Concrete Containment Leakage Prediction
An Overview of Recent Work

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ABSTRACT

The end of 1988 concludes 6 years of EPRI-sponsored research aimed at development of a test-validated methodology for the realistic prediction of overpressure capacity of concrete containments. As the research progressed, various phases of the work have been described in SMIRT 8, and 9 Volume J publications, as well as Containment Integrity Workshops held by the USNRC and post-SMIRT conferences on concrete containments. The purpose of this paper is to summarize the program, draw some unifying conclusions regarding concrete containment overpressure behavior, and point out recent developments in the program such as a leakage prediction methodology and simplified containment analysis software. In order to provide structural analysts with a usable criteria, a methodology for predicting liner tearing was developed which consists of using ABAQUS-EPGEN (a general purpose finite element program co-sponsored by EPRI and Hibbitt, Karlsson, and Sorensen, Inc.) to perform 2D global analyses and then applying curves of liner strain magnification factors to the global liner strains. Post test conclusions of the Sandia 1:6 Scale Model experiment are also discussed. Using the methods developed in the EPRI program, pretest predictions of the leakage locations and the leakage pressure were in good agreement with the model test. Finally, the current level of understanding of concrete containment analysis and behavior is reviewed in the context of current regulatory requirements in the United States.

INTRODUCTION

In the past several years, considerable research effort has been devoted by the Electric Power Research Institute (EPRI) and the U.S. Nuclear Regulatory Commission to the behavior of concrete reactor containments under severe accident loadings. The evidence gathered during the experimental and analytical phases of the EPRI work clearly supports leakage rather than burst as the most likely failure mode. The dominant failure mechanism has been found to be liner rupture caused by the interaction of the liner and its anchorage system with the concrete at major stiffness discontinuities. On the basis of this work, failure criteria and an analysis methodology for predicting concrete containment leakage has been developed. Experimental evidence supporting this leakage prediction methodology is summarized herein. The conclusions of this evidence, discussed in earlier SMIRT papers (Rashid et al, 1985 and 1987; Dameron et al, 1987), has thoroughly demonstrated the hypothesis that for a gradually increasing pressure, leakage at a pressure significantly less than the burst pressure is the most likely failure mode. More importantly, an early liner rupture would not grow beyond the size required to maintain equilibrium between pressure increase and leakage because (a) the structure's residual stiffness at initial rupture is sufficiently large to restrain the liner from rapid expansion; and (b) the liner tearing is a stable fracture because of the highly redundant crack arrest behavior offered by the concrete backing, i.e. liner crack growth requires further pressure rise.

EXPERIMENTAL EVIDENCE OF LINER TEARING

Five examples of liner tearing (or liner distress) are briefly discussed as an overview of the experimental evidence supporting the leakage prediction methodology. The first four are from the EPRI-sponsored containment specimen test program at Construction Technology Laboratories (CTL) in Skokie, Illinois (Julienn et al, 1984, and Hanson et al, 1986). The test program included full-scale structural specimen tests of special regions of containments, and prestressed as well as reinforced concrete containment types were investigated. This and other test data from CTL has been applied to verification of analytical methods, tabulation of strain concentration factors near discontinuities, and forming conclusions regarding general behavior patterns such as liner tearing and liner-concrete interaction. Figure 1 shows the locations of the liner tears and distressed areas in several of these specimen tests. The fifth example, the Sandia 1:6 scale reinforced concrete containment model, has provided vast information for studying the failure behavior of reinforced concrete containments. An unwrapped view of the cylinder liner surface is shown in Figure 2, indicating the many liner tears that occurred near the end of the test. The experimental evidence derived from these five examples is summarized below.

Specimen 2.5. Wall-Basemat Juncture - Prestressed Geometry

A full scale model of the wall-skirt-basemat region of a typical prestressed containment was subjected to the meridional force, shear and bending moment that would occur in an actual containment during overpressure. The circumferential liner anchorage at the wall-skirt juncture and the termination of meridional liner stiffeners at this location caused strain concentrations that led to tearing as shown in the figure. Correlation of measured strains to pre- and post-test analysis (as described by Dameron et al, 1987) has resulted in the development of wall-skirt-basemat strain magnification factor curves.

Specimen 2.4. Wall Specimen With Penetration - Prestressed Geometry

The wall specimens with penetrations were designed to represent a square section of the containment wall with a medium sized (30 to 42 inch diameter) process penetration. The presence of a penetration causes severe stiffness discontinuity. Specimen 2.4 was loaded with a hoop to meridional stress ratio of 2:1 plus an outward punch force. The specimen developed a large liner tear at the liner-penetration juncture at a far field strain across the specimen well below that corresponding to global failure in an actual containment.

Specimen 3.2 - Prestressed Geometry with Penetration; Inward Punch Shear Force

Similar to 2.4, this specimen utilized the 2:1 applied stress ratio but included a series of increasing inward punch loads. An inward punch force simulates the case of a piping penetration that is restrained against axial motion, thus constraining a point on the containment wall. Liner strain concentrations at the ends of the stiffeners reached peak strain levels large enough to tear the liner, while the global strain was still below global failure levels.

Specimen 3.3 - Wall With Penetration - Reinforced Geometry

This specimen was loaded in the same way as Specimen 3.2, but for a reinforced concrete geometry. One notable difference was the addition of a thickened liner region around the penetration. This detail was also used for the penetrations in the 1:6 scale model. With this detail, the largest liner strain occurs at a radius just beyond the thickened region. The liner strain concentration for this test was successfully predicted by analysis, and here, as with the other specimens, strain measurements and pre- and post-test analyses were used to develop strain concentration factor curves for this type of geometry.

Sandia 1:6 Scale Reinforced Concrete Containment Model

The Sandia model was designed with construction details and penetrations that are similar to many existing LWR containments (Clauss, 1987). After the maximum pressure was reached and the model was unloaded many liner tears were visible near various penetrations, as shown in Figure 2. The EPRI/ANATECH series of pretest analyses was successful in predicting the locations of liner strain

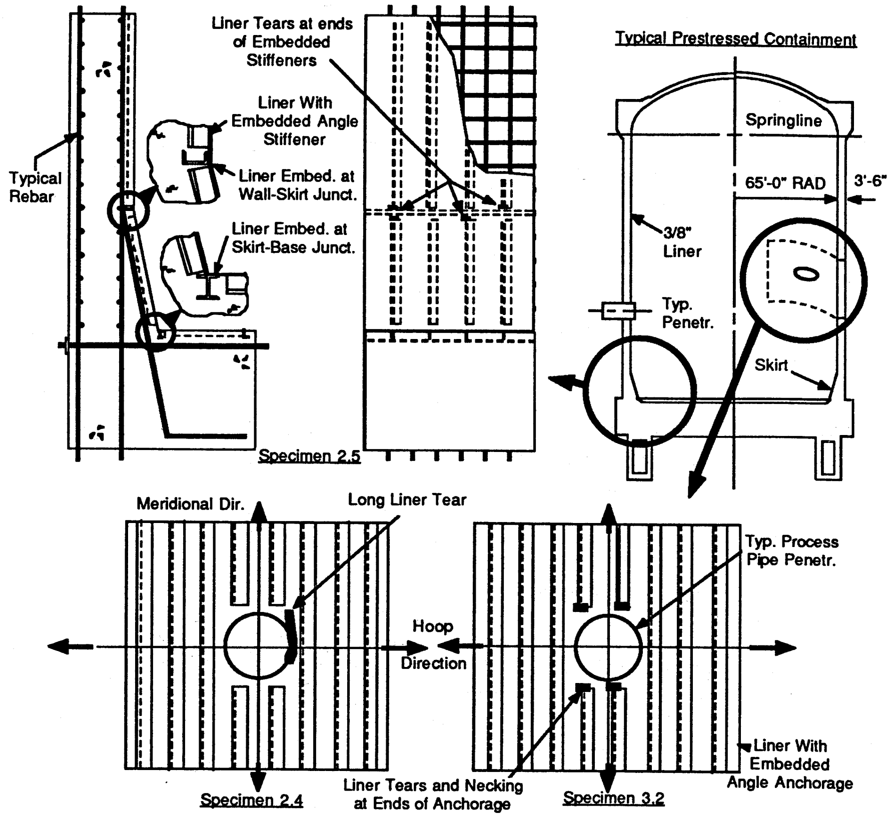

Figure 1. CTL Tests. Upper: Specimen 2.5, Wall-Base Juncture. Lower: Specimens 2.4 & 3.2, Prestressed Cont. Wall Elements

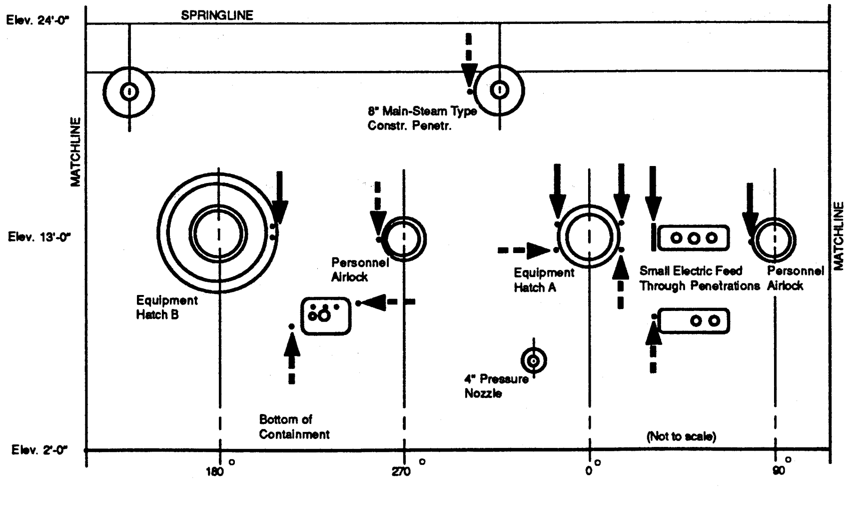

Figure 2. "Unwrapped Inside View" of Sandia 1:6 Scale Model Cylinder. Arrows Indicate Liner Tears and Distressed Areas After the Test.

concentrations, distressed areas, and tears, and the methodology developed in the present work accurately predicted the ultimate leakage pressure in the test. Post-test efforts using the test's detailed strain measurements have been very useful in the further development of strain concentration curves for different types of stiffness discontinuity geometries.

LEAKAGE PREDICTION METHODOLOGY

Calculation of local strain states near discontinuities which cause liner tears requires very localized modeling of the liner, concrete, rebar, and liner anchorage using specialized material and computational modeling techniques unique to concrete containment structures. While these techniques have been developed and extensively utilized in the EPRI containment research, their use is not practical for examining all possible tearing locations of individual containments on a case-by-case basis. Instead, these techniques have been used in conjunction with a liner rupture criterion, to construct a simplified analysis procedure for predicting leakage in concrete containments. A general outline of the procedure is as follows. The analyst must first conduct 2D analysis of the containment to compute global liner strain histories versus pressure. Separate sets of strain concentration factor curves (K) versus normalized pressure ($P_n = P/P_{design}$) and separate sets of stress biaxiality factors (β) have been developed for each class of major stiffness discontinuity for reinforced and prestressed containments. These are: (a) wall-base juncture, (b) equipment and personnel hatches, (c) main-steam and other medium penetrations, and (d) the springline. Guidelines are provided on typical construction details and other factors which may influence these curves. The K values give effective strains based on global directional strains. The β values are needed to make the liner tearing criteria depend on multiaxiality of stress. Finally, a "gage length" factor (α) is given for localization of strain peaks based on experiment and analysis results. α establishes a measure of the localization of the actual strain relative to what can be measured in an experiment. The containment analyst selects stiffness discontinuity locations which are of interest, then at a particular location computes the equivalent peak uniaxial strain ε_p from the formula

$$\varepsilon_p = K\,\alpha\,\beta\,\varepsilon_{global} \qquad (1)$$

at several pressures. The analyst then constructs strain failure as the intersection of ε_p with his uniaxial material test data, and thus obtains the leakage pressure at stiffness discontinuity locations. The peak strains at the stiffness discontinuities are the product of three factors (K, α, and β) times the calculated global strain quantity that corresponds to the location being evaluated. At the pressure and location where the peak strain meets or exceeds the uniaxial failure strain, a liner tear is predicted to occur. Once liner tearing occurs, the criteria assumes that the tear (or tears) will grow in a stable manner until an equilibrium leakage rate through the tear(s) is achieved.

OTHER RECENT DEVELOPMENTS IN CONTAINMENT ANALYSIS

Successful implementation of the leakage prediction criteria described above is contingent on the accurate calculation of global liner strains within the containment. The focus of part of the latest work has been to document a procedure for global concrete containment analysis for calculation of global behavior and to develop automated procedures to facilitate simplified concrete containment analysis. Development of the latest analysis capabilities has been in three major areas as described by Dameron et al, 1989. First, the concrete constitutive model which has been developed in previous phases of the research, has been significantly improved to include compressive plasticity and 3D computational capability. Second, an automated rebar generator has been developed for use with ABAQUS-EPGEN which generates complex finite element program rebar input for 2D or 3D grids from simple spatial rebar definition commands. While 3D analysis is not generally required to use the leakage prediction methodology, it is definitely required for more precise investigations of local penetrations and other containment details.

The third major development area is the automation of 2D axisymmetric grid generation which forms the basis of the input to the leakage prediction methodology. Two library models have been developed which generate optimized grids for typical reinforced and prestressed LWR containments found in the United States. For any containment similar to the two prototype grids, the library model software automatically tailors the optimized grid to the new structure with input of a few geometry parameters. The result of running the library model software is the generation of a complete ABAQUS-EPGEN input deck. These developments were fully documented by Dameron, 1989. The grids and analysis guidelines are the result of performing many similar 2D computations in which grid densities, modeling details, load increment sizes, and nonlinear solution strategies have evolved and have been experimentally verified.

STRAIN CONCENTRATION CURVES AND EXAMPLE APPLICATION

The K and β curves that have been produced to support the criteria have been recently published in an EPRI report (Dameron et al, 1989), and there is insufficient space in this paper to include such data. Instead, an example application for a typical prestressed containment is described. The typical containment for the example was shown in Figure 1. The first step is a global axisymmetric analysis, ignoring penetrations and local effects. Four locations should then be checked: (1) the wall-skirt juncture; (2) a medium penetration, i.e., the fuel transfer ports; (3) the equipment hatch; and (4) the springline. The global strain quantities to be input to Equation 1 are meridional strain for the wall-skirt juncture and the springline, and hoop strain for the penetrations, taken at the proper elevations. The K and β values are read off of curves in the leakage prediction methodology report. The results of the application of Equation 1 to the global liner strains are plotted in Figure 4. This shows the relative magnitude of peak strains versus pressure and shows that in this case the wall-skirt juncture is most likely to tear first at a pressure of 148 psi.

A similar exercise can be performed for typical reinforced concrete containments. One interesting comparison that has been performed is to see what the criteria produces for the Sandia 1:6 scale model geometry. The results of this exercise show potential tears developing at medium penetrations at 142 psi, at equipment hatches and personnel air locks at 144 psi, at the wall-base juncture at 152 psi, and at the springline at 156 psi. This shows good correlation with the experimental results.

CONCLUSIONS FROM THE RESEARCH AND FUTURE GOALS

The EPRI program for concrete containment research has achieved several major advancements in the technology of concrete containment behavior prediction. Several significant results of this program can be cited: (a) the leak-before-break failure mode, with its reduced risk implications, has been placed on firm technical grounds and was thus advanced from a mere hypothesis to a proven and generally accepted behavioral phenomenon; (b) the level of understanding of concrete containment overpressure behavior achieved in the program has given the nuclear power industry a sound technical basis for addressing regulatory issues; and (c) the program has culminated in a set of guidelines and procedures for the deterministic prediction of concrete containment leakage. The goal of future work is to extend the leakage prediction methodology to a probabilistic level where utilities can perform risk assessment of their containment structures within the Probabilistic Risk Assessment (PRA) framework. This will involve the characterization of probability distributions for all of the terms of equation 1 and the convolving of these distributions into final leakage probability distributions.

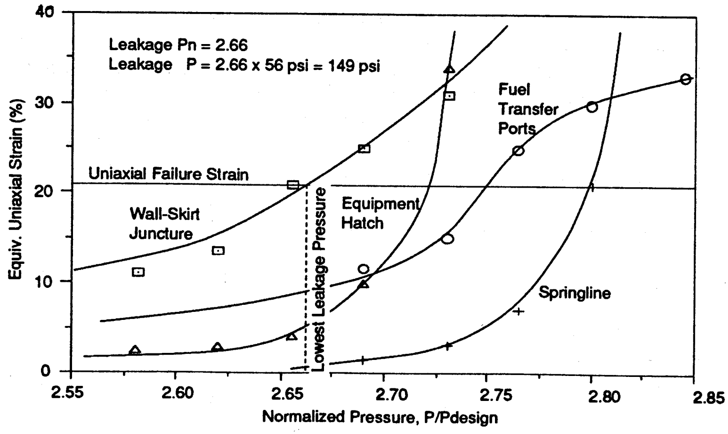

Figure 3. Containment Example - Check Peak Strains Against Uniaxial Failure Strain

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