STRUCTURAL ANALYSIS OF A PWR VESSEL
NOZZLE-TO-HEMISPHERE

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The structural analysis of a PWR vessel hemispherical cover has been currently performed in the past. The purpose of the present study was to estimate, in a more accurate way, the stress concentrations which occur at the junction of a control rod nozzle to the hemispherical cover. The connection located at maximum slope, with reference to an horizontal axis, was selected for calculations, owing to most conservative assumptions. The study was restricted to the structure defined as follows. In a longitudinal direction, symmetry due to neighbouring part and radial symmetry led to two vertical limiting planes ; in a meridional direction, the choice was directed by the qualitative results of a previous finite element analysis of an entire cover with holes, which showed that vertical planes surrounding the junction were translated as rigid bodies. Therefore, only one quarter of the nozzle, and the attached spherical part, were considered. The analysis was carried out using several finite element programmes of the CASTEM system built by the Commissariat à l’Energie Atomique (CCOC for the mesh, BILBO for f.e.m. computations, ...).

The mesh was composed of 1629 nodes and 294 3-D isoparametric quadratic brick type elements. An internal unit step pressure and a thermal shock of 100³ K in 50 sec. were the retained loadings.

First, the computation of a transient response to the thermal shock was performed in order to determine temperature charts for a following linear elastic analysis. The choice between imposed temperature or heat flow as boundary conditions required a preliminary study on a simplified axisymmetrical model for which stresses were calculated in both cases, showing thus the most conservative hypothesis. Then the comparison between the analytical solution of a heat transfer problem in spherical coordinates, and similar finite element computations, enabled adjusting time step in view of accuracy and numerical stability of the results.

The major problem raised by the subsequent mechanical analysis was that of the magnitude of the displacement to prescribe on one side of the structure. It was solved by assuming that the global behaviour of the structure was identical with the one of an equivalent piece of spherical cover without hole.

For internal pressure loading case, combined effects of pressure and prescribed unit boundary displacements were compared to equilibrating reactions estimated from the equivalent structure, thus supplying the prescribed displacements magnitude.

For thermal loadings, these global displacements were computed on a whole hemispherical shell with cylindrical flange, accounting for thermal characteristics of each part. Average temperatures were preliminarily calculated at each time using a finite difference code.

Maximum equivalent stresses were then determined for selected temperature charts ; they appeared at lower part of the nozzle to sphere junction for t = 700 sec. and at upper part for t = 4000 sec.

The results of this study will enable making use of Bugey reactor instrumentation measurements, in view of a further fatigue analysis of PWR vessel.
1. **INTRODUCTION**

Safety rules applied to nuclear power plants have led to the requirements for accurate calculations of stress states in components operating under severe conditions. This is especially the case for the PWR vessel hemispherical covers as in EDF's BUGEY plant. Such a structure is loaded by internal pressure and high transient temperature gradients. Therefore, structural analysis of complete hemispherical covers have been currently performed in the past. However, it has become necessary to estimate the stress concentration occurring at the junctions of control rods to the vessel cover. Unfortunately, the refined analysis of the whole cover with nozzles would lead to prohibitive man power, computer core and time costs. Therefore, it seemed reasonable to restrict the study to one nozzle and the surrounding part of the spherical cover, with application of adequate boundary conditions. The different steps of the calculation as well as the methods adopted for the determination of the suitable boundary conditions are presented in this paper. Measurements supplied by the BUGEY reactor instrumentation will be postprocessed in view of a further fatigue analysis of PWR vessel, on the basis of the results of the present study.

2. **DESCRIPTION OF THE STRUCTURE**

2.1 **Choice of a typical nozzle** (fig. 1 and 2)

Obviously it appears necessary to consider only an isolated hole, with consistent boundary conditions, in order to get accurate but quite simple structure.

First, we consider a fictitious but conservative location of the studied nozzle using the following assumptions:

- the hole has to be as far as possible from the cylindrical axis. So the penetration angle reaches 45°, the distance to the axis is 1290 mm.
- it seemed easier to consider a nozzle belonging both to a meridional plane, and also to a symmetrical plane of the square net created by the control rods system.
- the nozzle has been cut at the upper part in order to minimize the size of the problem and to eliminate boundary disturbances.

The mesh has been built out of 294 isoparametric cubic elements (20 nodes each, 3 d.o.f. per node). The whole structure involves 1829 nodes (stiffness matrix bandwidth : 1023, population : 289702) (fig. 4).

Seen from the far top, the structure is a quarter of a 150 x 150 mm square (the control rod pattern size). (on fig. 4 : two quarters have been gathered).

2.2 **Boundary conditions remarks**

Of course, the restriction of the problem to so small a model asks a special attention to the boundary conditions for mechanical as well as for thermal computations.

- The meridional plane is a symmetry plane : no normal displacements and no thermal flux exchange.
- About the other edges, an investigation has been performed among FRAMATOME previous global computations. It appears that
  - the plane issued from the nozzle axis has the behaviour of a symmetry one
  - the two other remain parallel to themselves during the transformation. Their movements are caracterized by two normal translation intensities U and V. Without further information, we assume that no heat exchange occur along these edges.
It is remarkable that the regular pattern of the control rods creates numerous unnatural symmetries on the spherical PWR cover.

3. MECHANICAL COMPUTATIONS

3.1 Scope - boundary conditions

3.1.1 An internal unit pressure step (1 kgf/mm^2) is prescribed along the inner face of the nozzle.

We first assume a shear stress distribution on the edges in order to assume perfect vertical equilibrium. This distribution has been performed using theoretical results about thick sphere.

3.1.2 We prescribe on a second and third step unit displacement U and V as defined before. By this computation we get the associated total normal reaction R_U and R_V normal to the edge. We then adjust the final value of U and V in order to get the same global R_U and R_V value as in the case of a non perforated sphere.

3.1.3 Finally we perform a superposition of the three previous stress and displacement computed fields.

3.2 Results

Let us consider three loading cases

1. p = 1 kgf/mm^2  \quad U = 0  \quad V = 0
2. p = 0  \quad U = 1 \text{ mm}  \quad V = 0
3. p = 0  \quad U = 0  \quad V = 1 \text{ mm}

The induced reactions are

\begin{align*}
\text{case 1} & : R_U = 60760 \text{ kgf} \\
\text{case 2} & : R_U = 2549411 \\
\text{case 3} & : R_U = 30194
\end{align*}

\begin{align*}
\text{case 1} & : R_V = -750376 \\
\text{case 2} & : R_V = 3651088
\end{align*}

Note that R_V^2 = R_U^3 (Maxwell-Betti Reciprocity theorem). The actual value of displacements are

\begin{align*}
U & = -1.5044 \times 10^{-2} \text{ mm} \\
V & = 4.397 \times 10^{-2} \text{ mm}
\end{align*}

The maximum induced stress intensity 17.73 kgf/mm^2 occurs on the inner face of the penetration tube.

4. THERMAL CALCULATIONS

The transient response of the structure under a water temperature increase is studied in view of subsequent thermo-mechanical calculations. Most problems arise from the choice of boundary conditions and direct integration time step.

4.1 Boundary conditions

The inner stainless lagging of the cover is accounted for by means of an exchange Newton type condition. Since the water inside the nozzle is quite stagnant, one thinks of a zero temperature condition, but this seems rather penalizing and it is advisable to investigate also the zero heat flow condition. The choice of the most conservative assumption is directed by the analysis of an axisymmetric structure, shown on fig. 3, obtained by rotation of one side of the 3D structure around the nozzle-axis.
The DELFINE program helps first determining temperature distribution variations with time for the two previous conditions (zero temperature or zero heat flow inside the nozzle), the structure being subject to a 10° C shock.

Iso temperature curves are displayed using the ESPACE program, showing the influence of the nozzle on the cover part. However, the conclusion of the study requires a stress analysis which is performed by means of the PASTEL program, for selected temperature charts. Here again, the real behaviour of the structure is straddled by two extreme cases: spherical displacements or zero horizontal displacements prescribed to the limiting ring of the cover part. In the first case, maximum stresses appear at \( t = 120 \) s for the zero heat flow condition while the zero temperature condition is more conservative in steady state. In the second case, because of hindered displacements, maximum stresses are obtained in steady state for the zero heat flow condition. In both cases, they are located inside the nozzle. Consequently, the zero heat flow condition has been adopted for the 3D structure.

### 4.2 Choice of time step

In order to avoid any numerical instability, time steps must be chosen in accordance with the direct integration algorithm implemented in the program. BILBO uses a Crank-Nicholson finite difference scheme, lying at the limit of unconditional stability. Therefore, upper and lower bounds for time steps are imposed by stability and accuracy considerations. Consequently it seems advisable to adjust the time step on a simple structure for which an exact solution is available. The selected structure is a spherical sector, meshed in the same way as the cover part. Temperature distribution under a 100° C shock has been investigated for various time steps and compared with the analytical solution. On figure 4 are displayed the curves of temperature variation across the sector at different times, for a 10 s time step. Results show that the lower and upper bounds are respectively 10 s and 25 s, but the oscillating behaviour of the solution is still sensible at nodes located on the inner skin. Therefore, in order to reduce the thermal shock effect, the temperature was supposed to raise gradually, following a slope defined on several time steps. Tests were performed on various slopes, for different time steps. Finally, a slope running on 5 time steps of 10 s each was adopted for the 3D thermal calculation, giving satisfactory results as shown on fig. 5.

### 4.3 Three dimensional thermal calculations

Following the conclusions to the two preliminary studies, the transient response of the structure subjected to a 100° C thermal shock in 50 s was calculated up to 8000 s with successive 10 s, 50 s and 500 s time steps. Results were stored for further use.

5. **THERMO-ELASTIC CALCULATIONS**

5.1 **Strategy**

The purpose of these calculations is to find the maximum stresses in the structure when subjected to a time-varying temperature field.

For the determination of adequate boundary conditions, only available results relate to an axisymmetric global structure (reactor cover with flange) subjected to thermal shocks quite similar to the one considered. The analysis of these results leads to the conclusion that the same type of boundary conditions as in the internal pressure case, may be
adopted. It offers the great advantage of saving the stiffness matrix previously inverted.

Therefore, thermo-elastic calculations are carried out according to the following strategy:
- computation of stresses \( \sigma_1 \), for given temperature chart and prescribed zero displacements \( U \) and \( V \) (see § 3 for notations).
- combination with stresses \( \sigma_2 \) and \( \sigma_3 \) calculated for prescribed unit displacements, given way to total stresses:

\[
\sigma = \sigma_1 + \frac{U}{U} \sigma_2 + \frac{V}{V} \sigma_3
\]

where \( U \) and \( V \) are the intensities of the actual displacements to prescribe.

5.2 Determination of prescribed displacements

The idea for the determination of variations of \( U \) and \( V \) with time, consists in calculating \( U \) and \( V \) for a spherical cover with flange but without holes. These displacements are due to the thermal expansion of the cover and the restraining influence of the flange because of its greater thermal inertia. Practically, mean temperatures in cover and flange are first computed using the TUYAU code of EDF/SEPTEN.

Meanwhile, the influence of the flange of the cover is investigated by means of the AQUAMODE axisymmetric shell finite element program of the CEASMET system. These studies have led to algebraic formula giving the required displacements \( U \) and \( V \) in terms of the mean temperatures defined above.

5.3 Results

From the results of § 3, the state of stress \( \sigma' = U \sigma_2 + V \sigma_3 \) may be determined. Fig. 7 shows the variation of the maximum equivalent stress in the structure. This maximum is always located inside the nozzle, first at the lower part of the junction, then at the upper part, following the heat front progression.

For temperature charts selected at quite regular intervals, the state of stresses \( \sigma_1 \) was computed using the BILBO program.

Maximum total stress \( \sigma = \sigma_1 + \sigma' \) is shown on fig. 8; the curve presents two maxima, one at \( t = 400 \) s located at the lower part of the junction, the other at \( t = 4000 \) s at the upper part. The maximum reached value for a 100° C shock is 58 kgf/mm².

It may be noticed that in steady state, the stress falls to 3.4 kgf/mm² proving, a posteriori, the good representation of boundary conditions.

References

[1] "The finite element method in engineering science" - M. ZIEKIEWICZ
fig 1. Geometry of the PWR cover

fig 2. Typical chosen nozzle and axis

fig 3. Axisymmetric mesh for thermal analysis

fig 4. 3-D mesh for mechanical, thermal transient analysis
fig. 5. thermal result with unit step loading

fig. 6. thermal results with smooth slope loading

fig. 7. maximum stress intensities due to prescribed boundary displacements.

fig. 8. Maximum stress intensities variation along edge lines.
FLOW CHART OF DIFFERENT USED COMPUTATIONAL CODES