EVALUATION OF CONTAINMENT PRESTRESSING FOR CERNAVODA NPP UNIT 2: CONSIDERING THE ACTUAL CONSTRUCTION SEQUENCE

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ABSTRACT

The CANDU[TM] 6 reactor system is contained within a post-tensioned concrete containment structure. The construction of the Unit 2 concrete containment structure, located in Cernavoda, Romania, started in early 1980's. The initial prestressing of the containment structure was performed intermittently in 1980's, whereas the final prestressing was completed in year 2002.

This paper presents the evaluation of the change of the construction schedule on the final prestressing of the containment structure. The load cases relevant to prestressing included in this work are: Dead weight; Prestressing and Creep.

Computer Code SOLVIA 99 was used to analyze the models for both the original design and the actual construction schedules. Each load was defined in association with a time-function, which describes the load variation according to construction schedule. Creep coefficients were calculated using DIN4227, EC2/DIN1045-1, ACI 209R-92. The creep code analysis was intended to evaluate the original design margin against the latest codes. The latest code for creep effect evaluation is the EC2 European code, also adopted by Germany as DIN 1045-1; which follows the CEB-FIP Model Code of 1990.

Final results indicate that there are no unfavorable effects on the final prestressing forces and on the containment structure stress state due to delayed construction schedule.

Keywords: Containment Structure, Prestressing, Creep, Construction Sequence

1. CONSTRUCTION HISTORY

The Cernavoda CANDU[TM] 6 containment structure consists of a base slab, perimeter wall, ring beam and upper dome. These are all post-tensioned reinforced concrete elements. Figure 1 shows the containment structure and the geometry used for the modeling.

The construction of the Cernavoda Unit 2 Reactor Building Containment Structure began with the limestone rock excavation. A reinforced concrete sub-base was cast in 1983. The pouring of the concrete base slab took place between June and July, 1983. 20% prestressing of the base slab was finished in August, 1983, while the balance of 80% prestressing was finished in June, 1984.

The construction of the perimeter wall by slip-forming began in Nov., 1983. It ended at top elevation after 17 days and 20 hours, completing the total height of 42.33 m. 20% horizontal prestressing of the perimeter wall was finished in May, 1984. The balance (final 80%) of the perimeter wall horizontal and vertical prestressing was finished in April and July 2002, respectively.

Using the slip-form top walkway at the upper end of the perimeter wall, the construction of the lower ring beam was finished in April, 1984; 100% horizontal prestressing of this member was completed in Aug, 1984. The upper ring beam was finished in May, 1985; prestressing of this member was finished in June, 1985. The upper dome concreting was completed in May, 1985. After completion of the upper ring beam and the upper dome concreting, 20% vertical prestressing of the perimeter wall was finished in May, 1986. Initial 20% prestressing of the upper dome was completed in July, 1987, while the balance of 80 % of the upper dome cables was completed in Oct. 2002.

Table 1 summarizes both the original design as specified by Atomic Energy of Canada (AECL) and the actual construction schedule for the containment structure. Two construction schedules, AECL design and actual were used to define time intervals between concreting and the 1st (initial 20%) and 2nd (remaining 80%) prestressing stages. As can be seen, significant delays occurred between the actual construction schedule relative to the AECL design schedule for the two prestressing phases of the perimeter wall and the upper dome.

It should be pointed out that the only parameter differing from the AECL design was the delayed prestressing time schedule. As a consequence, in this paper only time-dependent effects on containment prestressing are to be examined and evaluated. Since the time span between the initial and final prestressing was about 18 years, shrinkage effects need not to be considered for the final prestressing; hence, only creep effects are accounted for in the analysis and compared with those in the AECL design. Creep is the time-dependent deformation of concrete under constant compression stress, which results in long term prestress losses. The purpose of this work was to evaluate the effects of the change of the remaining prestressing construction schedule on the containment structure of Unit 2 and its ability to perform its functional performance requirements.

2. DELAYED PRESTRESSING

A BBRV [TM] (Birkenaier, Brandestine, Ros) post-tensioning system was used which consisted of a bundle of 7 mm diameter wires cut to predetermined lengths and stressed in accordance with the design requirements. Due to actual sequence of construction, the delayed prestressing work to be completed for the Unit 2 Reactor Building Containment Structure involved:

- 75.5% perimeter wall horizontal prestressing (111 cables out of total 147)
- 83.0% upper dome prestressing (117 cables out of total 141)
- 80.6% perimeter wall vertical prestressing (100 cables out of total 124)

Two basic analyses are carried out for the following situations:
1. Creep corresponding to AECL design construction schedule
2. Creep corresponding to actual construction schedule

The final target can be rendered through interpretation of differences between 1 and 2 above, and evaluation of the effects of these differences on the final prestressing.
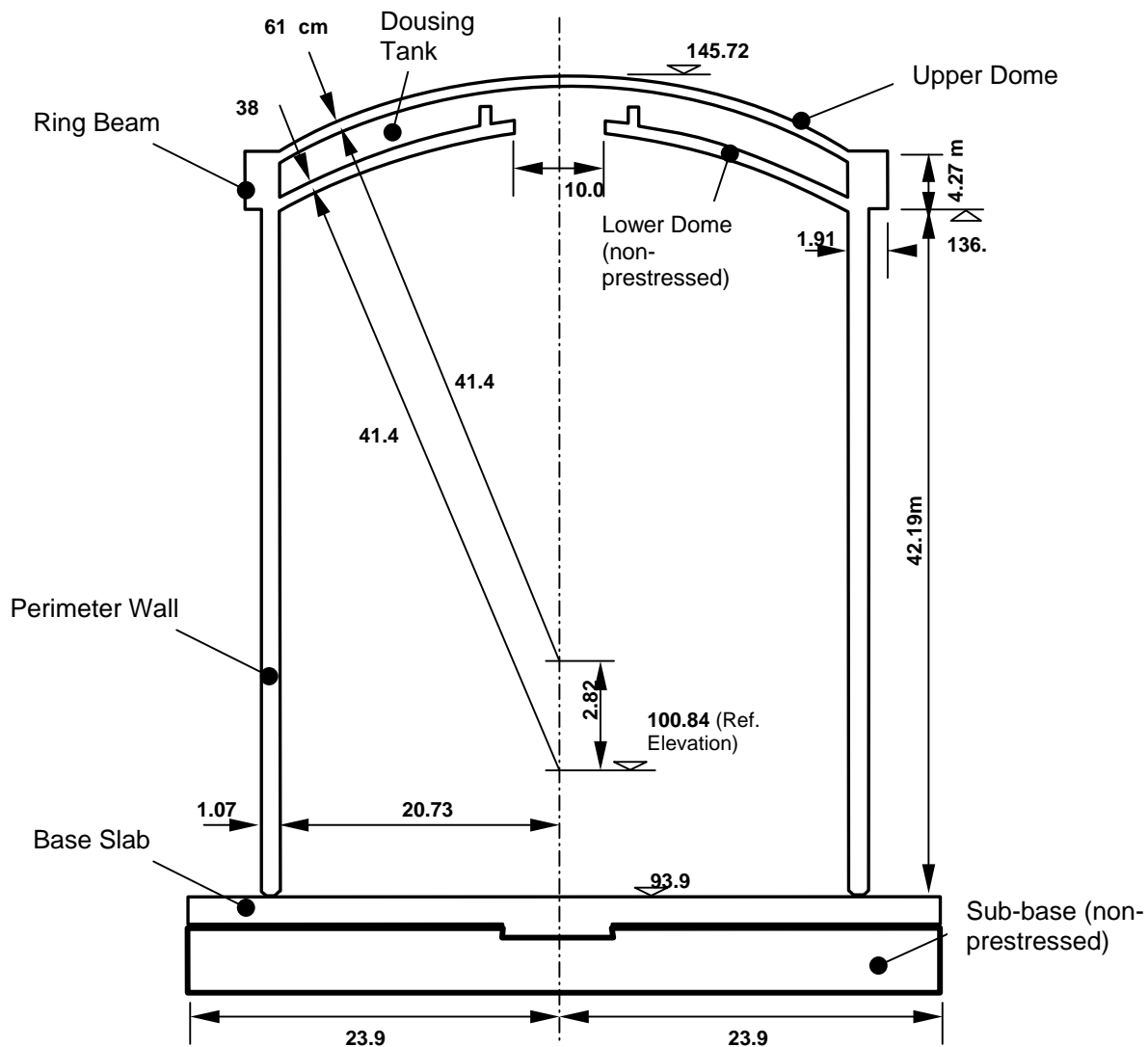
Figure 1 Containment Structure Prestressed Elements and Their Geometry

3. METHODOLOGY

The phenomenon of creep leads to a reduction in the compressive stresses induced in concrete by the application of the prestressing forces. Owing to creep, the reduction of the concrete stresses induced by prestressing naturally is proportional to the prestressing force. Generally, the creep deformation is expressed in terms of the ratio $\varphi_t = \dfrac{\varepsilon_c}{\varepsilon_e}$, between the creep strains, ε_c, under constant stress and the elastic strain, ε_e; where φ_t is known as the creep coefficient. The analysis flowchart is presented in Figure 2.

SOLVIA 99 [1] is the Swedish version of ADINA computer code. SOLVIA has advanced non-linear capability including elastic/plastic creep materials. SOLVIA 99 was used to analyze the axial-symmetric model for both original design and actual construction schedules. Each load was defined in association with a time-function, which described the load variation according to construction schedule. The creep effect was considered by using creep-material with appropriate creep law.

Table 1 Construction Schedule of Containment Structure

Construction Sequence	Construction Schedule (days)	
	AECL Design	Actual Schedule
Base slab: pour concrete	0	0 / 20.06.83
Base slab: tension 20% of cables	20	53
Perimeter wall: start slip-forming	30	142
Perimeter wall: complete slip-forming	50	160
Base slab: tension 80% of cables	70	367
Perimeter wall: tension 20% horizontal cables	100	331
Lower ring beam + lower dome: pour concrete	325	413
Lower ring beam: tension 100% cables	350	425
Upper ring beam: pour concrete	475	697
Upper dome: pour concrete	475	711
Upper ring beam: tension 100% cables	500	714
Perimeter wall: tension 20% vertical cables	500	1053
Upper dome: tension 20% cables	500	1474
Temporary openings A, B: pour concrete	875	5120
Perimeter wall: tension 80% horizontal cables	950	6900
Perimeter wall: tension 80% vertical cables	950	7000
Upper dome: tension 80% cables	950	7100

4. ANALYSIS OF APPLICABLE CODES

The governing code was DIN 4227 [2] for the original AECL design to determine the time dependent effect of creep. However the latest codes were used for comparison purposes. Creep coefficients were calculated using DIN4227, EC2/DIN1045-1 [3] and ACI 209R-92 [4]. The creep code analysis was intended to evaluate the original design margin against the latest codes. The criteria considered in various creep codes are summarized in Table 2.

The Romanian STAS 10107/0-90 [5] followed the guidelines of DIN4227 standard. The American ACI 209R-92 is based on laboratory tests and considers a number of influences which no other code does, such as fine aggregate, air content, etc. On the other hand, it does not consider the concept of massivity (i.e. a measure of the lateral perimeter of an element exposed to the environment through which concrete water is evacuated versus cross-sectional area). This code gives analytical formulae for the creep coefficient, thus eliminating human error. The creep coefficients for early age concrete rise very steeply to relatively high values, after which the curve is almost flat; thus the general aspect differs from the curves of other codes in the early age.
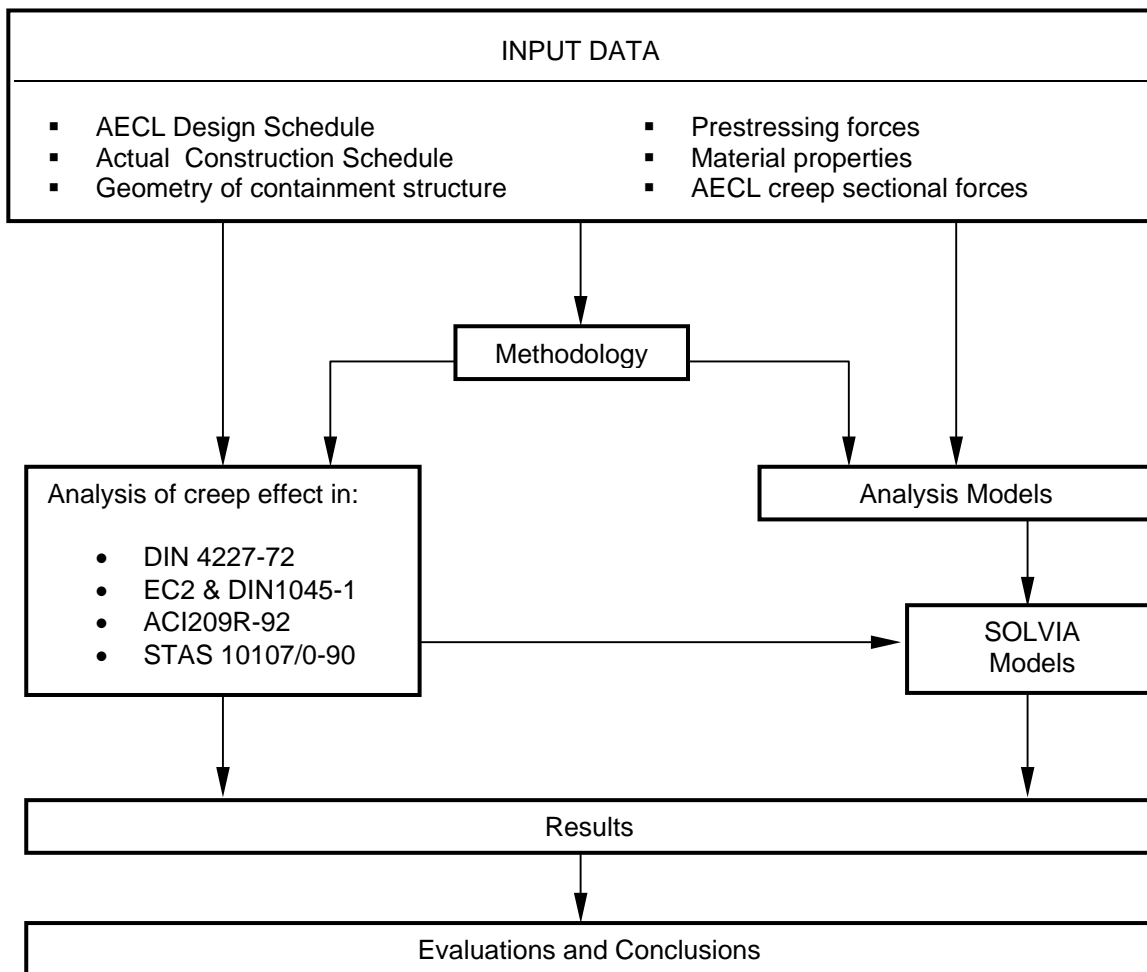
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┌─────────────────────────────────────────────────────────────────────────────┐
│                                 INPUT DATA                                   │
│                                                                             │
│   ▪ AECL Design Schedule              ▪ Prestressing forces                 │
│   ▪ Actual Construction Schedule      ▪ Material properties                 │
│   ▪ Geometry of containment structure ▪ AECL creep sectional forces         │
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Figure 2 Analysis Flow chart

During the analysis of codes, the latest code is the EC2 European code, also adopted by Germany as DIN 1045-1; it follows also the CEB-FIP Model Code of 1990.

The methodology in DIN 4227-72 was applied, consisting of reading values of the appropriate coefficients in the diagrams. These values were used to represent diagrams in which the total normalized strains induced by prestressing were represented versus time in days, for both the design and actual construction schedules.

Table 3 presents the final creep coefficients, φ_t, calculated using DIN 4227-72 considering the design and actual construction schedule for the 2nd prestressing phase. As can be noticed that final creep coefficients based on the actual construction schedule are smaller than the original AECL design schedule.

Figure 3 shows the effect of construction schedule on the total vertical prestressing of the perimeter wall using original design code. As can be seen from this figure that delayed prestressing resulted in significantly lower strain values.

As a result when applying the 2nd prestressing phase, the concrete is much older than initially supposed in the design. An aged concrete is less prone to creep effects for the same stress level. Thus, the final strains due to total prestressing at t=∞ including creep are:
  • 73% of the AECL design values (perimeter wall, vertical prestressing)
  • 81% of the AECL design values (perimeter wall, horizontal prestressing)

- 62% of the AECL design values (upper dome prestressing)

Table 2 Criteria Considered in Creep Codes

	Criterion	DIN 4227-72	EC2 and DIN1045-1	ACI209R-92	STAS 10107/0-90
Concrete composition	Concrete grade	●	●		●
	Cement grade	O	O		
	Aggregate type	O		O	O
	Percent of fine aggregate			O	
	Air content			O	
	Slump	O		O	O
Member geometry	Size/average thickness, volume-to-surface ratio, etc.	D_w	h	h, v/s	b_f
Environmental conditions	Environmental temperature	O	O		O
	Transformed concrete age, depending on temperature	●	●		●
	Ambient relative humidity	●	●	●	●
Loading influences	Concrete (transformed) age at loading date	●	●	●	●
	Level of concrete stress	●	●		●
	Time-hardening of modulus of elasticity		O		

Legend:

- ●   basic criterion
- O   secondary criterion

Consequentially, prestressing forces are greater than considered in the AECL design and do not result to unfavorable effect on the containment stresses.

Table 3 Final Creep Coefficients $\varphi\infty$

Structural Member and Percentage Prestressing	DIN 4227-72 AECL Design Schedule		DIN 4227-72 Actual Construction Schedule	
	φ_∞	φ_∞ x percent prestr.	φ_∞	φ_∞ x percent prestr.

Perimeter wall Vertical Prestressing	19.4%	1.480	0.287	1.240	0.241
	80.6%	1.230	0.991	0.540	0.435
Perimeter wall Horizontal prestressing	24.5%	1.900	0.466	1.760	0.431
	75.5%	1.220	0.925	0.550	0.415
Upper Dome In-plane prestressing	17.0%	2.180	0.371	1.270	0.216
	83.0%	1.580	1.311	0.550	0.457

Figure 3 Effect of construction schedule on total vertical prestressing strains (normalized) for perimeter wall according to DIN 4227-72

4.1 COMPARISON OF CREEP COEFFICIENTS

Figure 4 shows the comparison between creep coefficients computed according to various codes (DIN 4227-72, EC2 and DIN 1045-1, ACI 209R-92) for 80% vertical prestressing in the.perimeter wall. The creep code analysis is intended to evaluate the original design margin against latest codes. As can be seen from this figure that the DIN 4227-1972 used in the AECL design leads to conservative results as compared to the latest German DIN 1045-1, EUROCODE EC2, and ACI 209R-92 codes.
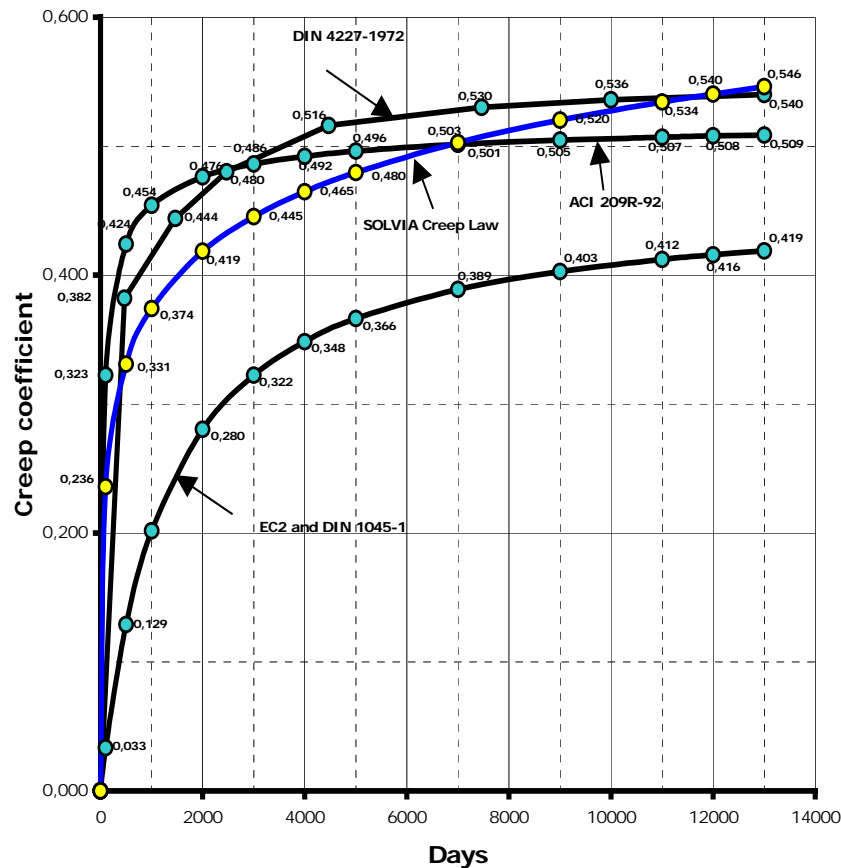
Figure 4 Comparison of creep coefficients using various codes for aged concrete (perimeter wall, 80% vertical prestressing)

5. RESULTS

The SOLVIA model validation was done for 100% prestressing load case (without creep). Comparison of results shows a good agreement between original design AECL analysis results and new results generated using SOLVIA model.

The following analyses were performed using the validated SOLVIA model:
- o dead weight without creep
- o dead weight with creep
- o 20% prestressing without creep
- o 20% prestressing with creep
- o 80% prestressing without creep
- o 80% prestressing with creep
- o dead weight + 100% prestressing without creep
- o dead weight + 20%presstressing + 80% prestressing including creep according to construction schedule

Two type of analysis were performed. SOLVIA V1 consists of separate analysis for dead weight, 20% prestressing and 80% prestressing with and without creep each with the appropriate creep function according to design and effective construction schedules. The creep effect was calculated for each analysis step by subtracting "Without creep results" from "With creep results". The total creep effect was obtained combining dead weight creep, 20% prestressing creep and 80% prestressing creep.

SOLVIA V2 consists of single analysis using program capability to define time dependent loads according to design and effective construction schedule. Only one average creep law was used for all

type of loads named SOLVIA creep.

Figure 5 shows vertical displacement history of the full analysis (SOLVIA V2) including creep corresponding to the effective construction schedule for the perimeter wall. This figure clearly indicates the creep effect after each load step (similar shape as compared to the creep strain diagrams).

Figures 6 and 7 show meridional and hoop stresses for the upper part of the containment (domes and ring beam) using SOLVIA -V2 due to dead weight, prestressing and creep. As can be seen from these figures that mainly compressive stresses result in the upper dome.

Figures 8 and 9 show the comparison between original design and actual construction schedule for the total creep effect using SOLVIA V1 modal analysis. The comparison shows lower creep forces corresponding to the actual construction schedule. SOLVIA V2 analysis for actual construction schedule produced much lower creep forces than SOLVIA V1 analysis. This comparison shows that AECL original design is conservative for creep load case.
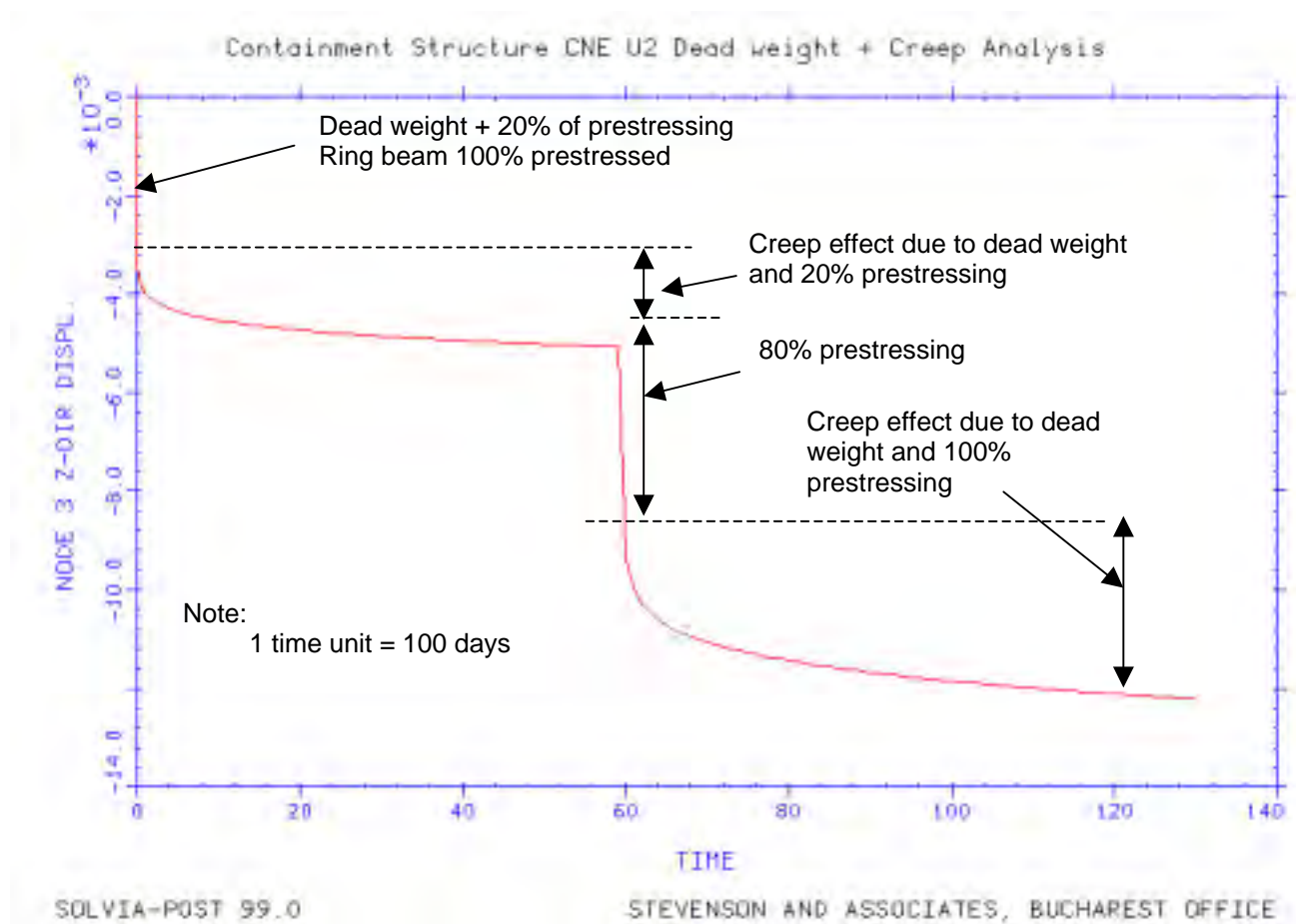

Figure 5 Displacement History Including Creep for Effective Construction Sequence (SOLVIA 2)
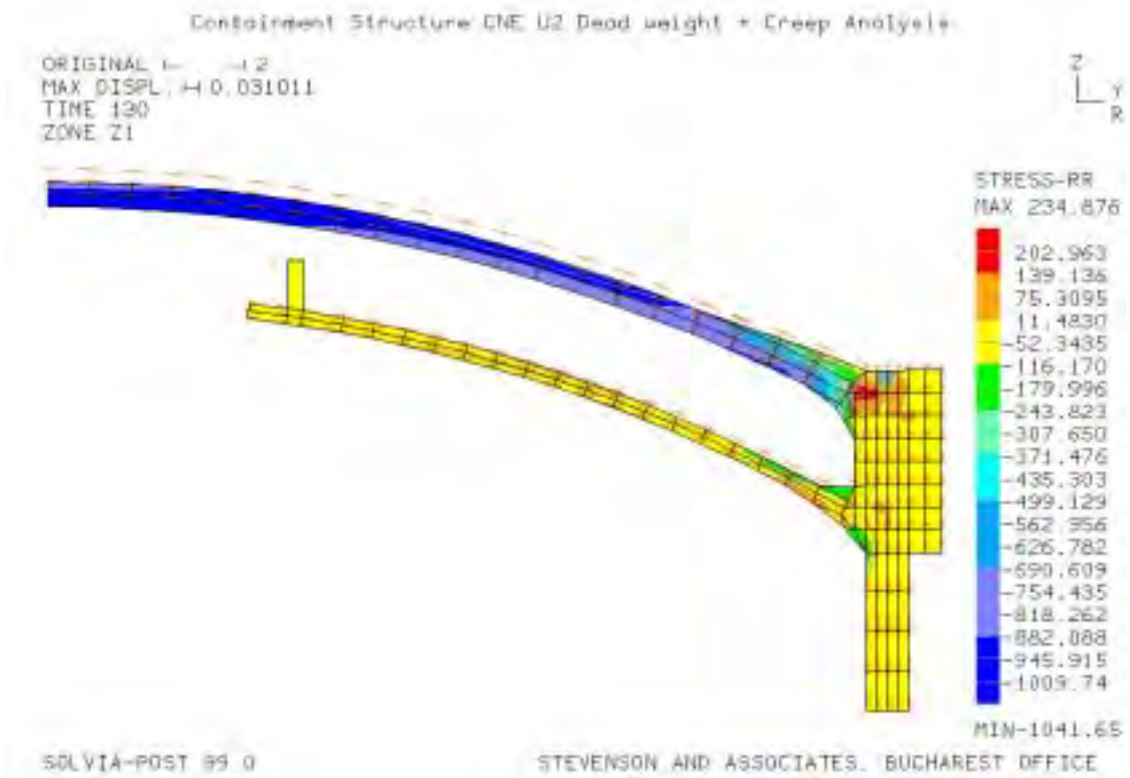
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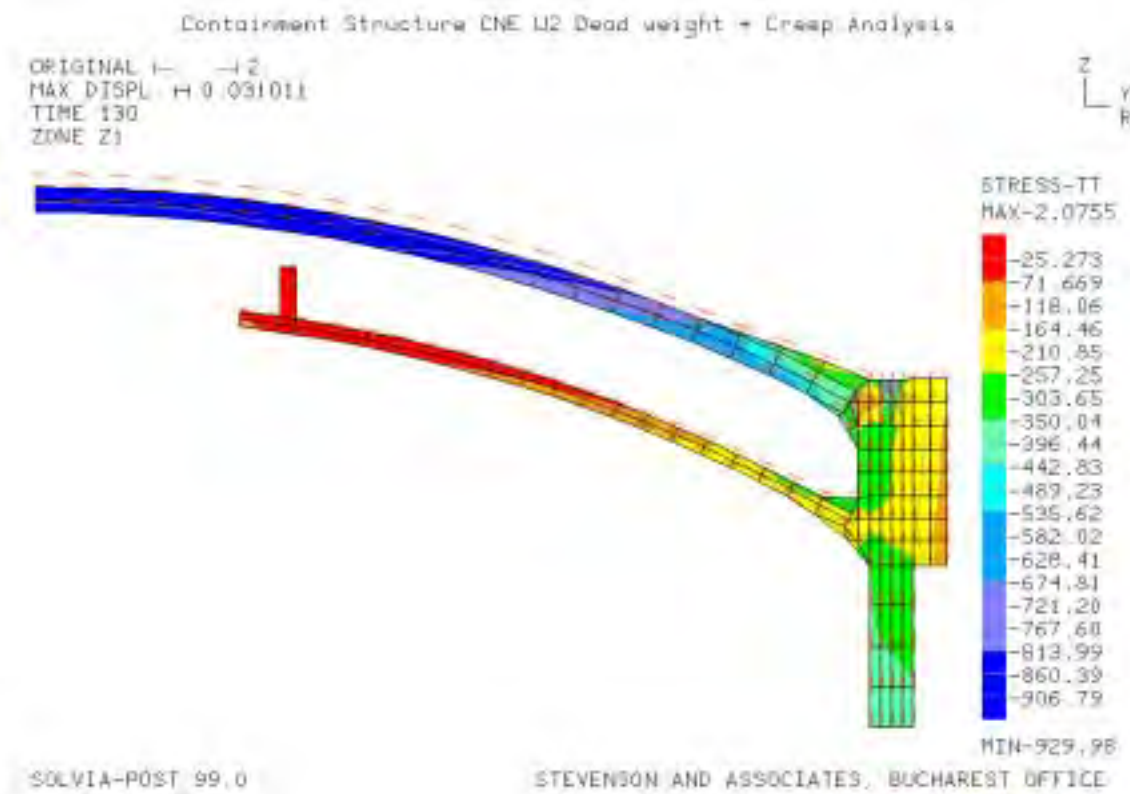*Figure 6 SOLVIA V2 Upper Dome + Ring Beam Meridional Stress Diagram [t/m2]*

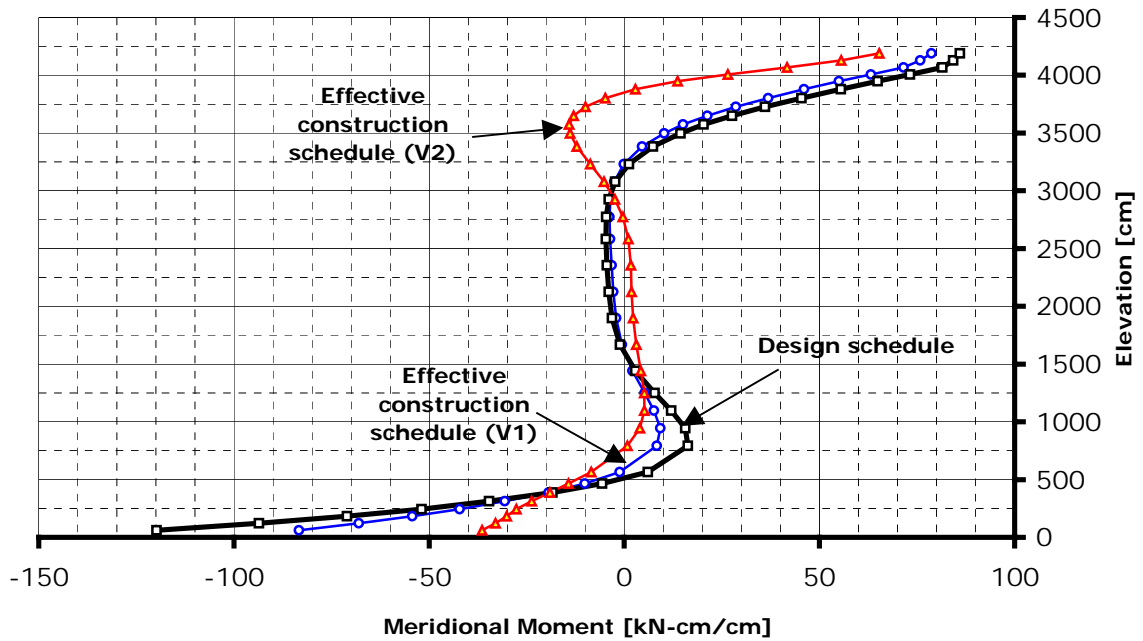*Figure 7 SOLVIA V2 Upper Dome + Ring Beam Hoop Stress Diagram [t/m2]*

Figure 8 SOLVIA: Perimeter Wall, Creep Load Case. Comparison between Design and Effective construction schedule (Meridional Moments)
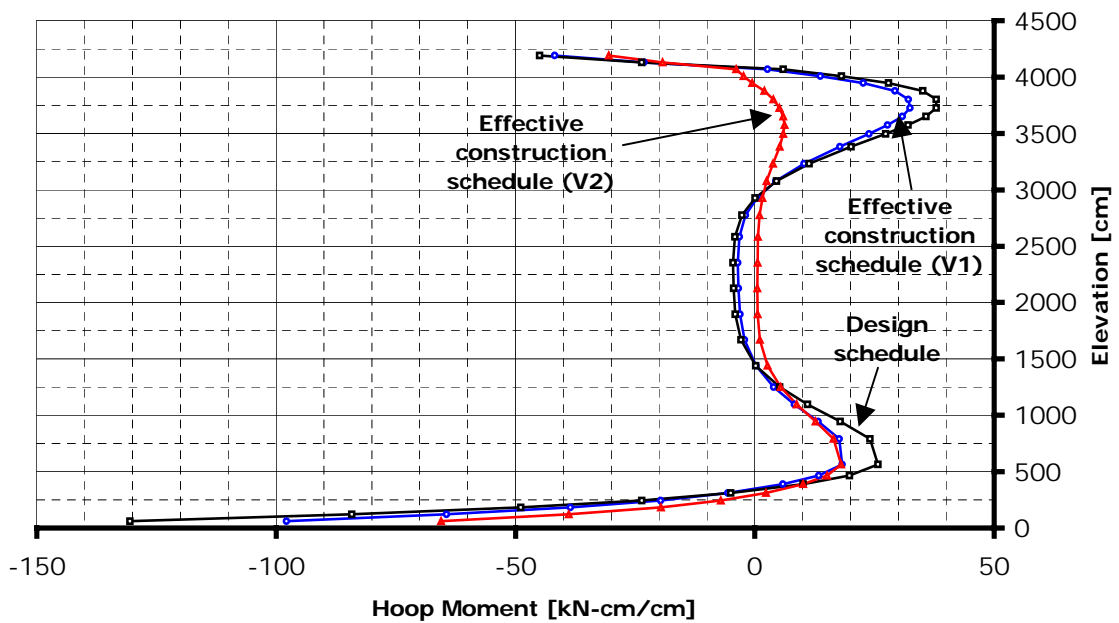

Figure 9 SOLVIA: Perimeter Wall Creep Load Case. Comparison between Design and Effective construction schedule (Hoop Moments)

6. CONCLUSIONS

The following are the conclusions:

1. For actual construction schedule, final creep coefficients, φ_∞, for the 2nd prestressing phase are smaller than the original AECL design schedule based on DIN 4227-1972 methodology. Smaller creep results in lower total prestressing losses which in turn produces higher prestressing forces than the original design values.

2. Based on the validated axi-symmetric SOLVIA analysis model, the creep-induced sectional forces, corresponding to the actual construction schedule, are smaller than those in the AECL design schedule. For bending moments induced by creep, critical areas are in the vicinity of joints with base slab and ring beam.

3. The analysis of various creep codes shows that the DIN 4227-1972 used in the AECL design report leads to conservative results as compared to the latest German DIN 1045-1, EUROCODE EC2, and ACI 209R-92 codes. If the same containment would be designed today using the latest codes, the predicted creep will be considerably smaller than in the original design.

4. There are no unfavorable effects induced by creep in the final prestressing forces and in the containment structure state of stress, due to delayed construction schedule. Therefore, the structure will meet its functional performance requirements based on original design basis code and the use of the latest codes / standards.

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