Introduction

The potential impacts of climate change have caused an increase in the popularity of nuclear energy this century. With the increased number of nuclear plants comes an increased risk of a meltdown causing radioactivity to spread far outside the confines of the plant. Concrete containment buildings ensure radioactivity does not spread far in the event of an accident. Understanding how much material would leak from them when cracked allows plant operators to determine when a containment structure needs to be repaired due to an unsafe amount of radioactive material going out, preventing unnecessary repairs or replacements when leakage is negligible which will extend the service lives of containment buildings and save on costs. The leakage rate also allows us to understand when hazardous levels of radiation will reach the outside world, helping prepare evacuations when necessary.

As a result, much research has been devoted to leakage through concrete walls, particularly cracked walls to determine how much radioactive gas would leak in the event of a meltdown and to determine the safest possible materials for a containment building. This paper is intended to provide a summary of existing research regarding gas flow through cracked concrete walls and to determine where future research on the subject may be needed.

Pressure Differential

All papers found except Mishra et al. (2016) agreed that flow rate was linearly proportional to the pressure difference between outside and inside the specimen. Lee & Park (2024) found a coefficient of determination (R^2) of 0.67 to 0.96. Rizkalla et al. (1982) found its modified pressure gradient P'' (see glossary) to be linearly proportional to flow rate per unit crack length.

Mishra et al. (2016) noted that the relation is linear when permeability is the dominant source of flow, becoming nonlinear as cracks begin to form. I have not determined why this paper disagrees with the rest, though I suspect it could be related to there not being a clearly favourable path.

Tailhan et al. (2020) found that using pressures at both ends rather than internal pressure for

Picandet et al. (2019) noted apparent gas permeability k_A is inversely proportional to both pressure differential and volumetric flow rate, though this inverse proportion is only linear for pressure in laminar and slip flow. The opposite is true for the relation between k_A and flow rate (Picandet et al. 2019).

Wall characteristics

The aggregate grading curve has no noticeable impact on leakage when reinforcement is present (Greiner & Ramm 1995).

Stronger concrete had less leakage (Soppe et al. 2008). Same effect applies to mortar (Ismail et al. 2006).

The relation between l/w ratio and leakage is half-logarithmic with leakage decreasing as l/w increased. There is a sharp decline at l/w = 3, believed to be the result of the flow becoming turbulent (Buss 1972).

When height/length ratio <= 2 for a shearwall, flow rate increases with increased length (Wang 2008).

Wall thickness

Wall thickness is inversely proportional to leakage (Okamoto et al. 1995), though Nagano et al. (1989) has shear stress/strain equations where that thickness has an exponent attached (1.96 for strain, 2.53 for stress).

"The ratio of leakage rate change to wall thickness change (δQ/δt) increased at higher gauge pressure (1.3-1.6x greater at 80kPa than at 40kPa)" (Lee & Park 2024). When plate thickness increased 75 to 100 mm, leakage decreased 91%, from 100 to 150 mm it decreased 50% (Lee & Park 2024).

Crack spacing increases linearly with the increase in wall thickness with a 0.5 slope (Wang 2008).

Reinforcement

Leakage rate per unit crack length decreased with an increased reinforcement ratio, though part of this was attributed to narrower cracks: From 0.7% to 1.3%, it decreased 90%. From 1.3% to 2.0%, a 50% decrease was observed (Lee & Park 2024).

Horizontal reinforcement ratio (perpendicular to the force applied) does not affect flow as much as vertical reinforcement ratio. The amount the reinforcement ratio affects flow declines as it increases, except when forces are high.

When concrete is uncracked, flow is dominated by voids near reinforcing steel, causing flow to increase with more reinforcement. This effect increases at high water saturation until even the steel-concrete interface also gets filled with water. Equivalent crack properties to these voids can be found by measuring airflow (Sogbossi et al. 2017).

Using threaded roads instead of a bar does not affect leakage (Dury 2018).

Crack characteristics

When the first cracks form, permeability increases 10-50 or 40 times (Soppe & Hutchinson 2008, Girrens & Farrar 1991). Hamilton et al. (2004) stated 400 times, but the comparison was not equal.

Uncracked behaviour can not be exhibited once a crack has been formed, even when the specimen is compressed (Bruce et al. 2022, Dury 2018). When lateral displacement increases past 25 µm (15 µm residual when load is removed), crack width begins to increase (Picandet et al. 2019).

Segmented tube systems were noted to be significantly less airtight than continuous (Park et al. 2013). Flow in steel-lined tubes appeared to be controlled by the liner's cracks with concrete being damaged first, suggesting a steel liner would increase strength (Hanson et al. 1987, Acharya et al. 2013).

Flow rate is proportional to the cube of crack width (perhaps average crack width) (Bruce et al. 2022). Lee & Park (2024) found each specimen's coefficient of determination (R^2) was different, with one specimen as high as 0.91-0.94 and another as low as 0.58-0.71. Bruce et al. (2022) noted that flow rate is not always proportional to the cube of crack width (agreeing with Lee & Park (2024)). Crack width of multiple cracks can be approximated for use in equations: $\Sigma W_i^3 = 1.42NW_{avg}^3$ (Rizkalla et al. 1984).

Dury (2018) found a linear relationship between crack width and flow rate.

Leakage went up geometrically when cracks "widened and increased in number" (Okamoto et al. 1995).

Tortuosity and a high Reynolds number decrease leakage rate (Dury 2018, Niklasch et al. 2005). Crack geometry has a greater impact when cracks are narrow (<50 μm) while its impact is nonexistent at higher crack widths (>140 μm) (Tailhan et al. 2024).

Flow rate is linearly proportional to crack length.

Aerosol-specific flow

Flow rate declines with bigger aerosol particles (Dury 2018). Aerosol flow can be very turbulent, preventing equations for air from working well with aerosols (Wang et al. 2024). This is different from air flow, which is usually turbulent or assumed as such (Ismail et al. 2006) Aerosol retention appeared stable with changes in Reynolds number (Wang et al. 2024).

Forces and Temperature

Flow rate is proportional to shear stress to the power of *n*, where *n* is 3.84 (Nagano et al. 1989).

Flow rate is proportional to shear strain to the power of *n*, where *n* is 1.77 (Nagano et al. 1989).

A greater number of load cycles increases leakage (Soppe et al. 2008).

Concrete expands when it is heated, causing cracks to decrease in size which will decrease leakage (Herrmann et al. 2017).

Equations and their Reliability

For the most part, equations overestimate leakage when uniaxial tests are conducted. Rizkalla et al. (1984) or a Suzuki et al. (1989, 1992) formula was most accurate. A Rizkalla model was found to be able to give a flow rate with a 20% error for cracked mortar (Ismail et al. 2006).

Lee & Park (2024) noted the Suzuki et al., Rizkalla et al., and Greiner & Ramm equations generally overestimate leakage for uniaxial tests. Lee & Park (2024) credits this firstly to the equations' assumption of uniform crack width, which the paper noted was lower near the reinforcing steel where the crack width is more important in determining leakage. When crack width at the reinforcement was estimated from reinforcement strain, Rizkalla et al. (1984) was close. Roughness and the uncertainty of a crack's full penetration also impact the leakage rate predictions from the existing equations (Lee & Park 2024).

For both uniaxial and biaxial tests, Greiner & Ramm (1995) and Nagano et al. (1989) vastly overestimated the leakage (16-93x for uniaxial, 3-15x for biaxial). For uniaxial specimens, Rizkalla et al. (1984) does so to a lesser degree. The Suzuki et al. (1989, 1992) models were closest to accurate, with the 1989 formula having results that are 0.6 to 3.0 times the experimental flow rate (Soppe & Hutchinson 2012). All formulae made the best estimates at the highest and lowest load steps, with the worst estimations being around $P/P_0 = 2.00$. For biaxial specimens, Rizkalla et al. (1984) appeared to be the best while Suzuki et al.'s models underestimated flow slightly (Soppe & Hutchinson 2012).

Wang & Hutchinson (2005) found that Suzuki et al. (1992) and Rizkalla et al. (1984) most closely matched the experimental data, with Suzuki et al. (1989) underestimating leakage and Nagano et al. (1989) generally overestimated with a high amount of uncertainty. This was similar to the result in Soppe et al. (2012), though in that case experimental flow rates appeared higher as Suzuki et al. (1989, 1992) were closest to accurate.

Suzuki et al. (1989, 1992) were tested on pressures below 0.2 bar. These equations are good in low pressures—particularly those below 0.2 bar—but underestimated flow at higher pressures (Riva et al. 1999, Mishra et al. 2016). Rizkalla et al. (1984) performed well in higher pressures and overestimated at lower pressures (Mishra et al. 2016).

Greiner & Ramm (1995) noted its equation and others overestimated leakage when reinforcement was added. Riva et al. (1999) noted the overestimates from this equation are likely the result of it testing on higher pressures (1-8 bar) and not taking dynamic viscosity into account. Badoux (2002) found Greiner & Ramm (1995) worked best with crack widths below 0.3 mm, while Suzuki et al. was best above 0.3 mm.

Bahr & Sievers (2017) found with a Vercors experiment that equations taking Reynolds number into account (Rizkalla et al. (1984), Gelain (2012)) were most accurate, though all overestimated the leakage.

List of Equations

Crude Poiseuille equation: $Q = \frac{W^3 \Delta P}{12\mu T}$ (Suzuki et al. 1987).

Formulae using pressure difference:

- Buss (1972): $V_{L2} = \frac{\Delta P(2+\frac{\Delta P}{P_2})b\, W_1^3 g}{300L(1+\frac{\Delta P}{P_2})\gamma_2 \upsilon_1}$
- Nagano et al. (1989) for shear stress: $q = C\Delta P\frac{\tau^n}{t^m}$, where C = 2.27 x 10^{-4}, n = 3.84, m = 2.53, ΔP is measured in mmAq, τ is measured in kgf/cm^2, and Q is in L/(min*m^2).
- Nagano et al. (1989) for shear strain: $q = C\Delta P\frac{\gamma^n}{t^m}$, where C = 236, n = 1.77, m = 1.96.
- Nagano et al. (1989) for crack characteristics: $Q = LW^3\frac{\Delta P}{12\mu t}$, where Q is measured in cm^3/s, L and W are measured in cm, and μ is measured in gf/cm^2.
- Suzuki et al. (1987a): $\alpha_1(W) = 0.0034(60W + 0.9)$, where $Q = \frac{\alpha_1(W)W^3\Delta P}{\mu T}$.
  - Suzuki et al. (1987b) noted a_1 actually varies depending on your concrete mix.
- Suzuki et al. (1989): $Q = \alpha_1\frac{W^3(P_1-P_2)}{\mu t}b$, where b is total measured crack length, μ is dynamic viscosity of air, and α_1 is empirically derived. $\alpha_1 = \frac{1}{12\bar{\alpha}}$, where $\bar{\alpha} = \frac{6.5*10^{-4}}{W} + 1$, where W is avg crack width.
- Suzuki et al. (1992): $Q = \alpha_2\frac{W^3(P_1-P_2)}{\mu t}b$, where $\alpha_2 = 15.3W + 0.00756$.
  - Crack width 0.102-0.508 mm, Pressure 13.7-103.4 kPa, flow rate 9.8-295.0 cm^3/s

Formulae using squared pressure difference:

- Buss (1972): $\frac{P_1^2-P_2^2}{2P_1} = \lambda\frac{Lv_1\gamma_1}{d*2g}$, where v_1 is the inlet flow velocity, $\lambda = \frac{1200}{Re}$ for .01 < Re < 10^2, γ_1 was gas' specific gravity, and d is hydraulic diameter. $\lambda_{BS} = \frac{1200\upsilon}{v_1 d}$ where υ is kinematic toughness.

- Rizkalla et al. (1982 & 1984): $\frac{P_1^{\,2}-P_2^{\,2}}{L} = \frac{k^n}{2}(\frac{\mu}{2})^n(RT)^{n-1}(\frac{Q_2 P_2}{B})^{2-n}\frac{1}{\sum_{i=1}^{N} W_i^{\,3}}$
    - based on experimental data, $k = 2.907 * 10^{-7}(\Sigma W_i^{\,3})^{0.428}$, $n = \frac{0.133}{(\Sigma W_i^{\,3})^{0.081}}$.
    - Equivalent crack width: $\Sigma W_i^{\,3} = 1.42 N W_{avg}^{\,3}$. Equations can be modified appropriately.
- Suzuki et al. (1989): $Q = \frac{\sqrt{a(W)^2+4b(W)CW^3}-a(W)}{2b(W)}$, where $C = \frac{(P_i^{\,2}-P_o^{\,2})}{2\rho_0 P_{atm} T}$.
    - For this experiment, $a(W) = \frac{12(4.33*10^{-5}W^{-1.5}+1)\,\mu_0}{\rho_0}$, $b(W) = \frac{3.41*10^{-4}}{W}$
    - *A* and *b* will vary depending on which concrete is used.
    - Specifically applies when pressure is within 20% of atmospheric and flow is laminar.
- Used in Okamoto et al. (1995):
    - $Q = \frac{100}{H} V \frac{P_2 T_1}{P_1 T_2}$, where *V* is in litres, H is in hours, and Q is in L/h.
    - $Q = aA\Delta P^{\frac{1}{n}}$, where *a* is a coefficient in (h^{-1} m^{-2} $(mmAq)^{-1}$), *A* is in m^2, *P* is in mmAq, and $1 \leq n \leq 2$.
- Greiner & Ramm (1995): $Q_2 = ((P_1^{\,2} - P_2^{\,2})B^2W^2\frac{RT*2W}{P_2^{\,2}*\lambda L})$
    - $\lambda = (\frac{0.105k^{0.409}}{W})^{(1/(1.739ln(k/0.414)))} + 0.20k^{0.3043} - 0.024$
- Ismail et al. (2006) for laminar flows: $Q_2 = \frac{4(P_1^{\,2}-P_2^{\,2})BW^3}{P_2 L\mu k}$, where k = $0.0523W^{1.716}$.
- Gelain (2012): $w = (\frac{\lambda Q^2 L_w(1+\xi)RT}{a^2*2(P_i^{\,2}-P_o^{\,2})})^{\frac{1}{3+2b}}$, where λ is friction loss coefficient, and based on the experimental date a_1 = 1205000, a_2 = 3558000, b_1 = b_2 = 1.357.
- Tailhan et al. (2023a) for realistic cracks: $\frac{P_j^{\,2}-P_i^{\,2}}{l} = \frac{8RT}{b^2 w_h^{\,2} M}(\frac{2f}{w_h} + \frac{1}{l}ln(\frac{P_i}{P_j}))Q^2$

Other Formulae:
- Tinkler et al. (1987) [27]: $Q = \Sigma G_j B_j W_j$, where *j* is a subshell of the structure, G is mass flow rate per unit area ($G = p_{o,e}\sqrt{\frac{k}{RT_0}}M_e(\frac{2+M_e^{\,2}(k-1)}{2})^{\frac{k+1}{2(1-k)}}$ for adiabatic flow), B total is crack length, W is crack width.
- Picandet et al. (2009): $\frac{1}{k_A} = \frac{1}{k_V} + Q(\frac{\beta M P_{atm}}{RT\mu A})$, where *M* is gas molar mass, β is a constant (m^{-1}).
    - $k_{v0} + k'_v = k_v$; $k'_V = \frac{\xi w^3}{\Delta*12}$ where ξ is a roughness reduction factor.
    - Derivative equation for k'_v: $\frac{k'_V(d)}{k_{V0}} = 1 + \frac{\xi(\gamma\sigma_{res})^3}{k_{V0}\Delta*12}$
    - ξ can not be accurately determined, but it is higher in HPC i.e. less rough cracks. HFPRC is rougher but not as much as ordinary concrete.
- Mishra et al. (2016): $\dot{m}_{Pe} = \sqrt{\frac{\gamma}{RT_i}}P_i A_i M_i$, where *i* refers to inlet, $\dot{m}_{Pe}$ is mass flow rate through penetration, M_i is mach number calculated from Fanno flow tables

- This paper used a mathematical model which used this as well as Rizkalla, Nagano, Suzuki.
- Wang et al. (2023) for aerosols: $-ln(P) = e^{-6.1}((\frac{Q}{A})^2 d^2 C_c)^{-2.68\eta^2+6.75\eta-3.52}$, where η is the tortuosity.

Data Reliability

Leakage measurements were less reliable when leakage was low (Nagano et al. 1989, Lee & Park 2024).

Conclusion

Studies of gas leakage through concrete are studied in this review. Most papers agree that pressure differential is linearly proportional to leakage rate and all agree a proportional relationship exists. The relationship between l/w ratio and leakage rate is decreasing as l/w increases and is half-logarithmic. Wall thickness is inversely proportional to leakage, though to what exponent the proportionality is varies in the literature. With increased reinforcement, leakage decreased but the percentage decrease declined as more reinforcement was added. Reinforcement was more effective parallel to the applied force than perpendicular to it. While reinforcement decreases leakage through cracks, it increases leakage through uncracked concrete due to voids forming on the concrete-rebar interface.

When a crack forms, permeability increases 10-50 times and uncracked behaviour can not occur even when the cracked concrete is compressed. Flow rate is linearly proportional to the crack length and cube of crack width, though the coefficient of determination for this relation varies from 0.58 to 0.94. Tortuosity and high Reynolds numbers lead to a decreased flow rate, but this primarily affects large particles. Particles under 50 micrometres are not affected by crack geometry, while aerosols are not impacted by crack geometry. Aerosols have a significantly lower flow rate than air and air equations can not be used for them. Shear stress and strain are proportional to flow rate, though the exact correlations are stress and strain to the powers of 3.84 and 1.77, respectively. Temperature increases causing expansion which reduces crack size.

Various equations have been proposed using this information, and several papers found analyzed the accuracy of these equations. Most find Rizkalla and Suzuki to be the best equations, with Suzuki working best under low pressure (<0.2 bar). Meanwhile, the Greiner & Ramm (1995) equation was generally found to be an overestimate while the Nagano et al. (1989) equation was found to be unreliable. The differences in reliability suggest that none of the existing equations are ideal and a new equation taking both low pressures and high pressures into account would be more accurate.

Separate from accuracy in air tests, the equations found did not appear to take aerosol particles into account despite the particle size in aerosols having a major impact on leakage. This is particularly important considering fission products are released as aerosols (Huang et al. 2025). The data relating to aerosols should be further developed to find an equation so leakage of fission products can be better understood.

Glossary of terms

- τ - Shear stress
- $f = 24/Re$
- γ - Shear strain ($*10^{-3}$)
- H - Time

- A - Wall area
- R - Gas constant
- M - Molar mass
- t - Wall thickness
- L - Crack length
- W - Crack width
- ΔP - Pressure differential
- P'' - Modified pressure gradient as used by Rizkalla et al. (1982) -> $P'' = C|\frac{P_2 Q_2}{B}|^{2-n}$, where C is a constant equal to $(\frac{k^*\mu}{2^*2})^n (RT)^{n-1} (\sum_{i=1}^{n} W_i^3)^{-1}$.
- P - Absolute pressure
    - P_g - Gauge pressure
- T - Absolute temperature
- V - Volume (usually of testing chamber)
- Q - Volumetric flow rate
- q - Flow rate per unit area
- μ - Viscosity
- C_c - Cunningham slip coefficient
- η or ξ - Tortuosity
- Constants: C, n, m, k.

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