Model	Membrane (:)	Thin shell	Thin shell	Thin shell	Thin shell	Thin shell	Thin shell
Discretisation	FD	FD	FD	FD	FD	FE	FE
Time integration	Explicit	Explicit	Explicit	Explicit	Explicit	Explicit	Explicit
Number of segments	61	20	42	75	75	75	17
Number of layers	1	4	5	3	3'		5
Strain hardening	Mech. subl.	Isotropic	Mech. subl.	Mech. subl.	Isotropic	Isotropic	Isotropic
Time step (*)	16 - 6	35	55	20	20	20	60
FLUID/STRUCTURE							
Type of coupling	Weak	Strong	Strong	Weak	Weak	Weak	Weak
COVER GAS MODEL	Gas bag	Gas bag	Continuum	Gas bag	Gas bag	Gas bag	Gas bag
BUBBLE MODEL	Continuum	Gas bag	Gas bag	Gas bag	Gas bag	Gas bag	Gas bag

(*) Microseconds FD = Finite differences FE = Finite elements
(:) Only for the main vessel

TABLE 1 COMPUTER CODE OPTIONS AND MODELS

	SEURBNUK UK	SEURBNUK JRC	PISCES PI	ASTARTE ENEA	CASSIOPEE ENEA	SIRIUS CEA	SEURBNUK /EURDYN JRC	MEAN VALUE
Total roof impulse (MNs) at 150 ms	22.2	23.6	26.0	22.32	22.9	23.4	24.1	23.5
Total roof impulse (MNs) at 250 ms	48.1	52.0	52.7	49.8	54.7	52.1	53.8	51.9
Peak cover gas pressure (MPa)	1.9	2.5	2.5	2.1	2.6	2.5	2.44	2.36
Initial roof impact time (ms)	116	116	122	114	114	117	117	116.5
Impact velocity (m/s)	13.4	12.9	11.3	17.4	14.8	13.9	12.8	13.8
Vessel max. hoop strain (%)	3.7	3.4	2.9	4.3	3.3	3.3	3.15	3.44
Inner tank max. hoop strain (%)	2.2	2.5	2.8	2.2	2.1	2.7	2.32	2.40
Vessel max. strain energy (GJ)	0.182	0.219	0.220	0.219	0.186	0.173	0.201	0.200
Bubble max. energy release (GJ)	0.354	0.346	0.346	0.351	0.332	0.377	0.345	0.350

TABLE 2 RESUME OF COMPUTED RESULTS

Parameter		Nominal value	Range
Numb.	Name		
1	σ_1 Bubble energy (BEN)	600 MJ	200 — 1000
2	σ_2 Bubble pressure (BPR)	10 MPa	5 — 15
3	σ_3 Cover gas gap (COG)	1 m	0.2 — 1.8
4	σ_4 Roof mass (ROM)	100 MN/m^2	50 — 150
5	σ_5 Yield stress (YST)	105 MPa	70 — 140
6	σ_6 Plastic modulus (PLM)	3 GPa	1.5 — 4.5

TABLE 3 PARAMETERS CONSIDERED IN THE SENSITIVITY ANALYSIS