Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division V

PREDICTION OF AIR-LEAKAGE RATE THROUGH LINED CONTAINMENT UNDER SEVERE ACCIDENT CONDITIONS

Sourav Acharya[1], Ajai Pisharady[1], and L. R. Bishnoi[2]

[1]Scientific Officer, Siting & Structural Engineering Division, Atomic Energy Regulatory Board (AERB), Mumbai, India (sacharya@aerb.gov.in) (sourav_acharya@yahoo.co.uk)
[2]Head, Siting & Structural Engineering Division, Atomic Energy Regulatory Board (AERB), Mumbai, India

ABSTRACT

Prestressed concrete containment vessel (PCCV) is the ultimate barrier in a nuclear power plant against radioactivity release during normal accident conditions. In certain PCCVs, steel liners are provided at inner surface to control leakage rate during accident conditions. Qualification of PCCV for air leakage resistance up to its design pressure is done through tests. Estimation of air leakage for beyond design basis accident or severe accident conditions using analytical technique is very complex and computationally challenging. An attempt has been made in this paper to estimate the air leakage rate of a lined containment for severe internal accidental pressure. The strain induced liner damage is coupled with available formulation for air leakage through cracked concrete section to estimate the leakage through lined concrete containment section. In this study, it is assumed that air will leak through cracked concrete but amount of leakage will be controlled by the degree of damage in the co-located liner. The damage of liner is initiated at its critical *J*-integral value; J_{cr}. Leakages are calculated based on different damage propagation patterns, such as linear, parabolic and power variation from initiation of damage to final damage for different J_{cr} values of liner material. Finally a probabilistic study is conducted considering variability of all these parameters and it is observed that the test values are within the zone of mean and 95% confidence curve.

INTRODUCTION

The Atomic Energy Regulatory Board (AERB) of India and the U.S. Nuclear Regulatory Commission (USNRC) undertook a joint Standard Problem Exercise-3(SPE-3) regarding containment performance under severe accident conditions as a round robin analysis based on 1:4 containment model test results conducted at SANDIA National Lab, USA. The SPE-3 is a sequel of earlier round robin analysis (ISP-48), in which the estimation of air leakage rate was not attempted. Main objective of the SPE-3 was to revisit the structural behavior of the containment for severe accidental internal pressure and prediction of leakage rate during this pressure time-history. Leakage rate though containment structure during severe accident is an important parameter to assess radiological impact of such accidents. It forms an important input for Level-2 probabilistic safety assessment (PSA Level-2).

This paper proposes a methodology to predict leakage rate through the wall of prestressed concrete steel lined containment vessel due to severe internal pressure. Semi-empirical formulation available in literature for air leakage through prestressed concrete section (without steel liner) is coupled with steel liner damage to predict the effective leakage rate of the steel lined containment.

LITERATURE REVIEW

There are many semi-empirical formulae reported in literature for estimating air leakage through a concrete section viz. Rizkalla et al.(1984a), Nagano et al. (1989), Suzuki et al. (1989, 1992), Greiner and Ramm (1995), Riva et al. (1999) reported a comparative study of these formulae and observed that for a general case, where pressure variation and range of crack width are large, formula suggested by Rizkalla et al.(1984a) estimates better leakage. The formula proposed by Suzuki (1992) estimates reasonable leakage for low pressure difference. The leakage rate calculation using these formulae is straight forward if crack width and pressure gradient are known and these may be applied directly for unlined reinforced concrete containment. In another study, Rizkalla et al. (1984b) again suggested a step by step procedure to determine crack width, crack spacing and number of cracks for prestressed concrete containment section. The physics of leakage is complex for steel lined prestressed concrete containment. Dameron et al. (1993) suggested a formulation for leakage rate through lined containment with the assumption that leakage would occur regardless of whether the concrete crack is aligned with the liner tear. So, the leakage was estimated based on liner crack width (average liner strain multiplied with liner anchorage spacing or gauge length) postulating a single crack in a vulnerable gauge length/area.

METHODOLOGY OF LEAKAGE ESTIMATION

Assumptions

- The containment is loaded by prestress, internal pressure and temperature only.
- The crack width and number of cracks in prestressed concrete containment section are functions of strain in prestress cables.
- There will not be any leakage until the prestressed concrete section is cracked.
- Vertical through-the-wall cracks, due to hoop strains in prestressing cables are considered for leakage calculations as contribution of circumferential cracks was seen to be insignificant.
- The leakage rate through concrete cracks is controlled by the extent of liner damage at co-locations besides the pressure gradient.
- Properties of air are considered constant throughout.

Calculation of Number of Cracks and Crack Width

Number of cracks and crack width are the major parameters for leakage calculation assuming air leakage from inside of the containment to outside through the cracks in concrete section based on differential pressure and temperature inside the containment. Number of cracks and crack width in concrete section of prestressed concrete containment vessel (PCCV) are estimated using the methodology suggested by Rizkalla et al. (1984b). The formulation for crack width calculation requires estimation of lost bond length and bond transfer length of prestressing steels, strain in prestress cable and mean strain, which is a function of the ratio of cable stress at load step to cable stress at onset of section cracking, Equation 1.

$$W_{av} = \varepsilon_{s2} l_0 + \varepsilon_m l_t \qquad \varepsilon_m = \varepsilon_{s2}\left|1-\left(\frac{f_{s2,cr}}{f_{s2}}\right)^2\right| \qquad l_0 = \frac{f_{s2,cr}}{6500(psi)} d_b \qquad l_t = s - l_0 \qquad (1)$$

Where, W_{av}=average crack width, ε_{s2} = strain in prestressing steel perpendicular to the crack, l_0= length of loss of bond in inches, l_t= bond transfer length, ε_m= mean strain in prestressing steel, $f_{s2,cr}$ = average stress in prestress steel at on-set of concrete section cracking, f_{s2} = average stress, d_b = equivalent diameter of tendon and s = spacing of prestressing steel cables.

In walls containing prestressing tendons parallel to the direction of cracking, through-the-wall cracks occur at the same spacing as the tendons. When the tendon spacing exceeds twice the wall thickness an additional through-the wall crack will occur midway between the tendons. The number of through-the wall cracks stabilizes, when strain in prestress cable reaches 0.002., i.e. no new crack formation after the cable attains a strain of 0.002. At any given strain less than 0.002, the number of through-the wall cracks can be expressed as given in Equation 2 below:

$$N = N_{twc}\left[\frac{\varepsilon_{s2} - \varepsilon_{s2,cr}}{0.002 - \varepsilon_{s2,cr}}\right] \tag{2}$$

Where, N_{twc} = final number of through-the wall cracks according to the method described above, N = number of such cracks corresponding to strain ε_{s2} and $\varepsilon_{s2,\,cr}$ = average strain in prestressing steel at on-set of concrete section cracking. The numbers of cracks are rounded off to the nearest whole number.

Estimation of Leakage Rate

In this study, it is assumed that air will leak through cracked concrete but amount of leakage will be controlled by the degree of damage in the co-located liner. Since the concrete wall is a sub-stratum to the liner in containment, both will experience the stress severity at identical locations and hence the likely leakage path would be through the co-located parts of concrete and liner as this would also be the path of least resistance for air flow. Thus determination of liner damage at any loading/pressure stage is important in estimating leakage through lined PCCV.

In absence of detailed fracture mechanics calculations for linear damage based on some assumed initial flaw sizes, it is assumed here that the liner damage permitting leakage akin to (i.e. opening of the flaws) initiates when the induced liner stress correspond to the liner critical fracture toughness, (i.e. critical value of J-integral, J_{cr}). The ultimate liner damage, when it ceases to control the leakage through cracked concrete, is assumed to occur when the induced liner strain reaches the failure strain/elongation. This failure strain is a function of the uniaxial rupture strain and the state of strain in the liner. The rupture strain value is thus modified using a triaxiality factor as proposed by Dameron et al. (1991) for the biaxial state of strain in the containment wall. Assuming hoop stress to meridional stress ratio of 2.0, the triaxiality factor (TF) works out to be 1.7. This assumption is considered to be reasonable in light of the stress analysis results, which indicate no damage in the dome area. The TF value is kept constant for all cases, variation of TF based on stress variants is not considered. To estimate the initiation of leakage, one has to estimate the co-relation between average strain and fracture toughness expressed as J-integral value. This can be done considering equal probability of an initial flaw at all sections and applied global strain/displacement at critically stressed location of liner. Figure 1 shows the variation of J-integral at different strains of liner due to internal pressure analyzed by Dameron et al. (2012).

To calculate leakage through cracked concrete containment, formulae proposed by Rizkalla et al. (1984a) is used, Equation 3.

$$\frac{p_1^2 - p_2^2}{t} = \left(\frac{k^n}{2}\right)\left(\frac{\mu}{2}\right)^n (RT)^{n-1}\left|\frac{p_2 Q}{B}\right|^{2-n} \frac{1}{\sum_{i=1,j} W_j^3} \tag{3}$$

where, $\sum_{i=1,j} W_j^3 = 1.42 N W_{av}^3$ and N = number of cracks and W_{av} = average crack width

$$n = \frac{0.133}{\left(\sum W_i^3\right)^{0.81}} = \frac{0.195}{\left(N W_{av}^3\right)^{0.063}} \text{ and } k = 2.907x10^7\left(\sum W_i^3\right)^{0.428} = 8.702x10^6\left(N W_{av}^3\right)^{0.367}$$

Where, Q = flux through the wall (ft^3/s), B = crack length (ft), W = crack width (ft), t = wall thickness, p_1 = upstream pressure (lb/ft^2), p_2 = downstream pressure (lb/ft^2), μ = dynamic viscosity of air or gas used (lb s/ ft^2), T = absolute temperature (^{o}R), R = gas constant (sqft/s^2 ^{o}R). W_{av} is the average crack width of the total concrete section of interest. Typical values of μ and R are 1.80 x 10^{-5} Pa-s and 1716 sqft/s^2 ^{o}R respectively.

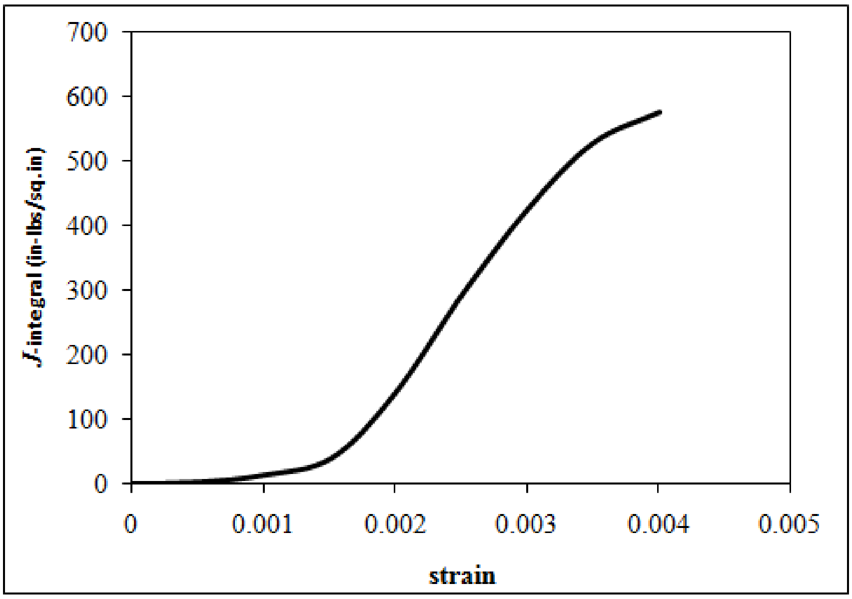


Figure 1. Variation of J-integral at different strains of steel liner due to internal pressure, Dameron et al. (2012)

STEP BY STEP LEAKAGE RATE CALCULATIONS

Step-1: Analysis of full 3D model of containment is done numerically using Finite Element (FE) technique up to its ultimate capacity due to internal pressure. Layered composite shell elements, ABAQUS-6.10 (2010), to represent liner and concrete sections with smeared reinforcements and prestress are used for FE analysis, Figure 2.

Step-2: Strains and stresses of prestress cable in hoop direction (received as output of FE analysis) in each gauge area, (assumed here same as finite element area of 0.2 x 0.2 m^2), for whole containment (13900 elements) for a particular state of internal pressure are captured and stored.

Step-3: Strains in hoop direction of steel liner are also captured and stored in similar manner.

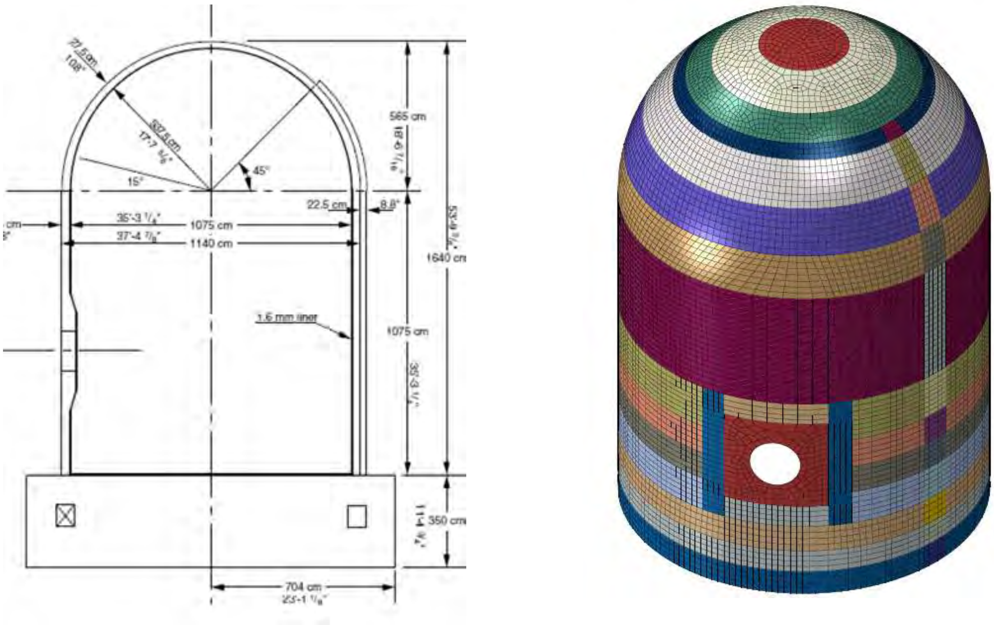
Step-4: Prestress cable strains are checked against concrete cracking strain to establish on-set of cracking in the element areas.

Step-5: Crack widths and number of cracks are calculated for each element/gauge area based on Equation 1 and Equation 2 respectively. Crack height is assumed to be the same as element height.

Step-6: Leakage is calculated for each element using the formula given Equation 3. Temperature variations may be considered during this stage of leakage calculation. For pressure alone, ambient temperature of 25 ^{o}C is considered.

Step-7: Liner strains are checked in every element for initiation of liner damage based on J_{cr}.

Step-8: If the liner strain is more than damage initiation strain, damage co-efficient is calculated for each of the three assumed variations of the damage co-efficient from zero to one, viz. linear (damage factor=1), parabolic (damage factor=2) and power variation (damage factor=1.5). Damage co-efficient is 1.0 at failure strain, which is 20% strain, multiplied with ductility factor (ductility factor, $DF = 2^{(1-TF)}$; Dameron et al. (1991)). For strains less than the damage initiation strain, damage coefficient is considered to be zero.



(a) (b)

Figure 2. (a) 1/4th Scale model of PCCV of SANDIA and (b) FE model of PCCV for simulation

Step-9: The damage co-efficient is multiplied with corresponding leakage rate through concrete to get the effective leakage rate through each element.

Step-10: Total leakage rate is calculated by summing up the effective leakage rates in all the elements. This leakage rate is then converted to %volume of containment per day.

Step-11: Step-2 to Step-10 is repeated for various load steps.

Step-12: Finally leakage in % Volume of containment /day is plotted with respect to pressure values in terms of multiples of design pressure.

An in-house code was developed to calculate the leakage rate considering above flow chart.

RESULTS

The initiation of liner damage is estimated based on critical *J*-integral values taken from the Model-2 report of phase-1 analysis of SPE-3 by Dameron et al. (2012), Figure 1. Typical J_{cr} value of 350 in-lbs/sq in is considered as mean value. So, three values of J_{cr} considered for leakage calculations are; 200,350 and 500 in-lbs/sq in. The corresponding average strains for damage initiation are 0.0022, 0.0028 and 0.0034 respectively. For calculating initiation of concrete cracking, composite section of containment wall is considered, which includes reinforcing steel as well as prestressing steel. The cracking strain of the homogenized composite section was calculated to be 0.000629. Crack widths were calculated following the methodology of Rizkalla et al. (1984b) when the induced strain exceeded the cracking strain, Equation 1. Leakage rates were estimated for three cases representing linear, parabolic and power variations of the damage factor.

Figure 3, 4 and 5 show the leakage rate variation (in terms of % volume of containment) with respect to multiples of design pressure (P_d) for different damage factors along with the experimental values for J_{cr} of 350, 200 and 500 in-lbs/sq in respectively.

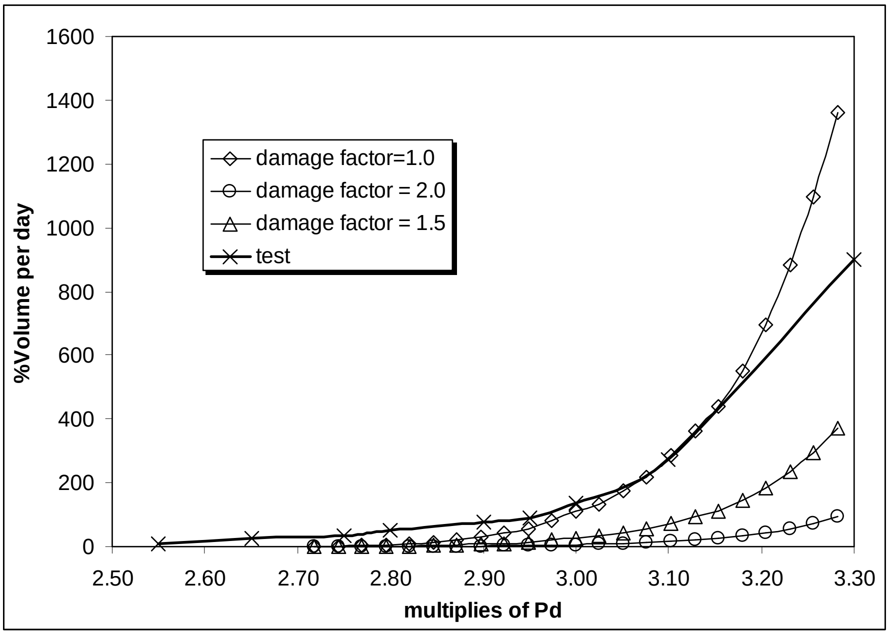


Figure 3. Variation of leakage rate at multiplies of design pressure (P_d) for J_{cr} = 350 in-lbs/sq.in.

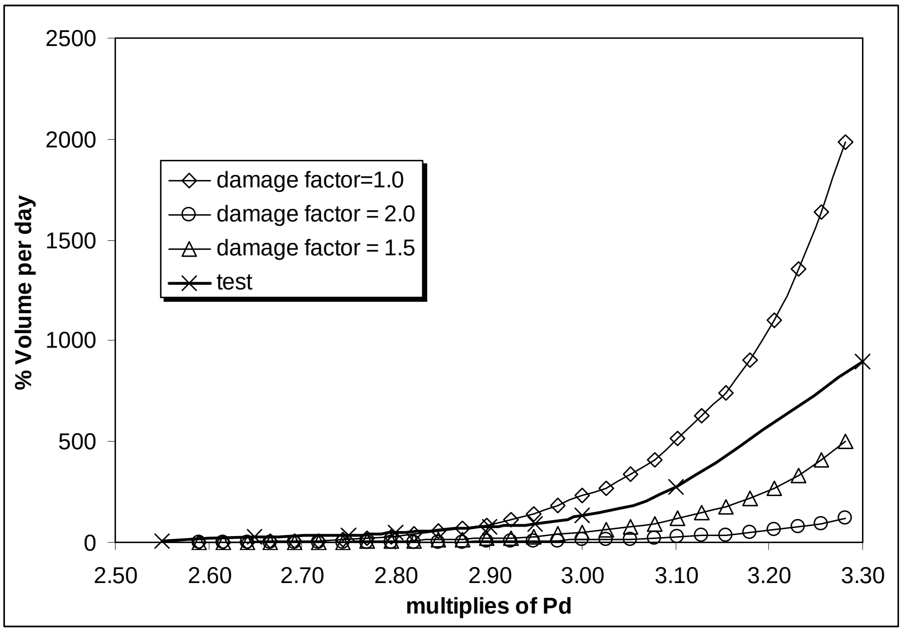


Figure 4. Variation of leakage rate at multiplies of design pressure (P_d) for J_{cr} = 200 in-lbs/sq.in.

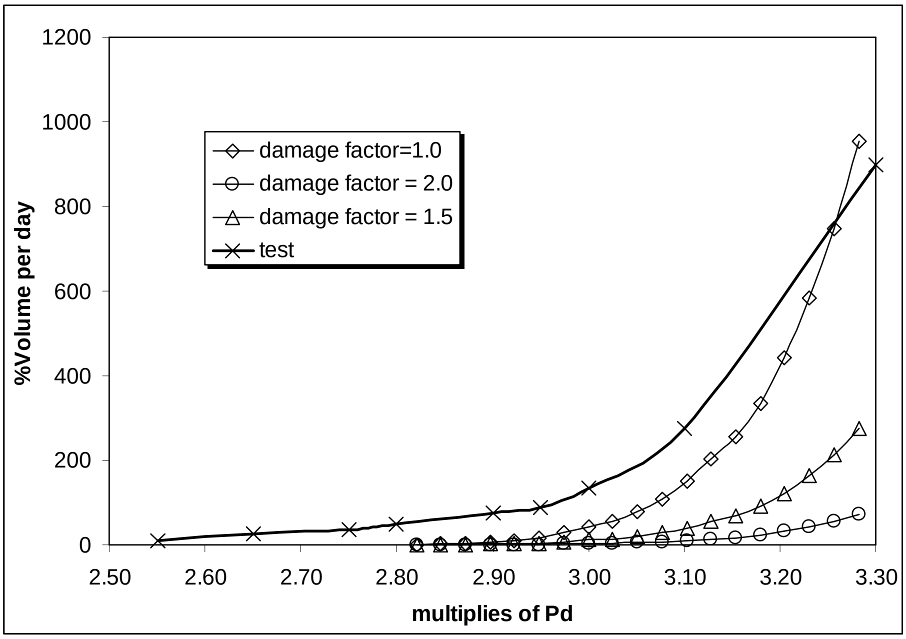


Figure 5. Variation of leakage rate at multiplies of design pressure (P_d) for J_{cr} = 500 in-lbs/sq.in.

Probabilistic Study

Probabilistic estimation of leakage rate was another objective of phase-2 study of SPE-3. An attempt was made for this exercise based on variations of liner fracture properties, liner damage factors and concrete tensile strengths while estimating the leakage rate.

Three basic parameters were varied, viz. liner damage strain based on J_{cr} value (200, 350 and 500 in-lbs/sq in), damage factor of liner (1.0, 1.25, 1.5, 1.75 and 2.0) and maximum tensile stress of concrete (2.11, 2.48 and 2.85 MPa). Experimental data of concrete compressive strength at different pour height of containment wall were found to vary ± 15%. It is assumed the tensile strength of concrete was also assumed to vary in similar manner. However, the analysis of 3D FE model is done using the tensile strength of concrete as 2.48MPa only and the variation in tensile strength was accounted while calculating concrete cracking strains and crack sizes. Five different damage factors of liner are taken to consider the maximum uncertainly in this newly introduced major parameter. The probabilistic analysis is done for this study without the effect of temperature. Total 36 pressure load steps (beginning from 2.66 P_d) are considered and each load step consists of 45 values of leakage rate due to the above stated parametric variations. Based on histogram plot of variation of data for a particular load step, Weibull distribution fits well these data. The leakage rates are calculated for mean, 95% and 5% confidence, Figure 6.

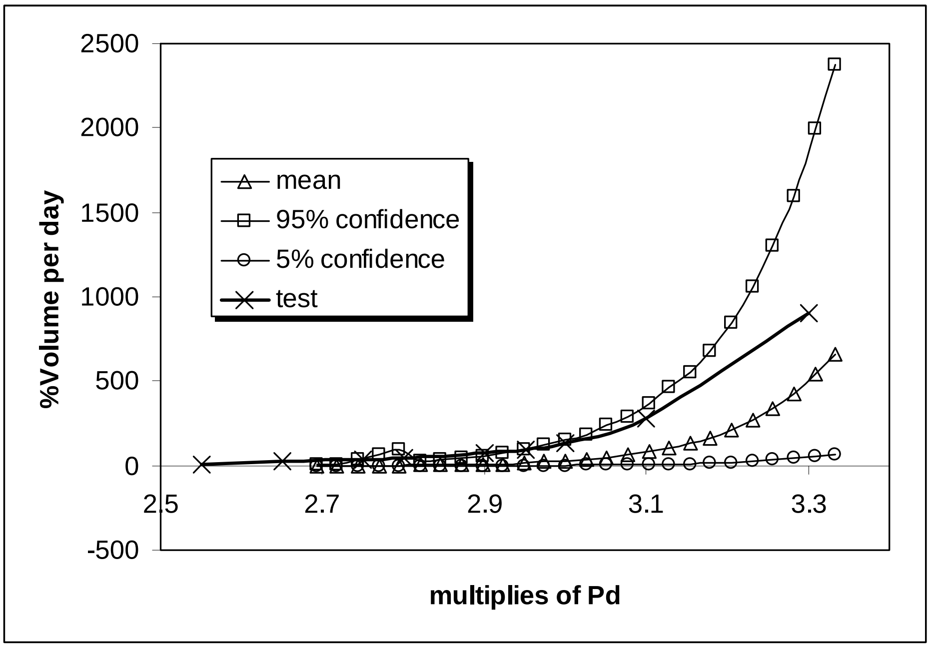


Figure 6. Leakage rate (% Volume per day) with respect to multiplies of design pressure (P_d) for mean, 95% and 5% confidence and PCCV test results

CONCLUSIONS

The following conclusions are drawn from the study:

- Leakage rate increases with increase in internal pressure of containment as expected. The leakage rate follows a power law with respect to internal pressure.
- Initiation of leakage depends on initiation of liner damage, though concrete section cracks much earlier than initiation of liner damage.
- Parabolic damage variation (damage factor = 2.0) of liner produces minimum leakage, whereas linear damage (damage factor = 1.0) produces maximum leakage.
- A probabilistic study shows that experimental results lies between mean and 95% confidence curve.
- The proposed methodology enables estimates of global leakage rates variation with containment pressure up to severe accidental pressures. The main advantage of the proposed methodology is that it depends on overall degree of liner damage instead of individual linear tear.
- The estimated leakage rate is a major input for Level 2 probabilistic safety analysis (PSA), which can be used for radiological impact assessment (RIA) under severe accident conditions.

NOMENCLATURE

B crack length (ft)
J_{cr} critical J-integral value
N the number of such cracks corresponding to strain
N_{twc} the final number of through-the wall cracks according to assumptions as described above
Q flux through the wall (ft^3/s)
R gas constant ($sqft/s^2\ ^oR$)

T absolute temperature (^oR)
W crack width (ft)
W_{av} average crack width

d_b equivalent diameter of tendon
f_{s2} average stress in prestress steel
$f_{s2,cr}$ average stress in prestress steel at on-set of concrete section cracking
l_0 length of loss of bond in inches
l_t bond transfer length
p_1 upstream pressure (lb/ft^2)
p_2 downstream pressure (lb/ft^2)
s spacing of prestress cable
t wall thickness

ε_m mean strain in prestressing steel
ε_{s2} strain in prestressing steel perpendicular to the crack
$\varepsilon_{s2, cr}$ average strain in prestressing steel at on-set of concrete section cracking
μ dynamic viscosity of air or gas used ($lb\ s/ ft^2$)

REFERENCES

ABAQUS-6.10 (2010), "ABAQUS 6.10 User Documentation - Theory manual", Dassault Systems Simulia Corp., Providence, RI, USA.

Dameron, R. A., Dunham, R.S., and Rashid, Y.R. (1991). "Conclusions of EPRI Concrete Containment Research Program", *Nuclear Engineering and Design*, 125, 41-55.

Dameron, R. A., Rashid, Y. R. and Tang, H. T. (1993). "Leak Area and Leakage Rate Prediction for Probabilistic Risk Assessment of Concrete Containments Under Severe Core Conditions", *Proc. SMIRT-12*, Session H (H05/6), 181 – 185.

Dameron, R. A., Chang, P. and Bogage, A. (2012). "PCCV SPE3 Model 2 Results - Tech Memo" An interim report for SPE3 Round Robin Exercise, *www.sandia.gov/spe3*.

Greiner, U. and Ramm, W. (1995). "Air Leakage Characteristics in Cracked Concrete", *Nuclear Engineering and Design*, 156, 167 – 172.

Nagano, T., Kowada, A., Matumura, T., Inada, Y. and Yajima, K. (1989). "Experimental Study of Leakage Through Residual Shear Cracks on RC Walls", *Proc. SMIRT-10*, Session Q, 139 – 144.

Riva, P., Brusa, L., Contri, P. and Imperato, L. (1999). "Prediction of Air And Steam Leak Rate Through Cracked Reinforced Concrete Panels", *Nuclear Engineering and Design*, 192, 13-30.

Rizkalla, S. H., Lau, B. L. and Simmonds, S. H. (1984a). "Air Leakage Characteristics in Reinforced Concrete". *J. Structural Engineering*, ASCE, 110 (5), 1149 – 1162.

Rizkalla, S. H., Simmonds, S. H. and MacGregor, J. G. (1984b). "Cracking of P/C Nuclear Containment Structures", *J. Structural Engineering*, ASCE, 110 (9), 2148 – 2163.

Suzuki, T., Takiguchi, K., Hotta, H., Kojima, N., Fukuhara, M. and Kimura, K. (1989). "Experimental Study on The Leakage of Gas Through Cracked Concrete Walls", *Proc. SMIRT-10*, Session Q, 145 – 150.

Suzuki, T., Takiguchi, K. and Hotta, H. (1992). "Leakage of Gas Trough Concrete Cracks", *Nuclear Engineering and Design*, 133, 121 – 130.

Wang, T., Hutchinson T. C., Hamilton, C. H., Pardoen, G. C. and Salmon, M. W. (2004). "Gas Leakage Rate Through Reinforced Concrete Shear Walls: Numerical Study", *13th World Conference on Earthquake Engineering*, Canada, Paper No. 34.