Predicting and Preventing Wellbore Leakage

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1 Overview of the Field

Wellbore leakage is a significant concern in Canada and also more globally. Methane has $\sim$ 30 the global warming potential of CO_2 and consequently all significant industrial leakage has an impact on national and international emissions targets. Evidently, gas emissions do not respect international borders. It is likely that gas leakage has been occurring since wells began being drilled. However, many developments 50-100 years ago were focused at (light and accessible) crude oil, with gas production regarded incidental. The past 50 years have seen many changes in the oil and gas industry and also societally. Some of these are listed below.

- Natural gas has become a valued commodity for heating
- The advent of horizontal drilling and fracking of gas reservoirs has meant increased productivity from gas wells.
- Increased public scrutiny in emissions
- A consequent shift in industrial concerns regarding sealing of wells, no longer only a concern for the effects on productivity.
- As we hit end-of-life for many wells constructed in the past 30-50 years, there has been a realization that methods to safely seal and abandon are not well studied.
- Scandals associated with "orphan wells" (operators who walk away from their end-of-life commitments) have been publicised in US and Canada, resulting in regulatory scrutiny and increased attention from responsible operators.

Thus, Canada is entering an era of P&A (Plug and Abandonment) in which 1000's of oil & gas wells will be abandoned annually for the foreseeable future, highlighting the critical question of safe long-term abandonment of these wells. Equally, there is attention in general on well construction methods as one can no longer divorce later abandonment leakage from that occurring during production, i.e. making better wells mean they can be decommissioned in a safer way. This workshop brought together mathematically oriented scientists and engineers to develop complementary and interlinked studies addressing knowledge gaps underlying these societally important issues.

2 Recent Developments and Open Problems

By their nature, study of industrial problems in this field is interdisciplinary, needing understanding of the mechanics of sealing between surfaces, the fluid mechanics of slurries and other non-Newtonian fluids, knowledge of cleaning fundamentals, operational insights and an appreciation of how solutions can be implemented in an industrial setting. Well cementing is a relatively young science, with the first research papers appearing in the late 1960's and the first texts appearing in the late 1980s/early 1990s. Plug and abandonment is even less well studied.

The more mathematically involved problems in this field tend to involve mathematical models that have a physical basis, either simplifications of real processes practiced in the field, or involving data analysis and modelling. These include the following.

1. Understanding which wells are leaking and what are their principal characteristics. Depending on regulatory jurisdiction, different data is archived on wells and accessible to different degrees. Some data is proprietary and in other cases it is simply not centrally archived, all of which makes database construction time consuming. Western Canada has some of the most transparent regulatory authorities and best public access, particularly in BC. The main point is that not all wells are the same: differentiated by the type hydrocarbons, depths of well, depths of any intermediate zones, well inclination, completion type, stimulation operations (fracking), etc. With over 550,000 wells in Western Canada alone, one needs to focus in on specific wells likely to leak and filter out others. After this, restricted data sets can be analysed statistically and/or used to calibrate leakage models. Eventually this might be a promising area for Machine Learning algorithms.

2. In Western Canada, the most common cement plug placement is currently the dump bailing technique. In this method, the cement slurry (heavy fluid) is injected into the wellbore fluid (light fluid), driven by buoyancy into the circular casing near the bottom of the well. The fluid injection is made using a cylindrical shaped bailer that has a diameter smaller than that of the closed-end well casing and typically the cement is placed on top of a bridge plug. Reports show the many wells plugged using the dump bailing method actually leak and eventually damage the environment. The suspected cause is that the fluids may mix during placement and due to the relatively small volumes (compared to other operations), some form of contamination may be the cause. Our objective is to provide fluid mechanics understanding about this process, for improvement and optimization, while addressing environmental concerns.

3. Off-bottom plug placement: many cement plugs in different wells are placed above liquid, i.e. with no mechanical support below. Given that the cement is denser than the fluids below, it is natural that there is a tendency to mechanically destabilize. This leads to a series of problems that are interesting from the fluid mechanics perspective. First, during pumping into the well, is it possible that the pumping induces local mixing that reduces the destabilization of the plug? Secondly, what happens when we extract the placement tubing from the well: is there a possibility that this may destabilize? Thirdly, once the tubing is removed and there is no more pumping, how is the plug able to remain static in the well for long enough that the cement can thicken during hydration, i.e. many hours.

4. In plug and abandonment operations, prior to placing the cement plug, cleaning the target area (i.e. inside and outside the casing) is an essential step, aiming to avoid cement contamination and to increase cement-casing bonding. Nowadays, jet cleaning processes are believed to be an environmentally friendly technology to enhance the cleaning efficiency in plug and abandonment operations. In the jet cleaning process, a (cleaning) fluid is injected into the target area to remove any unwanted fluids/materials. Our focus in this area is to characterize jet energy, mixing and removal efficiency, in order eventually maximize/optimize jets for cleaning plug and abandonment process.

5. Squeeze cementing is an operation in which a thin cement is pumped at pressure into cracks, micro-annuli and fissures, behind the casing. The aim is to repair any leakage pathways by filling with the cement. There are difficulties in deciding what type of constitutive model is appropriate to describe this process (pure filtration, non-Newtonian liquid, or both). Then there is an underlying complexity in designing the operation, in that the geometry and extent of leakage pathways is unknown. At best we

might hope to prescribe a statistical distribution of geometries and then would like to give a statistical estimate of the depth of penetration of the cement.

3 Format and Progress Made

Seven main academic participants, two observers and one industrial participant took part in the focused research group:

1. Soheil Akbari (PhD student, Université Laval)
2. Ian Frigaard (Faculty, University of British Columbia)
3. Ida Karimfazli (Faculty, Concordia University)
4. Abdallah Ghazal (PhD student, Concordia University)
5. Hossein Hassanzadeh (PhD student, Université Laval)
6. James Ireland (CNRL)
7. Mahdi Izadi (PhD student, University of British Columbia)
8. Seyed Mohammad Taghavi (Faculty, Université Laval)
9. Elizabeth Trudel (Faculty, University of British Columbia - Okanagan)

This was the first time that this group had been able to meet for research in person since 2019. There were many topics to be discussed and clarified amongst the group. The workshop was originally intended for 2020 and postponed twice. Thus, we made use of the time to look at drafts of papers, both finalizing ongoing work and starting on new papers. On the industrial side, two of our initial industrial participants (from Sintef and Schlumberger) were no longer able to attend. Instead a collaborator from CNRL participated. Thus, the meeting had a more Canadian flavour than originally intended. Each day had a presentation on one of the 5 topics outlined. This was followed by 1-2 hours of discussion around the topic, setting goals for collaborative research tasks and the next steps. The remainder of the time was spent working in smaller groups on these research areas. In addition there was time to plan out more long term collaborative research on an ongoing NSERC-PTAC funded grant, recently continued.

4 Outcome of the Meeting

As well as a good team-building experience, the week was productive in all our main directions.

1. Data modelling: we were able to review current models of leakage which had been validated against BC leakage data. Some time was then spent in exploring ways in which this model could be adapted to evaluate operational effects on leakage. As examples, the effect of low top of cement, different perforation patterns and penetration depths for squeeze cementing, leakage from intermediate zones. A collaborative paper has followed on from this, due to be submitted in early 2023. At the same time, we were able to discuss characteristics of wells that we might explore in the new NSERC-PTAC project.
2. Dump bailing: During the workshop, we were able to collaboratively develop a simplified model regarding the drainage problem of cement slurry in the dump bailing method. The model delivered the drainage time, which we compared with previously obtained experiments, showing good agreement. We are currently running more experiments to make further comparisons with the model, which we will hopefully submit as a journal paper during 2023.

3. Cleaning and jetting operations: During the workshop, we discussed fluid mechanics results collaboratively obtained regarding the cleaning/jetting problems in plug and abandonment operations. In particular, we discussed about experimental results to analyze the jet flow dynamics where a Newtonian fluid (representing the jet fluid) is injected into a viscoplastic ambient fluid (representing cement slurry). The results were based on a combination of non-intrusive experimental methods, including high-speed imaging, time-resolved tomographic particle image velocimetry (TR-Tomo PIV), and planar laser induced fluorescence (PLIF) techniques. We were able to study the jet flow behaviour versus the main dimensionless numbers governing the flow, in terms of the flow regimes, morphological behaviour, mixing index, jet radius, jet velocity profile, vorticity, average kinetic energy, and turbulent kinetic energy. This allowed us to finalize a journal article submitted to the Journal of Non-Newtonian Fluid Mechanics.

4. Off-bottom plug placement: research over the past few years has been exploring the mechanisms of stabilizing the flow when injecting dense slurry into a Newtonian liquid. In the extensive 2D studies conducted it appears that the downward moving stream of fluid eventually destabilizes, which has the effect of reducing the downwards flow and pushing the cement slurry upwards into its intended position. This appears robust after variations in pie size, flow rate and rheology, with more sensitivity found if the inlet pipe is asymmetrically positioned. Other strand of research have explore the effects of withdrawing the pipe and finally on the post-placement stable (idealized as a Rayleigh-Taylor flow). The week gave us the opportunity to plan out a review article on this topic, which we will start to write in 2023.

5. Squeeze cementing: Two directions have been followed here. Firstly, we have modelled squeeze cementing of micro-annulus as an invasion (filling) process into a slowly varying Hele-Shaw cell. Here we are seeing that the geometry of the cavity has a very significant effect on the penetration depth. Secondly, we have developed a multiphase model to track the cement particles and understand their role in filling a cavity. We had the opportunity to develop this model further, to account for leak-off effects as well as shear-induced migration. We are working towards a collaborative paper that explores this new model and the transition between filtration and rheology induced stopping.

We are thankful to BIRS for the opportunity to get together for this focused week, and in particular to the BIRS staff for ensuring everything ran smoothly.