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LARGE SODIUM WATER REACTION CALCULATIONS IN A LMFBR STEAM GENERATOR

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RESUME :

The French approach to the analysis of large and violent sodium water reactions is presented. The basis for choosing the Design Basis Accident is discussed. An energetical analysis of the physical phenomena involved stresses the specific needs for computing tools. The feature of these tools are then described, and a validation test is presented. Finally, industrial applications are described.

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1. INTRODUCTION

In the past 15 years, the French approach to the comprehension, analysis and simulation of sodium water reactions in LMFBR's, has been twofold. In a recent paper (1), we described the R&D program which has been set up in order to understand and model the time behaviour of realistic leaks. Experimental and theoretical data accumulated thus far has provided sufficient information for the demonstration of the Steam Generator safety with respect to realistic water leaks.

In the present paper, we shall discuss the safety approach to large, hypothetical, sodium water reactions. The diagram presented in Figure 1 describes the logical chain of developments and calculations which has been followed for the SPX1 and SPX2 safety demonstrations. The following will be discussed :

- definition of the Design Basis Accident (DBA),
- Computer Code Developments,
- Computer Code Validation,
- Steam Generator and Secondary Loop design calculations.

2. THE DESIGN BASIS ACCIDENT

The different modes of heat exchange tube failure have been discussed in (1). They are :

- the self wastage of an initial crack, which tends to enlarge that crack and create an intermediate leak,
- creation of a secondary leak from the impingement wastage due to the self-wasted initial leak,
- creation of a secondary leak due to the swelling and bursting of a tube caused by overheating (see (2)).

The evaluation of the time characteristics of these phenomena has been obtained from a large number of experiments, and comparison with the response times of the safety devices installed on French LMFBR's shows that the water leak rate always remains smaller than the value corresponding to the Double Ended Guillotine rupture (DEG) of a heat exchange tube.

Thus, the Design Basis Accident chosen for the Safety Analysis of French Fast Breeders, is the Double Ended Guillotine rupture of a heat exchange tube occuring in one millisecond.

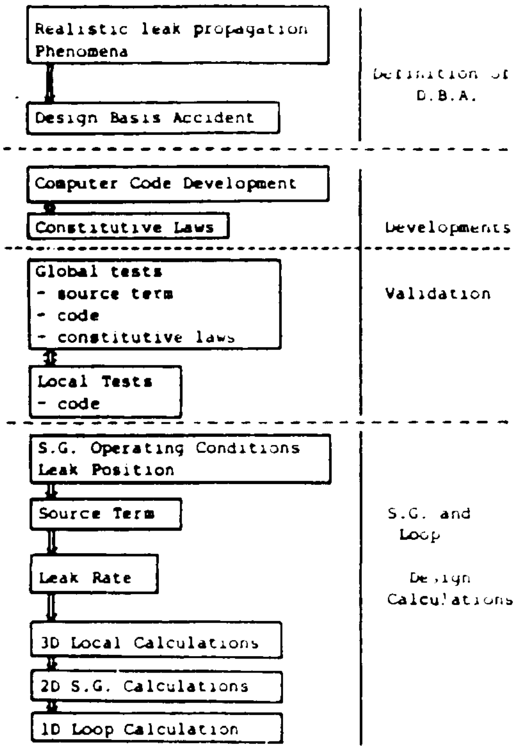


Figure 1 : The French Approach to sodium water reaction calculations

3. THE NEED FOR SPECIFIC COMPUTING TOOLS

The steam generators for Superphenix 2 are described in Reference 3 and presented in figure 2. The physical behaviour of a large sodium-water reaction during the first hundred milliseconds of occurrence can be described as follows :

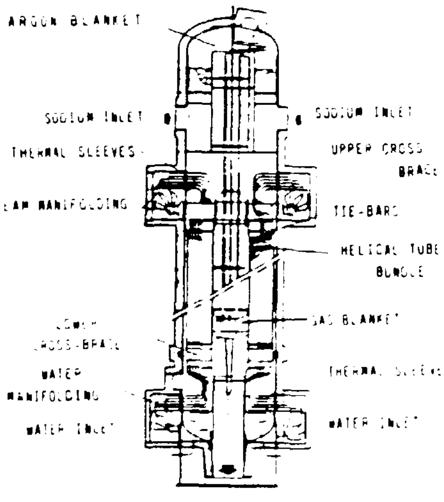
- the reaction between water and sodium creates hydrogen and sodium hydroxide. It is quasi-instantaneous and highly exothermic.

This leads to a fast local buildup of reaction gases which tend to compress the surrounding sodium, thus creating acoustic waves and large hydraulic displacements of fluid. This is the first step of energy transfer. Its characteristic time is around one millisecond,

- the second step of energy transfer is generally not taken into account for safety calculations : it covers all phenomena of heat transfer between the gas bubble and the surrounding medium (sodium, tube bundle and S.G. internal structures). These phenomena tend to reduce the internal energy of the gas bubble,
- the third step of energy transfer consists of the spatial propagation of pressure waves. Locally, due to the large dimensions of the steam generator, they propagate in a highly three-dimensional fashion. Further away from the reaction zone, the waves propagate in a two-dimensional fashion, and they finally become one dimensional when reaching the secondary loop. The propagation of waves in the steam generator is very anisotropic, due to the specific geometry of the helically wound tube bundle,

FIGURE 1

SUPERPHENIX 2
STEAM GENERATOR



- during this phase, some energy is lost from damping in the sodium, and some energy is transfered to the S.G. structures. Due to the combination of these phenomena (propagation, damping and fluid-structure interaction), the pressure peaks generated in the reaction zone are greatly reduced. Furthermore, a special device has been designed to dampen these peaks : it consists of a gas blanket located in the lower part of the steam generator, in a central location very close to the propagation path of the pressure waves. When a pressure peak reaches the free level of sodium, a negative peak is created, which contributes to reduce the overall pressure. Thus, it has been possible to obtain acceptable pressure peaks in the components of the secondary loop : the Pump and the Intermediate Heat Exchangers. This action is part of an overall cost reduction scheme,
- the fourth step of energy transfer has already been mentioned earlier : the dynamic interaction between the fluid and the surrounding structures enables those to acquire some energy, either as kinetic energy, elastic deformation energy, or plastic deformation energy. Of course, part of this energy (kinetic energy and elastic deformation) is transfered back to the sodium, after having been distributed throughout the whole structure : this phenomena enables for a large reduction of local peaks, as it distributes spatially their energy. Thus, fluid structure interaction has to be taken into account explicitly when analyzing the effects of a large sodium water reaction ; furthermore, all the structures whose location enables such phenomena to occur, have to be modelled explicitly :
  - . the tube bundle consists of eighteen radial layers of helically wound tubes, and is supported by a structure composed of vertical tie rods, screws and tube clamps. Effectively, this internal structure divides the bundle into 6 sectors which are partially independant in the azimuthal direction, for hydraulic and acoustic effects,
  - . the bundle surrounds a thick cylindrical shell which contains quasi-static sodium,
  - . the bundle is surrounded by a thin shell, called the "bundle envelope", which serves as a flow shroud. The ratio of thickness over diameter of this shell is very small. Thus, it moves quite freely, and large displacements occur when it is subjected to important dynamic loads,
  - . the bundle envelope is separated from the outer shell of the steam generator by a thin slice of flowing sodium. The steam generator outer shell and the bundle envelope are welded together above the bundle. In the case of a large dynamic load inside of the bundle envelope, this thin slice of sodium is compressed, dampens the movement of the bundle envelope, and transfers part of the reaction energy to the steam generator outer shell,
  - . the bottom of the steam generator has a complex structure which can be seen in Figure 2. Two important details should be singled out. First, it can be noted that, whereas the largest part of the sodium flow follows the central path around the vertical axis of the steam generator, a small portion of that flow is derived through the expansion bends zone, and flows back to the main stream through a thin annular region. Thus, there exist two possible paths for the propagation of acoustic waves, which have to be modelled carefully in order to obtain correct estimations of the pressure peaks travelling in the secondary loop. The second

point to be noted is the existence of the free level of gas already mentioned earlier. Its purpose is to attenuate all the pressure waves reaching the bottom end of the steam generator : thus, explicit and accurate modelling of its behaviour is necessary.

The needs for computational tools can be obtained from the previous description of the physical phenomena, the geometries and the material behaviours. In order to obtain a correct computation of a large sodium water reaction, a computer code should integrate the following features :

- fast dynamic analysis of solids and fluids, fluid structure interaction being taken into account explicitly. Analysis should be performed in 3, 2 and 1 dimensions,
- the formulation should take into account large displacements,
- detailed modelling of complex geometries should be possible,
- specific constitutive laws should be available for the local modelling of the sodium-water reaction and the tube bundle.

4. THE DEVELOPMENT OF PLEXUS

The French Commissariat à l'Energie Atomique developed the computer code PLEXUS, in order to model accurately physical problems involving fast dynamic behaviours.

A detailed description of PLEXUS has already been published elsewhere (5). Thus we shall just overview the main features of the code. PLEXUS is a general program for fast dynamic analysis, using the finite element method. It performs three, two and one dimensional calculations for fluids and structures and takes into account fluid-structure interaction (FSI). In general, the resolution in time is explicit, but in some cases an implicit method can be used.

A Lagrangian or an A.L.E. (Arbitrary Lagrange Euler) formulation can be used. The A.L.E. formulation is available for solving two and three dimensional problems. In the case of the Lagrange formulation an automatic remeshing is available. The formulation takes into account large displacements and large strains.

Specific developments were necessary for the realistic calculation of the consequences of a sodium-water reaction ; a specific constitutive law for the reaction medium has already been discussed (4) ; a constitutive law for the modelling of acoustic wave propagation in the tube bundle has been implemented. It is discussed below.

5. HELICAL TUBE BUNDLE HOMOGENIZATION TECHNIQUE

It has been shown (see (6)) that, the propagation of plane 1D waves in a tube (section S, length L) containing a tube bundle, and some fluid, is equivalent to the propagation of plane 1D waves in a tube (section S', length L') containing only fluid :

Pose :

$$x_L = \frac{\text{bundle pitch (direction of propagation)}}{\text{tubes external diameter}}$$

$$x_T = \frac{\text{bundle pitch (normal direction)}}{\text{tubes external diameter}}$$

Then :

$$\frac{S'L'}{SL} = 1 - \frac{\pi/4}{x_T x_L}$$

$$\frac{S'L}{LS'} = \frac{1}{x_L}\left[x_L - 1 - \frac{\pi}{2}x_T + \frac{2\,x_T^2}{\sqrt{x_T^2 - 1}}\ \mathrm{Arctg}\sqrt{\frac{x_T + 1}{x_T - 1}}\right]$$

By comparison to calculations with explicit modelling of the tube bundle, the above formulas have been shown to yield an excellent approximation of the wave propagation phenomenon.

The generalization of these relations to multidimensional problems is straightforward. As a result, and for each natural local direction I (radial, axial and tangent to the helical tube bundle), it is possible to define new physical properties for a homogenized fluid equivalent to the fluid + bundle medium :

- specific mass $\rho_I = \rho\left(\frac{L'}{L}\right)_I\left(\frac{S}{S'}\right)_I$

- sound velocity $C_I = C\left(\frac{L}{L'}\right)_I$

The resulting anisotropic fluid has been successfully implemented in PLEXUS for 3 and 2 dimensional problems.

6. THE VALIDATION OF PLEXUS

In the course of trying to validate PLEXUS for the analysis of large sodium-water reactions, two possible paths have been followed :

GLOBAL TESTS

A series of large tests has been devised, which cover the whole range of physical phenomena occuring during a large sodium-water reaction. Thus they necessitate the application of the entire chain of industrial calculations already presented in Figure 1 (water leak rate calculations, source term estimation, PLEXUS calculation with specific constitutive laws).

Such a validation test has already been presented else where (4,7) and results show a very good agreement between experimental and computational data.

LOCAL TESTS

In this category of tests, only one step of the chain of industrial calculations is being tested : namely, the PLEXUS computations. Thus, it was necessary to devise an experimental setup where the dynamic source would be perfectly known, thus allowing for immediate comparison between experimental and computational results.

Such a test had already been performed during the Superphenix 1 HCDA program : it is the MANON 11 test whose purpose was to present a 1000 MJ release in the core of SPXI [illegible] .

TEST DESCRIPTION

The MANON test vessel consists of a thin cylindrical shell (diameter : 360 mm, height : 380 mm, thickness : 1,25 mm) whose top and bottom ends are hermetically sealed by quasi rigid plates. The vessel is filled with water.

A spherical charge (diameter : 60 mm) made out of a well known potent explosive is located at the center of the vessel. This explosive is ignited at time 0. The shell deformations are recorded by a high speed cinematography process until the end of the experiment at time t = 2 ms.

COMPUTATIONAL APPROACH

Figure 3 shows the axisymmetrical meshing which was established. It comprises three parts :

- the spherical gas bubble,
- the water,
- the outer shell.

The top and bottom ends are assumed to be rigid. The 2D A.L.E. version of PLEXUS was used, thus enabling the meshing to "follow" the frontier between gas and water whilst being homogeneously modified over the water region. Thus, no mesh dimension is drastically reduced, and the calculation can be performed at low cost. Fluid Structure Interaction is modelled explicitly.

Figure 4 shows the modified meshing at time t = 2 ms, and Figure 5 indicates the calculated and mesured shell deformations versus time. There is an excellent agreement between the 2 sets of data.

Currently, more validation tests are being performed, most of them being concentrated on the 1D version of the code.

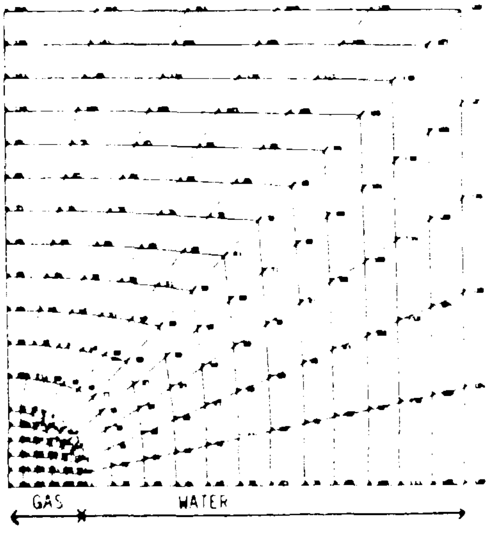


FIGURE 3 INITIAL MESHING

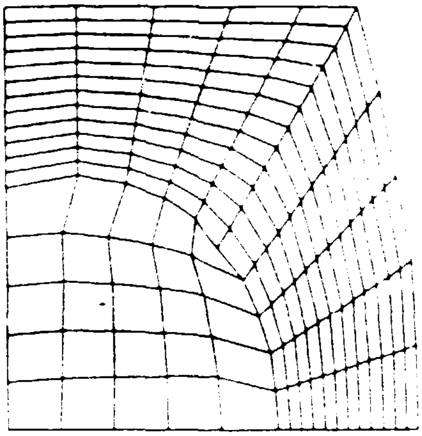


FIGURE 4 MESHING AT T = 2 MS

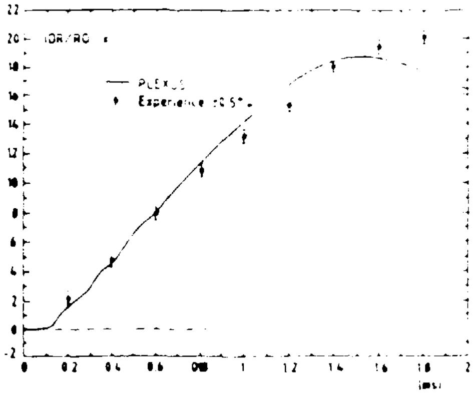


FIGURE 5 VESSEL DIAMETER VS TIME

7. THE INDUSTRIAL APPLICATION OF PLEXUS

PLEXUS is now currently used by CEA and NOVATOME for performing industrial calculations of large sodium-water reactions for the Superphenix 2 steam generators.

We shall present here an example describing how the pressure at the steam generator outlet is computed by making use of two coupled 3D and 2D models . the 3D model is used to estimate the local acoustical and mechanical behaviours in the neighbourhood of the reaction ; computed pressure loads at the boundaries of that model are then injected as boundary conditions in a 2D axisymetrical model of the bottom part of the steam generator. This calculation yields the pressure at the steam generator sodium outlet and the mechanical loads on the S.G. support structures.

The elements of these calculations are the following :

- leak location : the leak is assumed to occur in the economizer zone of the steam generator at full power, where, due to specific

thermodynamical conditions on the water side, the water leak rate reaches the highest possible value.
It is also assumed that the leak occurs on the most external layer of tubes, in order to maximize local mechanical consequences,

- source term : in order to maximize mechanical consequences, conservative hypotheses are used to estimate the source term (4),
- geometry of 3D model : Figure 6 represents the 3D meshing.
  It takes into account the following structures and fluids :
  . 3 cylindrical shells : the external shell, the tube bundle envelope and the central plenum shell. The external shell diameter is approximately 3 meters
  . the tube bundle supporting structures, which divide the steam generator into 3 sectors. These structures are modelled by specific finite elements which introduce a singular pressure loss, partial wave reflection and transmission, and a time delay in pressure wave transmission
  . the sodium in 3 regions (central plenum, tube bundle, and outer sodium slice between bundle envelope and steam generator outer shell). The bundle is modelled by means of the technique exposed in chapter 5
  . fluid-structure interaction is taken into account at all possible locations,

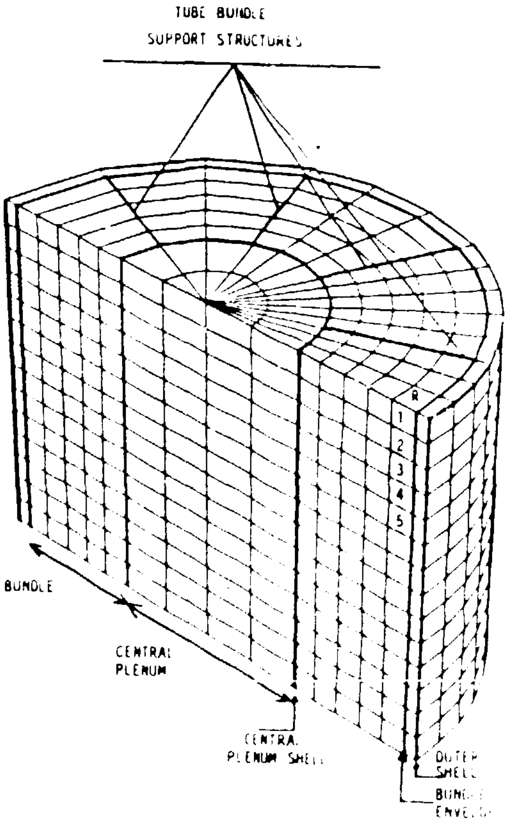


FIGURE 6 3 D STEAM GENERATOR MODEL

- formalism for 3D calculation : the formulation is Lagrangien for both the fluid and the structures,
- geometry of 2D model : Figure 7 represents the 2D meshing. Additionnally to the elements already introduced in the 3D model, one can note :
  . the bottom closure of the central plenum,
  . the free level of gas,
  . the central structure connected to the lower cross-braces,
  . the steam generator bottom head and support structures,
- formalism of 2D calculation : the formulation is Eulerian for the fluid and Lagrangien for the structures. Fluid structure interaction is taken into account, as is the tube bundle.

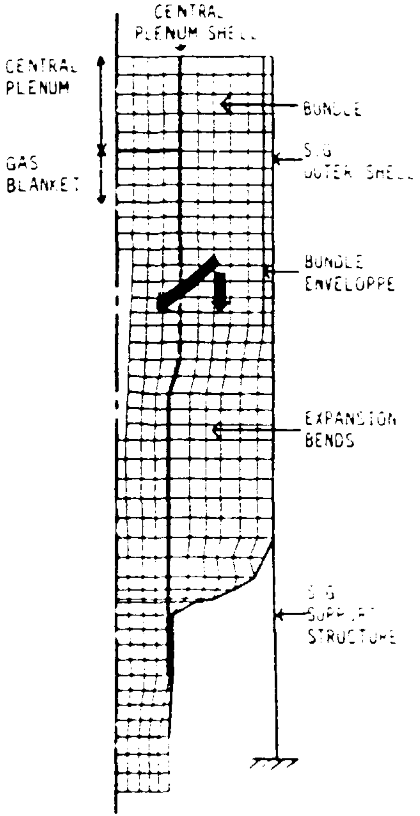


FIGURE 7 2 D S.G MODEL

Results : Figure 8 represents the pressures in the reaction zone, up to 5 milliseconds. The computed results show that the stresses, always remain in the elastic domain.

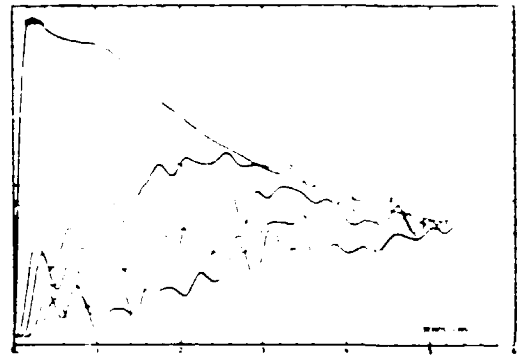


FIGURE 8 PRESSURES IN THE REACTION ZONE

MESH NUMBERS : SEE FIG. 6

8. CONCLUSION

The French R&D program for analyzing large sodium water reactions has reached two objectives :

- through large series of experimental results, the time dependant behaviour of a realistic leak has been estimated. Thus a conservative definition has been obtained for the D.B.A.,
- computational tools have been developed and validated which permit a realistic estimation of the mechanical consequences of a large sodium-water reaction.

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