Behaviour of Inner Containment Structure of an Indian PHWR during Proof Testing

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ABSTRACT

The present Indian pressurised heavy water reactors (PHWR) being designed and constructed have a double containment system where the inner containment (IC) is a prestressed concrete cylinder with a prestressed concrete spherical segmental dome. The outer containment (OC) encompasses the IC and is made of reinforced concrete. To ensure the structural integrity of the IC under design basis accident (DBA) pressure and elastic behaviour of the IC, the containment is pressurised to its design pressure and deflections and strains of IC are measured. A scheme of instrumentation for IC to this effect is finalised at the design stage. This paper presents a comprehensive study of the performance of the instrumentation in measuring the deflections and strains with respect to the analytical values obtained from the finite element (FE) analysis. This paper also discusses briefly about the design of IC. Based on the detailed comparison it is concluded that the behaviour of the IC structure and the developed stresses are matching well with the theoretical predictions and the stresses developed in the IC structure are well within the specified limit of the selected design code.

INTRODUCTION

The present Indian PHWRs being designed and constructed have a complete double containment system where the IC structure is a prestressed concrete cylinder of M35 (cube strength, f_{ck}) grade concrete capped with a prestressed concrete segmental dome of M60 (f_{ck}) grade concrete. The OC structure covers the IC structure completely and is a reinforced concrete structure. Fig.-1 shows a typical PHWR containment system. The IC dome of a typical 220 MWe PHWR is provided with four large steam generator (SG) opening to facilitate replacement of the same at later date, if situation arises, during the operating life of the plant. Presence of these large SG openings in prestressed concrete dome poses challenge both in design as well as in construction leading to closely spaced bands of prestressed cables in certain zones.

Design of the structural elements of the typical IC structure of Indian PHWRs is based on limit state concept as per the French Code RCC-G[1] along with the supporting documents BPEL[2] and BAEL[3]. The IC structure is proof tested under the full design pressure. This internal pressure will develop in a possible event of DBA due to Main Steam Line Break (MSLB). The proof test is carried out to demonstrate that in a possible event of DBA the IC behaves elastically as assumed in the design.

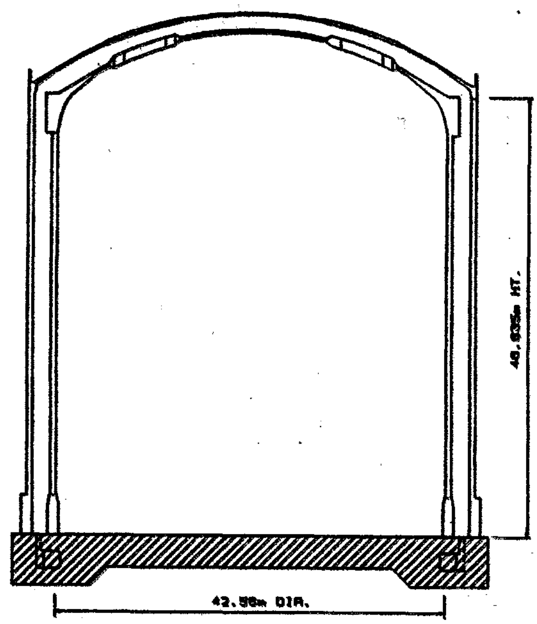


FIG-1: INDIAN PHWR CONTAINMENT SYSTEM

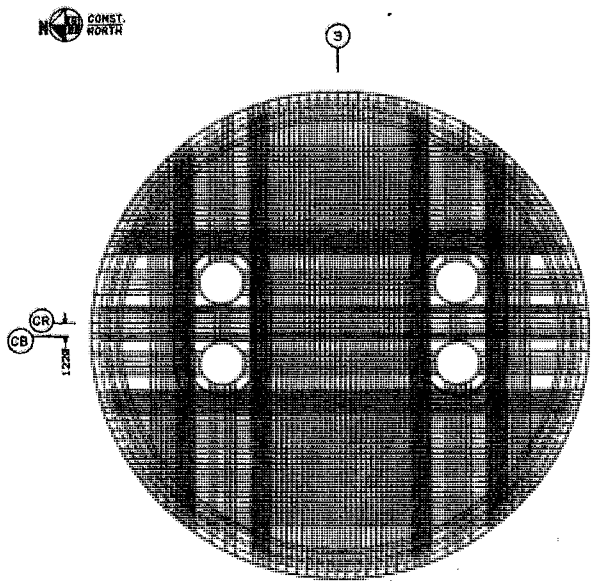
This paper discusses the design aspect of IC in brief and presents the proof testing scheme and results obtained from actual proof testing, the analysis of IC under internal pressure and the comparison of the results obtained from the analysis with that of the actual test.

DESIGN OF IC

The IC of a typical Indian PHWR is designed as a prestressed concrete cylinder with 610mm thickness capped with a segmental spherical dome with 450mm thickness. The IC wall is connected to the IC dome by a ring beam.

The IC is prestressed with 19K13 system that consists of 19 strands of 12.7mm nominal diameter low relaxation steel conforming to IS:14268[4] and IS:6006[5]. The IC wall is prestressed with horizontal C-type cables with spacing approximately 270mm c/c. The vertical prestress in the IC wall is imparted partially by pure vertical cable running from raft to the top of the ring beam and partly by the inverted J-type cables running from the raft to the other side of the ring beam. The IC dome is prestressed by the inverted J-type cables and inverted C-type cables placed orthogonally in two layers at the mid-depth of the concrete shell at a spacing of 450mm c/c in general portion and at a spacing of 225mm c/c at the closely spaced bands. These closely spaced bands are generated because of the presence of the four large SG openings in the dome. A typical cable layout in the IC dome is shown in Fig.-2.

The IC has been designed for an internal pressure of 17.3 T/m^2, which has been estimated based on the DBA due to MSLB. FE analysis has been carried out for various applicable loads on the IC structure in order to estimate forces and moments developed in the containment structure. One half of the IC structure is modelled exploiting the symmetricity of the structure. The SG openings in the IC dome and the Main Airlock Barrel (MALB) opening in the IC wall have been modelled. The FE discretisation of IC structure is shown in Fig.-3. The IC structure has been designed using the above analysis results as per the provisions of the design code. Radial stresses generated in the prestressed double curvature structure, i.e., the spherical segmental dome portion in the present case, due to the curvature, transition and stress concentration effect needs to be looked into in detail. Special design criterion has been adopted in designing the IC dome for radial stresses.



CR – Centre of Reactor, CB- Centre of Reactor Building

FIG-2: PRESTRESSING CABLE LAYOUT IN IC DOME

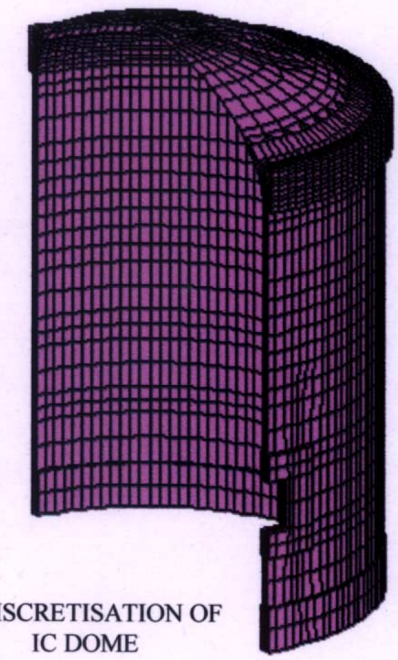


FIG.-3: FE DISCRETISATION OF IC DOME

The design of the IC has been carried out in such a way that the IC behaves elastically under DBA and the leakage from the IC under such DBA scenario is within the stipulated limits. In order to ensure the structural integrity of the IC under the DBA pressure and to ensure elastic behaviour of the IC, the containment is pressurised upto its design pressure and the behaviour of the IC has been monitored during the proof testing.

SCHEME OF INSTRUMENTATION FOR PROOF TESTING

The primary containment was pressurised upto its design pressure at approximately five equal pressure stages with pressure hold for 30 minutes at each stage before the vertical deflections / radial dilations and the strain measurements were taken. Prior to pressurisation of the containment, dummy runs were taken to establish stability of the instruments as well as generating base line data for varying weather condition. Also local proof tests at the design pressure were carried out for cable EPs, pipe EPs having expansion bellows and airlock for the structural integrity.

During the proof test the IC structure was pressurised with oil free air to 17.3 T/m^2 (g) at the rate of 2.0 T/m^2 (g) per hour. The depressurisation of the primary containment was carried out following the five pressure steps and reading of measuring instruments were taken.

A scheme of instrumentation is finalised before the commencement of the construction of IC. The deflections of the IC structure under proof testing are measured using dial gauges. A total number of thirty-three (33) locations are used for the measurement of deflection. The vertical deflections of the IC dome and the radial dilation of the IC wall is measured with reference to the outer containment under deflection measurement scheme. The locations of deflection measurements in IC dome are shown in Fig.-4.

A total number of fifty-eight (58) surface mounted electric resistance strain gauges (SMER), sixteen (16) number of surface mounted vibrating wire strain gauges (SMVWSG) and twelve (12) number of embedded type vibrating wire strain gauges (EVWSG) are used to measure strains in IC structure.

Due regard has been given to capture the strains around the large openings such as SG opening in IC dome and MALB in the IC wall. Attention has also been given to capture the radial stresses (out-of-plane stresses) in the dome. The radial stresses have been found to be critical in the closely spaced bands of the prestressing cables in the IC dome at the thickening end of the transition zone of SG opening (refer Fig.-1 and Fig.-2). Hence, strain gauges are embedded at these locations to compare the theoretically predicted strain values with that of the actual one.

The EVWSGs are embedded approximately at the mid-depth of the IC dome. The SMERs and SMVWSGs are mounted either on the inner or on the outer surface of the IC wall. The strain gauges are connected to automatic data loggers. The locations of strain gauges in IC wall, IC dome general portion and around SG openings are shown below in Fig.-5, Fig.-6 and Fig.-7 respectively.

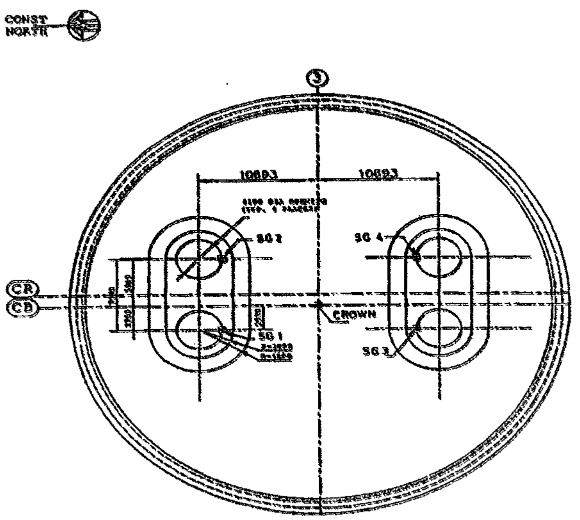


FIG.-4: LOCATIONS OF DEFLECTION MEASUREMENT IN IC DOME

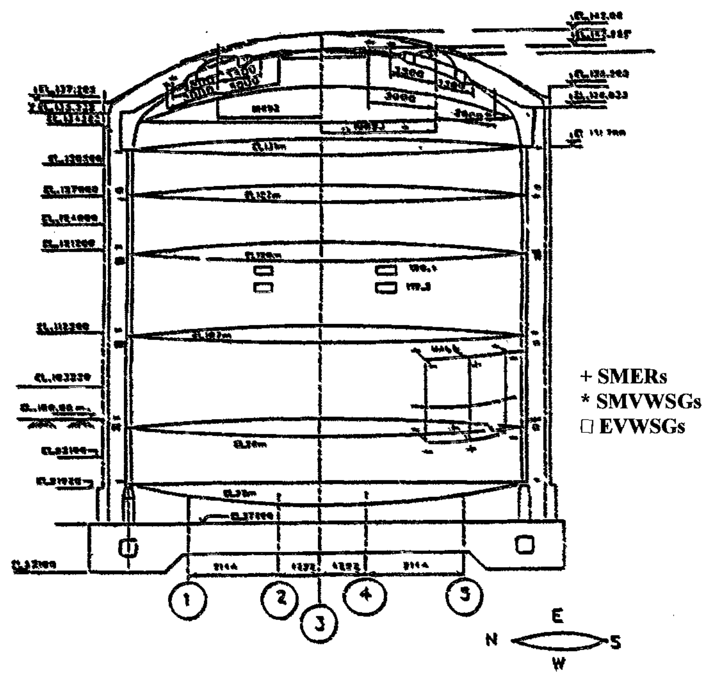


FIG.-5: LOCATIONS OF STRAIN GAUGES (SMERs, SMVWSGs and EVWSGs)

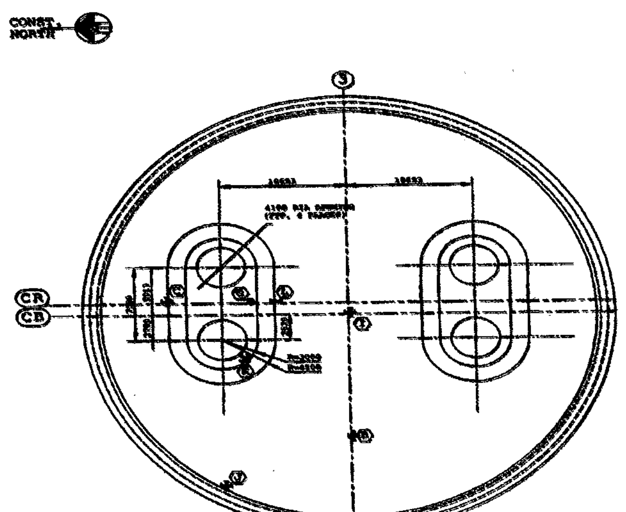


FIG.-6: LOCATIONS OF EVWSGs IN IC DOME

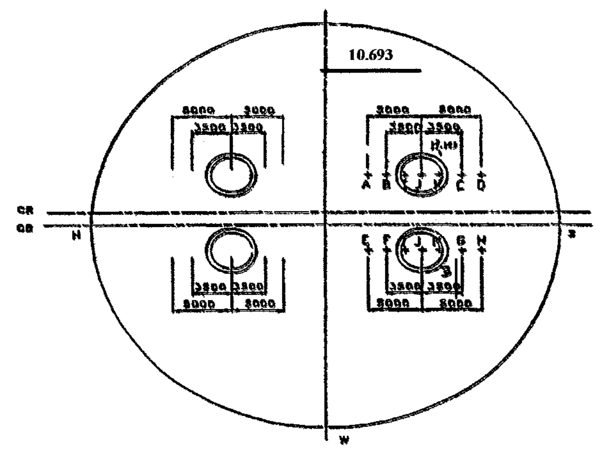


FIG.-7: LOCATIONS OF SMERs AROUND SG OPENING IN IC DOME

ANALYSIS OF IC UNDER DESIGN PRESSURE

RCC-G indicates different values of Young's Modulus (E-value) of concrete for different kind of actions viz., permanent action, variable action and accidental action. The IC was initially analysed considering a shell model with the E-value corresponding to the variable action under internal pressure (17.3 T/m^2) and the strains at predetermined locations as shown in Fig.-5 and Fig.-6 above were obtained.

Based on the performance of the shell model in predicting the strains in the discontinuity areas, a need was felt to consider a separate detailed FE model consisting of general shell elements and 3-D brick elements in order to improve the prediction of strains in the IC structure under internal pressure. The IC wall, ring beam and the ring beam–dome junction have been modelled using 3-D brick elements and the dome portion has been modelled using general shell elements. Rigid links have been provided at the interface of brick element and general shell element to have compatibility of displacements.

Since the internal pressure is gradually developed with sufficient time for stabilisation, the E-value as specified in RCC-G corresponding to variable loading has been considered in the initial analysis. It was observed that the predicted analytical deflections during proof test are, in general, on the higher side compared to the observed values. This indicates that there is a need to consider higher E-value in the analysis compared to the one suggested by RCC-G for variable loads lasting more than twenty-four hours. In view of this, parametric study has been carried out varying the E-value of the IC in order to estimate the effective E-value compatible with the measured deflections. Based on the parametric study it has been observed that the E-value of the structure, thus calculated, falls in between the E-value suggested by the design code for the variable and the accidental action. The E-value, thus estimated, has been used for the computation of strains from the stresses obtained from the FE analysis.

Calculations Of Strains From The Global Analysis Result Of Finite Element Analysis

Based on the actual locations (i.e., coordinates) of the points where the strains are measured at the site during proof testing of IC, the appropriate elements or nodes in which the strain gauges are situated have been identified on the finite element model. In-plane strain in IC dome portion is calculated at the centroid of the element or at the node in the direction of the gauge as follows:

$$S_{xp} = S_{xx}\cos^2\theta + S_{yy}\sin^2\theta + 2S_{xy}\sin\theta\cos\theta \quad (1)$$

$$S_{zp} = S_{zz}\cos^2\theta + S_{yy}\sin^2\theta + 2S_{zy}\sin\theta\cos\theta \quad (2)$$

where, S_{xp} & S_{zp} are in-plane stresses in x and z direction respectively

S_{xx}, S_{yy}, S_{zz}, S_{zy}, S_{xy} are stresses in global direction of FE model

θ is the angle subtended with the vertical axis of the dome and the line joining the centre of the dome and the point under consideration

Strain gauges in the IC wall portion are located on north and south end of the wall. Hence, the meridional strain is strain in global Y-direction and circumferential strain is strain in global Z-direction in the IC wall portion. The strains thus calculated are modified for the Poisson's effect as follows:

$$\varepsilon_x = \varepsilon_{xp} - \nu * \varepsilon_{zp} \quad (3)$$

$$\varepsilon_z = \varepsilon_{zp} - \nu * \varepsilon_{xp} \quad (4)$$

where ε_x, ε_z = strain in x and z direction respectively corrected for lateral strain component

ε_{xp}, ε_{zp} = strain in the plane of dome in x and z direction respectively

ν = Poisson's ratio

COMPARISON OF PREDICTED AND MEASURED DEFLECTIONS AND STRAINS DURING PROOF TESTING AND DISCUSSION OF THE RESULTS OBTAINED

Table-1 below compares the theoretical and observed deflections of IC structure at various locations due to internal pressure.

Table-1 shows the comparison of deflections between the observed and predicted values. The comparison shows that the deflection/dilation values are quite in agreement. Hence it can be said from the Table-1 above that the E-values taken for the IC wall, ring beam and dome for the analysis of IC structure under internal pressure loading is representing the actual E-value of the IC structure constructed.

Strain measurement made in the IC dome is compared with those obtained from FE analysis results in Table-2 below. It can be observed from the Table-2 that out of a total of eighty six (86) different type of strain gauges, only three (3) have not worked during the proof testing.

TABLE-1: Comparison of Deflections in IC

Portion in RB	Response Type	Location	Observed Deflection Values during Proof Test[#]		Deflection Values obtained from FE Analysis[#]	
			El. (m)	Mag. (mm)	El. (m)	Mag. (mm)
IC WALL	Radial Dilation	East End	94.1	2.41	94.4	2.80
			111.6	4.02	112.027	3.50
			117.6	4.64	117.383	3.53
			122.9	4.10	122.74	3.81
		South End	94.1	2.71	94.4	2.75
			111.6	3.96	112.027	3.23
			117.6	3.75	117.383	3.28
			122.9	2.97	122.74	3.59
		North End	94.1	2.46	94.4	2.75
			111.6	2.91	112.027	3.23
			117.6	3.77	117.383	3.28
			122.9	4.02	122.74	3.59
		West End	94.1	1.40	94.4	1.60
			111.6	2.57	112.027	1.67
			117.6	3.67	117.383	2.29
			122.9	4.06	122.74	2.92
IC RING BEAM	Radial Dilation	East End	136.0	-1.39	136.035	-1.17
		South End		-1.12		-1.18
		North End		-0.75		-1.18
		West End		-0.83		1.36
	Vertical Deflection	East End	136.0	...	136.035	2.26
		South End		3.11		2.25
		North End		2.89		2.25
		West End		2.68		2.15
IC DOME	Vertical Deflection	Crown	-	9.76	-	9.76
		SG1	-	8.69	-	7.84
		SG2	-	8.71	-	7.81
		SG3	-	8.38	-	7.84
		SG4	-	8.86	-	7.81
MALB OPENING	Radial Dilation	Top	-	0.40	-	0.59
		Bottom	-	1.03	-	1.11
		North	-	0.53	-	1.44
		South	-	0.93	-	1.44

Note: [#] El. stands for the elevation at which the readings are taken
Mag. stands for the Magnitude recorded or analytically predicted
"... " indicates that the Dial Gauge at this location has not worked.

It can be observed from Table-2 below that in general the observed and analytical strains compare well. However, the observed strains at El. 92.0m are more than that of the analytical value. This may be attributed to the local stiffening of IC wall due to the local thickening and additional reinforcement provided for the MALB opening.

The measured circumferential strains during proof testing at El. 98.0m and 120.0m on the northern and southern sides are not same. From the symmetry of the geometry of the structure and loading, it can be said that the strain measurement should show similar value at this location. The analytical values obtained from FE analysis also show the similar trend. Hence, it can be said that the SMVWSGs mounted in circumferential direction at these locations have not performed well.

The strains recorded by SMERs and SMVWSGs in the meridional direction at the same location on the southern side at El. 107.0m is opposite in nature and the magnitudes recorded vary widely. The analytical strain obtained from FE analysis at this location matches closely with those recorded by SMVWSGs. Similarly, the observed circumferential strain values at El. 120.0m by SMERs and SMVWSGs at the same location on the northern side also vary widely. But at this location the analytical strain value obtained from FE analysis is matching closely with those recorded by the corresponding SMERs.

Table-2: Comparison of Strains in IC

Portion of RB	Elevation (m)	Location of Strain Gauge		Type of Response	Observed strain during Proof Testing (10^{-6}) (*)			Strain Values obtained from FE Analysis
		Face	Location		SMER	SMVWSG	EVWSG	
IC WALL	92.0	OUTER	North	Meridional	56	‡	‡	30.98
				Circum.	79	‡	‡	63.50
			South	Meridional	54	‡	‡	30.98
				Circum.	85	‡	‡	63.50
	98.0		North	Meridional	‡	23	‡	58.05
				Circum.	‡	27	‡	163.53
			South	Meridional	‡	34	‡	58.05
				Circum.	‡	114	‡	163.53
	107.0		North	Meridional	57	...	‡	46.05
				Circum.	132	116	‡	157.33
			South	Meridional	-29	64	‡	46.05
				Circum.	150	133	‡	157.33
	120.0		North	Meridional	54	39	‡	44.70
				Circum.	143	85	‡	163.63
			South	Meridional	58	41	‡	44.70
				Circum.	138	129	‡	163.63
	127.0		North	Meridional	113	109	‡	94.33
				Circum.	139	161	‡	104.59
			South	Meridional	98	95	‡	94.33
				Circum.	95	...	‡	104.59
	131.0		North	Meridional	73	‡	‡	17.40
				Circum.	40	‡	‡	-24.50
			South	Meridional	86	‡	‡	17.40
				Circum.	29	‡	‡	-24.50
IC WALL MALB PORTION	-	OUTER	Top-North	Circum.	47	‡	‡	74.04
			Top-South	Circum.	48	‡	‡	74.04
			Bot-North	Circum.	40	‡	‡	76.43
			Bot-South	Circum.	44	‡	‡	76.43
			Mid-North	Meridional	35	‡	‡	44.29
			Mid-South	Meridional	39	‡	‡	44.29
IC DOME GENERAL PORTION	-	MID SURFACE	B	North-South	‡	‡	116	112.31
				East-West	‡	‡	105	118.20
			C	North-South	‡	‡	107	80.24
				East-West	‡	‡	40	54.22
			E	Circum.	‡	‡	98	105.00
				Radial	‡	‡	49	36.50
			G	Through Thickness	‡	‡	-42	-34.83
			I	North-South	‡	‡	117	97.24
				East-West	‡	‡	119	135.20
			J	North-South	‡	-63.00	‡	-17.33
				East-West	‡	77.00	‡	19.49
			L	North-South	‡	‡	119	74.62
				East-West	‡	‡	...	95.78

Table-2: Comparison of Strains in IC (Contd...)

Portion of RB	Elevation (m)	Location of Strain Gauge		Type of Response	Observed strain during Proof Testing (10^{-6}) (*)			Strain Values obtained from FE Analysis
		Face	Location		SMER	SMVWSG	EVWSG	
IC DOME SG OPENING PORTION	-	OUTER	A	North-South	113	‡	‡	94.31
				East-West	100	‡	‡	89.87
			B	North-South	22	‡	‡	37.46
				East-West	114	‡	‡	81.10
			C	North-South	152	‡	‡	86.50
				East-West	92	‡	‡	62.64
IC DOME SG OPENING PORTION	-	OUTER	D	North-South	230	‡	‡	158.11
				East-West	73	‡	‡	44.74
			E	North-South	117	‡	‡	78.55
				East-West	95	‡	‡	85.49
			F	North-South	22	‡	‡	39.36
				East-West	93	‡	‡	79.83
			G	North-South	128	‡	‡	89.29
				East-West	69	‡	‡	65.78
			H	North-South	188	‡	‡	194.75
				East-West	44	‡	‡	43.45

Note: "‡" indicates that the strain has not been monitored using this type of strain gauges at these locations
"..." indicates that the Dial Gauge at this location has not worked.

In the dome region, a good matching is observed in the strain values recorded by the EVWSGs and the analytical prediction. The little variation in measured strains by EVWSGs and the corresponding analytical strain values in the general area may be attributed to the variation of depth of embedments from the mid-surface, approximations in the modelling etc. Large differences in the measured and predicted strains are observed near the springing of the dome (stain gauge no. J, refer Fig.-6). The springing portion of the dome is very disturbed area from the geometry and the prestressing cable layout point of view. Hence, this variation in predicted and observed strains is envisaged.

CONCLUSION

Based on the present study the following conclusions are drawn:

i). The EVWSGs are found to be highly reliable and accurate in capturing the strains in the concrete structures.

ii). Actual embedments of the strain gauges and the effect of creep of concrete shall be considered in the detailed analysis of IC under internal pressure to predict the strain values more accurately in the containment during proof testing. If the linear analysis is carried out in the absence of detailed such creep analysis, use of appropriate E-value assessed with the help of deflection measurements taken during proof testing can be used without sacrificing the accuracy of the calculations.

iii). The strains measured in the IC dome during proof testing shows that the overall development of stresses is within allowable limits. Hence it can be concluded that the assumption of linear behaviour of the IC in the design during DBA is demonstrated.

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ABSTRACT:

The present Indian PHWRs being designed and constructed have a double containment system wherein the inner containment is a prestressed concrete cylinder capped with a prestressed concrete segmental dome. The outer containment encompasses the inner containment and is made of reinforced concrete. The inner containment dome of a typical 220 MWe PHWR is provided with four large openings in order to facilitate replacement of steam generator at later date during the operating life of the plant. Presence of these large openings in prestressed concrete dome posses difficulty in terms of design and construction leading to concentration of prestressed cables in certain zones.

The design philosophy of the inner containment structure is based on limit state concept. The various limit states specified in the French Code RCC-G along with the supporting documents BPEL and BAEL are adopted for designing the structural elements. In order to ensure the structural integrity of the inner containment under the design basis accident pressure and to ensure elastic behaviour of the inner containment, the containment is pressurised upto its design pressure. Deflections and strain measurements are also done during this structural integrity test using vibrating wire strain gauges (VWSG) and surface mounted electrical strain gauges (SMER) connected to automatic data-logger at locations covering the entire Inner Containment in order to capture both membrane as well as radial strains.

This paper presents the scheme of instrumentation in the inner containment structure of an Indian PHWR of 220 MWe series during proof testing and a comprehensive study of the performance of the instrumentation in measuring the strains and deflections in the IC dome during the structural integrity test. The behaviour of the inner containment dome during the structural integrity test are also presented by comparing the measured strains and deflections in the Inner Containment with those computed using finite element analysis during the design stage. On the basis of detailed comparison, it is concluded that the behaviour of the IC dome and the developed stresses are matching well with the theoretical prediction and the stresses developed in the IC dome are well within the specified limit of the selected design standard / code.

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