THEORETICAL AND EXPERIMENTAL STUDIES ON BELLOWS TYPE EXPANSION JOINTS BEHAVIOUR OF CHINON 3 PRIMARY COOLANT SYSTEM

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SUMMARY

In rebuilding the primary coolant circuit of the Chinon 3 reactor (natural uranium-graphite-gas) it was necessary to qualify certain components, including the bellows type expansion joints.

These joints, of diameter 1800 millimeters, are designed to support a working pressure of 30 bars for a maximum temperature of 410°C.

They are hydraulically formed with a double stainless steel membrane. With regard to mechanical resistance, calculations by finite elements in the elastic field have shown the yield stress of the metal used for the waves to be widely overstepped for the specified working values, calculations were undertaken in the elastoplastic field with metal strain hardening during the cyclic pressure and angular deformation undergone by the bellows joints on the reactor.

The results of these calculations, carried out with the PASTEL programme in kinematic strain hardening, were interpreted with a view to estimating the resistance of the joints under fatigue conditions.

Failure fatigue tests on three bellows joints, identical with those equipping the reactor showed that the lifetimes estimated from calculations allied with the breaking cycle number values obtained experimentally.

The vibration study of the bellows was performed in two stages. A series of vibration tests was performed on a real bellows joint. By comparing the experimental results with calculations using the finite elements method for revolution shells it was possible to qualify the representation of the waves and reinforcement rings.

The resonant frequencies and modes were calculated for the various joints under reactor conditions. According to the excitation sources considered, the amplitude of the displacements and stresses can be determined from these characteristic modes.

The corrugations are protected internally from the aerodynamic effects of the gas flow by an inner sleeve welded to the primary piping upstream and free downstream. The annular space between this sleeve and the corrugations forms a resonant volume liable to be excited by flow-induced pressure fluctuations.

It was possible to calculate the characteristic resonance frequencies and modes of this gas column (air at normal temperature and pressure). A full-scale mock-up test under conditions corresponding to the calculation hypotheses gave experimental proof of the calculation results.

Owing to the good correlation between the results of these two studies an attempt was made to calculate the acoustical behaviour of these cavities for nominal running conditions (temperature and pressure) as a function of the known excitation sources.

The results obtained from all these tests show that the use of bellows type expansion joints on a primary reactor circuit offers the same guarantees of reliability and resistance as any other circuit component under pressure, as long as the strains they undergo remain within the limits specified by the regulations and nuclear codifications.
1. **Introduction**

The primary coolant system of the Chinon 3 reactor, of the natural uranium/graphite/gas type, underwent extensive repairs in 1973 and 1974 (figure 1).

One of these operations involved replacing all the bellows type expansion joint fitted on the system. This operation required the qualification of new bellows meeting the following specifications:

- Diameter ................. 1800 mm
- Design pressure ........... 30 bars
- Design temperature ...... 410 °C

AISI 316 L stainless steel was selected as the material for the new double wall hydroformed bellows, featuring reinforcement rings between each wave (figure 2).

Qualification procedures dealt with mechanical strength (especially fatigue strength) and the risk of vibrations of mechanical or acoustic origin.

2. **Mechanical strength**

In order to supplement the bellows manufacturer's own design work, we carried out calculations of the elastoplastic deformation of bellows waves, as well as fatigue strength tests, so as to estimate the service life of the bellows on the reactor.

Deformation calculations were carried out by the finite element method with the use of the Pastel program developed at the Commissariat à l'Energie Atomique [1].

This program led to the definition of two plies bearing against each other without friction, and without the possibility of disengagement from each other. The outer ply bears against the reinforcement rings in accordance with the same basic assumptions.

The bellows comprise seven or nine convolutions. The calculated profile, limited to the first wave, is divided into 2 x 30 elements (figure 3).

2.1 **Law of metal behavior**

The tensile tests introduced into the computations were plotted from tensile tests on specimens cut out of a hydroformed bellows.

Elastoplastic computation is generally carried out by proceeding from an initial unstressed state and progressively increasing the load. In the case of these bellows, which are subject to cyclic loads with substantial plastification, we attempted to use the computations to reproduce the evolution of deformations through several cycles.

It is known that the characteristic curves of materials vary during the initial cycles, but these variations are generally unknown owing to the lack of experimental results.

We adopted a bilinear kinematic hardening law as shown in figure 4. The asymptote of the rationalized tensile curve was drawn. The elastic region is equal to twice the inferred yield strength defined by the intersection of
this asymptote with the prolongation of the elastic portion of the curve.

2.2 Loading
The cyclic loading applied to the bellows wave agreed with those shown in the diagram in figure 5. The pressure of 40 bars is the cold fatigue test pressure.

2.3 Results
With this type of bellows, the deformations reach a maximum at the wave top on the inner ply, which is slightly thicker than the outer ply. The curve in figure 6 shows the variations in deformation between two cycles.

2.4 Interpretation of results
The results furnished by computations were interpreted by the use of ASME 3 code fatigue strength curves [3].

These curves were considered extremely conservative by the bellows manufacturers. However, they can be employed to determine the maximum allowable number of cycles, as in the case of all nuclear pressure vessels.

Another possibility is to employ the results of a fatigue fracture analysis of hydroformed bellows subjected to combined bending and internal pressure cycles [2].

The curve reproduced in figure 7 permits the determination of a mean "statistic" fracture curve and an "early" fracture curve, from which the service life of the unit can be estimated.

In the present case, for a deformation range of 1.94% during the computation cycle, the following items were derived:

- Maximum allowable number of cycles according to ASME 3 .................. 70 cycles
- Estimated start of fracture ........ 320 cycles
- Mean of fractures .................. 2000 cycles

The ASME figure can be seen to differ from the mean of fractures by a factor of about 30, and from early fractures by a factor of about 5.

In the case of double wall bellows, it should be possible to determine a maximum allowable number of cycles greater than the ASME figure, since in this case the inner ply breaks first and the user is warned by the detection of a leak between the two walls.

The fatigue strength tests of a bellows at scale 1, to which the cold cycle was applied, provided the following results:

- Fracture of inner diaphragm ......... 1380 cycles
- Fracture of outer diaphragm ......... 2827 cycles

These results are in agreement with the above interpretation.

3. Vibration analysis

3.1 Mechanical vibrations
In order to qualify the schematization, the bellows waves and reinforcement rings for design purposes, a series of vibration tests were conducted
on an actual unit at the manufacturer's works.

The bellows, fitted with its sleeves, was placed vertically on a wooden frame insulated from the ground.

The different resonance frequencies were determined by exciting the structure with an exciter exerting a blank noise type force.

The natural modes were computed by using the finite element method applied to circular shells. The structure is defined by its generating line. The natural modes are axisymmetric or exhibit a harmonic azimuthal variation ($\cos n\theta$). In the calculations, it was assumed that the two ply of the wave were independent of each other, and the elasticity of the rings was taken into account.

A comparison was made of the experimental and calculated results pertaining to the most important resonances.

<table>
<thead>
<tr>
<th></th>
<th>mode 0 (Hz)</th>
<th>mode 1 (Hz)</th>
<th>mode 2 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>5.4</td>
<td>9.6</td>
<td>37.5</td>
</tr>
<tr>
<td>Calculated</td>
<td>5.5</td>
<td>8.8</td>
<td>38.3</td>
</tr>
</tbody>
</table>

Transposition to conditions prevailing in a reactor requires a computer program, but in the case of structures as complex as these bellows, it is preferable to validate computer results by experiments.

Evaluation of bellows vibration levels in service conditions involved the following:

- Calculation of the associated natural frequencies and natural modes in operating conditions of the reactor.
- Determination of the vibration amplitude as a function of different excitation sources.

The natural modes and frequencies were calculated for three types of expansion joint. Schematization defined in section 1 was employed. The bellows were inserted to the level of the pipes.

Calculations were carried out for modes $n = 0$ and $n = 1$. The significant resonances ranged between 14 and 75 Hz. These resonances correspond essentially to an axial displacement of the rings, with the waves acting a spring. The mode 1 resonances (antisymmetric axial displacement of rings) were similar to those of mode 0, except for the first, the frequency of which was substantially higher and the meridian shape different. The pipes were immobilized in all cases.

The effect of internal pressure on resonance frequencies was analyzed. The frequencies increase between 13 and 20 % depending on the mode in question.

For the significant resonance modes, the maximum stress/maximum velocity ratio is substantially constant. Regardless of resonance frequency, for a maximum bellows velocity of 1 mm/sec, the stress is in the neighborhood of
2.5 kg/mm².

In view of the range of frequencies employed (14 to 75 Hz), the only possible disturbing excitation source would be the circulator, at its fundamental frequency.

3.2 Acoustic resonances

An expansion bellows designed for the Chinon J reactor system was subjected to noise measurements, in order to determine experimentally the acoustic resonances of the annular space lying between the bellows waves and the internal aerodynamic protection shell of these waves.

This cavity was excited by a blank noise generated by two loudspeakers placed inside the bellows.

The resonance frequencies and maxima distribution were determined by spectral analysis of 17 measurements.

Resonance calculations of the bellows placed in the test conditions (air at ambient temperature) were carried out by the standard method for determining the natural frequencies and modes of resonators. As the inner diameter was large, the problem was dealt with as a plane.

The following results were obtained:

<table>
<thead>
<tr>
<th>experimental frequency (Hz)</th>
<th>calculated frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>104</td>
</tr>
<tr>
<td>320</td>
<td>314</td>
</tr>
<tr>
<td>565</td>
<td>517</td>
</tr>
<tr>
<td>1090</td>
<td>1046</td>
</tr>
</tbody>
</table>

The good agreement revealed between experimental and calculated results led to an attempt to extrapolate these results to actual operating conditions (pressurized carbon dioxide at elevated temperature) by calculations.

A detailed analysis of the effect of different aerodynamic excitation sources (circulator, elbow blading, steam generator) on the various components of the system (piping, blading, bellows) is covered by a separate paper delivered to this conference [4].

4. Conclusions

The analyses and tests undertaken on this type of component led to a clearer determination of the service possibilities of expansion bellows. Knowledge of mechanical loads (pressure, temperature, angulation) and estimation of the number of stresses occurring in time (vibrations, oligocyclic fatigue) served to confirm these determinations.

Additional mechanical tests, conducted during restarting phases on this component inserted in the primary system, provided proof that the estimates made fell well within the determined limits.

Vibratory stresses determined on the most highly loaded wave of this component on the basis of vibration measurements (mechanical and acoustic
excitation) showed that the most highly stressed portion of the bellows exhibited very little strain for these two effects.

The overall results obtained by these analyses and tests showed that the use of bellows type expansion joints in a primary reactor coolant system offers the same guarantees of reliability and strength as any other component in the pressurized system.

Nevertheless, it is necessary to make sure that the loads applied to the bellows remain within the design limits.

References


Figure 1  Perspective view of Chinon 3 primary coolant system.

Figure 2  Bellows type expansion joint of Chinon 3.
Figure 3. Computation mesh.

Figure 4. Hardening law adopted for calculations (stress-strain curve).

Figure 5. Bellows loading diagram.
Bilinear strain hardening hypothesis
Yield Strength 45 hbars
Pressure: 40 bars
Angulation: ±0.045 radian for 7 waves

\[ \Delta \varepsilon = 194\% \]

Residual 0.68%

State \( \text{①} \) \rightarrow \text{State \( \text{③} \) }

Figure 6 Variations in maximum deformation during load cycles.

Figure 7 Ring reinforced bellows fatigue test results.