The analysis of violent sodium-water reactions with PLEXUS

Ph.Finck
Novatome, Lyon, France
Present address: Argonne National Laboratory, Applied Physics Division, Ill., USA
Y.Blanchet
Commissariat à l'Energie Atomique, CEN Cadarache, DRNR, St-Paul-lez-Durance, France
M.Lepareux & B.Schwab
Commissariat à l'Energie Atomique, CEN Saclay, DEMT, Gif-sur-Yvette, France

1. INTRODUCTION.

The computer code PLEXUS (HOFFMANN et al. 1984) has been developped for performing dynamic analyses of transients with fluid-structure interaction in 1D, 2D and 3D geometries. For the past few years it has been widely used and validated for the assessment of steam generators behaviour in case of a sodium-water reaction in the French LMFBR projects Phenix, Super-Phenix 1 and Super-Phenix 2. The PLEXUS code has now replaced the 3D Eulerian hydrodynamic code VERSEAU previously used for SPX1 steam generators design and is able to tackle with most of problems encountered during pressure transients following a sodium-water reaction.

The purpose of this paper is to give a general survey of the different methodologies developped in the frame of safety and design calculations performed with PLEXUS including fluid-structure interaction effects, in order to obtain realistic loads on steam generators and secondary loops resulting in more economical designs.

The following are the major considerations covered in this paper : description of phenomena encountered during violent sodium-water reactions, development and validation of specific features in the PLEXUS code, steam generator and secondary loop design calculations.

2. PHENOMENOLOGICAL ANALYSIS OF VIOLENT SODIUM-WATER REACTIONS.

For large steam generators, four successive steps of calculation have to be performed for analysing the mechanical effects of a sodium-water reaction on the S.G. and the secondary loop of the reactor : $Na + H_2O \rightarrow NaOH + 1/2\ H_2 + Q$.

2.1. In close proximity to the leak, Q gives rise to a 3D propagation of acoustic waves and fluid displacements, creating asymmetric loadings on the bundle enveloppe and the S.G. outer shell with large fluid-structure interactions and large displacements of the shells.

2.2. Further away from the reaction zone the acoustic waves quickly become 2D axisymmetrical and travel up and down the steam generator ; they are partially attenuated when reaching the gas plenum on top of the steam generator.

2.3. Then the waves are 1D when reaching the intermediate loop and define a new loading for secondary pumps and intermediate heat exchangers.

2.4. Finally the gas bubble has sufficiently grown in the steam generator after a few tens of milliseconds to give rise to quasi-static pressure buildup in the loop.

According to the type of S.G. which is being analysed the transfer of chemical energy Q follows different paths :

- for the serpentine tubes, small diameter PHENIX steam generators, fluid-structure interaction has only secondary effects and energy is mostly concentrated in 1D acoustic pressure waves.
- for the helical tubes SPX1 and SPX2 steam generators (Figures 1, 2), which have complex internal structures, energy follows all possible paths : acoustic 2D and 3D waves, fluid-structure-interaction and mechanical waves propagation.
- for the straight tubes SPX2 steam generators (Figure 3) the energy paths are similar to those for the helical tube S.G. ; nevertheless, the outer diameter of the component being quite smaller, only 2D effects have to be considered.

In order to improve the analysis of those phenomena CEA has integrated in PLEXUS many salient features based on the needs of users for design and safety considerations :

- fast dynamic analysis of solids and fluids, with fluid-structure-interaction in one, two and three-dimensional configurations.
- a general formulation taking into account large displacements, large deformations, geometrical and material behaviour non-linearities.
- a detailed modelling of complex media such as helical or straight tube bundles is possible by making use of particular behaviour models.
- specific constitutive laws have been implemented in the code for the local modelling of the sodium-water reaction.
- specific finite elements for modelling bursting discs and bundle support structures and various features for treating the motion of piping systems in the presence of a fluid : connections between branches, varied boundary conditions, local singularities.

3. COMPUTER CODE DEVELOPMENT AND VALIDATION.

Originally PLEXUS performed 3D structural dynamic analysis and has been validated by comparison with the CASTEM system codes BILBO and TEDEL. Then a 2D axisymmetric version was developped for structural and hydrodynamic analysis and major features have been included for treating violent sodium-water reactions in LMFBR steam generators.

The 3D and 2D versions are now available with Lagrangian, Eulerian or A.L.E. (Arbitrary Lagrange Euler) formulations. Several validations involving fluid-structure interactions during pressure wave transients have recently been performed for the 2D version. Some of them, such as the MANON test (figure 4) or the BA-11 sodium-water reaction experiment (figure 5) have already been described elsewhere (SCHWAB B et al. 1985, FINCK P et al. 1984). Two other sodium-water reaction tests, SI 1-5 and CL 6, performed at CEA Cadarache, have produced data for validating the PLEXUS 2D version. In the latter the reaction was initiated by the guillotine rupture of one tube filled with vapour instead of water : figure 6 shows that the pressure peaks in the first 8 milliseconds are predicted with a good accuracy in the plane of the reaction.

In a third step it was necessary to develop a 1D version of PLEXUS in order to assess the loadings in secondary circuits after a sodium-water reaction. The first stage consisted of implementing a pure hydrodynamic

1D code in which the pressure waves propagation was validated by comparison to data obtained from INTERATOM for validation of HEINKO and ROLAST codes.

These experiments account for elastic and plastic interactions of pressure waves in more or less complex tube geometries filled with water: straight tubes, elbows, reservoirs. PLEXUS calculations are still under way but the first results show a good prediction of acoustic waves in 1D geometries.

In a second stage a 1D structural possibility was coupled to the 1D hydrodynamics to account for fluid-structure interaction, motion of fluid due to moving pipes and deformation of the pipe walls. A tube whip experiment performed at CEA Cadarache has been interpreted using an uncoupled approach (MILLARD A et al. 1985) : first the dynamic pressure in the ruptured pipe was evaluated with PLEXUS, assuming the motion of the pipe would not change significantly its value, then this pressure was introduced in TEDEL code for calculating the mechanical response of the pipe. The effects of an elbow and of phase change (vaporization) were taken into account in the PLEXUS pipe model. However, the coupling between fluid and structure being too weak in these experiments, additional data are needed to provide with a complete validation of the 1D PLEXUS code.

4. INDUSTRIAL APPLICATIONS.

4.1. 1D calculations (Phenix steam generators).

In case of a sodium-water reaction in Phenix the growth of the reaction bubble is reduced by the size of the steam generator. In order to assess the loadings after one tube guillotine rupture a 1D-Euler PLEXUS calculation has been performed : the steam-water leak rate is obtained by modeling the 2-phase steam-water flow in the tube and taking into account, at each time step, the strong hydrogen bubble counterpressure which reduces the leak rate (figure 7). In the same coupled calculation the leak rate is injected in the 1D pipe representing the S.G.-module and gives rise to a sodium-water reaction.

4.2. 2D straight tube steam-generator calculations.

The current conception of SPX2 straight tube S.G.'s comprises in the top and bottom sodium phenums a complex structure, named "thermal protection", which serves as a thermal baffle for the top and bottom tube plates. It consists of a thick circular plate, perforated for each individual tube, and a U-shaped support skirt (figure 8).

In case of a violent sodium-water reaction occurring right under the thermal protection, an important axisymmetrical pressure peak is applied to its lower face (figure 9). Thus large displacements can be observed. Safety criteria impose that the displacements are small enough to avoid mechanical failure of non leaking heat exchange tubes.

4.3. 2D and 3D helical tube steam generator calculations.

The pressure at the SPX2 steam generator sodium outlet and the mechanical loads on the S.G. support structures have been estimated in case of a sodium-water reaction by making use of a 3D calculation followed by a 2D axisymmetrical calculation both performed with PLEXUS Lagrangian version (see Fig. 10 and FINCK P. et al. 1986 for the detailed description of these models). The pressure loading in the 2D calculation is issued from the 3D model and is supposed to be applied at the six top meshes of figure 10.

Figure 11 shows that the calculated sodium pressure in the vicinity of the reaction are of the same order of value as the initial pressure source and that the pressures reached at the sodium outlet are less than 5 bar which, compared with the 18 bar of the reaction pressure, stresses on the efficiency of the free level to reduce the pressure peaks in the S.G. lower end. In this 2D calculation stresses in the S.G. support skirt have also been evaluated. This calculation has been followed by a 1D-PLEXUS calculation in order to assess the consequences of pressure waves propagation in the secondary sodium circuit and to make sure of the integrity of the intermediary heat exchanger.

5. CONCLUSION.

PLEXUS code developments and validations have now reached a stage which permits answering most of safety and design questions in case of violent sodium-water reactions in LMFBR steam generators. Up to now it has shown efficient for any kind of French S.G. designs (Phenix, Super Phenix 1, Super Phenix 2). Also, accounting for fluid-structure interaction in PLEXUS has helped reduce the conservatism of previous evaluations.

REFERENCES.

FINCK P., BLANCHET Y., LEPAREUX M., SCHWAB B. 1986. Large sodium-water reaction calculations in a LMFBR steam generator. The science and technology of fast reactor safety. Guernsey U.K.

HOFFMANN A. et al. 1984. PLEXUS, a general computer program for fast dynamic analysis. Conference on structural analysis and design on nuclear power plant. Porto Alegre, Brazil.

MILLARD A., JAMET P., LIEUTENANT J.L., SCHWAB B., GOETSCH D. 1985 Whip analysis of guide-pipes of instrumentation below PWR vessels. 8th SMIRT Brussels, Belgium.

SCHWAB B., FINCK P., BLANCHET Y., LAPICORE A. 1985. Three-dimensional sodium-water reaction calculations with fluid-structure interaction for LMFBR steam generators. Third international conference on boiler dynamics and control. Harrogate, U.K.

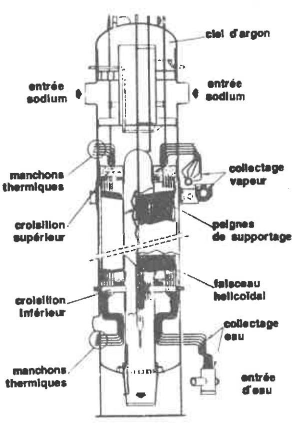

Fig.1 GENERATEUR DE VAPEUR SUPERPHENIX 1

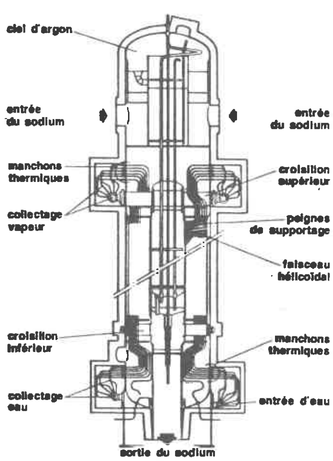

Fig. 2 GENERATEUR DE VAPEUR SUPERPHENIX 2

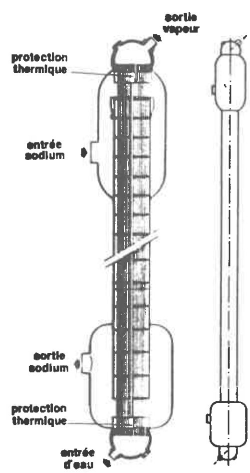

Fig.3 GENERATEUR DE VAPEUR A TUBES DROITS

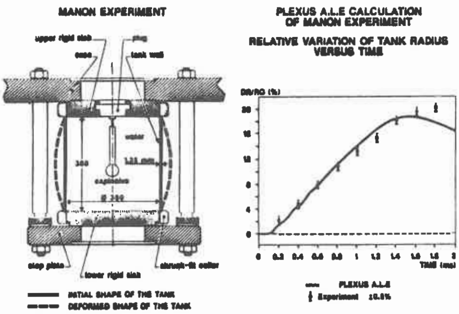

Fig.4 MANON EXPERIMENT: MEASURED AND CALCULATED WALL DISPLACEMENT HISTORY

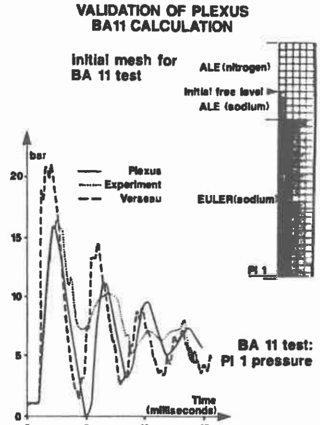

Fig.5 SODIUM-WATER REACTION BA 11 TEST: CALCULATED AND MEASURED PRESSURE HISTORY

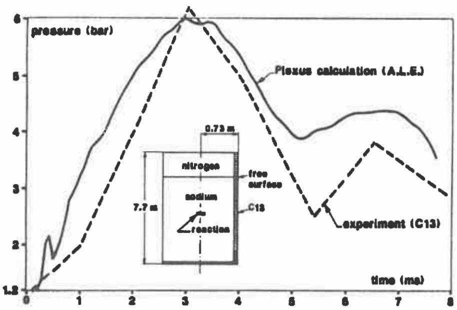

Fig. 6 CL6 SODIUM-WATER REACTION CALCULATION : COMPARISON OF PLEXUS WITH THE EXPERIMENT (pressure in sodium at reaction level)

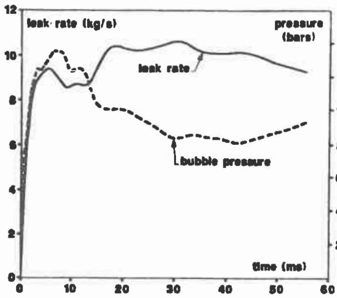

Fig. 7 PHENIX EVAPORATOR 1 TUBE GUILLOTINE RUPTURE : LEAK RATE AND BUBBLE PRESSURE

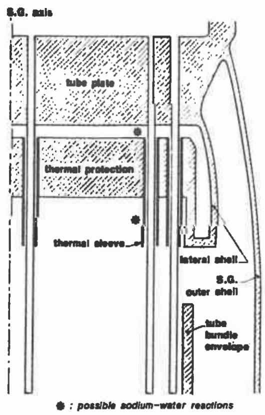

Fig. 8 STRAIGHT TUBE STEAM GENERATOR : UPPER END

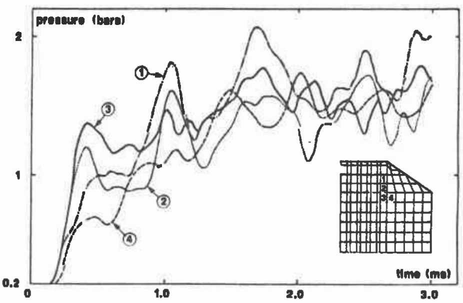

Fig. 9 STRAIGHT TUBE STEAM GENERATOR MODEL: CALCULATED PRESSURES

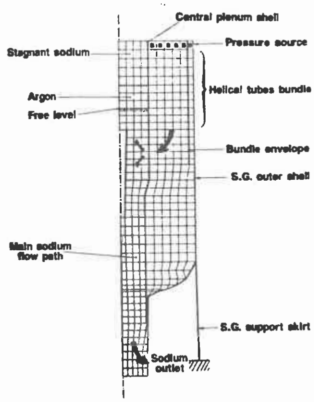

Fig. 10 2D STEAM GENERATOR MODEL

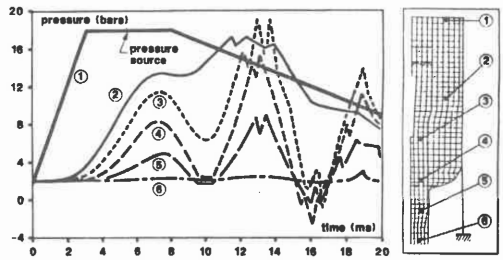

Fig. 11 2D HELICAL STEAM GENERATOR MODEL (LOWER END)
PRESSURES ATTENUATION IN SODIUM OUTLET REGION