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SUMMARY

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 description, requirements and analysis of such a system design for the Clinch River Breeder Reactor Plant (CRBRP) is presented in this paper.

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.

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 metal 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 against the consequences of 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 between 2.0 and 0.5% 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, form 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. The cell liners are designed to withstand all plant design basis conditions and to maintain their limited leakage function during the entire 30 year plant life. 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 .36% volume per day in-leakage under a 2.5 inch (6.4 cm) water gauge negative pressure differential. This limits leakage of oxygen into the cell which limits the cost of the gas processing system required to maintain the cell oxygen content below 2%, thus limiting the duration of any potential sodium fire.
2. The cell liner shall be designed for a maximum long term operating temperature of 180 deg F (82 deg C). This assures liner performance for the most severe operating mode during plant life.
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. All lined cells are subject to radiation effects. Also, potential corrosion behind the liner must be accounted for.
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. In addition, the liner

is designed to withstand a massive, instantaneous spill of several thousand gallons of liquid sodium at a temperature of 1000°F (538°C).

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. This criteria assures liner integrity will be maintained during and after a seismic event.

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. Potential degradation of concrete from high temperature effects will be avoided and function of the liner anchorage will be maintained.

8. The cell liner system shall be designed to vent gases to preclude pressure buildup behind the liner. Gases generated by heat up of the concrete could generate excessive pressure behind the liner unless venting is provided.

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. These limits have been developed from material uniaxial test data with additional margin provided to account for biaxial state of tensile stress.

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 (≥ 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 behind the cell liner to less than 5 psig (0.35 Kg/cm^2g).

CELL LINER SYSTEM DESIGN DESCRIPTION

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

[1] Higher temperature 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.

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 details of the cell liner system are shown on Figures 1 and 2.

STRUCTURAL ANALYSIS

The liner design is based on a fixed concept wherein the liner plate is rigidly anchored at the corners and penetrations. Alternate concepts such as free floating and semi-fixed liner designs were also studied. However, strain behavior of the fixed concept was found to be the least sensitive to high temperature effects from sodium spills and maximum calculated strains are well within the allowables.

Calculations have been conducted to investigate the adequacy of the liner-anchor system under large liquid metal spill conditions. They consist of elasto-plastic analyses using the computer program ANSYS. To 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. 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 analysis investigated strains at a wall to floor corner. A model of a 15 inch (38 cm) wide strip (equal to the spacing of the stud anchors) was investigated considering all conditions noted above for the wall panel. No lateral support was assumed by the floor insulating gravel. The results give a maximum effective strain of 2.3% in the liner plate and 1.7% in the anchors. Since the strains obtained are much below the allowables specified in Table 2, it is concluded that liner integrity is maintained.

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. 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.

CONCLUSIONS

Steady state analysis of the CRBRP liner system has been completed and results to date demonstrate the adequacy of the design to mitigate the effects from sodium spills. Further analysis is being performed. Maximum strains calculated at critical locations are well within the prescribed limits, and peak structural concrete temperatures are maintained below the maximum defined limits.

ACKNOWLEDGEMENTS

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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 cell walls

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

Table 2

Limits for Structural Design of CRBRP Cell Liners

	Liner-Strain Allowable		Allowable Anchor Loads	
Category	Membrane	Combined Membrane plus Bending	Mechanical Loads	Displacement Limited Loads
Load Combinations A and B	$\varepsilon sc=0.002$ $\varepsilon st=0.001$	$\varepsilon sc=0.004$ in./in. $\varepsilon st=0.002$ in./in.	Lesser of: Fa=0.67Fy Fa=0.33Fu	0.25 δ u
Load Combination C	$\varepsilon sc-0.005$ $\varepsilon st=0.003$	$\varepsilon sc-0.014$ in./in. $\varepsilon st=0.010$ in./in.	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. δ_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.

FIGURE 1
TYPICAL CELL LINER
ISOMETRIC — CORNER DETAIL

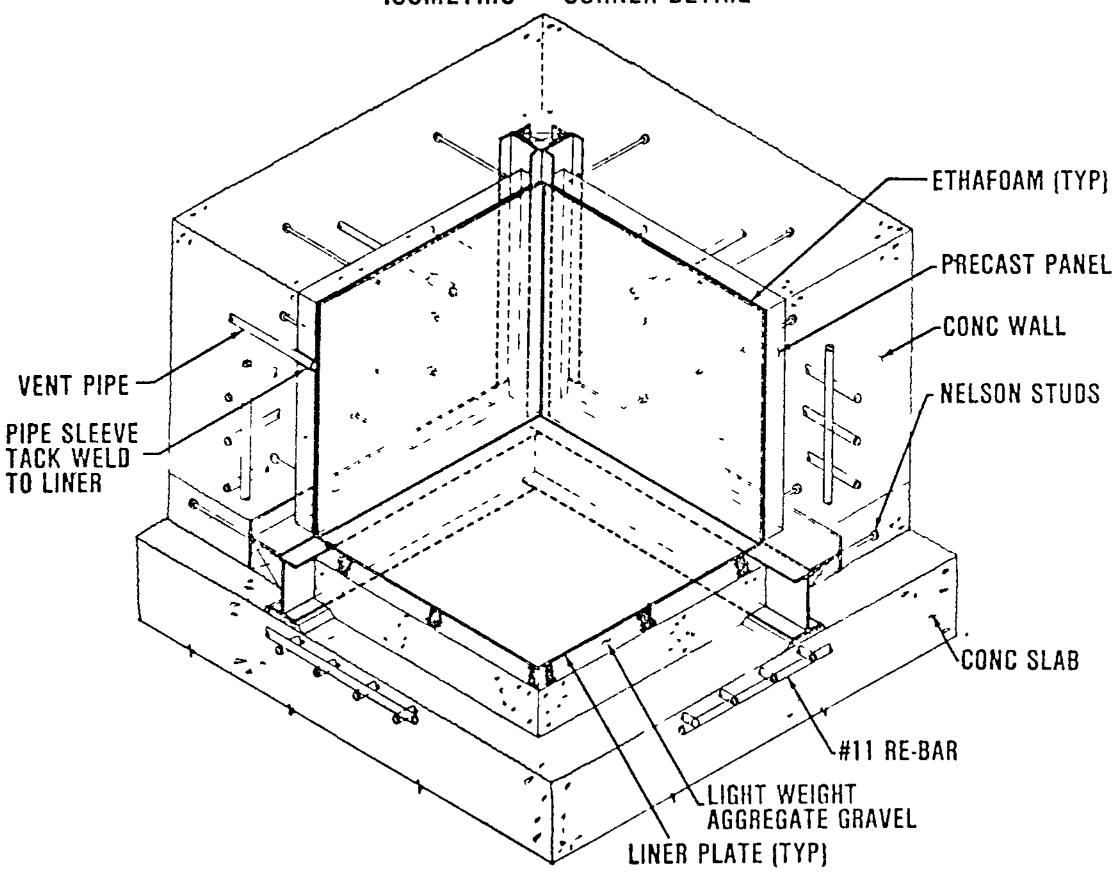

FIGURE 2
FLOOR & WALL DETAIL