Possible indicators for CO_2 leakage along wells

Stefan Bachu[1], Theresa L. Watson[2]

[1]Alberta Energy and Utilities Board (EUB),
4999-98th Ave., Edmonton, AB, T6B 2X3, Canada

[2]TLWatson & Associates,
1922-9th Avenue SE, Calgary, AB, T2G 0V2, Canada

Abstract
Implementation of CO_2 storage in geological media requires a proper assessment of the risk of CO_2 leakage from storage sites, particularly through and along wellbores. One method of assessing the potential for CO_2 leakage through wells is by mining databases that usually reside with regulatory agencies for information about the condition of existing wells. The Alberta Energy and Utilities Board (EUB) collects from industry and stores information about more than 315,000 oil and gas wells, and injection wells in the province of Alberta, Canada. A preliminary analysis of this information indicates that ~4.6% of these wells have recorded surface casing vent flow (SCVF) or gas migration (GM) through wellbore annuli or outside casing. Data analysis shows that there is a correlation between these occurrences and economic activity, technology changes and regulatory changes. The analysis further shows that the source of SCVF/GM is mostly in relatively shallow strata, with the gas originating at less than 700 m depth in ~90% of the occurrences. This information is representative for potential gas leakage along wellbores in the shallower part of mature sedimentary basins, and can be used in stochastic models for assessing the risk of leakage from CO_2 storage sites in geological media.

Keywords: CO_2 leakage, wells, surface casing vent flow, gas migration

Introduction

Carbon dioxide capture and geological storage (CCGS) is a means for climate change mitigation that is technologically feasible and with immediate potential for implementation. A particular critical issue that needs addressing before large-scale implementation is that of storage safety. A basic premise is that some CO_2 leakage will occur over time, the main question thus being what is an acceptable level of cumulative leakage over time and at all sites that still meets the needs for stabilization of CO_2 concentration in the atmosphere [1, 2]. Storage safety refers to the potential harm to other resources, equity and life that a CO_2 leak may entail. The probability and effects of leakage from CO_2 storage sites need assessment by both the operator and regulatory agency during the application and permitting process, during the operational phase and after site abandonment [3].

Any fluid in the subsurface, especially a buoyant one like CO_2, will migrate laterally within the injection unit and may leak upwards across formations through faults and fractures and/or defective wells [1, 4]. The potential for CO_2 leakage through fractures and faults can be well managed through proper geological characterization and selection of the storage site, and through proper operating procedures. Managing the potential for CO_2 leakage through wells is more difficult. Exploration and production wells have been drilled, completed and abandoned since the middle of the 19th century, with variable technology and materials, and with no or under variable regulatory regimes. Well materials (cements, steel, elastomers, etc.) will or may degrade over time, particularly in the presence of corrosive agents such as saline formation water and CO_2 [5, 6]. Thus, the potential for leakage through existing wells needs to be assessed for site selection and remediation. New wells will also be subjected to the same in-situ conditions as the existing wells.

The problem of potential CO_2 leakage through existing wells is particularly important for mature sedimentary basins with a long history of hydrocarbon production and high well density. Because hydrocarbon production occurs from various stratigraphic intervals, the density of wells at surface and in shallower strata is actually higher than that allowed for a single producing oil or gas pool. The number of wells that penetrate a given formation decreases with depth, adding a third dimension to the problem of areal well distribution and density. The change in time in the quality and characteristics of materials used in wells and in well completion and abandonment, and the degradation in time of well materials add the fourth dimension to this complex problem. Furthermore, unsuccessful exploration wells ('dry holes') are usually immediately abandoned, while production wells are abandoned only after 30-50 years of production. This extreme variability in well spatial distribution, materials, technologies and other externalities compounds the complexity of the problem of potential CO_2 leakage through and/or along wells that needs addressing in a stochastic framework in order to provide meaningful evaluations of the potential, effects and risk of CO_2 leakage from geological storage sites [2, 5]. This paper presents an analysis of >300,000 wells drilled for ~100 years in the province of Alberta, Canada, to provide some insight regarding the potential for and occurrence of gas leakage from shallow horizons through and along wells, or, in the event of isolation failure in deeper horizons, the ability of the uphole construction to keep fluids or gases from reaching the surface.

Data and Results

Assessing the potential for CO_2 leakage through wells can be done through laboratory experiments on, and field testing of well materials. However, given the exceedingly low number of such experiments and/or tests compared with the number of wells and variability in their characteristics, this work is valuable particularly for improving the technology for future wells, but is not statistically representative for existing wells. Another approach to assessing the potential for CO_2 leakage is to mine databases that usually reside with regulatory agencies for information about the condition of existing wells. The Alberta Energy and Utilities Board (EUB), the regulatory agency for energy resources production and conservation in the province of Alberta, Canada, collects from industry and stores information about all the deep wells in the province (oil and gas, injection and disposal), whose number at the end of 2004 was ~316,500. Drilling started in Alberta late in the 19th century, with the oldest recorded abandoned well being from 1893, and the first commercial gas field developed in 1901. Until the late 1930's, drilling and production were not regulated. In 1938 the Alberta Petroleum and Natural Gas Conservation Board (the precursor of today's EUB) was formed by the provincial government with the purpose and mandate of regulating the oil and gas industry. The industry took off after the discovery in 1947 of major oil reservoirs and, consequently, the Board promulgated in 1949 the Oil and Gas Act. Drilling in the province since then followed basically the economic cycle of the oil and gas market, with increased activity after the oil embargo in 1973 and the Iranian revolution in 1979, industry collapse in the mid-late 1980's, and very strong increase since the mid 1990's, reaching a level of more than 20,000 new exploration and production wells per year (Figure 1).

A well usually consists of several casing strings. Potable groundwater is protected by surface casing, which is cemented along its full length. Dry holes are usually abandoned with cement plugs, without any other casing other than surface casing. Seventy three percent of the wells in the province are cased. Approximately 51% of the wells in Alberta are active (producing or injecting), and 34% are abandoned, with the remaining 15% being inactive or suspended. Approximately 50% of the abandoned wells were drilled and abandoned (D&A), with no production casing. Deeper casing strings were not always fully cemented; however regulations generally require that production zones and other sensitive strata are hydraulically isolated with cements. Since 1966, EUB has been making changes to cementing requirements to address zonal isolation and requires that wells drilled in certain regions of the province are cemented full length.

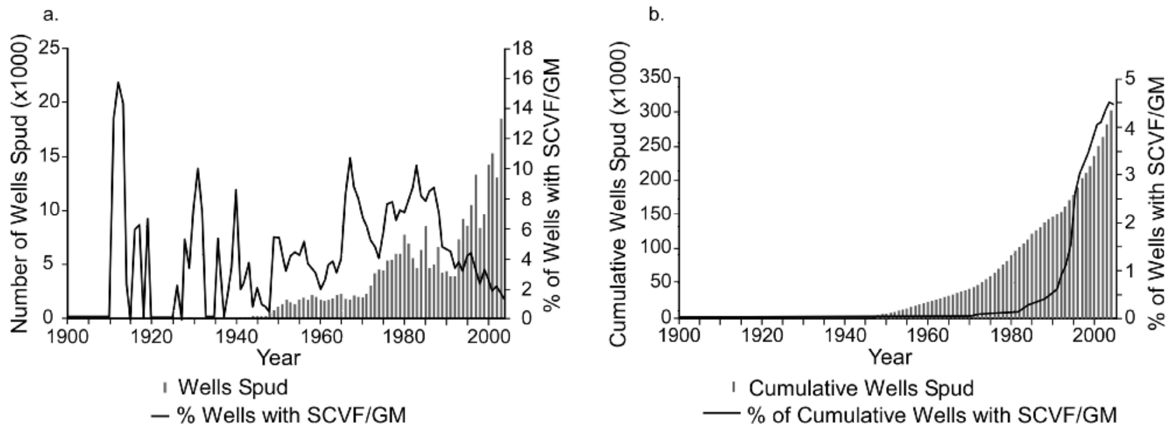
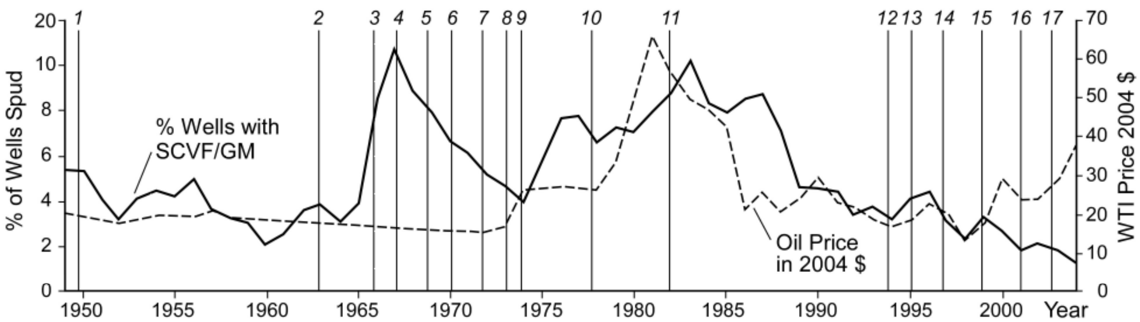


Figure 1 Drilling activity and occurrence of surface casing vent flow (SCVF) and/or gas migration (GM) along wells in Alberta, Canada: a) yearly, and b) cumulative to 2004. The occurrence of SCVF/GM is related to the year of well drilling, not to the year of discovery.

In the past wellbore construction was mainly focused on the economic production or conservation of conventional oil and gas resources. Little or no value was placed on unconventional resources that are difficult to produce, such as coal bed methane and shale gas, which in Alberta are typically found in shallower Cretaceous strata. Consequently, requirements did not stipulate that these zones be cemented in many areas, and where cementing was required, companies often utilized lower-density cementing material to reduce hydrostatic pressures on deeper depleted or weak zones. In Alberta, wellbore leakage is mainly from these shallow zones and shows up at surface as surface casing vent flows between casing strings (SCVF), or as soil gas migration (GM) outside of the largest casing. In contrast, since the implementation of the Oil and Gas Act, deeper horizons have been protected by quality cementing for the economic recovery of resources.

Since 1995 operators have to report SCVF and GM cases upon detection, after spud or at abandonment on all wells. In both cases the cause is poor cement sealing due to poor removal of drilling mud, stimulation or production practices, poor bond to casing or rock caused by swelling clays, cement shrinkage or poor filter cake removal, cement contamination during the placement/circulation process, poor cement setting particularly in deviated and horizontal wells, degradation by formation fluids, or just cement absence [7, 8]. Since 1995, SCVF has been recorded in 12,458 wells in Alberta, 1,843 wells record GM and 176 wells record both (in total ~4.6% of the number of wells). Only 286 open-hole wells (0.5% of D&A wells) record SCVF/GM, while SCVF/GM in cased wells is 6.1%. This discrepancy may be due to regulations for open-hole well abandonment being in the past more stringent than for cased wells by requiring zonal isolation. Until 2003, cased-hole abandonment did not specifically require zone isolation behind casing. On the other hand, one may argue that leakage from abandoned wells will not be detected unless it shows up at the surface as gas migration by affecting vegetation, and this may skew the statistics.

A small peak in the incidence of SCVF/GM in early 1950's (Figure 2) corresponds with the discovery of the Pembina Cardium oil field, the largest in North America. The peak of late 1960's coincides time wise and geographically with the discovery of and intensive drilling in the Zama and Rainbow Lake oil fields of northwestern Alberta, when requirements were for cementing 91 m (300 ft) above producing Middle Devonian formations. Overlying productive formations discovered subsequently in Upper Devonian strata were not cemented, and these are generally the sources of SCVF/GM in wells in that area. Southeastern Alberta is another region that has experienced a high incidence of SCVF for wells drilled during that period, and the significant decrease in the % of wells with SCVF/GM in late 1960's and early 1970's (Figure 2) corresponds with changes in regulatory requirements in regard to minimum cementing and surface casing requirements. The increase and subsequent decrease in the % of wells with SCVF/GM drilled between 1974 and early 1990's (Figure 2) correspond with increased drilling (Figure 1a) spurred by high oil prices following the oil embargo of 1973 and Iranian Revolution in 1979, and the drop in activity when the oil price collapsed in the mid 1980's (Figure 2). Although the oil price increase since late 1990's led to drilling at a torrid pace in the last decade, the incidence of SCVF or GM in wells drilled during this period is much lower, dropping well below the average (Figures 1a and 2).



1. Oil and Gas Act
2. First SC requirements
3. First cement requirements
4. Update of SC requirements
5. Update of SC and cementing requirements
6. Intermediate casing
7. Conductor pipe requirements
8. Update of SC requirements for SE Alberta
9. Update of SC requirements for south-central Alberta
10. Cementing guide
11. Update of cementing guide
12. Requirements for GW protection and SCVF checking
13. 10-year inactive well program initiated
14. Well abandonment guide, sour well licensing
15. Requirements for SCVF/GM testing
16. Long Term Liability program replaces 10-year inactive well program
17. Update of allowable gradient for serious SCVF

Figure 2 Percentage of wells drilled in Alberta since promulgation of the Oil and Gas Act in 1949 that record surface casing vent flow and/or gas migration (SCVF/GM). The wells are referred to the year of drilling. Major regulatory changes are indicated on the timeline, and the price of oil (WTI in 2004 $) is also shown as an indicator of economic activity.

Testing for SCVF/GM is currently conducted generally according to regulations at rig release and at abandonment. It is not clear if the time lag between well spud and SCVF/GM detection is due to a real time lag in leakage to occur and/or manifest itself at the surface, or is an artifact caused by testing being required only since 1995. An analysis of the 345 wells that were drilled and abandoned since 1995, when the new regulations were introduced, and that record SCVF/GM suggests that there is a time factor involved that may also contribute to the divergence since 1998 of the correlation between activity/price and SCVF/GM occurrence (Figure 2); however this hypothesis requires further investigation. Repair of SCVF/GM is required immediately only for serious leakage, otherwise repair may be deferred to the time of abandonment. Non-serious SCVF was defined in 1995 as sweet gas flow less than 300 m^3/d with a corresponding pressure buildup less than the depth of surface casing shoe times a hydrostatic gradient of 11 kPa/m. In 2003 the hydrostatic gradient has been reduced to 9.8 kPa/m to further protect uncovered useable groundwater. All other cases of sweet gas leakage (high leakage rate or high pressure buildup) and of leakage of sour gas or liquids (oil or water) are classified as serious and require immediate well repair. Only 2% of recorded SCVF/GM cases were serious based on flow rate, and 0.8% were serious based on flow of liquids.

Gas migration occurs mainly in the shallower heavy-oil producing area of Alberta where thermal methods are used for oil recovery and these may contribute to cement sheath failure. Approximately one third of the SCVF /GM cases in this area occur in deviated wells, suggesting that casing centralization and/or cement slumping may contribute to the increased incidence of leakage in deviated wells. Thus, although generally technology has a neutral or slightly positive effect on the incidence of SCVF/GM, it appears that production techniques had a negative effect in the case of thermal oil recovery and of deviated and horizontal wells.

The source of the gas was identified and/or recorded in very few cases of SCVF/GM; however, from these data it appears that the source is mostly in relatively shallow strata, with the gas in 70% of the identified occurrences originating at less than 500 m depth, and in ~90% of the occurrences originating at less than 700 m depth. This is likely due to the fact that deeper, producing zones are much better isolated during well completion and abandonment, while shallower parts are not cemented, or the cement quality is poorer.

The above information suggests that procedures for assessing the risk of CO_2 leakage from a geological storage site should consider two zones in the sedimentary succession: a deep zone that would include the storage site itself, the immediately confining aquitard (caprock) and the strata up to a depth of 800-1000 m, and the shallower zone above it, all the way to the ground surface. In regard to the potential for CO_2 leakage along and through wells within and from the shallower zone, the data indicate that assessment criteria should include the following information:

- well age;
- well status (active, inactive, abandoned);
- well casing, or lack thereof;
- well direction (vertical, deviated, horizontal);
- cementing interval(s);
- level of drilling activity;
- global and local events that may have affected drilling practices; and
- regulations and their timeline of being introduced.

Development of a risk assessment procedure based on the above criteria would significantly improve the ability to assess the suitability of sites for CO_2 geological storage, the screening criteria for site selection, the application and permitting process, and the development of monitoring programs to track the movement and possible leakage of CO_2 from a storage site.

Conclusions

The shear number of wells in Alberta and the data recorded with Alberta Energy and Utilities Board provide a statistically significant sample for evaluating the potential for leakage along wells in mature, densely drilled sedimentary basins like those onshore in North America, with a long history of hydrocarbon exploration and production. The analysis of the cases of SCVF/GM in Alberta suggests that the following factors are possible indicators of the potential of a well to leak.

1) Economic activity, as expressed by the oil price. It is hypothesized that in periods of high activity with high demand for drilling rigs and time at a premium, the rush to complete the wells and move on to other sites has a negative effect on completion quality and well integrity.
2) Geopolitical events, which affect oil price and demand, hence the activity level.
3) Local events, such as the discovery and development of large oil fields have impacted the SCVF/GM incidence rate as these fields were typically discovered prior to the discovery of overlying reserves which were not isolated, or because the technology was not adequate to construct wellbores to withstand the rigors of completion, production and/or injection. Local events in other parts of the world may be of a different nature, particularly in regions plagued by political instability and armed conflict.
4) Some technological changes and their application, such as horizontal and slant well technology, and thermal production strategies, also affect negatively the quality and/or strength and integrity of well casing and cements.

5) Well completion (cased or open hole); it seems that abandoned open-hole wells have a lower incidence of leakage than cased wells as a result likely of more stringent abandonment regulations.
6) Regulatory requirements and their time of introduction/implementation, however, have the greatest impact, to the point that stringent regulatory requirements may decouple the statistical link between any of the previous factors and wellbore integrity.

Surface casing vent flow and gas migration are expressions at surface of gas leakage along wellbores in the shallower part of mature and intensely drilled sedimentary basins, at depths less than those recommended for CO_2 geological storage. Although leakage at greater depths is harder to detect, it is believed that its rate of occurrence is much lower than that of SCVF/GM due to better construction and abandonment practices and more stringent regulations for zone isolation in the past. As a result, zones that may be suitable for CO_2 storage are more likely to have adequate zonal isolation prior to CO_2 injection. Thus, the information presented in this paper is not representative for the potential for CO_2 leakage from the storage unit itself, but rather for leakage once CO_2 reaches shallower horizons where CO_2 will likely be in gas phase, particularly the protected groundwater and vadose zones. This information can be used to develop a methodology for ranking wells in terms of their potential for leakage on the basis of such factors as type, status, location and drilling date in the context of global and local events and of changes in the regulatory requirements for well completion, monitoring and abandonment. The analysis and well-assessment methodology presented here can be applied to any other region in the world where CO_2 storage is envisaged and where the risk of leakage through and along wells needs assessment.

List of References

- [1] Celia MA, Bachu S. Geological sequestration of CO_2: is leakage unavoidable and acceptable? In: Gale J, Kaya Y, editors. Sixth International Greenhouse Gas Technologies Conference, Amsterdam: Elsevier; 2003, v. I, p. 477-82.
- [2] Pacala SW. Global constraints on reservoir leakage. In: Gale J, Kaya Y, editors. Sixth International Greenhouse Gas Technologies Conference, Amsterdam: Elsevier; 2003, v. I, p. 267-72.
- [3] Longworth HL, Dunn GC, Semchuck M. Underground disposal of acid gas in Alberta, Canada: regulatory concerns and case histories. SPE 35584, In: Gas Technology Conference, Calgary, AB, Canada, April 26 - May 1, 1996, p. 181-192.
- [4] Bachu S, Celia MA. Assessing the potential for CO_2 leakage from geological storage sites. In: McPherson BJ, Sundquist ET, editors. The science and technology of carbon sequestration, Washington, DC: American Geophysical Union; 2006, in press.
- [5] Davis KE, McDonald LK. Potential corrosion and microbiological mechanisms and detection techniques in solution mining and hydrocarbon storage wells. In: Underground injection science and technology, Tsang C-F, Apps JA, editors, Amsterdam: Elsevier; 2005, p. 177-192.
- [6] Scherer GW, Celia MA, Prévost J-H, Bachu S, Bruant R, Duguid A et al. Leakage of CO_2 through abandoned wells: role of corrosion of cement. In: Thomas DC, Benson SM, editors. Carbon dioxide capture for storage in deep geologic formations – results from the CO_2 capture project, Amsterdam: Elsevier; v 2, p. 827-48.
- [7] Watson TL, Getzlaf D, Griffith JE. Specialized cement design and placement procedures prove successful fo rmitigating casing vent flows – case histories. SPE 76333. Gas Technology Symposium, Calgary, AB, Canada, April 30 - May 2, 2002, 9 p.
- [8] Watson TL. Surface casing vent flow repair – a process. Paper CIM 2004-297. Fifth Canadian International Petroleum Conference and 55th Annual Technical Meeting of the Petroleum Society, Calgary, AB, Canada, June 8-10, 2004, 9 p.