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Pretest Round Robin Analysis of 1:4-Scale Prestressed Concrete Containment Vessel Model[1]

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1. INTRODUCTION

Sandia National Laboratories (SNL) is conducting a Cooperative Containment Research Program that is co-sponsored and jointly funded by the Nuclear Power Engineering Corporation (NUPEC) of Japan and the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research. The purpose of the program is to investigate the response of representative scale models of nuclear containments to pressure loading beyond the design basis accident and to compare analytical predictions to measured behavior. This objective is accomplished by conducting static, pneumatic overpressurization tests of scale models at ambient temperature. This research program consists of testing two scale models: a steel containment vessel (SCV) model (tested in 1996) and a prestressed concrete containment vessel (PCCV) model, which is the subject of this paper.

Prior to pressure testing the scale models, a number of regulatory and research organizations were invited to participate in a pretest Round Robin analysis to perform predictive modeling of the response of scale models to overpressurization. Seventeen organizations responded and agreed to participate in the pretest PCCV Round Robin analysis activities:

AECL	Atomic Energy of Canada Limited	Canada
ANL	Argonne National Laboratory	U.S.
CEA	Commissariat a l'Énergie Atomique	France
EDF	Électricité de France	France
Glasgow	University of Glasgow	U.K.
HSE	Health and Safety Executive	U.K.
IBRAE	Nuclear Safety Institute	Russia
INER	Institute of Nuclear Energy Research	Republic of China
IPSN	Institut de Protection et de Sûreté Nucléaire	France
JAERI	Japan Atomic Energy Research Institute	Japan
JAPC	The Japan Atomic Power Company	Japan
KINS	Korea Institute of Nuclear Safety	Korea
KOPEC	Korea Power Engineering Company	Korea
NUPEC	Nuclear Power Engineering Corporation	Japan
PRIN	Principia/EQE	Spain
RINSC	Russia International Nuclear Safety Center	Russia
SNL	Sandia National Laboratories/ANATECH	U.S.

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DISCLAIMER

DISCLAIMER

Each participant was supplied with the same basic information, including the design drawings of the PCCV model and the material properties of the structural components. Each participant used his own chosen analytical methods and performed independent analyses.

2. DESIGN OF THE PCCV MODEL

The prestressed concrete containment vessel (PCCV) model is a uniform,1:4-scale model of the containment structure of Unit 3 of the Ohi Nuclear Power Station in Japan. Ohi Unit 3 is a 1180 MWe pressurized-water reactor (PWR) plant designed and constructed by Mitsubishi Heavy Industries (MHI) and operated by Kansai Electric Power Company. The Ohi-3 containment vessel is a steel-lined, prestressed concrete cylinder with a hemispherical dome and two vertical buttresses. The design pressure is 0.39 MPa.

The model was designed by MHI and Obayahsi Corporation. The approach to designing the model was to scale the design of the Ohi-3 containment to the extent possible and include as many representative features of the prototype as practical. Specific considerations in designing the model are summarized below.

- Geometry: The configuration and overall dimensions (height, radius, thickness) were scaled 1:4 from the prototype. While the basemat thickness was scaled from the prototype, the footprint of the basemat was selected so that the bending stiffness of the basemat at the junction with the containment wall was preserved. The overall geometry is shown in Figure 1.

- Liner: The liner thickness was scaled directly from the prototype resulting in a liner thickness of 1.6 mm. In the prototype, the liner anchorage consists of meridional T-anchors throughout the cylinder and dome. Anchorage of the model liner consists of scaled T-anchors in the cylinder portion and stud-type anchors in the dome. Circumferential spacing of the vertical anchors was expanded in the model by a factor of three to simplify fabrication, except in areas around penetrations and other discontinuities. To the extent practical, all liner details were similar to the prototype.

- Penetrations: All penetrations were scaled from the prototype (geometry, thickness), and the equipment hatch (E/H), and personnel airlock (A/L) are functional with pressure seating covers. The main steam (M/S) and feedwater (F/W) penetration sleeves are scaled but are terminated with heavy, bolted, pressure seating blind flanges and covers which are used for instrumentation, power, and gas feed-throughs.

- Concrete: There was no scaling of the concrete for the model; however, maximum aggregate size was limited to 10 mm to facilitate placement.

- Reinforcing Steel: All reinforcing ratios in the prototype are maintained in the model. Rebar areas were scaled, but there was no attempt to match individual bars. Bars ranging in size from 6 mm to 22 mm in diameter were place in two orthogonal layers on each face, and shear reinforcing was included.

- Tendons: Each tendon in the prototype was matched in the model, 90 meridional hairpin tendons and 108 360° hoop tendons. Individual tendon areas were scaled, resulting in three 13.7 mm seven-wire strands per tendon.

Details of the design, including the design drawings, and construction are reported in the PCCV test report.[1]

Prestressing levels for the model tendons were selected so that the net anchor forces (considering all losses due to anchor seating, elastic deformation, creep, shrinkage and relaxation) at the time of the Limit State Test matched those expected in the prototype after 40 years of service. One further

[1] Hessheimer, M. F. "Overpressurization Test of a Prestressed Concrete Containment Vessel Model. To be published.

adjustment was made by increasing the vertical tendon stress level to account for the additional gravity load in the prototype, which is lost in the geometric scaling.

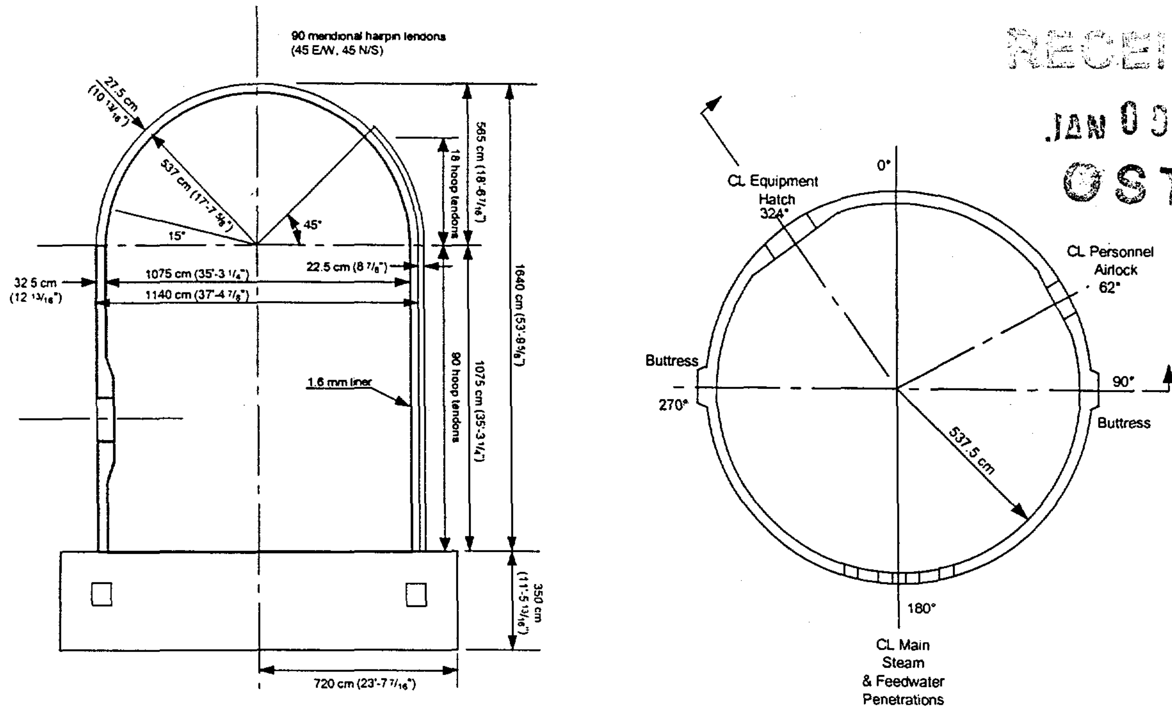

Figure 1 Prestressed Concrete Containment Vessel (PCCV) Model Geometry

2.1 Material Properties

The material specifications for the model components are the same as for the prototype and are summarized below.

Liner:	Japanese Industrial Standard (JIS) SGV410
Liner Anchors:	JIS SS400
Basemat Rebar:	JIS G3112, SD490 and SD390
Shell Rebar:	JIS G3112, SD390 and SD345
Tendons:	JIS G3536
Concrete:	450 kg_f/cm^2 and 300 kg_f/cm^2 at 91 days

Actual properties for all components were obtained from standard tests of samples of the construction materials. Standard coupons of the liner and liner anchor material were tested in uniaxial tension. Both full-sized and machined specimens of each size of rebar were tested in uniaxial tension. Separate tension tests of individual strands and the full tendon system (including anchorage hardware) were conducted. The results of these tests were made available to all the Round Robin participants.

Because pretest analyses and model construction occurred simultaneously, actual properties of the concrete were not available to the Round Robin participants. Compression tests of a trial mix, using the identical specifications and component materials (cement, aggregate, admixtures) as the concrete in the model, were conducted and provided to the Round Robin participants for pretest analysis. Subsequent to these tests, standard tests of concrete specimens obtained from batches of the model concrete were conducted for quality control purposes and to characterize material properties at the time of prestressing and the Limit State Test.

3. INSTRUMENTATION

3.1 Model Instrumentation

The instrumentation suite was designed to provide information on the overall response of the model as well as areas that were expected to exhibit significant local response modes. The data collected from these transducers will be compared to the pretest analyses and, it is hoped, will lead to improvements in analysis methodologies. The instrumentation is not designed to "capture" specific failure events or rapid changes in the response variables, although the data, coupled with posttest analysis and physical inspection, should allow a reconstruction of the events resulting in the failure of the model.

A total of 1506 transducers, consisting of strain gages, displacement transducers, load cells, and pressure and temperature sensors, were installed on the model. The placement of these instruments was based on experience from previous model tests and preliminary analyses [1,2,3]. In addition to these discrete response measurements, an acoustic monitoring system along with a suite of video and still cameras will be used to monitor the overall response of the model.

The global coordinate system and cardinal azimuths and elevations used to describe the model and the instrumentation suite are shown in Figure 2. The model global coordinate system is left-handed and originates at the center-top of basemat with the Z-axis (vertical) up and counterclockwise from 0°, as shown in the figure. The cardinal elevations are numbered 1(top of basemat) through 13 (apex), and the cardinal azimuths, typically at 30° intervals, are labeled A (0°) through L (324°). One additional cardinal azimuth, Z, was introduced at 135° to represent the axisymmetric response of the model. (This azimuth was assumed to be relatively unaffected by structural discontinuities and a reasonable location for comparison with axisymmetric analyses.) Given this coordinate system, the buttresses are located at 90° (D) and 270° (J), the personnel airlock (A/L) at 62° (C), the main steam and feedwater line penetrations at 180°(G), and the equipment hatch (E/H) at 324° (L).

3.2 Standard Output Locations

Reporting and comparison of the pretest Round Robin analyses was standardized by specifying fifty-five (55) response variables (displacement, strain, etc.) corresponding to specific transducers on the PCCV model. These response variables were selected to provide a comparison of the predictions of the global and local response of the model based on engineering judgment, past experience, and preliminary analysis results. The participants were asked to submit response predictions as a function of gage pressure at each of these Standard Output Locations (SOL) illustrated in the developed elevation in Figure 3. The preliminary and pretest analyses performed by Dameron et al. [1,2] provided results that guided the selection of these locations.

4. PRESSURE TESTING

The prestressed concrete containment vessel (PCCV) model was subjected to a series of quasi-static pressurization tests leading to functional failure or rupture during the Limit State Test. Figure 4 illustrates the nominal pressure time history, and each phase is summarized below. The model was depressurized between each test. Nitrogen gas at ambient temperature (nominally 21°C) was used as the pressurization medium for each test. All pressure tests were conducted in a quasi-static manner by pressurizing the model in increments and holding pressure until the model response and pressure reach equilibrium. The pressurization system was designed to maintain the model at a constant pressure (within ±3kPa) up to a maximum leak rate of 1000% mass/day. The results of the pressure tests will be reported at a later date.

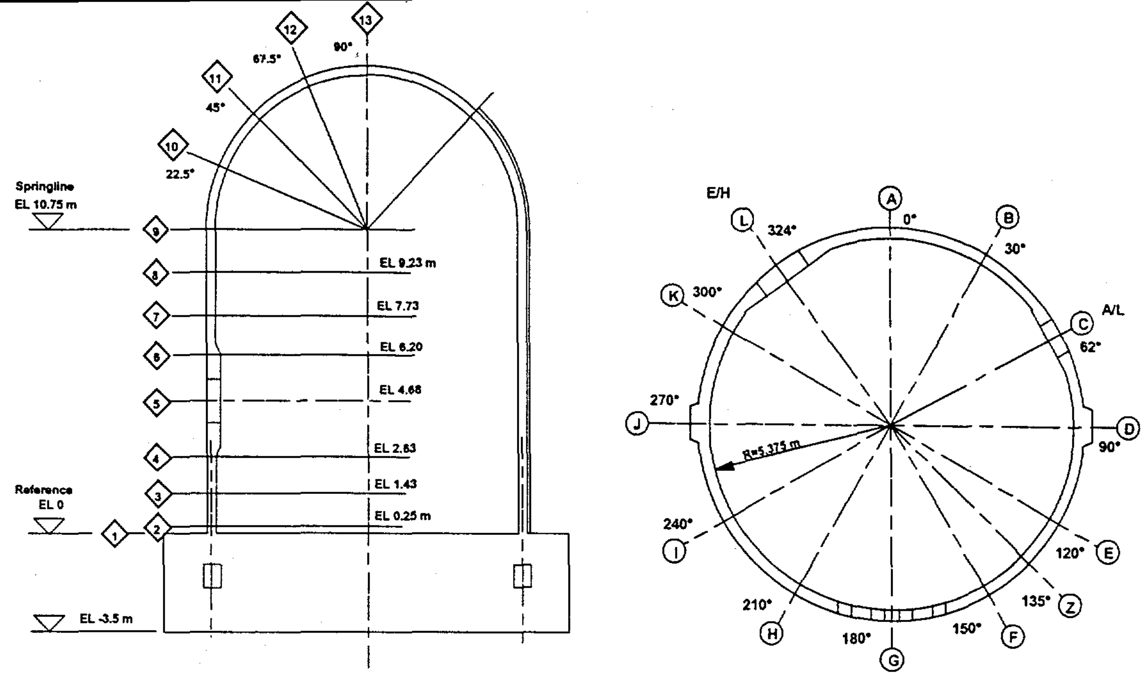

Figure 2 PCCV Model Coordinate System and Cardinal Lines

4.1 System Functionality Test (SFT)

The model was pressurized to 0.5 P_d (0.2 MPa) in three increments holding pressure for one hour or longer at each step, depending on the duration needed to perform all system functionality and leak checks.

4.2 Structural Integrity Test and Integrated Leak Rate Test

The Structural Integrity Test (SIT) and the Integrated Leak Rate Test (ILRT) were conducted as one continuous test, following a sequence that combined Japanese and U.S. standards for each test. First, during the SIT, the model was pressurized in five equal increments at a rate of 20 percent of the test pressure per hour up to the maximum test pressure of 1.125 P_d (0.44 MPa). The SIT pressure was maintained for one hour, then the model was depressurized to the ILRT pressure of 0.9 P_d (0.35 MPa). The model was held at the ILRT pressure for a minimum of one hour to allow the model atmosphere to stabilize before the start of the leakage rate test, which lasted for 24 hours. After the ILRT was completed, the model was depressurized in steps matching the initial SIT-pressurization phase to allow for comparison of the response at each increment of pressure.

4.3 Limit State Test

The Limit State Test (LST) fulfilled the primary objectives of the PCCV test program, i.e., to investigate the response of representative models of nuclear containment structures to pressure loading beyond the design basis accident and to compare analytical predictions to measured behavior.

Initially, the model pressurization sequence matched the pressurization sequence followed for the SIT to allow comparison of the model response to two cycles of loading. Incremental pressurization of the model then continued, holding pressure at each step until the equilibrium and stability critieria were met. Periodic leak checks were also conducted at multiples of 0.5 P_d. The Limit State Test was terminated when the pressurization system was no longer able maintain pressure because of excess leakage.

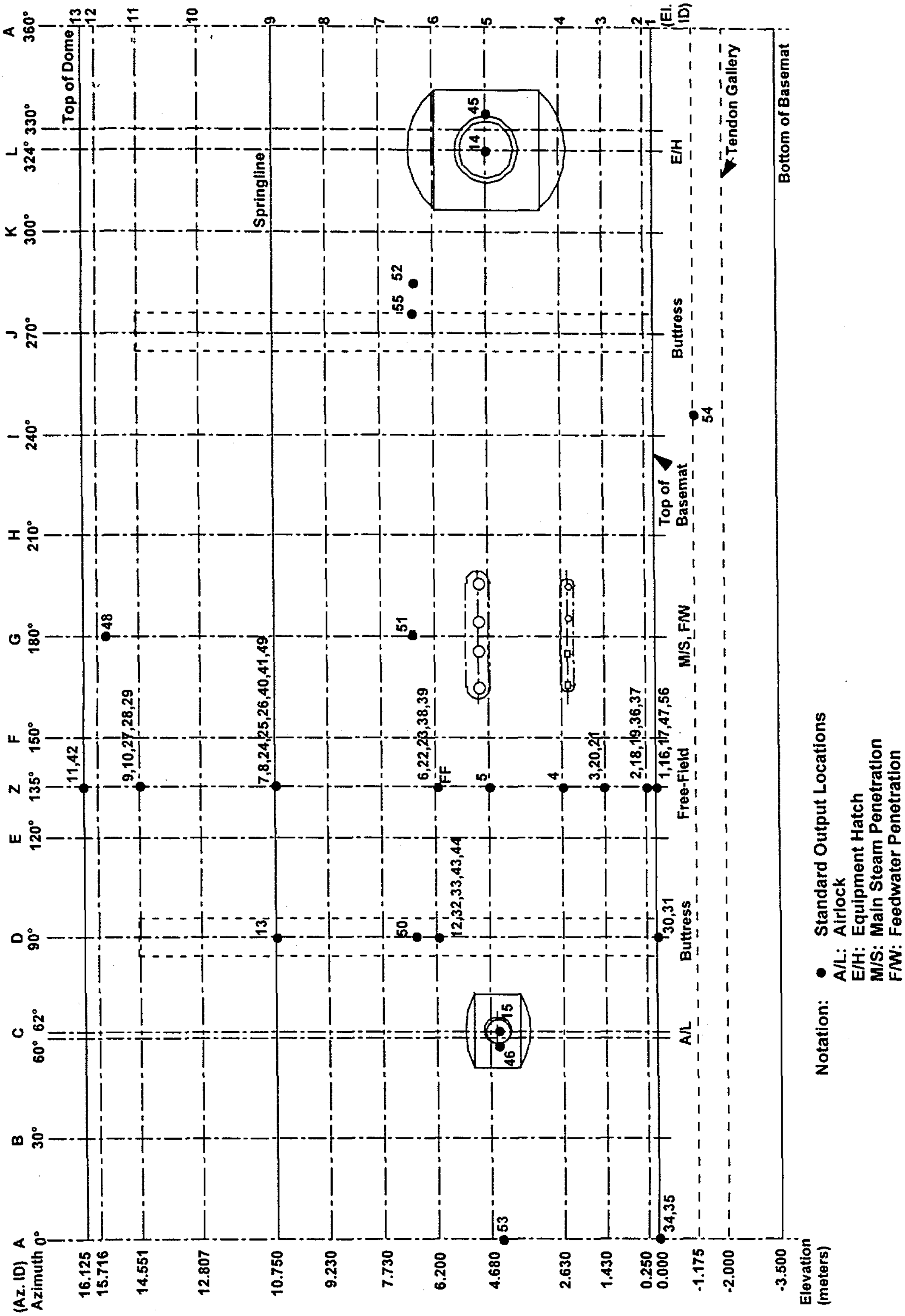

Figure 3 Developed Elevation of PCCV Model and Standard Output Locations

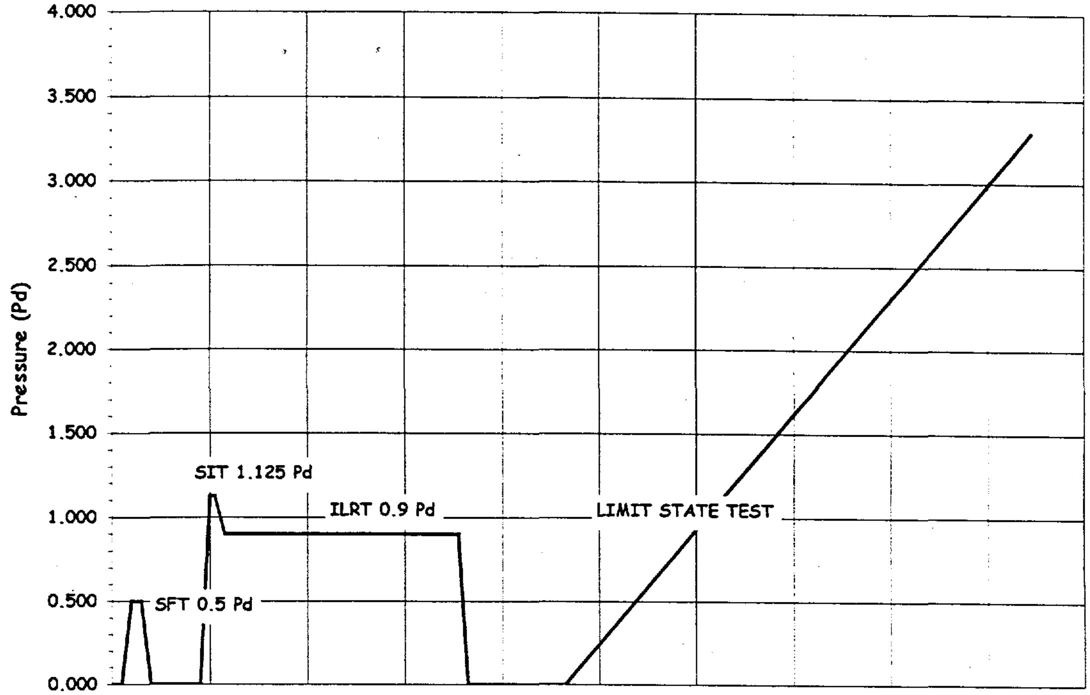

Figure 4 Pressurization Sequence for the PCCV Model Test

5. PRETEST ANALYSIS

Each Round Robin participant developed an indepenedt approach to the pretest analysis, including selection of models and codes, application of the design information provided and criteria for interpreting or evaluating the results. Every participant was asked to provide a report summarizing their analysis, and these are reported by Luk [3]. Tables 1 and 2 provide a brief summary of the codes, modeling approaches, and material models used by each participant to facilitate comparison of the analyses. Although each participant was asked to predict the response at each of the 55 Standard Output Locations (SOL), the majority of participants submitted predictions only at a subset of locations because of limitations in the analysis approach used. These results were compiled into composite plots for each SOL. These composite plots are also provided in [3].

In addition to submitting response predictions at the SOLs, each participant was asked to provide a best estimate of failure pressure and mechanisms of the PCCV model. These are summarized in Table 3. Table 3 also summarizes predictions of the pressure for various milestones (onset of cracking, yielding, etc.) leading up to failure.

6. SUMMARY

The work reported herein represents, arguably, the state of the art in the numerical simulation of the response of a prestressed concrete containment vessel (PCCV) model to pressure loads up to failure. A significant expenditure of time and money on the part of the sponsors, contractors, and Round Robin participants was required to meet the objectives. While it is difficult to summarize the results of this extraordinary effort in a few paragraphs, the following observations are offered for the reader's consideration:

- Almost half the participants used ABAQUS as the primary computational tool for performing the pretest analyses. The other participants used a variety of codes, most of which were developed "in house."

Table 1 Modeling Approaches Used in the Pretest Analyses

Participant [Code]	Model					Concrete	Liner	Rebar	Tendon	Cylinder Prestress Avg. or @135 (MPa)	
	General	Basemat	Penetrations	Buttress	# Elements					Hoop	Meridional
ANL [TEMP-STRESS, NEPTUNE]	2D Axisym; shell	no	no	no	650	shell	offset membrane	embedded bars in shell	Hoop: ring Merid: truss, sliding no friction	350 kN (245 kN 30% red.)	470 kN
AECL [ABAQUS]	2D Axisym	yes		yes	85,000			rebar subelement	truss, no friction	Uniform Initial stress	
	3D	no	E/H, A/L			8-node solid	4-node membrane	rebar subelement	truss, no friction	927	1272
CEA [CASTEM]	Axisym @ 135	yes	no	no	5105	4-node solid	shell	Hoop: ring Merid: shell	Hoop: ring & shell Merid: shell tied to concrete	Uniform 269 kN	470 kN
EDF [ASTER]	1/8 w/ sym. multi-layer shell	yes	no	no	6120 DOF	multi-layer shell	shell layer	smeared shell layer	smeared shell layer tied to concrete	Uniform 513 174 kN	844 286 kN
Glasgow [In-house]	3D	mp	no	yes		8-node solid		smeared tied to concrete	smeared tied to concrete		1377 467 kN
INER [ABAQUS]	3D slice (45°) (135° - 180°)	yes	no	no	n/a	3D solid element, C3D20	3D shell element S8R	n/a	n/a	1185 MPa	1436 MPa
IPSN [CASTEM]	3D slice (2 deg)	yes	no	no	2,513	solid	shell	discrete	truss	453 kN	303 kN
JAERI [ABAQUS]	3D symmetric shell model (90° - 180°)	yes	no	yes	8,237	shell	shell	rebar subelement	bar element	350 kN	470 kN
	2D Axisym shell	no	no	no	382	shell	shell	rebar subelement	merid: rebar subelement hoop: shell	350 kN	470 kN
JAPC [FINAL]	Global (Axisym, 3D)	yes		yes	2,000	multi-layer shell	shell	shell	truss	Friction loss considered	
	Local (3D)		E/H, A/L		20,000	8-node solid	anchor as springs	truss	w/ friction element		
	Local (liner)		M/S								
KINS [DIANA]	3D multi-layer shell	yes	E/H, A/L	yes	2,000	shell	shell	smeared layer	bar, bonded	Friction and setting loss calculated by code	
KOPEC [ABAQUS]	3D multi-layer shell	yes	E/H, A/L	yes	1,720	4-node shell	shell	bar, bonded	bar, bonded	724	varies
	2D Axisym	soil			209	8-node solid	3-node shell				
HSE [ABAQUS]	3D global	yes	E/H, A/L	yes	140,662	8-node solid	Membrane	rebar subelement	Merid: truss w/ sliding	1031	1388
	3D slice	soil				3 thickness	anchor as spring		initial stress	350 kN	471 kN
	2D liner										
NUPEC [ABAQUS]	Axisym	yes	no	no	1,279	4-node solid	shell	rebar subelement	Hoop: rebar subelement Merid: shell	991	503-470 kN @loading end
	Axisym	yes	no	no	2,194	4-node solid (duplicate)	shell	rebar subelement	rebar	991	470 kN
	3D local	no	no	yes	15,810	8-node solid (duplicate)	shell	rebar subelement	beam w/ friction	453-394 kN	470 kN
	3D local	no	E/H	yes	16,567	8-node solid (duplicate)	shell	rebar subelement	beam w/ friction	453-394 kN	470 kN
	3D local	no	A/L	yes	16,425	8-node solid (duplicate)	shell	rebar subelement	beam w/ friction	453-394 kN	470 kN
	3D local	no	M/S	yes	13,081	8-node solid (duplicate)	shell	rebar subelement	beam w/ friction	453-394 kN	470 kN
IBRAE [CONT]	2D Axi-sum	no	no	no	2,700	4-node solid	4-node solid	Thin layers	Distributed load		
	3D	yes	yes	yes	24,508	8-node solid	8-node solid	Thin layers	Distributed load	331.5 kN	467.5 kN
PRINCIPIA [ABAQUS]	2D Axisym solid	yes soil	no	no	510	8-node solid	3-node shell	rebar	Hoop: rebar Merid: truss w/ friction	929	1142
RINSC [DANCO]	3D (90 deg)	no	E/H	no		shell		thin wall layers	shell ribbons	350 kN	470 kN
SNL/ ANATECH [ABAQUS]	2D Axisym	yes	E/H	yes	4,000	solids	shell/membrane	rebar subelement	truss w/ friction tie	797	1334
	3D R-Theta		A/L		60,000					1109	
	3D Local		M/S								

Table 2 Material Properties used in the Pretest Analyses

Participant	Cylinder/Dome Concrete			Liner			Cylinder/Dome Rebar				Tendons		
	E (MPa)	fc' (MPa)	ft (MPa)	E (MPa)	fy (MPa)	Strain	Grade	E (MPa)	fy (MPa)	Strain	E (MPa)	fy (MPa)	Strain
ANL				Best fit			Average of 390&490				Best fit		
	27,000	47.3	3.45	240,900	386	33%	SD 390 SD 490	210,500 210,500	422 456	6.90% 7.50%	206,120	1,604	3.25%
AECL													
	26,790	44.13	3.45 e_{cr}=60□	198,389	383	5%		166,194 210,539	364 556	7% 18%	217,672	1,750	3%
CEA	Ottosen						Average for each size and type				191,000	1,703	5%
	27,000	44 □r=0.9%	3.45	183,000	457	14%							
EDF	Nadai B with fixed crack @ 90 deg												
	29,470	54.52 □u=0.005	2.55 □u=0.0005	232,000	383	30%		190,000	439.00 445.00	20%	200,000	1,750	3.4%
Glasgow													
	38,100	44.13	3.4 4.06 (?)	224,000	398			183,000	470		200,000	1,750	
INER							Data fit						
	32,552 29,619	44.13 39.16	2.284 2.078	228,000	375	(perfectly plastic)					211,784	1,482.5	2.5%
IPSN	Ottosen			n/a			n/a				n/a		
	27,000	44	3.45										
JAERI							Multi-linear elasto plastic for each size						
	29,100	617	3.82	217,000	381	5%					210,000	1,594	2.5%
JAPC	Darwin-Pecknold, shear retention			Multi-linear	f	ε	Multi-linear elasto plastic		f	□	Multi-linear	f	□
	29,400	44	3.33	215,745	382 382 408 436 457 500	0.177% 2.00% 2.44% 3.60% 5.00% 33.00%		185,082	459 459 554 589 644	0.25% 1.53% 4.00% 6.00% 21.29%	196,132	1,520 1,746 1,902 1,912 1,940	0.78% 1.10% 3.70% 0.08% 20.00% e_u=3.5-8%
KINS	Hognested, tension stiffening			Multi-linear elasto plastic			Multi-linear elasto plastic				Multi-linear elasto plastic		
	29,500	54.3	3.83	210,000	383	33%		210,000	482 490	8% 9%			3.5%
	(Avg. SC & FC)												
KOPEC	Menetrey-William						Bi-linear approximation for each size and type						
	26,970 27,950	47.3 39.16	3.45 3.37	218,700	376	33%					191,000	1,691	3.51%

Table 2 Material Properties used in the Pretest Analyses (continued)

Participant	Cylinder/Dome Concrete			Liner			Cylinder/Dome Rebar				Tendons		
	E (MPa)	fc' (MPa)	ft (MPa)	E (MPa)	fy (MPa)	Strain	Grade	E (MPa)	fy (MPa)	Strain	E (MPa)	fy (MPa)	Strain
HSE	Chen-Chen (smeared crack) + damaged E			Elastic plastic (mean value)			Elastic plastic (mean value)				Elastic plastic (mean value)		
	27,950	88	4.4	219,650	382	11%	SD345-D6	169,000	370	30%	224,230	1,740	4%
							SD345-D10	182,000	370	24%			
							SD390-D10	183,000	477	21%			
							SD390-D13	183,000	440	24%			
							SD390-D16	183,000	450	22%			
							SD390-D19	184,000	470	22%			
							SD390-D22	191,000	465	26%			
							SD490-D10	187,000	500	21%			
							SD490-D13	184,000	548	16%			
							SD490-D16	185,000	490	17%			
							SD490-D19	186,000	514	18%			
NUPEC	Smeared Crack			Average of test data									
	27,000 28,000	49 42	3.45 3.37	219,000	377	8%		185,000	459	12% 18%	194,000	1,470	3%
IBRAE													
2D 3D	27,000 26,970	40 44.13	3.45 3.84	210,000	380	33%		18,500	450	33%	200,000	1,700	3.3%
PRINCIPIA	Chen-Chen with strain softening			Elastic-plastic									
	27,000 28,000	44 55	3.6 3.6	219,000	384	28%	SD390 SD490	186,000 185,000	460 526	19% 17%	220,000	1,742	8%
RINSC													
	27,000	49	3.5	n.a.	n.a.	n.a.	Both	200,000	400	n.a.	210,000	1,690	n.a.
SNL/ ANATECH	ANACAP-U, smeared crack			Data Fit			Data Fit				Data Fit		
	33,000		2.64 (80μ										

fc' = uniaxial strength
fy = yield strength

Table 3 Pretest Analysis Results (MPa)

Participant	Cracking		Liner Yield	Rebar Yield		Hoop Tendon Stress				Pressure @ Failure	Free-Field Hoop Strain	Mode
	Hoop	Meridional		Hoop	Meridional	Yield	1%	2%	3%			
ANL	0.68	0.64	1.00	1.07	1.35	1.23	1.37	1.53	1.61	1.51 1.62	1.69% 3.31%	local liner tear (El. 6.4 m) midheight hoop tendon failure at El. 6.4 m
AECL (3D) (Axl)	0.97 0.87	0.85 0.78	— 1.06	— —	— —	— —	— —	— —	— —	0.94 1.24		complete cracking axisymmetric yield
CEA	0.70	0.50								1.60 1.70		numerically unstable
EDF	0.47	0.86		0.88	1.03	1.30	1.34	1.38	1.91	1.95		
Glasgow	0.95		1.00 1.10		0.87 1.60							
INER	0.69	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.81	n/a	n/a
IPSN	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
JAERI	0.92	0.74	1.20	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.24	buckling at dome portion or local fracture by bending in cylinder portion
JAPC	0.60	0.65	0.96	0.98	1.25	1.15	1.25	1.37	1.42	1.45 1.55		Rupture of structural elements (tendon, rebar, or liner) placed in the hoop direction at a wall height of about El. 7 m.
KINS	0.39	0.62		0.86	1.27		1.25	1.33	1.37	1.25 1.44		tendon rupture
KOPEC (2D) (3D)	0.64 0.61		1.01 0.94	1.20 1.08		1.03 1.41	1.32	1.36	1.39	1.30 1.51		tendon @ 3.55%
HSE/NNC	0.57	0.57			1.70	1.60	1.60	1.75	1.75	1.98	3%	Liner tear with extensive concrete cracking at buttress region.
NUPEC	0.82	0.59	1.02	1.25	1.45		1.33	1.49	1.57	1.49 1.57	3%	tendon rupture
IBRAE	0.70	0.78	1.15	1.22	0.90	1.01	1.15	1.21	1.25	1.26		tendon rupture
PRINCIPIA	0.56	0.92		0.96	1.00 1 16	1.30				1.30		tendon yielding
RINSC	n.a.	1.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.50	n.a.	hoop failure of vessel
SNL/ ANATECH	0.59	0.57		0.86	1.10		1.18	1.27	1.32	1.18 1.25 1.40 1.42	2%	local liner strain (lower bound) 16% liner strain @ E/H-best guess tendon rupture 2% global strain (upper bound)

- Only a few participants reported on "hand calculations" used to corroborate the finite element calculations, although it is suspected many more participants performed checks that they did not include in their reports.
- Almost every participant performed some type of simplified analysis that "smeared" or omitted spatial discontinuities before proceeding to more-detailed three-dimensional analyses.
- The majority of participants tried to account for some "slip" between the tendons and the concrete, although most also chose to assume that tendon forces were uniform along the length of the tendon.
- All participants used the material property test data provided as the basis for their material models, although there was some variation in how the material data were used. Some participants chose to average the data for a group of materials while others chose to define subsets of material properties that more closely matched the test data.
- Predictions of elastic response were, for the most part, very consistent up to the onset of global yielding (hoop) which appears to occur around 2.5 P_d or about 0.8 to 1.3 MPa. Predictions of response diverge significantly beyond this point with responses varying by a factor of three to five or more at a given pressure.
- There are considerable differences in the predictions of some local strains, such as those close to a penetration, after global yielding has occurred.
- Nevertheless, the predicted capacity of the model is fairly consistently bounded at 4 to 5 P_d. For failure predictions based on material failure of the steel components (liner, rebar or tendons), the average predicted pressure at failure is 3.6 P_d or 1.46 MPa.
- Approximately half the participants predicted failure based on structural failure, i.e., rupture of rebar or tendons, while approximately half the participants predicted functional failure from excessive leakage through a tear in the liner and/or cracks in the concrete. No one predicted failure from a shear failure or by leakage through the penetrations.

Future reports will include the results of the pressure tests as well as comparisons of the test results with the Round Robin pretest predictions.

7. REFERENCES

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