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

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ABSTRACT

Seventeen international organizations performed independent pretest predictions of the response of a 1:4-scale Prestressed Concrete Containment Vessel model subjected to a static overpressurization test. Each participant in this Pretest "Round Robin" analysis was supplied with design information for the model and was asked to submit analysis results at a number of locations on the model where instrumentation was installed to measure the response. Each group was also asked to predict the most likely failure mode and corresponding pressure. All the participating groups were invited to a Pretest meeting to inspect the model, discuss analysis methodologies and compare results. This paper summarizes the pretest "Round Robin" analysis results.

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 Ingenieros Consultores, S.A.	Spain
RINSC	Russia International Nuclear Safety Center	Russia
SNL	Sandia National Laboratories/ANATECH	U.S.

[a] *This work is jointly sponsored by the Nuclear Power Engineering Corporation and the U.S. Nuclear Regulatory Commission. The work of the Nuclear Power Engineering Corporation is performed under the auspices of the Ministry of Economy, Trade and Industry, Japan. Sandia is a multi program laboratrory operated buy Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract Number DE-AC04-94AL85000..*

The purpose of the Round Robin effort was to provide a forum for researchers in this area, and the industry in general, to apply current(state-of-the-art) analysis methodologies to predicting the response and capacity of the PCCV model. A previous paper emphasized the analysis methodology employed by each participant [1]. This paper emphasizes the results of the independent analyses, however, we have consciously avoided making judgements regarding which approach, code, model, etc. is 'better' than the others. By presenting the results in an unbiased manner, we hope to allow the readers to draw their own conclusions. 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.

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.[b]

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 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.

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. 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

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

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.

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. As the model was pressurized, periodic leak checks were conducted by holding pressure and monitoring pressure and temperature and calculating the apparent leak rate. The Limit State Test was terminated when the pressurization system was no longer able maintain pressure because of excess leakage.

PRETEST ANALYSIS

Each Round Robin participant developed an independent 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 [2]. 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 2. The preliminary and pretest analyses performed by Dameron et al.[3,4] and Kashiwase[5] provided results that guided the selection of these locations. Although each participant was asked to predict the response at each of the 55 SOLs, 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.

A sample of the predicted response at the Standard Output Locations are provided in Figures 3 through 7. These plots represent the axisymmetric or free-field response of the model which is represented by Azimuth 135°. This azimuth was chosen to represent the axisymmetric response of the model due to the relative absence of any major structural discontinuities. Figures 3 shows the predicted radial displacement at the mid-height of the cylinder wall where the maximum response is expected. Figures 4 and 5 show the predicted vertical displacement at the springline and at the dome apex. Figures 6 and 7 show the hoop rebar and liner strain at the cylinder wall mid-height. All the composite plots are provided in [2].

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. Table 1 summarizes these estimates and predictions of the pressure for various milestones (onset of cracking, yielding, etc.) leading up to failure.

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."
- 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.

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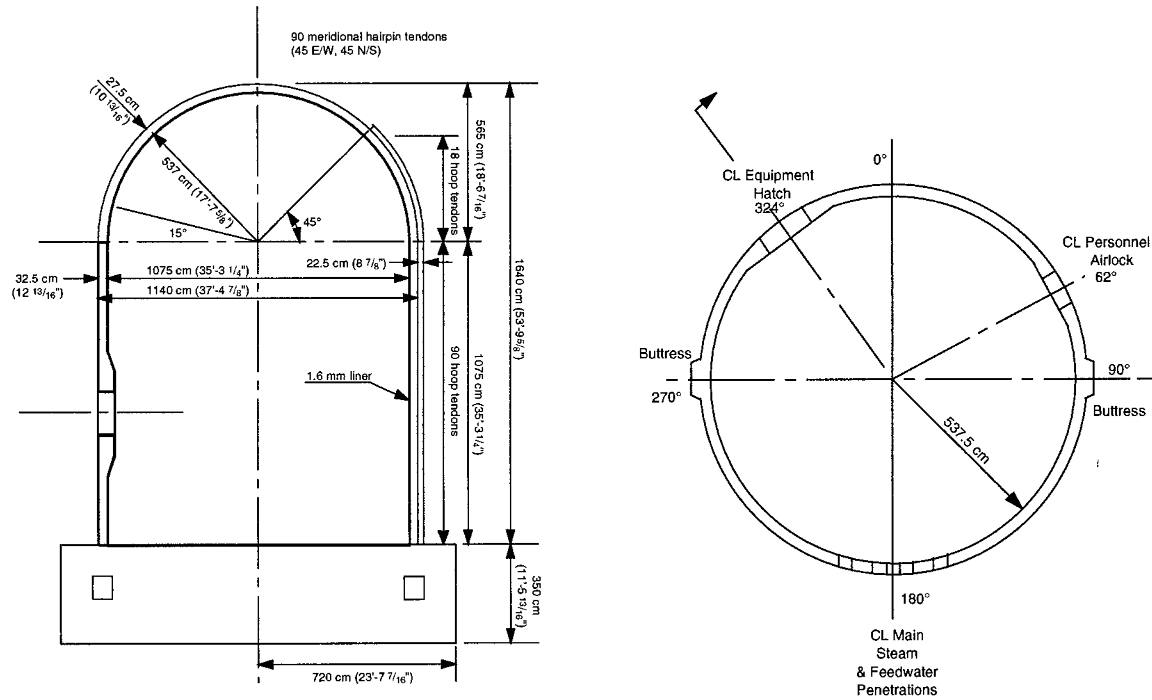

Figure 1 Prestressed Concrete Containment Vessel (PCCV) Model Geometry

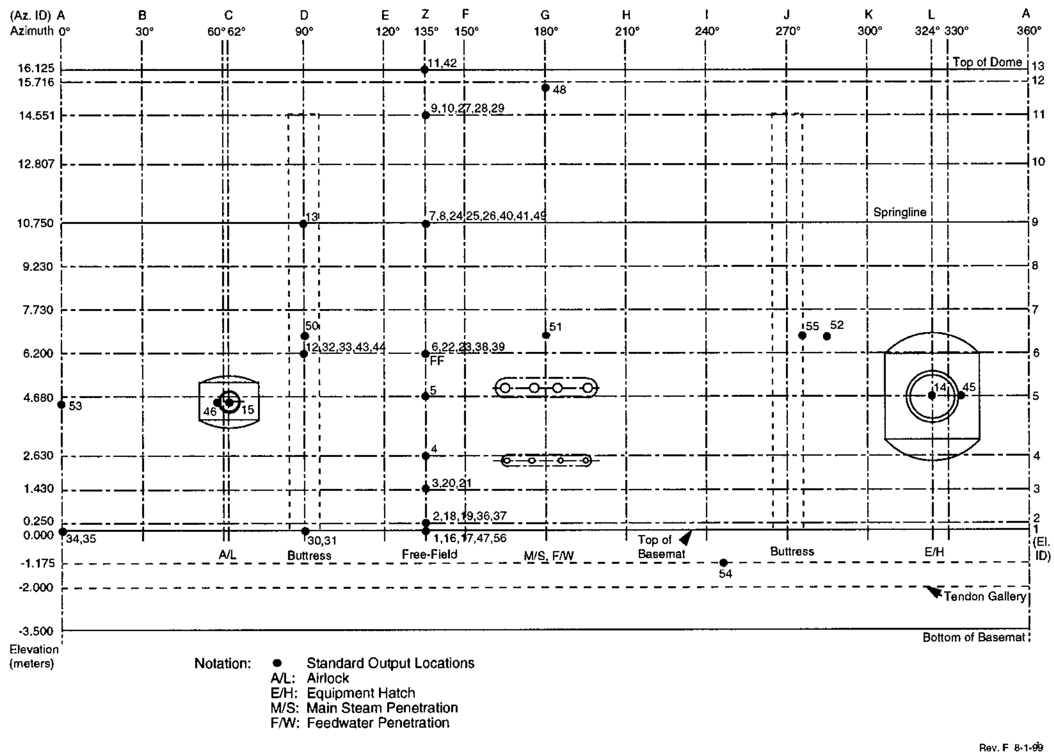

Figure 2 Developed Elevation of PCCV Model and Standard Output Locations

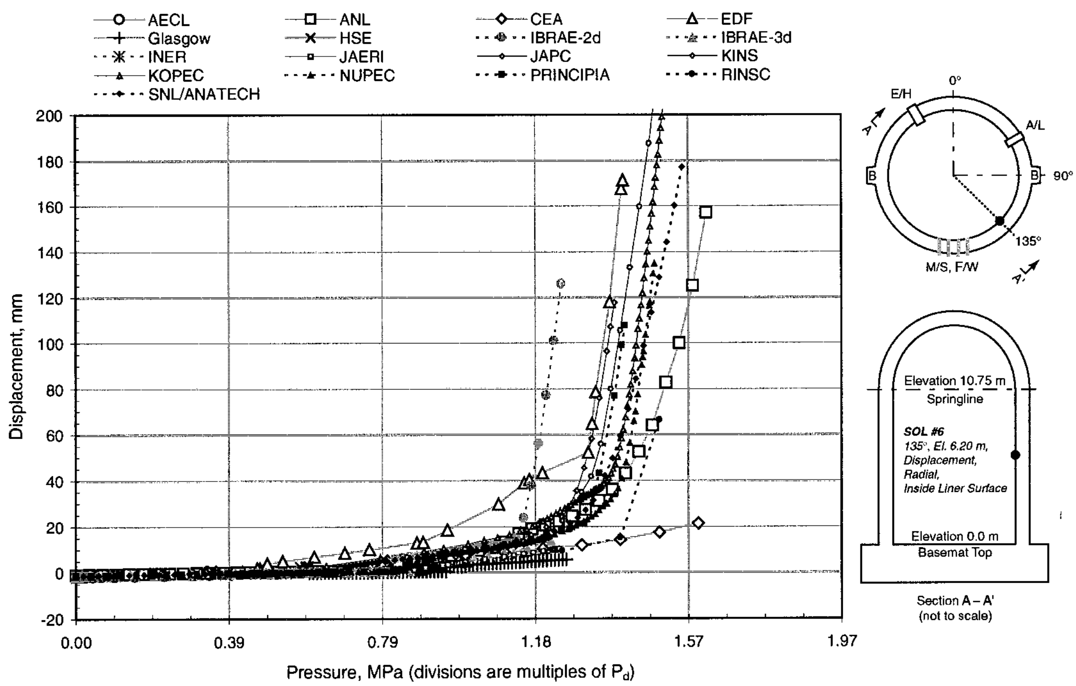

Figure 3 Radial Displacement at Cylinder Wall Mid-height (SOL 6)

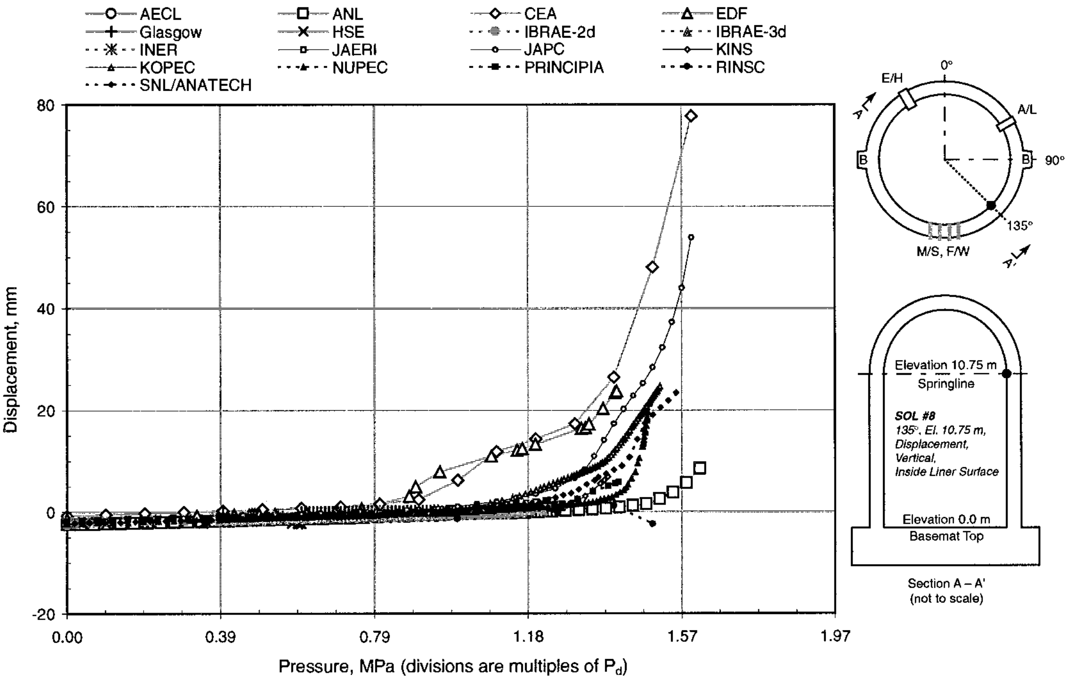

Figure 4 Vertical Displacement at Springline (SOL 8)

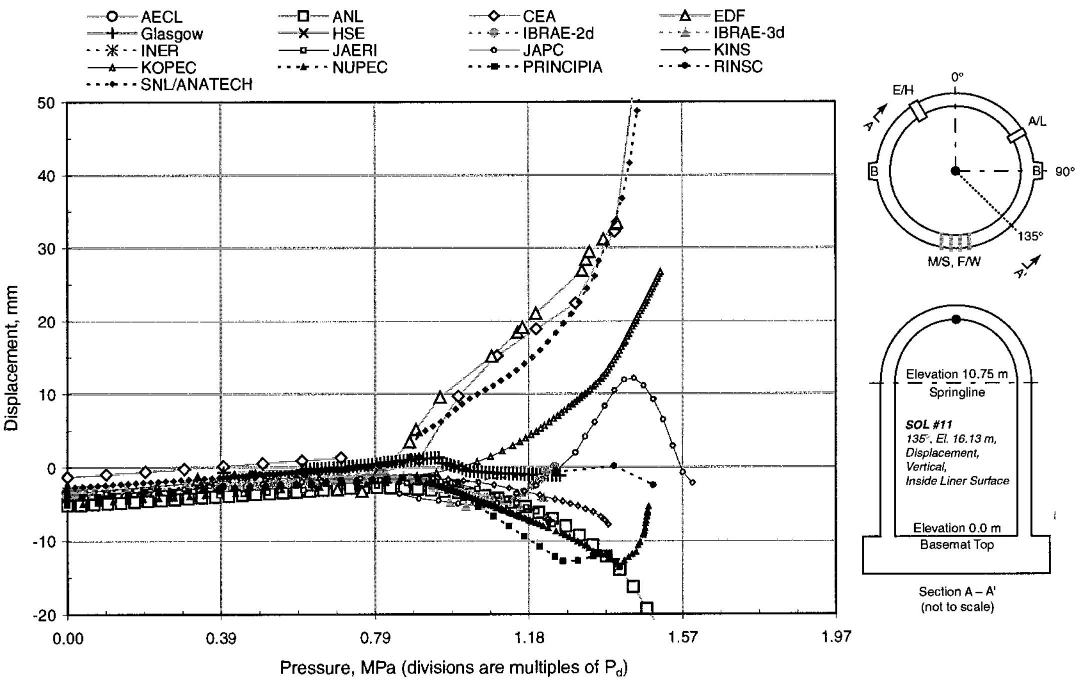

Figure 5 Vertical Displacement at Dome Apex (SOL 13)

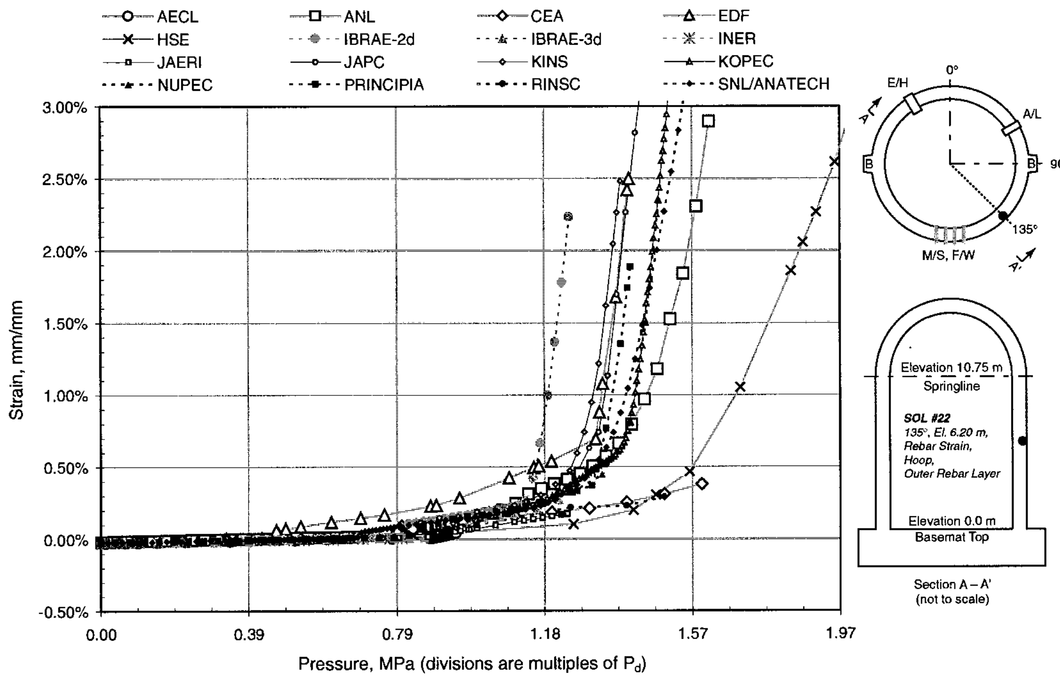

Figure 6 Hoop Rebar Strain at Cylinder Wall Mid-height (SOL 22)

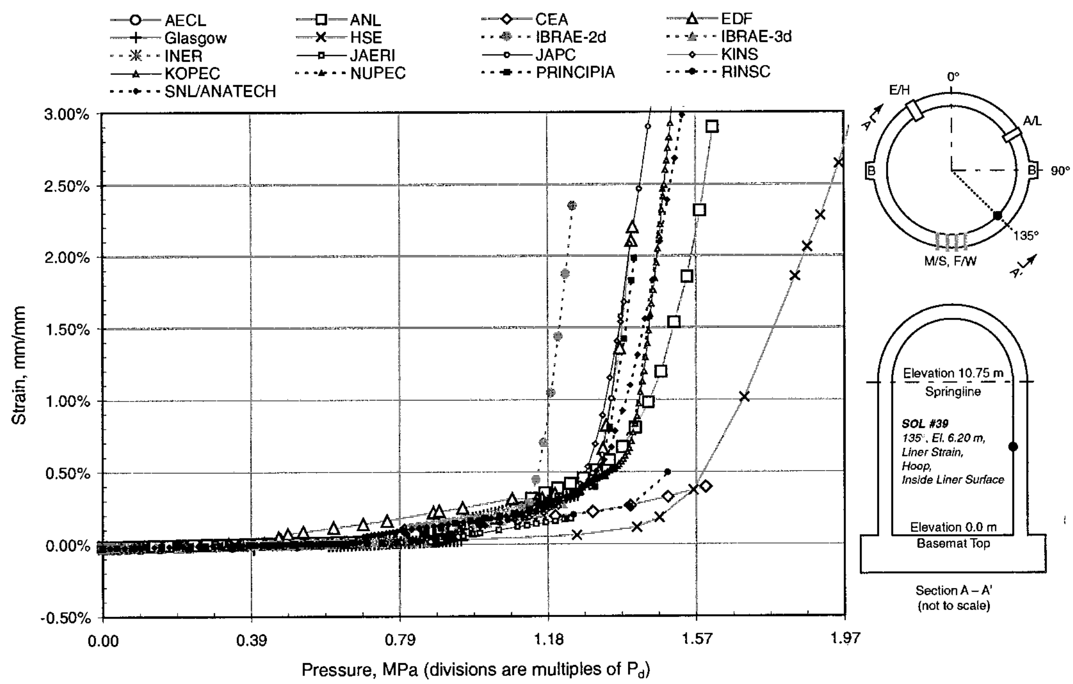

Figure 7 Hoop Liner Strain at Cylinder Wall Mid-height (SOL 39)

Table 1 Summary of Round Robin Event Predictions as a Function of Pressure (MPa)

Participant	Cracking		Liner Yield	Hoop Tendon Stress		Pressure @ Failure	Free Field Hoop Strain	Mode
	Hoop	Meridonal		Yield	2%			
ANL	0.68	0.64	1.00	1.23	1.53	1.51 1.62	1.69% 3.31%	local liner tear (Elev. 6.4 m) mid-height hoop tendon failure at Elev. 6.4 m
AECL (3D) (Axi)	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		1.30	1.38	1.95		
INER	0.69					0.81		
JAERI	0.92	0.74	1.20				1.24%	buckling at dome portion or local fracture by bending in cylinder portion
JAPC	0.60	0.65	0.96	1.15	1.37	1.45 1.55		Rupture of structural elements (tendon, rebar or liner) placed in the hoop direction at a wall height of about El. 7m.
KINS	0.39	0.62			1.33	1.25 1.44		tendon rupture
KOPEC (2D) (3D)	0.64 0.61		1.01 0.94	1.03 1.41	1.36	1.30 1.51		 tendon @ 3.55%
HSE/NNC	0.57	0.57		1.60	1.75	1.98	3%	Liner tear with extensive concrete cracking at buttress region.
NUPEC	0.82	0.59	1.02		1.49	1.49 1.57	 3%	 Tendon rupture
IBRAE	0.70	0.78	1.15	1.01	1.21	1.26		Tendon Rupture
Principia	0.56	0.92		1.30		1.30		tendon yielding
RINSC		1.00				1.50		hoop failure of vessel
ANATECH (SNL)	0.59	0.57			1.27	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)
U. Glasgow	0.95		1.00 1.10					