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LEAK AREA AND LEAKAGE RATE PREDICTION FOR PROBABILISTIC RISK ASSESSMENT OF CONCRETE CONTAINMENTS UNDER SEVERE CORE CONDITIONS

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Abstract

The fundamental gap in knowledge for estimating release for probabilistic risk assessment of concrete containments subject to beyond design basis loads is in estimating leak areas and leakage rates. By evaluating the available literature and carefully studying the test results, several generic rules are postulated for leak areas and leakage rates of concrete containments. These rules, coupled with Rizkalla's theory-based leakage flow equations and empirically-based crack roughness constants, provide a realistic estimate of leak rates through liner tears in concrete containments.

1 Introduction

The containment building of a light water reactor nuclear power plant represents the ultimate barrier against the release of radioactivity to the environment. Consequently, evaluating the containment's leakage and failure characteristics during postulated severe accidents is a critical part of the risk assessment process. In earlier works sponsored by the Electric Power Research Institute (EPRI) [1-3], the following major milestones in containment behavior study subject to extreme internal pressures were accomplished: a) the development of a comprehensive methodology for the response and analysis of concrete containment structures, b) verification and acceptance of the leak-before-break phenomenon and c) the development of a concrete containment leakage prediction methodology.

The leakage criterion that was developed is a deterministic measure of liner rupture and is postulated to lead to a leakage rate that is in equilibrium with quasi-static pressurization. This postulate, which was first put forth heuristically on the basis of historical evidence [4], was later verified by the Sandia 1:6 scale model test [5-7]. By this hypothesis, at leakage rates below the equilibrium leakage rate, multiple liner ruptures can occur at different pressure levels (pressure levels below the structural limit state). This implies then that **rapid** pressurization could trigger more than one failure location with the possibility of exceeding (at elevated pressures) the NUREG-1150 [8] definition of leakage area before equilibrium is reached. Under such conditions, in estimating release risks, the relationship between leak rate and leak size is required. Specifically, one needs to quantitatively determine the leak area assigned to each tear location for a given pressure and calculate gas transport through the leak area.

This paper proposes a procedure for leak area determination and postulates a prediction formula for leak rate as function of tear size and internal pressure based on results of the EPRI-sponsored leak rate tests at Construction Technology Laboratories (CTL) [9, 10], leak rate measurements performed on the Sandia 1:6 scale model, and measurements and analytical methods introduced by Canadian researchers [11-14].

2 Leak Area

By evaluation of the available literature [11-14] and observations of the specimen behavior [10, 11], it is found that in most cases, if liner tearing occurs in a region experiencing far-field rebar yield, leakage rate can be assumed to be governed by the liner tear aperture itself and will not be affected by any obstruction to leak path posed by the concrete.

The liner anchorages, either welded studs or embedded Ls or Ts, are found to provide effective liner anchorage which enhances liner strain concentration and guides the trajectory of a liner tear [6, 9, 10]. Based on this observation, it can be postulated that the anchorages also isolate strain concentrations to the particular liner region between anchorages. More specifically, if a strain concentration occurs on the side of an anchorage, the anchorage being still embedded in the free-field concrete will block any local strain effects from reaching the other side of the anchorage. Therefore, the local effects of a tear will be manifested over one liner "span" between anchorages. This makes stud or anchorage spacing perpendicular to crack trajectory a critical parameter for predicting liner crack width.

Fig. 1 shows the liner plate including a pre-manufactured six-inch flaw tested at CTL. A detailed finite element analysis of the liner plate was performed to study the strain field ahead of the advancing crack tip. The analysis versus experiment crack tip comparison shown in Fig. 2 illustrates that: a) the first 0.75 inches of the new crack has a blunt tip so that the crack edges behind the blunt tip are relatively parallel and b) the crack width in the previously uncracked material has an average crack width of approximately

$$w = \varepsilon_{global} \times s = 1.64\% \times 16 \text{ inches} = 0.26 \text{ inches} \quad (1)$$

where ε_{global} is the far-field global strain and s is the liner span between anchorages perpendicular to the liner crack.

Applying Eq. 1 to the Equipment Hatch A tear and the long tear at the electric feed through of the Sandia 1:6 Scale Model, the predicted tear widths are 0.04 inches and 0.11 inches, respectively. These widths compare well with post-test inspections of the model.

Liner crack length is more difficult to postulate, but from analyses and observations in [1-4], one can conclude that a liner tear at a strain concentration location can be considered to extend along the trajectory of a uniform peak strain field. In the case of the 20-inch long tear next to the electric feed through in the 1:6 Scale Model, the peak strain was uniform along the edge of the rectangular insert plate, thus the tear ran the entire length of the uniform strain field. In the case of the advancing tear in the CTL tested liner plate, the crack tip strain rapidly attenuated ahead of the crack tip because of the strong constraint offered by the concrete backing; thus, the tear was arrested. At curved penetration insert plates, the strain field is a maximum at the equator of the penetration but gradually decreases away from the equator [9]. Using these data along with the observation that the liner anchorages tend to act as liner crack formers leads to the following postulated rules for crack length: a) at strain concentrations where a long trajectory of equal peak strain occurs, a tear will run the length of the peak strain trajectory and b) at other strain concentrations, the tear will be assumed to run a length s equal to one anchorage spacing. This length is conservatively large, but it is based on the premise that peak strain will be minimum midway between anchorages.

The above rules serve as a basis to estimate leak areas.

3 Leak Rate

To postulate leakage rate, one must consider a typical concrete crack in the vicinity of a liner tear. Based on Eq. 1, the closest concrete crack to a liner tear will always be as wide or wider than the liner tear itself. On the basis of the very rapid leak rates observed in various tests, one can further assume that leakage will occur regardless of whether the concrete crack is aligned with the liner tear. Based on this assumption, it is postulated that in the post-rebar-yield regime containment leakage can be characterized by the sketch in Fig. 3. The aperture width was defined by Eq. 1 and the aperture length, B, was defined in the preceding section. The distance to be travelled by the containment contents is L, the containment thicknesses. This idealization of gas flow through containment cracks is identical to the idealization used by Rizkalla [12-14] except that here the length is defined by the liner tear length, whereas, Rizkalla's crack extent is the concrete crack length since Rizkalla was concerned with the CANDU Canadian Plant containments which have no liners. It is recognized that the leaking gases will spread somewhat vertically in the wall cracks, as shown by the dashed lines in Figure 3, but this effect is assumed to be relatively unimportant for estimating total mass transport through the crack.

With the modification to include the liner tear aperture, Rizkalla's development of the theory-based leakage flow equations, with empirically based crack roughness constants, are adopted for estimating leak rates through liner tears in concrete containments. Following the derivation outlined in [12], we obtain

$$p_1^2 - p_2^2 = \frac{f\,L}{2W}\,\frac{p_2^2}{RT}\,\frac{q_2^2}{B^2W^2}\,\{\,\frac{4W}{fL}\ln\left(\frac{p_1}{p_2}\right) + 1\} \qquad (2)$$

where subscripts 1 and 2 represent conditions at the beginning and at the end of the crack, respectively. R and T are the gas constant and the absolute temperature respectively; q is the rate of flow of gas at the end of the crack; w is the crack width; L is the thickness of the concrete wall in the direction of gas flow; B is the length of the crack; and f is the dimensionless friction coefficient factor. The first term of Eq. 2 in the bracket is very small compared to unity and can be neglected. Hence,

$$p_1^2 - p_2^2 = \frac{f\,L}{2W}\frac{p_2^2}{RT}\frac{q_2^2}{B^2W^2} \tag{3}$$

The dimensionless friction coefficient factor, f, depends on the Reynolds number, Re, and the wall roughness, k, and it can be expressed in general for both laminar and turbulent flow as

$$f = (k/Re)^n \tag{4}$$

where n is the flow coefficient, which can be determined experimentally; and both n and k are functions of crack width. Rizkalla formulates an average smeared crack width, but for the purposes of leakage through a liner tear, a single crack of width, w may be assumed.

$$k = 2.9 \times 10^7\, w^{1.3} \tag{5}$$

$$n = 0.133/(w)^{0.24} \tag{6}$$

4 Test Correlations

Calculations are performed based on Eqs. 2 to 6 to compare the leak rate measurements which are available from the CTL pre-cracked liner plate and the Sandia 1:6 Scale Model tests. The calculation results are summarized in Table 1. Note that the roughness coefficient "k" in Table 1 was increased for the liner plate calculation to improve the correlation. This may be justified because of the increased roughness that exists for full scale concrete and aggregate. In general, the correlations obtained are good, thereby establishing a basis for using this approach. More leak rate test data would be useful to further calibrate this methodology, but the results of application of the method is very encouraging considering the current lack of a test verified leak rate prediction capability.

5 Concluding Remarks

The developments discussed in this paper have been implemented into leakage prediction methodology software [15]. Leak size is related to global strain and certain geometry considerations which are input parameters, such as anchorage spacing and type of stiffness discontinuity. The leakage rate is related to the liner tear size and shape, the containment pressure differential, and the physical properties of the gas inside the containment. This implementation represents a significant enhancement to the previously developed leakage prediction methodology [3] and is essential for realistic treatment of radionuclide release in the framework of probabilistic risk assessment under postulated severe accident scenarios.

6 References

1. Dunham, R. S., et al., "Methods for Ultimate Load Analysis of Concrete Containments." EPRI Report NP-4046, June 1985.

2. Dameron, R. A., et al., "Methods for Ultimate Load Analysis of Concrete Containments: Second Phase." EPRI Report NP-4869M, March 1987.

3. Dameron, R. A., et al., "Methods for Ultimate Load Analysis of Concrete Containments, 3rd Phase, 1st Tier Report: Criteria and Guidelines for Predicting Concrete Containment Leakage." EPRI Report NP-6260M, February 1989.

4. "Prestressed Concrete Reactor Vessel Model," General Atomic, USAEC Report GA 7097.

5. Clauss, D. B., "Round Robin Pretest Analyses of a 1:6 Scale Reinforced Concrete Containment Model Subject to Static Internal Pressurization." SAND87-0891, NUREG/CR-4913, 1987.

6. Clauss, D. B., "Round Robin Analysis of a 1:6 Scale Reinforced Concrete Containment Model Pressurized to Failure: Post-Test Evaluations." SAND89-0349, NUREG/CR-5341, 1989.

7. Dameron, R. A., et al., "Analysis of the Sandia 1:6 Scale Reinforced Concrete Containment Model - Interim Report." EPRI Report NP-6261, March 1989.

8. "Severe Accident Risk: An Assessment for Five U. S. Nuclear Power Plants," NUREG-1150, Vol. 1, U. S. Nuclear Regulatory Commission, June 1989.

9. Hanson, N. et al., "Concrete Containment, Phase 2: Structural Elements with Liner Plates - Final Report." EPRI Report NP-4867M, August 1987.

10. Hanson, N. et al., "Concrete Containment, Phase 3: Structural Elements with Penetration Sleeves - Final Report." EPRI Report NP-6259M, March 1989.

11. Murray, D. W., "A Review of Explosive Characteristics of Prestressed Secondary Containment Near Ultimate Load," J. of NED, Vol. 5-2, pp. 157-164, 1979.

12. Rizkalla, S. H., et al., "Air Leakage Characteristics of Prestressed Concrete Containments." SMiRT-6, Session J, August 1981.

13. Rizkalla, S. H., et al., "Leakage of Pressurized Gases through Unlined Concrete Containment Structures." SMiRT-7, Session J, August 1983.

14. Tinkler, J., et al., "The Prediction of Air Leakage Rate through Cracks in Pressurized Reinforced Concrete Containment Vessels." SMiRT-3, Session J, August 1985.

15. Castro, J. C., et al., "A Probabilistic Approach for Concrete Containment Leakage Prediction." EPRI Report TR-102176,T1, April 1993.

Table 1

COMPARISON OF THEORETICAL LEAK RATES WITH MEASUREMENTS FROM CTL SPECIMEN 2.2 AND THE SANDIA 1:6 SCALE MODEL

Description	Geometry Parameters					Leak Rate	
Description & Data Pt. #	W (in)	P1 (psig)	P2 (psig)	L (in)	B (in)	Calculated* (scfm)	Measured (scim)
CTL Plate Data Point 1	0.0199	80.7	14.7	42.00	7.000	35.49	35.1
CTL Plate Data Point 2	0.0199	72.7	14.7	42.00	7.000	31.14	25.2
CTL Plate Data Point 3	0.0318	78.7	14.7	42.00	8.000	52.52	47.1
CTL Plate Data Point 4	0.0318	68.7	14.7	42.00	8.000	44.44	35.1
CTL Plate Data Point 5	0.0894	76.7	14.7	42.00	8.000	96.17	93.9
1:6 Model	0.0300	139.7	14.7	9.75	0.125	11.74	8.0
E.H. A	0.0300	159.7	14.7	9.75	0.125	13.77	9.0
(Upper Right)							
1:6 Model	0.0300	139.7	14.7	9.75	0.125	11.74	10.0
E.H. A	0.0300	159.7	14.7	9.75	0.125	13.77	12.0
(Upper Left)							
1:6 Model E.F. Pen	0.1800	159.7	14.7	9.75	22.00	4204.46	4000.0

* For the CTL plate, a full-scale specimen with large aggregate, the roughness coefficient (k) in Eq. 5 was multiplied by 1000. For the 1:6 Scale Model, a scale model with micro-concrete, the unmodified roughness coefficient in Eq. 5 was used.

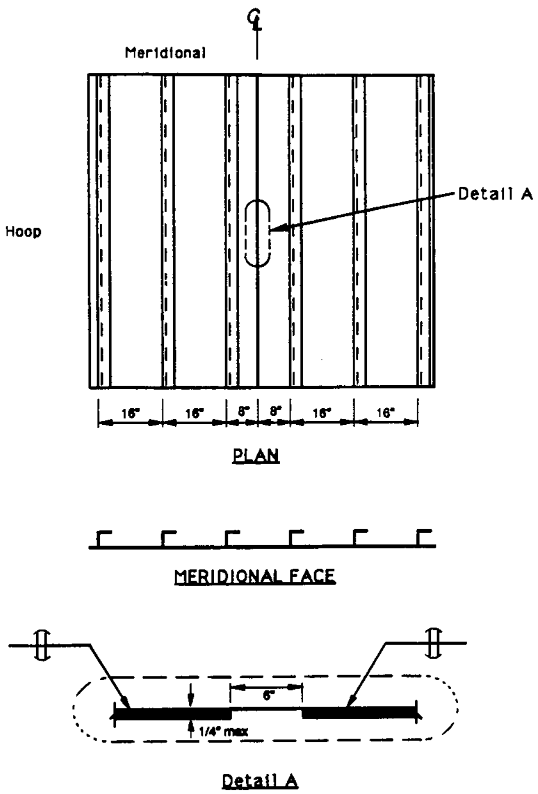

Fig. 1 CTL Pre-Cracked Liner Plate Details

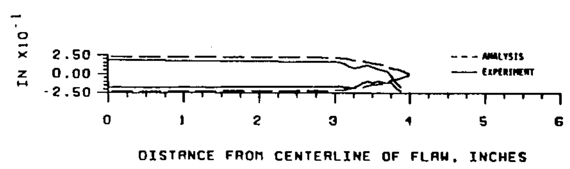

Fig. 2 CTL Liner Plate Crack Shape Comparison

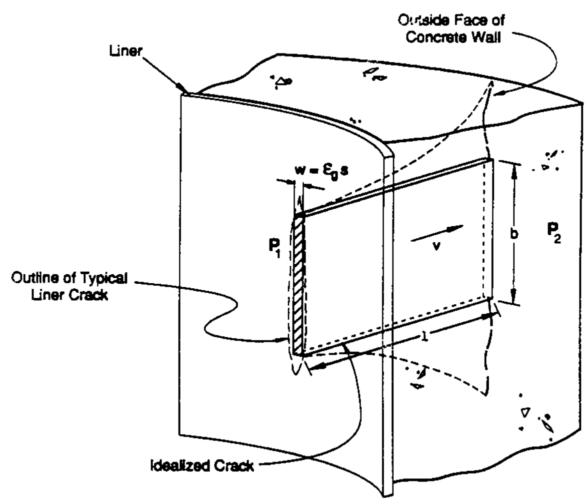

Fig. 3 Idealization of Gas Flow Through Liner Tear