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AN ASSESSMENT OF LONG-TERM STRUCTURAL BEHAVIOR OF AN ASYMMETRIC MULTI-CAVITY PCRV

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Abstract

The use of multi-cavity prestressed concrete reactor vessels (PCRVS) with a symmetric configuration to house gas-cooled reactor components is well established. Recent design development of the PCRV for High Temperature Gas-Cooled Reactor (HTGR) systems incorporates an asymmetric arrangement of major cavities with the center of the core cavity offset from the geometric center of the vessel. The asymmetric layout allows a more effective utilization of space in grouping all the heat-exchanger cavities together over a portion of the PCRV resulting in overall vessel size reduction, and facilitates separation of safety-related piping from main steam piping.

A study has been undertaken at General Atomic Company to assess the effects of the asymmetric, offset core configuration on the long-term behavior of the multi-cavity PCRV. Of special interest is the prediction of concrete creep deformation which influences stress redistribution, prestress losses, and liner strains. The implication of the offset core cavity with respect to PCRV movements and liner design is examined.

This paper presents the results of an analytical investigation of the creep effects of an asymmetric, off-set core PCRV configuration using the finite element method. The concept of effective elastic modulus is employed to characterize the concrete creep under long-term loads and temperatures. This approach, assuming validity of the principle of superposition, permits a systematic consideration of concrete aging and variation of temperature in time. In the light of uncertainties in the many parameters that influence concrete creep characteristics and the lack of validation of more complex rheological models under realistic test conditions, the use of this simple method of effective elastic modulus is justified for a preliminary assessment of the time-dependent vessel response. The effective moduli for loading histories considered were obtained by a creep function derived from PCRV concrete properties test data. The finite element model was based on the proposed PCRV for a 900-MW(e) steam cycle HTGR. In the three-dimensional finite element analysis, traditional isoparametric brick and membrane elements were used to model the concrete and liners, respectively. Two loading histories were developed to provide the bounds to the creep effects of an asymmetric multi-cavity vessel.

1. Introduction

Prestressed concrete reactor vessels (PCRVs) have been adopted for use as primary containment for high-temperature gas-cooled reactor (HTGR) systems. PCRVs offer the advantages of on-site construction and inherent safety characteristics due to the highly redundant nature of the prestressing systems. In the multi-cavity configuration, the heat exchangers are enclosed within cavities in the barrel wall for better loop separation and component in-service inspection and general access. The structural behavior of the multi-cavity PCRV with a symmetric configuration is fairly well established through model testing and analytical studies. Some of these studies are included in a licensing topical report [1] submitted to and approved by the U.S. Nuclear Regulatory Commission (NRC). More recent development of the PCRV for the HTGRs incorporates an asymmetric cavity arrangement for major components with an offset core as part of the continuing design optimization effort. At General Atomic Company, an investigation has been undertaken to study the effects of the asymmetric, offset core configuration on the long-term behavior of the multi-cavity PCRV. The preliminary results of this ongoing investigation enable an initial assessment to be made.

2. Creep Analysis

2.1 Analytical Model

The finite element model for the three-dimensional creep analysis was based on the PCRV for a 900-MW(e) Steam Cycle HTGR as shown in Fig. 1. As can be seen, the asymmetric, offset core configuration results from grouping all steam generator cavities close together to achieve significant PCRV size reduction. Taking advantage of the condition of near symmetry, a 180° sector of the top half of the vessel was considered in the analytical model. Traditional isoparametric brick and membrane elements were used to model the concrete and steel liners, respectively. The refueling penetrations in the PCRV top head were not modeled directly. The reduced stiffness of the perforated zone was represented by solid elements with an equivalent elastic modulus. The finite element model includes major cavities for the core, two steam generators and core auxiliary heat exchangers. The model consists of 462 20-node isoparametric brick and 199 membrane elements with a total of 2763 nodal points.

2.2 Effective Modulus Method

The effective modulus method is a well-known approximate method of analysis for concrete creep. This simplified method is known to give excellent accuracy when concrete aging is negligible [2]. In this study, the effective modulus method is modified to incorporate the effects of concrete aging and variation of temperature in time. In the analysis, the normal finite element procedures for elastic solutions are applied at each time step under consideration. The concrete modulus of elasticity of each solid element is replaced by an effective elastic modulus. The effective (or sustained) modulus is defined as:

$$E_{eff} = \frac{1}{\varepsilon_{sp} + C_{sp}} \qquad (1)$$

in which ε_{sp} = specific elastic strain (strain per unit stress)

C_{sp} = specific creep strain.

Eq. (1) can be rewritten as

$$E_{eff} = \frac{E\ (\tau,\ T)}{1 + \frac{C_{sp}}{\varepsilon_{sp}}} = \frac{E\ (\tau,\ T)}{1 + \phi(t,\tau,T)} \tag{2}$$

where $E(\tau,T) = \frac{1}{\varepsilon_{sp}}$ = instantaneous elastic modulus at age τ and temperature T,

t = time under load,

$\phi(t,\tau,T)$ = creep coefficient,

and $J(t,\tau,T) = \frac{1 + \phi\ (t,\tau,T)}{E\ (\tau,T)}$ = creep function.

Therefore,

$$E_{eff} = \frac{1}{J(t,\tau,T)} \tag{3}$$

To account for the effects of concrete aging and variable temperature, a systematic superposition of specific strain curves is necessary as illustrated in Fig. 2. The cumulative specific strain at time, t, for a given load history with variable temperatures is determined in the manner defined by the following expression:

$$J(t) = J(t,\tau_1,T_1) + \sum_{i=1}^{n} \left[J(t,\tau_{i+1},T_{i+1}) - J(t,\tau,_{i+1},T_i)\right] \tag{4}$$

Once the cumulative specific strain curve is established, the effective modulus for each element is given by eq. (3).

2.3 Creep Function

The creep function employed in the effective modulus method was derived from test data of an extensive PCRV concrete properties study conducted for General Atomic Company by the University of California at Berkeley [3]. Test results provide strength and creep characteristics of high strength concrete under long-term loads at elevated temperatures up to 71°C (160°F). Concrete specimens at three ages of loading (28, 90, and 270 days) subjected to stress levels representing 30%, 45%, and 60% of the concrete compressive strength were tested. By curve fitting the test data, a creep function embodying aging and temperature parameters results as follows:

$$J(t,\tau,T) = 10^{A+B} \tag{5}$$

where $A = (0.11 - 0.03965 \log \tau + D) \log t$,

$B = \log \frac{1}{E(\tau,T)}$,

$D = [(854 + 294 \log \tau)/10^6]T^{0.967}$,

and $E(\tau,T) = [5.871 - 0.000429T^{1.48} + (3.3047T^{-0.34} - 0.4686)\log \tau] \times 10^6$.

Plots of specific strains with time on a log-log scale for three testing temperatures at various ages of loading are presented in Fig. 3. Each data point represents an average value of three concrete creep specimens. The close correlation of curve fit with the data points verifies the accuracy of the creep function.

2.4 Loading Conditions

A three-dimensional PCRV creep analysis based on the postulated operating conditions is highly involved because of the complicated history of loading and temperature during the design life of the vessel. Conservative, simplified assumptions on the various ages of loading, pressurization, and operating temperatures are therefore made for the load histories in the analysis to keep the computational effort reasonable. Two load histories, as illustrated in Fig. 4, are developed to provide bounds for the concrete creep deformation. Load History I assumes that subsequent to the initial proof pressure test, the vessel remains at normal operating pressures after steady-state temperature is achieved. In Load History II, the vessel remains unpressurized over the 40 years of design life. The liner/concrete interface temperatures are indicated in Fig. 4. At various stages of the loading history, the prestressing forces are adjusted to acocunt for losses due to concrete creep and steel relaxation.

3. Discussion of Results

3.1 Prestress Loss

The prestress losses computed in this analysis include the effects of elastic shortening, shrinkage, concrete creep, and prestressing steel relaxation. At each time point, creep deformations and steel relaxation factors estimated according to time under load and temperature conditions were used to correct the prestress level.

In Load History I, circumferential prestress losses are found higher in the top head than the barrel as expected because of the relatively high prestress level applied to the top head. In addition, the prestressing steel on the circumference of the top head experiences less of the operating pressure effects. The vertical prestress losses are higher in the inner ligaments than elsewhere because of the concentration of tendons in the inner ligaments. The tendons in the inner ligaments also experience comparatively higher concrete creep and steel relaxation due to the prevailing temperature condition. Maximum prestress losses for both circumferential and vertical prestressing determined from Load History I are shown in Fig. 5.

3.2 Stress Redistribution

The analysis predicts significant thermal stress reduction and redistribution due to concrete creep. The distributions of thermal stresses alone in the PCRV ligaments resulting from a steady-state temperature profile with a liner/concrete interface temperature of 65°C

(150°F) are shown in Fig. 6, which clearly demonstrates the self-limiting nature of the thermal stress. At the end of the vessel design life (over a time span of 40 years) an average of 85% reduction of the compressive thermal hoop stress around the core cavity at PCRV mid-height is indicated. Similarly, the tensile thermal stress in the outer ligament is reduced by 70%. Figure 7 shows the stress distribution due to initial prestress and the combined effects of effective prestress, cavity pressure and temperature loading. It is evident that concrete creep promotes a more gradual total stress redistribution with time.

3.3 Creep Factors

The creep factors in Fig. 8 represent the maximum compressive end-of-life creep based on Load History II assuming that the vessel remains unpressurized for its entire 40-year design life. This loading history assumes no relief from operating pressures. A more realistic operating history would yield considerably less creep. These creep factors may be used conservatively for the preliminary design of PCRV cavity liners.

3.4 PCRV Movements

The PCRV movements are obtained by analyzing the vessel under the two assumed load histories. The radial displacements shown in Fig. 9 represent the maximum range of movements of the PCRV core cavity wall at the end of the vessel's life. The probable movements are expected to be within this range. The relative radial movements of the refueling penetration region in the PCRV top head from the vessel's vertical axis are shown to be less than 2 mm (0.08 in.). Asymmetrical movements around the core cavity wall are anticipated due to variation in wall thickness resulting from the offset core configuration. Such movements are of the order that can be accommodated in the design tolerance.

4. Conclusions

This preliminary assessment indicates that the long-term structural behavior of an offset core PCRV does not depart significantly from that predicted by previous analyses for vessels with a symmetric arrangement of major cavities. Prestress losses and concrete creep factors calculated are within the range nromally used for the PCRV design.

Acknowledgement

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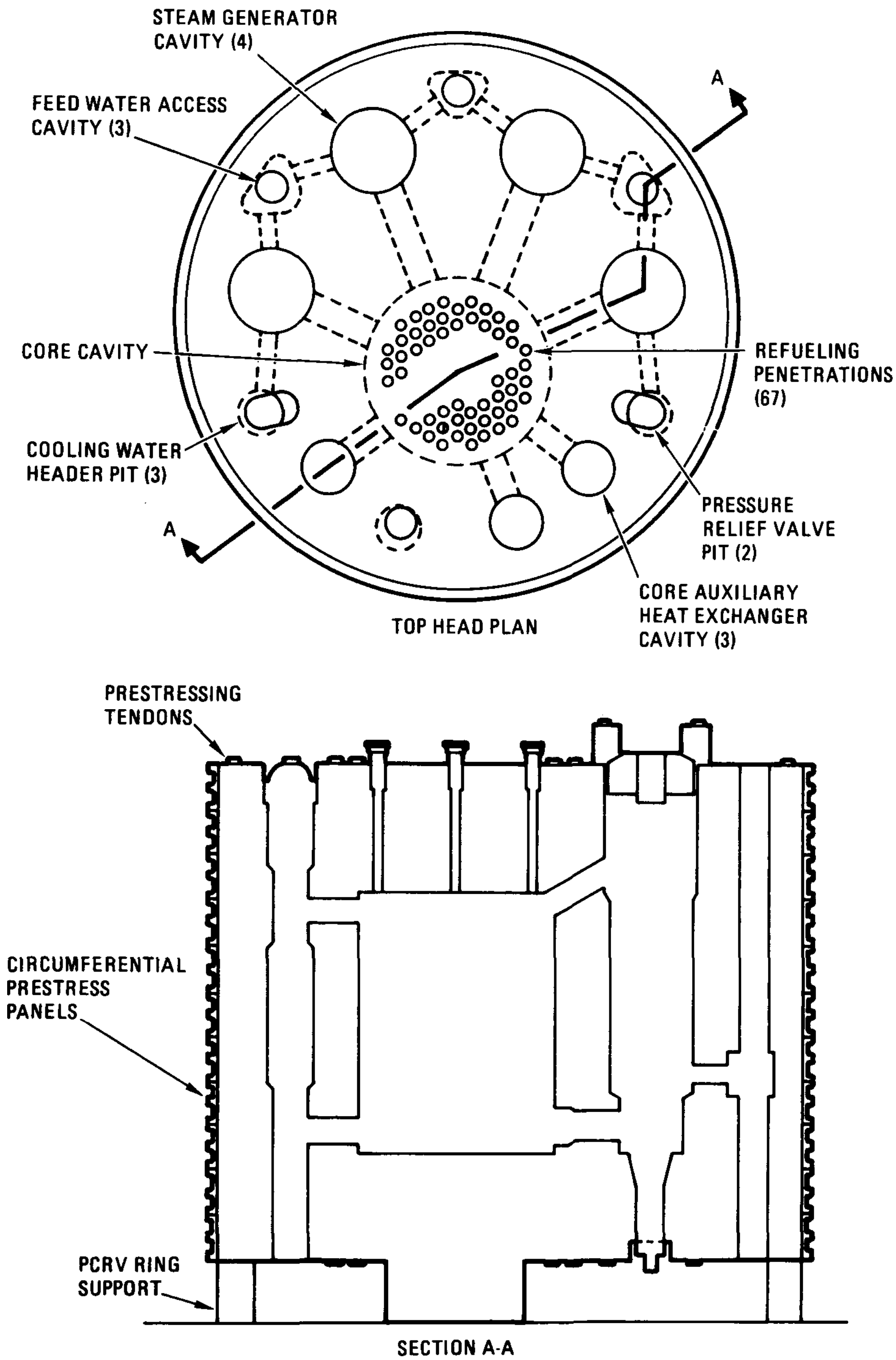

Fig. 1. Multi-cavity PCRV for 900-MW(e) HTGR

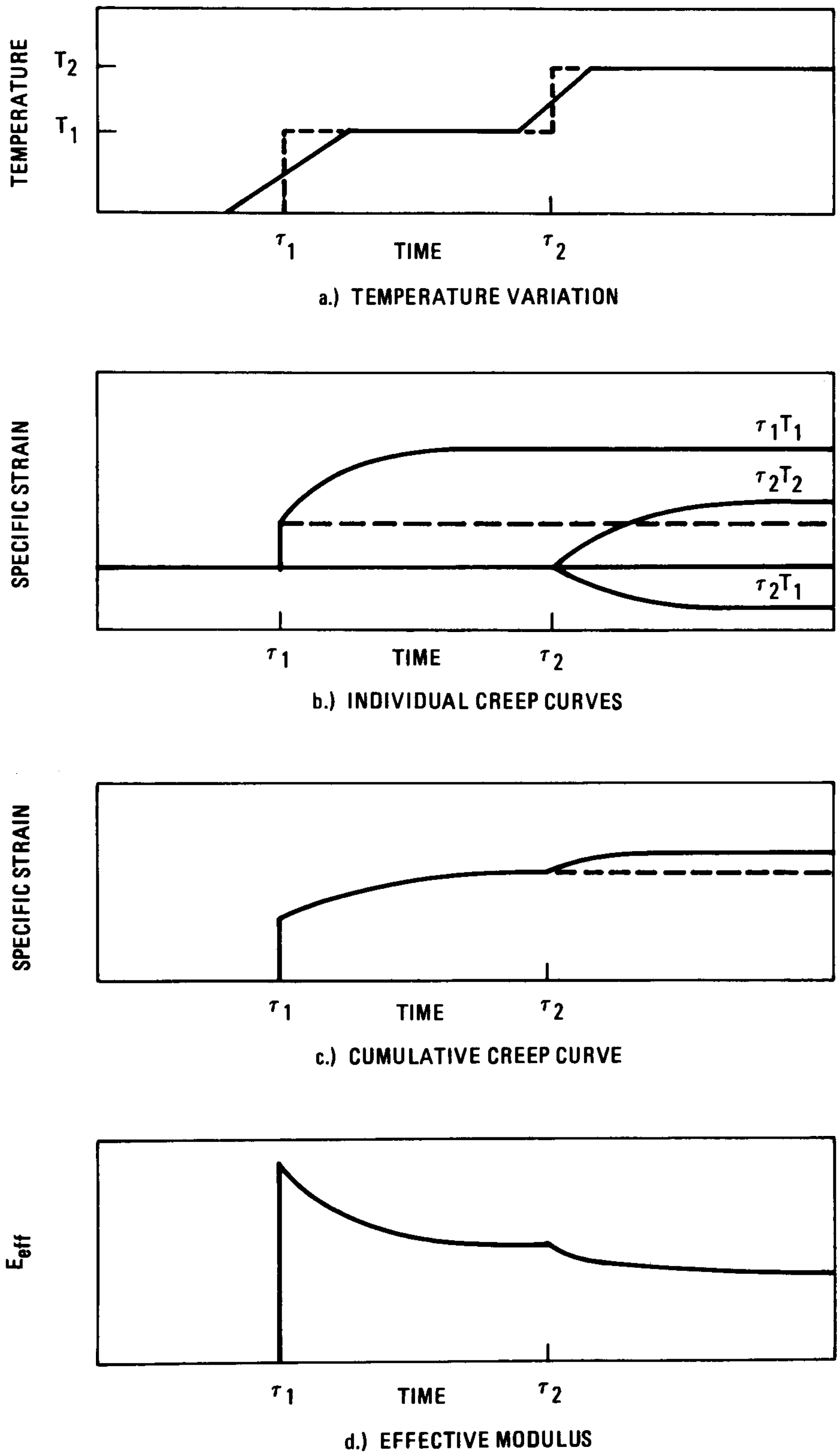

Fig. 2. Superposition scheme to determine effective modulus

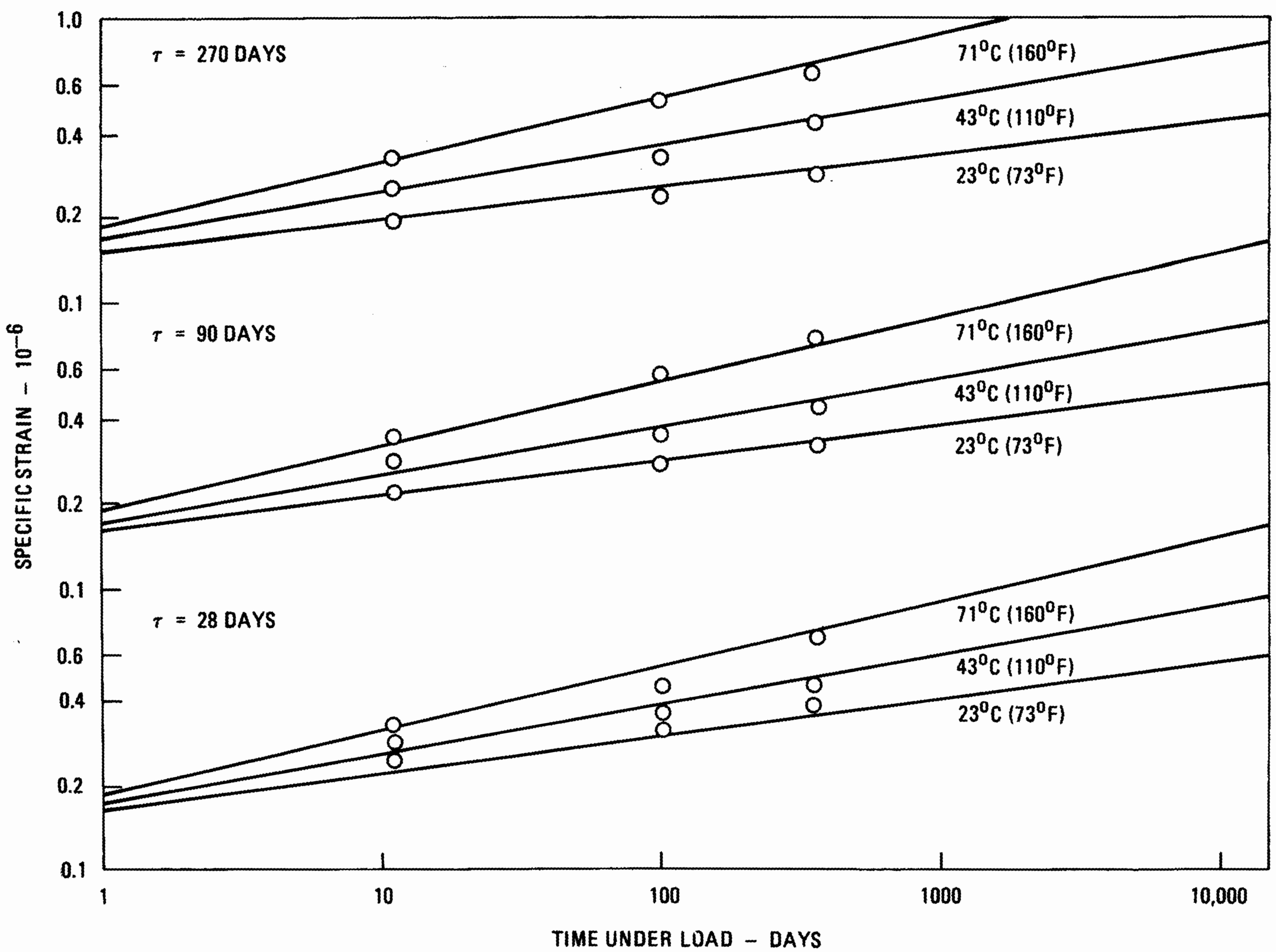

Fig. 3. Specific strain curves at various ages of loading and temperatures (GA data)

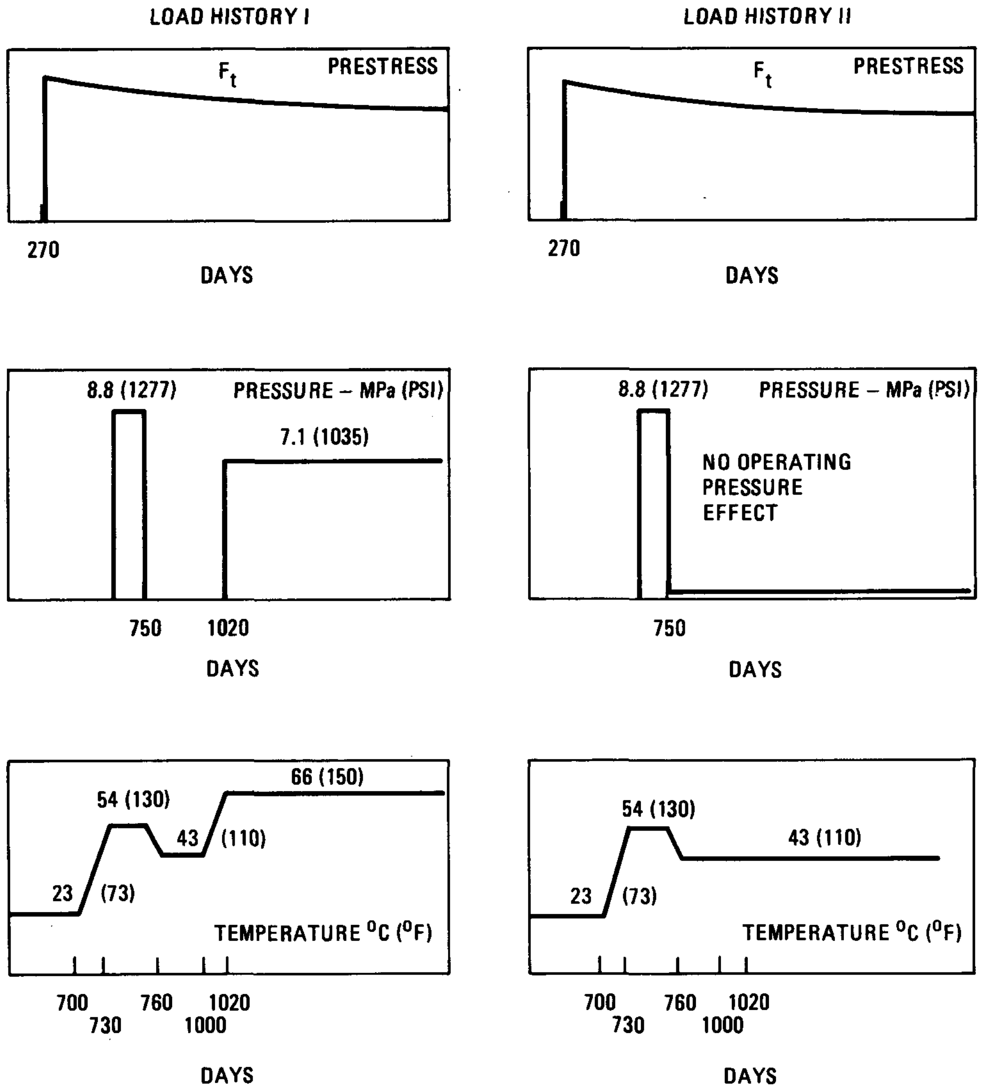

Fig. 4. Load histories

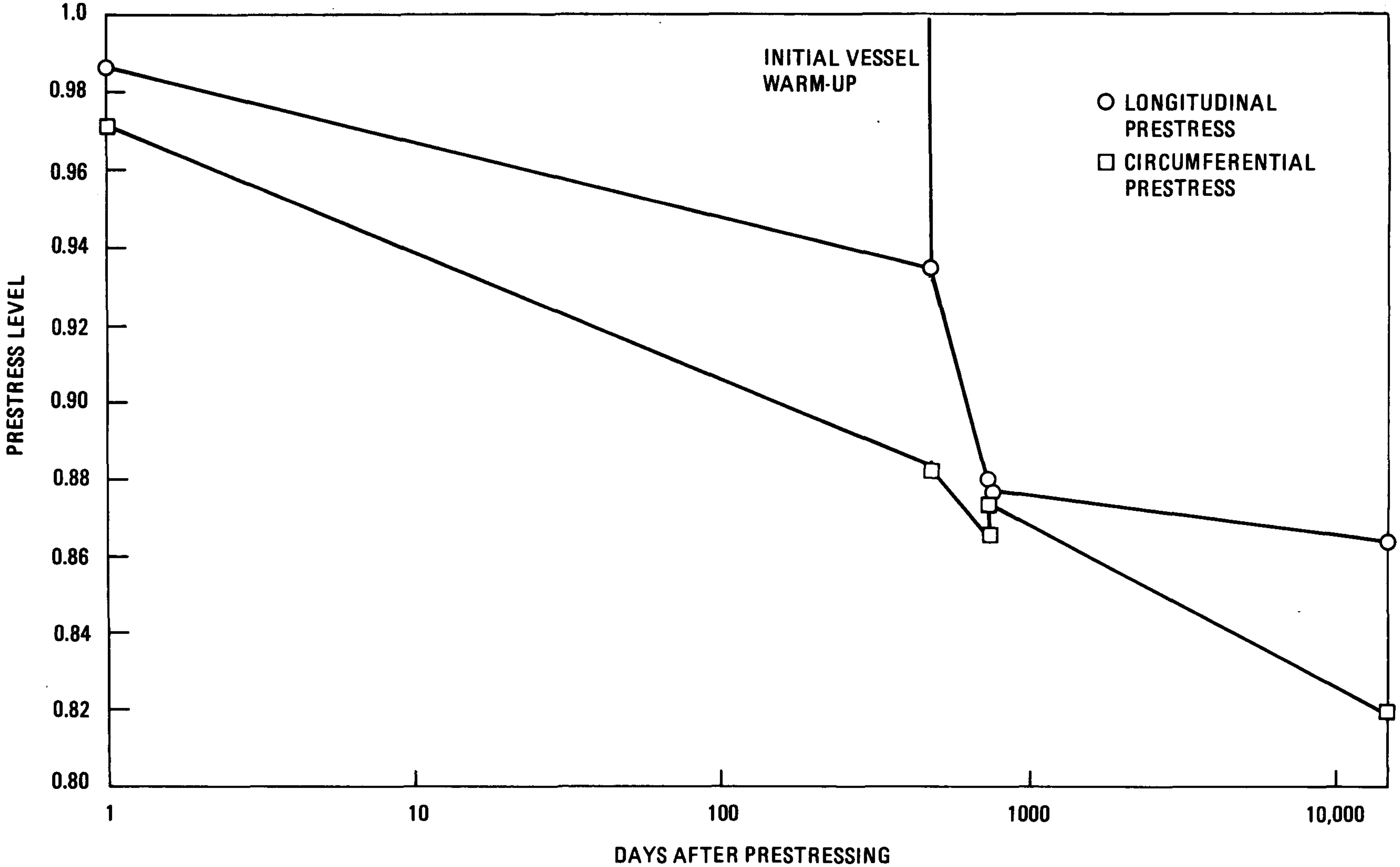

Fig. 5. Prestress losses with time (Load History I)

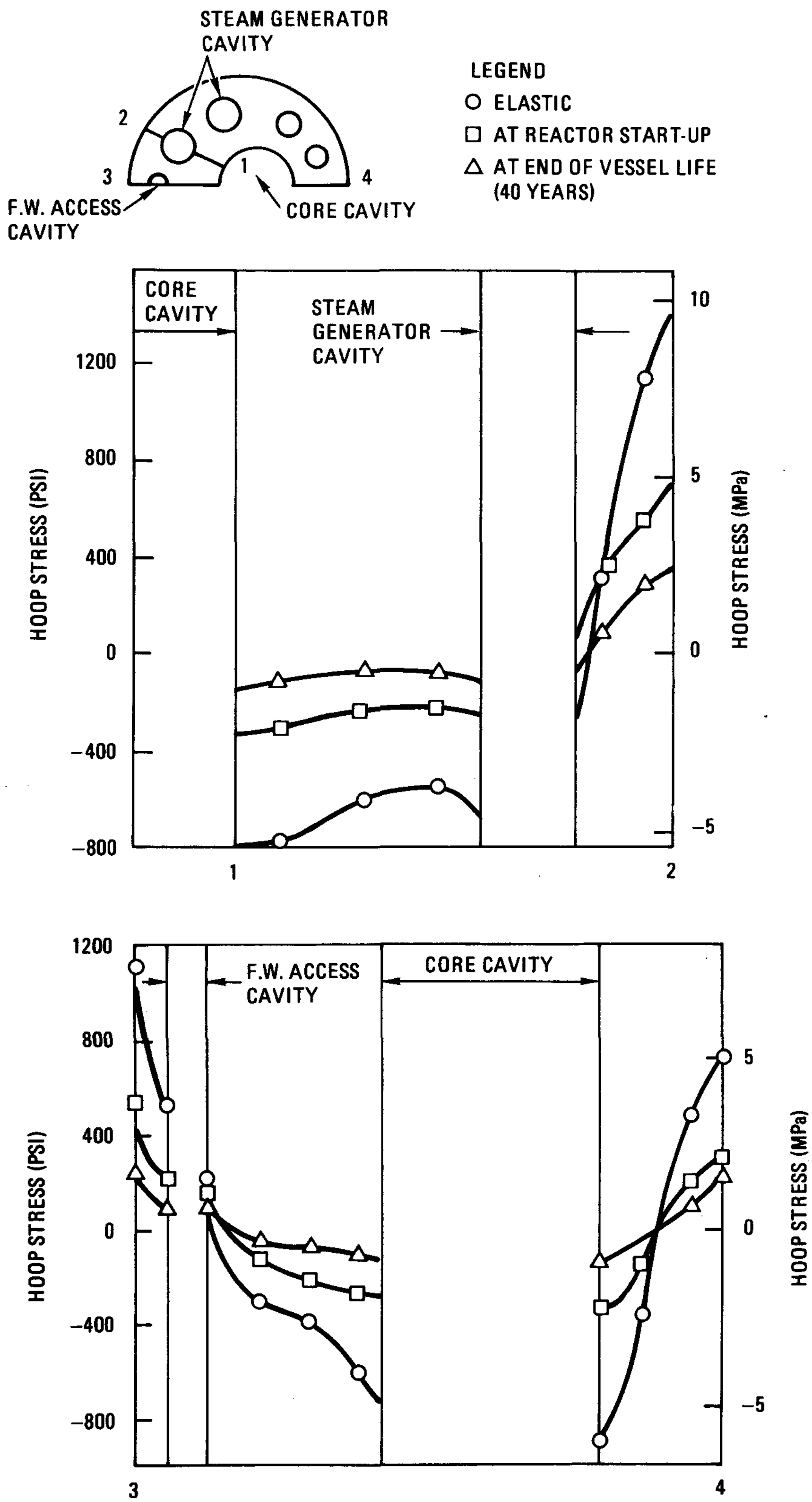

Fig. 6. Thermal stress redistribution due to concrete creep at PCRV midheight

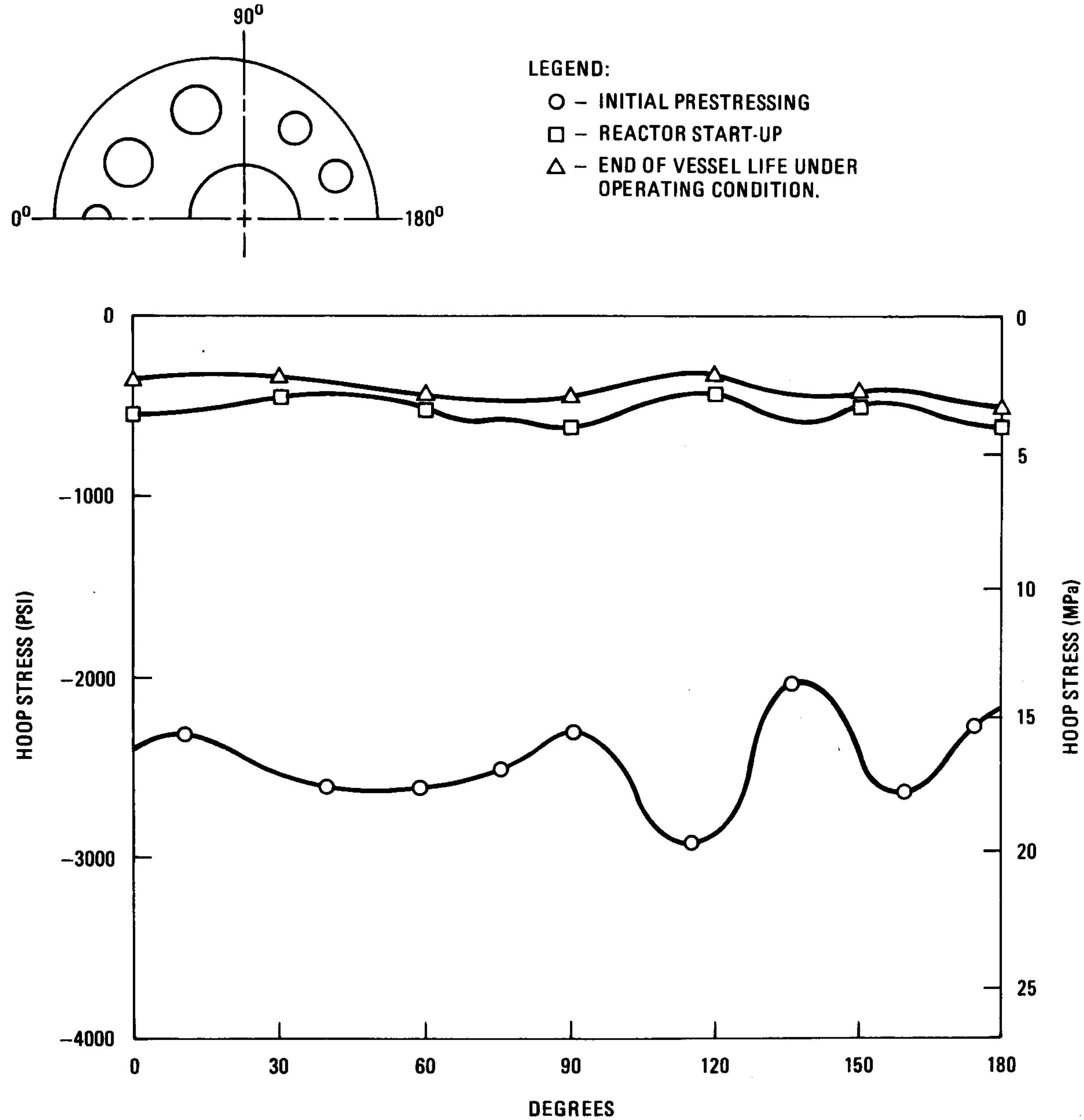

Fig. 7. Stress distribution around core cavity at PCRV midheight (Load History I)

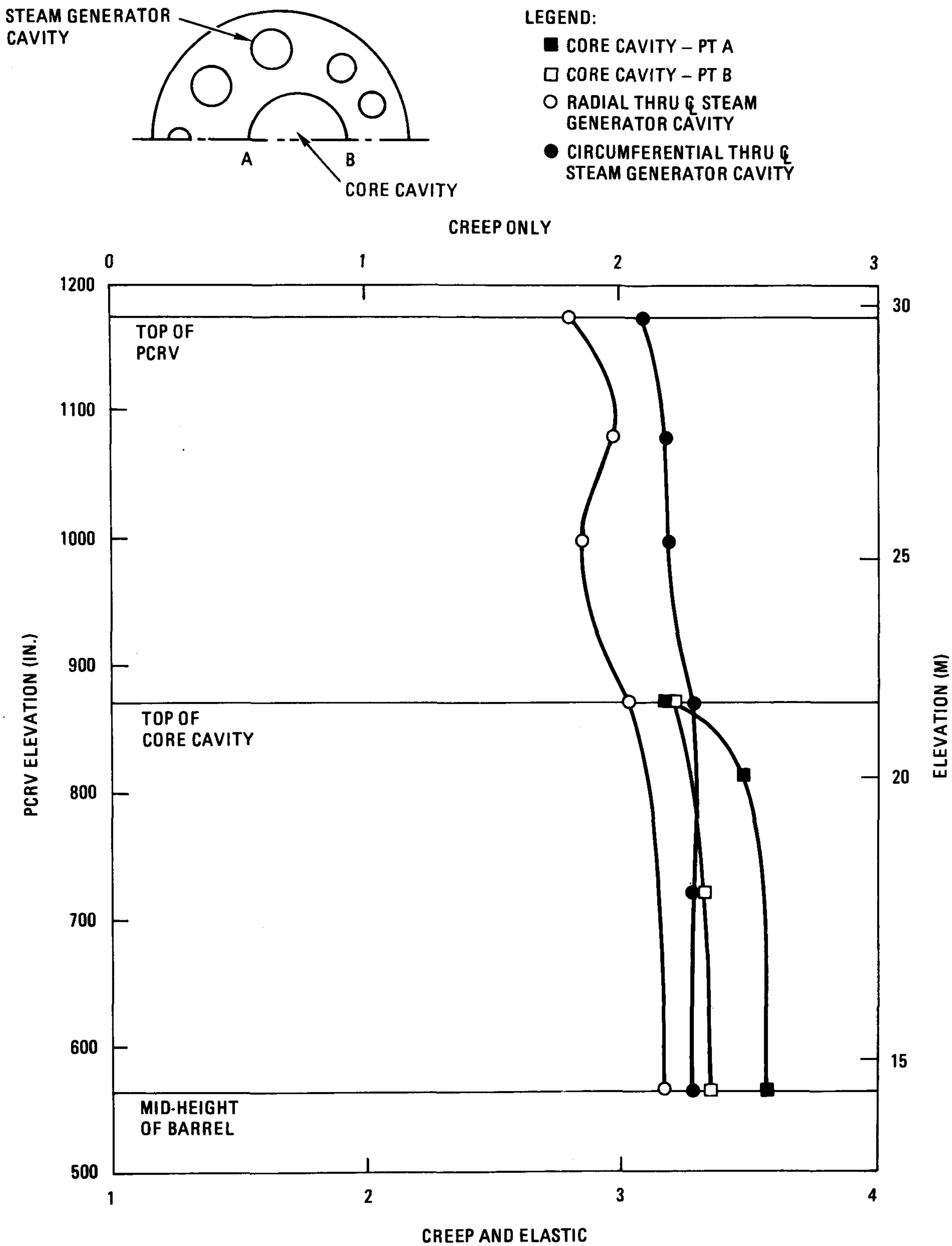

Fig. 8. PCRV creep factors (Load History II)

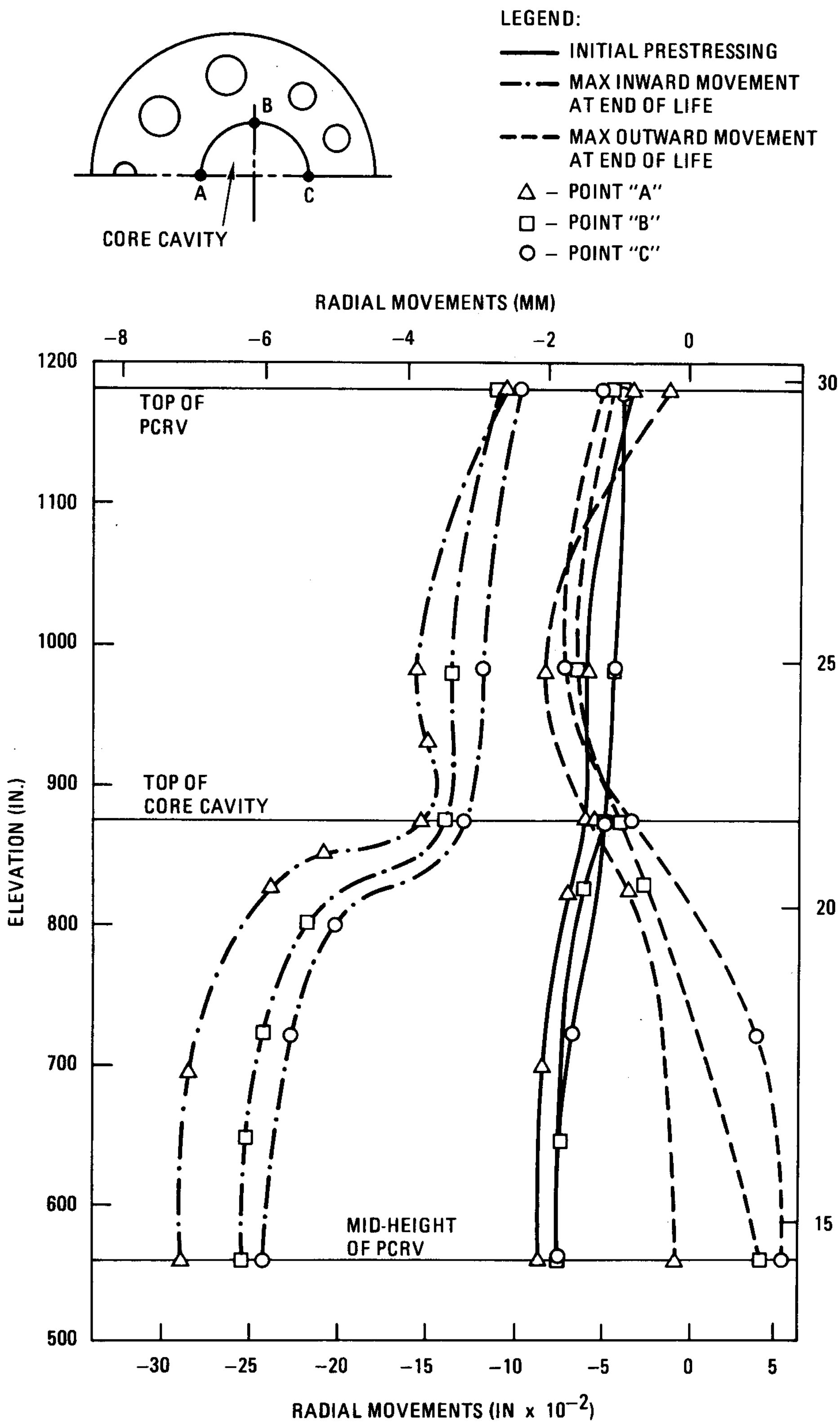

Fig. 9. PCRV movements