Evaluation of the Potential for Gas and CO_2 Leakage Along Wellbores

Theresa L. Watson, T.L. Watson & Associates, and **Stefan Bachu,** Alberta Energy Resources Conservation Board*

Summary

Implementation of carbon dioxide (CO_2) storage in geological media requires a proper assessment of the risk of CO_2 leakage from storage sites. Leakage pathways may exist through and along wellbores, which may penetrate or be near to the storage site. One method of assessing the potential for CO_2 leakage through wells is by mining databases that usually reside with regulatory agencies. These agencies collect data concerning wellbore construction, oil and gas production, and other regulated issues for existing wells. The Alberta Energy Resources Conservation Board (ERCB), the regulatory agency in Alberta, Canada, collects and stores information about more than 315,000 oil, gas, and injection wells in the province of Alberta. The ERCB also records well leakage at the surface as surface-casing-vent flow (SCVF) through wellbore annuli and gas migration (GM) outside casing, as reported by the industry.

The evaluation of a leakage pathway through wellbore casing or annuli and what causes these wellbore leaks are the first step in determining what factors may contribute to wellbore leakage from CO_2-storage sites. By using available data, major factors that contribute to wellbore leakage were identified.

Data analysis shows that there is a correlation between these SCVF/GM and economic activity, technology changes, geographic location, and regulatory changes regarding well completion and abandonment. Further analysis indicates a relationship between low-annular-cement top, external corrosion, casing failure, and wellbore leakage (SCVF/GM). Other factors that could affect the presence of wellbore leakage, such as wellbore deviation, surface-casing depth, and wellbore density, were also investigated.

This paper presents the findings of the data analysis and a method to evaluate the potential for leakage along wells in an area where CO_2 storage is intended. This information is useful not only for future operations of CO_2 storage in geological media, but also for current operations relating to the exploration and production of hydrocarbons.

Introduction

The possibility of removing CO_2 from an industrial-emission stream and storing it in deep geological media to reduce the impact on the atmosphere of green-house gas is being investigated extensively (Metz et al. 2005). More than 80 CO_2-injection schemes have been in operation since as early as the 1970s for tertiary oil recovery as miscible floods (Moritis 2006), with the side benefit of CO_2 removal from the atmosphere. Other gas-injection schemes are also in use within the oil and gas industry, such as natural-gas storage and acid-gas disposal.

In the case of CO_2 sequestration, the storage unit must be near-leak-free, to the atmosphere or to other geological formations, to justify the costs and to meet safety requirements and greenhouse-gas-reduction objectives. This paper focuses on human-induced leakage paths, in particular wellbores that were previously drilled for exploration and production of oil and gas reserves and were subsequently abandoned. The work reported here determines important factors that can be used to predict which wellbores are most likely to leak or have future abandonment liability and if these wellbores will impact CO_2-storage schemes adversely in the future. The analysis is based on data for more than 315,000 wells drilled up to the end of 2004 in the province of Alberta.

Background

Potential Wellbore-Leakage Pathways. Figs. 1a and 1b illustrate typical wellbore-construction and -abandonment profiles for Alberta. From these diagrams, one can identify potential leakage pathways from a CO_2-storage reservoir or gas-bearing formation. For a leak to occur, three elements must exist (Watson 2004):

1. A leak source.
2. A driving force such as buoyancy or head differential.
3. A leakage pathway.

Because the main objective of the investigation is the evaluation of the potential of CO_2 leakage from a storage site, the first two conditions are being met; the leak source is the injected or stored CO_2, and the driving force is provided by CO_2 buoyancy and possibly by the pressure increase because of injection. Therefore, because a leak source and a driving force are present, any leakage pathway along wellbores will allow CO_2 to escape from the storage site. Leakage pathways to be discussed include

1. Poorly cemented casing/hole annulus.
2. Casing failure.
3. Abandonment failure.

These leakage pathways are a pre-existing condition of the wellbore in the absence of CO_2 and have the potential to leak with or without additional possible effects caused by the presence of CO_2, such as cement degradation and casing corrosion. Data gathered from ERCB sources and well-log examinations are used to describe the potential of leakage from wellbores in general. The investigation does not differentiate the consequence of a leak to atmosphere, nonsaline groundwater, or other deeper horizons. It is assumed that any leak of natural gas from a source formation or CO_2 outside of the storage site is undesirable.

Abandonment Methods and Requirements. ***Wells Drilled and Abandoned.*** Fig. 1a depicts a typical openhole abandonment scenario in Alberta. Regulations require that any porous zone be isolated or covered to prevent cross flow between geological formations. In addition, nonsaline groundwater (defined as water containing less than 4,000 mg/L total dissolved solids) be covered with cement and isolated from potential hydrocarbon-bearing zones.

After the downhole cement plugs have been set, the well must remain open for inspection for a minimum of 5 days. After this time, the well is checked for static-fluid level or other indications of plug leakage (such as bubbling in the fluid) before the casing can be cut and capped below grade level. The arrows in Fig. 1a indicate possible leakage pathways from potential storage or gas-bearing formations.

Wells Drilled, Cased, Completed, and Abandoned. Fig. 1b depicts a typical cased-hole abandonment after reservoir depletion and some potential leakage pathways. There are three main types of zonal abandonment in Alberta:

1. Bridge-plug capped with cement above perforations.
2. Retainer and cement squeezed into perforations.
3. Cement plug set across perforations.

Because 2003 regulations require zonal isolation behind casing and that nonsaline groundwater be protected. In many cases, older wells were constructed with low-annular-cement tops, allowing many zones to be in communication behind casing. Under the

---

* Now with Alberta Research Council.

This paper (SPE 106817) was accepted for presentation at the E&P Environmental and Safety Conference, Galveston, Texas, 5–7 March 2007, and revised for publication. Original manuscript received for review 8 January 2007. Revised manuscript received for review 9 April 2008. Paper peer approved 26 May 2008.

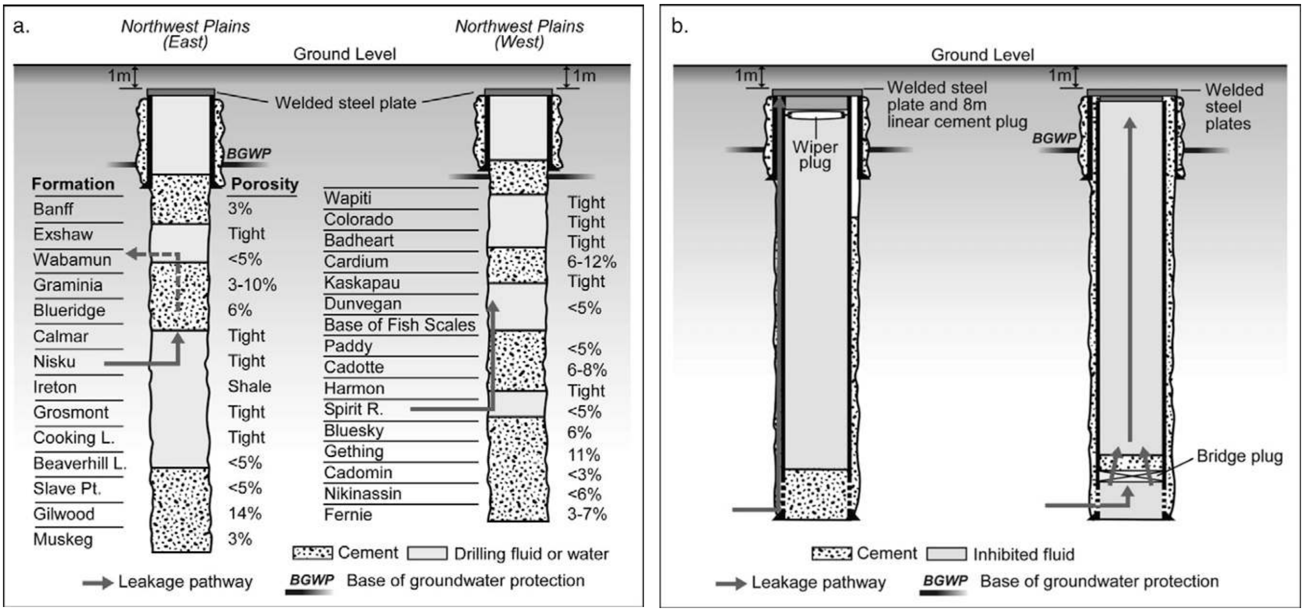

Fig. 1—Typical well abandonments in Alberta, Canada: (a) drilled and abandoned open hole; (b) cased, completed, and abandoned.

current regulations, a cement squeeze would be required to achieve isolation before final abandonment.

Wellbores must be abandoned with inhibited fluid inside of the casing and must be pressure tested to a minimum of 7000 kPa. Before cutting and capping of the production and surface casing, the well must be checked for SCVF and GM. If flow is detected, then repair operations to stop the flow must be undertaken before abandonment.

Wells Drilled, Cased, and Abandoned. Wells drilled, cased, and abandoned have requirements similar to the preceding case, with the exception of isolation of the perforated interval.

Testing for SCVF and GM. SCVF is commonly encountered in the oil and gas industry and is variously referred to as sustained annular pressure, sustained casing pressure, annular-gas pressure, casing-vent flow, or annular-gas flow. This condition exists when gas enters the exterior production-casing annulus from a source formation below the surface-casing shoe and flows to surface or builds gas pressure at surface. For the remainder of this paper, the condition will be referred to as SCVF.

In Alberta, the ERCB requires that all wells drilled and cased be tested for SCVF within 60 days of drilling-rig release and before final abandonment (*ID 2003-01* 2003). Wells that have positive SCVF and exhibit gas-flow rates greater than 300 m^3/d, have liquid-hydrocarbon flow, have saline-water flow, or have stabilized buildup pressures greater than 9.8 kPa/m to the depth of the surface-casing shoe, must be repaired immediately. Wells with positive SCVF that fall below these criteria must be checked regularly, with results reported to the ERCB and with repair required at the time of abandonment. Regulations require that surface-casing vents remain open to ensure that pressure does not build up against the surface-casing shoe and to allow for SCVF monitoring. **Fig. 2** shows diagrammatically (left) and photographically (right) a typical wellhead equipped with a surface-casing vent, indicating access to the surface-casing/production-casing annulus.

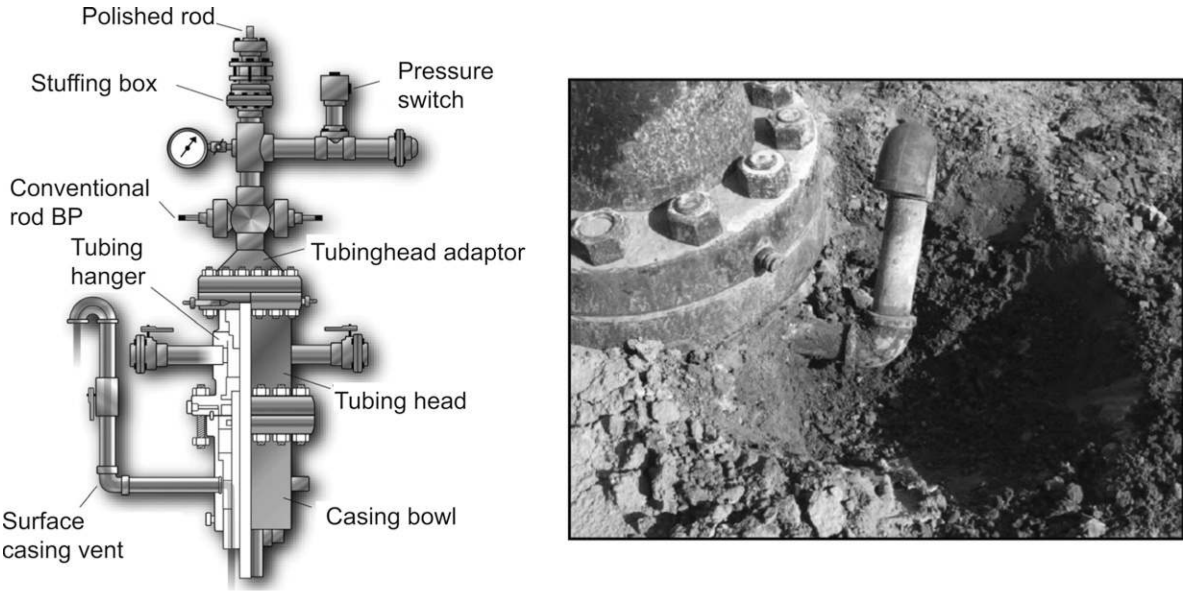

Fig. 2—Diagram and photograph of typical wellhead with surface-casing vent installed (BP: blowout preventer).

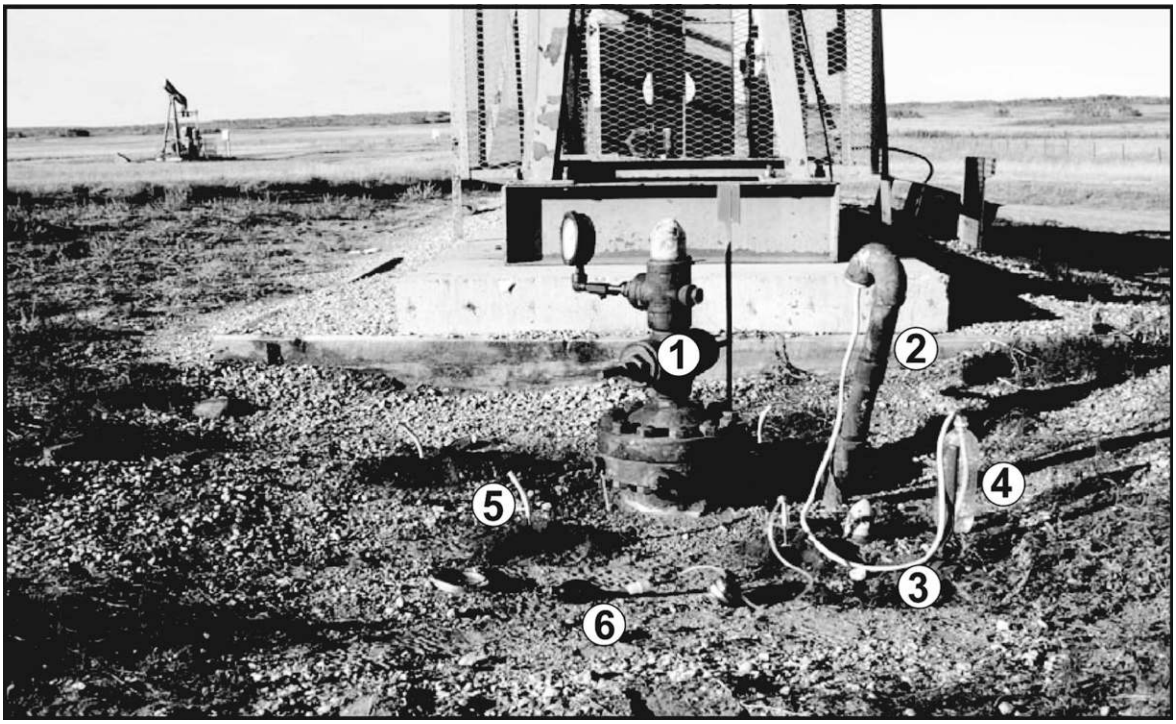

Fig. 3—Wellhead with bubble-test apparatus installed on surface-casing vent, and GM test holes surrounding the wellhead. The numbers are the following: 1—wellhead; 2—surface-casing vent; 3—hose connected to surface-casing vent to direct flow; 4—container with water to observe gas bubbles; 5—GM-test hole; 6—hand pump to direct the accumulated gas to the lower-explosion-limit meter.

The test for SCVF (bubble test) requires that a small hose be attached to the surface-casing vent and the flow directed into a container filled with water. If bubbling is observed in the water, the well is deemed to have SCVF and further testing is then required to determine stabilized buildup pressure and flow rate. **Fig. 3** is a photograph of a typical test apparatus connected to the surface-casing vent at the wellhead. Generally, this test is adequate to determine if further investigation is required; however, in wells with very low flow rates, this test may not identify all potential SCVF. As an example, **Fig. 4** shows a long-term buildup test in a well that, over a 3-year period, exhibited no flow on the annual bubble test and, therefore, could have been cut and capped. The test shows that pressure in this well built up to 550 kPa over a period of 40 days. High buildup pressures may potentially force gas into underground water aquifers (Saskatchewan Research Council 1995).

Soil GM occurs when gas migrates outside of the cemented surface casing. Soil GM can be caused by deep gas from formations below the surface-casing shoe migrating upward past the surface-casing shoe. This leakage may be caused by poor surface-casing cement or by fracturing of cement or rock at the surface-casing shoe caused by overpressuring. GM may also occur from shallow gas accumulations located above the surface-casing shoe leaking through poorly cemented surface casing

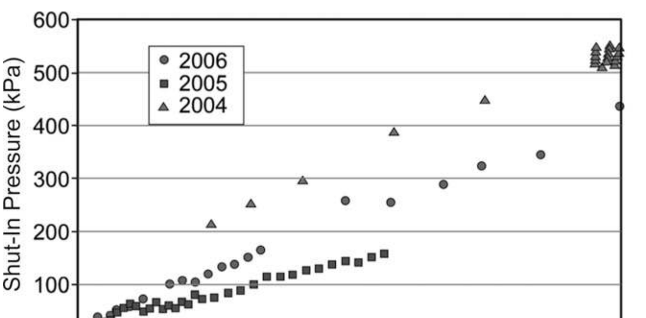

Fig. 4—Annual long-term pressure-buildup tests for SCVF in a well that passed the required bubble test.

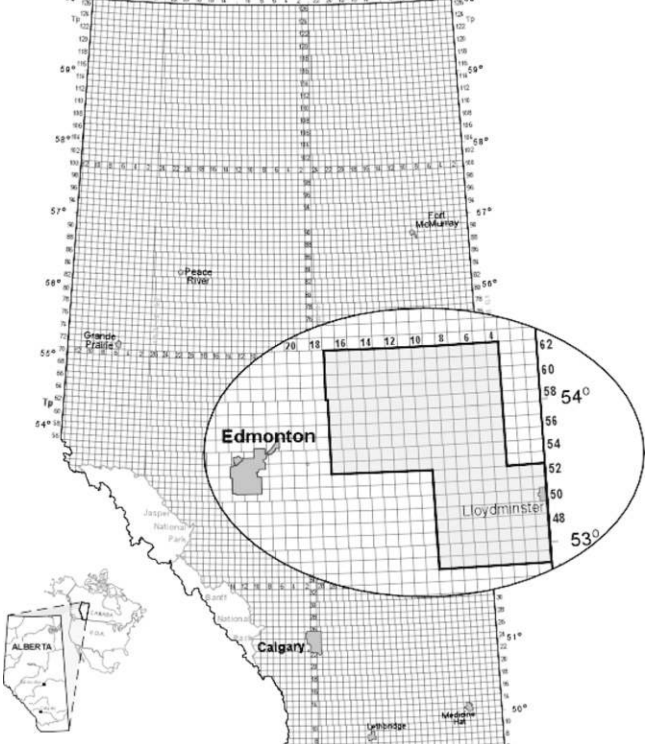

Fig. 5—Location of the test area in Alberta where, by regulation, wells have to be tested for GM.

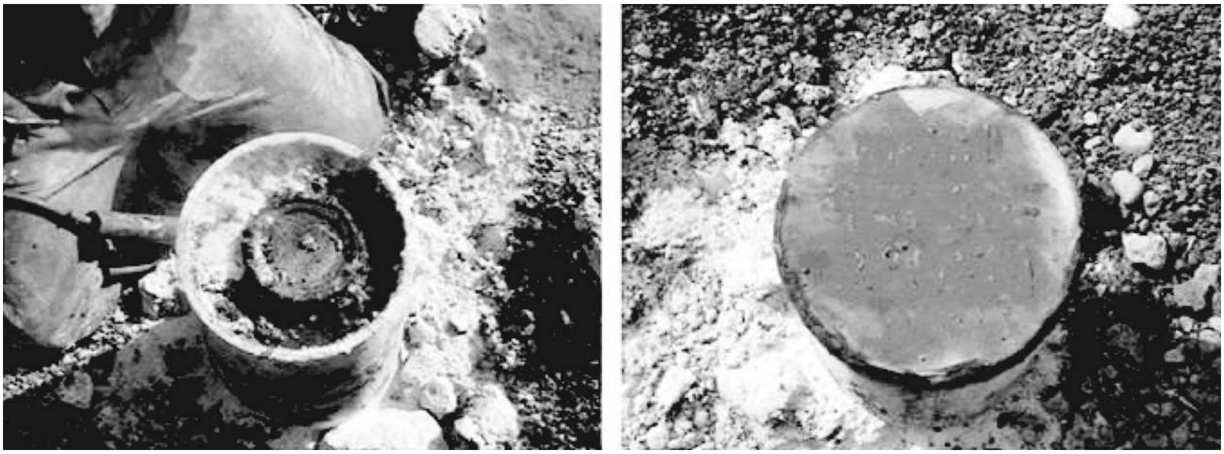

Fig. 6—Illustration of wellbore cut and cap on production casing and surface casing.

(for example, in Alberta, the ERCB's reserves database records gas reservoirs as shallow as 36 m below ground level).

Testing for GM is required in Alberta by regulation in a special area (test area) identified in **Fig. 5.** The ERCB designated this area for testing because field observations indicated high occurrence of GM compared to other areas of the province. In this area, GM testing is required within 60 days of drilling-rig release and before final well abandonment. Many operators conduct this test as part of their due diligence when abandoning a well anywhere in the province. The GM test consists of boring small holes in the soil to a minimum depth of 50 cm in a test pattern radiating out from the wellbore. The holes are stoppered to allow gas to build up, and a reading of lower explosion limit is made to detect combustible gas. Fig. 3 also shows GM testing being conducted at a wellsite before abandonment. If gas is detected, further investigation is conducted to determine if GM is present.

Testing for SCVF and GM became a requirement in Alberta in 1995. Before this, no testing was required and any SCVF/GM that may have been detected by the well operator was not required to be reported to the ERCB. Wells abandoned before 1995 could have been cut and capped with SCVF and/or GM present.

Cut and Cap. After a wellbore is abandoned downhole and all requirements have been met, the well must be cut and capped. The wellhead is excavated to a minimum of 1 m below grade and cut off. Caps are then welded on the production casing and surface casing, as shown in **Fig. 6.** On the basis of field experience, these caps are prone to leakage. Leakage through the well-casing cap may occur if the welding is of poor quality or is corroded. **Fig. 7** illustrates a leaking cap on a previously abandoned wellbore checked before re-entry.

Data Mining To Determine the Potential for and Factors Affecting Wellbore Leakage

The ERCB, the regulatory agency for energy resources production and conservation in Alberta, collects and stores information about all the deep wells in the province (oil, gas, injection, and disposal). At the end of 2004, there were approximately 316,500 wells. The province covers an area of 664,332 km^2, approximately 85% of which is underlain by the Alberta basin, and accounts for approximately 76% of the wells drilled in western Canada. 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. Drilling and production were not regulated until the late 1930s. In 1938, the Alberta Petroleum and Natural Gas Conservation Board (the precursor of today's ERCB) was formed by the provincial government with the purpose and mandate of regulating the oil and gas industry.

The ERCB collects, from the industry, well and production data on a routine basis. This information is readily available to the public. The data include information such as casing size, casing weight, borehole depth, completion intervals, production method, abandonment method, stimulation, gas composition, and geological formations. This information is available in electronic format and served as the pillar for the database used to evaluate wellbore-leakage potential.

In addition, ERCB maintains information regarding SCVF, soil GM, casing failures, and nonroutine abandonment as reported by the industry. Details within this data set, which is not publicly available, include SCVF/GM source, depth, pressure, fluid type, detection date, and repair information. Casing-failure information includes failure depth, failure cause, detection method, and date.

Fig. 7—Illustration of leaking casing caps found at wellbore re-entry on surface casing and production casing.

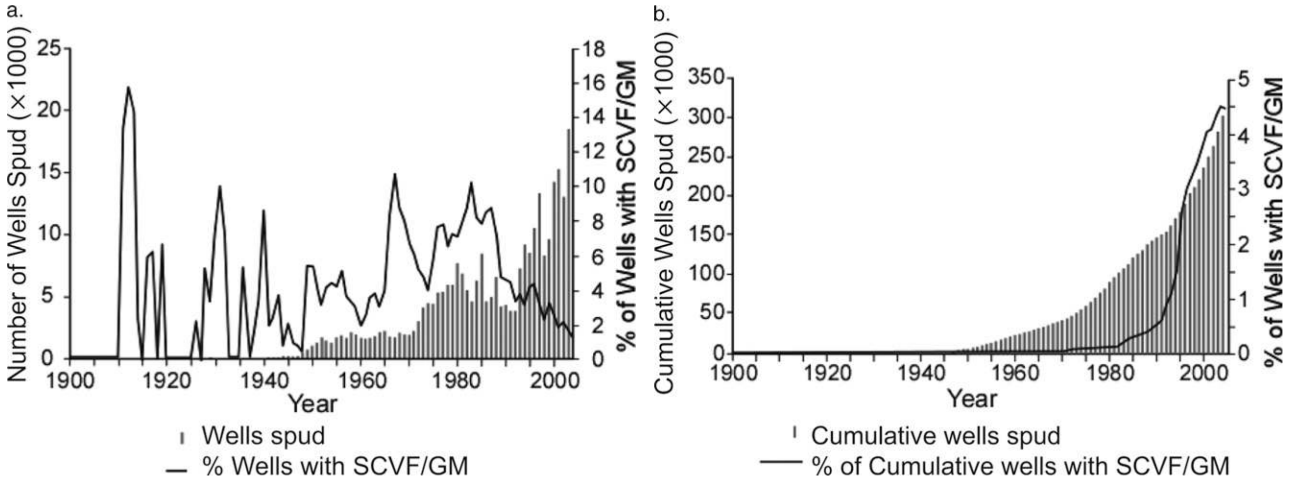

Fig. 8—Historical levels of drilling activity and SCVF/GM occurrence in Alberta: (a) by year of well spud and (b) by cumulative wells drilled.

Nonroutine-abandonment information includes reported openhole plug failures, re-entry information, and other special abandonment requests and approvals. This information was used to provide a baseline of known wellbore leakage against which potential indicators can be evaluated. **Fig. 8** shows historical drilling activity and occurrence of SCVF in Alberta over the last 100 years, both as a percentage of wells spudded in a given year and as cumulative over time.

Historical documents within the ERCB's archive library were reviewed to determine regulatory changes that may have impacted the potential for wellbore leakage. **Fig. 9** indicates important historical regulatory changes against the occurrence of SCVF/GM in time. The archives were also used to develop an electronic-data table of historical primary-cementing requirements. Actual annular cement-top information was not available within the existing electronic information, and the historical-regulation requirement was used as a default for the cement top in the wellbore. The historical oil price, obtained from public sources and expressed in constant USD, was used as an indicator for the level of economic activity that potentially could have affected drilling, well completion, and well abandonment practices. Because the data mining was performed in 2005 based on the data to the end of 2004, Figs. 8 and 9 do not include the recent increase in oil price and the sustained level of drilling of approximately 20,000 new wells per year; however, the absence of these very recent data do not affect the conclusions of the study because very few of the newly drilled wells have been abandoned.

Casing-inspection logs that indicated both internal and external corrosion were evaluated against cement-bond logs (or equivalent). Data were collected for approximately 500 wells. These wells were selected for analysis on the basis of the existence of both SCVF/GM and casing failure in the same well or on the basis of geographic location in fields known to have a high incidence of SCVF/GM or casing failure. Information on casing and cement condition were recorded against a depth register to determine the effects of cementing on casing corrosion. A smaller subset of these wells (142) had adequate data to conduct full evaluations.

Alberta Environment, the provincial agency responsible for the protection of nonsaline groundwater, maintains and is currently updating a public database that indicates the depth, either in meters or by formation, to which groundwater must be protected. This information was used to determine groundwater depths compared to surface-casing, annular-cement, and casing-failure depths.

Results

Various factors were investigated using the assembled database to determine if the potential for leakage could be assessed on the basis of well information that is generally available for a large

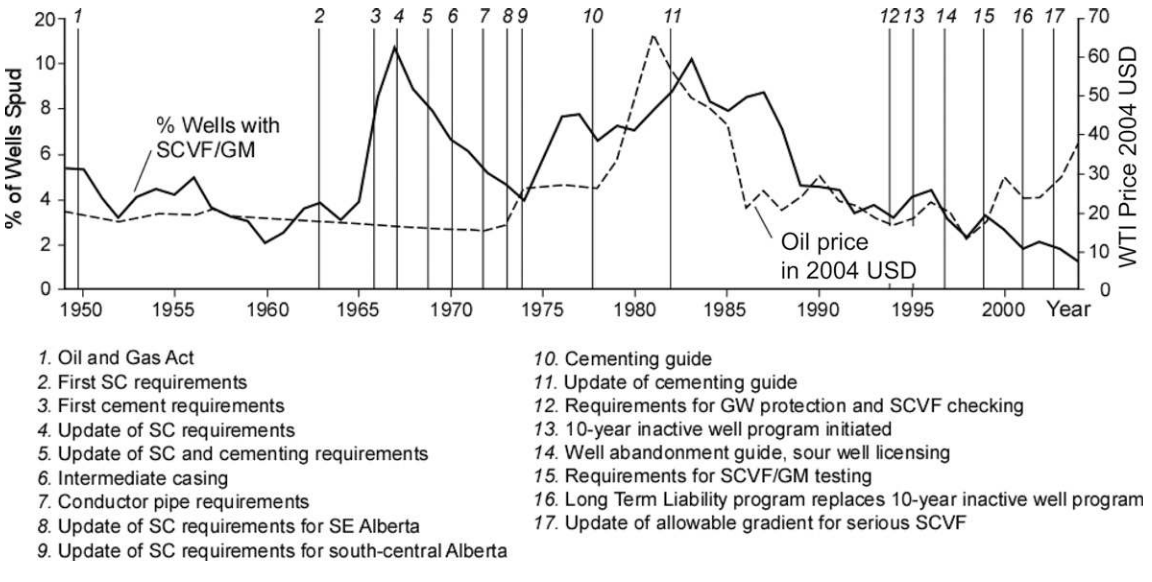

Fig. 9—Occurrence of SCVF/GM in Alberta in relation to oil price and regulatory changes (SC: surface casing, GW: ground water, WTI: West Texas Intermediate).

well population. The following is a discussion of the factors investigated (from the least important to the ones having a major effect), including their impact and possible explanations for the level of impact that they show.

Factors Showing No Apparent Impact. ***Well Age.*** *Well* age was expected to have a significant impact on wellbore leakage because of poorer wellbore-construction techniques and materials in the past and absent or more-relaxed regulatory requirements. The data, however, did not support this expectation. It was determined that this is because the mandatory testing requirement for SCVF/GM did not come into effect until 1995, and many older wells abandoned before 1995 would not have had SCVF/GM reported. Because of a lack of available data, it is unknown if well age has an impact on wellbore leakage. Other factors evaluated relate directly or indirectly to age, on the basis of construction or abandonment practices, such that well age is captured by other factors.

Well-Operational Mode. Well-operational mode, such as producing oil or gas, injecting water or solvents, disposal of liquid waste or acid gas, or observation, did not have any effect on the occurrence of wellbore leakage in the form of SCVF/GM. Thermal-operational modes, such as steam-assisted gravity drainage, cyclic-steam, and steam-injection wells were expected to have a higher occurrence of leakage as a result of the casing and cement being subjected to thermal stresses. The available data did not show this correlation, possibly because of the fact that wells of this nature are newer and largely still operational. The original SCVF/GM testing would have been conducted before thermal activity in the well and before cement-sheath damage. Until a large number of these wells are abandoned and retested, the effect of thermal operations will not be quantifiable. Regarding all other wells, small differences were noted in casing failures during the well-operational life by operational mode, but these failures are not a factor after repair and abandonment.

Completion Interval. No correlation was found between the depth of the SCVF/GM source and the depth of the completion interval. This result was subsequently supported by the casing and cement logs that show that the majority of wells have good cement quality and zonal isolation deep in the wellbore. **Fig. 10** depicts a typical cement quality deeper in the wellbore, near the completion interval, and the SCVF source in shallower formations where cement is typically poor or nonexistent.

H_2S or CO_2 Presence. The presence of hydrogen sulfide (H_2S) and CO_2 in the produced hydrocarbons was investigated for a possible link to casing corrosion, both internal and external. No definitive link was established. This is likely because of the requirement for sour-gas wells to be equipped with packers to protect the internal walls of the production casing. Usually in Alberta, H_2S is found in deep carbonate formations where cement-bond qualities are typically better (see Fig. 10), thus protecting the exterior casing wall from corrosive fluids.

Factors Showing Minor Impact. ***Licensee.*** The effect of a particular company (licensee) on the occurrence of wellbore leakage was investigated in a particular area of high incidence of SCVF/GM in eastern Alberta. The initial assumption was that various companies may have different well-construction practices, and this may be reflected in the incidence of SCVF/GM. **Table 1** compares the overall well count and leakage occurrences for two companies that operate the majority of the wells in that area. The data indicate that the wells owned and operated by one company have a much higher incidence of GM and a much lower incidence of SCVF than the wells operated by the other. However, a clear relationship between SCVF/GM and licensee was not evident in the data. Individual company drilling practices may have influenced the overall reliability of the wells; however, other factors, such as a company's internal standards for testing and reporting of SCVF/GM may also influence the analysis.

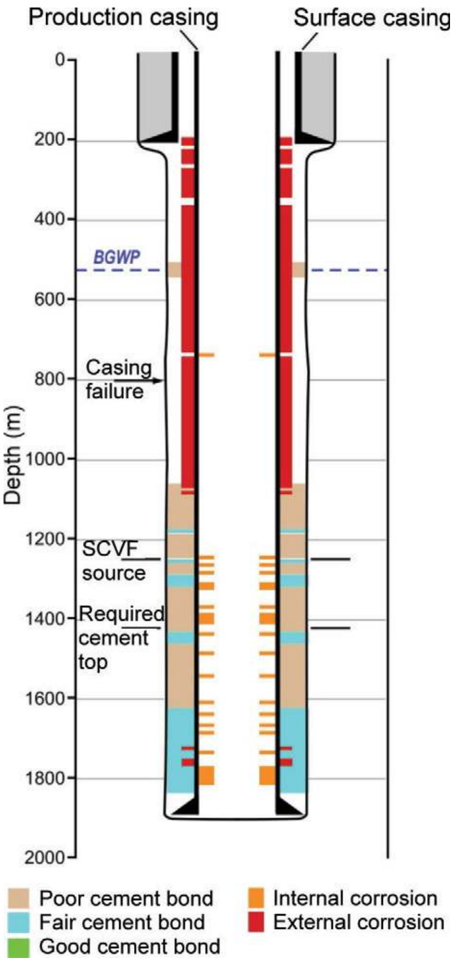

Fig. 10—Cement and casing quality in a well located in the Haynes field, Alberta, Canada.

Surface-Casing Depth. Surface-casing depth was not found to have an overall effect on well leakage for SCVF/GM. However, the surface-casing-setting depth does have an effect on whether the leakage would present at surface as an SCVF or a GM. Generally, as the surface-casing depth increases, the occurrence of SCVF decreases while the occurrence of GM increases. This indicates that GM sources are typically above surface-casing-shoe depths and that the GM occurrence is impacted by cementing practices for surface casing.

Total Depth. The occurrence of SCVF/GM increases slightly with the well total depth. This correlation can be attributed to deeper wells having generally larger uncemented intervals in their upper part, leaving source formations open to flow.

Well Density. On the basis of other studies that have shown a relationship between well density and SCVF/GM (Getzlaf et al. 2003), it was expected that well density has a significant effect on

TABLE 1—LICENSEE COMPARISON IN TERMS OF WELL-LEAKAGE OCCURRENCE

Licensee	% Total Well	% Reported SCVF	% Reported GM	Ratio of SCVF to Well Total	Ratio of GM to Well Total
Licensee A	11.3	7.5	36.2	0.66	3.2
Licensee B	35.4	43.2	52.6	1.2	1.5

TABLE 2—COMPARISON OF SCVF/GM OCCURRENCE IN THE PROVINCE TO THE TEST AREA

	Alberta	Test Area	Percentage in the Test Area	Deviated Wells in the Test Area
Total number of wells	316,439	20,725	6.5%	4,560
Wells with SCVF	12,458	1,902	15.3%	1,472
Wells with GM	1,843	1,187	64.4%	1,550
Wells with GM/SCVF	176	116	65%	–
SCVF percentage	3.9%	9.2%	–	32.3%
GM percentage	0.6%	5.7%	–	34%
Combined percentage	4.6%	15.5%	–	66%

the occurrence of wellbore leakage. In areas of high well density, well-to-well cross flow may occur and result in a single well leaking to surface through many nearby wellbores. However, this was not supported in the analysis of the test area. One possible reason is that areas with higher well density comprise newer wells that may not have been tested sufficiently or that are cemented better. Because this factor has been reported in other studies, it has been retained as a minor factor for this analysis.

Topography. Information about serious SCVFs and GM flows, saline-water flows, and liquid-hydrocarbon flows at wells located in or near river valleys has been reported anecdotally, and in some cases has been well documented, such as in the case of a well in the valley of Peace River in Alberta that discharged brine and natural gas for decades (Bellis et al. 2004). River valleys may facilitate GM and SCVF because of the removal of overburden. This reduction in elevation reduces the available hydrostatic pressure that controls flows to surface. The potentially shallow overpressured gas zones (in comparison to elevation at drill location) pose problems in well control and have a higher potential for GM through cement even in properly cemented wellbores (Gonzalo et al. 2005). However, data analysis did not find a strong correlation between topography and SCVF/GM occurrences.

Factors Showing Major Impact. ***Geographic Area.*** Fig. 5 indicates a specific test area within the province of Alberta. In the test area, it is required by regulation to conduct GM testing on all wells. **Table 2** summarizes the occurrence of SCVF/GM in the entire province compared to the test area. It is not clear if the extra testing requirements in this area result in a greater percentage of leaks being reported or if the occurrence rates are actually higher. It is presumed that the ERCB designated this area for special consideration because of observed problems, and thus, it is likely that the data accurately identify wells in this area as having a higher probability of leakage.

Wellbore Deviation. For the purpose of this study, any well with total depth greater than the true vertical depth was considered a deviated or slant well. Wells were investigated within the test area because both SCVF and GM testing is required in this area, hence the data set is more complete. Table 2 and **Fig. 11** summarize the data. From these results, it appears that well deviation does not significantly affect whether a well will have GM or SCVF because the occurrence rate is similar. However, the occurrence of GM and SCVF is higher in deviated wells than in vertical wells, indicating that wellbore deviation is a factor affecting overall wellbore leakage. Mechanical aspects such as casing centralization and cement slumping may contribute to the increased incidence of wellbore leakage in deviated wells (Jakobsen et al. 1991).

Well Type. Drilled and abandoned wells had reported SCVF/GM leakage-occurrence rates of approximately 0.5%. The overall leakage-occurrence rate reported for all wells, as shown in Fig. 8, is approximately 4.5%. Wells cased and abandoned have an overall leakage-occurrence rate of approximately 14%, with cased wells accounting for more than 98% of all leakage cases reported. This difference may be attributed to more-stringent abandonment requirements for drilled and abandoned wells historically.

Wells cased, completed, and abandoned have another potential leak path inside of the casing because of the perforated, or otherwise-completed, interval (see Fig. 1b).

Abandonment Method. The abandonment method in cased and completed wells in Alberta is predominately bridge plugs capped with cement. Investigations into the security of this abandonment method indicated that overall, bridge plugs held a pressure test of 7000 kPa in 90% of cases investigated in a small sampling of wells re-entered for production purposes. These bridge plugs had been in service for 5 to 30 years. Generally, the cement cap placed on top of the bridge plug was not evident, even though a tour-report review indicated that the cement had been dump bailed on the bridge plug. It is estimated from experience and from this small sample that, over a long period of time (hundreds of years), approximately 10% of these types of zonal abandonments will fail and allow formation gases to enter the wellbore. Other abandonment methods, such as placing a cement plug across completed intervals using a balanced-plug method or setting a cement retainer and squeezing cement through perforations, are expected to have lower failure rates long into the future.

In situations where CO_2 may have been injected for storage into depleted producing formations, bridge-plug failures may be higher because of CO_2 effects on the elastomers and metal used in the mechanical-plugging device (Schremp and Roberson 1975).

The final barrier to reservoir gases escaping to the overlying soil and the atmosphere is the welded casing cap. From investigations on well re-entry, these caps are highly unreliable. However, the casing-cap failures may in fact reduce the risk of overpressuring the surface-casing shoe, uncemented formations, and groundwater aquifers. Small leaks in the cap may act as an early warning that the wellbore integrity has been compromised. These leaks are generally identified as soil GM and are observed as dead vegetation directly above the abandoned wellbore.

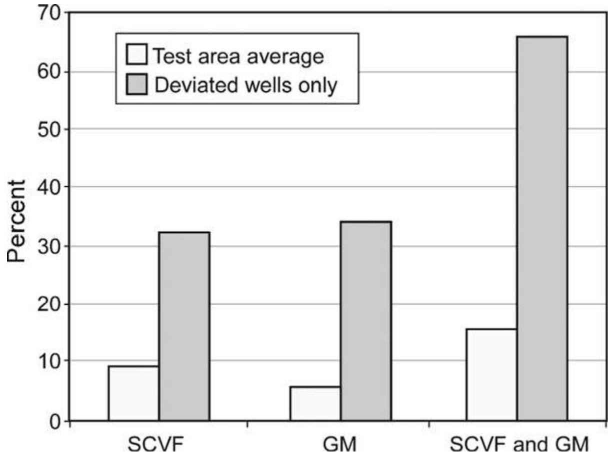

Fig. 11—Comparison of the occurrences of SCVF/GM in all the wells in the test area in Alberta (see Fig. 5) and in deviated wells only in the same region.

Oil Price, Regulatory Changes, and SCVF/GM Testing. Fig. 9 summarizes the occurrence rate of SCVF/GM in Alberta over time plotted against the historical oil price and important regulatory changes. The oil price is used as an indicator of economic and drilling activity in the province.

Between 1973 and 1999 there is a strong correlation between SCVF/GM occurrence and oil price. This correlation may be explained by the level of activity and equipment availability impacting wellbore-construction practices in the field. The pressure to do more with less may have had impacts on primary-cementing-placement practices. Also, with higher price came the economic incentive to develop the heavy-oil areas in Alberta that broadly correspond to the test area in Fig. 5. The development of heavy-oil pools, which require thermal recovery; high well density; and slant-, directional-, and horizontal-well technology, shows an impact. The technology advancement for thermal-oil production and slant wells, coupled with rising oil prices during this period, increased the occurrence of leakage.

The correlation between oil price and SCVF/GM starts to diverge in 2000. Data analysis indicates that this may be a result of SCVF/GM detection. Analysis of wells, both spud and abandoned because testing requirements were implemented in 1995, shows that 53% of wells in this group had SCVF/GM detected within the year before abandonment, while only 11% had SCVF/GM detected within the year after drilling-rig release. The other 36% of SCVF/GM were detected at some other point within the

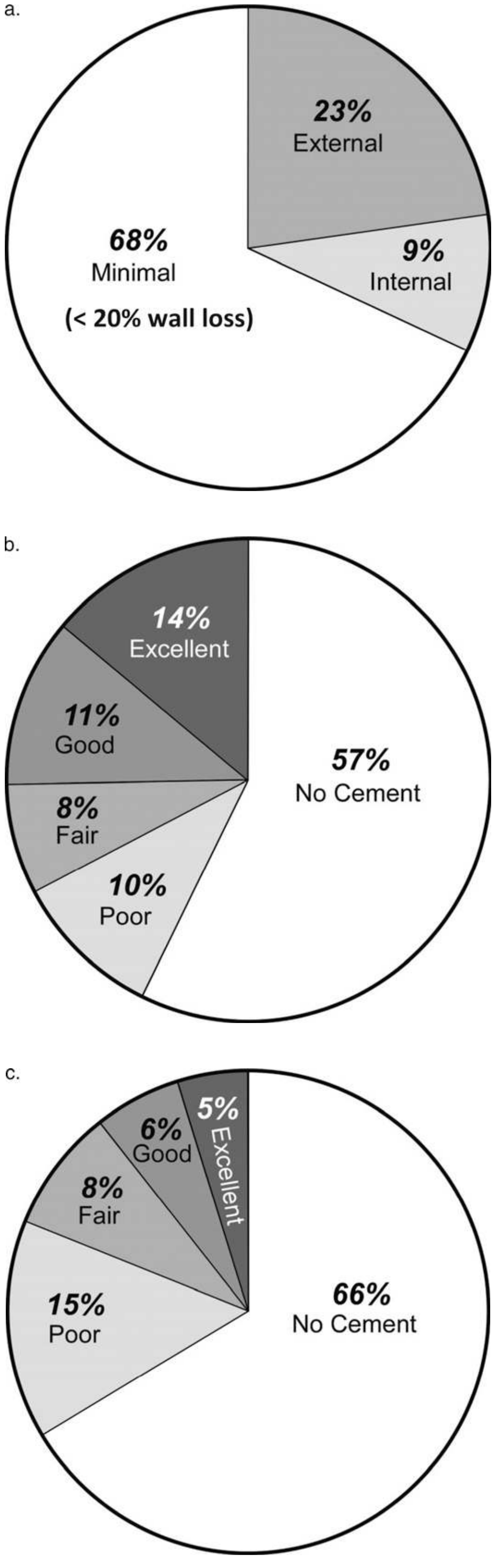

Fig. 12—Analysis of casing corrosion and cement-bond logs for 142 wells in Alberta: (a) corrosion location (based on 129 773 m logged), (b) casing failure compared to cement top and (c) external corrosion vs. cement quality (based on 10 442 m logged).

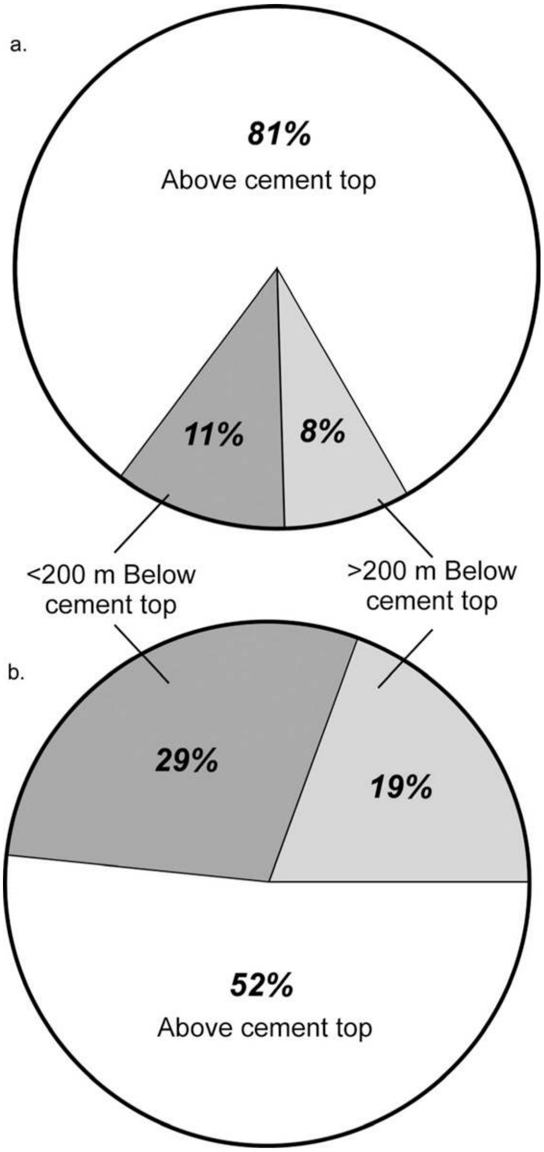

Fig. 13—Location of: (a) SCVF/GM source compared to cement top and (b) corrosion failure (casing failure compared to cement top), in relation to 64 wells in Alberta.

operating life of the well. It is possible that mud hydrostatic pressure may mask SCVF/GM for some period of time until mud contained in the annulus dehydrates, allowing gas to flow. Also, testing and reporting at the time of rig release may not be as rigorous as at the time of abandonment.

Wells spud after 1999, when the trends in SCVF/GM and oil price diverge, have a lower abandonment rate because they are still within their productive lifespan and, therefore, may not yet have had a secondary test to detect SCVF/GM.

Uncemented Casing/Hole Annulus. Low cement top or exposed casing was found to be the most important indicator for SCVF/GM. In addition, this wellbore condition has significant impact on external-casing corrosion, creating the potential for leaks through the casing wall. On the basis of the analysis of well logs for casing inspection and cement-bond quality in 142 wells, the following was determined:

1. The majority of significant corrosion occurs on the external wall of the casing **(Fig. 12a).**
2. A significant portion of wellbore length is uncemented (Fig. 12b).
3. External corrosion is most likely to occur in areas where there is no or poor cement (Fig. 12c).

On the basis of field experience and of cement-bond-log interpretations, it was determined that the top 200 m of the cemented annulus is generally of poor quality. The effect of low or poor cement was evaluated on the basis of the location of the SCVF/GM source compared to cement top. **Fig. 13a** clearly shows that the vast majority of SCVF/GM originates from formations not isolated by cement. Casing-failure location was also compared to cement-top location, as shown in Fig. 13b. Again, the majority of casing failures are in the regions of poor or no cement in the annulus.

Some wells in the investigated group showed external corrosion in areas where cement quality was determined to be good. Upon further investigation, it was determined that in most instances, cement channeling accounted for the areas of external corrosion in what appears to be good cement, as shown in **Fig. 14.**

The possibility of cement deterioration over time, especially over productive formations or formations that may be considered for CO_2 storage, was investigated for 11 wells in a region identified as having a high incidence of SCVF. **Fig. 15** compares cement-bond-log information between logs run 10 years apart. From this evaluation, it appears as though there may be some slight cement deterioration. However, because of technology changes in cement-evaluation tools and interpretation, the logs reviewed were very difficult to compare directly. Wellbore conditions such as low fluid level, foamy fluid, and pressure pass vs. nonpressure pass made a direct comparison in the wellbores investigated difficult. To evaluate cement-sheath deterioration properly, similar logs would have to be run at different times under similar wellbore conditions to achieve a direct comparison. No definitive conclusions could be drawn from the assessment of cement-evaluation logs run at different times in the well life.

Evaluation of well logs in 142 wells and experience indicate cement quality typically improves deeper in the well and in particular across completed intervals. Figs. 10 and 14 both illustrate this.

Prediction of Wellbore Potential for Leakage Based on Well Attributes

On the basis of the results presented previously, **Fig. 16** shows the relative probability of leakage from inside of the casing caused by zonal-abandonment failure, and **Fig. 17** presents a decision tree that uses general well attributes to estimate the probability of leakage in a well in the form of SCVF/GM. The factors or well attributes described in the preceding section are used to evaluate the probability of well leakage qualitatively.

1. Is the well cased, or drilled and abandoned? From the information presented, drilled and abandoned wells have a very low occurrence of leakage, as documented in the ERCB data. Only 0.5% of all drilled and abandoned wells have reported leakage. Cased wells account for 98% of the SCVF/GM incidence in the ERCB data.

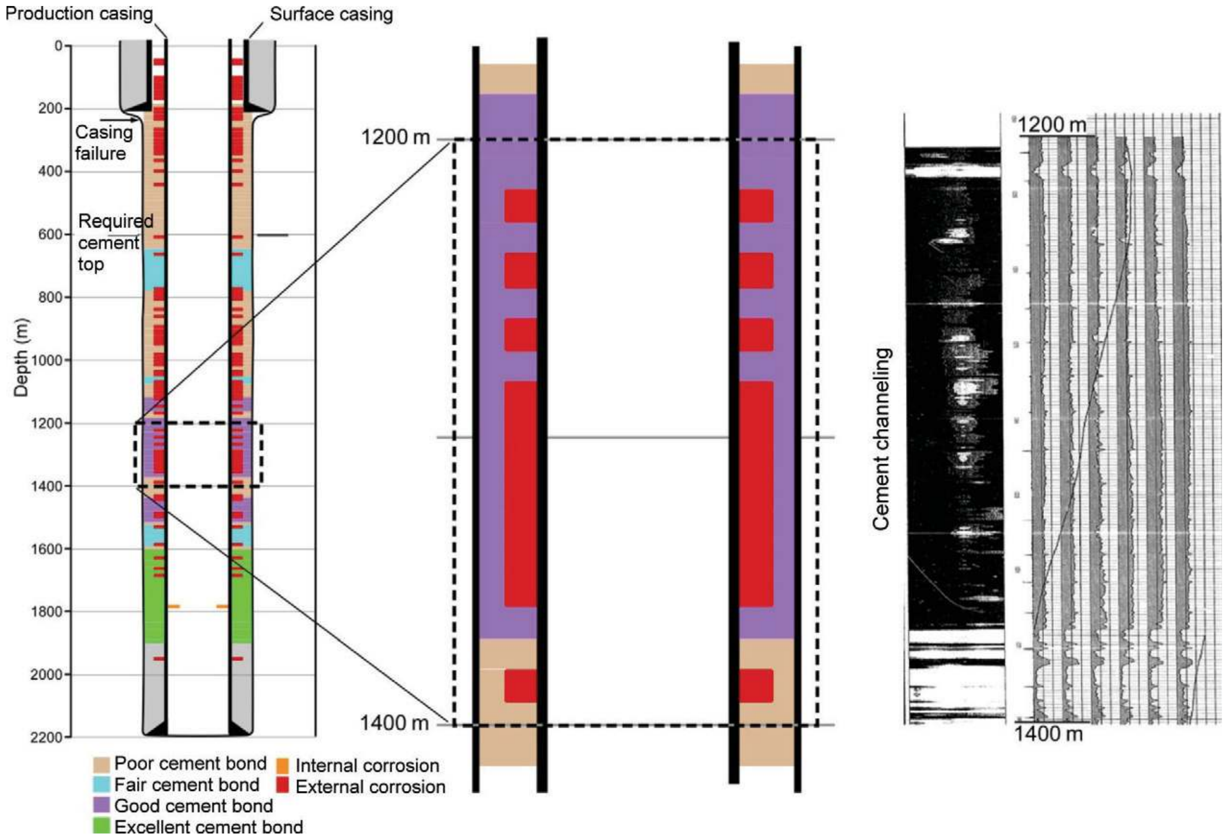

Fig. 14—Example of well-log analysis showing cement-bond quality and casing corrosion, with example of corrosion caused by cement channeling in good cement.

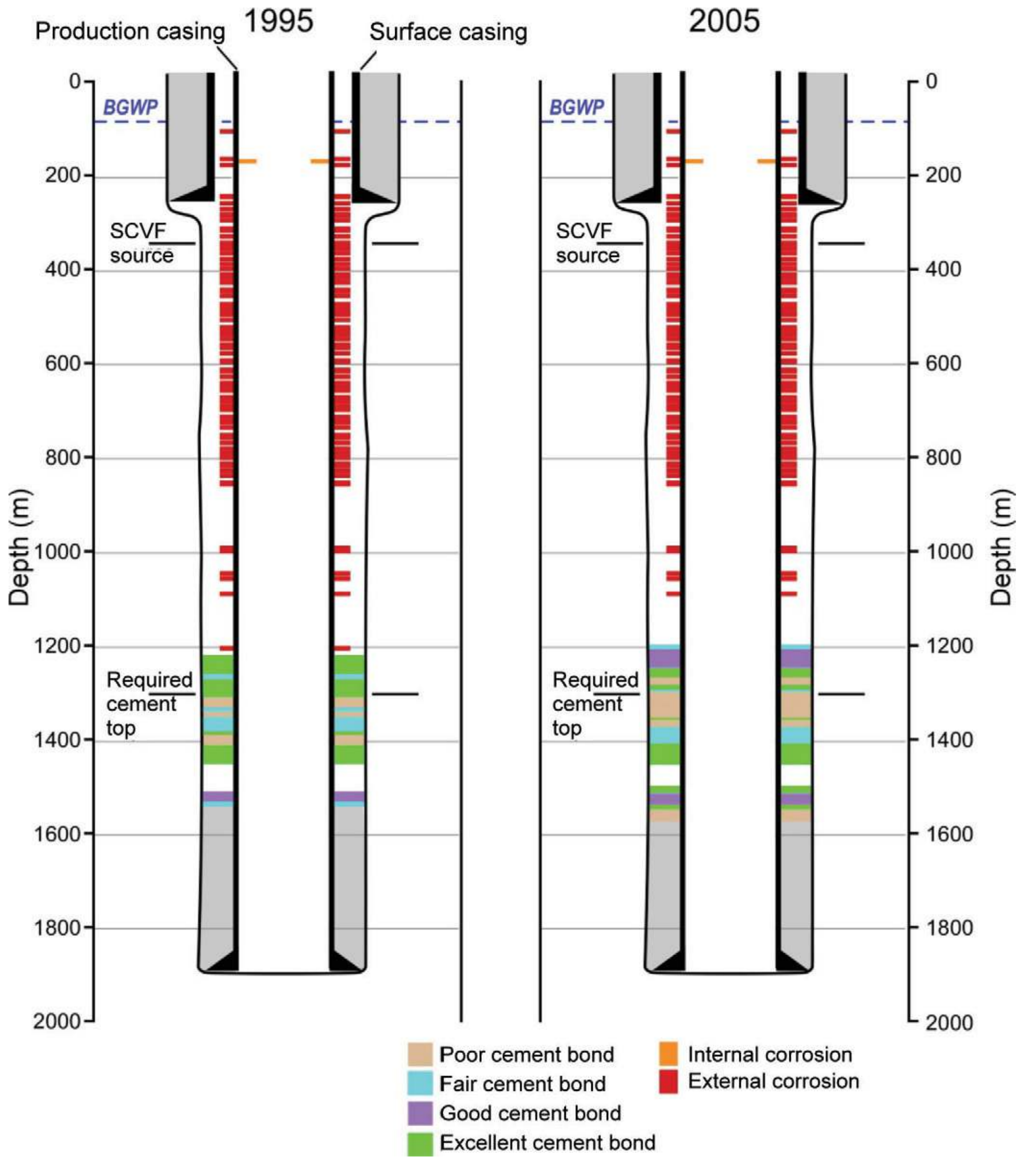

Fig. 15—Example of bond-log interpretations run 10 years apart in a well located in the Zama field. Casing corrosion presentation is from 1995 only.

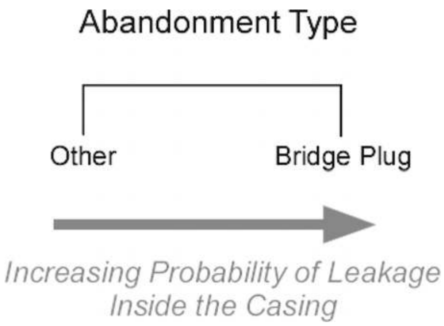

Fig. 16—Decision tree for assessing the potential for well leakage inside production casing.

2. In Alberta, important regulatory changes came into effect in 1995 requiring the testing for SCVF/GM. Was the well abandoned before or after 1995? Wells abandoned after 1995 should exhibit lower probability of leakage because any detected leakage would have been repaired before wellbore abandonment.

3. Was the well drilled before the introduction of regulatory changes in 1995 in a period of time with high relative oil prices? The information shows a strong correlation between the percentage of wells with leakage and the oil price. It is hypothesized that higher oil price led to greater activity with a limited supply of equipment and manpower. The only way to increase the number of wells drilled was to drill them faster, potentially leading to substandard cementing practices.

4. Is there a high incidence of SCVF/GM in a particular area? The information presented shows that in a certain area, the wells are more prone to leakage. This may be because of specific conditions relating to geology and shallow gas accumulations in the area, but this requires further investigation.

5. What is the historical cement-top requirement? The information shows that cement absence is possibly the highest predictor of SCVF/GM and casing failure, as shown in Fig. 13.

Conclusions

1. General well attributes that could be found in the databases of regulatory agencies or in the industry can be used to predict which wells have a high probability of leakage. The method, developed on the basis of well data from Alberta, can be generalized and applied to other basins and/or jurisdictions.
2. The majority of leakage occurrence is because of time-independent mechanical factors controlled during wellbore

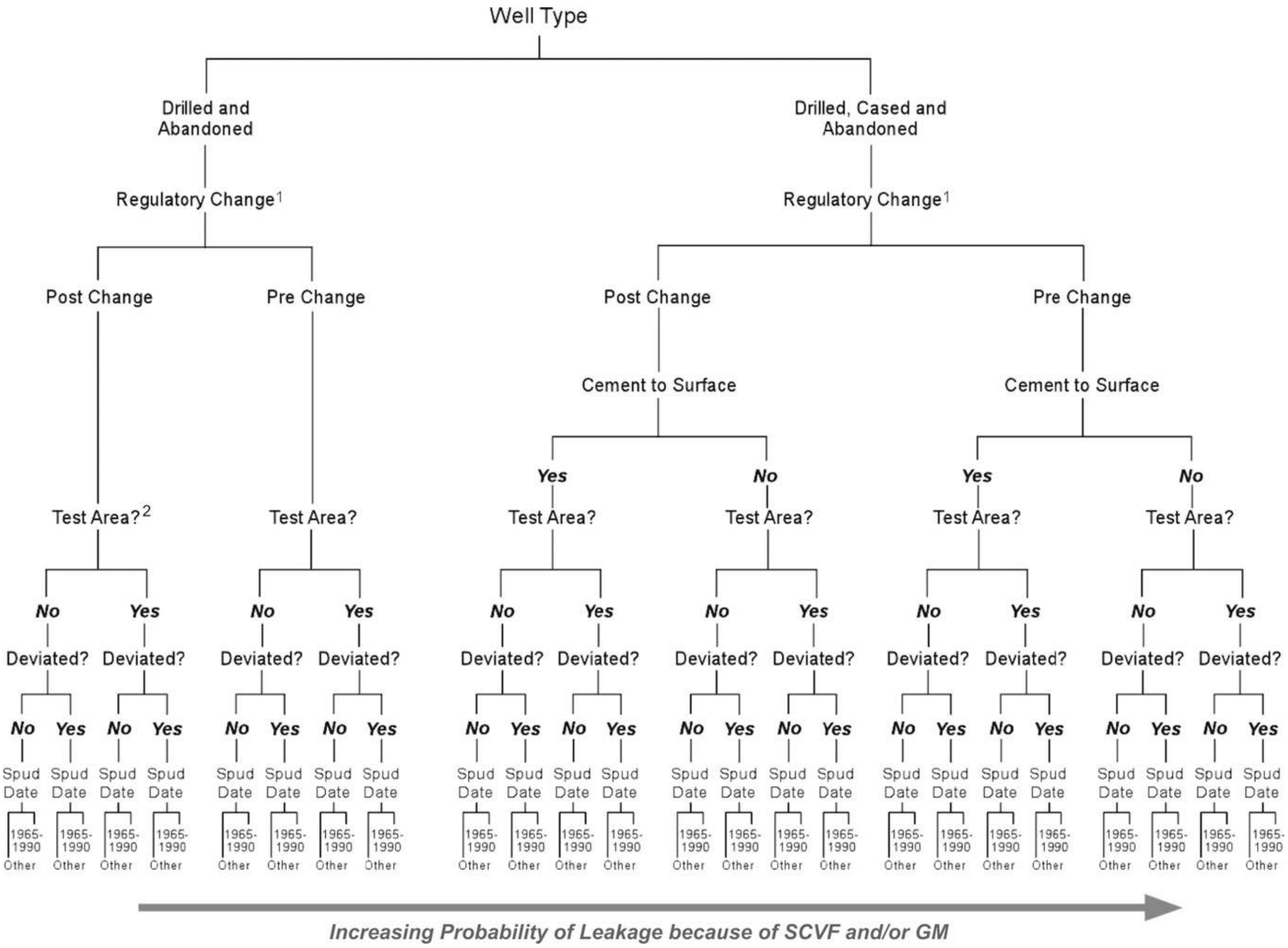

Fig. 17—Decision tree for assessing the potential for well leakage inside and outside surface casing (SCVF and GM). Notes: ^{1} In Alberta, regulations regarding well-abandonment procedures were changed in 1995 (see Fig. 9); ^{2} The test area is defined as an area in Alberta where GM was observed and where testing for GM is required by regulation (see Fig. 5).

drilling, construction, or abandonment—mainly cementing. Several of these factors may be inferred from readily available information such as spud date relating to regulation, oil price, and technology.

3. Exposed (uncemented) casing is the main factor in the occurrence of SCVF/GM and casing failure.
4. Good-quality cementing will likely protect wellbores against cement degradation and casing corrosion by reducing contact with formation or injected fluids.
5. Enforced regulations are critical in controlling and detecting wellbore leakage from annular flow (SCVF/GM), casing failure, or zonal-abandonment failure.
6. Cement-log evaluations indicate that the majority of wellbores are well cemented and zonally isolated in the deeper sections (across economically productive formations) of the wellbore, thus reducing the probability of leakage through casing/openhole annuli from deep uncompleted reservoirs.
7. Deep hydrocarbon reservoirs or saline aquifers that are penetrated by fewer wells should be considered for CO_2 storage to minimize the potential for well-to-well cross flow or vertical-wellbore leakage to overlying strata, shallow groundwater aquifers, and possibly to the atmosphere.
8. Abandonment methods should incorporate adequate methods to withstand CO_2 attack, especially where elastomers and steel are the main plugging materials.

Acknowledgments

The authors would like to acknowledge Roy Van Der Sluis of Baker Atlas for providing well logs and interpretation assistance.

References

Bellis, C.J., Bothwell, P.D., Burke, L.H., Grace, R.D., MacDonald, R.R., and McLellan, P.J. 2004. Design and Execution of a Successful Well Kill on the World's Longest Running Blow-out. Paper SPE 90542 presented at the SPE Annual Technical Conference and Exhibition, Houston, 26–29 September. DOI: 10.2118/90542-MS.

Getzlaf, D., Kattenburg, R., and Watson, T. 2003. Gas migration database helps improve vent flow risk assessment. Paper CADE 2003-001 presented at the CADE/CAODS Drilling Conference, Calgary, 20–22 October.

Gonzalo, V., Aiskely, B., and Alicia, C. 2005. A Methodology To Evaluate the Gas Migration in Cement Slurries. Paper SPE 94901 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, 20–23 June. DOI: 10.2118/94901-MS.

ID 2003-01: 1) Isolation Packer Testing, Reporting, and Repair Requirements, 2) Surface casing venting flow/gas migration testing, reporting, and repair requirements, 3) Casing Failure Reporting. 2003. Calgary, Alberta: EUB/ERCB.

Jakobsen, J., Sterri, N., Saasen, A., Aas, B., Kjosnes, I., and Vigen, A. 1991. Displacements in Eccentric Annuli During Primary Cementing in Deviated Wells. Paper SPE 21686 presented at the SPE Production Operations Symposium, Oklahoma City, Oklahoma, USA, 7–9, April. DOI: 10.2118/21686-MS.

Metz, B., Davidson, O., De Coninck, H.C., Loos, M., and Mayer, L.A., ed. 2005. Intergovernmental Panel on Climate Change. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge, UK: Cambridge University Press.

Moritis, G. 2006. Special Report: EOR/Heavy Oil Survey. *Oil and Gas Journal* **104** (15): 37–57.

Saskatchewan Research Council (SRC). 1995. Migration of methane into groundwater from leaking production wells near Lloydminster. CAPP Report 1995-001, Canadian Association of Petroleum Producers (CAPP), Calgary, Alberta (March 1995).

Schremp, F. and Roberson, G. 1975. Effect of Supercritical Carbon Dioxide (CO2) on Construction Materials. *SPEJ* **15** (3) 227–233. SPE-4667-PA. DOI: 10.2118/4667-PA.

Watson, T.L. 2004. Surface casing vent flow repair—A process. Paper CIM 2004-297 presented at the 5th Canadian International Petroleum Conference, Calgary, 8–10 June.

Theresa Watson owns and operates T.L. Watson & Associates. She has extensive local and international experience in long-term liability management, wellbore integrity, regulatory compliance, wellbore construction, and the repair of problem wells, including severe GM and abandonments. Recently, Watson has been heavily involved with the International Energy Agency, investigating CO_2-storage potential. Watson is a member of several organizations including SPE, the Petroleum Technical Alliance of Canada, and the Association of Professional Engineers, Geologists, and Geophysicists of Alberta. She has authored and presented several papers dealing with GM repair, cementing techniques, and wellbore-failure prediction. Watson received her BS in chemical engineering from McGill University in Montreal, Canada.

Stefan Bachu is the principal scientist for CO_2 storage at the Alberta Research Council in Edmonton, Canada. His main areas of interest are CO_2 storage in geological media, and hydrogeology and geothermics of sedimentary basins. As a lead author in the Intergovernmental Panel on Climate Change (IPCC) special report on CO_2 capture and storage, Bachu co-shares in the Nobel Peace Prize awarded in 2007 to IPCC and Al Gore. His MS and PhD degrees in engineering are from Bucharest Polytechnic University and Technion-Israel Institute of Technology, respectively.