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PCRV DESIGN AND PRESSURE LIMITS FOR GCFR*

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ABSTRACT

This paper presents a review of PCRV design with special emphasis on pressure limitations for large GCFRs. Discussion on major factors affecting PCRV design includes tendon layout requirements; location and arrangement of major components, especially the steam generators, auxiliary heat exchangers, and main and auxiliary circulators; and the balance-of-plant interface requirements.

Joint PCRV and containment design efforts are required to evaluate the impact of the horizontal circulator cavity on the PCRV design pressure limitation. Without major departure from current design practice and the benefit of detailed assessment of limiting factors, operating pressures up to 120 bars are found technically feasible.

INTRODUCTION

The use of prestressed concrete for pressure vessels is well established. Prestressed concrete reactor vessels (PCRVs) have accumulated over 80 reactor-years of successful operating experience in gas-cooled nuclear power plants in England and France. More recently, the PCRV has been applied at Fort St. Vrain as the primary containment for the high-temperature gas-cooled reactor (HTGR) system. This has been followed by development of the multicavity vessel concept. A major safety advantage of the multicavity PCRV is that the entire primary system and a portion of the secondary coolant system of the GCFR plant can be contained in a single vessel with the inherent safety characteristics of prestressed concrete designs. The following discussions

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summarize the design considerations of the multicavity vessels for a GCFR plant, with special emphasis on important factors governing the PCRV design and pressure limits.

PCRV DESIGN CRITERIA

The structural response of a properly proportioned PCRV to increasing cavity pressure can be categorized into three regimes, as shown in Fig. 1. Regime I is characterized by essentially linear elastic response to short-term pressure changes in the operating range. In Regime II, nonlinear behavior indicates the onset of concrete cracking. Load-deformation response of the PCRV is elastic and reversible upon unloading. Progressive concrete cracking and yielding of steel elements occur in Regime III.

The PCRV design is required to satisfy two basic performance criteria in serviceability and safety throughout its design life. First, the PCRV must be designed to have elastic responses to operating pressures. Due consideration in design is given to time- and temperature-dependent structural efforts, including concrete creep and shrinkage and steel relaxation. Secondly, the PCRV design is required to demonstrate its structural integrity against failure for a postulated overpressure condition. Even though pressurization of the PCRV beyond the pressure relief level is considered inconceivable, the PCRV must show an ultimate load capacity of at least twice the maximum cavity pressure as a measure of the reserve strength during normal operation. The vessel is proportioned such that as its ultimate structural capacity is approached, the PCRV response should be gradual, observable, and predictable. Various load categories and load combinations are considered in the PCRV design. To ensure that the structural performance requirements are met, the PCRV is designed to meet the stress/strength limits specified in the ASME Code, Section III, Division 2.

FACTORS GOVERNING PCRV DESIGN

Apart from the structural performance requirements, major factors affecting PCRV design include loop arrangement, component size and location, and tendon layout. A typical nuclear steam supply (NSS) system layout for the three-loop 300-MW(e) GCFR plant is shown in Fig. 2. The PCRV layout incorporates three steam generator and auxiliary heat exchanger cavities arranged symmetrically around the central core cavity, as illustrated in Fig. 3. A similar arrangement is employed for the six-loop plant. Recent gas-cooled reactor designs, where applicable, have used asymmetrical layouts to achieve size reductions for the PCRV and containment building. Asymmetric arrangements also provide cost and safety advantages in grouping steam generators and their associated piping closer together and away from the safety-class piping for the auxiliary heat exchangers. When the number of main loops permits, the core cavity is offset from the geometric center of the PCRV for better space utilization, as demonstrated in the PCRV layout for the two-loop plant (Fig. 3).

For the GCFR designs, a major design consideration is the inclusion of horizontal cavities for main circulators in the PCRV. The location of large, horizontal circulator cavities in the PCRV bottom head precludes the use of circumferential wire-winding on the lower portion of the PCRV. The required prestressing in this region is provided by linear tendons. The resulting tendon layout for the horizontal circulator zone has a significant impact on the PCRV sizing. Other PCRV design aspects involve the PCRV support system, support/containment mat interface, and balance-of-plant (BOP) requirements.

PCRV ANALYSIS

Analysis of the PCRV is performed to demonstrate that the vessel is designed for service conditions stipulated in the design specification by maintaining the levels of stress, strain, and deformations to limits that ensure an essentially elastic response under normal service life. The elastic stress analysis, including temperature effects, is performed at General Atomic (GA) using three-dimensional finite element computer codes. Invoking the conditions of symmetry, only one-sixth of the PCRV is considered in the analysis. The finite element model is depicted in Fig. 4.

The model represents a 60-degree sector of the PCRV which is bounded by the vertical planes through the centers of the steam generator cavity and the auxiliary heat exchanger cavity (Fig. 2). The 20-node isoparametric brick elements are used to model the PCRV concrete, while 8-node membrane elements are used for steel penetration liners.

For simplicity, only major cavities, namely, the reactor core cavity, steam generator cavity, auxiliary circulator cavity, horizontal main circulator cavity, and the cross ducts, are modeled. The PCRV support pedestal and containment mat are included in the finite element model. The loadings considered in the analysis are prestressing forces, maximum cavity pressure, and normal operating temperatures. Based on GA experience, the loading combinations for initial prestressing and normal operating conditions are considered critical in PCRV sizing. Stress contours across the vertical section of the PCRV through the steam generator and core cavities for the critical loading conditions are presented in Figs. 5 and 6. Figures 7 and 8 show the stress contours in a horizontal section at midheight of the PCRV barrel. As can be seen from the stress contours, the PCRV has been conservatively sized for a 9.3 MPa (93-bar) operating pressure.

The overall stress patterns in the PCRV are representative of the anticipated PCRV structural response. The stress results indicate that concrete compressive stresses in the inner ligament and tensile stresses in the outer ligament are the critical design conditions. The stress contours show stress concentrations on the junction of vertical steam generator and horizontal circulator cavities. Local high concrete stresses are considered acceptable since they are not detrimental to the long-term behavior and safe performance of the vessel. The stress results have established the feasibility of locating the horizontal circulator cavity in the PCRV bottom head.

PRESSURE LIMITATION

Theoretically, the design pressure of the PCRV can be as high as the allowable compressive stresses in the concrete. This implies that for a concrete compressive strength of 44.8 MPa (6500 psi), the operating pressure of the vessel could be of the order of 20 MPa (200 bars) if no account is given to practical and economic considerations. In Fig. 9, a general trend of the relation between operating pressures and PCRV diameters has been established on the basis of overall PCRV stress and layout requirements. For high operating pressures, the penetration liners and closures, the complexity of structural geometry, and the effectiveness of prestressing have significant influences on the PCRV design pressure limits. Limitation of operating pressures for the concrete core cavity closure and penetrations is governed by the ligament stresses. One potential design problem involves the introduction of the horizontal circulator cavity into the PCRV bottom head. Prestressing forces required to counteract the high pressures in the horizontal circulator cavity may cause unacceptable tensile stresses in the containment mat. Joint PCRV and containment design efforts will be required to evaluate the impact of the horizontal circulator cavity on the PCRV design pressure limitation.

Without major departure from current design practice and without the benefit of detailed assessment of limiting factors, operating pressures up to 12 MPa (120 bars) are found technically feasible.

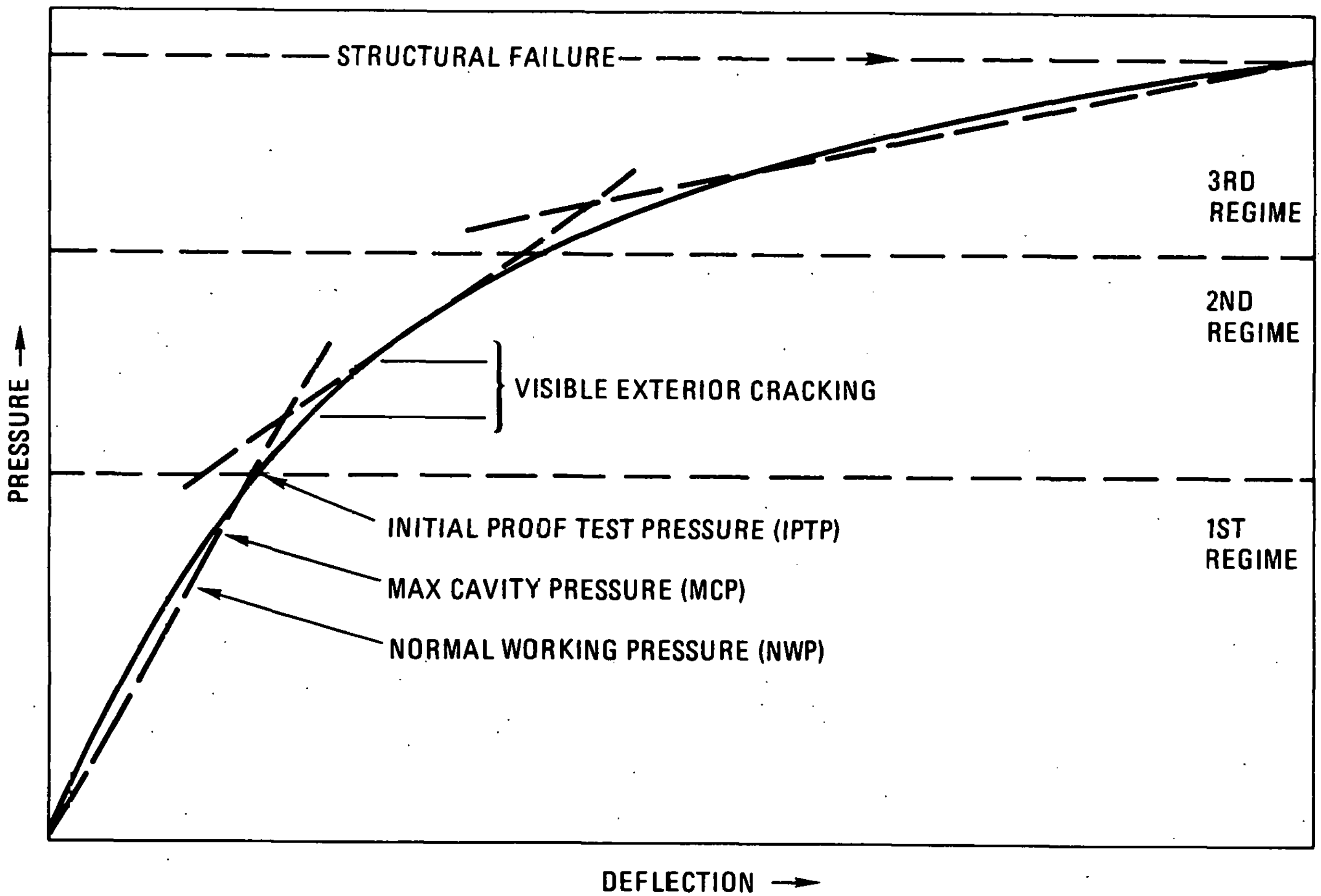

Fig. 1. PCRV structural response to increasing cavity pressure

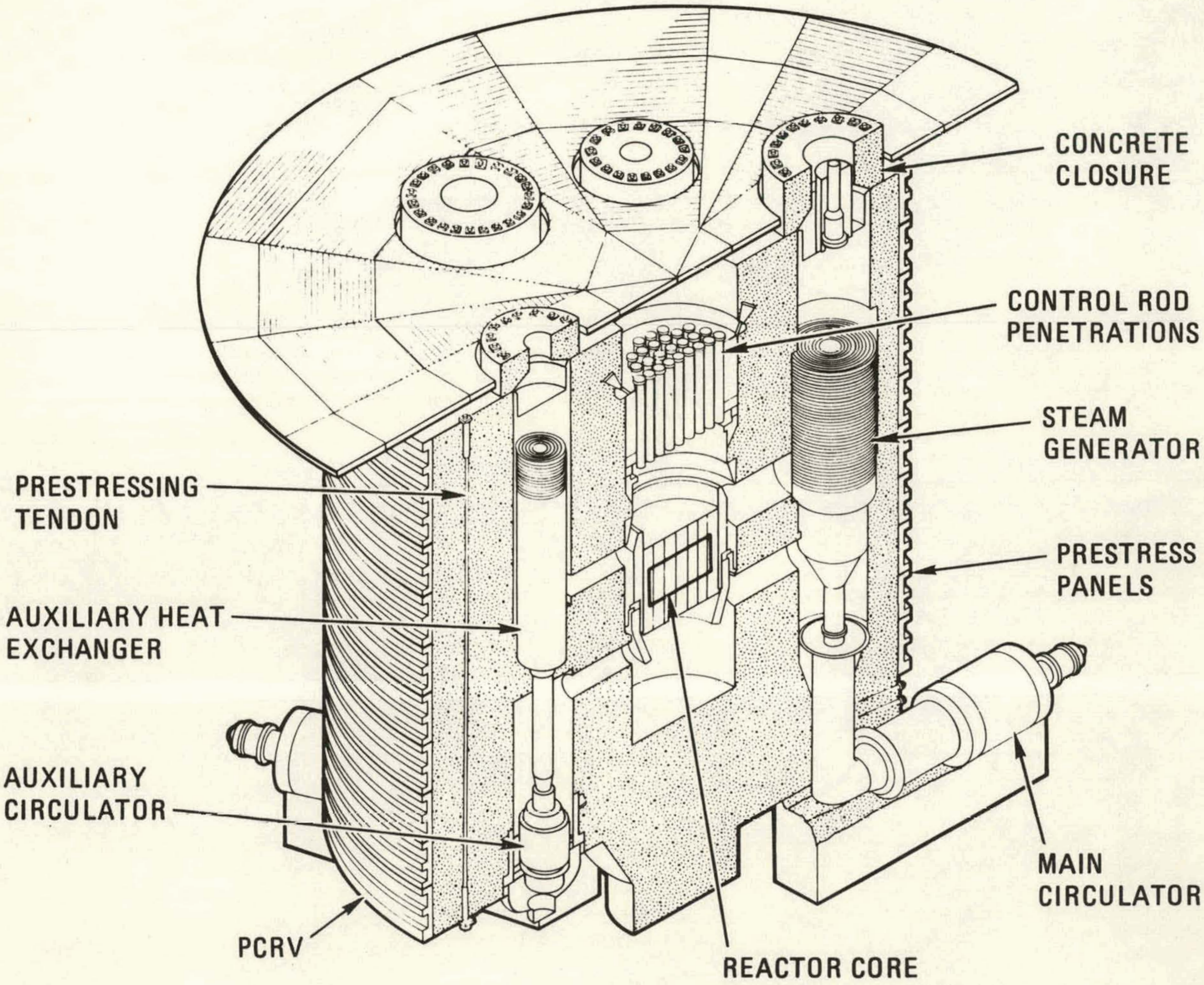

Fig. 2. 300-MW(e) GCFR nuclear steam supply system

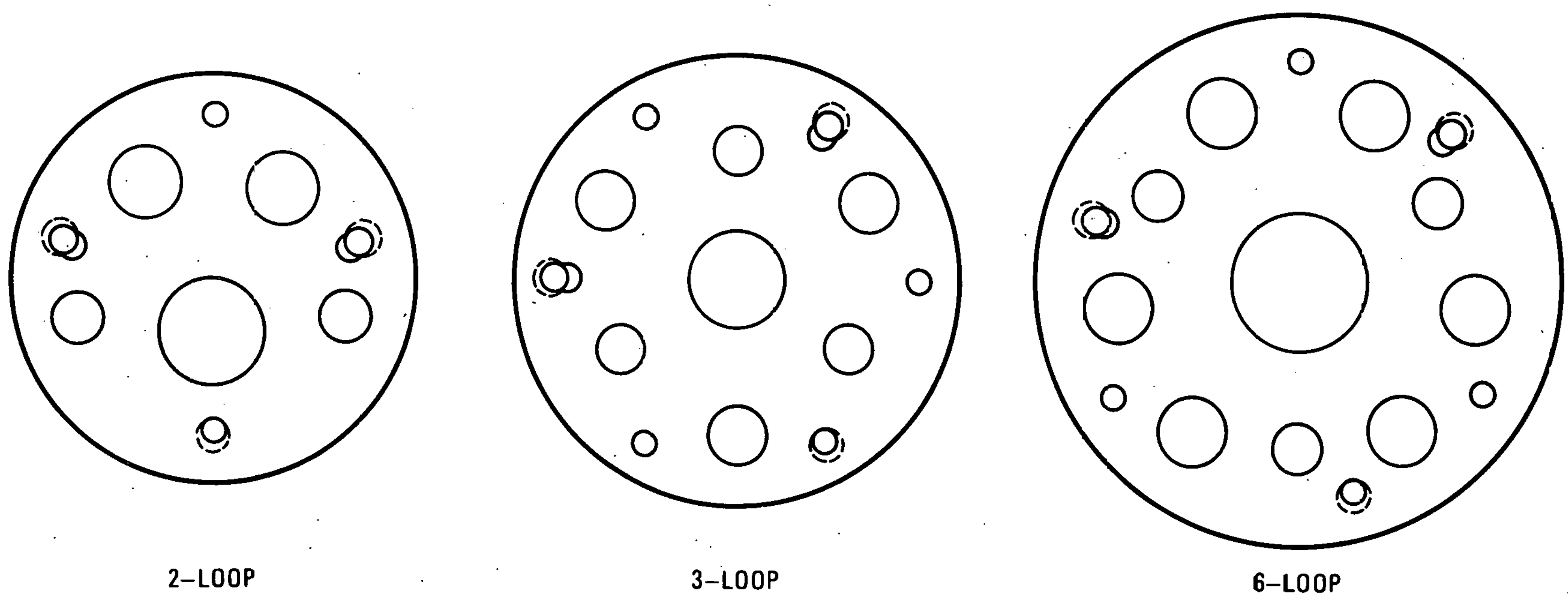

Fig. 3. Summary of GCFR PCRVs with upflow core (top exhaust steam generator)

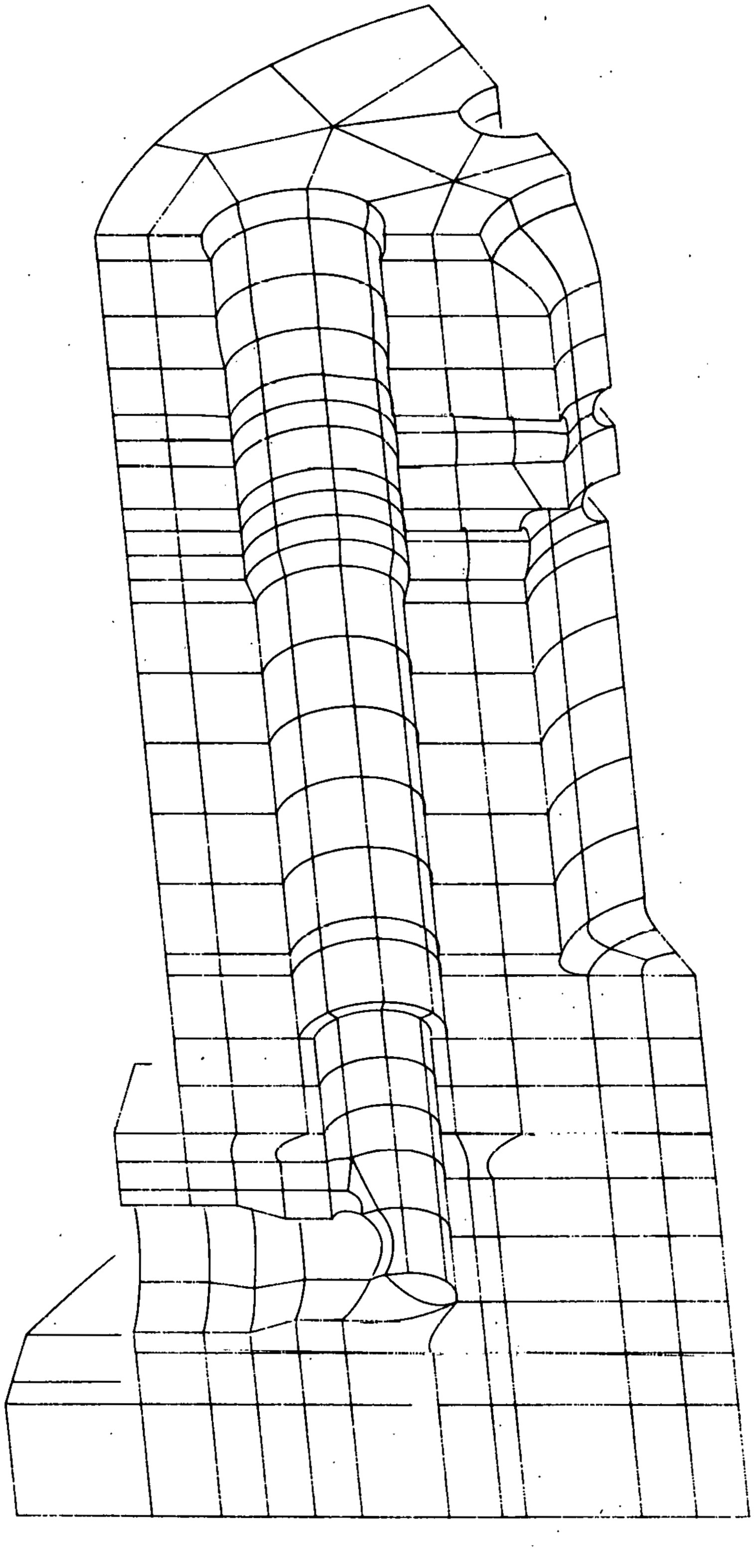

Fig. 4. GCFR PCRV model with horizontal circulator

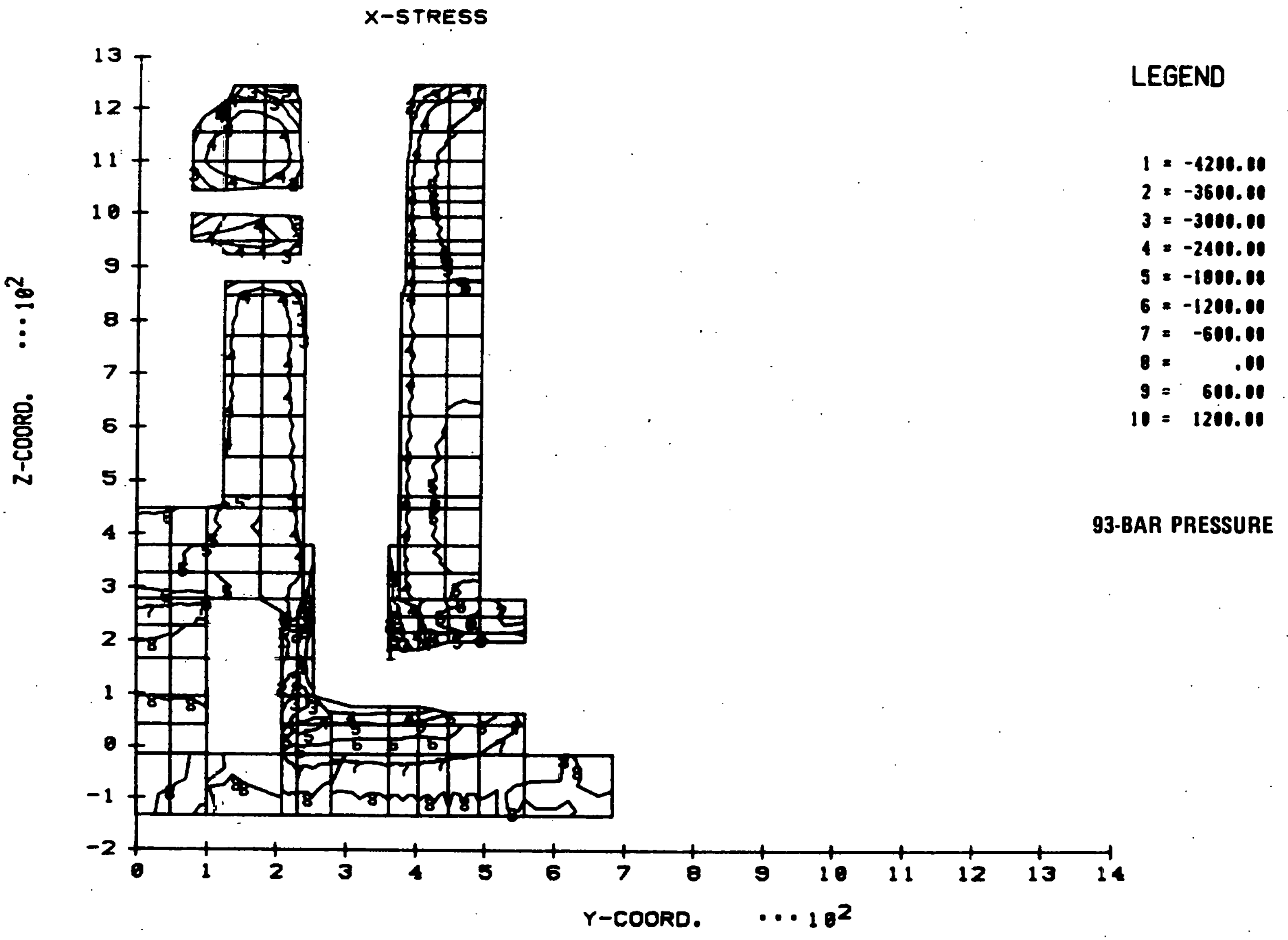

Fig. 5. PCRV stress contours due to initial prestress condition

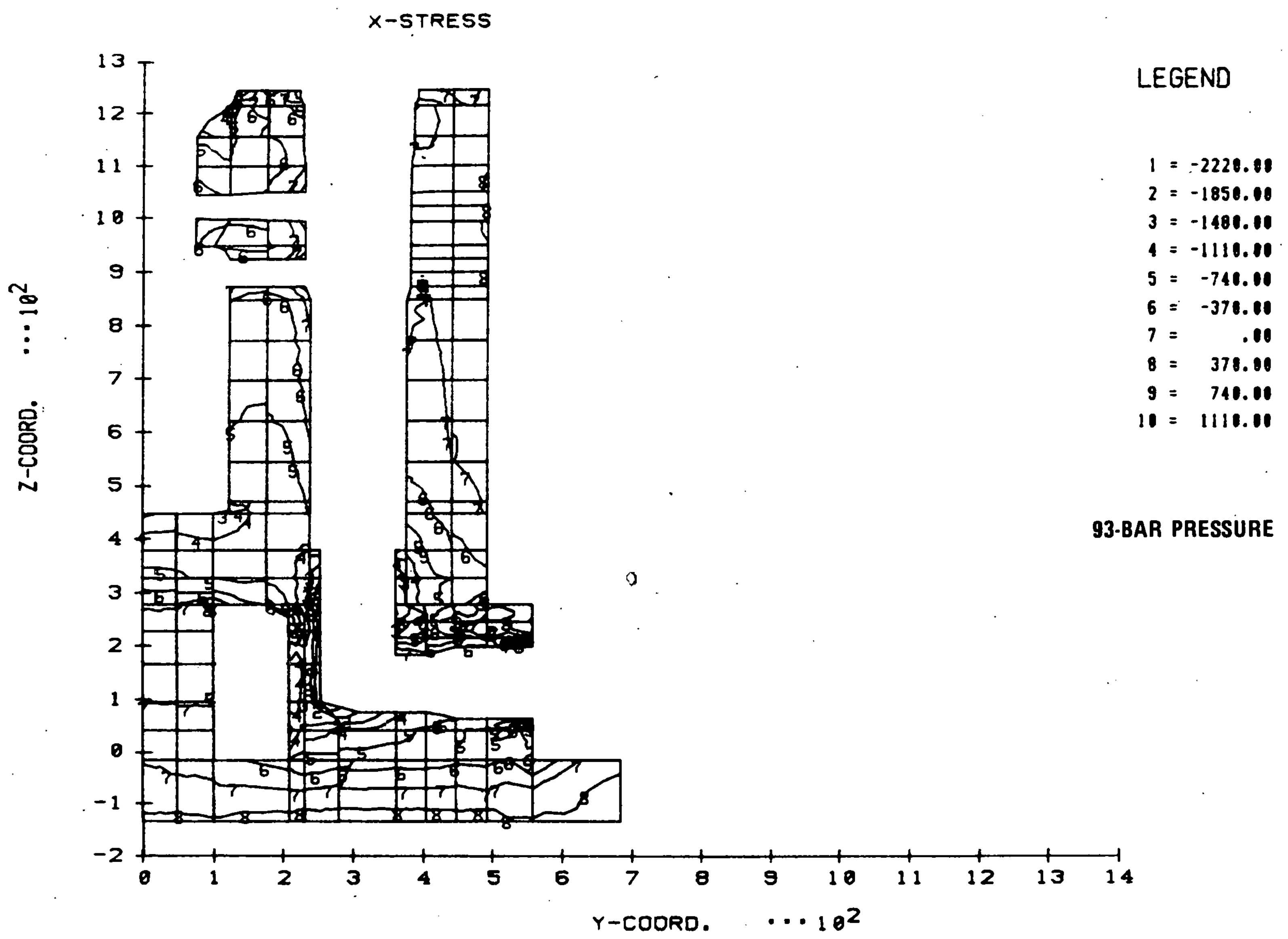

Fig. 6. PCRV stress contours due to normal operating condition

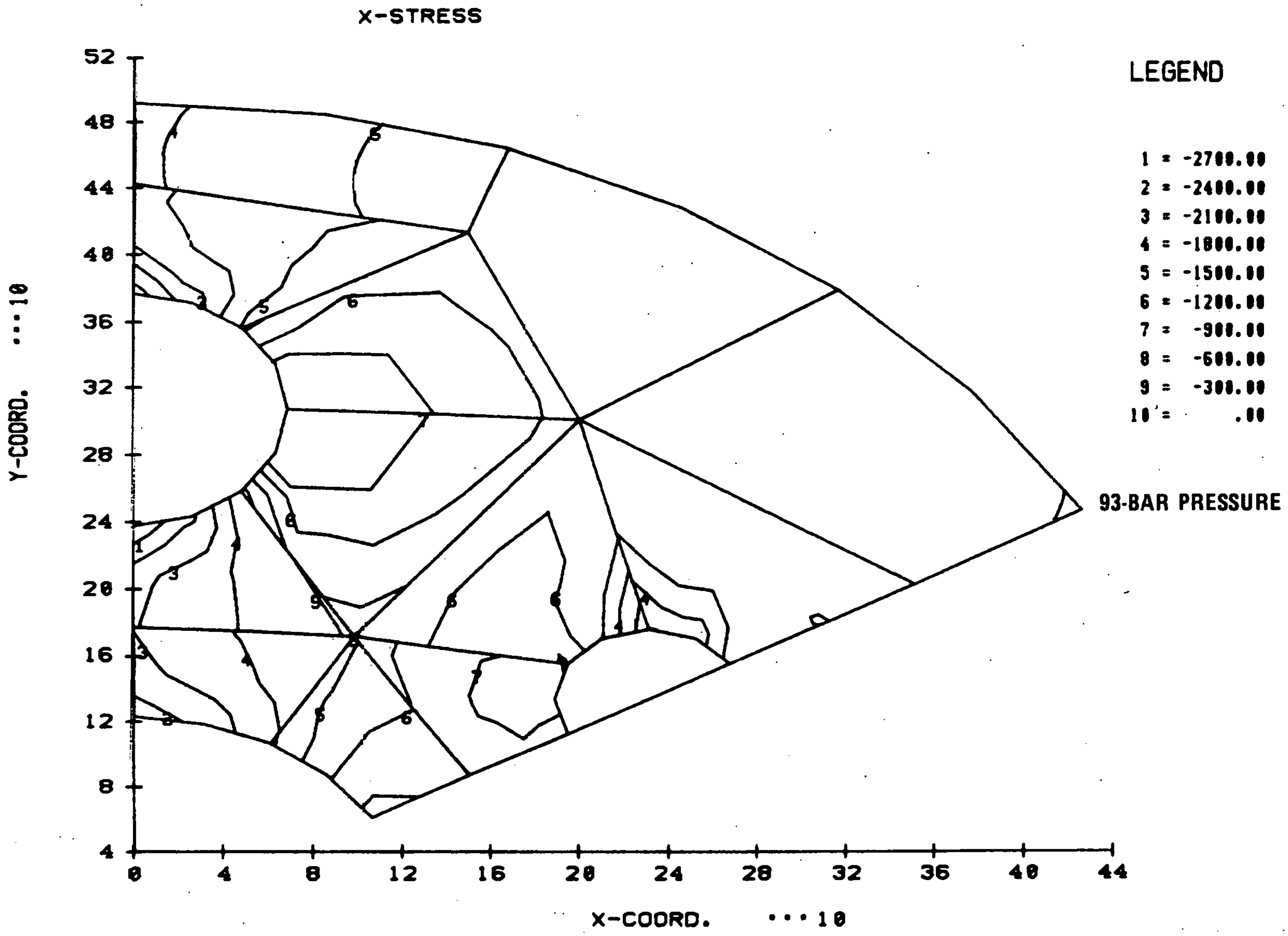

Fig. 7. Stress contours at PCRV mid-height due to initial prestress condition

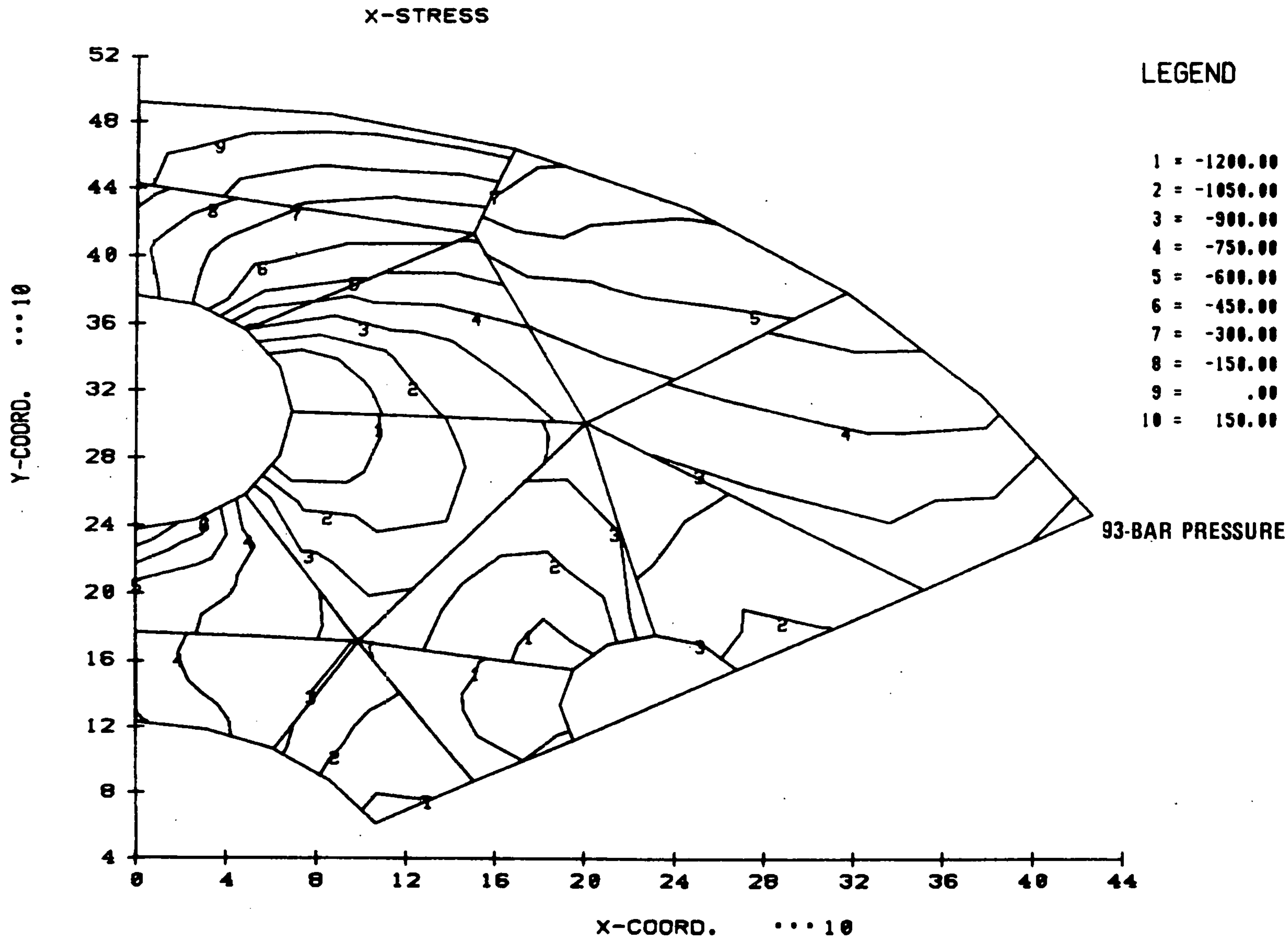

Fig. 8. Stress contours at PCRV mid-height due to normal operating condition

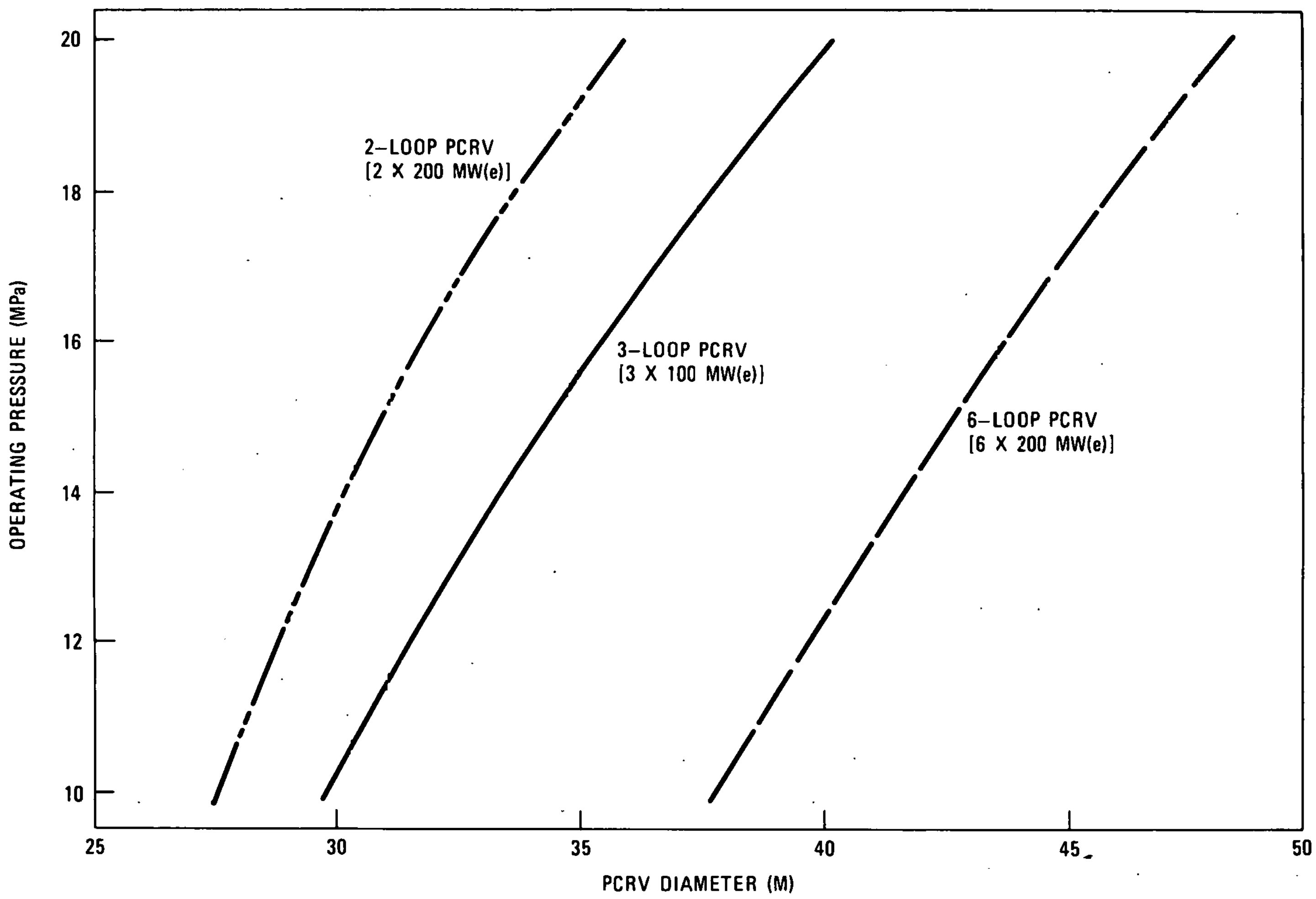

Fig. 9. PCRV fcr GCFR with upflow core (top exhaust steam generator)

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