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DESIGN AND ANALYSIS OF PCRV CORE CAVITY CLOSURE*

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ABSTRACT

Design requirements and considerations for a core cavity closure which led to the choice of a concrete closure with a toggle hold-down as the design for the Gas-Cooled Fast Breeder Reactor (GCFR) plant are discussed. A procedure for preliminary stress analysis of the closure by means of a three-dimensional finite element method is described. A limited parametric study using this procedure indicates the adequacy of the present closure design and the significance of radial compression developed as a result of inclined support reaction.

INTRODUCTION

The closure for the prestressed concrete reactor vessel (PCRV) reactor core cavity in the present design of the GCFR is a deep, circular concrete structure with a large number of penetrations lined with steel tubes (Fig. 1). These penetrations are needed for refueling, in-service inspection, and housing of control rods and instrumentation. The closure is a part of the primary pressure boundary. As such, its design is subject to stringent requirements similar to those for the PCRV. In this paper design requirements and considerations for the core cavity closure are discussed first. This is followed by a

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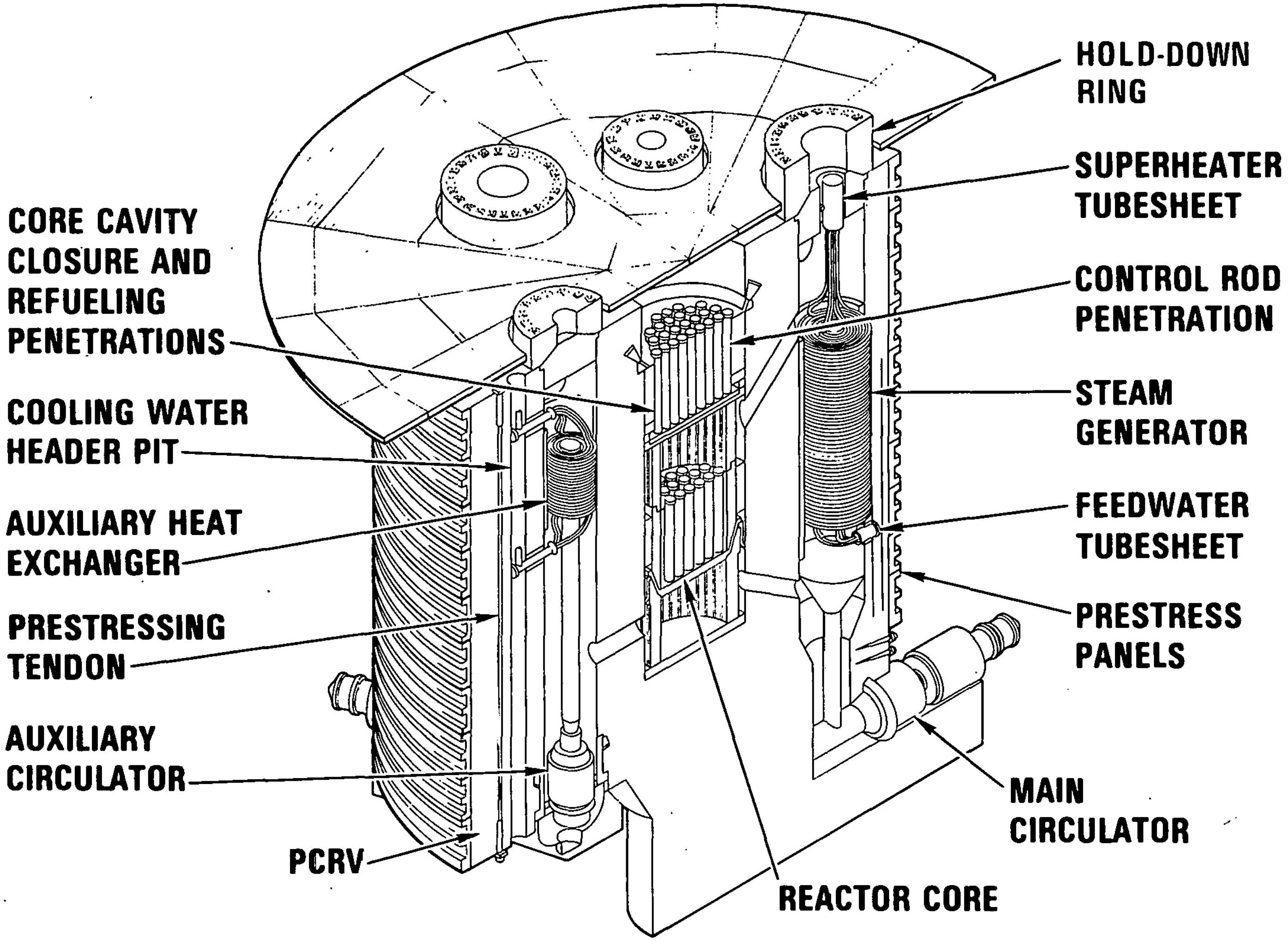


Fig. 1. GCFR nuclear steam supply system

description of the preliminary stress analysis procedure used and a discussion of analysis results which illustrate the effects of closure design parameters.

DESIGN REQUIREMENTS

The following functional requirements apply to the design of a core cavity closure:

1. Provide a leak-tight closure for the cavity.
2. Provide multiple penetrations.
3. Provide a suitable temperature environment for the control rods.
4. Provide radiation shielding for operating personnel.
5. Be removable for the purpose of installation and/or removal of reactor internal components.
6. Be capable of being inspected.

From structural points of view, the closure must be able to:

1. Meet requirements of the ASME Boiler and Pressure Vessel Code, Section III, Divisions 1 and 2 (Refs. 1, 2).
2. Resist high pressure under normal operating conditions.
3. Develop an ultimate capacity in excess of twice the magnitude of maximum cavity pressure.

4. Provide space for flow restrictors which, when installed, will prevent the development of a postulated flaw into a large flow area.

Finally, it is desired that the closure design be adaptable to a larger size plant without a major change in design concept.

DESIGN CONSIDERATIONS

Design alternatives considered for the closure were a steel dome, a welded steel closure, and concrete closures with a concrete ring or toggle hold-down. A number of advantages led to the choice of a concrete rather than a steel closure. A concrete closure can use conventional thermal barriers and liner cooling and can keep the control rod drives cool without difficulty. A thick concrete closure provides biological shielding. Sufficient redundancy exists, and no single postulated flaw can cause the closure to fail. There is no uninspectable weld or thick forging for the penetrations A concrete closure possesses a considerable overload margin and can be readily scaled up.

For hold-down of the closure, the toggle design developed and test-proven by Swedish engineers (Ref. 3) was selected since there is no large forging to limit the design and it is readily adaptable to a larger size plant. Because the toggles transmit the load in compression, no fracture toughness problem exists. In addition, the toggle design is recessed in the PCRV, while a hold-down ring must be located on top of the PCRV.

A welded metallic Omega seal is used for leak-tightness, since a metallic or elastomer O-ring type seal requires precompression. An Omega seal has the added advantage of being permanent.

A concrete closure with a toggle hold-down is illustrated in Fig. 2.

PRELIMINARY ANALYSIS

The concrete closure described above is a complex three-dimensional structure. Under operating conditions, the closure is subjected to cavity pressure on its bottom surface, on its circumferential surface, and inside all penetrations. The closure transmits the combined pressure load into the PCRV through the support bearing pads and the toggles (Fig. 2). To determine whether a closure design under consideration can meet the structural design requirements without any potential major design change, a preliminary stress analysis is performed. The preliminary analysis must be reliable and reasonably accurate since the closure design has a direct bearing on the PCRV dimensions. Such a preliminary analysis is also used for the Oak Ridge National Laboratory (ORNL) closure tests (Ref. 4) and the sizing of the commercial plant closure.

In a preliminary analysis the core cavity closure is analyzed to determine its elastic stresses under maximum cavity pressure (MCP). The analysis results are compared with the stress allowables given in the ASME Code (Ref. 2) assuming uncracked concrete. To analytically establish whether a closure possesses an ultimate capacity in excess of 2 MCP is difficult. The experimental program in progress at ORNL is primarily for the study of closure ultimate capacity. However, the elastic stress requirement controls the closure design.

The preliminary analysis of the core cavity closure described in this paper utilizes a three-dimensional finite element method employing the

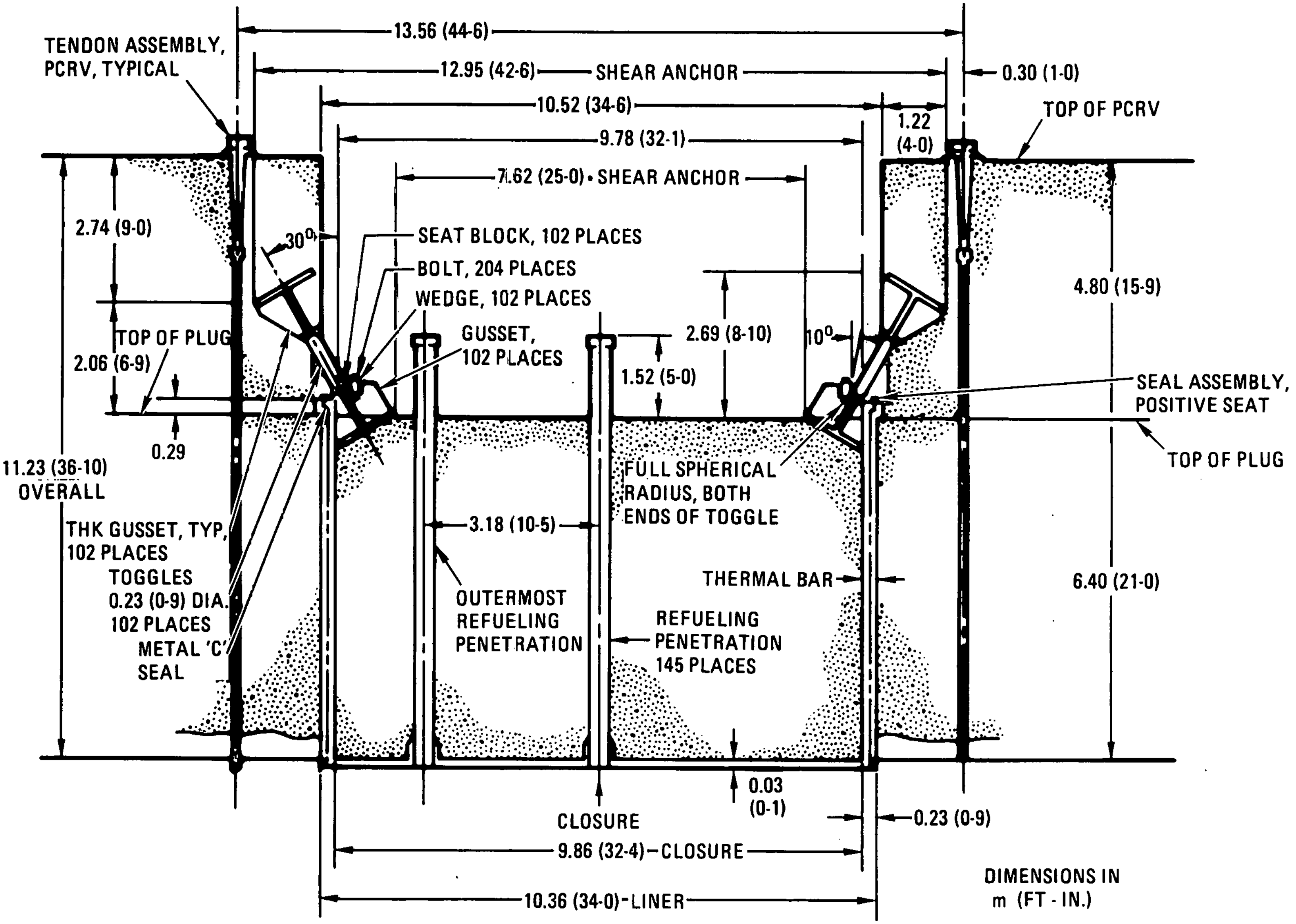
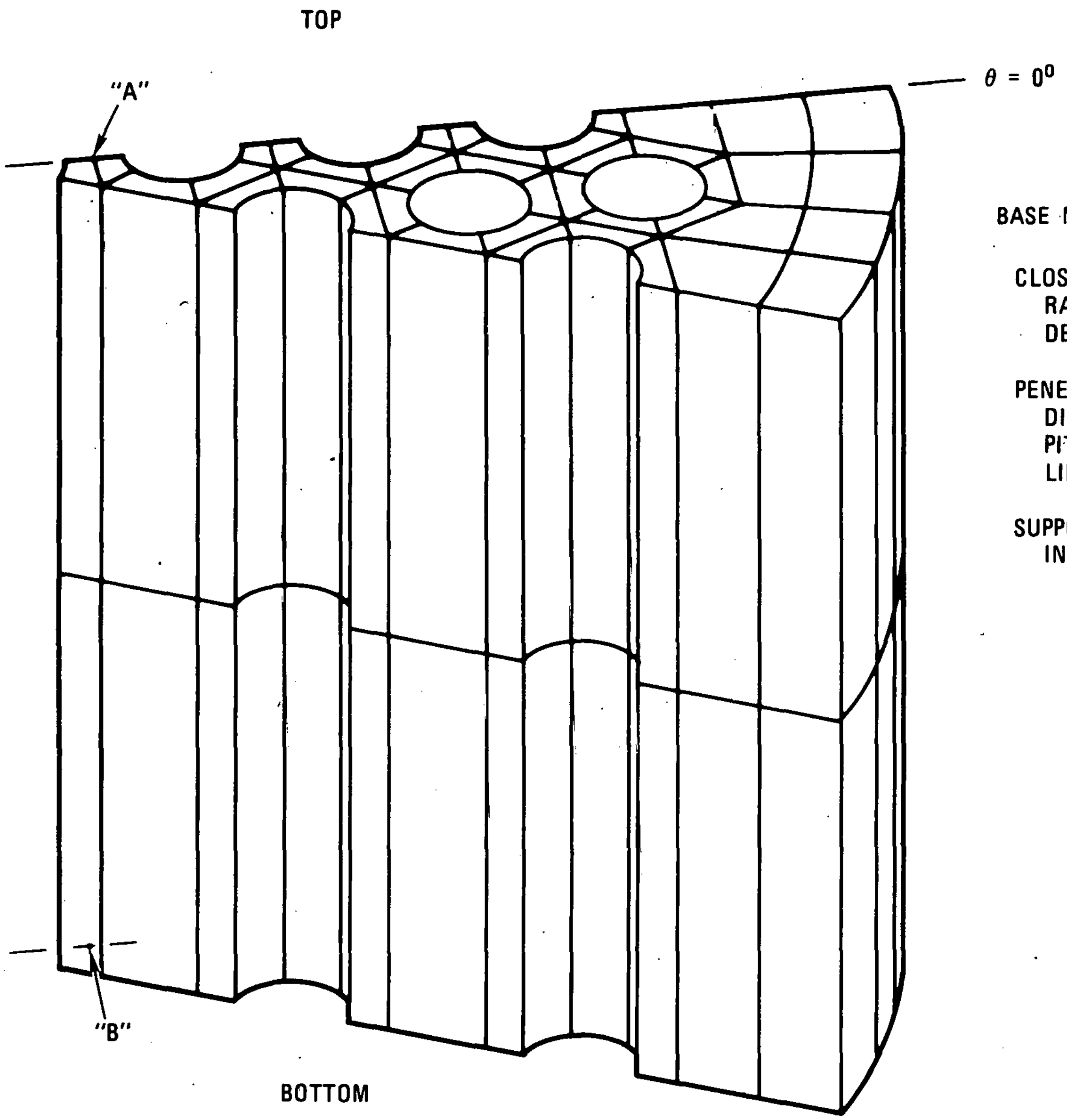


Fig. 2. Concrete closure with a toggle hold-down

computer code THREED (Ref. 5). The THREED code uses 20-node three-dimensional linear elastic elements and 8-node two-dimensional linear elastic elements and is quite efficient. By using a relatively small number of elements and by approximating the closure support details, a simplified analysis model is obtained. To facilitate the time-consuming model mesh generation, a preprocessor program was written (Ref. 6). This program automatically creates a model of a closure with a triangular pattern of holes and generates the card images necessary for describing the model geometry, the loading, and the boundary conditions in the computer code. This makes it possible to perform a normally very time-consuming three-dimensional analysis in approximately two to four days.

A typical automatically generated model of a closure is shown in Fig. 3. Because of symmetry, only a 30-degree segment of a closure need be analyzed. With the closure supported along the top edge and subjected to the combined pressure loading described earlier, critical stresses are found at "A" for the maximum tensile average ligament stress and at "B" for the maximum compressive average ligament stress (Fig. 3). High stresses are also found in the support region. However, since this region is not modeled accurately in the preliminary analysis, these stresses do not provide a true stress picture in the region. Any local high stress in this region can be remedied through minor changes in design details.

To avoid excessive computer running time and unwarranted complexity for a preliminary analysis, the preprocessor (Ref. 6) generates a model in which each ligament width is covered by two elements. It does permit use of any number of element layers in the depth direction. The accuracy of three-dimensional analysis using the preprocessor-generated model with two vertical element layers, also limited in the interest of simplicity, was assessed by comparing the results obtained with those from two refined models of the identical closure. The number of elements in a given horizontal cross section was quadrupled in the first refined



BASE MODEL

CLOSURE:
RADIUS = 2.54 m (100 IN.)
DEPTH = 2.62 m (103 IN.)

PENETRATIONS:
DIAMETER = 343 mm (13-1/2 IN.)
PITCH = 505 mm (19-7/8 IN.)
LINEAR THICKNESS = 13 mm (1/2 IN.)

SUPPORT REACTION:
INCLINATION = 30 DEG

Fig. 3. Preliminary analysis model

model and the number of layers of elements through the closure depth was doubled in the second refined model. The calculated stresses showed differences of no more than 1 MPa (150 psi), and the preprocessor-generated model (such as that shown in Fig. 3) is considered adequate for preliminary analysis purposes.

PARAMETERS AFFECTING CLOSURE BEHAVIOR

Using the preliminary stress analysis procedure described above, a limited parametric study was performed to better understand the behavior of the closure and to assess the effects of important design parameters. Parameters considered were inclination of support reaction, support region stiffness, ligament width, and closure depth. Dimensions given in Fig. 3 were used as the base for change in parameters. These dimensions are for the prototype closure specified for the ORNL test program (Ref. 3). All calculations are based on an MCP of 10.2 MPa (1480 psi).

The most significant effect observed is perhaps that of the inclined support reaction. This is shown in Fig. 4, where the hoop stress versus radial distance is plotted for the edge $\theta = 0°$ (see Fig. 3). With the reaction inclined, its horizontal component exerts a radial compression at the closure top. This significantly reduces the stresses developed in the ligaments. Without the reaction inclined, the ligament stresses, particularly the tensile stress along the top edge, far exceed the code stress allowables, requiring a greater closure depth and hence PCRV dimensions. Assuming uncracked concrete, the code stress allowables for normal operating conditions are 3.70 MPa (537 psi) in tension and 29.8 MPa (4320 psi) in compression [concrete strength = 55.2 MPa (8000 psi), C = 1.2, see Ref. 2].

The bearing pads provided at the support region for the transmission of load affect the ligament stresses, particularly near the closure top. To assess this effect, a model similar to the base model (Fig. 3) except

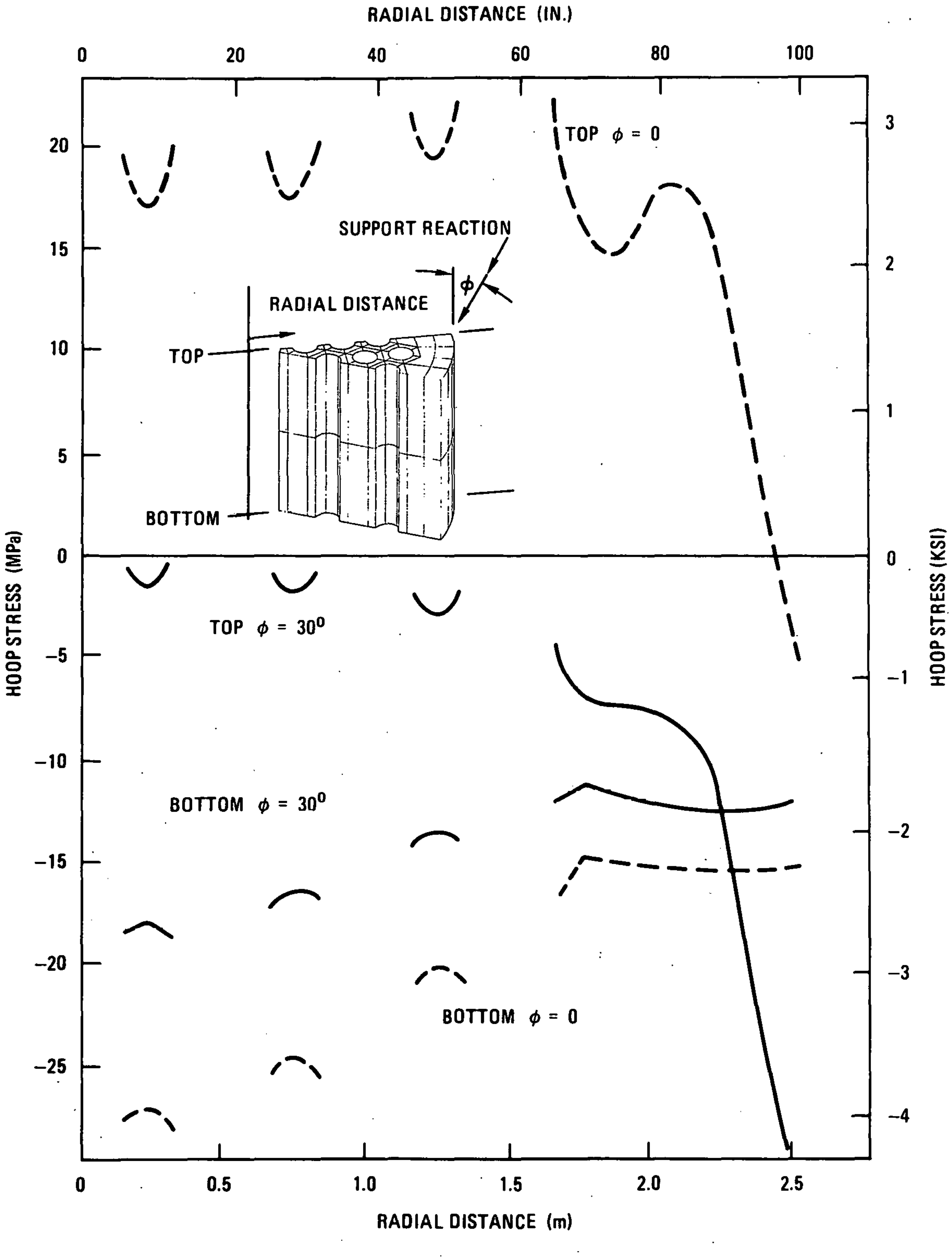


Fig. 4. Effect of inclined support reaction

for a layer of stiffer elements along the support region (Fig. 5) was analyzed. The modulus of elasticity used for these elements was obtained by a smearing technique based on the steel and concrete areas in the support region. Comparison of the hoop stress versus radial distance curve (along a top edge) for this model with the corresponding curve for the base model (see Fig. 5) reveals that the ligament stresses actually increase with the existence of stiffer support elements. Since the bearing pads are required components, the increases in the ligament stresses in the order of magnitudes indicated in Fig. 5--3.45 MPa (500 psi) for maximum tensile and 1.38 MPa (200 psi) for maximum compressive ligament stresses--should be added to the stress results when the analysis model does not include the stiffer support elements.

The effect of ligament width is illustrated in Fig. 6. As expected, a reduction in ligament width gives rise to higher ligament stresses. The increase of 2.07 MPa (300 psi) in maximum tensile ligament stress will probably prove to be excessive in most situations. It is further noted that the minimum ligament width may be governed by the layout requirement rather than the stress requirement. The base model ligament width of 162 mm (6.4 in.) is probably close to the practical minimum.

Figure 7 shows the effect of closure depth on the magnitudes of maximum tensile and compressive average ligament stresses. A clear trend is that the reduction in these ligament stresses becomes insignificant once the closure depth exceeds, say, 50% of the diameter. With stress allowables of 3.70 MPa (537 psi) tension and 29.8 MPa (4320 psi) compression and considering the effect of bearing pads discussed earlier, these curves suggest that for the base model the depth of 50% of the diameter is adequate from a ligament stress point of view.

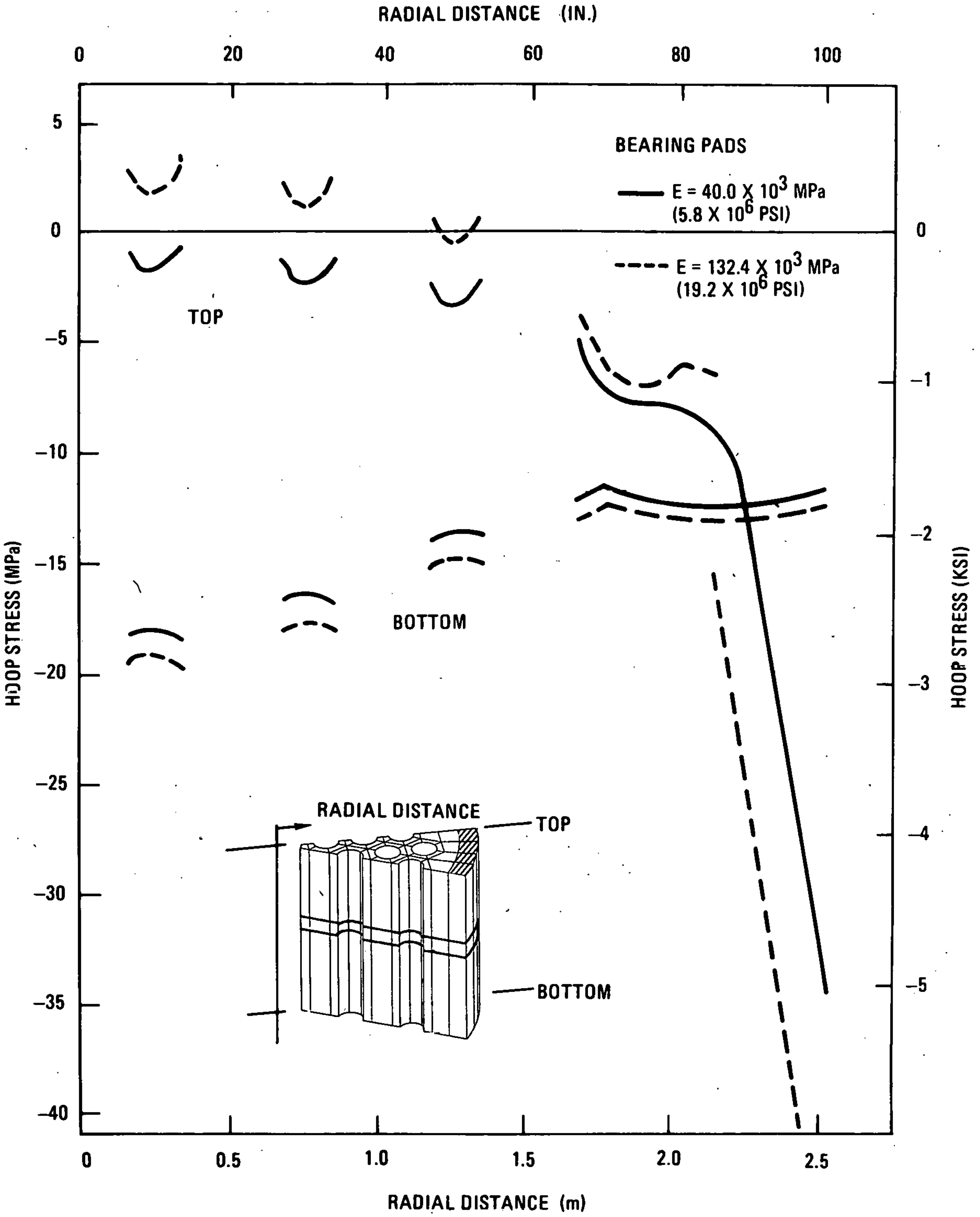


Fig. 5. Effect of bearing pads

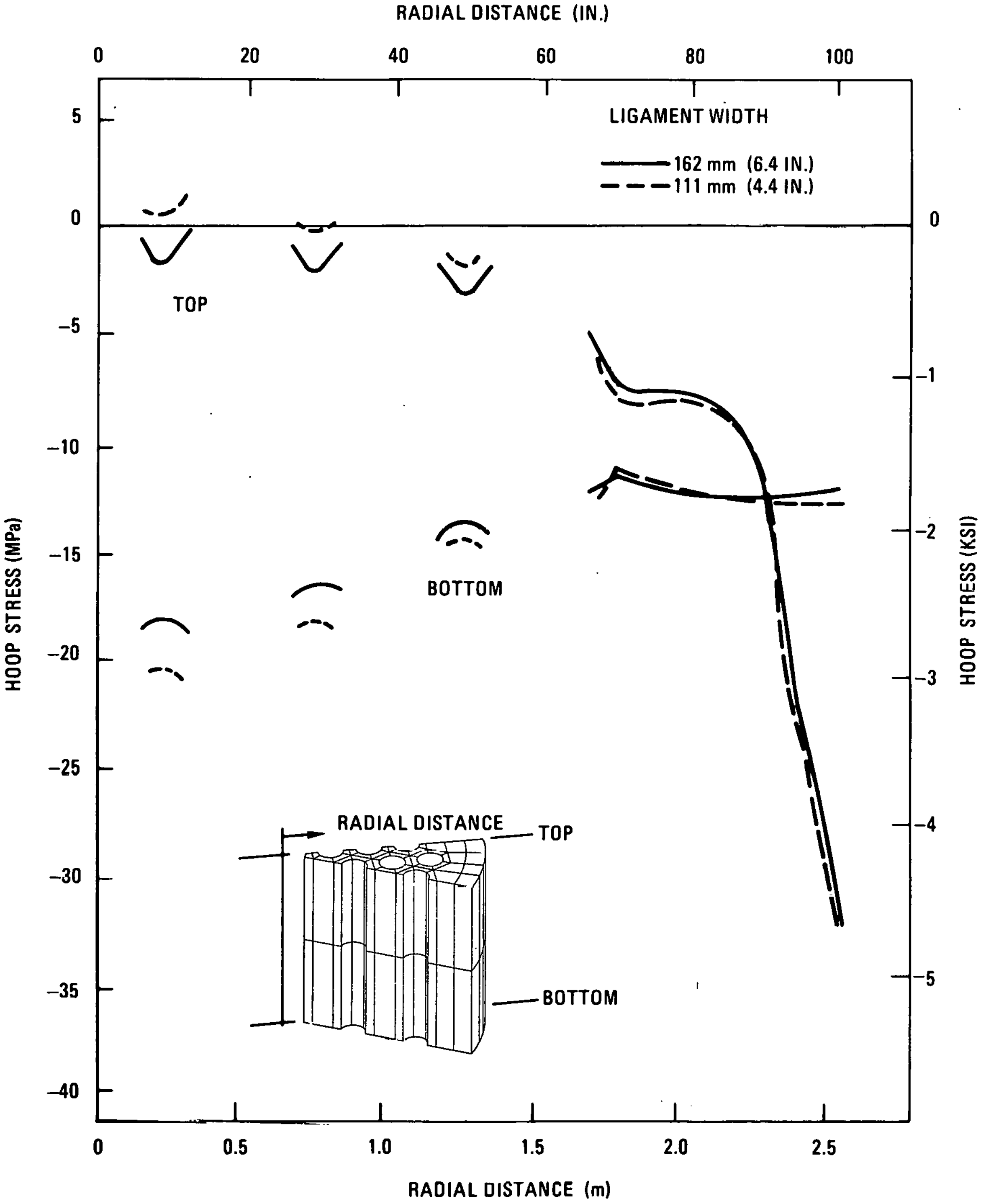


Fig. 6. Effect of ligament width

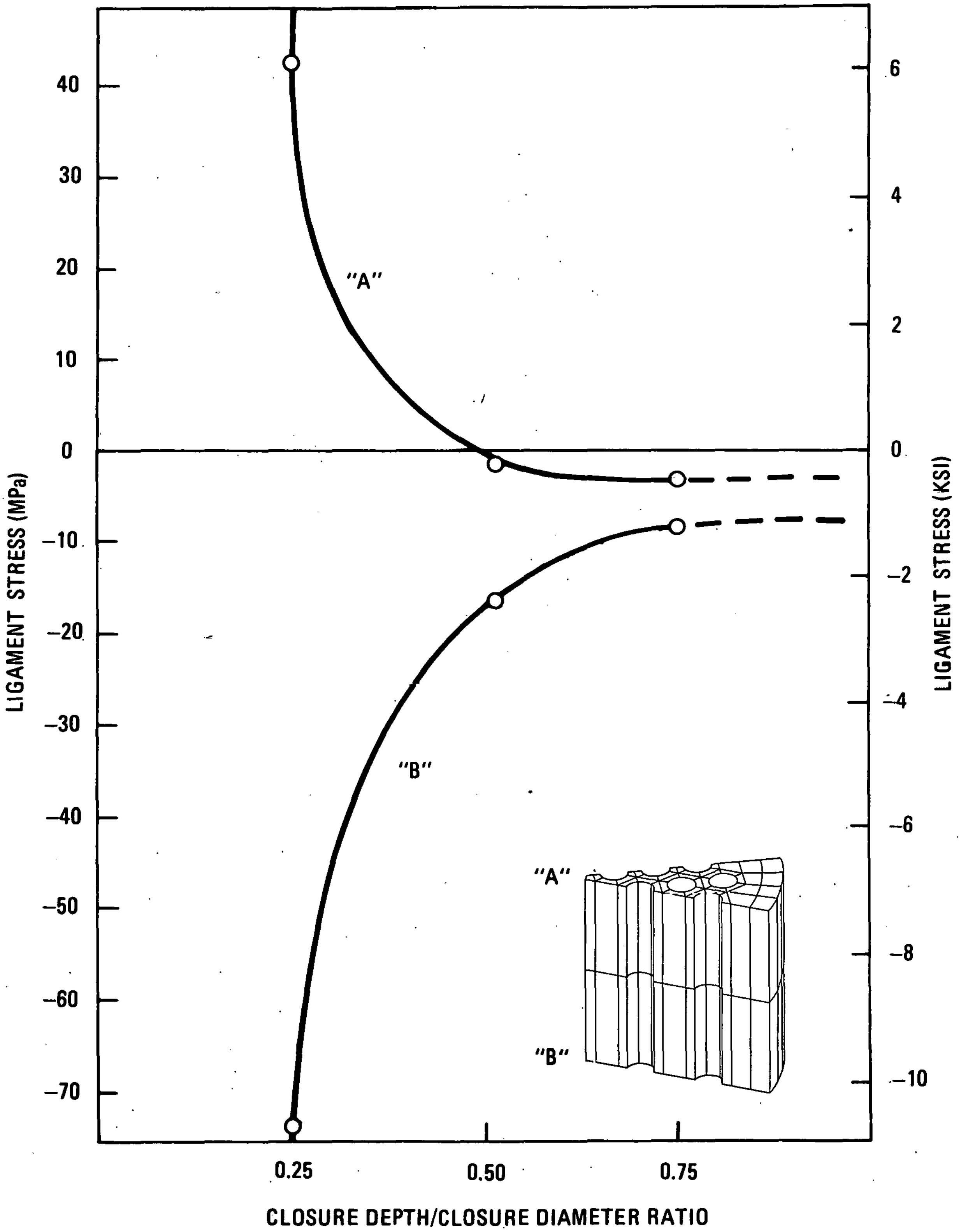


Fig. 7. Effect of closure depth on maximum ligament stresses

CONCLUSION

Design requirements and considerations for the GCFR PCRV concrete cavity closure led to a design which features a concrete closure with a toggle hold-down. A simplified three-dimensional stress analysis performed for the closure shows that the present design is generally adequate. However, there are other problems not addressed in this paper which require future work. These include cooling tube routing within the closure, design and analysis of the bearing pads, thermal stresses, analysis for the core disruptive accident, evaluation of shearing stress allowables, etc.

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