

2. TWO CONCEPTS OF STEAM GENERATORS FOR FAST REACTORS COOLED BY LIQUID SODIUM

Two concepts of steam generators for LMFBR's are known (from the viewpoint of liquid sodium flow):

1. The liquid sodium flows at the shell side, outside the heat transferring tubes.
2. The liquid sodium flows inside the heat transferring tubes.

2.1 Steam generators with sodium at the shell side

Steam generators used at power plants BN 350 and BN 600 in Russia, Super Phoenix in France are some examples of those with sodium at the shell side. The water and water steam flow inside the heat transferring tubes.

2.2 Steam generators with sodium flow inside the tubes

Steam generators with sodium flow inside the heat transferring tubes and water/steam at the shell side have been called inverse steam generators. This inverse design proves to be very preferable from the leakage viewpoint because the evaluation of the tube wall damage is, as a rule, uncomparably slower and qualitatively different to the steam generator types where water flows inside the tubes [3].

Hydraulic characteristics of leaked tube change in time because sodium-water reaction products deposit at the tube inner surface. Therefore the tube cross section for sodium flow reduces in time and tube hydraulic resistance increases in time.

Three types of flow conditions in leaked tube could occur [3,4]:

a) Passage conditions characterized by a steady state flow rate of sodium above the leak position and of sodium and reaction products mixture below the leak position. Damage process of the tube target wall is similar to that of tube walls if the steam generator with sodium at the shell side is leaked.

b) Expulsion conditions characterized by a separation of both reagents water and sodium and by expulsion of sodium from leaked tube by a hydrogen bubble. In such conditions no damage of target tube wall and no leakage growth have been experimentally observed.

c) Pulsation conditions occur when the sodium changes the flow direction in the leaked tube temporarily in correlation to the tube cross section filling by hydrogen and to repeated contacts of both reagents.

The ranges of flow conditions mentioned above depend on steam generator design parameters, tube geometry, leak size and location. If the pressure difference between the inlet and outlet sodium chamber decreases at a steady leak rate, the passage conditions change into pulsation conditions and later expulsion conditions. Such transition of flow conditions can occur if both the leak rate as well as the tube hydraulic resistance increase. The latter is of particular importance. The expulsion conditions may occur in the inverse steam generator only at comparatively large water into sodium leak

rates when the tube hydraulic characteristics remain stable. However, the reaction products deposit at the tube inner surface below the leak point and the tube hydraulic resistance increases in time consequently.

Mathematical models and computer codes have been developed for flow condition estimation.

Figure 1 presents the calculated data of flow conditions that have been in good agreement with experimental results. The experiments were carried out at a steam generator model with 37 vertical tubes of 8 mm I.D. and 1370 mm length.

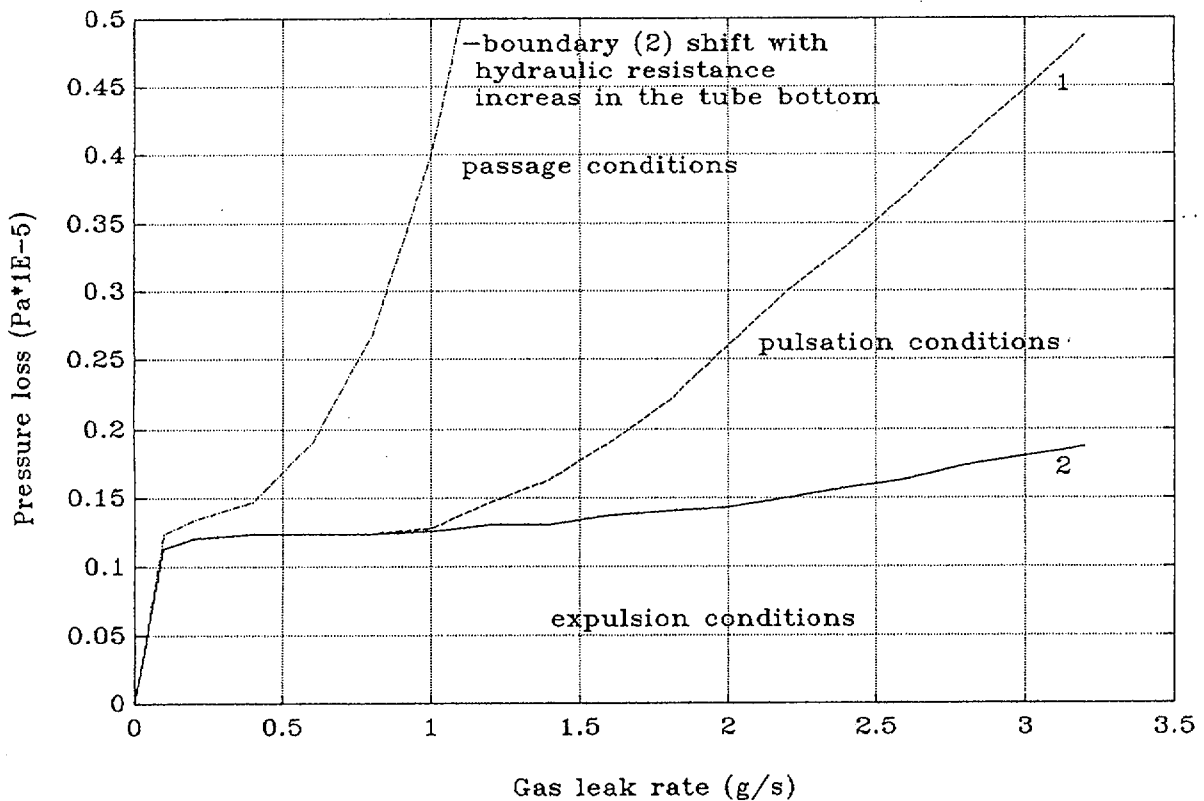


FIG.1. Boundaries of flow conditions

The point for gas injection into sodium was situated at a distance of 1220 mm below the inlet sodium chamber. A qualitative description of the boundary shift with the increase in the hydraulic resistance at the sodium tube outlets are given in the Fig.1, too.

A series of damage experiments was performed at two inverse steam generator models to study expulsion conditions. One of them with 19 tubes, and the second with 15 tubes. The tubes of $\varnothing 22 \times 2.5$ mm were manufactured from a steel of the type 2.25Cr1Mo. The steam of approx. 2 g/s flow rate was injected into sodium with temperatures between 350°C and 400°C in a time period up to 10 minutes. No wastage of the target tube wall have been found and no self wastage phenomena have been observed.

The self-wastage rate as well as damage rate of the target tube wall in an inverse steam generator is similar to that in a steam generator of the traditional concept for small leaks and passage flow conditions [5]. But the sodium velocity in tubes of the inverse steam generator is essentially higher than in the traditional one. The experimental data on the influence of sodium velocity on wastage rates published in [6,7,8,9] are not of consistent nature.

Therefore experimental studies have been performed to specify such relations for the specific conditions of an inverse steam generator.

The experiments were carried out on a special test rig at sodium flow velocity in tubes of 0 to 5.96 m/s and

temperatures of 435°C to 460°C and 435°C to 450°C respectively. The tubes of 17 mm I.D. (the target wall distance is 17 mm) fitted with leak holes of 0.25 mm, 0.48 mm and 0.60 mm in diameter were used. The steam pressure was up to 9.5 MPa at the shell side.

The results of experiments are in Fig 2. The wastage rate on sodium velocity dependence is proved to be significant for inverse steam generator conditions. The tube wall wastage rate in inverse steam generator is hundred times smaller than that in the traditional one at sodium velocity in tube of 3.5 m/s (standard velocity in tubes of an inverse steam generator), 16 mm tube I.D. and water leak rate of 0.5 g/s. The target

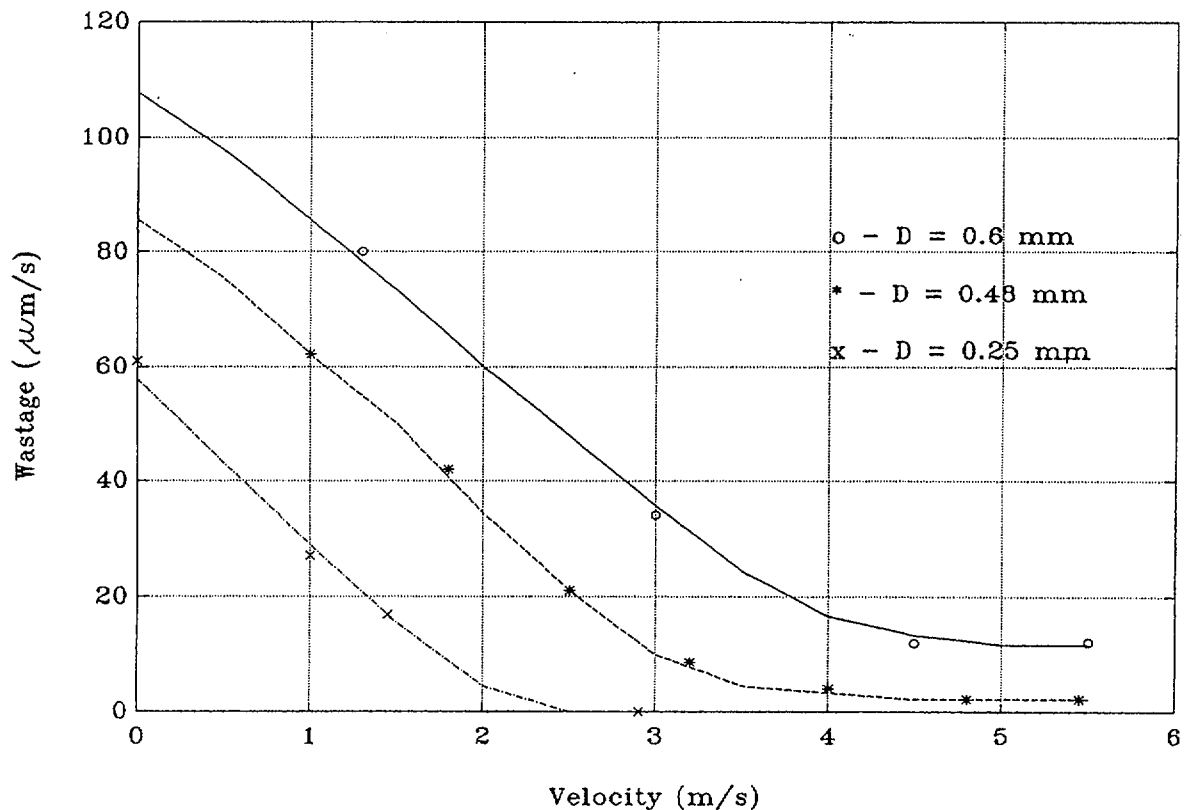


FIG.2. Target tube wall wastage rate as a function of sodium flow velocity

wastage would occur only at passage conditions in the tube and decrease with the relative time of sodium presence in the tube. The direct measurements of the wastage rate at pulsation conditions showed it was three to five times smaller than the water leaks into sodium flow with passage conditions. Furthermore the experiments showed that the peaks of target wall temperature fluctuations did not attain the temperature of the reaction zone.

Therefore in the leaked tube of the inverse steam generator process of hole self-wastage, process of target tube wall wastage as well as reaction products deposition at the tube inner surface below the leak point came true at the same time.

To apply the obtained results of experiments to the safety analysis of inverse steam generators mathematical models considering flow dynamics, thermochemistry of sodium water reaction and process thermodynamics in the leaked tube are necessary. The developed model [10] includes effects as:

- dynamic flow conditions
- hydroxine dissolution and its reaction with sodium
- hydride and oxide crystallization
- precipitation of the hydroxide solid particles at the tube walls
- heat transfer in the leaked tube as well as in the tube bundle
- wastage rate of target tube wall and hole self-wastage
- characteristics of used leak detecting sensors and systems

One more advantage of the inverse steam generator should be mentioned here. All above described processes come true within one cylindrical tube, e.g. in a simple geometry. This makes possible to perform sufficiently accurate study of some individual constants or relations using the one-tube models or those with several tubes which have geometry and flow conditions identical to those of real steam generators. While developing the mathematical model such constants as, for example, the constant of rate of the direct sodium-sodium hydroxide reaction, the matter liquor fraction captured by the reaction product crystallization, the parameter for the hydrogen bubble size distribution as well as the probability for bubble collapse, have been specified during the experiments.

The verification of the calculation procedures has been carried out using 7-tube inverse steam generator model. The tube bundle of the model was made from tubes of 16x2.7 mm, 10.7 m length. The tube material was of the type 2.25Cr1Mo. The thermal power of the model was 550 kW. Operating parameters of the steam generator during the experiment were as follows : sodium inlet/outlet temperatures - 475/280°C, water and steam temperatures - 237/453°C, steam pressure - 8.8 MPa. Steam of 500°C temperature and 10 MPa pressure was injected into one of the peripheral tubes of the tube bundle through a hole of 0.125 m I.D. (the design water flow rate was 0.14 g/s). The steam flow rate remained constant during the experiment.

A through-hole of 1 mm I.D. occurred in the target tube wall in 480 seconds. The steam injection was finished in

680 seconds. The calculations predicted the formation of the through-hole in 500 seconds. Consequently a very good agreement between calculated and measured data was achieved.

Theoretical and experimental analysis of actual inverse steam generator structures showed that the transition to the expulsion conditions of the flow in the leaked tube occurs before the target tube wall was burned through in all the range of actual operation conditions. In Fig. 3 there is a calculated dependence of damage depth in the target tube on leak position along the MMISG tube length. An initial leak of $W_0 = 0.01$ g/s at the time t_0 with an exponential increase of self-damage rate ($W = W_0 + a \cdot e^{b(t-t_0)}$) was considered.

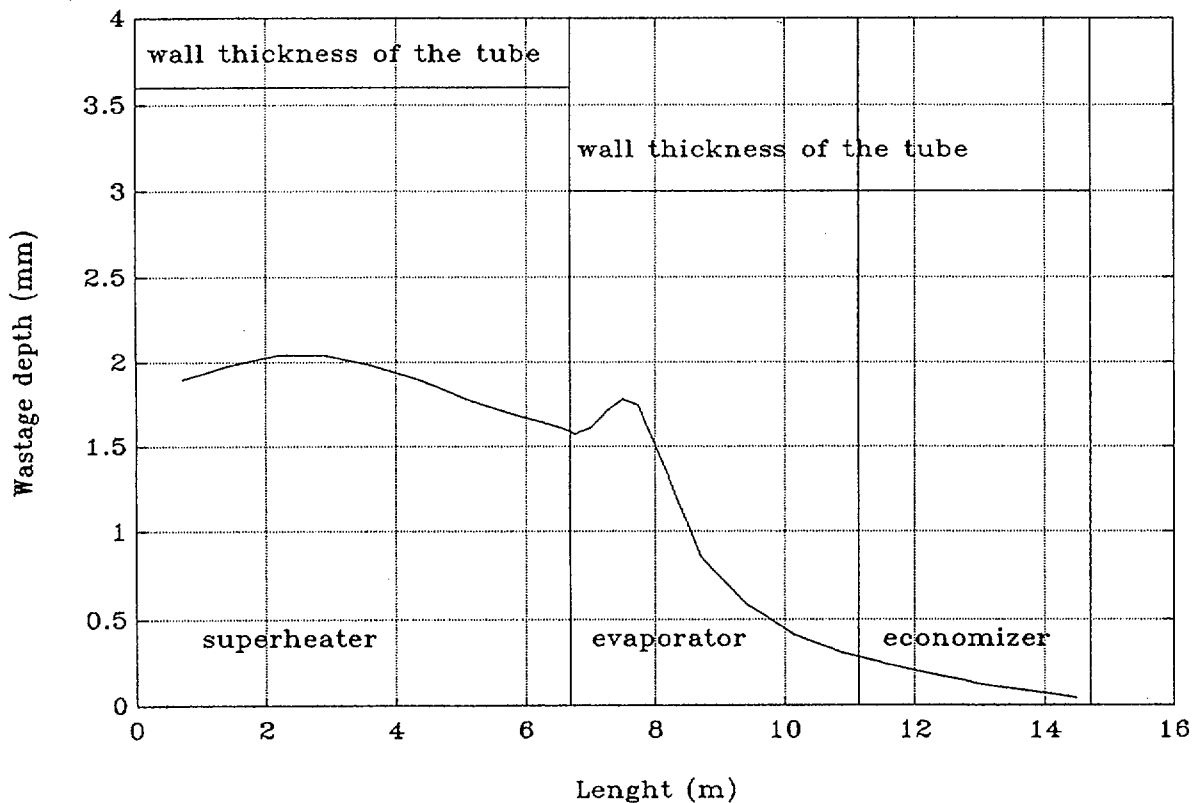


FIG.3. Dependence of damage depth in the target tube wall on leak position along the MMISG tube length

An another of positive properties of the inverse steam generator design consists in the fact if suddenly a leak of more than 0.2 g/s rate occurs it will not increase in time. Results of computation for such leaks are given in Fig. 4. There is a dependence of damage depth in the target tube of the MISG on the constant leak rate for the leak position close to module sodium inlet (most danger area from the viewpoint of damage rate).

In accordance to computation results no damage of the target tube wall can be expected in the MMISG as well as in the MISG at the moment of sodium expulsion and consequently smaller amount of water reacts with sodium. Furthermore the damaged area is concentrated to one tube only.

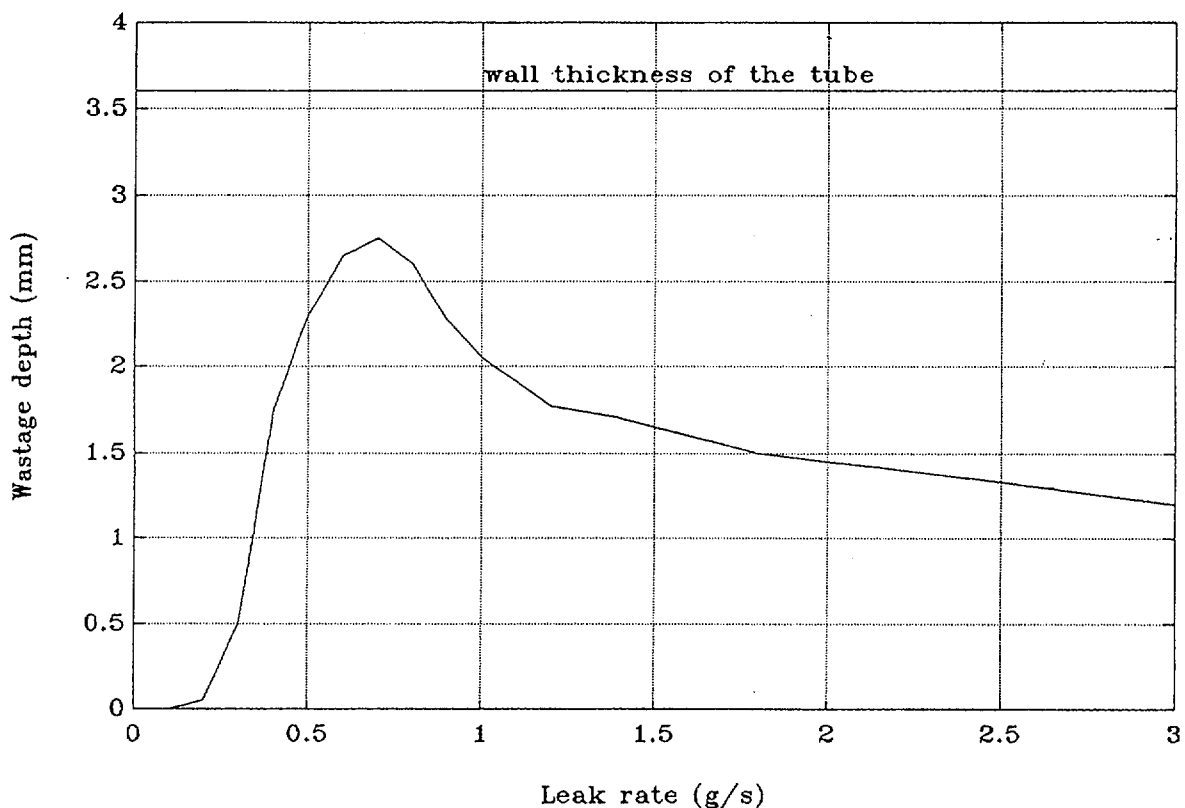


FIG.4. Dependence of damage depth in the target tube wall of the MISG on the constant leak rate for the leak position close to module sodium inlet

A probability of an accident with large water into sodium leak in tubes is hypothetical only. It is to be mentioned that the hydrogen flow rate into the sodium buffer tank caused by a tube leak in inverse steam generator is incomparably larger than caused by similar leak situation in a steam generator of the traditional concept [11]. It enables to detect and monitor water into sodium leaks in an inverse steam generator very effectively by measurements of hydrogen concentrations in cover gas, of pressure increase in sodium buffer tank and by rapid detection of hydrogen bubbles in sodium outlet pipeline [12].