Hele-Shaw Cell of Varying Thickness for Modeling of Leakage Pathways

EGU2020-10609

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Introduction

- Canada is the fourth largest producer of natural gas
- 98% of the national production of natural gas takes place in the provinces of British Columbia (BC) and Alberta
- A recent study shows that 28.5% of the wells drilled since 2010 in BC have exhibited wellbore leakage

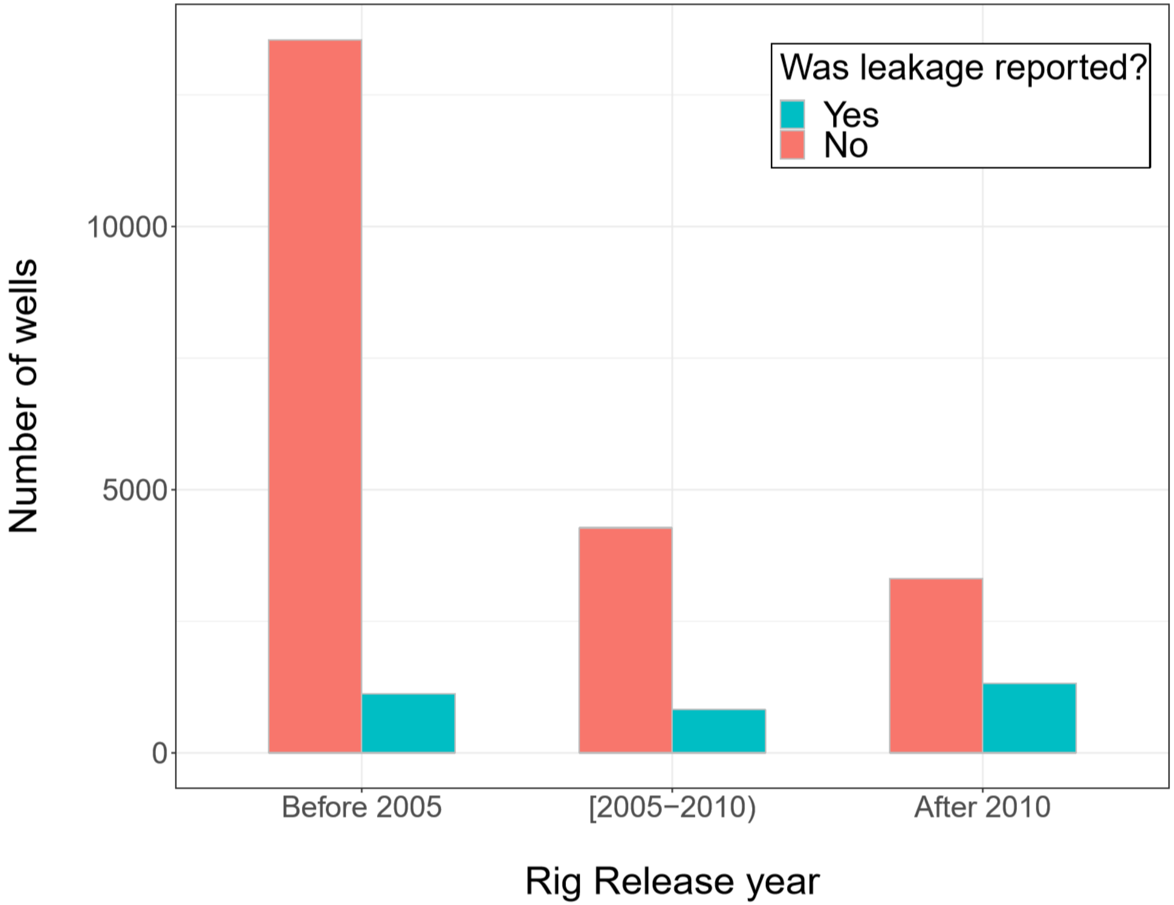

Figure 1: Incidence rate of wellbore leakage in BC [1]

Wellbore leakage

- Unwanted flow of hydrocarbons from the reservoir or other hydrocarbon bearing formations along the wellbore
- Surface casing vent flow (SCVF): leakage occurs through the surface casing vent assembly
- Gas migration (GM): leakage occurs through a permeable formation or pathways intersected by the well

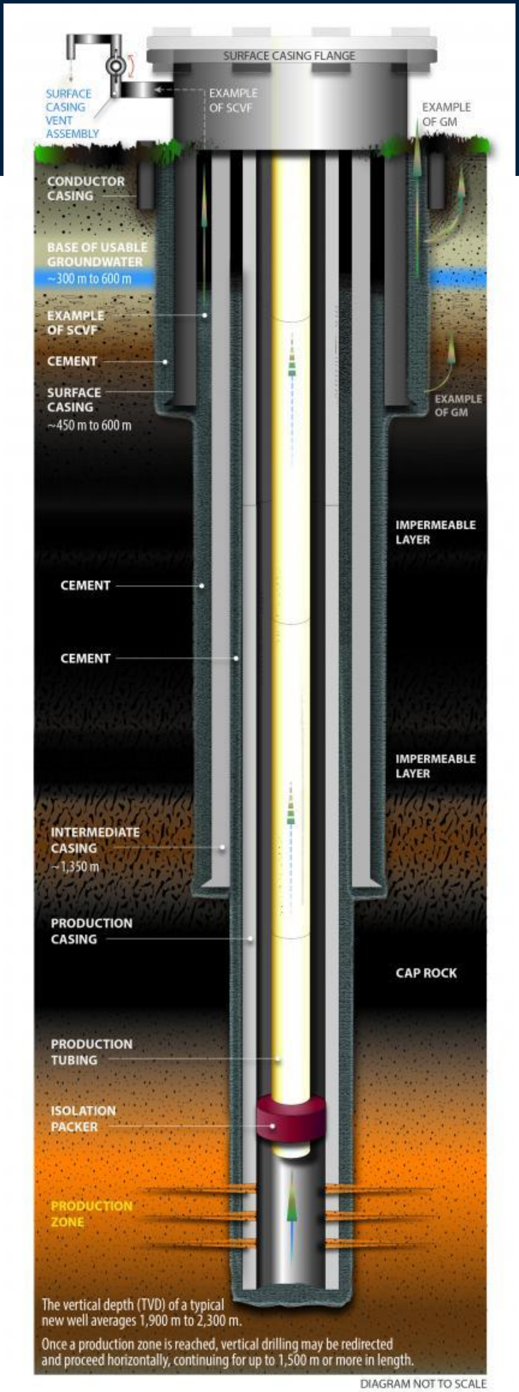

Figure 2: Schematic of wellbore leakage [2]

Leakage pathways

- Wellbore leakage occurs through pathways found in the cement sheath
- Microannulus
  - at the cement/casing interface (a,b)
  - at the cement/formation interface (f)
- Cracks (e)
- Cement sheath (c)
- Microannuli can be created due to
  - Cement shrinkage (dry microannulus)
  - Debonding due to temperature or pressure cycling in the well (dry microannulus)
  - Poor mud displacement during primary cementing (wet microannulus)

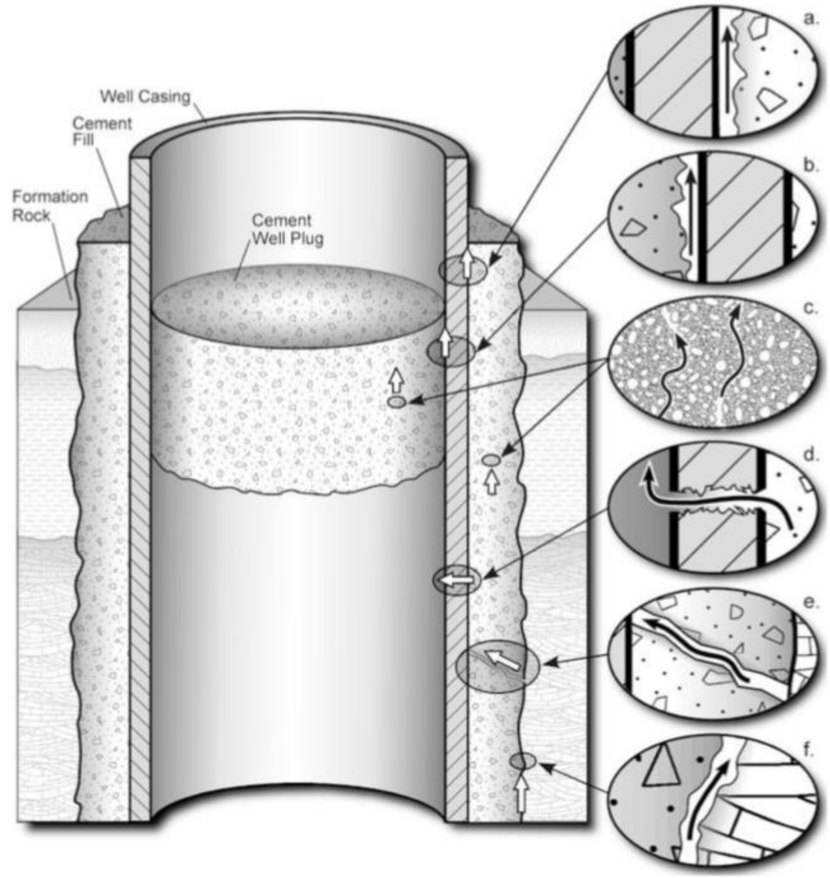

Figure 3: Schematic of leakage pathways [3]

Wellbore leakage model

- Generate a representative microannulus using stochastic means
- The microannulus is unwrapped and flow through it can be modeled using the Hele-Shaw flow
- The thickness of the microannulus (h) at various points in the cell is obtained by sampling a cumulative distribution function (CDF) using inverse transform sampling

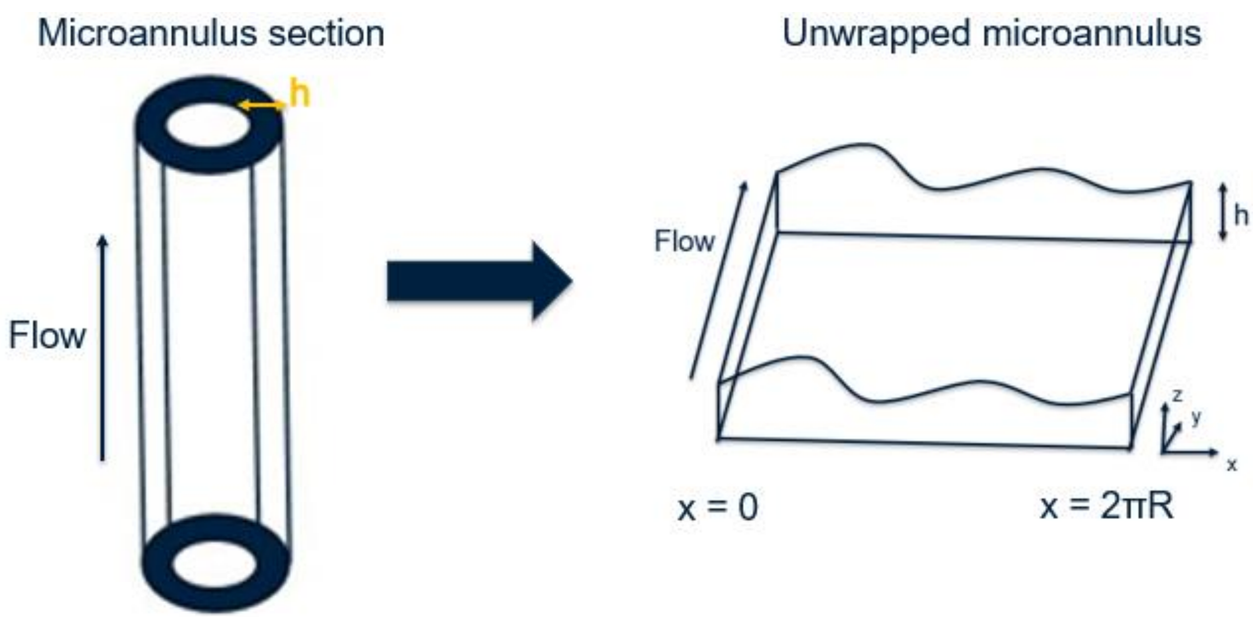

Figure 4: Schematic of an unwrapped section of microannulus

Gamma distribution

- A modified gamma distribution is used to represent the possible values of microannulus thickness
- A gamma distribution has two parameters, the shape parameter k and the scale parameter θ
- A third parameter, the bonding percentage is added to account for the probability of the cement sheath being bonded with the interface (either rock formation or casing). In this case there is no microannulus (h = 0 μm)

$$\boxed{MODIFIED\ CDF = B + (1 - B)\left[\frac{1}{\Gamma(k)}\gamma\left(k, \frac{x}{\theta}\right)\right]}$$

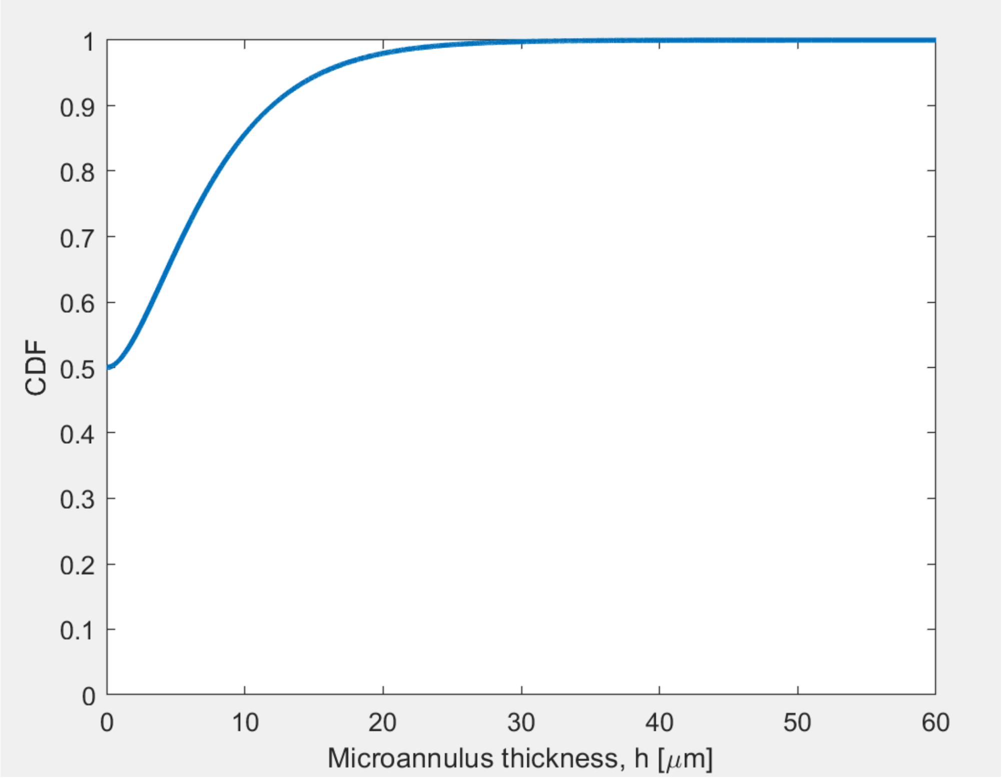

Figure 5: Modified CDF for a gamma distribution with parameters k = 2, θ = 4, B = 0.5

Methodology

- Microannulus thickness (h) is obtained inverse transform sampling of a modified gamma CDF
- If bonding occurs (h=0 µm), flow has the opportunity to leak through the cement sheath
  - The microannulus thickness is related to the cement permeability (k) through the flow between smooth parallel plate and Darcy's law
- Flow between two smooth parallel plates : $Q = -\frac{Wh^3 \Delta P}{12 \mu L}$
- Darcy's law: $Q = -\frac{k A \Delta P}{\mu L}$
- Therefore: $k = \frac{h^2}{12} \rightarrow h = \sqrt{12k}$
- API recommendation: cement permeability should be below 0.1 mD [4]
  - h = 0.0346 µm
- Range of values for microannulus thickness are obtained from the literature and used to determine the distribution parameters

Dry microannulus - Shrinkage

Value	Reference
External shrinkage: 1.2 vol. %, dependence on w/c ratio	Justnes et al. 1995 [5]
External shrinkage: 2 vol. % (no additives), down to 1 and 0.6-0.7 vol. 5 based on % CaCO3	Justnes et a. 1995 [5]
1-2% external shrinkage, dependence on w/c ratio	Lyomov 1997 [6]
Shrinkage increases with decreasing w/c ratio. Varied from 0.7 to 1.2 vol. % (external)	Justnes et al. 1996 [7]
Early stage of cement setting, massive shrinkage due to water expulsion (dependent on formation property)	Dusseault and Gray 2000 [8]
Stiffer formation (higher Young's modulus) leads to a higher possibility of microannulus development (cementing is better if the rock is ductile)	Oyarhossein and Dusseault 2015 [9]
Higher Young modulus (formation) improves cement's ability to resist debonding (from)	De Andrade et al. 2015 [10]
External volumetric shrinkage: less than 1%, no evidence of full microannulus development was found but rather some unbonded surface. 0.5 % bulk shrinkage, retraction of 20 microns for 7 ID and 8.5 OD cement sheath.	Nelson and Guillot 2006 [11]

Dry microannulus – Temperature and pressure cycling

Value	Reference
Mean h: 20 microns, std dev. 4 microns	Lavrov 2018 [12]
0 to 40 microns	Bois et al. 2011 [13]
0 to ~20-30 microns, nearly 100% of cases below 50 microns. Large microannulus: 25 microns	Garcia Fernandez et al. 2019 [14]
100 to 1000 microns (0.1 to 1 mm)	Skorpa and Vralstad 2016, Noor-Corina 2020 [15,16]
0 to 80 microns at casing-cement interface, 0 to 0.15 microns at cement rock interface	Wise et al. 2020 [17]
Fracture thickness: 17,20 microns or 25-500 microns	Todorovic 2016 [18]
T(low, mode, high): fracture aperture (10,50,200) microns. Microannulus gap (3,20,70) microns. Fracture width (1,2,3) mm	Ford et al. 2017, Arild, et al. 2017 [19,20]
Effective aperture of fracture: 12 to 35 microns	Huerta et al. 2009 [21]
Equivalent microannulus thickness: 8.1 to 12.8 microns based on pipe roughness	Noor-Corina 2020 [16]
Calculated microannulus: 56 and 65 microns, other sample 13 to 22 microns	Aas 2016 [22]

Dry microannulus – Bonding percentage

Value	Reference
Cement/Casing interface: after temperature cycling, B = 77%, 82%. Cement/rock interface: B = 96%, 99%	De Andrade et al. 2014 [23]
Debonding at cement/formation interface may be due to large stiffness different between the two material	Wise at al. 2020 [17]
B = 10% to 99% depending on rock type and drilling fluid, lower value of B for OBM, then WBM then pristine. 60-70% and 80% for WBM.	Opedal et al. 2014 [24]
Poor bonding quality in eccentric sections (on the narrow side)	Palacio 2020 [25]
Interface porosity, various rock type and drilling fluid. Worst with sandstone and WBM, best with sandstone and no mud. Rock and mud type very important. Interface porosity between 0.06% and 1.11% (interface pores volume/total sample volume)	Opedal et al. 2013 [26]
Higher B for shale than for sandstone, B changes based on number of thermal cycle. B between 97.5 and 96% for sandstone and 99.5 and 98.0% for shale.	De Andrade et al. 2015 [10]
Pressure cycling: cement/formation interface, no debonding observed, casing/cement, 99.1% bonding after cycling	Skorpa et al. 2018 [27]
Significant portion of wells are uncemented or have poor bonding (67% total, other 33% has fair, good or excellent bonding)	Waston and Bachu 2009 [28]

Dry microannulus – Distribution parameters

- Gamma distribution
  - $mode = (k - 1)\theta$
  - $mean = k\theta$

Type of microannulus	Mode [μm]	Mean [μm]	Bonding %	k	θ
Debonding (temperature and pressure cycling)	20	40	50	2	20
Shrinkage	0.5% -> 41.7	1% -> 83.6	30	1.995	41.9

Dry microannulus – Sampling rate

- On the physical mesh, how many times should the CDF be sampled to find the value of microannulus thickness?
- Magnitude of changes in the vertical direction are much less important than in the azimuthal direction

Well vertical direction

Well azimuth

Poor bonding/microannulus

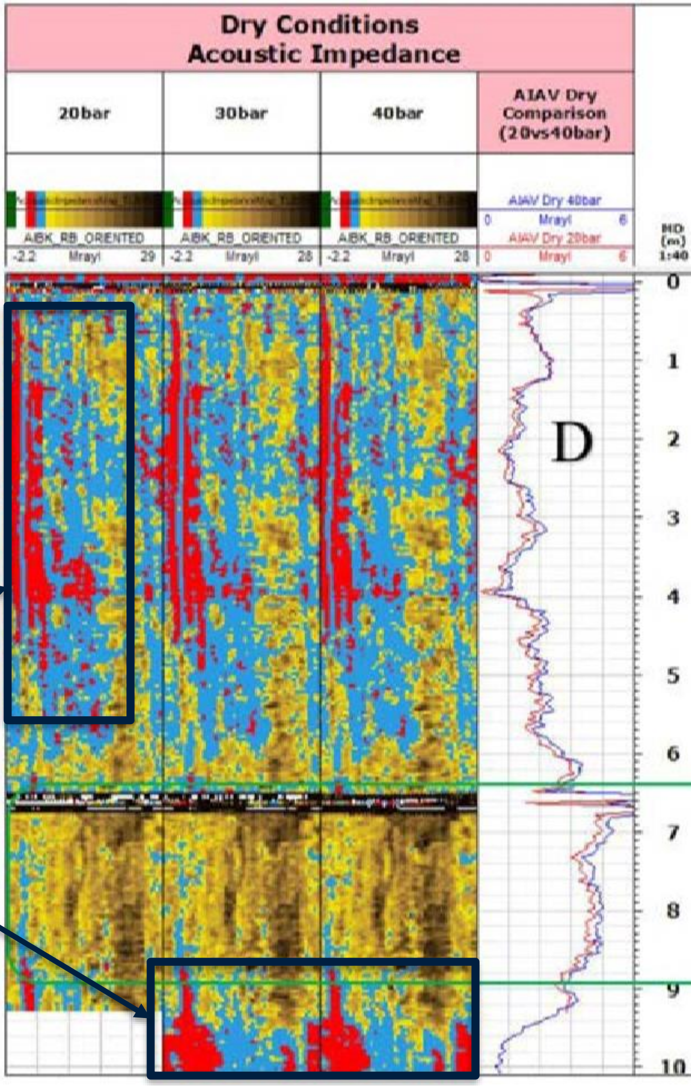

Figure 6: Acoustic impedance maps of a well section. Adapted from [25]

Results - Example 1

- Dry Microannulus caused by temperature and pressure cycling
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - k = 2
  - Θ = 20
  - B = 50%
- Sampling points
  - In x direction: 10
  - In y direction: 5

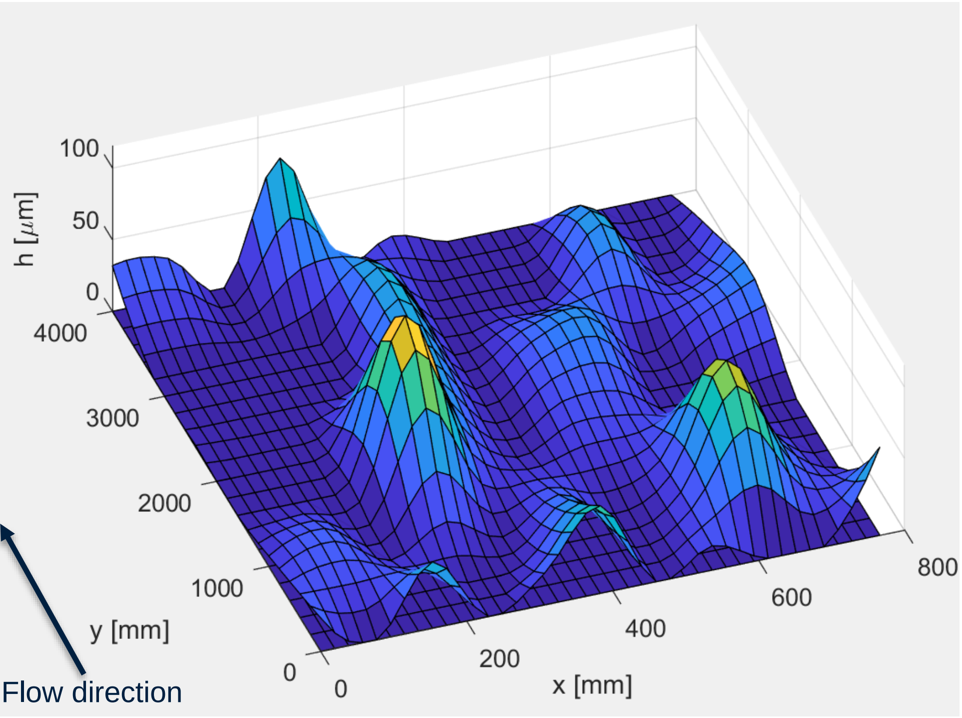

Figure 7: Microannulus of varying thickness

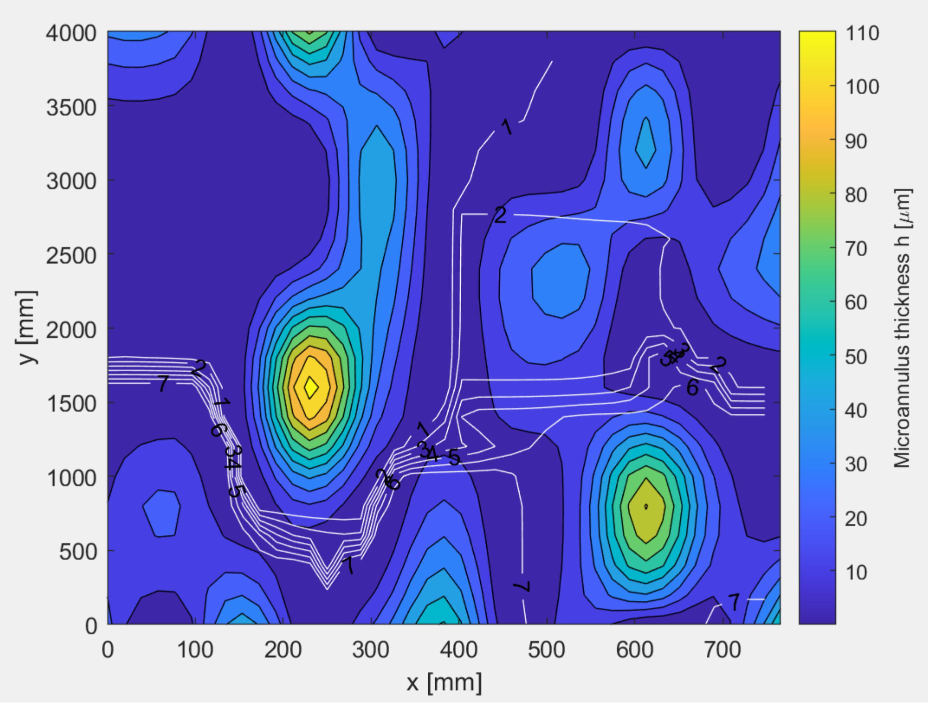

Figure 8: Microannulus of varying thickness and contour of pressure drop along the length of the microannulus

Results - Example 2

- Dry Microannulus caused by temperature and pressure cycling
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - k = 2
  - Θ = 20
  - B = 50%
- Sampling points
  - In x direction: 10
  - In y direction: 5

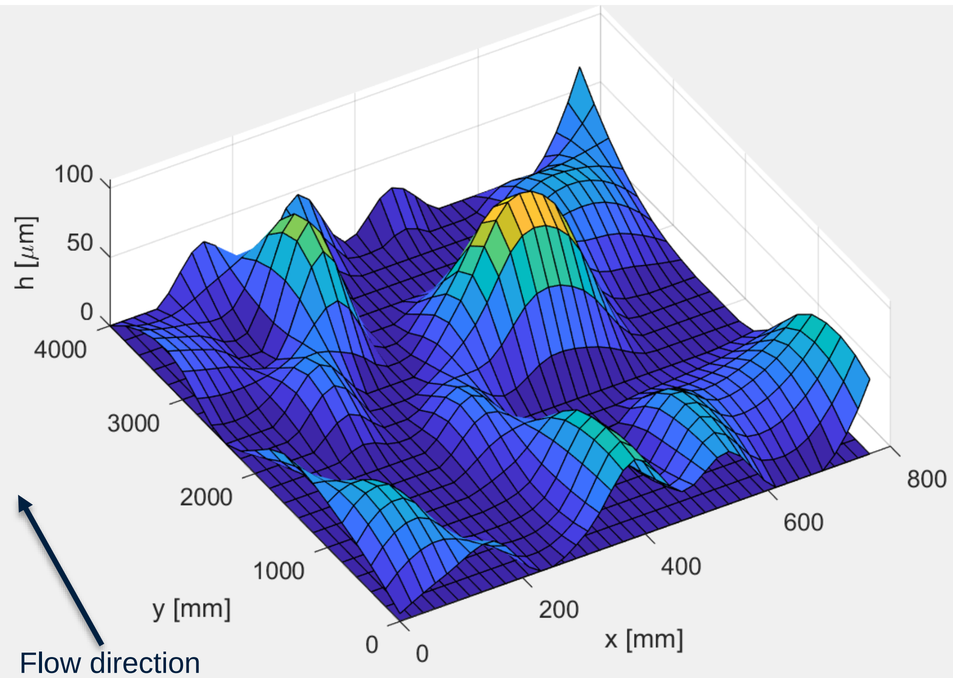

Figure 9: Microannulus of varying thickness

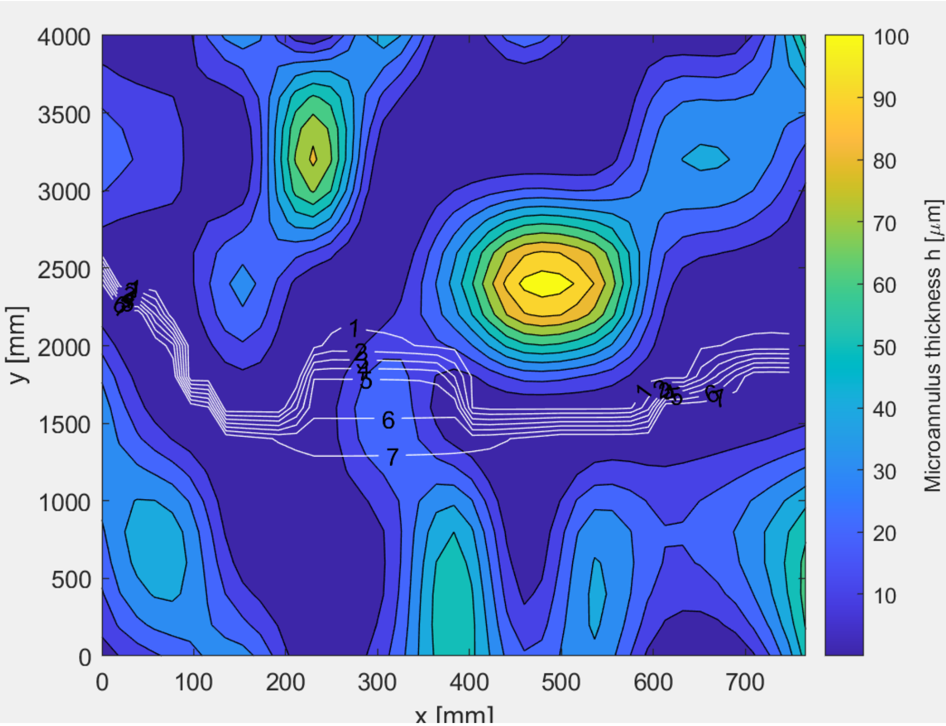

Figure 10: Microannulus of varying thickness and contour of pressure drop along the length of the microannulus

Results - Example 3

- Dry Microannulus caused by cement shrinkage
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - k = 1.995
  - Θ = 41.9
  - B = 30%
- Sampling points
  - In x direction: 10
  - In y direction: 5

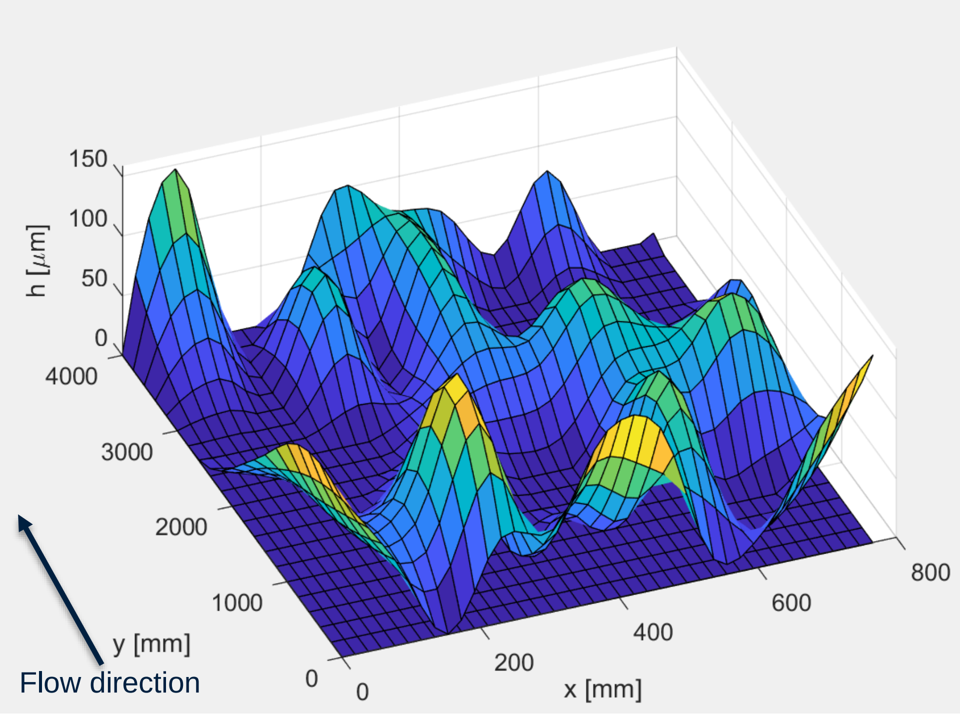

Figure 11: Microannulus of varying thickness

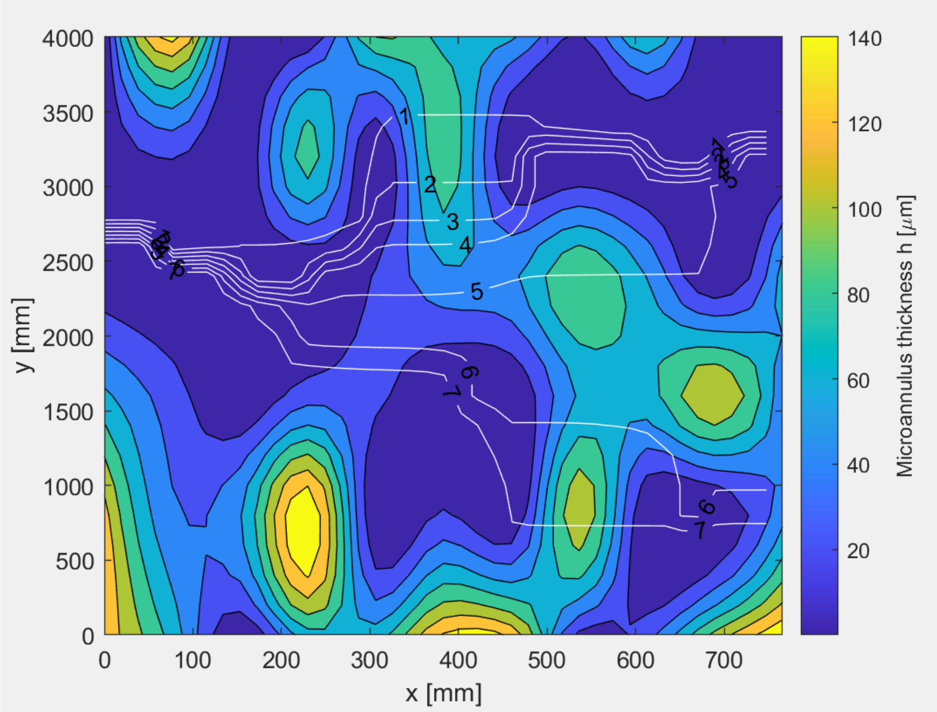

Figure 12: Microannulus of varying thickness and contour of pressure drop along the length of the microannulus

Results - Example 4

- Dry Microannulus caused by cement shrinkage
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - k = 1.995
  - Θ = 41.9
  - B = 30%
- Sampling points
  - In x direction: 10
  - In y direction: 5

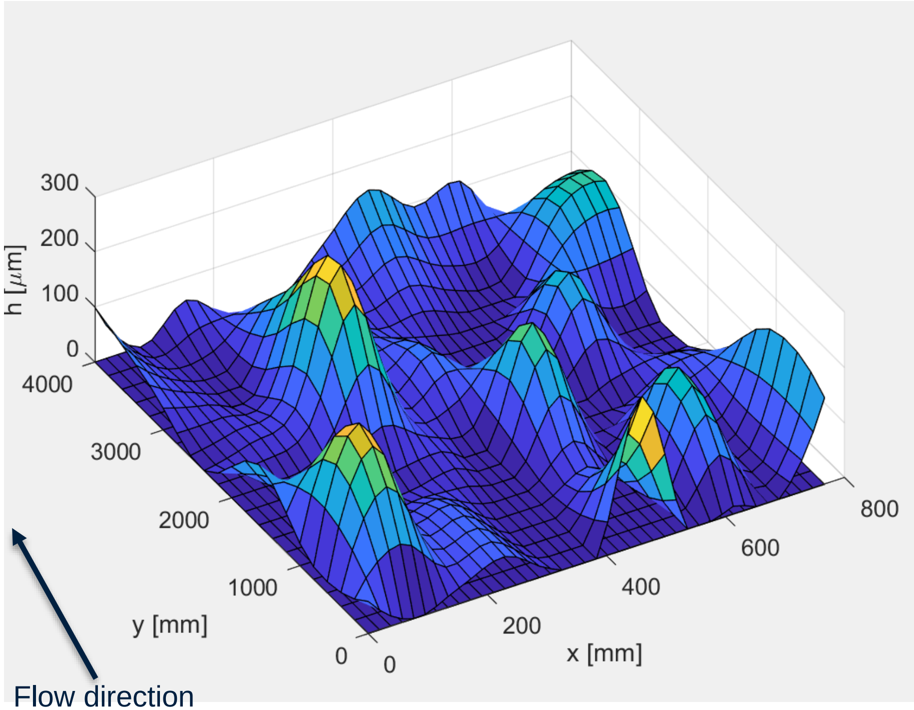

Figure 13: Microannulus of varying thickness

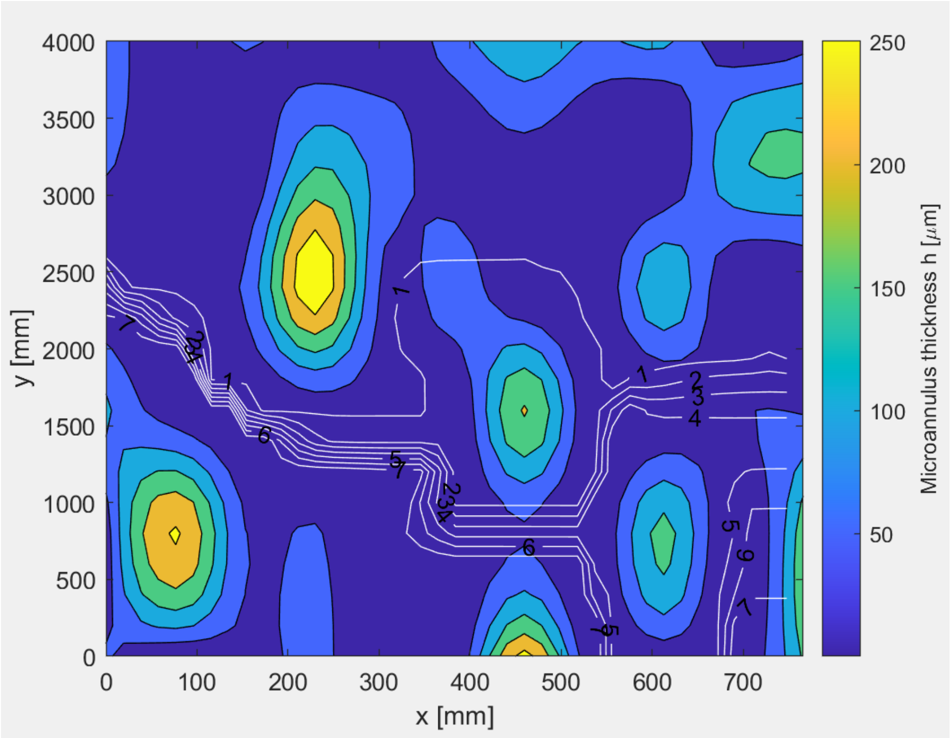

Figure 14:Microannulus of varying thickness and contour of pressure drop along the length of the microannulus

Summary and future work

- Short microannulus section were generated using a gamma distribution
  - Pressure drop across the section is presented
- What is the effect of varying various parameter on the effective permeability?
- Leakage pathways: wet microannulus
  - Flow through dehydrated mud
- Leakage pathways: Cracks

Thank you!
Questions/Comments?

References

[1] E. Trudel, M. Bizhani, M. Zare, and I. A. Frigaard, “Plug and Abandonment Practices and Trends : a British Columbia Perspective,” *J. Pet. Sci. Eng.*, no. Submitted, pp. 1–28, 2019.

[2] British Columbia Oil and Gas Commission, "Managing Well Integrity," Accessed 29 04 2020. [Online]. Available: https://www.bcogc.ca/public-zone/managing-well-integrity.

[3] S. E. Gasda, A. E. Stefan, B. Ae, and M. A. Celia, “Spatial characterization of the location of potentially leaky wells penetrating a deep saline aquifer in a mature sedimentary basin,” *Environ. Geol.*, vol. 46, pp. 707–720, 2004.

[4] American Petroleum Institute, “API RP 10B-2 : Recommended Practice for Testing Well Cements,” 2013.

[5] H. Justnes, D. Van Loo, B. Reyniers, P. Skalle, J. Sveen, and E. J. Sellevold, “Chemical shrinkage of oil well cement slurries,” *Adv. Cem. Res.*, vol. 7, no. 26, pp. 85–90, 1995.

[6] S. K. Lyomov, B. Reyniers, P. Skalle, and O. B. Lile, “Chemical shrinkage of oil well cement slurries,” in *48th Annual Technical Meeting of The Petroleum Society*, 1997, vol. 7, no. 26, pp. 85–90.

[7] H. Justnes, A. Van Gemert, F. Verboven, and E. J. Sellevold, “Total and external chemical shrinkage of low w/c ratio cement pastes,” *Adv. Cem. Res.*, vol. 8, no. 31, pp. 121–126, 1996.[8] M. B. Dusseault, M. N. Gray, and P. a Nawrocki, “Why Oilwells Leak : Cement Behavior and Long-Term Consequences,” *SPE International Oil and Gas Conference Exhibition SPE 64733*, no. SPE-64733, p. 8, 2000.

[9] M. Oyarhossein and M. B. Dusseault, “Wellbore Stress Changes and Microannulus Development Because of Cement Shrinkage,” in *49th US rock Mechanics/Geomechanics Symposium*, 2015.

[10] J. De Andrade, S. Sangesland, J. Todorovic, and T. Vrålstad, “Cement Sheath Integrity During Thermal Cycling: A Novel Approach for Experimental Tests of Cement Systems,” in *SPE Bergen One Day Seminar*, 2015.

[11] E. B. Nelson and D. Guillot, *Well Cementing*, 2nd Edition, Sclumberger, 2006.

[12] A. Lavrov and M. Torsæter, “All microannuli are not created equal: Role of uncertainty and stochastic properties in well leakage prediction,” *Int. J. Greenh. Gas Control*, vol. 79, no. February, pp. 323–328, 2018.

[13] A.-P. Bois, A. Garnier, F. Rodot, J. Sain-Marc, and N. Aimard, “How To Prevent Loss of Zonal Isolation Through a Comprehensive Analysis of Microannulus Formation,” *SPE Drilling and Completion*, pp. 13–31, 2011.

References

[14] S. Garcia Fernandez, E. N. Matteo, M. R. Taha, and J. C. Stormont, “Characterization of wellbore microannuli,” *J. Nat. Gas Sci. Eng.*, vol. 62, no. November 2018, pp. 13–25, 2019.

[15] R. Skorpa and T. Vrålstad, “Visualization and Quantification of Fluid Flow through Degraded Cement Sheaths,” in *SPE Bergen One Day Seminar*, 2016, pp. 1–9.

[16] A. Noor Corina, N. Opedal, T. Vra, R. Skorpa, and S. Sangesland, “The Effect of Casing-Pipe Roughness on Cement-Plug Integrity,” *SPE/IADC Drilling Conference and Exhibhition*, 2020.

[17] J. Wise *et al.*, “Wellbore Characteristics that Control Debonding Initiation and Microannuli Width in Finite Element Simulations,” *J. Pet. Sci. Eng.*, vol. 191, no. February, 2020.

[18] J. Todorovic, M. Raphaug, E. Lindeberg, T. Vrålstad, and M. L. Buddensiek, “Remediation of leakage through annular cement using a polymer resin: A laboratory study,” *Energy Procedia*, vol. 86, no. 1876, pp. 442–449, 2016.

[19] E. P. Ford, F. Moeinikia, H. P. Lohne, Ø. Arild, M. M. Majoumerd, and K. K. Fjelde, “Leakage Calculator for Plugged and Abandoned Wells,” in *SPE Bergen One Day Seminar*, 2017

[20] Ø. Arild, H. P. Lohne, M. M. Majoumerd, E. P. Ford, and F. Moeinikia, “Establishment of a Quantitative Risk-Based Approach for Evaluation of Containment Performance in the Context of Permanently Plugged and Abandoned Petroleum Wells,” in *Offshore Technology Conference*, 2017.

[21] N. J. Huerta, S. L. Bryant, B. R. Strazisar, B. G. Kutchko, and L. C. Conrad, “The influence of confining stress and chemical alteration on conductive pathways within wellbore cement,” *Energy Procedia*, vol. 1, no. 1, pp. 3571–3578, 2009.

[22] B. Aas, J. Sørbø, S. Stokka, I. Drillwell, A. Saasen, and D. N. Oljeselskap, “Cement Placement with Tubing Left in Hole during Plug and Abandonment,” in *IADC/SPE Drilling Conference and Exhibition*, 2016.

[23] J. De Andrade, M. Torsaeter, J. Todorovic, N. Opedal, A. Stroisz, and T. Vralstad, “Influence of Casing Centralization on Cement Sheath Integrity During Thermal Cycling,” in *IADC/SPE Drilling Conference and Exhibition*, 2014.

[24] N. Opedal, J. Todorovic, M. Torsaeter, T. Vralstad, and W. Mushtaq, “Experimental Study on the Cement-Formation Bonding,” in *SPE International Symposium and Exhibition on Formation Damage Control*, 2014.

References

[25] G. O. Palacio, D. Gardner, L. Delabroy, and A. Govil, “An evaluation of the cement sheath quality of casing sections recovered during a well abandonment operation,” *SPE/IADC Drilling Conference Proceedings*, March, 2020.

[26] N. Van Der Tuuk Opedal, M. Torsæter, T. Vralstad, and P. Cerasi, “Potential leakage paths along cement-formation interfaces in wellbores; Implications for CO2 storage,” *Energy Procedia*, vol. 51, pp. 56–64, 2013.

[27] R. Skorpa and T. Vrålstad, “Visualization of Fluid Flow Through Cracks and Microannuli in Cement Sheaths,” *SPE Journal*, vol. 23, no. 04, pp. 1067–1074, 2018.

[28] T. L. Watson and S. Bachu, “Evaluation of the Potential for Gas and CO2 Leakage Along Wellbores,” *SPE Drilling and Completion*, vol. 24, no. 01, pp. 115–126, 2009.