LMFBR steam generator tube-to-tubesheet weld with dissimilar ferritic steels – Qualification tests and inelastic analyses

B.Daron & P.Butstraen
Division Nucléaire et Tuyauteries, Stein Industrie, Vélizy-Villacoublay, France
A.Vanderschaeghe
Laboratoire, Stein Industrie, Lys-lez-Lannoy, France

1 SODIUM-HEATED STEAM GENERATOR DEVELOPED BY STEIN INDUSTRIE

The steam generator developed by STEIN INDUSTRIE is characterized by its modular design : several small, elongated steam generators (modules) are installed in parallel between a distributor and a sodium header. The advantage of such an arrangement is to limit the impact of an incident or even of a sodium-water reaction : it is possible to reparate, remove or replace a defective module without having to shut down the relevant secondary loop completely for the whole duration of the servicing operation.

The heat-exchange tubes (OD 15 mm, thickness 2.5 mm) are subject to high pressure - 190 bar (2750 psi) - and high temperature - 490°C (914°F) - and are manufactured from the steel offering the best characteristics for this use, i.e. a ferritic steel containing 9 % Cr and 2 % Mo stabilized with niobium and vanadium (AFNOR standard Z 10 CD Nb V 9.2) and commonly known as EM 12. Its properties are as follows :

- high yield strength at hot temperature,
- low creep susceptibility,
- good corrosion resistance,
- low expansion coefficient.

However, since it is not possible to use this steel for large items (water and steam boxes and their tubesheets), STEIN INDUSTRIE turned towards a ferritic steel containing 2.25 % Cr and 1 % Mo (AFNOR standard 10 CD 9.10) for those parts.

The somewhat different metallurgical and mechanical properties of these two steels and the use of a quick and automatic welding procedure providing inspectable tube-to-tubesheet weld caused STEIN INDUSTRIE to initiate a test programme to insure this conception.

2 WELDING PROCEDURE ADOPTED

The type of welding involved means it has to be done away from the actual tubesheet. The tubes are therefore welded to bosses (or teats) machined on the internal faces of the tubesheets (see fig. 1).

Welding is by the internal process without filler metal and with gas shielding. Stress-relieving heat treatment at approximately 700°C (1300°F) is then performed.
To qualify the nondestructive test procedures and welding processes, over a hundred test assemblies were made.

3 QUALIFICATION TESTS PERFORMED

3.1 Metallurgical characterization tests

The following tests were carried out :

- progressive grinding,
- micrographic examination,
- tensile tests,
- Vickers hardness tests.

Neither the progressive grinding nor the micrographic examinations revealed the presence of any cracks.

The tensile tests at 20°C and 500°C (70°F and 932°F), carried out on full-size specimens after machining away the reinforcements from the weld beads, gave the following results :

- at 20°C ultimate stress : 512 MPa (74.3 ksi)
- at 500°C ultimate stress : 356 MPa (51.6 ksi).

In both cases rupture occurred outside the weld, in the part made of 2.25 Cr . 1 Mo.
The maximum hardness value was found in the weld. Its level was 325 HV5.

3.2 High-temperature mechanical strength tests

Three assemblies were subjected to creep-rupture tests at a temperature of 500°C (932°F) in order to check that welding did not reduce the mechanical strength of the joint to a value below the mechanical strength of the weaker steel (2.25 Cr . 1 Mo).
Two assemblies were subjected to an internal pressure of 677 bar (9 820 psi).
One assembly was subjected to an axial force of 17 560 N (3 950 1b).

These loads where chosen to create a mean stress of approximately 155 MPa (22.5 ksi) in the minimum section of the 2.25 Cr . 1 Mo boss. This stress should, at 500°C, lead to rupture after :

- 2000 hours according to the minimum creep-rupture stress curve given in the ASME III Code Case N47.
- 13000 hours according to the mean creep-rupture stress curve.

While these tests were being performed, finite-element calculations taking account of material plasticity and creep were carried out in order to obtain a more precise estimate of rupture time.
These calculations also take into account the stress concentrations and thermal stresses generated by the difference between the expansion coefficient of the two steels.

4 CALCULATIONS CARRIED OUT

The calculations were carried out on the mesh shown in Fig. 2 using the INCA program developed by the CEA. The modelled form is the "average" form observed on the welding samples.

The material characteristics vary with temperature. Their values at 500°C (932°F) are given below :

- Young's modulus

. 2.25 Cr . 1 Mo boss and 2.25 Cr . 1 Mo HAZ	: 174000 MPa (25250 ksi)
. EM12 tubes and EM12 HAZ	: 176750 MPa (25650 ksi)
. actual weld	: 175000 MPa (25400 ksi)

- Plasticity laws

  Use of bilinearized tensile curves characterized by proportional limit Sp and strain-hardening slope h.
  Pessimistically, the law adopted for 2.25 Cr . 1 Mo was extended to the actual weld.

  . 2.25 Cr . 1 Mo nipple and 2.25 Cr . 1 Mo HAZ Sp = 169 MPa (24.5 ksi)
  h = 10500 MPa (1520 ksi)

  . EM12 tube and EM12 HAZ Sp = 335.5 MPa (48.7 ksi)
  h = 15500 MPa (2250 ksi)

- Creep law

  The law adopted for 2.25 Cr . 1 Mo was extended to HAZ 2.25 Cr . 1 Mo and to the actual weld. This is a strain-hardening law :

$$\frac{d\varepsilon_c}{dt} = \frac{1}{T}\left(\frac{\sigma}{\sigma_m}\right)^M \varepsilon_c^{-\mu}$$

  where ε_c = creep deformation, t = time (hours)
  σ = Von mises stress (MPa)

$$\left.\begin{array}{l} T = 10^7 \text{ hours} \\ \sigma_m = 150 \text{ MPa} \\ M = 11 \\ \mu = 0.8 \end{array}\right\} \text{Constant for } 500°\text{C}$$

  The EM12 tube and the EM12 HAZ were assumed not to creep, as the ratio of the creep velocities, at the same stress, of 2.25 Cr . 1 Mo and EM12 is sufficiently high (50 to 100) for this simplifying hypothesis not to have any effect on the evolution of the stresses in the part made of 2.25 Cr . 1 Mo and the weld.

- Expansion coefficients (given between 20 and 500°C (70 and 932°F))

  . 2.25 Cr . 1 Mo boss $\alpha_1 = 14 \cdot 10^{-6}\ °C^{-1}$

  . EM12 tube $\alpha_2 = 12.4 \cdot 10^{-6}\ °C^{-1}$

  . Weld $\alpha_3 = 13 \cdot 10^{-6}\ °C^{-1}$

This value was determined from the percentages of Cr and Mo measured in the weld.

. EM 12 and 2.25 Cr . 1 Mo HAZ : Each HAZ includes three different expansion coefficients (one per layer of elements) permitting a gradual transition from α_3 to α_2 and from α_3 to α_1 .

In total, there are thus 9 different expansion coefficient used for the calculation.

The calculations are carried out assuming the assembly to be free of stresses at a temperature of 20°C.

5 RESULTS

5.1 Calculation results

- Pressure loading : redistribution of the stresses under the effect of plasticity and then of creep led to a less penalizing state of stress than expected. The most highly stressed point is node 571 of the mesh, at the limit of the boss and of the 2.25 Cr . 1 Mo HAZ, where Von Mises equivalent stress stabilizes at around 130 MPa. The rupture time obtained from this calculation is therefore approximately :

  - 10 000 hours according to the minimum rupture stress curve
  - 50 000 hours according to the mean rupture stress curve.

- Axial force loading : redistribution of the stresses under the effect of plasticity and creep was less marked for this loading than for pressure loading (the equilibrium must be respected in each horizontal section of the assembly, whereas it is established over the whole of the assembly for the internal pressure). Calculation showed a stress concentration at node 571 where Von Mises equivalent stress stabilizes at around 184 MPa. The rupture time obtained from this calculation is therefore approximately :

  - 300 hours according to the minimum rupture stress curve
  - 3 000 hours according to the mean rupture stress curve.

  The finite element calculation thus leads to rupture time predictions quite different from the initial forecasts based on the mean stress values.

In order to determine whether residual stresses resulting from the manufacturing process could modify the predictions, we repeated the calculation under pressure loading, assuming this time that the assembly was free of stress at the end of the heat treatment, taken to be at a temperature of 750°C (1382°F), and not at the ambient temperature.

Cooling from 750°C to 20°C would therefore generate a field of residual stresses.

After a rise to 500°C and application of the loading, the stress field was thus quite different from the stress field previously calculated (see fig. 3).

On the other hand, after calculation of 500 hours of creep, the stress fields obtained by both calculations had become virtually identical : this duration - short with regard to the rupture time - was sufficient to enable the creep to "efface" the stresses of thermal origin. The conclusion on the expected rupture time was therefore unchanged and subsequently reinforced.

5.2 Test results

To date no rupture or incipient rupture has been observed on the three assemblies, although the durations at high temperature are now :

- 14700 and 10000 hours for the pressure tests
- 15500 hours for the axial-force test.

5.3 Comparison between calculations and tests

The comparison is thus made in terms of rupture time.

		Forecast from mean stress	Finite element calculation	Experience
Pressure	t min.	2 000 h	10 000 h	> 14 700 h
	t mean	13 000 h	50 000 h	
Force	t min.	2 000 h	300 h	> 15 500 h
	t mean	13 000 h	3 000 h	

Although the pressure test does not enable a direct conclusion to be made, the axial-force test clearly indicates a safety margin as compared with calculations.

6 CONCLUSION

To weld steam-generating tubes of EM12 to a tubesheet provided with boss of 2.25 Cr . 1 Mo, STEIN INDUSTRIE has developed a process of internal welding without filler metal.

The characterization tests carried out on test assemblies have shown the excellent metallurgical quality of welding performed by this process.

High-temperature strength tests showed a safety margin as compared with the results of the finite element calculations.

The hypotheses made for these calculations which take into account the elastoviscoplastic properties of materials, and particularly the extension of the properties of 2.25 Cr . 1 Mo to the weld, can therefore be applied to steam-generator sizing calutations.

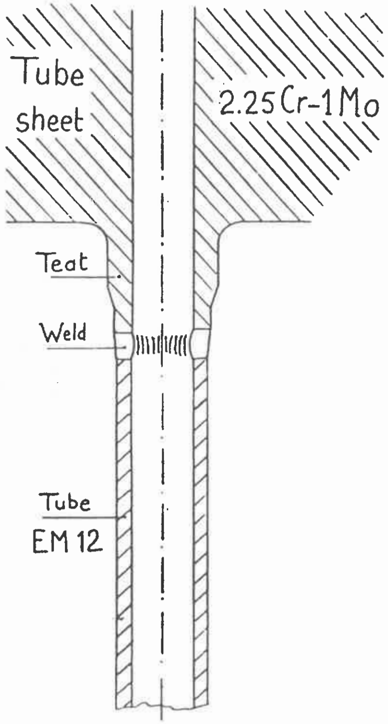

Fig. 1 : schematic vue of
tube-to-tubesheet
weld.

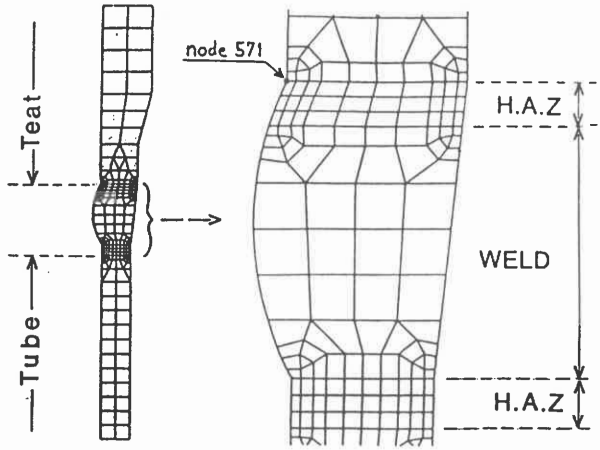

Fig. 2 : mesh used for calculations.
(731 nodes - 216 elements)

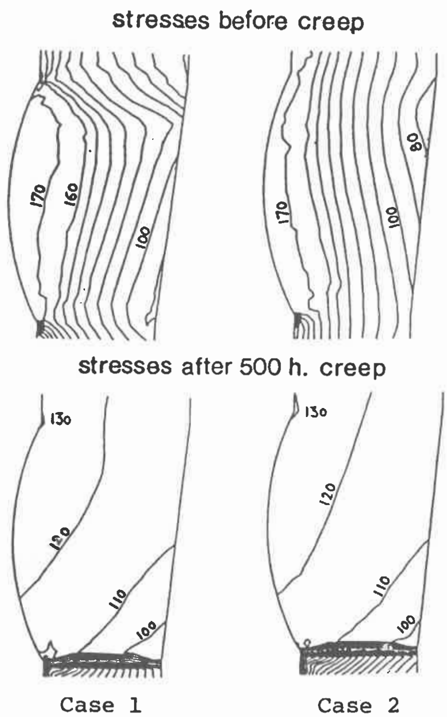

Fig. 3 : Pressure loading. Von Mises isostresses (MPa)
Case 1 : without residual stresses at 20°C
Case 2 : with residual stresses at 20°C