DOE/CL/98004--31

DE85 009014

CELL LINER DESIGN FOR LMFBR PLANTS

(REPORT NO. DOE/CL/98004-31)

ROBERT E. PALM AND RICHARD C. BURROW

CLINCH RIVER BREEDER REACTOR PLANT PROJECT
BURNS AND ROE, INC.
ORADELL, NEW JERSEY

PRESENTED AT
ASME/CSME PRESSURE VESSELS & PIPING CONFERENCE
MONTREAL, CANADA
JUNE 25-30, 1978

(ASME, SERIES PVP-PB-027)

CELL LINER DESIGN FOR LMFBR PLANTS

Robert E. Palm and Richard C. Burrow
Clinch River Breeder Reactor Project
Burns and Roe, Inc.
Oradell, New Jersey

ABSTRACT

Those areas or cells within LMFBR plants that contain radioactive sodium systems are provided with certain design features which eliminate or limit potential sodium/concrete reaction and thus protect the concrete structure in the event of an accidental sodium spill. The principal design feature within these cells that controls sodium spill effects is the cell liner system. The development of such a system design for the Clinch River Breeder Reactor Plant (CRBRP) is presented in this paper.

The basis for cell liner designs is described, including general design criteria, materials and welding requirements, system design requirements, load categories and loading combinations and allowable stress and strain levels. Results of stress analysis and design details of the cell wall and floor systems are presented, including provisions for protection of the concrete structure against high temperature effects.

The information included in this paper can be utilized directly or can formulate the basis for design of cell liners for commercial scale LMFBR's or future large scale liquid metal test facilities.

NOMENCLATURE

D	=	Dead Load including hydrostatic and permanent equipment load
E	=	Operating Basis Earthquake load
E'	=	Safe Shutdown Earthquake load
F_a	=	Allowable liner anchor force capacity
F_u	=	Liner anchor ultimate force capacity
F_y	=	Liner anchor yield force capacity
L	=	Live Load, including any movable equipment load
P_a	=	Differential pressure based on small sodium spill
P'_a	=	Differential pressure based on large sodium spill
P_o	=	Differential pressure under normal operating conditions
R_a	=	Pipe reaction of thermal effects from small sodium spill
R'_a	=	Pipe reaction of thermal effects from large sodium spill
R_o	=	Pipe reaction from normal operating conditions
T_a	=	Thermal effects from small sodium spill
T'_a	=	Thermal effects from large sodium spill
T_o	=	Thermal effects from normal plant cycling
ξ_{sc}	=	Allowable liner plate compressive strain
ξ_{st}	=	Allowable liner plate tensile strain
ξ_{μ}	=	Ultimate strain of liner or weld material
ξ_{ε}	=	Effective von Mises strain

INTRODUCTION

The use of liquid metals (sodium-Na, or sodium-potassium-NaK) as coolants in nuclear power plants results in significant advantages in thermal/heat transfer characteristics and low operating pressures. However, the chemical activity of liquid metals requires special effort to assure that accidental spills do not result in unacceptable safety hazards or economic losses. In the CRBRP, the precautions taken to mitigate liquid metal spills are in accordance with the following approach.

Systems containing radioactive sodium are located in cells inerted with nitrogen to maintain oxygen concentration at or below 2 percent thus reducing the amount of sodium which could burn should a spill occur. Each of the cells is completely lined with steel, not only to prevent inleakage of oxygen, but also to contain any spilled sodium. The liner, in addition to the insulation and venting provisions, forms the Cell Liner System discussed in this paper.

CELL LINER SYSTEM DESIGN REQUIREMENTS AND CRITERIA

Cell liners are provided for inerted cells containing radioactive sodium in order to mitigate the consequences of potential leaks from systems containing liquid metal within the cells. The function of the cell liners during normal operation is to limit leakage of oxygen into the cell, thus optimizing the capacity of the Nitrogen Distribution System and the Cell Atmosphere Processing System. The cell liners are designed to withstand all plant design basis conditions and to maintain their limited leakage function. During sodium spill events, the Cell Liner System functions to preclude chemical interaction between the liquid metal spilled and the structural concrete behind the liners, and to limit the temperature of all nearby structural concrete to acceptable levels.

Design Requirements

1. The liner shall be designed so that the average cell atmospheric leak rate does not exceed 1% volume per day in-leakage under a 2.5 inch (6.4 cm) water gauge negative pressure differential.

2. The cell liner shall be designed for a maximum long term operating temperature of 180 deg F (82 deg C).

3. The duty cycle for the cell liners shall be 10 times from 70 deg F (21 deg C) to 140 deg F (71 deg C), 100 times from 140 deg F (71 deg C) to 180 deg F (82 deg C), over the 30 year plant life.

4. The liner shall be designed to withstand radiation fluence and corrosion commensurate with its location in the plant, without degradation which would impair its function.

5. The liner in each cell shall maintain its integrity for liquid metal spills up to and including the largest spill resulting from a leakage crack in a pipe located in that cell. The through-wall leakage crack is a circular hole equivalent to 1/2 of the pipe inside diameter times 1/2 the pipe wall thickness.

6. The cell liners shall be designed as Seismic Category I structures. They shall be designed to maintain their integrity for the liquid metal spills identified in 5) above in combination with an Operating Basis Earthquake or a Safe Shutdown Earthquake. The Loading Combinations to be considered are given in Table 1.

7. The cell liner system shall be designed to limit the temperature of structural concrete to the limits of American Concrete Institute Standard ACI 318-71, "Building Code Requirements for Reinforced Concrete," supplemented by ASME Section III, Divison 2, paragraph CC 3440.

8. The cell liner system shall be designed to vent gases to preclude pressure buildup behind the liner.

Design Criteria

Each requirement in the preceding section is met through compliance with the criterion identified below using the same corresponding number.

1. The strain limits specified for Load Combinations A and B in Table 2 shall not be exceeded for those loadings.

2. See criterion 1).

3. A fatigue evaluation shall be performed in accordance with ASME Section III, Division 1.

4. The potential for brittle fracture of the liner shall be minimized by controlling the initial Nil-Ductility Temperature and controlling the amounts of trace elements (with high neutron capture cross sections) in the liner steel.

A corrosion allowance of 1/16 inch (0.16 cm) shall be included in analysis of the liner per ASME Section VIII, Division 1, Subsection C, Part UCS-25.

5. The strain limits specified for Load Combination C in Table 2 shall not be exceeded for sodium spills less than 25 Kg. The strain limits specified for Load Combination D in Table 2 shall not be exceeded for sodium spills greater than 25 Kg.

6. The strain limits specified for Load Combinations A, B, C and D in Table 2 shall not be exceeded for those loadings.

7. The following structural concrete temperature limits shall not be exceeded for normal operation or any other long term period ($\geq$ 24 hours)[1]:

Bulk concrete temperature 150 deg F (66 deg C)

Local areas (e.g. around penetrations) 200 deg F (94 deg C)

The following structural concrete temperature limits shall not be exceeded during an accident or any other short term period ($<$ 24 hours)[1]:

Interior surface 350 deg F (177 deg C)

Local areas (e.g. areas of impingement) 650 deg F (344 deg C)

8. Cell liner venting provisions shall vent sufficient gas to limit the pressure behing the cell liner to less than 5 psig (0.35 Kg/cm^2g).

---

1 Higher temperatures than those given here may be allowed if test results are provided to verify that the increased temperature does not cause unacceptable deterioration of the concrete nor cause unacceptable reduction in the strength of the concrete.

CELL LINER SYSTEM DESIGN DESCRIPTION

General

Radioactive sodium systems are located in 21 inerted cells in the Reactor Containment Building and 15 inerted cells in the Reactor Service Building. The cell structures are reinforced concrete, and each cell is completely lined (floor, side walls and ceiling) with a welded steel plate. The wall and ceiling liner plate are anchored to the structure with welded studs, however the back face of the liner is separated from its supporting structural concrete by an air gap and insulating concrete. The air gap is located between the liner and the insulating concrete. For the floor area, crushed insulating aggregate is provided on top of the concrete floor slab beneath the floor liner. A system of vent lines is provided to vent gases from behind the liner to non-inerted areas of the buildings. These gases are generated when the adjacent concrete is heated from a liquid metal spill. The preliminary design details for each of these features is described in the following paragraphs.

Liners

All of the liners are fabricated of 3/8 inch thick (.94cm) carbon steel plate. The wall and ceiling liners are prefabricated into panels composite with the insulating concrete and welded anchors in large sections to minimize field welding. The anchors for the wall and ceiling liner plates are 18 inch (46 cm) long, 1/2 inch (1.3 cm) dia welded Nelson studs which extend through the insulating concrete. The studs are anchored into the structural concrete and are located every 15 inches (38 cm) in a square grid pattern. The liner plates of the prefabricated panels are field welded to each other and to the floor liner using continuous welds with backing plates. At the corners, the liners are rigidly anchored to continuous steel sections embedded in the structural concrete to prevent excessive strain in the anchors as a result of thermal expansion.

The floor liners are made from carbon steel plates which are supported on continuous steel sections embedded in the concrete floor slab which project 4 inches (10 cm) above the slab. The floor liner plates are welded to each other, the supporting steel sections and the wall liners at the corners.

Piping or electrical penetrations through the cell liners are rigidly anchored to the liner by reinforcing plates and are sealed by one of the following methods:

a. Packing in a sleeve welded to the liner

b. Flued head or bellows welded to a pipe sleeve which is in turn welded to the liner

c. Welding a penetrating pipe directly to the cell liner.

Embedments for support of structural steel framing, piping hangers or snubbers and equipment are rigidly anchored by reinforing plates which are seal welded to the abutting liner plate. Sufficient anchorage is provided to carry the imposed loads directly into the concrete structure and independent of the liner anchor system.

Insulation

Insulation behind the wall and ceiling liners is provided in the form of 4 inches (10 cm) of precast perlite and sand insulating concrete. The physical and thermal properties of the insulating concrete will be determined as part of a Comprehensive Testing Program for Concrete at High Temperatures.

Insulation beneath the floor liner is provided in the form of 4 inches (10 cm) of compacted magnesium oxide refractory aggregate. The aggregate is placed on top of the concrete floor slab between the steel sections supporting the liner.

Venting

Behind the liner venting is provided through a continuous 1/4 inch (.64 cm) gap between the ceiling and wall liners and the insulating concrete, and through voids in the aggregate floor fill beneath the floor liner. In addition, vent holes are included in the steel sections supporting the floor liner to provide a continuous vent path. A system of vent pipes are connected to the vent path behind the liners. The gap is maintained by placement of 1/4 inch thermal plastic (ethafoam) behind the liner during prefabrication of the wall and ceiling panels, and the plastic material is removed before the panels are placed in the structure. Gases released from the concrete behind the liner pass through the gap (or through the aggregate and holes in the support sections of the floor liner) to collection points and then through the vent pipes to the non-inerted areas of the plant.

For details of the liner system, see Figures 1, 2, 3, 4 and 5.

STRUCTURAL ANALYSIS

The dead and live loads, seismic, thermal and pressure loads will influence cell liner behavior through the interaction of the liner-anchor system with the structural concrete. Since the structural concrete is far more rigid than the liner, the deformations of the concrete under these loads and the restraint it provides to the liner will determine the stress-strain condition of the liner-anchor system.

For conditions other than liquid metal spills, the stress levels in the cell liner are below the yield strength of the material. The maximum normal operating temperature (peak) will not exceed 180 deg F (82 deg C) and no significant stresses and strains will be imposed on the liners under these conditions. The cyclic temperature variation in the cells during the lifetime of the plant (10 cycles from 70 deg to 140 deg F and 100 cycles from 140 deg to 180 deg F) are within the ASME Code limitations such that cyclic fatigue should not be a problem. Based on Section NE-3222.4d of Section III, Division 1 of the ASME B&PV Code, for the specified temperature ranges and number of cycles, no fatigue analysis is required.

Preliminary calculations have been conducted to investigate the adequacy of the liner-anchor system under large liquid metal spill conditions, defined as spills in excess of 25 Kg. They consist of elasto-plastic analyses using the computer program ANSYS.

An analysis was conducted for a wall liner element 15 inches (38 cm) square. It was assumed that the corners, where the stud anchors are located, were rigidly supported on the basis that there are no unbalanced lateral forces acting on the anchors. The analysis considered transient conditions immediately after the sodium spill, an isothermal condition under a steady state of 1000 deg F (538 deg C) and a cooldown to an isothermal condition of 150 deg F (71 deg C). The maximum calculated strain was 1.7%.

To further investigate the wall cell liner-anchor system, an analysis was conducted using a mathematical model which represented 121 cell wall liner elements (11 elements square), of the 3/8 inch plate supported by 1/2 inch studs on a square grid pattern at 15 inches (38 cm) spacing. By using boundary conditions for symmetry, the model was reduced to a one-eighth segment (Figures 6 and 7). A 1/4 inch (.64 cm) air gap was assumed between the plate and the insulating concrete. An initial bow of 1/8 inch (.32 cm) in a panel near the center was assumed to find the effect of unbalanced lateral forces on the anchors. Two models were used: one in which it was assumed that the insulating concrete provides full lateral support to the studs, and another in which it was assumed that the insulating concrete was degraded and provided no lateral support. A uniform temperature of 1000 deg F (538 deg C) was imposed on the steel liner and anchors. Two cases were considered: with and without a 5 psi (0.35 Kg/cm^2) differential pressure acting on the back face of the liner. The results of these calculations show a maximum effective strain of 2.3% which is well below the allowable limit specified in Table 2.

Another preliminary analysis investigated strains at a bi-planar corner (wall to floor). The mathematical model is shown in Figure 8. Two models of a 15 inch (38 cm) wide strip (equal to the spacing of the stud anchors) were considered. In the first model the insulating concrete layer was assumed to provide full lateral support to the stud anchors; in the second it was assumed that the insulating concrete layer provided no lateral support. In both models it was assumed that the insulating gravel under the floor liner provided no lateral support to the floor anchors. A 5 psi pressure was applied on the back face of the liners (to simulate pressure buildup) and a uniform tempeature of 1000 deg F in both liner and anchors. The results give a maximum effective strain of 2.3% in the liner plate and 1.7% in the anchors. There is no substantial difference between the results of the two models. Since the strains obtained are much below the allowables specified in Table 2, it is concluded that liner integrity is maintained.

To determine the stud anchor yield force and displacement capacity and the ultimate force and displacement capacity, a mathematical model is used which includes the plate, weld of stud to plate, stud, airgap, insulating concrete and part of the structural concrete. Two cases of liner anchor restraint are considered:

1. that the insulating concrete has its full specified strength;

2. that the insulating concrete has no strength.

Incremental tangential displacements are imposed on the plate and the displacements, forces, stresses and strains are calculated in the steel elements and in the concrete surrounding the studs. The liner anchor yield force capacity and the yield displacement capacity correspond to that at the initiation of an effective von Mises strain equal to the uniaxial yield strain of the steel. The ultimate force and displacement capacity of the anchor correspond to that at the initiation of an effective von Mises strain equal to the uniaxial ultimate strain of the steel. In the analysis those concrete elements, where the excessive compressive strain show that the concrete has been crushed, are eliminated from the models. The most conservative values from these two analyses are used to represent the yield and ultimate characteristics of the anchor.

Buckling of the liner plates is anticipated due to the magnitude of the compressive thermal forces caused by the restraining actions of the concrete structure. Buckling in itself will not produce failure since the thermal deformations are self-limiting. However, due to the reduced load carrying capacity of a buckled panel, unbalanced lateral forces can be induced at the anchors. The liner-anchor system is designed such that under the unbalanced lateral forces on an anchor caused by the buckling of one panel while the adjacent panels remain in plane, the strains do not exceed the allowable limits. Buckling of all panels improve the stress-strain conditions at the anchors since the unbalanced lateral forces are reduced.

The stud anchors are designed to resist the shear forces induced when unbalanced forces exist between sections of the liner and the axial forces caused by the maximum specified pressure (5 psig) acting on the backside of the liner.

The complete analysis must consider other load conditions including thermal shock, thermal transients, and the heat-up and cooldown of the liner under the sodium spill accident; the effects of variations in steel properties and thickness and inclusion of the 1/16 inch corrosion allowance. The postulated breaks of sodium lines may generate hot sodium sprays on the liner. The effects of the hot spot on the liner, including dynamic impingement effects, if any, of the jet must also be considered in the analysis.

TESTING AND VERIFICATION PROGRAM

In support of the liner design, an intensive testing and verification program has been developed and is presently in progress. This paper does not address to the program details, however, its scope is outlined below.

1. Confirmation tests of liner plate and liner welding material properties under high temperature conditions.

2. Determination of concrete physical and thermal properties subject to high temperature tests on prototypic samples.

3. Small and intermediate scale tests of sodium/concrete interaction to determine reaction rate, concrete degradation and gas generation.

4. Large scale sodium dump test(s) on a prototypic cell liner system to confirm its behavior and capability to withstand large spill conditions.

CONCLUSIONS

Results obtained from analysis of the CRBRP liner system demonstrate the adequacy of the design to mitigate the effects from sodium spills. Maximum strains calculated at critical locations are well within the prescribed limits, and peak structural concrete temperatures are maintained below the maximum defined limits. Further, an intensive test program is in progress that will verify performance of the liner system under prototypic design conditions.

ACKNOWLEDGEMENTS

This paper is based on work performed by Burns and Roe, Incorporated under contract with the U. S. Department of Energy and performed in conjunction with Westinghouse Electric Corporation, Advanced Reactors Division. The authors express their deep gratitude for support contributed by Messrs Paul Fox, Chang Kim and George Clare of Westinghouse towards the development of the Clinch River design. Further gratitude is extended to Mr. George Sigal and Dr. Rajabhau Deshmukh of Burns and Roe for analysis work conducted in support of the design program. The authors express their appreciation to the efforts of Mr. Elias Debbas of Burns and Roe in the development of the design requirements and design concepts, and also to Ms. Maureen Frins in her careful preparation of the manuscript.

Table 1

Load Combinations for Structural Evaluation of CRBRP Cell Liners

Load Combination A	$D + L + T_o + P_o + R_o + E$
Load Combination B	$D + L + T_o + P_o + R_o + E'$
Load Combination C	$D + L + T_a + P_a + R_a + E'$
Load Combination D	$D + L + T'_a + P'_a + R'_a + E'$

Normal Loads

D = Dead Load including hydrostatic and permanent equipment load

L = Live Load, including any movable equipment load

P_o = Pressure differential across cell wall

T_o = Thermal effects due to fluctuations in plant power, cell cooling, initial plant startup

R_o = Static reactions and loads from piping and support restraints

Operating Basis Earthquake Load

E = Dynamic Load

Safe Shutdown Earthquake Load

E' = Dynamic Load

Small Liquid Metal Spill Loads

These loads result from spills less than 25 Kg of liquid metal

T_a = Thermal effects

P_a = Differential pressures on cell walls

R_a = Pipe reactions from thermal effects within the cell

Large Liquid Metal Spill Loads

These loads result from spills greater than 25 Kg of liquid metal

T'_a = Thermal effects

P'_a = Differential pressure on all walls

R'_a = Pipe reactions from thermal effects within the cell

Table 2

Limits for Structural Design of CRBRP Cell Liners

	Liner-Strain Allowable		Anchors-Force/ Displacement Allowable	
Category	Membrane	Combined Membrane plus Bending	Mechanical Loads	Displacement Limited Loads
Load Combinations A and B	εsc=0.002	εsc=0.004 inch/inch	Lesser of: Fa=0.67Fy	0.25 δ u
	εst=0.001	εst=0.002 inch/inch	Fa=0.33Fu	
Load Combination C	εsc-0.005 εst=0.003	εsc-0.014 inch/inch εst=0.010 inch/inch	Fa-0.9Fy Fa=0.5Fu	0.50 δ u
Load Combination D		SEE NOTE (1)		

Notes:

(1) The Von Mises effective strain (ξ_ε) shall not exceed 0.5 ξ_μ for membrane and 0.67 ξ_μ for combined membrane plus bending for both the liner and anchors.

where:

ε_{sc} = allowable liner plate compressive strain

ε_{st} = allowable liner plate tensile strain

F_a = allowable liner anchor force capacity

F_u = liner anchor ultimate force capacity

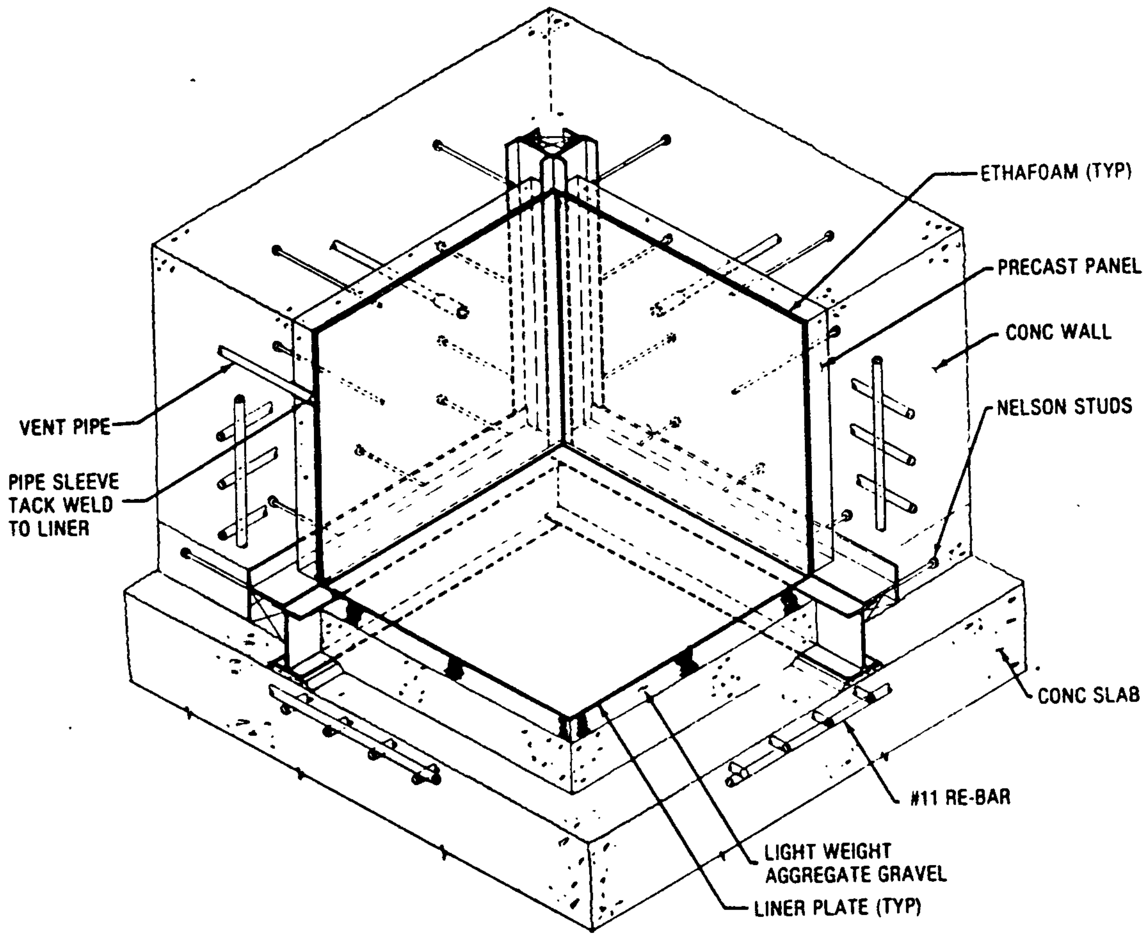
F_y = liner anchor yield force capacity

δ_u = ultimate displacement capacity for liner anchors

δ_u = ultimate strain of liner material under the environmental conditions of interest. ε_u shall be separately evaluated for weld metal and base metal; potential aging and hardening effects shall be considered.

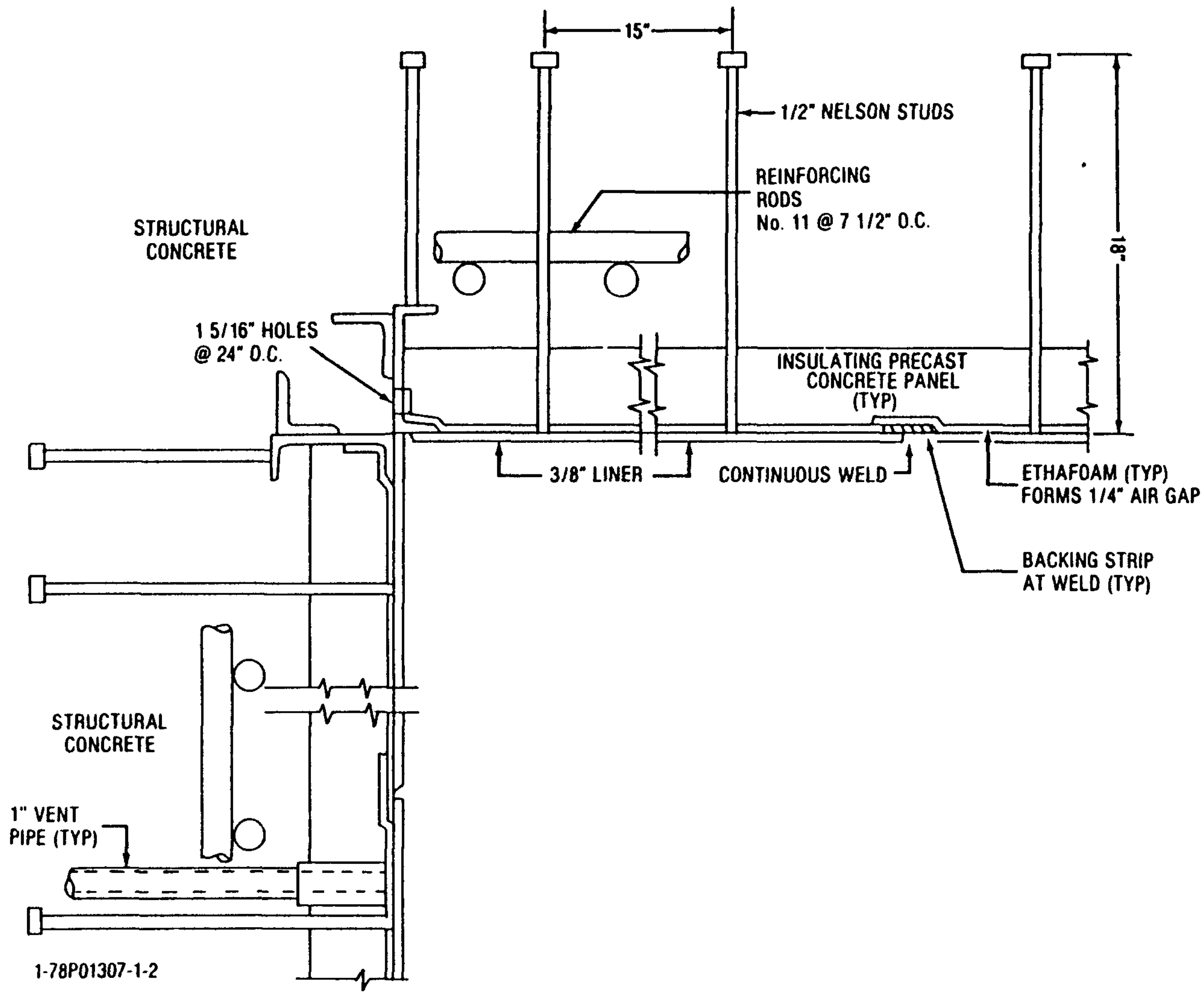
ξ_ε = Effective von Mises strain

ξ_μ = Ultimate strain of the material from uniaxial tensile test at the temperature considered.



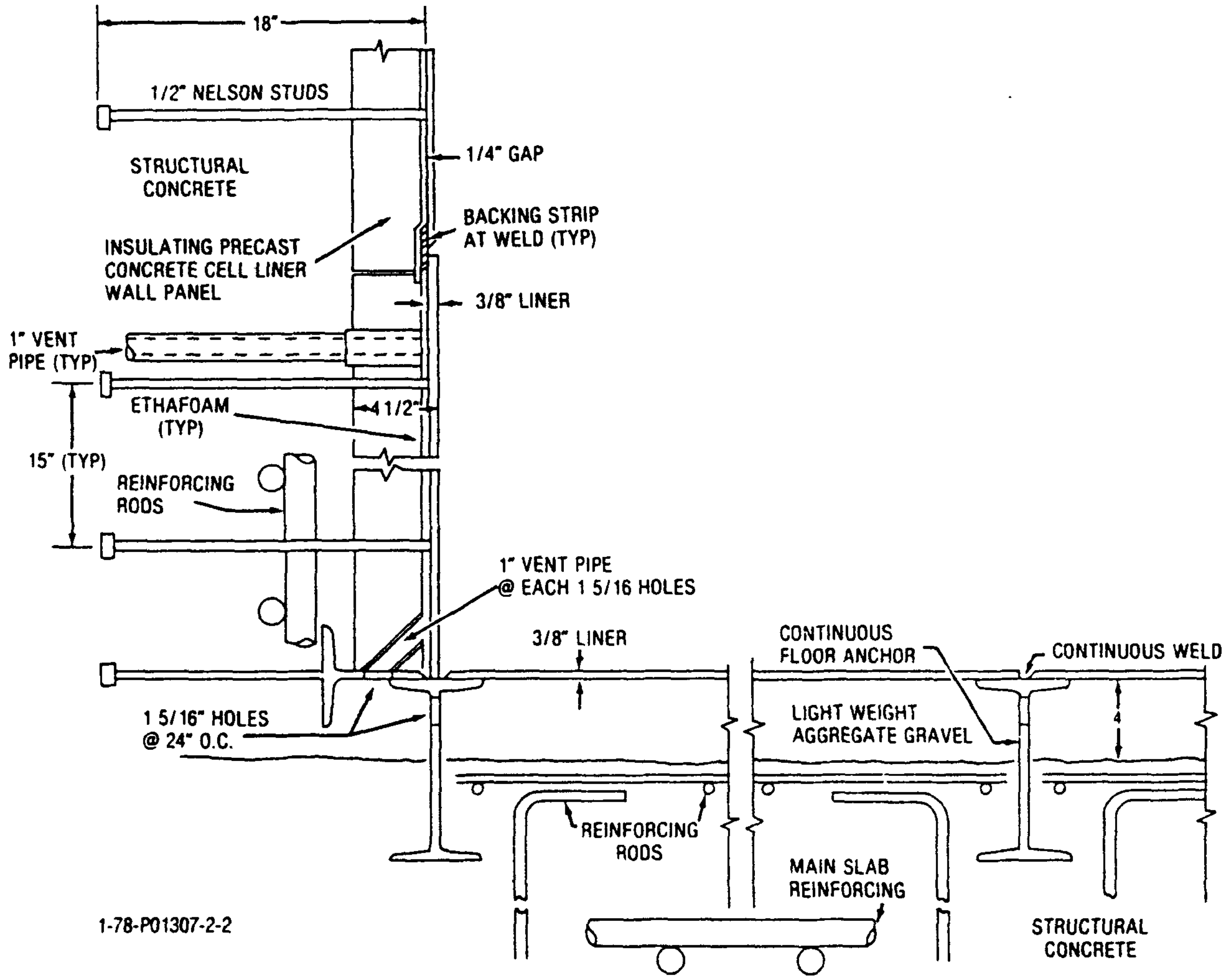
TYPICAL CELL LINER
ISOMETRIC — CORNER DETAIL

Figure 1



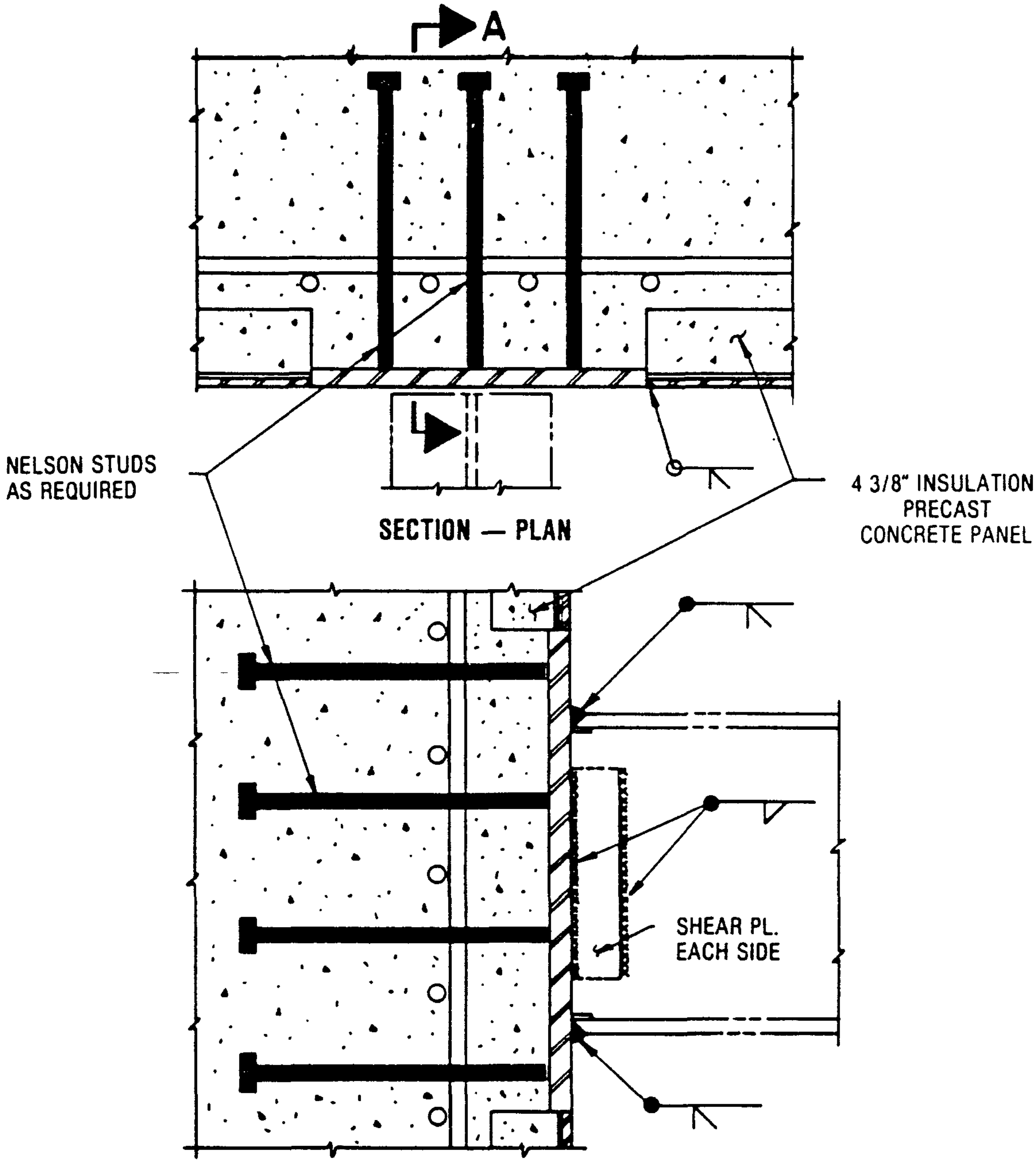
WALL-WALL SECTION DETAIL

Figure 2



FLOOR & WALL DETAIL

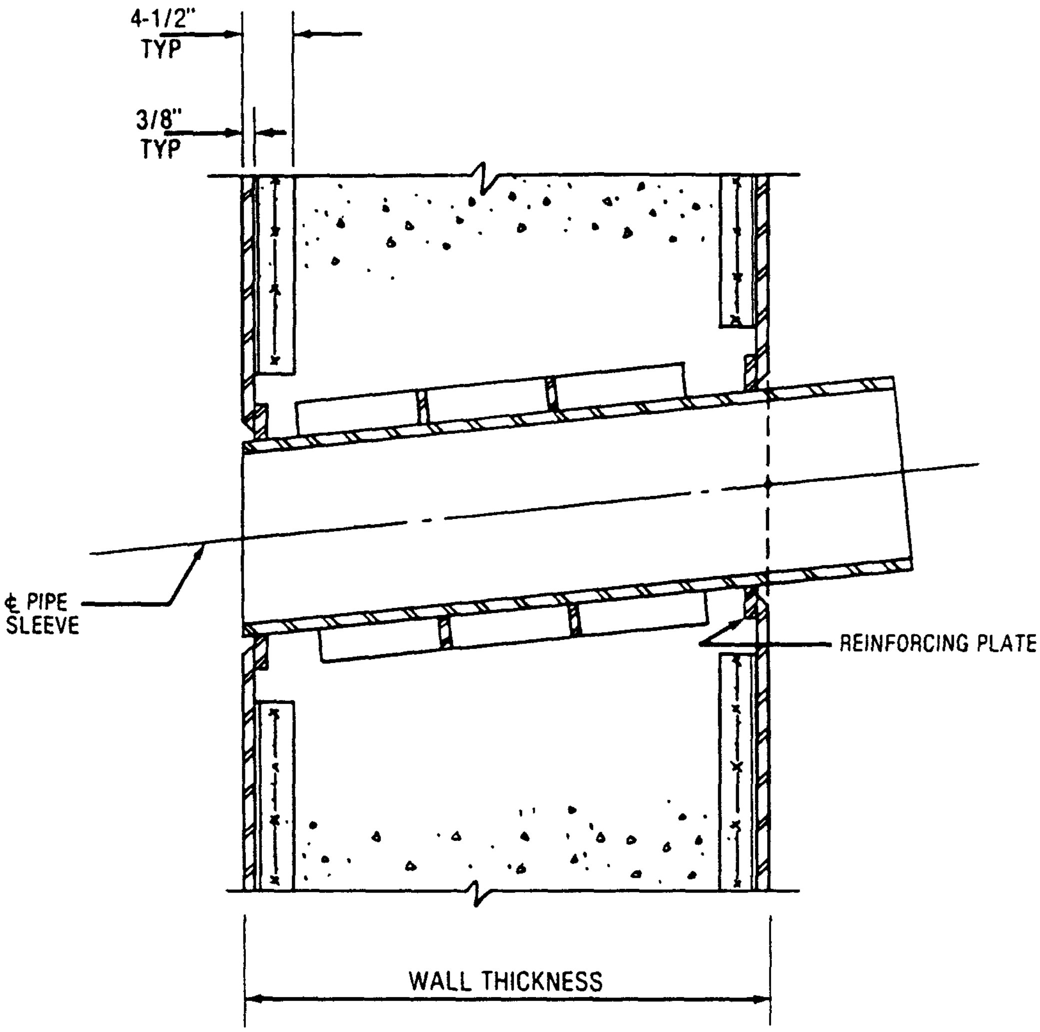
Figure 3



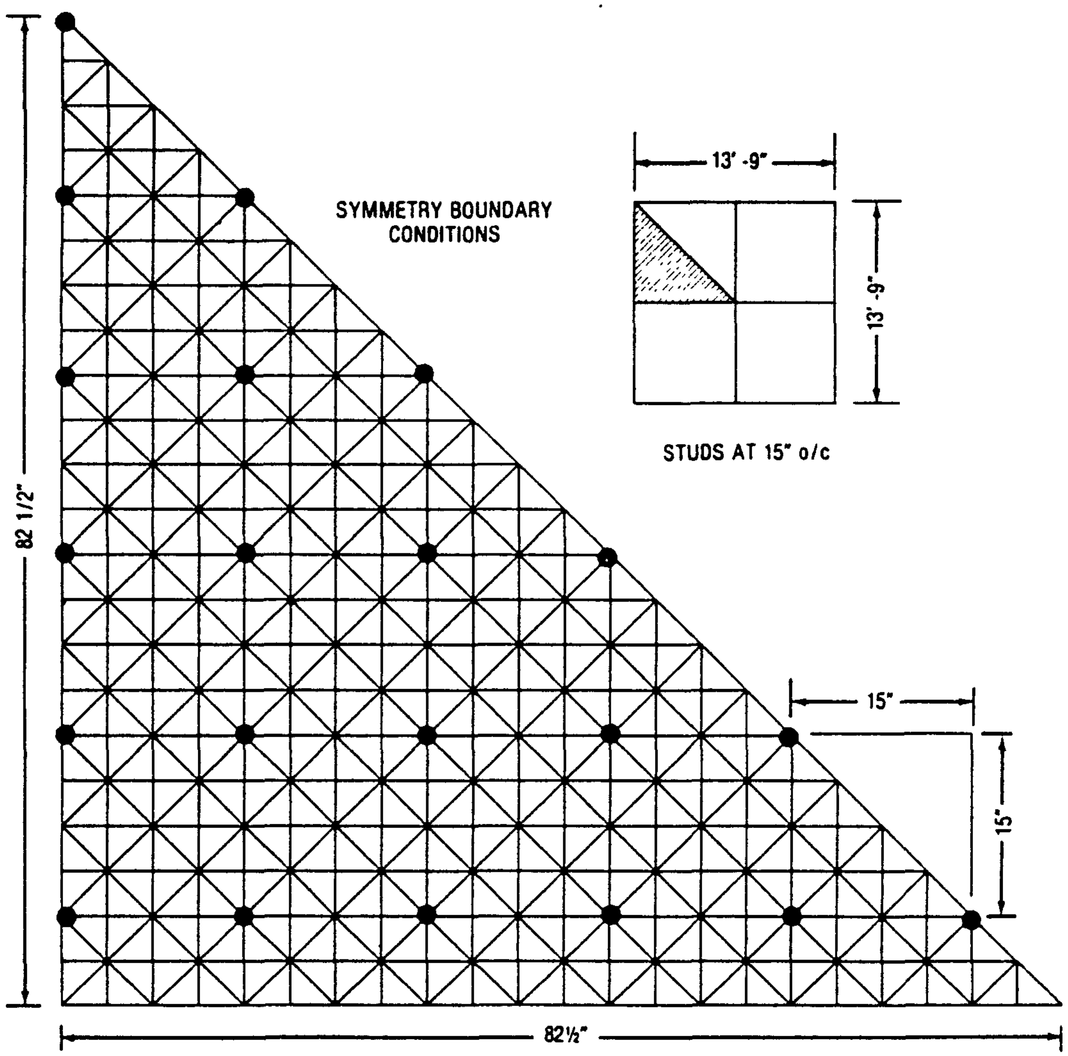
SECTION A-A

EQUIPMENT SUPPORT EMBEDMENTS IN LINED CELLS

Figure 4

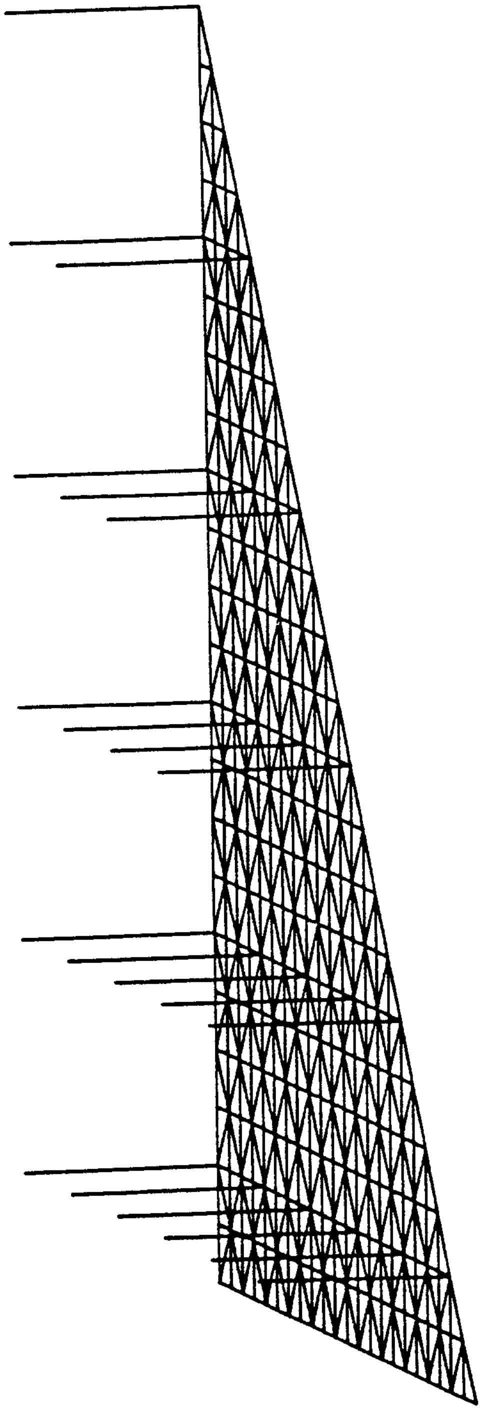


CELL LINER PENETRATION DETAIL
Figure 5



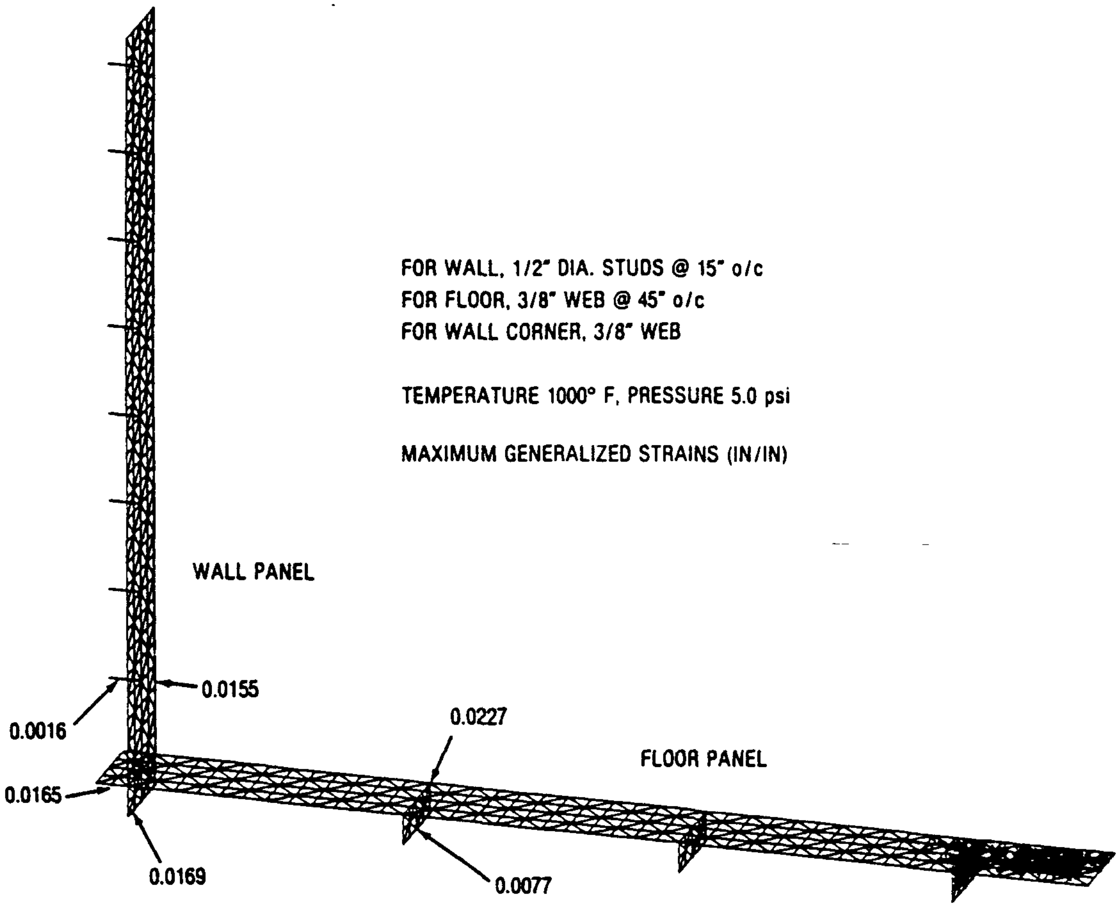
CRBRP: ANALYSIS OF LINER WITH STUD-TYPE ANCHORS

Figure 6



ANALYSIS OF LINER WITH STUD-TYPE ANCHORS

Figure 7



WALL-FLOOR LINER CORNER

Figure 8