Instrumentation Measurements During Pressure Test on Twenty 900 MW PWR Containments

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A review of instrumentation results are presented for 20 900MW PWR containments in France. As all the structures are of the same type it was decided to instrument more extensively the first unit to be built, Tricastin 1. The fewer instruments at the other units are simply to check that the overall behaviour was the same as for the Tricastin 1 Unit, except that the raft of the first unit constructed on each site is fully instrumented since soil conditions influence structural performance.

The pressure test were conducted in increments and decrements to 4.6bar. Instrument readings were taken, with visual inspection to detect any cracking. The result is a large number of measured values, from the strainmeters mainly and computer treatment was inevitable. The objective was to (i) check the design assumptions on materials properties (modulus and Poisson's ratio) and (ii) compare the Finite Element Method predictions with actual full-scale behaviour. A range of moduli from 29,000 MPa to 37,000 MPa was found for the cylinder and dome of each containment and it appeared that the Poisson's ratio was lower than expected. The finite element predictions at hatch and ribs were in good agreement, considering the measured elasticity moduli.

Readings were taken from the raft instruments during construction and prestressing as well as during the tests. Interpretation is more complex because of uncertainties as to the soil modulus, the pattern of soil reactions under the raft (elastic or Winckler springs) and moduli for cracked concrete. But displacements were in good agreement with the design analyses; the residual permanent depression after the test depended on the foundation soil type.

1 INTRODUCTION

After construction is completed, reactor containments, like all major civil engineering structures, are tested to check their capacity to withstand the reference loading. This test simultaneously serves to check their gas-tightness.

The tests are performed by subjecting the containment to internal air pressure in increments, over a period of several days. The reference pressure is 0.4 MPa and the successive levels are 0, 0.5 P, P,1.15 P, P, 0.5 P and 0.

Twenty-one 900 MW PWR containments of the same type have undergone this test at Tricastin, Gravelines, Dampierre, Saint Laurent, Blayais, Chinon and Cruas. They were all instrumented and monitored during construction, and during the prestressing phase.

2 DESCRIPTION OF INSTRUMENTATION SYSTEM

The most comprehensive instrumentation system was installed in the first containments to be built, some items being fewer in the later projects. Except for the last, Cruas 1, all these power plants were built on the same model. The superstructure is identical, and the rafts are designed to the specific features of the foundation soils of each site which was relatively soft ground at Tricastin, Gravelines, Dampierre, Saint Laurent and Blayais, and hard ground at Chinon and Cruas.

Tricastin 1, the first unit built, was provided with detailed instrumentation in a typical section of the structure, as well as at specific points. On the first units at each other site, there are fewer instruments in the superstructures, but the same number in the raft because of the differences in the foundation soils. The instrumentation less extensive for the other units serves to ensure that the overall behaviour of the structure remains identical to that of the first units tested in detail.

The first unit at Cruas, where the superstructure geometry is different from Tricastin 1 and the raft is placed on anti-seismic neoprene supports, had more comprehensive instrumentation. These differences in instrumentation are shown in the table of instrumentation installed in the different units concerned.

Topographic measurements and displacement measurements inside the containment serve to evaluate the deformation of the structure as a function of loading. The displacement measurements common to all units cover the following factors:

Topographic levelling of the service gallery at raft level: helps in assessing the overall displacement of the containment, in terms of subsidence and tilt; twelve targets on the building circumference.

Vertical deformation of the raft: these measurements are taken at thirteen hydraulic levelling pots positioned along two perpendicular diameters of the raft.

Horizontal deformation of the containment: twelve pendulums in four sections of the cylinder at three different heights, to evaluate the radial deformation of the containment at levels 10, 25 and 42m. Combined with measurements of the variations in raft diameter, by two perpendicular horizontal invar wires.

This system was supplemented at Tricastin 1 by external three-axis displacement measurements at about the 20m level on the perimeter of the containment, by means of the Vinchon apparatus.

This first group of instrument readings is supplemented by measurements of material deformation, corrected for temperature effects, because the temperature is liable to vary rapidly on the site during the test and during prestressing. These measurements concern the typical sections of the raft, cylinder and dome for standard units. Specific points of these structural components were specially instrumented on the first site, Tricastin 1, and then for Cruas 1, because of the changes made. Hence the behaviour of specific components (personnel hatch, equipment hatch, raft/cylinder and cylinder/dome junctions) was checked during these readings.

Deformation measurements were taken by vibrating wire (acoystic) strain gauges cast in the concrete in different numbers on the various nuclear units built. The strain gauges are generally positioned in pairs, near the inner and outer surfaces of the walls to record deformations under normal forces and deformations under bending forces. Deformations are measured in the vertical, tangential or radial direction depending on the location of the gauge.

Each deformation measurement is combined with a local temperature measurement, taken by thermocouples placed near the gauges.

For a typical 900 MW PWR unit, this instrumentation is:

4 radial deformation measurements at the centre of the raft,
16 vertical or tangential deformation measurements at level +23m in the cylinder
4 radial deformation measurements in the dome crown (Figure 1).

This minimum instrumentation is sufficient to check the behaviour of a containment, with reference to the abundant results obtained with the instrumentation of Tricastin 1.

The raft of the firstunit at each site is also equipped with multiple deformation measurement points on two perpendicular diameters. The foundation soils at Tricastin 1 and Blayais 1 were provided with Glotzl type total stress cells to analyze the force distribution on the container support surface.

The following table summarizes this instrumentation. All these measurements, which provide a large body of data for each pressure level at each containment, required computer processing for comparisons between the different sites.

Unit 1 Tricastin	Unit 1 at each site	Other units at each site	Unit 1 Cruas
TOPOGRAPHIC LEVELLING IN GALLERY			
12 locations	12 locations	12 locations	12 locations
LEVELLING BY HYDRAULIC POTS			
13 pots	13 pots	9 pots	13 pots
VARIATION IN RAFT DIAMETER			
2 invar wires	2 invar wires	2 invar wires	2 invar wires
CYLINDER DEFORMATION			
12 pendulums	12 pendulums	12 pendulums	12 pendulums
RAFT TEMPERATURE			
26 thermocouples	variable between 24 and 3 t/c	3 t/c	27 t/c
CONTAINMENT TEMPERATURE			
70 thermocouples	18 t/c	18 t/c	62 t/c
RAFT DEFORMATION			
50 strain gauges	variable between 50 and 4 s/g	4 s/g	38 s/g
CONTAINMENT DEFORMATION			
96 strain gauges	20 s/g	20 s/g	100 s/g
DYNAMOMETERS			
4	4	0	4
STRESSES UNDER RAFT			
44 Glotzl cells	Blayais 1 only	0	0
3-AXIS CYLINDER MOVEMENTS			
12 Vinchon apparatus	0	0	0

3 BEHAVIOUR OF SUPERSTRUCTURES

3.1 STRAIN GAUGES

From the measurements taken during the test, it is possible to plot, for a typical section of the cylinder for example, the curve of the mean vertical and tangential deformation of the mean fibre of the wall as a function of applied loading pressure. This stress/strain curve displays good linearity and good overall reversibility when the load is removed; the residual deformation casued by loading is very slight. The reference test case involves practically pure elastic behaviour of the structure.

Material deformation from the start of tendon sacking can be monitored as a function of time. Prestressing causes compression of the sections considered. This curve reveals creep of the concrete with time under the effect of prestressing. The pressure test causes espansion but the overall result is a net compression.

3.2 MODULI

The results from all the 900 MW units help in calculating the actual modulus of elasticity of the materials in the cylinder and dome of each containment. The prodedure is as follows:

The moduli for the first containment of this 900 MW PWR standard, Tricastin 1, were evaluated by comparison between the measurements and FEM predictions. Since the stresses and strains are known, the modulus can by determined easily.

For each of the other containments, the deformations measured in each section for each non-zero test increment were compared systematically with the corresponding values from Tricastin 1. An average multiplication factor was determined for the cylinder and dome of each dontainment by reference to Tricastin 1. This makes it possible to evaluate the moduli by reference to this initial nuclear unit.

containment no.	TR 1	TR 2	TR 3	TR 4	GR 1	DA 1	DA 2	DA 3	SL 1	SL 2	BL 1
multiplication factor	1	1.12	1.11	0.98	1.01	1.25	1.13	1.24	1.20	1.34	1.25
cylinder modulus MPa	36,000	32,140	32,430	36,770	35,640	28,800	31,860	29,030	30,000	26,870	28,800

The same calculation, made by reference to the results obtained at Dampierre 1, yielded values close to the previous ones, with a maximum relative error of 10%. The accuracy of the method can therefore be estimated at 10%.

This comparison reveals a clear differentiation in the moduli as a function of site location. The average modulus measured on the Rhone Valley sites (Tricastin, Cruas) is higher than the average measured on the Loire Valley sites (Dampierre, Saint Laurent, Chinon). This difference can be associated with the type of concrete aggregate employed.

This evaluation of moduli helps to compare the theoretical values of the mean stresses with the values resulting from strain measurements (E.) for each instrumented section. The table below presents this comparison for the mean tangential stresses in the cylinder for a number of sites. The theoretical value is 7.61 MPa.

	TR 1	TR 2	TR 3	TR 4	GR 1	DA 1	DA 2	DA 3	SL 1	SL 2	BL 1
E. (MPa)	7.68	7.59	7.88	8.15	8.30	7.36	8.31	6.42	7.48	7.35	7.56

The theoretical value shows good agreement with the experimental values. The finite element calculation predicts stresses with good accuracy, independently of the modulus, and the differences can be accounted for by the internal liner or the steel reinforcement. The calculation results are therefore corroborated by experiment to the extent that the measured deformations are similar to the calculated deformations. Excellent agreement can be obtained if one considers the influence of the Poisson's ratio on the theoretical calculation: a value of 0.16 helps to refine the results.

3.3 ANALYSIS OF CONTAINMENT DEFORMATIONS

The measurements taken with pendulums in the containment and invar wires in the raft serve to plot the deformations of the vertical wall as a function of test pressure. The variation in radius of the containment is not uniform along its circumference. This mechanism of containment ovalization cannot be explained by the presence of geometric discontinuities. The ribs on the wall alter the behaviour of the containment under pressure. This was specially analyzed with the instrumentation at Tricastin 1, and topographic readings helped to plot the deformation curve. The four deformation lobes were found to agree with the calculation results.

Similarly, the behaviour of specific points of the containment was checked during the measurements on Tricastin 1 and Cruas 1. The influence of the geometry of the equipment hatch was identified, in correlation with design forecasts. The high stress zones were also identified vertically above the inner surface, and horizontally on the outer surface of the skirt.

4 BEHAVIOUR OF THE RAFT

The behaviour of the containment raft depends on the foundation soil at each site. The first unit of each site is therefore instrumented in detail, and the mechanisms identified are:

- general subsidence of the structure,
- stress distributions in the foundation soil,
- raft deformation under prestressing or under testing,
- material deformations.

4.1 SOIL SUBSIDENCE

Foundation soil subsidence was identified by topographic readings in the gallery. This varies as a function of time during the different works construction phases, in accordance with the successive loads applied to the ground. Subsidence under the raft is not perfectly uniform, and differential subsidence variations of a few millimetres cause a slight tilting of the containment. The raft is sensitive to variations in thickness of the soil layers of different stiffness.

4.2 STRESS MEASUREMENTS

The stress measurements taken by Glotzl cells record the same processes of stress build-up as a function of time, with the scatter inherent in this measurement system. The measurements serve to analyze the stress distribution under the raft. It appears that the periphery of the foundation soil is more highly stressed than the central zone, similar to the findings of the mathematical model which included a depth of the foundation soil under the structure. This behaviour can also be reproduced with a spring model (Winckler's model) if spring stiffness is tailored to the different zones of the raft.

It is possible to follow the changing trend in load distribution on the raft as the construction proceeds.

4.3 ANALYSIS OF RAFT DEFORMATIONS

The system of levelling by hydraulic pots records variations in the geometry of the raft. During the prestressing phase, the raft tends to deform concave upwards, while dead weight alone has the opposite effect.

This process is accentuated during the pressure test. The periphery of the raft practically does not move, while the centre sinks 2 to 10mm under the effect of the pressure. The raft retains a residual deflection of a few millimetres, since the soil response is never perfectly elastic.

The Cruas 1 power plant rests on anti-earthquake neoprene supports, but the overall behaviour of the raft is unaffected by this arrangement.

4.4 STRAIN MEASUREMENTS

Strain measurements in the raft confirmed the results obtained during displacement measurements. The residual deformations resulting from the test and recorded by the acoustic strain gauges was limited ($\simeq 10 \mu /$). Practically pure elastic behaviour of the raft can be confirmed up to a pressure of about 0.25 to 0.3 MPa.

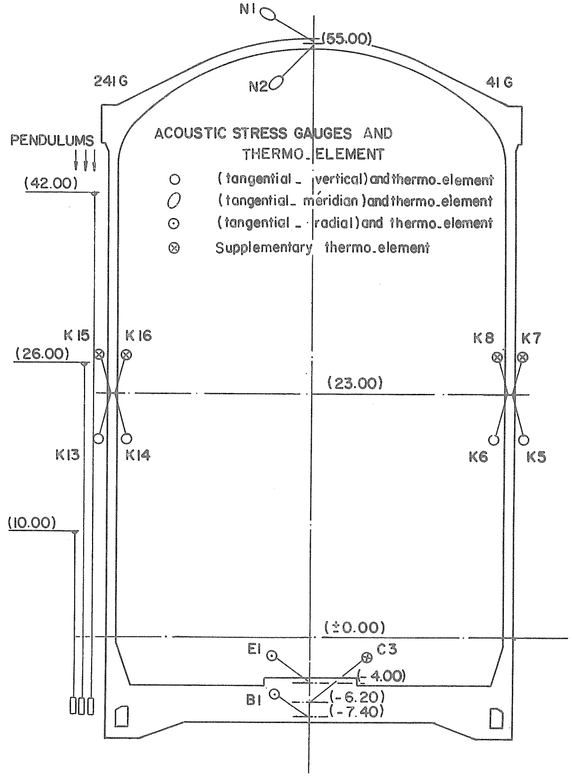
These strain measurements show that a weak tensile force exists at the centre of the raft, which has to do with the fact that the raft diameter does not change during the test. Detailed measurements at the junction zone between the raft and cylinder revealed a strong restraining force around the perimeter, which do not 'rotate' during the test. After the containment is prestressed, the raft can be considered as fully restrained on its periphery.

5 CONCLUSIONS

Instrumentation of these 900 MW PWR standard containments serves to confirm the satisfactory behaviour of the reactor building under the reference loading. The results obtained validated the design assumptions and analytical methods employed, especially by the finite element method, both for typical sections and for singularities.

The behaviour of the structure under the short test loading is elastic on the whole. The instrumentation revealed time-dependent concrete creep under the prestressing forces. The satisfactory records from Tricastin 1 over a period of five years confirms that it is effectively possible to monitor the behaviour of these containments throughout their operating life.

900 MW PWR
VERTICAL CROSS SECTION
TYPICAL INSTRUMENTATION



900 MW PWR
CYLINDER CROSS SECTION
TYPICAL INSTRUMENTATION