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Evaluation of the Potential for Gas and CO_2 Leakage along Wellbores

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Abstract

Implementation of carbon dioxide 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, Canada. 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 industry.

The evaluation of a leakage pathway through wellbore casing or annuli and what causes these wellbore leaks is a first step in determining what factors may contribute to wellbore leakage from CO_2 storage sites. By utilizing available data, major factors which 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 extensively investigated[1]. More than 80 CO_2 injection schemes have been in operation since as early as the 1970's for tertiary oil recovery as miscible floods[2], 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 other geological formations, to justify the costs and to meet safety requirements and greenhouse gas reduction objectives. This paper will focus on human created 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 which can be used to predict which wellbores are most likely to leak, have future abandonment liability and if these wellbores will adversely impact CO_2 storage schemes 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, Canada.

Background

Potential Wellbore Leakage Pathways

Figure 1 illustrates typical wellbore construction and abandonment profiles for Alberta, Canada. 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[3]:

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

Since 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 due to injection. Therefore, since 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, non-saline 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

Figure 1a depicts a typical open-hole abandonment scenario in Alberta. Regulations require that any porous zone be isolated or covered to prevent cross flow between geological formations. In addition, non-saline groundwater (defined as water containing less than 4000 mg/l Total Dissolved Solids - TDS) 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 five 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 Figure 1a indicate possible leakage pathways from potential storage or gas bearing formations.

Wells drilled, cased, completed and abandoned

Figure 1b depicts a typical cased hole abandonment after reservoir depletion and some potential leakage pathways. There are three main types of zonal isolation and abandonment:

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

Regulations since 2003 require zonal isolation behind casing and that non-saline 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 current regulations, a cement squeeze would be required to achieve isolation prior to final abandonment.

Wellbores must be abandoned with inhibited fluid inside of the casing and be pressure-tested to a minimum of 7000 kPa. Prior to cutting and capping of the production and surface casing, the well must be checked for surface casing vent flow (SCVF) and gas migration (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 similar requirements to the above with the exception of isolation of the perforated interval.

Testing for Surface Casing Vent Flow and Gas Migration

Surface casing vent flow (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 prior to final abandonment[4]. Wells that have positive SCVF and exhibit gas flow rates greater than 300 m^3/d, have liquid hydrocarbon flow, saline water flow or have stabilized build-up 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 and reported to the ERCB, 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. Figure 2 shows diagrammatically and an actual case of a typical wellhead equipped with a surface casing vent, indicating access to surface casing/production casing annulus.

The test for SCVF (bubble test) requires 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 build-up pressure and flow rate. Figure 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, Figure 4 shows a long term build-up test in a well that, over a three 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 build up pressures may potentially force gas into underground water aquifers[5].

Soil gas migration (GM) occurs when gas migrates outside of the cemented surface casing. Soil gas migration can be caused by deep gas from formations below the surface casing shoe migrating upwards past the surface casing shoe. This leakage may be caused by poor surface casing cement, or fracturing of cement or rock at the surface casing shoe due to overpressuring. Gas migration may also occur from shallow gas accumulations located above the surface casing shoe leaking through poorly cemented surface casing (for example, in Alberta, the ERCB's reserves data base records gas reservoirs as shallow as 36 m below ground level).

Testing for gas migration (GM) is required in Alberta by regulation in a special area (Test Area) identified in Figure 5. The ERCB designated this area for testing due to field observations of 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 also prior to final 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 (LEL) is made to detect combustible gas. Figure 3 also shows gas migration testing being conducted at a wellsite prior to 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. Prior to 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 prior to 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 Figure 6. Based on field experience, these caps are prone to leakage. Leakage through the well casing cap may occur if the welding is of poor quality or corroded. Figure 7 illustrates a leaking cap on a previously abandoned wellbore checked prior to 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 the province of Alberta, Canada, collects and stores information about all the deep wells in the province (oil and 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 ~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 1930's. 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 industry well and production data on a routine basis and this information is readily available to the public. It includes data on wellbore construction and production such as: casing size, casing weight, borehole depth, completion intervals, production method, abandonment method, stimulation, gas composition, geological formations, etc. This information is available in electronic format and served as the pillar for the data base used to evaluate wellbore leakage potential.

In addition, ERCB maintains information regarding surface casing vent flow, soil gas migration, casing failures and non-routine abandonment information as reported by 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 and cause, detection method and date. Non-routine abandonment information includes reported open-hole plug failures, re-entry information and other special abandonment requests and approvals. This information was used to provide a baseline of known wellbore leakage to evaluate potential indicators against. Figure 8 shows historic drilling activity and occurrence of surface casing vent flow in Alberta over the last 100 years, both as a percentage of wells spud in a given year, and 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. Figure 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 regulated requirement was utilized as a default for the cement top in the wellbore. The historical oil price, obtained from public sources and expressed in constant US$, was used as an indicator for the level of economic activity that potentially could have affected drilling, well completion and abandonment practices. Because the data mining was performed in 2005 based on the data to the end of 2004, Figures 8 and 9 do not include the recent increase in oil price and the sustained level of drilling of approximately 20,000 new wells/year; however, the absence of these very recent data do not affect the conclusions of the study since very few of the newly drilled wells have been abandoned.

Casing inspection logs which 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 based on the existence of both SCVF/GM and casing failure in the same well, or on 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 non-saline groundwater, maintains and is currently updating a public data base that indicates the depth, either in metres 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 based on well information that is generally available for a large well population. The following is a discussion of the factors investigated, from the least important to the ones having a major effect, 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 due to 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 prior to 1995 would not have had SCVF/GM reported. Due to 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, based on 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 (SAGD), 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 due to the fact that wells of this nature are newer and largely still operational. The original SCVF/GM testing would have been conducted prior to thermal activity in the well and 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. Figure 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 non-existent.

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 due to 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 Figure 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 internal requirements for testing and reporting of SCVF/GM may also influence the analysis.

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 a SCVF or 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

Based on other studies that have shown a relationship between well density and SCVF/GM[6], it was expected that well density has a significant effect on 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 might be that areas with higher well density are comprised of newer wells that may not have been sufficiently tested or that are better cemented. Because this factor has been reported in other studies, it has been retained as a minor factor for this analysis.

Topography

Information of serious SCVF/GM flows, saline water flows and liquid hydrocarbon flows at wells located in or near river valleys has been anecdotally reported, and in some cases well documented, as in the case of a well in the valley of Peace River in Alberta that discharged brine and natural gas for decades[7]. River valleys may facilitate gas migration and surface casing vent flow due to 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 gas migration through cement even in properly cemented wellbores[8]. However, data analysis did not find a strong correlation between topography and SCVF/GM occurrences.

Factors Showing Major Impact

Geographic Area

Figure 5 indicates a specific test area within the province of Alberta. In the Test Area it is required by regulation to conduct gas migration 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 areas 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 due to 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 (TD) greater than the true vertical depth (TVD) was considered a deviated or slant well. Wells were investigated within the Test Area since both SCVF and GM testing is required in this area, hence the data set is more complete. Table 2 and Figure 11 summarize the data. From these results it appears that well deviation does not significantly affect whether a well will have gas migration or surface casing vent flow as the occurrence rate is similar. However, the occurrence of gas migration and surface casing vent flow 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[9].

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 Figure 8 is approximately 4.5%. Wells cased and abandoned have an overall leakage-occurrence rate of approximately 14%, with cased wells accounting for over 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 due to the perforated or otherwise completed interval (see Figure 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 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 due to CO_2 effects on the elastomers and metal used in the mechanical plugging device[10].

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 over pressuring 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 gas migration, and are observed as dead vegetation directly above the abandoned wellbore.

Oil Price, Regulatory Changes and SCVF/GM Testing

Figure 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 cement placement practices. As well, with higher price came the economic incentive to develop the heavy oil areas in Alberta which broadly correspond to the Test Area in Figure 5. The development of heavy oil pools, which require thermal recovery, high well density, 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 since testing requirements were implemented in 1995 shows that 53% of wells in this group had SCVF/GM detected within the year prior to abandonment, while only 11% were detected within the year after drilling rig release. The other 36% of SCVF/GM were detected at some other point within the 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. As well, testing and reporting at the time of rig release may not be as rigorous as at time of abandonment.

Wells spud after 1999, when the trends in SCVF/GM and oil price diverge, have a lower abandonment rate as 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. Based on 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 (Figure 12a);
2. A significant portion of wellbore meterage is uncemented (Figure 12b);
3. External corrosion is most likely to occur in areas where there is no or poor cement (Figure 12c).

Based on field experience and on cement bond log interpretations it was determined that the top 200 m of the cement annulus is generally of poor quality. The effect of low or poor cement was evaluated based on the location of SCVF/GM source compared to cement top. Figure 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 Figure 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 is 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 Figure 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. Figure 15 compares cement bond log information between logs run ten years apart. From this evaluation it appears as though there may be some slight cement deterioration. However, due to 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 versus non-pressure pass, made a direct comparison in the wellbores investigated difficult. To properly evaluate cement sheath deterioration, 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, as well as experience, indicates that the cement quality typically improves deeper in the well and in particular across completed intervals. Figures 10 and 14 both illustrate this.

Prediction of Wellbore Potential for Leakage Based on Well Attributes

Based on the results presented previously, Figure 16 shows the relative probability of leakage from inside of the casing due to zonal abandonment failure, and Figure 17 presents a decision tree which utilizes general well attributes to estimate the probability of leakage in a well in the form of SCVF/GM. The factors or well attributes previously described are used to qualitatively evaluate the probability of well leakage.

1. Is the well cased, or drilled and abandoned (D&A)? 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 D&A wells have reported leakage. Cased wells account for 98% of the SCVF/GM incidence in the ERCB data.
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, as any detected leakage would have been repaired prior to 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 due to 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 Figure 13.

Conclusions

1. General well attributes that could be found in the databases of regulatory agencies or in industry can be used to predict which wells have a high probability of

leakage. The methodology, 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 due to time-independent mechanical factors controlled during wellbore 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/open hole annuli from deep uncompleted reservoirs.
7. Deep hydrocarbon reservoirs or saline aquifers which 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.

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Tables

Table 1: Licensee Comparison in terms of Well Leakage Occurrence

Licensee	% Total Well	% Reported SCVF	% Reported GM	Ratio SCVF:Well Total	Ratio GM: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%

Figures

Figure 1: Typical well abandonments in Alberta, Canada.

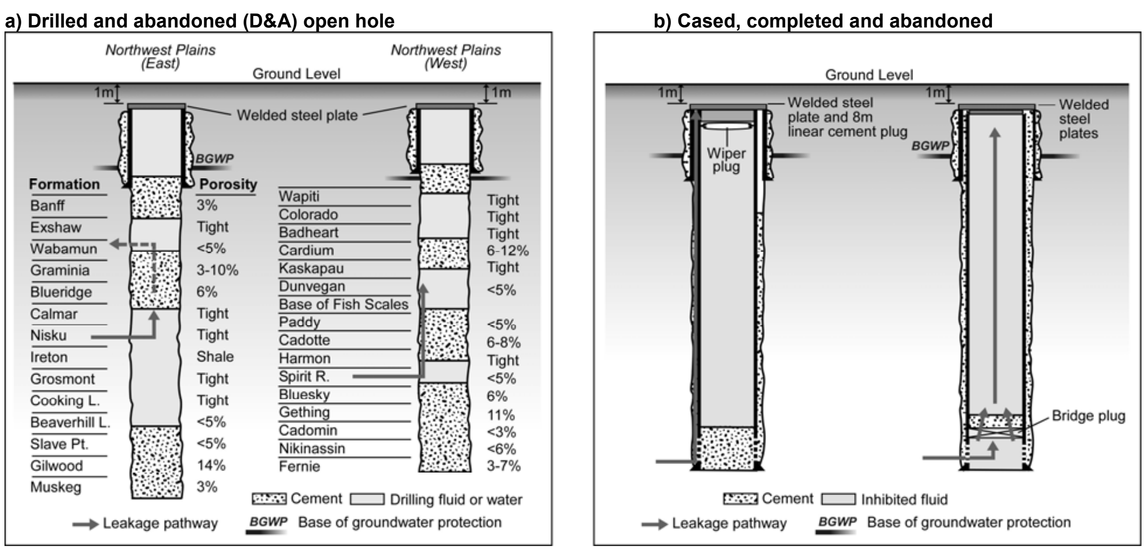


Figure 2: Diagram and illustration of typical wellhead with surface casing vent installed

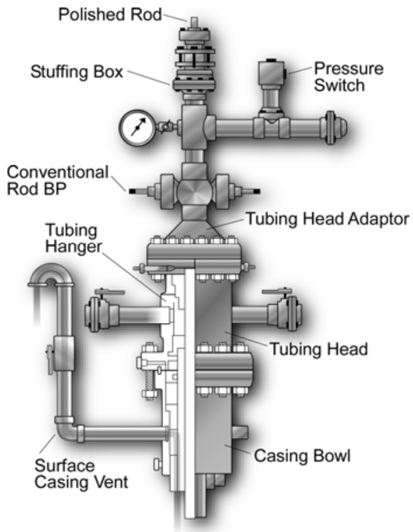
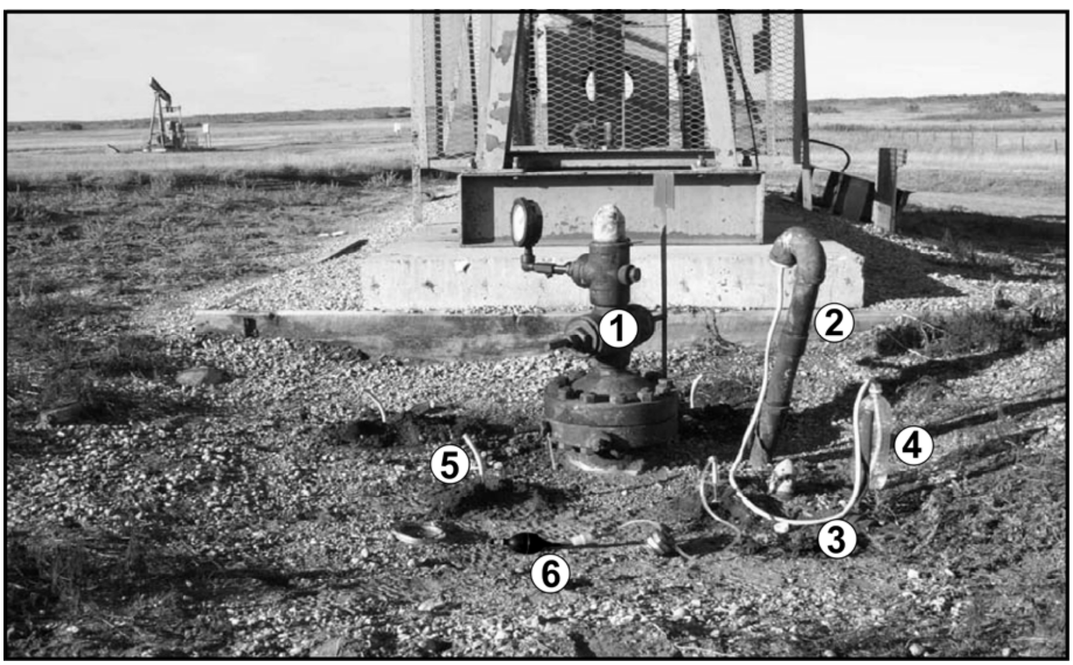


Figure 3: Wellhead with bubble test apparatus installed on surface casing vent, and gas migration test holes surrounding the wellhead.



1: Wellhead;
2: Surface casing vent (SCV);
3: Hose connected to SCV to direct flow
4: Container with water to observe gas bubbles
5: gas migration test hole
6: Hand pump to direct the accumulated gas to the LEL meter (LEL: Lower Explosion Limit)

Figure 4: Annual long-term pressure build-up tests for SCVF in a well that passed the required bubble test.

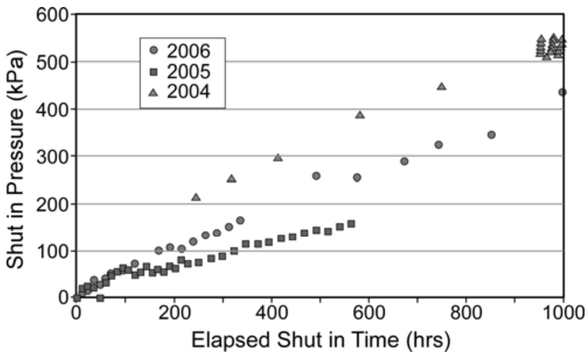


Figure 5: Location of the Test Area in Alberta where, by regulation, wells have to be tested for gas migration (GM)

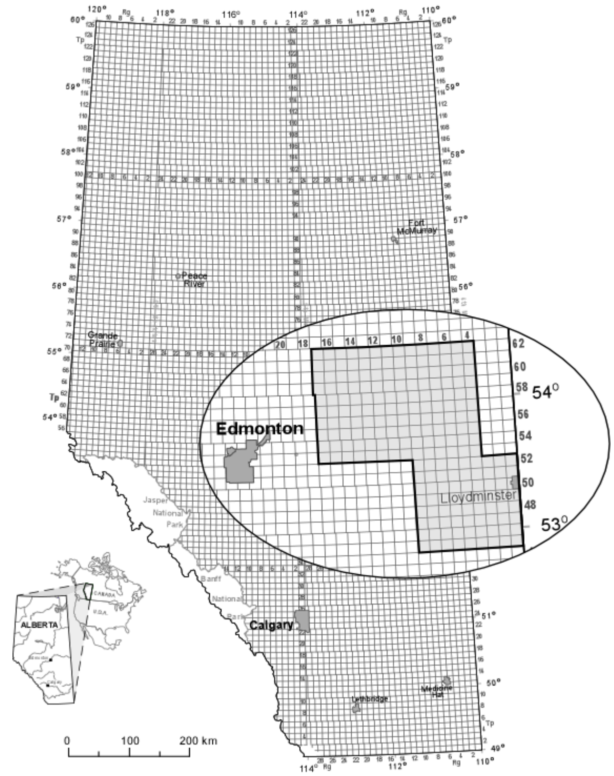


Figure 6: Illustration of wellbore cut and cap on production casing and surface casing.

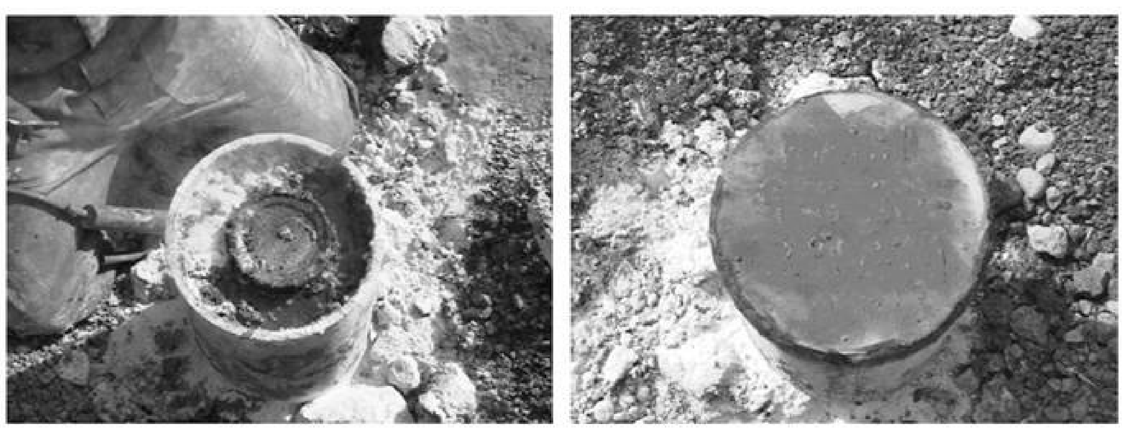


Figure 7: Illustration of leaking casing caps found at wellbore re-entry on surface casing and production casing.

Figure 8: Historic levels of drilling activity and SCVF/GM occurrence in Alberta

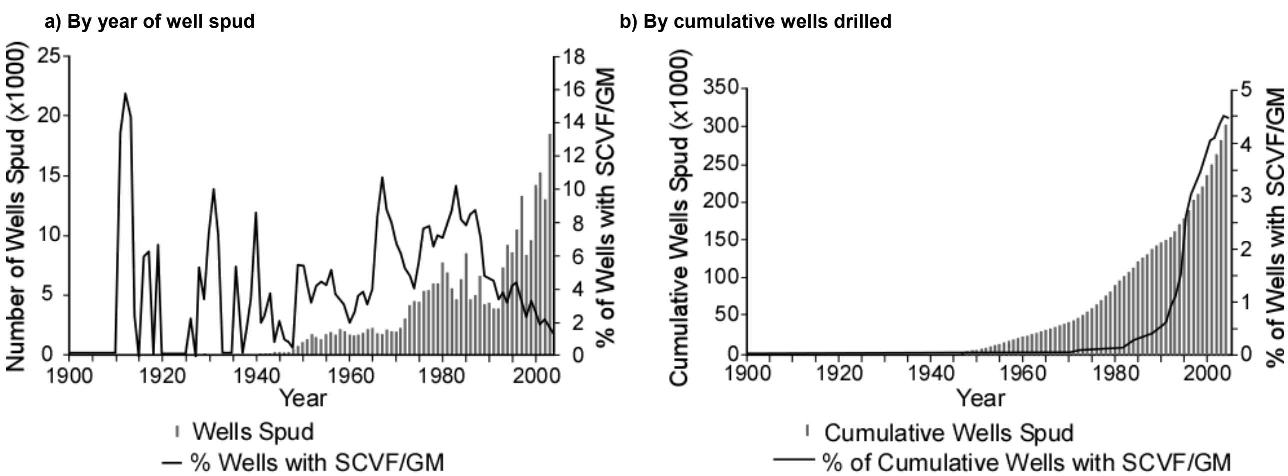


Figure 9: Occurrence of SCVF/GM in Alberta in relation to oil price and regulatory changes.

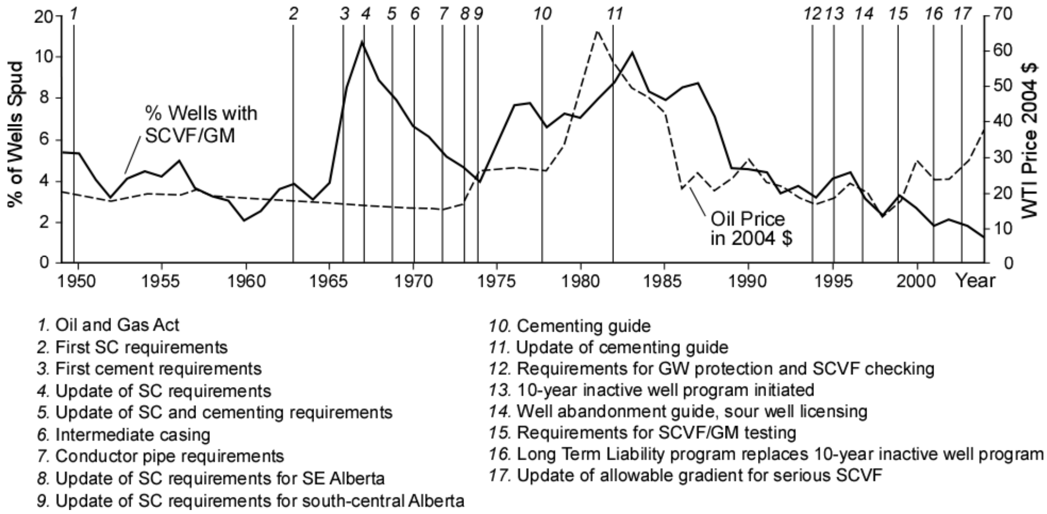


Figure 10: Cement and casing quality in a well located in the Haynes Field, Alberta, Canada.

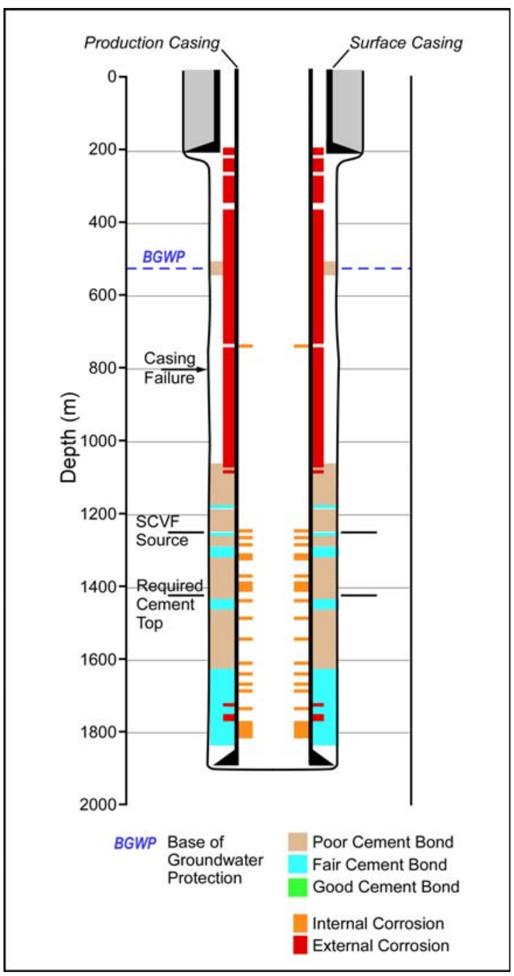


Figure 11: Comparison between the occurrences of SCVF/GM in all the wells in the Test Area in Alberta (see Figure 5) and in deviated wells only in the same region.

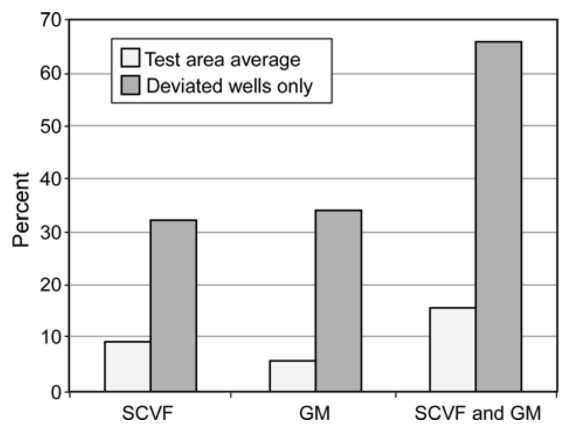
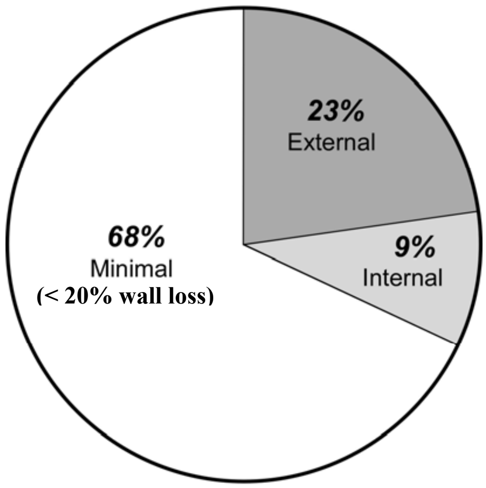
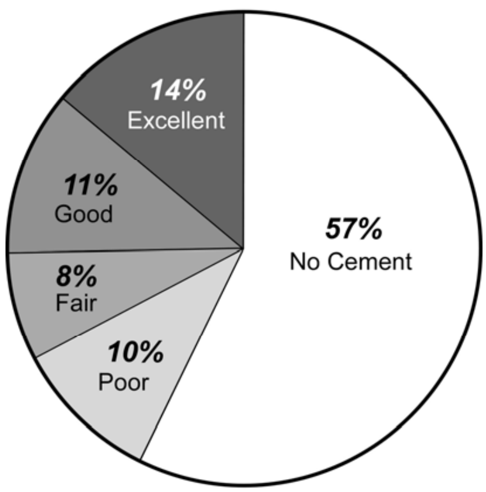


Figure 12: Analysis of casing corrosion and cement bonding logs for 142 wells in Alberta

a) Corrosion location (based on 129,773 m logged)



b) Casing failure compared to cement top



c) External corrosion vs. Cement quality (based on 10,442 m logged)

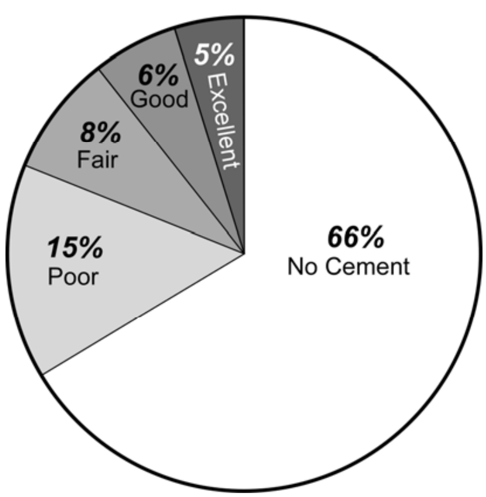
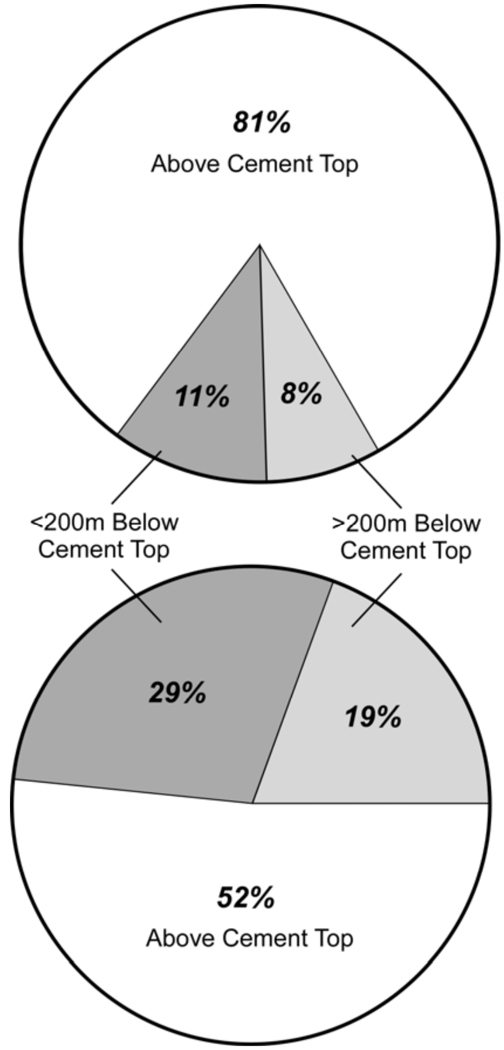


Figure 13: Location of: a) SCVF/GM source, and b) corrosion failure, in relation to 64 wells in Alberta.

a) SCVF/GM source compared to cement top



b) Casing failure compared to cement top

Figure 14: Example of well log analysis showing cement bond quality and casing corrosion with example of corrosion due to cement channeling in good cement.

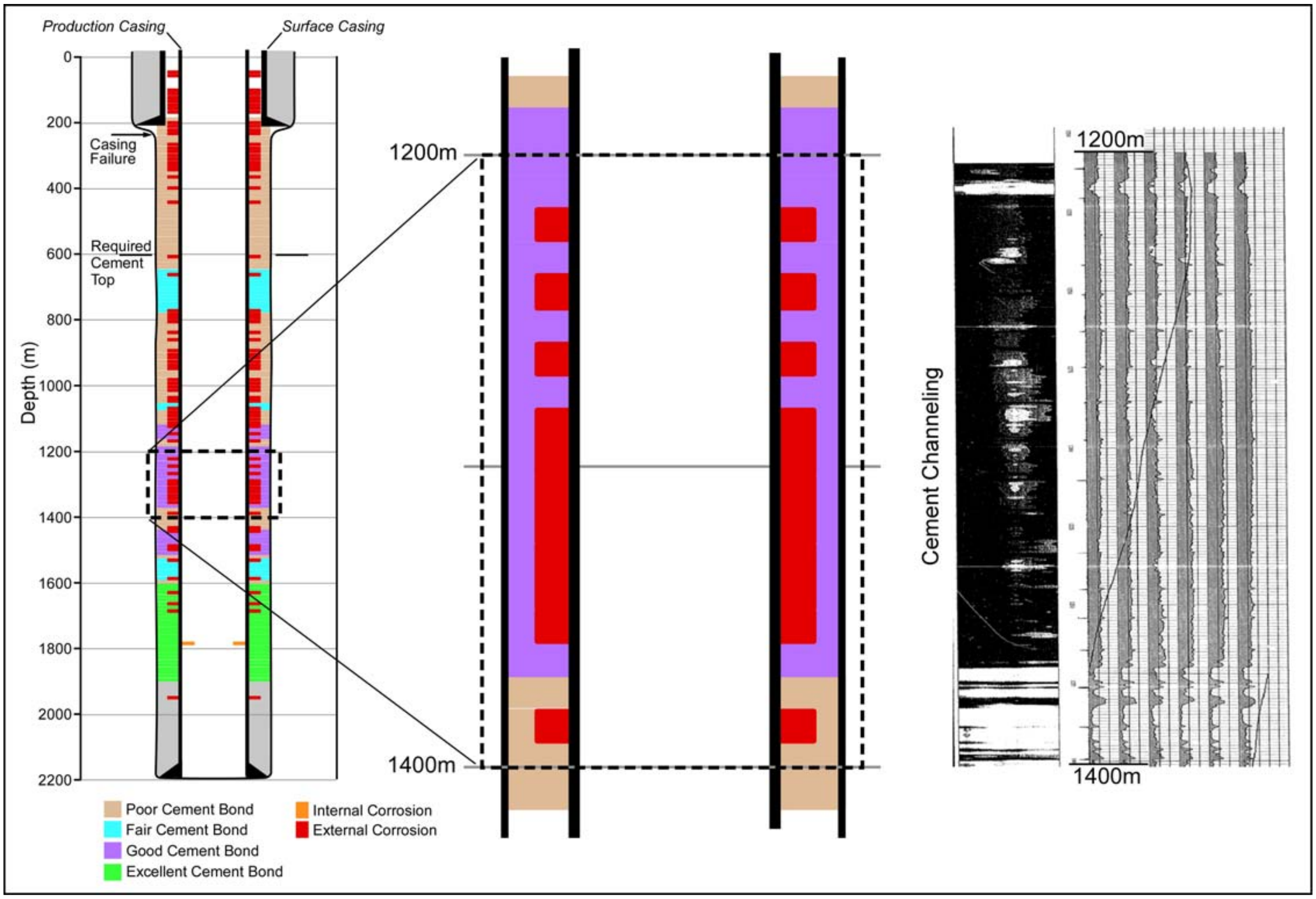


Figure 15: Example of bond log interpretations run 10 years apart in a well located in the Zama field. Casing corrosion presentation is from 1995 only.

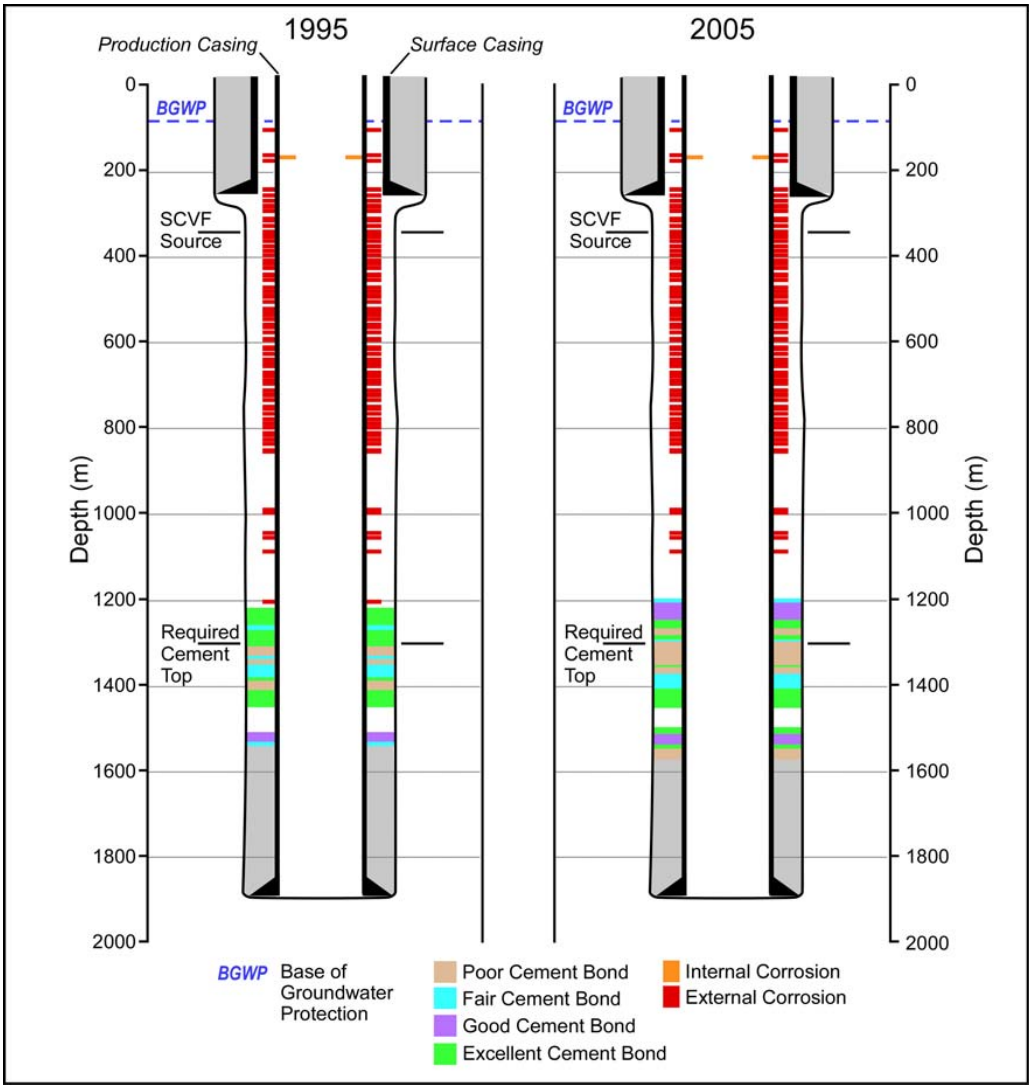


Figure 16: Decision tree for assessing the potential for well leakage inside production casing.

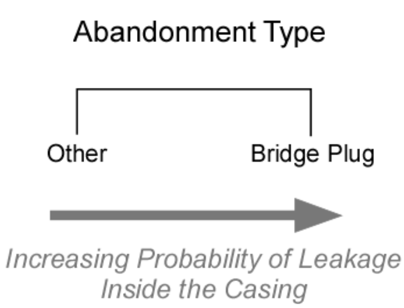


Figure 17: Decision tree for assessing the potential for well leakage inside and outside surface casing (SCVF and GM).
Notes:
[1] In Alberta, regulations regarding well abandonment procedures were changed in 1995 (see Figure 9);
[2] The Test Area is defined as an area in Alberta where gas migration was observed and where testing for gas migration is required by regulation (see Figure 5).