Appendix D

Leak Rate vs. Crack Length Calculations

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D.1 Introduction

In order to establish the sequence of events associated with the wastage, it is necessary to determine the coolant leakage rate as a function of crack size. Exponent used a three step process for determining the flow rate through the crack:

1. Determination of pressure drop and velocity through an ideal isentropic nozzle
2. Determination of the effective cross-sectional area of the crack
3. Determination of a pseudo discharge coefficient relating the flow rate through the actual crack to the flow rate through an ideal isentropic nozzle.

D.2 Determination of Velocity through an Ideal Isentropic Nozzle

The conditions directly upstream of the crack (2165 psi and 605 ˚F) are known, and it is possible to determine the flow rate through an ideal nozzle. The upstream pressure of the nozzle (2165 psi) is much larger than that of the ambient conditions (14.7 psi) so the flow through the nozzle will be choked. This means that the pressure at the exit of the nozzle will be higher than ambient pressure downstream of the nozzle and that the flow rate is independent of the down stream pressure as long as the downstream pressure is less than the choked nozzle exit pressure.

The flow through an ideal nozzle is isentropic (no heat addition or viscous losses). For isentropic flow through a constriction, as the downstream pressure is decreased, the velocity through the constriction will increase until a maximum value is encountered. In our calculations, the pressure at the exit of the crack was lowered, while re-calculating the local flow conditions, until a maximum velocity was found. The calculation showed that the downstream pressure for this choking condition is equal to the pressure at which steam begins to flash. For isentropic flow this corresponds to a pressure of 1550.7 psi at the local throat temperature of at 600.6 ˚F.

Because the temperature at the throat is not much different from that of the stagnation condition (605 ˚F), it is possible to approximate the pressure at the crack exit as the flashing pressure of water at the stagnation temperature. The flow remains in the liquid phase (with very little change in density) from the stagnation location to the crack exit, allowing the use of the Bernoulli flow equation (based on incompressible fluid flow) to approximate the flow rate through the ideal nozzle. This approach was used by DEI[1] and B&W[2]. For the Davis Besse conditions, this approximation gives a flow rate value that is 95.6% of the flow rate calculated using the full isentropic solution.

D.3 Crack Area and Geometry

Once the driving pressure differential is determined, the flow rate through an ideal nozzle scales directly with the nozzle area. The crack maximum width and surface area was determined using the Zahoor crack growth model[3]. The Zahoor model provides the crack area, and it is assumed that the crack opening area can be idealized as a very thin ellipse, allowing the calculation of the crack width as a function of crack height. The Zahoor model is based on the deformation of a crack on a pipe due to the stresses induced by the pressure differential across the pipe walls. The resulting cracks show a width to height ratio, which ranges from 0.0004 to 0.0006, depending on the crack height. The crack width values calculated range from 4 to 26 μm, for crack heights in the range of 0.4 to 1.8 in. The model also predicts that the crack gap completely closes for crack heights of 0.15" or less.

D.4 Discharge Coefficient

The flow rate through the actual crack will be less than the flow through an ideal nozzle of equivalent cross-sectional area, and will depend on the crack geometry and surface roughness. Compared to an ideal nozzle of the same cross-sectional area, a crack may only be able to flow 15% or less[4] of the maximum ideal flow rate. This drastic reduction in the flow is due to viscous losses along the crack channel. The ratio of real crack versus ideal nozzle flow rate can be determined via a pseudo-discharge coefficient, K, which is in turn based on the amount of friction though the crack.

Two approaches are used in the literature to determine the flow friction, and therefore K, through a non-ideal crack of a certain roughness and passage length:

1. It is possible to solve the friction pipe flow equation through the crack passage assuming incompressible liquid flow and either a laminar or turbulent friction coefficient. The flow rate through the passage can therefore be determined. This methodology was used in a previous failure analysis by B&W Nuclear Technologies[5]. Their method assumes that the local properties of the fluid remain unchanged through the crack and the pressure gradient across the gap can be modeled as that of turbulent pipe flow.

2. The friction coefficient across slits and cracks, as a function of slit geometry and surface roughness can be empirically correlated based on the ratio of measured flow rates through cracks of known geometry to the calculated flow rate through an ideal isentropic nozzle. This approach has been employed by several researchers, and the friction is normally a function of the crack geometry and surface roughness.

Both of the above methodologies are based on the crack width and passage length. In order to correctly determine the true flow rate through the crack, it is therefore necessary to determine the crack geometry.

Several different K-versus-crack-size relations[6,7,8] have been reviewed by Exponent. Regardless of the relation employed, the value of the K factor is difficult to estimate when the opening area becomes small relative to the surface roughness or the tortuosity of the channel.[9]

D.4.1 Dominion K Model

A previous study on the Davis Besse CRDM leak rates by Dominion Engineering[10], utilized a pseudo-discharge coefficient obtained from a study of leak rates through steam generator tubes[11]. Steam generator tubes have an OD ranging from 11/16" to 7/8", while the current CRDM nozzles have an OD of 4". The Davis Besse CRDM nozzles have wall thicknesses of 0.625", larger than the radius of the steam generator tubes described, so that the crack passage lengths through the tube wall will be very different in both cases. Since the friction losses, and therefore the value of K, will depend on the passage length through the crack opening, it is not clear if the empirical relation employed by Dominion is valid in this alternate geometry.

D.4.2 John et al. K model

The empirical relation derived by John et al.[12] allows the definition of a friction factor, ζ_c, as a function of crack size and surface roughness. A pseudo-discharge coefficient can, in turn, be calculated from the friction factor as: $K = \sqrt{1/(1+\xi_c)}$.

Their relation has been validated for subcooled flashing water flow over a range of slit widths from 200 μm to 640 μm, and surface roughness ranging from 5 μm to 240 μm, with a crack/slit passage length of 46 mm (1.81 in). The friction coefficient through the channel is based on the passage-length-to-width and width-to-roughness ratios, allowing the extension of the correlation to thinner cracks with shorter passage lengths.

The John model was validated using artificial and actual cracks with a lower surface roughness to crack width ratio than observed in the Davis Besse crack. The real cracks were generated using cyclic bending, which is expected to generate crack morphologies different than intergranular stress corrosion cracking observed at Davis Besse. The John model was not validated for cracks where the average roughness was larger than the measured crack opening. Nonetheless, the John model produces K factors similar to those used by DEI.

An upper bound of the surface roughness of nozzle #3 cracks would be ½ the grain size. The ASTM 3 grain size leads to 60 μm roughness, relative to the maximum calculated 26 micron crack width. Photographs of the crack show that the local roughness of the crack flow channels is significantly less than the grain size, and that the grain size instead is related to the tortuosity of the crack as the crack follows a zig-zagged pattern along grain boundaries.

Because the measured grain size of the crack is larger than the actual crack opening, it is not possible to use this measured roughness directly. In the present calculation an effective roughness factor, for use in the John et al. relation, was calculated by fitting the flow rate through the 1.83" long crack (nozzle #3, crack 1 at the later stage) to the 0.17 gal/min expected leakage. This results in an estimated surface roughness factor of 5 μm. This 5 μm effective roughness was therefore employed to predict the K factors at other crack sizes.

Figure D.1 shows a comparison between the K factors determined using the Dominion and John et al. relations at different crack sizes. The figure shows how the discharge coefficient is lowered as the crack height is reduced. When K goes to zero, there is no flow out of the crack. This condition is reached for the John et al. mode when the crack height is equal to 0.45". The Dominion equation allows the no-flow condition to be reached at 0.3". The flow rate for cracks larger than these critical value will rapidly grow due to the increase in crack area, coupled with the increase in K.

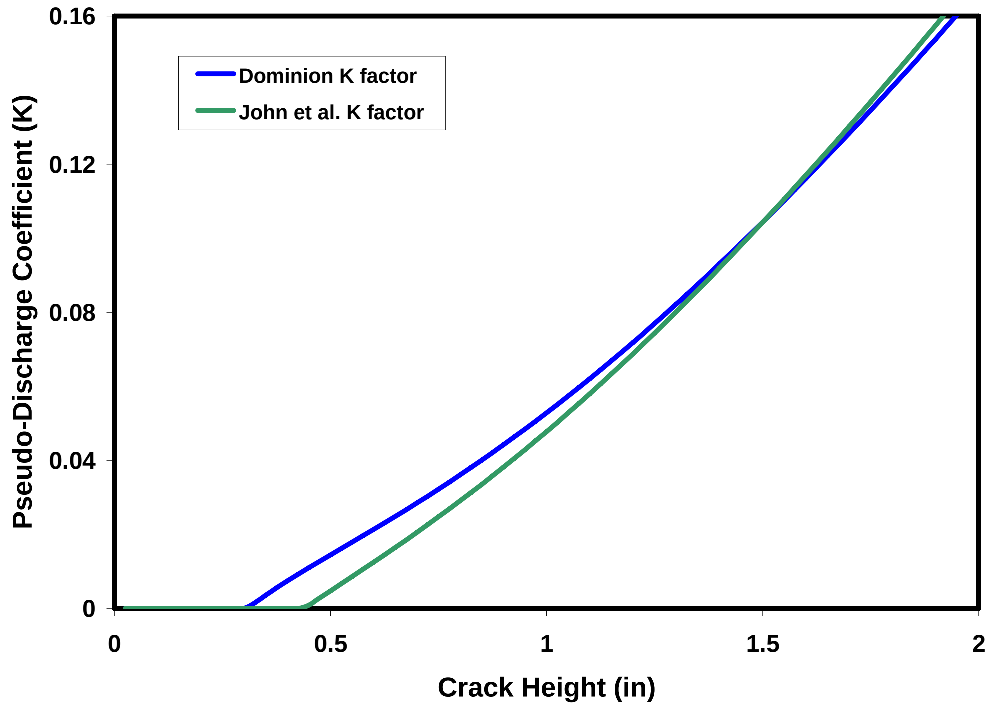

Figure D.1 Calculated pseudo-discharge coefficients versus crack heights for an elliptical crack

Figure D.2 shows the flow rate through the crack as a function of crack size for an ideal nozzle, and using the Dominion or John et al K factors. The two relationships are almost identical for the larger crack sizes. The flow rate correlations start to diverge in the region of small crack size, with the John et al. correlation predicting the flow rate decreases more rapidly as the crack size decreases below 0.5”. Both relationships indicate that elliptical cracks with heights < 0.5” will have leak rates under 0.001 gpm.

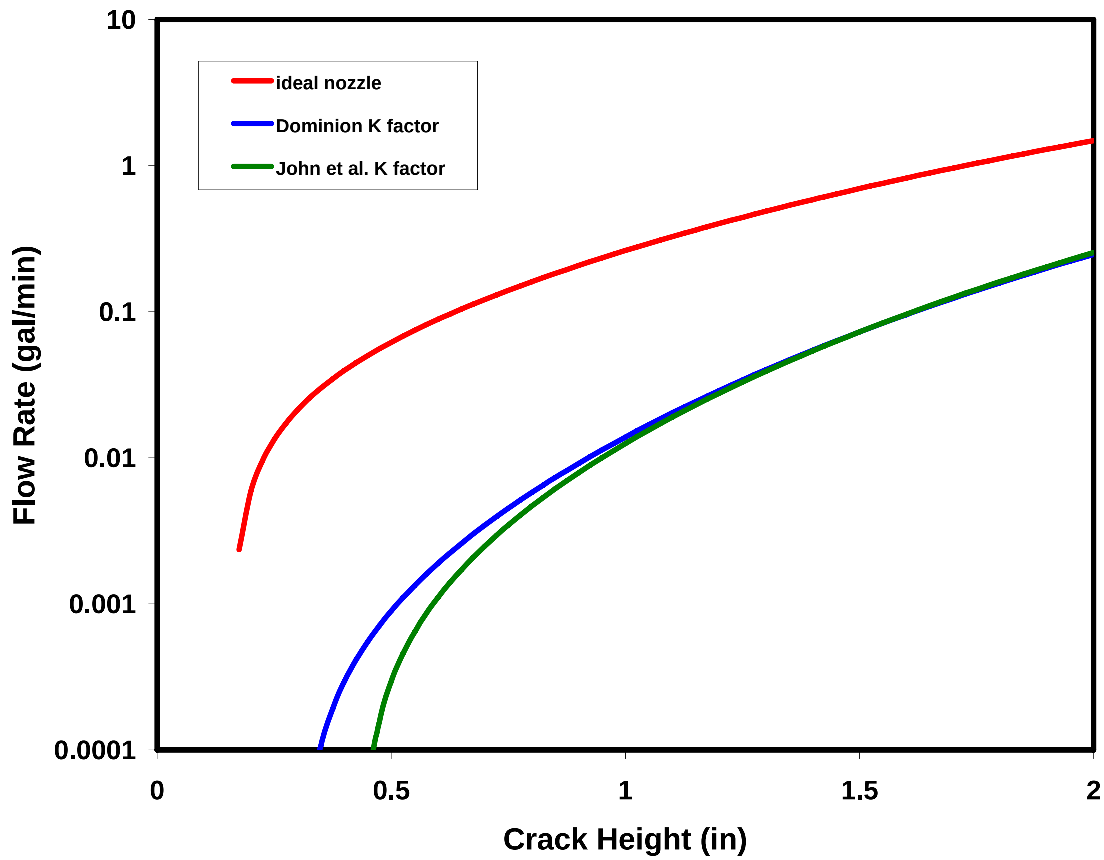

Figure D.2 Calculated flow rates versus crack heights for an elliptical crack

D.5 Calculation details for flow rate and exit conditions through idealized nozzle and crack

The reactor vessel pressure (2165 psi) and temperature (605 ˚F) upstream of the nozzle through-wall crack was used to calculate the mass flux of a two-phase flashing stream through an ideal (isentropic) nozzle, giving a maximum value of 76,450 kg/s.m^2. The actual mass flux through the crack is calculated using a discharge coefficient that accounts for non-idealities in the flow through the actual crack. Although the saturation pressure, and therefore the flashing conditions at the crack exit will depend on the crack geometry, the flow rate through the crack can be obtained using simplified a pseudo-discharge coefficient to account for the presence of a boundary layer (which limits the effective crack area) and the pressure drop along the crack passage (which reduces the flow rate at the crack exit). Depending on the crack size, the actual mass flux through the crack size varies from 0 to 11,000 kg/s.m^2.

The calculated exit pressure of the crack corresponds to the saturation pressure (1550 psi), where liquid begins to flash to vapor. As the jet of liquid exits the crack and enters the cavity in the reactor head, it will partially flash and expand as the pressure decreases to the pressure in the cavity. This expansion of the jet of fluid exiting crack was calculated isentropic expansion of the mixture to atmospheric pressure. Although there will be a finite time required for the flow to expand to ambient conditions, there is no available data on the characteristic flashing time of such jets; an assumption is thus made that the flashing of the liquid occurs instantaneously at the exit of the crack. The velocity, cross sectional area, and steam quality of the jet, when expanded to 1 atm, was then used as an inlet condition for the CFD model. The expanded jet consists of a high-speed (684 m/s) stream of wet steam (35% steam quality), 1 atm and 212 ˚F. The velocity of the expanded jet is not directly dependant on the crack size, and is only slightly dependant on the discharge coefficient. The discharge coefficient, which accounts for friction along the crack channel, will reduce the kinetic energy of the flow exiting the crack. Most of the final kinetic energy per unit mass, however, is due to the rapid expansion or flashing of the two-phase fluid from the crack face to atmospheric conditions, which is modeled as an isentropic expansion. The velocity of the two-phase fluid a few millimeters away from the crack will, however, be affected by the crack size, since the larger cracks will require a longer distance for the momentum to be dissipated into the surrounding volume.

As an example, the conditions at the exit of the crack (after expansion to 1 atm), provided as an input to the CFD model, for a crack flowrate of 0.17 gal/min are as follows:

- total mass flowrate = 0.0107 kg/s
- P_{out} = 1 atm
- $density_{mix}$ = 1.718 kg/m^3
- $density_{liq}$ = 958.1 kg/m^3
- $density_{gas}$ = 0.598 kg/m^3

- $temp_{mix}$ = 373 K
- $velocity_{mix}$ = 684.4 m/s
- $area_{gasinlet}$ = 9.11 x 10^{-6} m^2
- $area_{liquid\ inlet}$ = 1.07 x 10^{-8} m^2

D.6 Correlation of flow rate with crack size

A flat plate crack growth model was initially employed to obtain the width and area of the cracks as a function of their length. This model, however, was shown to give very large crack areas, which resulted in calculated flow rate values that were much higher than the historical coolant leak rates calculated by Davis Besse. The Zahoor crack growth model was used in order to provide a correlation of crack width with crack length. The crack area was determined assuming an elliptical-shaped crack. The cracks were assumed to extend into the weld area, and the full ellipse area was defined to be part of the crack exit. In our analysis, an assumption is made that the crack cross-sectional area is constant throughout the wall of the tube. The crack widths and areas calculated using the Zahoor model are:

$a_{nw} := aa \cdot f_W$

Nozzle	Crack No.	Effective Crack Length, 2a, **With Ratioed Weld Length** a_{nw} = (in)	Approximate Crack-center Opening Width w (in) $\overrightarrow{\delta\left(\frac{a_{nw}}{2},\sigma\right)}$ =	Approximate Crack Opening Area COA (in^2) $\overrightarrow{COA\left(\frac{a_{nw}}{2},\sigma\right)}$ =
1	7	0.91	0.0023	0.00164
2	2	1.33	0.0034	0.00352
2	4	0.06	0.0002	0.00001
2	6	0.92	0.0023	0.00170
2	8	0.39	0.0010	0.00030
2	10	0.74	0.0019	0.00111
2	13	1.23	0.0031	0.00302
3	1	1.83	0.0047	0.00670
3	4	0.63	0.0016	0.00080

Figure D.3 Crack sizes based on Zahoor model

The Dominion calculation K requires only the crack width, although it also depends on the crack passage length. The dominion relation is:

$$K(cw) := 0.6 \cdot \left[1 - \exp\left[-300 \cdot \left(\frac{cw}{in} - 0.00012 \right) \right] \right]$$

Figure D.4 Dominion relation for determining the pseudo-discharge coefficient

The relation derived by John et al. allows the definition of a friction factor, ζ_c, as a function of crack size and surface roughness. A pseudo-discharge coefficient can, in turn, be defined as: $K = \sqrt{1/(1+\xi_c)}$. The John et al. function for the friction factor is as follows:

$$\xi_c = 0.5 + \left(3.39 \cdot \log \frac{d_H}{R} - 0.866\right)^{-2} \cdot \frac{L}{d_H}.$$

Figure D.5 Calculation of friction factor for flow through a slit

Where d_H is the hydraulic diameter, L is the passage length through the crack or slit, and R is the surface roughness. It is important to note that this relation has been experimentally verified for crack widths much larger than the surface roughness. Our calculated crack widths are on the order of 25 microns or less. The surface roughness input should therefore be below this value, in order for the correlation to make sense. As a first approximation, a roughness factor for use in the John et al. relation was calculated by making the florate through the 1.83” long crack (nozzle #3, crack 1 at the later stage) be equal to the 0.17 gal/min expected leakage.

The roughness factor calculated in this manner is unfortunately much smaller (5 micron) than that expected from the crack surface evaluation (ASTM 3 grain size leading to 60 micron; about half the grain size).

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