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

PREDICTING LEAK RATE AS A FUNCTION OF PRESSURE FOR PRESTRESSED CONCRETE PRESSURE VESSELS

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ABSTRACT

Based on the existing research of behavior of steel-lined concrete containments, liner-tearing with associated leakage is the expected failure mode for slow pressurization of the containment. Fracture and tearing of the steel shell is followed by leakage through the tear aperture, and then through cracks in the concrete. The strain-failure criterion is the primary method used for predicting such tearing based on its widely used application from previous analysis on concrete containment severe accident studies. This paper proposes advancing methods for the prediction of liner tearing to predicting performance (leak rate) beyond the initial tearing event. The formulation, which takes into account geometry considerations of liner tears, and a leak rate through aperture formulation put forth by Rizkalla, calculates leak rates which are reasonably close to those measured in the Nuclear Power Engineering Corporation (NUPEC)/United States Nuclear Regulatory Commission (USNRC)/Sandia 1:4 Scale PCCV test model [1]. A significant driver of the formulation is the strain concentration factor K. Such factors have been proposed in earlier research, but the current work proposes refinements. For instance, taking liner-weld-zone-defects into account by increasing the effective K, might improve predictions of leak rate versus pressure.

INTRODUCTION & BACKGROUND

In the late 1980s-1990s, extensive research conducted by an Electric Power Research Institute (EPRI) sponsored research program investigated the failure mechanism of concrete containments [2]. In parallel with this, USNRC-sponsored research at Sandia was in progress, including scale model tests of several steel vessels, and in 1987, the 1:6 Scale Reinforced Concrete Containment [3]. During that time, and with the further evidence from the 1:4 Scale prestressed concrete containment vessel (PCCV) Model in the late 1990s, it became clear that leakage would occur before a concrete containment “breaks”. Thus, the predominate failure mode for slow pressurization of concrete containment vessels with steel-liners is liner-tearing with leakage.

Some of the experimental evidence supporting the leakage prediction methodology was performed at Construction Technology Laboratories (CTL) in Skokie, Illinois [summarized in 3]. This EPRI test program included full-scale structural specimen tests of special regions of prestressed and reinforced concrete containments. Figure 1 shows the locations of the liner tears and distressed areas in several of these specimen tests: a wall-skirt-basemat region and wall specimens with penetrations from typical concrete containments. Correlation of measured strains to pre- and post-test analysis resulted in the development of geometry-specific strain magnification factor curves.

To investigate the effect of penetrations on the wall of the containment, two different types of wall penetrations were studied. One wall specimen, labeled as Specimen 2.4 in Figure 1 was loaded with a hoop to meridional stress ratio of 2:1 (i.e., pr/t versus pr/2t) plus an outward punch force. The presence of the penetration caused severe stiffness discontinuities. The specimen developed a large liner tear at the liner-penetration juncture at a far field strain across the specimen that corresponds to global failure in an actual containment. The second wall specimen, known as Specimen (3.2) simulates the case of a piping penetration that is restrained against axial motion, thus constraining a point on the containment wall. This and other test data from the EPRI program were 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.

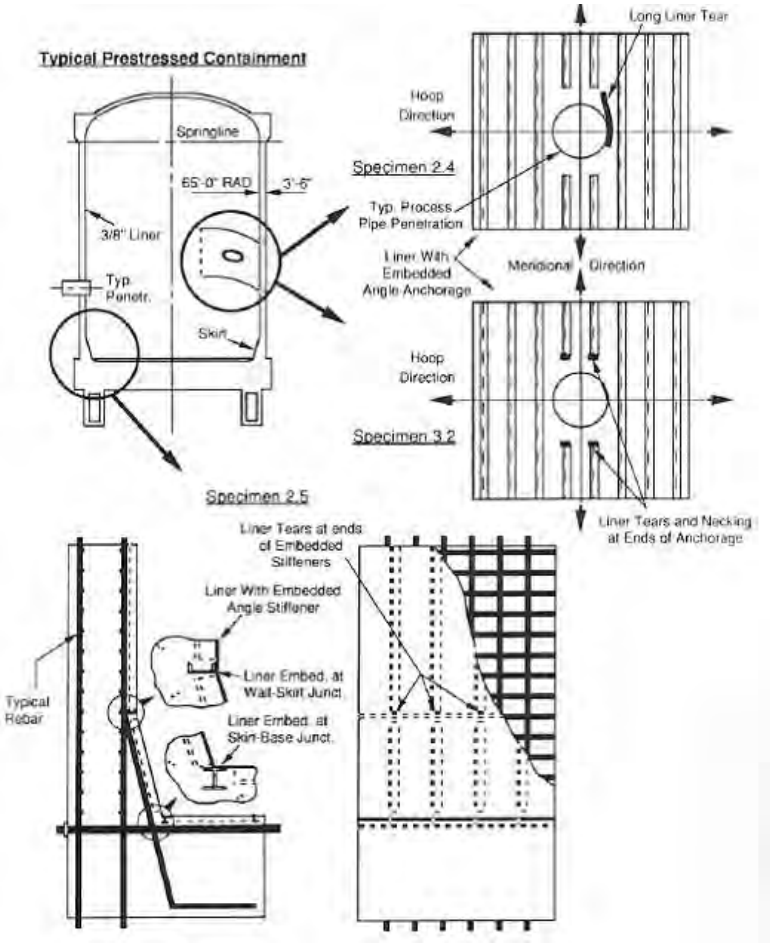

Figure 1. Liner tearing examples in EPRI/CTL tests [3].

The EPRI methodology, published in the early 1990s [4,5], was not advanced further for over a decade, but it has been revisited during post-test studies of the 1:4 Scale PCCV. One such study that was recently completed, known as the Standard Problem Exercise #3 (SPE #3) round robin analysis [6], involved participants from USA, India, UK, France, Germany, Sweden, Finland, and Japan, who each developed leakage prediction methodologies for PCCVs. The US Nuclear Regulatory Commission, Sandia National Laboratories (SNL), and Moffatt & Nichol applied the EPRI methodology, but also refined it. This paper addresses the methodology used to evaluate leakage and how it compared with the 1:4 Scale Sandia test.

PREDICTING LINER TEARING

During pressurization of the containment vessel, fracture and tearing of the steel shell is followed by leakage through the tear aperture, and then through crack in the concrete. Concrete cracks are certain to occur at containment wall strains large enough to tear the steel shell. To predict tears in steel shells consisting of plates, weld seams, stiffeners, and other details, two fundamental types of failure criteria are available: 1) strain-based failure criteria applied to unflawed steel material and components, and 2) fracture-based failure methods applied to postulated flaws, which are commonly found in welded steel structures. Both methods are appropriate to predict liner tearing, but require different sets of information needed on the material, the strain state, and the conditions surrounding a potential crack. Based on the information that is available, one method may be more advantageous to use. For concrete containment vessels undergoing severe accident analysis, the strain-base failure criteria is a good choice based on the vast amount of research on PCCVs using this approach. So, in this study, a strain-based failure criterion was applied to assess the initiation and propagation of cracks in the liner. The crack size is then used to determine leakage rate as a function of pressure.

CALCULATING LEAK RATES

The leakage phenomenon is shown schematically in Figure 2. Two steps beyond initial liner tear prediction are required: a. estimate tear sizes; b. estimate leak rate. For leak rate, several different numerical approaches have been studied and identified, but the Rizkalla formulation is selected to calculate leak rates through postulated liner tear areas [7].

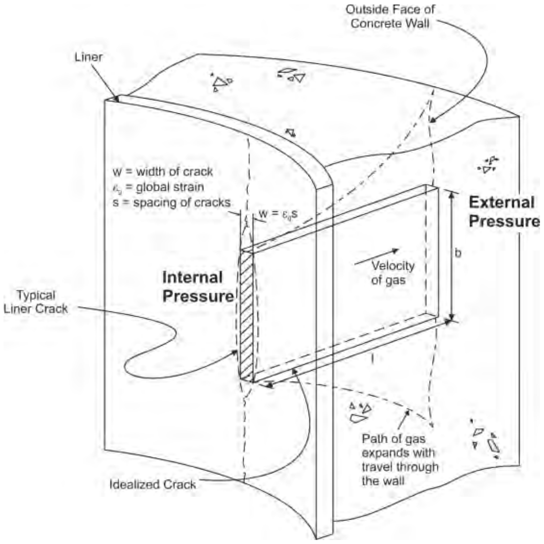

Figure 2. Idealization of flow of pressurized gas through a liner tear [4]

Liner Tearing Criteria

The calculation of local liner strain near discontinuities which cause liner tears requires very localized modeling of the liner, concrete, rebar, and liner anchorage using specialized material and computational models. While these techniques have been developed and extensively utilized, their use is not cost effective for examining all possible tearing locations of individual containments on a case-by-case basis. Instead, the aforementioned EPRI work developed a database of liner strain concentration factors (a fairly limited one) to construct a simplified analysis procedure for predicting leakage in concrete containments.

Separate sets of strain concentration factor curves (K) versus normalized global strain were developed. They are all based on a coordinated liner tearing criterion of the form:

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

Where ε_p is the equivalent peak uniaxial strain at a discontinuity location; this is the strain which is ultimately compared to uniaxial failure strain (max uniaxial elongation) obtained from liner coupon tests. K is the strain concentration factor, B is a stress biaxiality factor and ε_{global} is the global strain quantity that corresponds to the location where the local peak strain is being evaluated, in other words, the "driving strain" behind the concentrated peak strain. A quantity called "normalized global strain" is defined as:

$$\varepsilon_n = (E/\sigma_y)\ \varepsilon_{global} \qquad (2)$$

So ε_n is global strain, normalized to yield strain.

The tearing criteria itself is based on a multiaxial stress versus ductility formulation published by Manjoine [8], who cited tests on various ductile materials and proposed the following formula for the ductility ratio μ:

$$\mu = 2^{(1 - TF)} \qquad (3)$$

Where μ is the ductility (reduction) ratio and TF is the Davis triaxiality factor.

$$TF = \frac{\sqrt{2}}{- \qquad - \qquad -} \qquad (4)$$

But when the third principal stress is zero or nearly zero, as in the case of the containment liner,

$$TF = \frac{\sqrt{2}}{-} \qquad (5)$$

For instance when $\sigma_1 = \sigma_2$, TF = 2 and the ductility ratio is 0.5; i.e., failure strain reduces to half its uniaxial ductility limit. For the last two decades, many containment analysts have used this criteria for predicting onset of liner tearing; most have concluded that the criteria is reasonable, but that there is also extensive judgment involved in its application. Strains predicted by finite element models can be highly dependent on the level of detail (and mesh refinement) included in the model. And, as was seen in the 1:4 Scale PCCV Model, the existence of flaws in the material (especially at weld seams) mean that tears might occur at strains significantly lower than the absolute ductility of the material.

With this formula it is straightforward to calculate ductility ratios at various liner stress states. For example, for uniaxial tension, $\sigma_2 = 0$, TF =1, ductility ratio = 1. For $\sigma_1 = \sigma_2$ (the approximate stress condition in the containment dome), TF =2, ductility ratio = 0.5, which means that the liner will tear at an effective plastic strain of half the uniaxial failure strain. This range of application of Eq. (4) is plotted in Figure 3 with additional ductility versus biaxial stress data added from literature surveys. This forms the basis of the tearing criteria and the basis for defining the factor B. Although biaxiality effects are typically characterized as reducing ductility, the approach used for this methodology is a strain magnification approach. Therefore, the reciprocal of the ductility ratio is used to magnify the strain. This has been labeled the biaxiality coefficient (B), and for containment liners, under the assumptions of the above discussion it is a number ranging from 1.0 (perfectly uniaxial stress state) to 2.0 (1:1 biaxial stress state, $\sigma_3 = 0$). In other words,

$$B = \frac{\quad}{\quad} = - \qquad \text{where } 1.0 \leq B \leq 2.0 \qquad (6)$$

K is then defined to be a strain concentration factor associated with the stiffness discontinuity geometry.

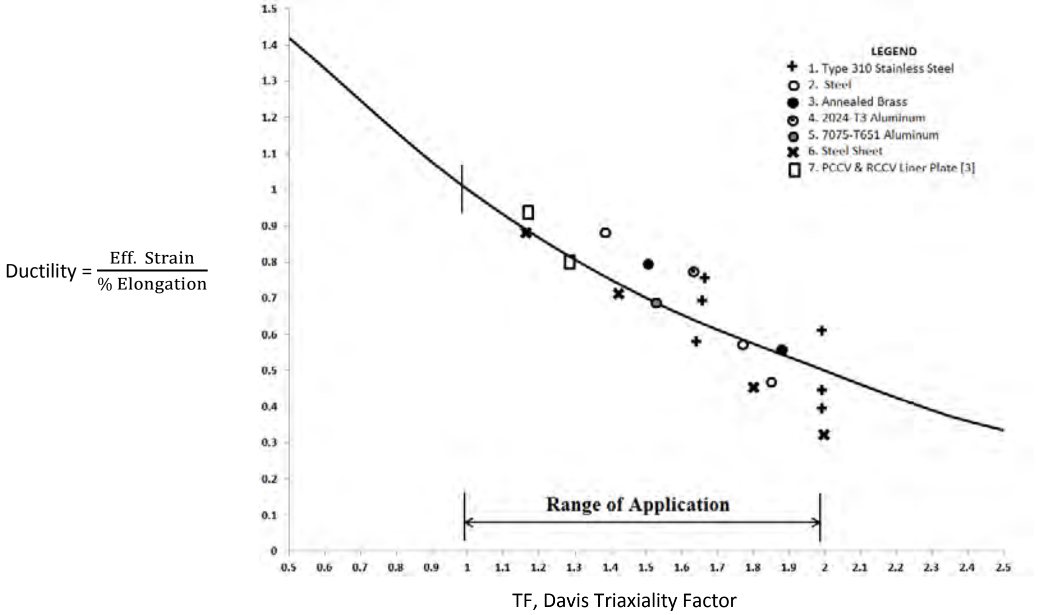

Figure 3. Reduced version of Manjoine's multiaxial failure criteria, relating to containment liners

Five fundamental strain concentration factor curves developed in the EPRI program for typical locations of concrete containment vessel liners are shown in Figure 4. An additional curve for typical penetrations of a reinforced concrete containment vessel is also shown in Figure 4. It can be noted in all these curves that from global strain equals zero, out to just past yield, the curves have quite similar shape. Several of the curves begin in the range of strain concentration factor (K)=10, then gradually increase as the locally intensified strain causes the material to yield and plastifies while the global, driving strain remains elastic. After the onset of global yield, the ratios tend to flatten out, because the material is fully plastic, both globally and locally. It also should be observed that, as a practical matter, the curves need only be considered out to normalized global strain of approximately 10 (red vertical line in Figure 4), i.e., global strain of approximately 1.9% (Equation (2), E=200GPa or $29\text{x}10^6$ psi and σ_y =380MPa or $55\text{x}10^3$ psi). No tested concrete containment vessel model has survived beyond this level of global strain without tearing the liner. After global strain begins to yield, the strain concentration versus global strain stabilizes within a range of approximately 17 to 30 (Figure 4), with an average of approximately K=25. For our proposed simplified approach to leakage prediction, this defines the shape of the K-curve. We believe that combining the strain concentration factor trends into one curve is within the range of uncertainty appropriate to the data available.

A. Liner Tearing to Tear Size

The standarized strain concentration curve proposed for strain concentration locations in PCCVs, is shown in blue in Figure 4. This curve is proposed for application to all liner strain concentration locations as follows:

1. Vertical weld seams straddle by horizontal stiffeners with a "rat-hole[1]"; based on observations from the PCCV test, the vertical extent of these affected areas will be 4 times the horizontal dimension of the rat-hole. (In the case of the PCCV 1:4 Scale Model, the rat-hole dimension is 35mm.)

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[1] A "rat-hole" is a construction detail where a perpendicular stiffening plate includes a cutout to facilitate welding of a joint.

2. Vertical weld seam adjacent to E/H, Airlock, Mainsteam, and Electric Feed Penetrations.

Knowing the tear length, the next step is to obtain a tear area through which leakage occurs. There are various methods put forth by researchers for computing crack widths. The most basic method uses the formula:

Crack width = strain x crack-spacing (for example, [9]) (7)

A simplified approximation of liner crack-spacing is the spacing between anchors. Strain is based on the formulated equivalent peak strain. Based on the Sandia PCCV 1:4 Scale Model material tests, when the equivalent peak strain reaches 21%, a tear is likely to occur.

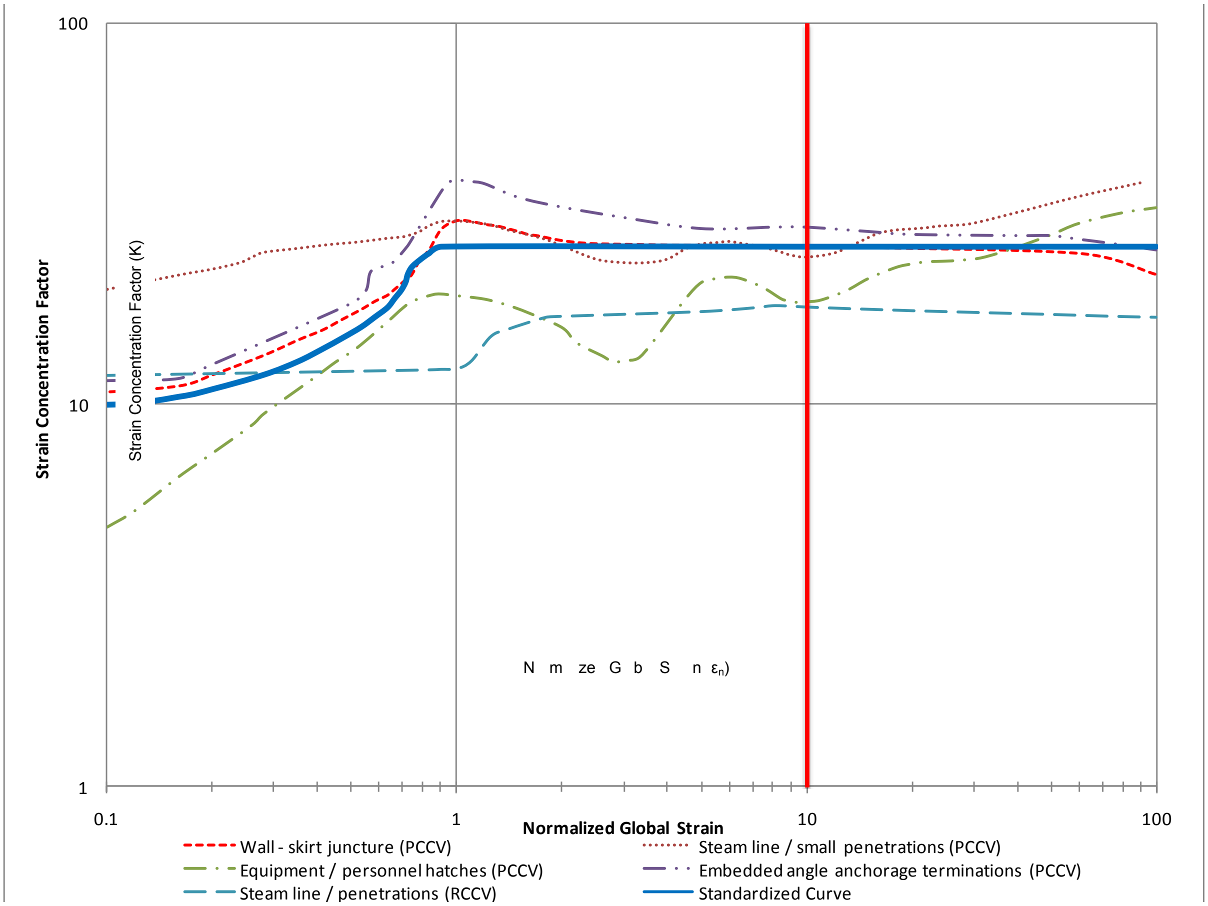

Figure 4. Strain concentration (K) factors at various locations around the PCCV

B. Tear Size to Leak Rate

Using the Rizkalla formulation, the leak rate can be predicted. The Rizkalla equation is as follows:

$$\frac{p1^2 - p2^2}{t} = \left(\frac{k^n}{2}\right)\left(\frac{\mu}{2}\right)^n (RT)^{n-1}\left|\frac{p2Q}{B}\right|^{2-n}\frac{1}{\sum_{i=1,j} Wj^3} \tag{8}$$

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

$$n = \frac{0.133}{(\sum Wj^3)^{0.81}} = \frac{0.195}{(NWav^3)^{0.063}}$$

Where,
Q = flux through the wall (m^3/s or ft^3/s),
B = crack length (m or ft),
W = crack width (m or ft),
t = wall thickness (m or ft),
p1 = upstream pressure (Pa or psi),
p2 = downstream pressure (Pa or psi),
μ = dynamic viscosity of air or gas used (1.983×10^{-5} kg/m-s or 3.94×10^{-7} lbf-s/ft^2 at 300° K or 100° F),
T = absolute temperature (°K or °R),
R = specific gas constant for dry air (287.058 J/kg-°K or 1716.49 ft-lbf/°R-lbf-slug), and
W_{av} is the average crack width of the total concrete section of interest.

STEPWISE APPROACH FOR LEAKAGE VERSUS PRESSURE

The 1:4-Scale model was analyzed through the full range of applied pressure, but key results were extracted at various pressure milestones. A matrix of an unwrapped view of the liner surface was created, outputting results every 4.8-degrees and approximately at elevations of 1.1 feet apart, beginning from the bottom of the vessel to the top of the dome. To predict leakage rate due to pressurization, the approach based on the strain-based failure criteria outlined in the previous section is applied in an example. For illustration, ABAQUS results from [10] for the 1:4-Scale PCCV at 3.3xPd will be used. To predict tearing of the liner, the global strains are transformed (Eq. 1) to an equivalent peak uniaxial strain at a discontinuity location, and this forms the basis of computing tearing. Global strains of the liner are taken directly from ABAQUS; they are mapped and illustrated by color-coding in Figure 5 for the entire surface of the liner. To demonstrate the numerical computations, an area near the E/H is used.

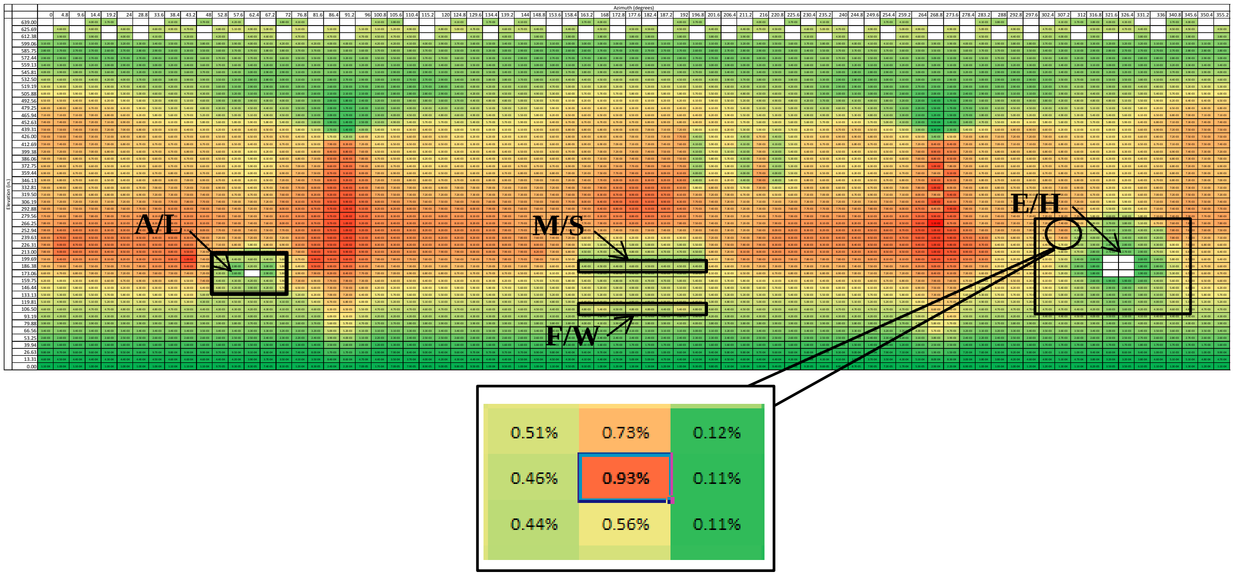

Figure 5: Liner strain map of entire surface at 3.3xPd

At 3.3xPd, the global strain at a specific location near the E/H is highlighted in Figure 5; $\varepsilon_{global} = 0.0093$. To obtain the peak strain, several strain concentration factors must be calculated. As mentioned earlier, the tearing criteria is based on a multi-axial stress versus ductility formulation. To calculate TF, the maximum and minimum in-plane principal stresses are obtained, in this case, σ_1 = 429 MPa (62,264 psi) and σ_2 = 237 MPa (34,388 psi), respectively. Substituting into Equations (5) and (6), TF = 1.79 and μ = 0.58, respectively. This leads to a biaxiality coefficient, B = 1.73. K is calculated by global strain divided by the normalized yield strain. The normalized yield strain, based on material properties (E = 195GPa or 28310ksi and σ_y = 376 MPa or 54.55ksi) is 0.0019. The global strain divided by the normalized yield strain gives a normalized global strain of 4.83. Entering Figure 4, K = 26. Therefore, the equivalent peak strain is 0.42.

As mentioned previously, when strain exceeds, 0.21, tearing occurs. Since 0.42 > 0.21, tearing has occurred. The Rizkalla method estimates leakage through a concrete section based on the crack width. Crack width depends on the spacing of anchors. Overlaying the anchor details onto the liner surface, as shown in Figure 6, average anchor spacing in the zone of interest is determined for the entire liner surface. Highlighted in green, i.e. opening locations, anchor spacing is approximately 15 cm (6 inches). Orange colored areas indicate a spacing of 45 cm (18 inches). Taking the equivalent peak strain and multiplying by the anchor spacing, the average crack width is 1.828 mm (0.072 inches).

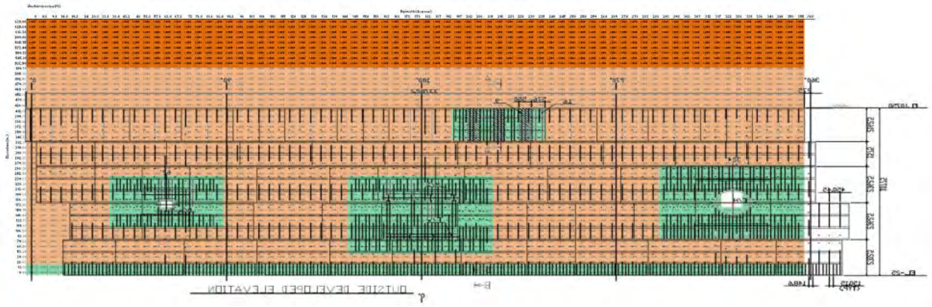

Figure 6. Mapping of anchor spacing of entire liner surface

Using Equation (8) and back-solving for Q, gives a leakage rate of 0.0136 m^3/s (0.48 ft^3/s). Summing all values across the entire liner surface, gives a leakage rate of 2.26 m^3/s (80 ft^3/s). The mapping of the liner surface at 3.3xPd, is shown below. Areas that are colored indicate places where the liner is torn and leakage occurs.

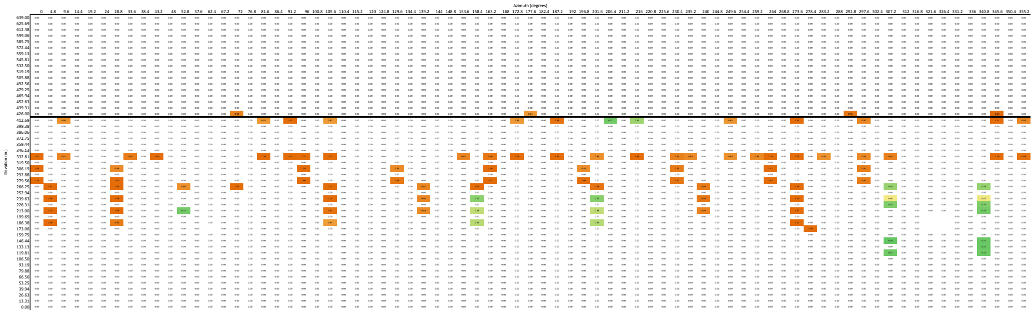

Figure 7. Mapping of Leakage Rate of Entire Liner Surface at 3.3xPd

INCLUDING EFFECTS OF DEFECTS ON LEAK RATES

As demonstrated, liner cracks are driven by liner hoop strain, magnified by a local strain concentration factor, K, and biaxiality factor, B. But the stiffness discontinuities associated with K almost always occur coincident with weld-seams (such as stiffener “rat-holes” or penetrations or embossments). Furthermore, defects in material and construction play a role in the occurrence of tears. This is summarized in the following excerpt from [10]:

"All of the 16 tear locations observed were near weld seams, with some variations in the presence or configuration of a rat-hole. Liner welding irregularities were present at almost all of the tear locations. These irregularities included points of extensive repair, such as grinding, points of discontinuous or missing back-up bars, or points with weld and liner seam fit-up irregular geometry."

The liner weld irregularities in the 1:4 Scale PCCV model have been well documented [11], and are summarized as follows:

- Visual observation showed extensive grinding and weld repair in the liner welds where most of the tears occurred. Ultrasonic measurements showed substantial reductions in thickness near these tears. Measurements showed ~23% thickness reductions in many locations, and more (up to 40% in a few locations). Several instances were found in which the liner adjacent to repair welds had been completely ground through and subsequently repair welded to provide pressure boundary integrity.
- Localized plastic deformation occurred in association with many of the vertical field welds, particularly in the vicinity of the tears. No evidence of brittle fracture was seen.
- Photos of the back side of the liner revealed irregularities (missing segments of back-up bars, discontinuous horizontal stiffeners) associated with a number of the tears.
- Mechanical testing showed only small strain localization in the heat affected zones – much less than observed in the liner base metal. Ultimate strength (~496 MPa or 72 ksi) was not degraded by welding.
- No evidence was found of material problems that could account for the premature tearing of the liner. Only one tear was associated with a weld defect. This was a lack-of-fusion defect, not porosity in the fusion zone.
- Metallography showed that nearly all of the tear areas had been ground at least 23%, both in preparation repair welding and followed repair welding. The report [11] concluded that most of the tears can be attributed to this excessive grinding.

RESULTS

Similar plots to Figure 5 and Figure 7 were completed to determine the leakage rate at various pressure milestones, and these are combined and plotted in Figure 8. The Figure also compares results found during the test study of the 1:4 Scale PCCV analysis. The comparison shows reasonably good agreement at Pressure 3.3xPd between the measurements and the methodology presented herein.

At pressures between 3.1xPd and 3.3Pd, the method somewhat under-predicts leak rate; the authors believe this may be related to the aforementioned liner welding and grinding issues. One way of incorporating defects is to modify K. For the 1:4 Scale PCCV analysis, grinding and inconsistent back-up bars, etc. have the effect of increasing "K". If, for example, we were to multiply "K" by 2, only for the locations where severe liner thinning or other defects were observed, we would get the second curve (green) shown in Figure 8, that for "flawed liner". This approach is promising but requires more test data to refine the method and the assumptions for "K".

CONCLUSION

This paper extends existing methods for the prediction of liner tearing toward predicting performance (leak rate) beyond the initial tearing event. The formulation, which takes into account geometry considerations of liner tears, and a leak rate through aperture formulation put forth by Rizkalla, calculates leak rates which are reasonably close to those measured in the NUPEC/USNRC/Sandia 1:4 Scale PCCV test model. A significant driver of the formulation is the strain concentration factor K. Taking liner-weld-zone-defects into account by increasing the effective K, might improve predictions of leak rate versus pressure.

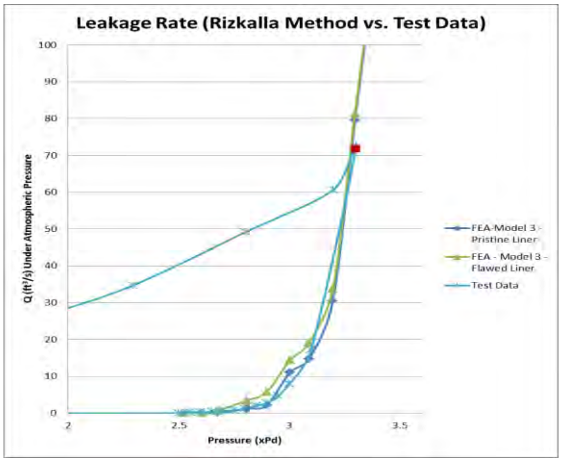

Figure 8. Leakage rate comparison with pristine liner and with K factor adjusted for "flawed" liner

ACKNOWLEDGEMENTS

This report was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the U.S. Nuclear Regulatory Commission.

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