A Simplified Approach for Predicting Containment Performance during a Severe Accident

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ABSTRACT

US Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research is conducting State Of the Art Reactor Consequence Analyses (SOARCA) for operating nuclear power plants in the United States. One of the inputs required for the consequence analysis is the containment performance over a range of internal pressure and temperature. In the past, individual nuclear power plant licensees have determined containment performance using different criteria and approaches to predict containment performance during a severe accident. This paper describes a simplified and realistic approach that can be used to predict the performance of pressurized water reactor (PWR) reinforced and prestressed concrete containments. This approach is based on the results of the NRC sponsored testing and analyses of containment models performed during the last 25 years at the Sandia National Laboratories (SNL), and testing by the Central Electricity Generating Board (CEGB) in United Kingdom.

INTRODUCTION

Extensive research and scale model testing of reinforced and prestressed concrete containments to determine behavior at beyond design basis accident pressure has been performed in the last 25 years at SNL [1] and CEGB [2]. Concrete containments start to leak before a complete rupture or failure. It is extremely difficult to accurately predict the location and leakage rate of the concrete containment due to beyond design basis internal pressure and temperature. Hessheimer and Dameron [1], and Dameron, Rashid, and Tang [3] provide guidance for predicting leak area and leak rate in containments. Hessheimer and Dameron [1] recommend a non-linear finite element analysis of the concrete containment to predict containment performance and leakage.

In the past, reactor severe accident progression analysis has often assumed that the concrete containment starts to leak through a small hole as soon as containment is pressurized. The area of the small hole is calculated based on nominal design leakage rate of 0.10 to 0.20 percent of containment volume per day at the design internal pressure. The area of the hole is assumed to remain constant until containment failure in the accident progression analysis. Results of concrete containment model tests [4, 5] indicate that leakage area increases appreciably with internal pressure. In addition, if the rate of pressurization is gradual and does not exceed the leakage rate, catastrophic failure of the concrete containment is not possible. This paper provides a realistic and simplified approach for predicting containment leakage rate that can be used in severe accident analysis.

REINFORCED CONCRETE CONTAINMENT TEST AND ANALYSES RESULTS

SNL tested a 1: 6 scale model of a representative PWR concrete containment in July 1987 [4]. Prior to performing the test, 10 international organizations performed an independent and separate (round robin) pretest analyses of the containment [6] to predict containment behavior. A summary of the round robin analyses and test results is presented in Table 1.

Hessheimer and Dameron [1] have concluded that global, free field strain of 1.5 to 2.0% for reinforced and 0.5 to 1.0% for prestressed concrete can be achieved before failure or rupture. In addition, leakage in concrete containment increases appreciably after the rebars and liner plate yield. Furthermore, under gradual increase in internal pressure, containment leakage continues to grow without failure and rupture. Using these criteria, containment failure and yield pressures were determined using the following simple equations. Containment failure pressure is defined here as the pressure when leakage is in excess of 100 percent of the containment volume per day. The results of these simple calculations, as shown in Table 1, are quite consistent with detailed finite element analyses using state of the art computer codes and test data.

$P_{fail} = (A_{hoop} * Y_{rebar@2\%} + A_{liner} * Y_{liner@2\%}) / R$

$P_{yield} = (A_{hoop} * Y_{rebar} + A_{liner} * Y_{liner}) / R$

Where:

P_{fail} = Containment failure pressure (containment leakage greater than 100 percent)
P_{yield} = Containment pressure at which hoop rebars and liner plate yield
A_{hoop} = Area of the hoop rebars
A_{liner} = Area of the liner plate
Y_{rebar} = Yield stress of the rebar
Y_{liner} = Yield stress of the liner plate
$Y_{rebar@2\%}$ = Stress in the rebar at 2% strain
$Y_{liner@2\%}$ = Stress in the rebar at 2% strain
R = Radius of the containment

The simplified analysis approach was then used to determine the behavior of three existing reinforced concrete PWR containments located in USA. The comparison of results using the simplified approach with information provided by three plant licensees in the Independent Plant Examination (IPE) reports is presented in Table 2. A review of this Table indicates that failure pressure predicted in the IPE reports for all three containments is 10 to 25 percent higher than the one obtained by simplified approach. Similarly, the pressure at which rebars and liner plate yield in the three containments, as reported in the IPE reports, varies from the simplified analysis by -4 to 40 percent. These differences in the predictions are similar to the ones reported by the round robin analysts for the 1:6 scale containment, and are due to the use of different analytical techniques and assumptions for failure criteria by licensees.

Table 1- Internal Pressure in 1:6-Scale Reinforced Concrete Containment at Initiation of Yielding and Failure

Source	Hoop Rebar and Liner Plate Yield MPa (psig)	Containment Failure MPa (psig) (Leakage >100%/day)
Round Robin Analyses (Maximum)	0.951 (138)	1.276 (185)
Round Robin Analyses (Minimum)	0.827 (120)	0.883 (128)
Round Robin Analyses (Average)	0.869 (126)	1.076 (156)
Test Data	0.820 (119)	1.00 (145)
Proposed Simplified Analysis	0.876 (127)	0.986 (143)

Table 2- Internal Pressure at Yield and Failure in Existing Reinforced Concrete PWR Containments

Item	Containment #1	Containment #2	Containment #3
Internal Pressure at Rebar and Liner Plate Yield from IPE Report MPa (psig)	0.758 (110)	1.000 (145)	1.248 (181)
Internal Pressure at Failure from IPE Report MPa (psig)	1.062 (154)	1.048 (152)	1.489 (216)
Internal Pressure at Rebar and Liner Plate Yield from Simplified Analysis MPa (psig)	0.779 (113)	0.848 (123)	1.062 (154)
Internal Pressure at Failure (Leakage > 100%) from the Proposed Simplified Analysis MPa (psig)	0.855 (124)	0.958 (139)	1.200 (174)

PRESTRESSED CONCRETE CONTAINMENT TEST AND ANALYSES RESULTS

SNL also tested a 1: 4 scale model of a PWR concrete containment in September 2000 [5]. Prior to performing the test, a round robin pretest analysis of the containment [7] was performed by 17 international organizations to predict containment behavior. A summary of the round robin analysis, test results, and results of simplified analysis based on free field strain of 1.0% for failure is presented in Table 3. The simplified approach for prestressed containment is similar to the one described above for reinforced concrete except that effect of prestressing steel is included in the pressure calculations.

Table 3 - Internal Pressure in 1:4-Scale Prestressed Concrete Containment at Initiation of Yielding and Failure

Source	Hoop Rebar and Liner Plate Yield – MPa(psig)	Containment Failure MPa (psig) (Leakage >100%)
Round Robin Analyses (Maximum)	1.248 (181)	1.979 (287)
Round Robin Analyses (Minimum)	0.855 (124)	0.814 (118)
Round Robin Analyses (Average)	1.034 (150)	1.413 (205)
Test Data	1.055 (153)	1.296 (188)
Proposed Simplified Analysis	1.062 (154)	1.331(193)

A review of the Table 3 indicates that there is a wide variation in predicted pressures by 17 organizations. The maximum predicted failure pressure is 2.4 times more than the minimum predicted failure pressure. However, the average round robin and the proposed simplified analysis predicted pressures are quite close to the pressures recorded during the test.

The simplified approach described above was then applied to the 1:10 Scale Sizewell B model. The results of proposed simplified analysis are compared with the 3-D finite element analysis and pressure test data in Table 4. The proposed simplified approach results closely match with detailed 3 dimensional non linear finite element analysis and test data.

Table 4 - Internal Pressure at Yield and Failure for the 1:10-Scale Prestressed Concrete Containment

Item	Test Result [2]	Proposed Simplified Approach	3-D Analysis [2]
Internal Pressure at Rebar Yield MPa (psig)	0.586 (85)	0.683 (99)	0.662 (96)
Internal Pressure at Failure MPa (psig) (Leakage > 100%)	0.772 (112)	0.738 (107)	0.738 (107)

CONTAINMENT LEAKAGE

The containment performance criteria used for severe accident analysis require prediction of leakage rate as a function of internal pressure and temperature. There is lack of experimental data for containment leakage beyond design pressure. Rizkalla et al. [8], Dameron et al. [3], and others have attempted to quantify leakage through concrete sections. This guidance cannot be used directly to determine leakage thru concrete containments in which steel liner plate is designed to act as a leakage barrier. Detailed 3-dimensional nonlinear analysis of the containments with equipment hatch and other penetrations is required to determine the local strains in the liner plate and concrete. The results of the 3-dimensional analysis can be used to determine airflow through the liner plate and containment concrete. All these complicated analyses will lead to leak rate predictions with large uncertainties due to variation in the properties of the materials, quality and porosity of welds, and concrete placement.

The relationship between containment leakage and internal pressures for reinforced concrete and prestressed concrete containment model tests from References 4 and 5 is shown in Figures 1 and 2 respectively. A review of these figures indicates that the concrete containments start to leak appreciably once the rebars have yielded or leakage rate is about

10 percent of the containment volume per day. Additional pressurization, after the rebars and liner plate yield, results in exponential increase in the leakage rate. Containment pressure does not increase significantly after leakage rate exceeds 100 percent of the containment volume per day. The liner welds and concrete crack after rebars and liner plate yields to create a path for leakage. The leakage occurs in areas such as equipment hatch, personnel airlocks and penetrations where local strains are substantially higher than the global strains.

The results in Figures 1 and 2 are for scale model tests of two concrete containments. Rebar and concrete crack spacing, and aggregate size can affect the leakage rates in full size containments. However, based on the results of testing and analyses presented above, it is reasonable to conclude that all containments start to leak once the rebars and liner plate yield. In addition, leakage becomes excessive once the strains in the reinforced and prestressed concrete containments reach about 2 and 1 percent respectively. Based on information of the containment model test results and analyses data presented in Figures 1 and 2, it is reasonable to assume that containment leakage of 10 percent of containment volume per day when rebars and liner plate yield. Similarly, leakage rate of 100 percent can be conservatively used in severe accident analysis when the containment global strains are 1-2 percent. Figure 3 shows the proposed relationship between leakage rate and internal pressure based on these assumptions. It is clear from Figure 3, that containment opening area (leakage) increases at a on a lognormal scale with pressure. Uncertainty in the leakage rate can be accounted for by using a variation of 50 percent in the rate as shown in Figure 3.

The location of the leakage can have a significant effect on the results of the severe accident analysis and dose rates. For instance, if the containment leakage occurs thru penetrations that are located inside adjoining plant buildings, the fission product release into atmosphere would be significantly less as compared to direct leakage to the environment. Previously, some of the severe accident analyses were based on the assumption that the leakage takes place at the top of the containment dome. A more realistic approach is to consider leakage to occur at equipment hatch and other penetrations as demonstrated by tests data, and non linear analyses.

CONCLUSIONS

The proposed simplified approach for predicting containment performance is an attempt to relate containment internal pressure to leakage rate. This approach has been developed by interpreting the results of the 25 years of testing and analyses of containments that was sponsored by NRC at SNL. Use of the proposed containment performance model will provide more realistic results as compared to the earlier approach used in the severe accident analysis. Further refinements to account for other parameters such as effect of leakage through containment bellows, equipment hatch and personnel hatch seals, rebar spacing, aggregate size on containment performance may be necessary if the results of the severe accident sensitivity analysis show that containment performance data has a significant impact on the final dose rate.

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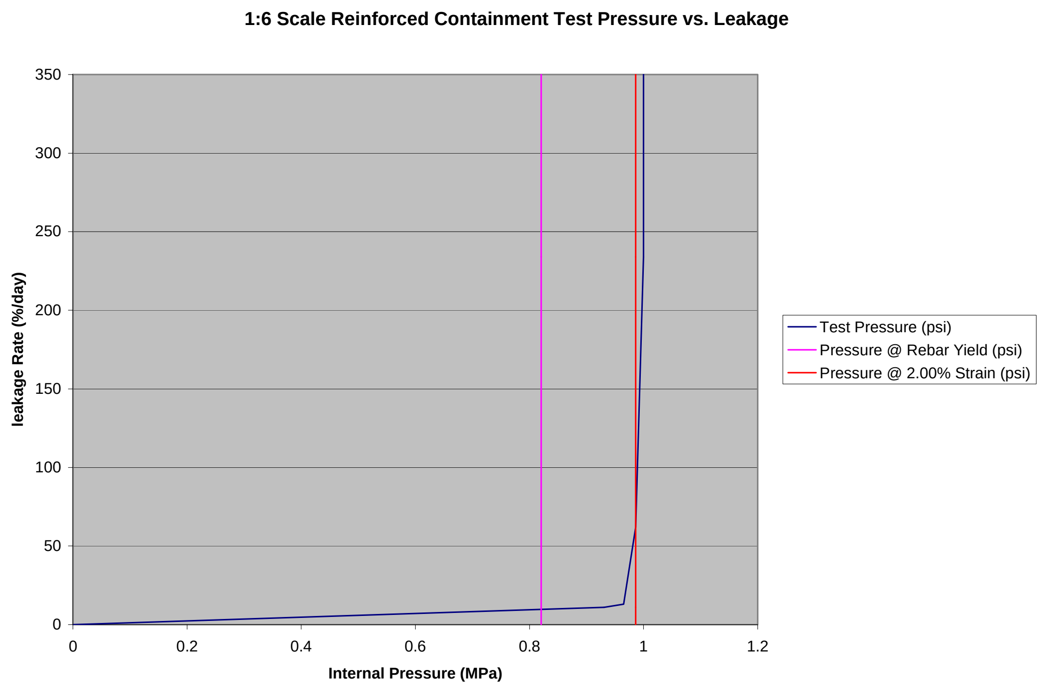

Figure 1

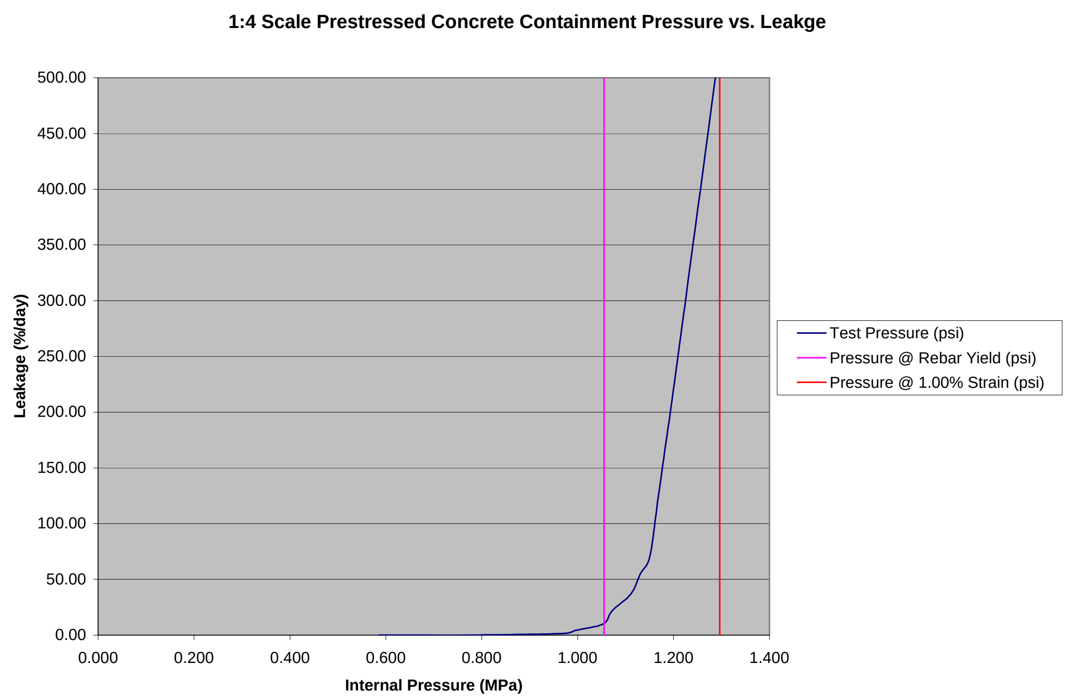

Figure 2

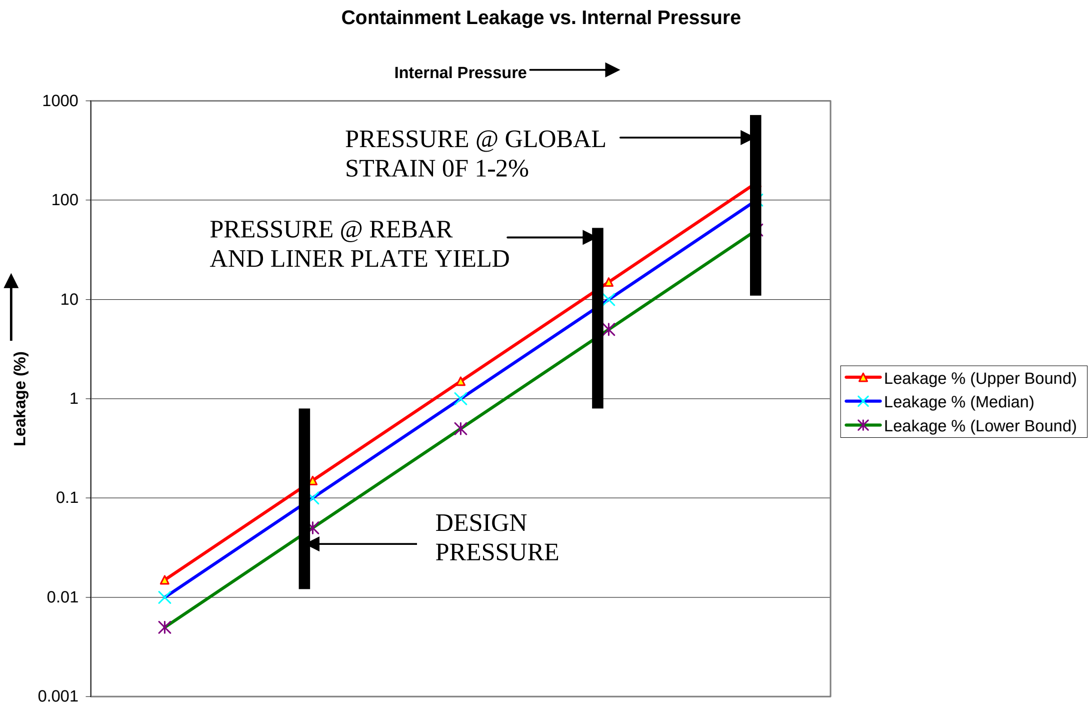
Containment Leakage vs. Internal Pressure
Internal Pressure
Leakage (%)
1000
100
10
1
0.1
0.01
0.001
PRESSURE @ GLOBAL
STRAIN 0F 1-2%
PRESSURE @ REBAR
AND LINER PLATE YIELD
DESIGN
PRESSURE
Leakage % (Upper Bound)
Leakage % (Median)
Leakage % (Lower Bound)

Figure 3