# AUPRF Methane Project Final Report

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| Name: | Ian Frigaard, University of British Columbia |
| Project Title: | Plug and Abandon Strategies for Canada's Oil & Gas Wells to stop Surface Casing Vent Flow (SCVF) and Gas Migration (GM) |
| Amount Awarded: | $120,750 x 4 |
| Total Spend to Date: | $120,750 x 3.5 |
| Project Completion Date: | Q4 2023 |
| GL Account Number: | 20-WARI-02 |

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| Have you received any funding from any crown corporations, government agencies including InnoTech Alberta, ERA or AER? If so how much and by which agency? | • From NSERC as part of the ongoing collaborative project<br>• $142,228 (cash) annually x 4 years |

## Summary of Outcomes

- The scientific and engineering outcomes are documented in Ref. [1-31].
- Our first paper the general review of P&A practices [26] has been highly cited (35 times since 2019 publication). We believe this is due to the combination of a comprehensive technical review plus relevant data from the BCOGC databases. A significant percentage of leakage (SCVF) was found in BC wells drilled after 2005, when the current trend of horizontal gas wells became dominant. There is evidence of industry response to regulatory change accounting partly for this and large differences in reported SCVF between the leading operators. We have investigated this with one operator but would have need assistance from others in order to progress to any conclusion.
- For off bottom placement of plugs we have explored the placement phase, both via simulation [11,12,14-17] and using experiments that are also relevant to dump bailing [1-10]. At sufficiently high placement rates the cement mixes well on exiting the pipe and travels up the well. At lower flow rates the mixing is delayed and waits for the fluid streams to destabilize. In some cases, part of the heavier fluid flows down the well to the barrier (e.g. bridge plug) before returning upwards. We have used the same apparatus to study effects of injector size, positioning and fluid rheology
- Our jetting/cleaning work [18-23] has succeeded to characterize free jets behaviour and we have benchmarked against other results. In the past year we have looked at how jets can penetrate through a perforation/hole and mobilize/clean the material behind.
- The regulations in Western Canada are largely prescriptive rather than involving risk assessment in P&A design [26]. The regulations target groundwater protection rather than emissions as their objective. The regulations do not have a physical rationale for many specific requirements, e.g. minimal lengths of plug. This is not uncommon in comparing between jurisdictions internationally. Many cement plugs placed on top of bridge plugs are not effectively pressure tested. There are no requirements on casing eccentricity when cementing.

- Data records are not kept consistently (between companies or jurisdictions), which makes it hard to conduct case studies of current practice in a systematic way, as would be needed for continuous improvement/optimization.
- As this project draws to its close, we have applied for continuation funding via an NSERC Alliance grant (under review), partnering with PTAC-AUPRF. This new project both continues the themes of the current project and extends the research into new areas.

**Scientific Achievements**

This is a long-term research project and the main achievements are in understanding better the scientific underpinnings of current P&A operations. This has been accomplished by a mix of mathematical models, computational simulation and laboratory scale experiments.

- Theoretical and computational models have targeted the following:
  - Plug placement dynamics. Systematic numerical studies of off-bottom plug placement reveal the dynamics that lead to failure or success of the process. These have included simulation studies on the effects of eccentricity or the placement tubing and variable injector size.
  - Preliminary computations have been made of post placement stability, i.e. after the pumps are turned off.
  - A model of squeeze cementing along a two-dimensional pore, including solid & liquid phases, and arrest of the penetrating cement at a critical distance. Initial work on extending this to leak-off and penetration around perforations.
  - A probabilistic model of leakage for a specific well. This model has been compared with available data on leakage rates for BC wells and then refined to include not only shrinkage micro-annuli but also wet micro-annuli and mud channels
- Dimensionally scaled lab experiments have been developed to study the following
  - Fluid placement, released from a pipe, i.e. modelling both dump-bailing and off-bottom releases.
  - Jetting and cleaning applications, through perforations.
  - Stability of off-bottom plugs after the pipe is withdrawn.

Our results on the above items are documented in the sources [1]-[31], listed below. We have also delivered a comprehensive up to date review of practice and well leakage of BC wells.

For the remainder of the project (approximately 1 year) we expect to make further advances in the areas listed above, particularly as the 5 PhD students finish writing their theses.

The group has organised and run 3 annual cementing forum workshops since this project has been running. In Calgary in May 2019, online in August 2020 and again in February 2022. The last of these meetings attracted over 70 participants, from Canada and international: academic, industrial and regulators. The online format has been surprisingly good for this, in allowing broad and cost effective participation i.e. no travel, remote connections etc., although in-person was markedly better for interaction with our partners and other stakeholder. We

hope to continue this forum/workshop in 2023, in person, and with project conclusions and recommendations.

*Presented and published work, in different categories:*

**Processes: Dump-bailing methods:**


[1] S. Akbari and S. M. Taghavi. "From breakup to coiling and buckling regimes in buoyant viscoplastic injections". Journal of Fluid Mechanics, in press (2022).

[2] S. Akbari and S. M. Taghavi. “Fluid experiments on the dump bailing method in the plug and abandonment of oil and gas wells.” Journal of Petroleum Science and Engineering 205: 108920 (2021).

[3] S. Akbari and S. M. Taghavi. “Injection of a heavy fluid into a light fluid in a closed-end pipe.” Physics of Fluids 32.6: 063302 (2020).

[4] S. Akbari and S. M. Taghavi. “Immersed buoyant viscoplastic injections”, Journal of Non-Newtonian Fluid Mechanics, Submitted (2021).

[5] S. Akbari and Taghavi. “Fluid placement in a closed end pipe with applications in plug and abandonment of oil and gas wells”. 25th International Congress of Theoretical and Applied Mechanics (ICTAM), Virtual Space, Italy (2 pages). (2021).

[6] S. Akbari and Taghavi. “Analyzing the fluid mechanics of the dump bailing method in the plug and abandonment of oil and gas wells”. 40th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Virtual Space, United States (9 pages) (2021).

[7] S. Akbari, S.M. Taghavi. “Fluid placement in a closed-end pipe with application in the plug and abandonment of oil and gas wells: experiments”. Canadian Society for Mechanical Engineering International Congress, Charlottetown, PEI, Canada (2021).

[8] S. Akbari and Taghavi. “Experiments on fluid placement in a confined pipe: fluid mechanics analysis for plug and abandonment applications”. 39th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Virtual Space, United States (8 pages) (2020).

[9] S. Akbari and Taghavi. “Fluid mechanics analysis of cement plug placement in dump bailing method”. 27th Canadian Congress of Applied Mechanics (CANCAM), Sherbrooke, Canada (4 pages) (2019)

[10] S. Akbari and Taghavi. “Viscoplastic fluid placements in a confined geometry with applications in the dump bailing method in the plug and abandonment of oil and gas wells”. 41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Hamburg, Germany (2022).


**Processes: Off-bottom plugs placement methods:**


[11] Ghazal, I. Karimfazli, “On the hydrodynamics of off-bottom plug placement: effects of geometry in a 2D model problem", Journal of Petroleum Science and Engineering, 212, 110153 (2022).

[12] Ghazal, I. Karimfazli, “On the hydrodynamics of off-bottom plug placement: A 2D model problem", Journal of Petroleum Science and Engineering, 203, 108613 (2021).
[13] A. Vogl, N. Waldal, P. Sarmadi, A. Fershtman, R. Mitishita, I. Frigaard. "Plug Cementing Stability". 41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Hamburg, Germany (2022).
[14] Ghazal, I. Karimfazli, “Off-Bottom Plug Placement: On the Effects of Pulling Out of the Hole", ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering, Hamburg, Germany, 2022.
[15] Ghazal, I. Karimfazli, “Injecting a Viscoplastic Fluid in a Channel Filled with a Lower Density Newtonian Fluid: Effects of Premixing", Canadian Society for Mechanical Engineering International Congress, Canada, 2021.
[16] Ghazal, I. Karimfazli, “Placing Off-Bottom Cement Plugs: Effects of Domain Geometry", ASME 2021 40th International Conference on Ocean, Offshore and Arctic Engineering, USA, 2021.
[17] Ghazal, I. Karimfazli, “Off-Bottom Plug Placement: How It Works?", ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering, USA, 2020.

**Processes: Sequential cleaning and cementing behind casing:**

[18] H. Hassanzadeh, A. Eslami, and S.M. Taghavi. "Positively buoyant jets: Semi-turbulent to fully turbulent regimes." Physical Review Fluids 6.5 (2021): 054501.
[19] H. Hassanzadeh, A. Eslami, S.M. Taghavi. “On the role of the viscosity ratio on buoyant miscible jet flows”. Environmental Fluid Mechanics. (2021) In Press.
[20] H. Hassanzadeh, A. Eslami, S.M. Taghavi. "Buoyant miscible jets in the plug and abandonment of oil and gas wells". 40th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Virtual Space, United States (8 pages) (2021).
[21] H. Hassanzadeh, A. Eslami, S.M. Taghavi. "Buoyant miscible jets in the plug and abandonment of oil and gas wells". 40th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Virtual Space, United States (8 pages) (2021).
[22] H. Hassanzadeh and S.M. Taghavi. "An experimental study on the stability of vertical buoyant jets". 27th Canadian Congress of Applied Mechanics (CANCAM), Sherbrooke, Canada (4 pages) (2019).
[23] H. Hassanzadeh and S.M. Taghavi. "Jet cleaning processes in the plug and abandonment of oil and gas wells: An experimental study on horizontal miscible jets". 41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Hamburg, Germany (2022).

**Processes: Squeeze cementing**

[24] M. Izadi and I.A. Frigaard "Squeeze cementing: a novel model for cement invasion into a pore". Journal of non-Newtonian Fluid Mechanics, in press (2021).
[25] M. Izadi, I.A. Frigaard and S.M. Taghavi. "Modeling Squeeze Cementing: A Microstructure-Based Continuum Model". 41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Hamburg, Germany (2022).

**Well leakage: Modeling well leakage & data analysis of identified well types:**

[26] E. Trudel, M. Bizhani, M. Zare and I.A. Frigaard. "Plug and abandonment practices and trends: A British Columbia perspective". Journal of Petroleum Science and Engineering 183, 106417 (2019).
[27] M. Bizhani, E. Trudel and I.A. Frigaard. "Plug and Abandonment Environment in British Columbia." 38th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2019), Glasgow, Scotland (2019).
[28] E. Trudel and I.A. Frigaard "Hele-Shaw Cell of Varying Thickness for Modeling of Leakage Pathways". EGU General Assembly Conference (2020).
[29] E. Trudel, M. Bizhani and I.A. Frigaard. "Plug and Abandonment Trends in Albertan Gas Wells". 40th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Virtual Space, United States (2021).
[30] H. Jung and I.A. Frigaard. "Evaluation of common cementing practices affecting primary cementing quality." Journal of Petroleum Science and Engineering 208, Part D, January 2022, 109622.
[31] I. Perser and I.A. Frigaard. "A Comprehensive Study on Intermittent Operation of Horizontal Deep Borehole Heat Exchangers." Energies, 15, 307, (2022).

## Number of Jobs Created

- *Concordia University:* full support for 1 PhD student and partial support for 1 MASc student.
- *Laval University:* Full support for 2 PhD students and 1 college student intern. Also, 1 postdoc and 2 undergraduate interns have supported the project, but with funding coming from other sources.
- *University of British Columbia:* full support for 2 postdocs (staggered) and 1 PhD; partial support for 1 intern, 1 PhD and 1 postdoc.

All project personnel are engineers and they are trained to enter industry and in particular address P&A operations in Western Canada. The 1st postdoc on the project has since entered the workforce in Calgary.

## Estimated GHG Reduction or Avoidances Occurring

The research performed on the project is long term and targeted at procedural operations, in particular those involving fluid mechanical issues during P&A as currently performed. Other research directions pursued by the group address primary cementing, which is more directly targeted at SCVF. It is hard to isolate impact of research on GHG emissions. To have no emissions relies on sealing the well properly at its construction stage, repairing prior to abandonment (if needed), then sealing the well via plugging. If all were successfully performed this would largely eliminate GHG emissions. Just as important, it would also eliminate other leakage damage, e.g. to aquifers, and damage to near surface ecology.

Our data analysis shows that 28% of wells drilled in British Columbia since 2010 were leaking. In our recent paper (E. Trudel, M. Bizhani, M. Zare, I.A. Frigaard, "Plug and abandonment practices and trends: a British Columbia perspective" J. Petrol. Sci. Engng., 183 (2019) 106417), we estimate the leakage at 1.5 tonnes of CH4 (methane) per year per well. Over an average

lifetime of 16.1 years this gives 24.15 tonnes of methane per well. CH4 is a greenhouse gas considered significantly more damaging than CO2. If only the ≈3400 wells were leaking the total emissions would be of concern but relatively minor on a global scale. If, however, the BC data is indicative of global trends, where there are many millions of wells, the perspective becomes more serious and more urgent. We are however unable to estimate the global severity.

| Period | Applied Research Cost | Admin Cost | Field Cost | Equipment / Capital Costs | Dissemination Costs | Communications Costs | Events Costs (workshops, forums, TIS, webinar) | Development of Best Practices | Comments<br><br>These amounts are the reported amounts per quarter. We will need to balance to these for the final report. |
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| Q3 2019 Nov - Dec | 3087 | 576 | 683 | 0 | 1985 | 0 | 0 | 0 | 0 |
| Q4 2019 Jan - Mar | 3085 | 2183 | 1281 | 15134 | 2330 | 0 | 0 | 0 | 0 |
| Q1 2020 Apr - Jun | 12854 | 1285 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Q2 2020 Jul - Sep | 7982 | 0 | 0 | 798 | 0 | 0 | 0 | 0 | 0 |
| Q3 2020 Oct - Dec | 8713 | 1133 | 0 | 1098 | 0 | 0 | 0 | 0 | 0 |
| Q4 2020 Jan - Mar | 11342 | 747 | 0 | 10220 | 0 | 0 | 0 | 0 | 0 |
| Q1 2021 Apr - Jun | 21355 | 2180 | 0 | 444 | 0 | 0 | 0 | 0 | 108,675 |
| Q2 2021 Jul - Sep | 11172 | 1219 | 0 | 2246 | 0 | 0 | 0 | 0 | 0 |
| Q3 2021 Oct - Dec | 19043 | 2309 | 0 | 3966 | 0 | 0 | 0 | 0 | 0 |
| Q4 2021 Jan - Mar | 8556 | 1206 | 0 | 3500 | 0 | 0 | 0 | 0 | 0 |
| Q1 2022 Apr - Jun | 21471 | 2472 | 0 | 499 | 2745 | 0 | 0 | 0 | 12,075 |