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Modelling of water leakage effects in fast breeder reactor steam generators

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ABSTRACT : The prediction of damage liable to be brought about by a water-sodium reaction jet is major avenue of research for the safety of sodium-cooled fast breeder reactors. The first part of this study consists in modelling the phenomenon of erosion-corrosion -commonly known as wastage- as it occurs on inpact of a water-sodium jet following a water leak in a steam generator. The aim of the second part is to characterize the products resulting from the water-sodium reaction jet.

1 INTRODUCTION

The effect of any loss of tightness in the heat exchanger tubes of fast breeder reactor steam generators is a water-sodium reaction whose consequences for safety and the availability of the facility can, in the absence of any protection (hydrogen & accoustic detection systems), prove to be considerable.

The postulated incident begins with the existence or the creation of an initiator fault, generally a crack which, in view of the chemical affinity between sodium and water, creates a reaction area. The flaw is then subjected to auto-erosion leading to an enlargement of the leak, which in turn brings about damage by the removal of material from neighbouring tubes, due to the action of the erosion-corrosion phenomenon. Penetration of the target tubes can then occur and hence give rise to further leaks. These leaks, with their greater steam flow rate, would cause a high temperature rise of the tubes subjected to the reaction jet resulting in their swelling and then bursting under the combined effect of the pressure in the tube and temperature.

2 STUDY BACKGROUND

Extensive theoretical and experimental means were devoted to the study of the water-sodium reaction by the Commissariat à l'Energie Atomique ; their main objective was to improve knowledge and understanding of the phenomena linked to the appearance and propagation of water leaks in steam generartors. The modelling that ensued has been, moreover, a contribution of major importance :

1. for the designer, for the definition of economical and safe devices, while ensuring the tightness of the secondary cooling system for any type of accident,
2. for the operator, for better knowledge of the consequences of leaks, thus limiting the unavailability of a steam generator after a water-sodium reaction.

The CEA has developed, with Electricité de France co-funding, the PROPANA computer code, designed to describe the propagation of leaks and their consequences. PROPANA is a two-dimensional program that represents leak auto-evolution phenomena, damage by erosion-corrosion (wastage) and the creation of secondary leaks by perforation of neighbouring tubes. The code comprises, among other things, the PERCEVAL module, that models the damage of tubes subjected to wastage by the reaction jet, and the HYDET module, that models the responses of the detection system for hydrogen present in the steam generator sodium.

The aim of the present study is a more thorough understanding of the water-sodium reaction jet in order to document the two PROPANA computer code modules, PERCEVAL and HYDET.

3 PARAMETRIC MODELLING OF THE IMPACTS CAUSED BY WATER JETS IN LIQUID SODIUM ON METALLIC TARGETS

3.1 *General remarks*

The phenomenon of tube erosion-corrosion due to the effect of a water-sodium reaction jet is known as wastage.

Since 1978, the CEA and EDF have carried out an analytic study with the aim to improve wastage velocity models (depth of material removed per unit of time). Two facilities were developed in order to implement this programm : JONAS (University of Poitiers, France, 1981-1990) and SUPER-JONAS (CEA, Cadarache, France, 1986-1990).

360 wastage pits were thus achieved on plane targets under various jet thermal-hydraulic conditions (Table 1). The different pits observed made it possible to define two types of wastage : central wastage and toroidal wastage (Figure 1).

An analysis of experimental results thus obtained enabled the parametric computer code PERCEVAL to be set up, the first version of which was published in 1987 by Ph. Hobbes.

3.2 *PERCEVAL 7 damage laws*

The formalization of PERCEVAL 7, whose variations as a function of *x* are illustrated in Figure 2, is as follows :

(1) Central wastage : $$w_c = w_{cM}\left(\frac{x-x_2}{x_{cM}-x_2}\right)^{N_c} \exp\left[N_c\left(1-\frac{x-x_2}{x_{cM}-x_2}\right)\right]$$

(2) Toroidal wastage : $$w_t = w_{tM}\left(\frac{x}{x_{tM}}\right)^{N_t} \exp\left[N_t\left(1-\frac{x}{x_{tM}}\right)\right] f(x)$$

(3) Outer diameter : $$\frac{d_e}{S_0} = \frac{A}{\sin(\theta)}\left(\frac{x}{d_0}\right)^B$$

(4) Torus diameter : $$\frac{d_t}{S_0} = \frac{A}{\sin(\theta)}\left(\frac{x}{B\, d_0}\right)^C \exp\left[C\left(1-\frac{x}{B\, d_0}\right)\right]$$

where $f(x)$ is a function that limits the toroidal wastage to x_{3b}. S_0 represents the cross-section of the injector.

w_{cM}, w_{tM}, x_{cM}, x_{tM}, x_2, x_{3a}, x_{3b}, N_c, N_t, A, B and C are expressed as a function of the experimental parameters thanks to a certain number of coefficients determined by Rosenbrock's method (1966).

PERCEVAL 7 has been qualified statistically by means of both the JONAS - SUPER-JONAS data base and an international data base constituted by points from the literature (911 points).

3.3 *Application to SUPER-PHENIX and European Fast Reactor*

To illustrate the qualification of PERCEVAL 7, the model's predictions were compared to characteristic points of the SUPER-PHENIX and EFR (K. Föster 1990) steam generators These points are of particular importance for the safety analyses of these facilities since they are typical of the thermal-hydraulic operating conditions of the steam generators (Figure 3).

The results provided by PERCEVAL 7 are satisfactory as demonstrated in Figure 4 in which the model's predictions (in the form of a maximal law) are compared to the experimental points as a function of the water flow rate at the break.

VARIABLES		EXPERIMENTAL FIELD
d_0	diameter of the injector (mm)	from 0,7 to 1,4 mm
θ	impigment angle of the jet (deg)	from 20 to 90 deg (J) & 90 deg (S-J)
x	injector-target distance (mm)	from 1 to 75 mm
t_{Na}	sodium temperature (°C)	from 300 to 600°C
p_{Na}	sodium pressure (bar)	atmospheric pressure
u_{Na}	sodium velocity (m/s)	static sodium
t_{Eau}	water temperature (°C)	from 250 to 600°C
p_{Eau}	water pressure (bar)	from 6 to 13 bar (J) & from 10 to 180 bar (S-J)
m_0	water flow rate at injector (g/s)	from 0,4 to 17 g/s
$\bar{x}_{Eau}$	steam quality	1 (vapour phase)
–	target material	alloy 800, ferritic steel or stainless steel

Table 1. Experimental conditions of the tests performed in JONAS and SUPER-JONAS

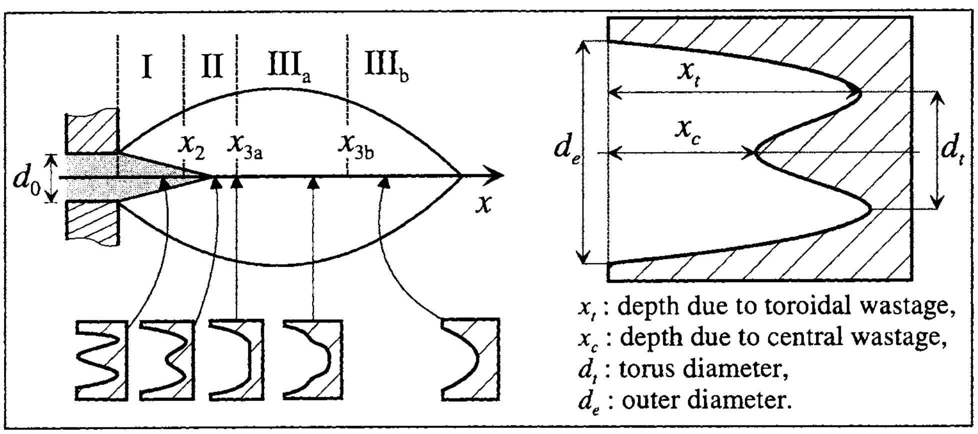

Figure 1. Wastage pits observed and types of wastage

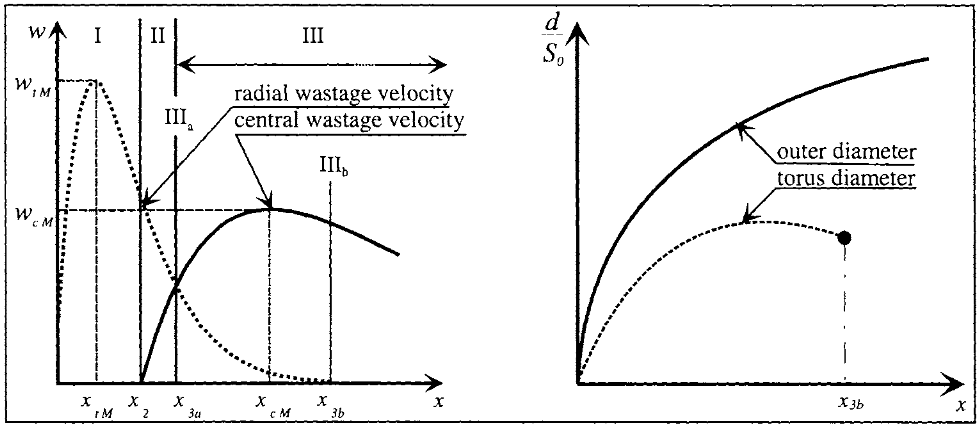

Figure 2. Variations of PERCEVAL 7 formalization versus x

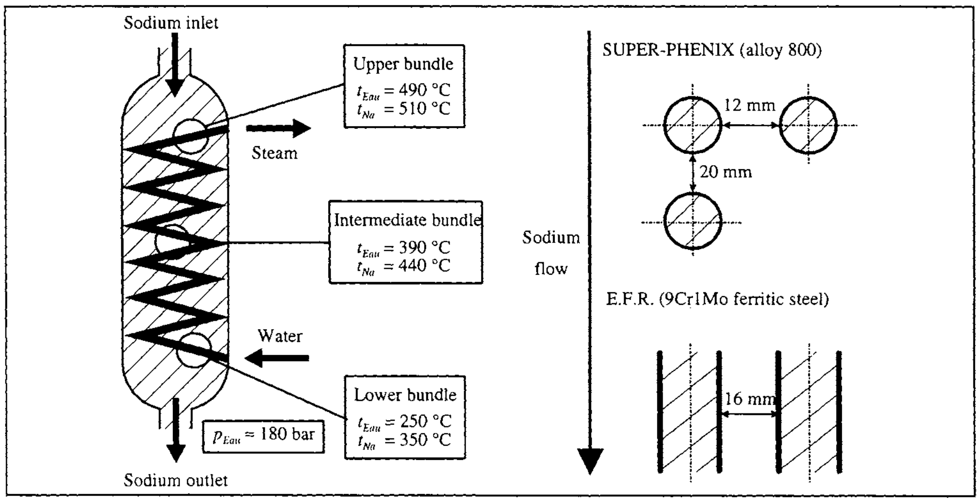

Figure 3. Thermal and material characteristics of steam generators

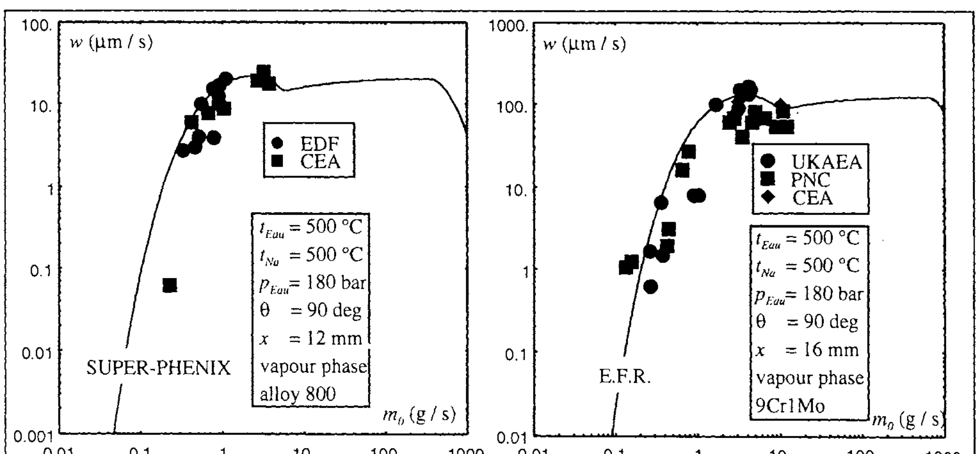

Figure 4. Comparaison of PERCEVAL 7 with SG upper bundle characteristics

4 CHARACTERIZATION OF THE PRODUCTS FROM THE REACTION JET

4.1 *Presentation*

The MEPHYSTO tests (Measurement of the hydrogen percentage present in the sodium and the oxygen content) were performed by the EDF Studies and Research Department at Chatou (France) from july 1990 to august 1991.

The aim of the tests was to gain more accurate knowledge of the decomposition kinetics of sodium hydroxide in circulating liquid sodium, the dissolution kinetics of hydrogen gas in the same medium and the percentage of products generated by the water-sodium reaction jet.

The test loop (Figure 5) consisted of a 'piston' reactor constituted by a tube 82 mm in diameter and 93 m long in which sodium circulated in isothermal regime.

Injections of liquid sodium hydroxide, hydrogen gas or water vapour were made.

The evolution of the concentrations of hydrogen present in sodium was monitored by six sensors located at regular intervals in the circuit, whose principle was based on the diffusion of the hydrogen through a nickel membrane.

4.2 *Modelling*

The experimental system was a closed loop with recycling and transient injections of co-reagents. The soda, hydrogen gas and water vapour were injected at constant flow rates during a shorter period time than the circulation time of the sodium in the loop in order to avoid mixing of fresh and partially converted reagents.

The hydrogen detectors essentially showed diffusional resistance to the transfer of the hydrogen and could be treated in transient operating conditions as linear systems ; their operation was thus analysed and their transfer function established.

The transfer functions relative to the evolution of the soda and the hydride were also established, the sodium-soda reaction velocity being considered as reversible or non reversible ; the reactor was considered as a cascade of perfectly mixed reactors. This hypothesis was justified by the turbulent Peclet's number of the section concerned (J. Villermaux 1993). The order of the reactions was considered as equal to one in all cases (linear treatment).

The sodium-hydrogen reaction was treated in the same way but was considered as irreversible.

The transfer functions of the closed loop system were established.

The parameters of the models were defined by means of the two-measurement method (Aris) which consist in using the ratio of the Fourier transforms of the responses of two successive measurements. Inversion by fast Fourier transform and comparison with the model allowed the parameters of the model to be defined by means of the Rosenbrock's method.

4.3 *Results*

The results concerning the decomposition constant for the soda appear to be coherent, but present values about 400 times greater than the mean of the results in the literature, with half-life times of the order of a second.

The dissolution kinetics of the hydrogen gas in the sodium is difficult to establish insofar as the hydrogen flow rate is not accurately known, and the same is true of the diameter of the injected bubbles. A simple model of bubble disappearance, however, involving a hypothesis concerning the initial diameter of these bubbles, enabled these results to be utilized, and led to a dissolution velocity that was significantly lower than the velocity predicted by A.C. Whittingham (1976).

The overall balance made on hydrogen carried out by steam injections gives satisfactory results.

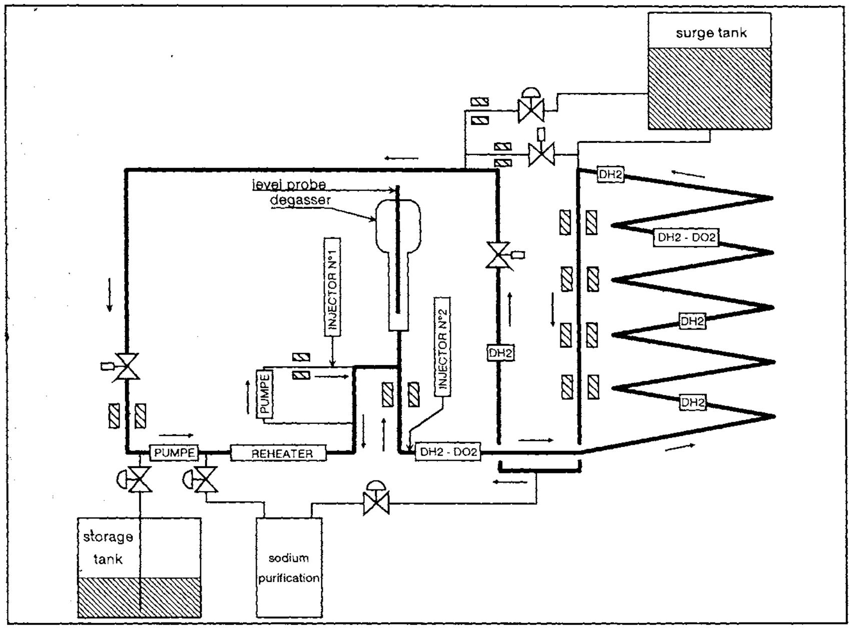

Figure 5. The MEPHYSTO test circuit

5 CONCLUSION

The PERCEVAL 7 model has significantly advanced the prediction of wastage since, for the first time, accurate three-dimensionel calculation of the damage is possible.

Analysis of the MEPHYSTO tests has been allowed the formation of products generated by the water-sodium reaction to be characterized with greater accuracy.

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