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Monitoring of Prestressed Concrete Containment Vessel at Temelin Nuclear Power Station, Unit 1

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ABSTRACT

The state of stress and deformation of the prestressed concrete containment vessel (PCCV) at the Temelin NPP was monitored by various systems of measurement. A comprehensive analysis of the PCCV was performed, including seismic analysis. The concrete of the PCCV was also monitored long-term in the laboratory. The measurement results were compared with the results of computer modelling and laboratory tests. This paper describes the PCCV structure, specifically the secondary tensioning; the structural integrity test; the system of measurement and comparisons; and the analysis of PCCV.

1. Introduction

At present, 2 x 1000 MW blocks of the Temelin NPP are being completed with PWR reactors and prestressed concrete containment. A structural integrity test (SIT) of the first block was held from December 1998 to January 1999. The SIT included compression tests, which were monitored by various systems of measurement. Before the SIT test, a structural analysis was done, and compared with the test. The comparison of the pre-SIT analysis and results of the SIT is ongoing, but some conclusions from this comparison are currently available and presented in this paper.

2. Description of containment of the Temelin Nuclear Power Station

The Temelin NPP PCCV Unit 1 is designed from prestressed concrete. This containment has a cylinder shape with an inner diameter of 45 m, covered by a dome shaped spherical cap. The shape is outlined in Fig. 1. The wall thickness of the cylinder is 1200 mm and 1100 mm for the dome. These dimensions were determined by the construction requirements, and including biological protection. The cylinder of the containment is fixed into a reinforced concrete slab 2.4 m thick at level +13.2 m. The concrete for the containment is grade B40 with a density of 2350 kg/m^3, according to Czechoslovak Standards (CSN). It is designed as a hydrotechnical concrete. The hermetic properties of the containment are provided by an 8 mm thick carbon steel liner plate attached to the inside surface of the PCCV.

System of prestressing

The cylinder wall is prestressed by 96 prestressing tendons placed in a spiral trajectory with the angle of inclination from the horizontal at 35.05^{O}. The tendons are anchored in the top of the circumferential rim and in the lower part their direction is changed by steel blocks placed in the reinforced slab of the floor (Figure No.1). The dome is prestressed by two systems of prestressing tendons placed in normal sections of the dome. There are 36 tendons in the dome in total. Prestressing tendons in the cylinder and dome consist of 450 wires of 5 mm in diameter. The prestressing force, required from the project, imposed by the prestressing unit is 10 MN (1000 t). The tendons are placed ungrouted in polyethylene tubes. Protection against corrosion is provided during production of the tendons by sinking the cable into warmed grease, and the anchors are preserved after installation of the tendon to the structure.

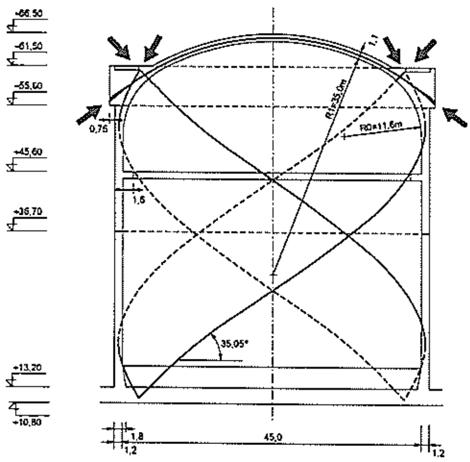

Figure 1 : Scheme of position of tendons in dome and cylinder of the NPP Temelin

3. Measuring System of PCCV at the Temelin NPP

Containment is an important safety system which serves as a protection against radioactivity, and is therefore continuously measured during building construction. It is assumed that the containment will be observed and analysed at all times during the operation of the plant.

Careful attention is paid to methods for the verification of the condition of the containment. Several systems of measurements are used to observe the states of stress and strain. These systems are briefly described below:

1. The first system uses vibration wire strain gauges, which measure stress and strain in the containment with gauges made in Russia and the Czech Republic. The vibration wire gauges are placed in the walls of the cylinder and dome in four measuring sections. They are placed at six height levels in the cylinder and at three height levels in the dome. The gauges are placed on the reinforcement re-bars in the concrete of the dome and cylinder and on the surface of the cylinder. Beside the strain gauges on the re-bars, there are also temperature sensors. There are over 200 string gauges in the containment in total.

2. The next system of measurement observes the size of prestressing force by a magnetoelastic method (MEM). This method is based on changes of the electromagnetic field of the measuring instrument related to stress in loaded elements inside the magnetic field. This method was used in the Czech Republic for measuring the force in the tendons of suspension bridges and was modified for the prestressing system of the NPP Temelin. This method is used for measuring the size of the prestressing force at several points along the length of the prestressing tendons of the dome and cylinder. This method was also used for the determination of the coefficient of friction between the tendon and the walls of the polyethylene tubing.

3. In addition to measurement by magnetoelastic method (which measures the force on a restricted number of tendons, particularly two tendons in the cylinder and two tendons in the dome), also used were strain gauges LY 116/120 HOTTINGER, which were glued to a bolt of the prestressing anchor. The stress is measured by four pairs of gauges placed on each anchor of the tendons within the dome and cylinder.

4. System DFM is an additional check system installed only during the SIT. The system measured vertical displacements of the dome at four locations by inductive gauges W-50-HBM, and horizontal displacement of cylinder on level +36.90 and +47.00. Overall number of inductive gauges was 16. The system was completed by checking resistance strain gauges and gauges around hermetic input area.

Collection of measuring data was automatic during the SIT and will be during the operation of the plant.

A summary of the measuring systems is shown in TABLE No. 1. The extent of measurements is considerable, but it is important to appreciate that the containment is, from the nuclear safety point of view, the most important structure of the NPP. Moreover, the calculations for the containment were not included in the Russian project documentation and a new, unique method was used for the prestressing of the containment.

Table 1 : Summary of the measuring systems used for observation of the containment of NPP at Temelin

Abbreviation of the measur. system	Type of gauge	Static parameter measured	Projects
NDS	type of vibration wire strain gauge: PSAS (on re-bars) PLDS (in concrete of the containm.) PLPS (on the inner surface of the cylinder) PTS (in concrete of the containm.)	σ_a stress in re-bars (kPa) ε_b strain of concrete u displacement approximately in the middle of the cylinder °C temperature of concrete	gauges made in USSR
SDM	Vibration wire strain gauge: - in concrete of the containment - on re-bars - measuring temperature	ε_b strain of concrete ε_a strain of re-bars °C temperature of concrete	check gauges made in the Czech Republic
MEM	gauges measuring on the base of magneto-elastic principle are placed on polyethylene tube of prestressing cable	$F_{(t)}$ prestressing force (MN)	gauges MEM of TSUS Bratislava, Slovakia
HOTTINGER	resistance strain gauge placed on anchor bolts of prestressing system	$F_{(t)}$ prestressing force in the place of the anchor (kN)	
DFM	1.inductive gauges installed only for period of the SIT: - on level +36.90, +46.60 (cylinder) - on level +36.90 (dome) 2.check system of resistance str. gage	u displacement of cylinder at horizontal direction u displacement of dome at vertical direction ε_v strain of steel liner	

Long-term monitoring of PCCV in the laboratory

Reological changes of the concrete of the containment are observed by long-term laboratory tests of specimens (prisms of size 100x100x400 mm), which were sampled from the structure during the placing of concrete of the cylinder and dome.

Check methods which were used for the SIT

Check methods were used during three phases for the PCCV of the Temelin NPP: pre-SIT, SIT and post SIT.

Pre-SIT inspections include the following :

- measuring and inspection of cracks on the concrete surface of PCCV and preparation of a crack map
- measuring and inspection of hermetic part and elaborating of drawing documentation
- inspection of steel structures concerning SIT
- inspection of the extent of prestressing force by prestressing jack and other methods (MEM, Hottinger, NDS, SDM)

SIT inspections include the following :

- inspection of the cylinder and dome surface, detailed measurement of cracks with data logging, including drawing of location on the crack map
- inspection of carbon steel liner plates

- inspection of anchorage system

Post-SIT (instantly after unloading) inspections include the following :

- inspection of the concrete surface cracks of cylinder and dome, anchorage system of prestressed tendons and some steel structures
- inspection of cracks on the surface and elaborating of the crack map
- use of acoustic method to detect and record cavities or other failures

4. The completed analyses

Designs of reactor building including containment and some other structures were prepared in the former Soviet Union (the designing organisation was AEP Moscow). Designs were obtained without static and dynamics calculations, which were consequently worked out according to Czech and international standards and specifications. The containment was made according to the Czech Standards - Codes of Practices.

The structure of the PCCV was checked for the following loads:

1. Maximal project accident is characterised by over pressure p_a=0.40 MPa and temperature inside of the containment of t= 150^{O}C.
2. Extreme seismic load with the greatest acceleration in a horizontal direction 0.1g and 0.07g in a vertical direction.
3. Pressure wave is calculated with an excess pressure at its front of 30 kPa.
4. Impact of an aeroplane:
   a) of weight 7t with a speed at the moment of impact of 100 m/s
   b) of weight 20t with a speed at the moment of impact of 200 m/s.

Table 2 : Combinations of loading for the Temelin PCCV

		Permar		Long-time		Short-time live load				Extreme events						
		Dead load	Prestressing	Load of pipes and mechanisms	Working load	Strength test	Cranes and others	Break of operation conditions	Loads during meteorological events	Extreme project accident	Seismic load	Extreme seismic load	Incidental load by reason of seismic load	Pressure wave by reason of explosion	Impact of aircraft - 7t	Impact of aircraft - 20 t
PCCV Objekt no. 800/02	1	+	+	+	-	+	-	-	+	-	-	-	-	-	-	-
	2	+	+	+	+	-	+	-	+	-	-	-	-	-	-	-
	3	+	+	+	-	-	+	+	+	+	-	-	-	-	-	-
	4	+	+	+	-	-	-	-	-	-	+	-	-	-	-	-
	5	+	+	+	+	-	-	-	-	-	-	+	+	-	-	-
	6	+	+	+	+	-	-	-	+	-	-	-	-	+	-	-
	7	+	+	+	+	-	-	-	+	-	-	-	-	-	-	+
	8	+	+	+	+	-	-	-	-	-	-	-	-	-	+	-
Foundation part Obj. no. 800/03	1	+	-	+	-	-	-	-	-	+	+	-	+	-	-	-
	2	+	-	+	+	-	-	-	-	-	-	+	+	-	-	-
	3	+	-	+	+	-	+	-	-	-	-	-	-	+	-	-
	4	+	-	+	+	-	+	-	-	-	-	-	-	-	+	-

5. Pre-SIT analysis, on the strength of which was prepared the SIT tests.

Combinations of loading used in analyses for the Temelin PCCV are shown in Table 2.

4. Structural integrity test

The structural integrity test was carried out from Dec. 1998 to Jan. 1999, according to the pressure history with levels of pressure 0.0, 0.07, 0.18, 0.29, 0.40, 0.46 MPa. The pressure was increased gradually up to 0.46 MPa, then decreased according to the same levels of pressure. Maximum displacement in the vertical direction occurred at the dome 18.0 mm and in the horizontal direction at the cylinder 7.66 mm. The maximum displacements were under the maximum pressure in each direction. Fig. No.2 shows the relationships between pressure and displacement in the horizontal direction at the cylinder. Results of measured displacements showed the elastic and symmetrical behaviour of PCCV.

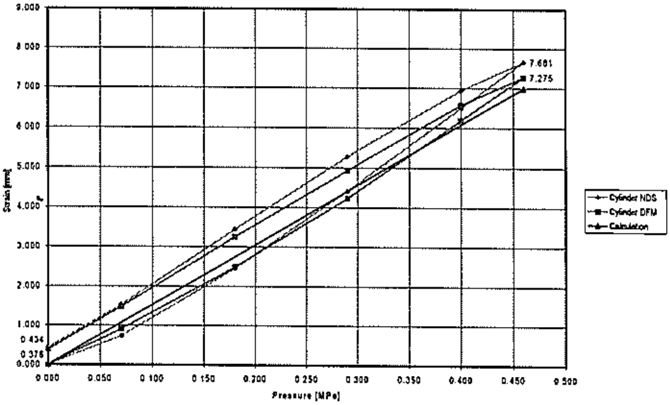

Figure 2 : Displacement Behaviour of horizontal direction at the Dome

Temperature

Figure No. 3 shows the time history of temperature inside the PCCV. The temperature variation of the internal temperature gauges was relatively constant, except outside the gauge. The temperature variation did not interfere with the measurement of the SIT.

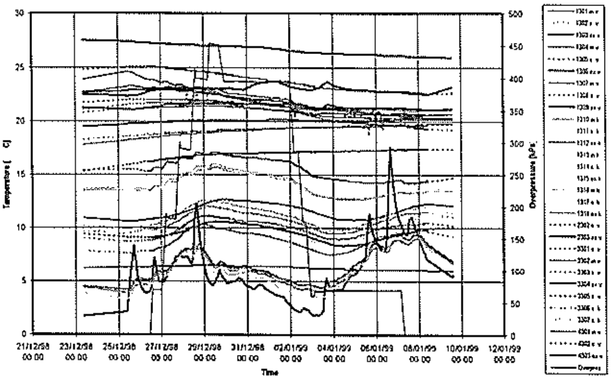

Figure 3 : Temperature and pressure variation during the SIT

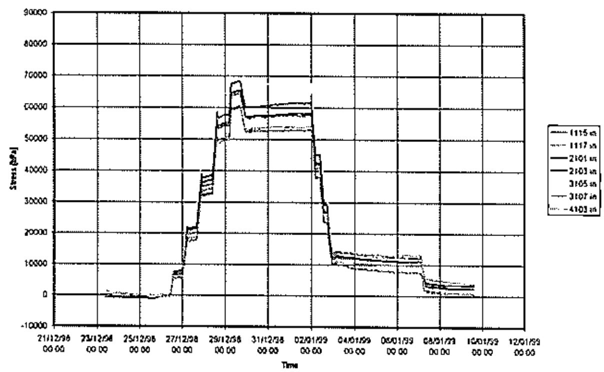

Figure 4 : Stress variation ($\Delta\sigma_s$) – cylinder

Pre-SIT tests of materials and PCCV structure

Crack map and failures of concrete

After a visual inspection of concrete surface cracks and other failures, a detailed crack map was prepared. A similar map was done before and after the prestressing of PCCV.

Concrete strength tests

Concrete strength tests were carried out by a Schmidt impact hammer. These tests show that the average concrete strength of PCCV was 64.3 Mpa, which satisfied the design criteria.

Concrete is observed long-time in Centrum-MCT laboratory with specimens that have a prism shape and are described in chapter no. 3. The results of the tests were used during the prestressing of PCCV and for the pre-SIT analyses.

Prestressing and stress of PCCV

A check of prestressing force was carried out in the location of the anchorage by prestressing jacks. Random set of tendons were chosen (6 dome t. and 12 cylinder t.).

Measured values were statistically evaluated. The average prestressing force value of the dome was 9532 kN with 95% safety interval <9619;9445> and 9062 kN for cylinder with 95% safety interval <9214;8909>. Prestressing forces tests were also measured by MEM and Hottinger methods.

Steel liner and structures

Visual inspection of steel liner was carried out. The cavity map was then prepared. The tightness of the steel liner was checked including site welds.

5. Conclusion

Measurement during the SIT confirm that the design criteria was satisfied. The PCCV structure was returned after unloading to the initial position more than 80%. Rates between non-elastic and total strain at the cylinder were measured DFM gauge 0.052<0.2mm (PLPS gauges 0.056<0.2mm) and at the dome DFM gauges 0.027<0.2mm (Standard CSN 732030). The stress variations ($\Delta\sigma_s$) in tendons show elastic behaviour. Inspections confirm that during the SIT failures of concrete or steel liner didn't occur.

However, the evaluation of the SIT results is currently ongoing and the comparison between measured and calculated displacement has not been finished yet. It can be shown that differences of displacement at maximum pressure are less than 15 %. The containment structure approximates the behaviour predicted by the theoretical analysis.

6. References

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