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REVIEW PAPER - PRODUCTION ENGINEERING

Global regulations and practices for well integrity management: a review

Marcel Schulz[1] · Mayukh Talukdar[1] · Isabelle Pfander[2] · Greg Lackey[3] · Luisa Röckel[1] · Andrew Wojtanowicz[4] · Frank Schilling[1] · Philipp Blum[1]

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Abstract

The integrity of oil and gas wells ensures safe operations and preserves air and water quality. Thus, it is important to identify and repair well integrity issues that cause unwanted gas movement within a well system. Sustained casing pressure (SCP) and surface casing vent flow (SCVF) are key well integrity indicators. This study presents the first review of SCP/SCVF government regulations and industry guidelines across major oil- and gas-producing countries, including the USA, Canada, Australia, Norway, Russia, and China. Regulations vary widely: the USA, Canada, and Russia have specific regulatory requirements, while Australia and Norway leave more responsibility to operators. China relies on guidelines from state-owned companies. Major oil- and gas-producing provinces in Canada require pressure to be released to the atmosphere as SCVF. The U.S. industry guideline API RP 90 underpins offshore SCP regulations in multiple countries, but no global standard exists. Routine annulus pressure or flow monitoring is required in 38% of U.S. states, 15% of Canadian provinces and territories, as well as in Norway and Russia, whereas China and Australia do not have such requirements. Diagnostic testing for SCP or SCVF is required in 12% of U.S. states, 38% of Canadian provinces and territories, and Russia. However, testing is not mandated in China, Australia, and Norway. This study proposes a minimum standard workflow that can be included and adjusted in jurisdictions without SCP/SCVF regulations. The proposed workflow includes routine monitoring, diagnostic testing when anomalies occur, and remediation, providing a structured approach to well integrity management.

Keywords Well integrity · Sustained casing pressure · Surface casing vent flow · Regulations · Monitoring · Leakage

Abbreviations

API	American Petroleum Institute
B/B test	Bleed-down/build-up test (Diagnostic test based on a pressure release (bleed-down) of an annulus and the following rise (build-up) of the pressure curve within 24 h)
GHG	Greenhouse gas
GM	Gas migration
MAASP	Maximum allowable annulus surface pressure (maximum pressure that is allowed at the well-head, calculated for each annulus)
MAWOP	Maximum allowable wellhead operating pressure (maximum operating pressure that is allowed at the wellhead, calculated for each annulus)
NOPSEMA	The National Offshore Petroleum Safety and Environmental Management Authority (Australia)
NORSOK	Translates to "The Norwegian Shelf's Competitive Position" (industry standards)
SCP	Sustained casing pressure (pressure in annuli that rebuilds when it is bled down and that

✉ Marcel Schulz
marcel.schulz@kit.edu

[1] Institute of Applied Geosciences (AGW), Karlsruhe Institute of Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany

[2] National Energy Technology Laboratory (NETL), 1450 Queen Avenue SW, Albany, OR 97321, USA

[3] National Energy Technology Laboratory (NETL), 626 Cochran Mill Rd, Pittsburgh, PA 15236, USA

[4] Craft & Hawkins Department of Petroleum Engineering, Louisiana State University (LSU), 3207 Patrick F. Taylor Hall, Baton Rouge, LA 70803, USA

is not caused by thermal fluctuations or the operator)

SCVF Surface casing vent flow (gas or liquid flow through the open surface casing annulus)

Introduction

Deep wells are an essential component of the global energy system as they are required for all subsurface energy projects, including hydrocarbon production and storage, geologic carbon storage, hydrogen storage and geothermal (Economides and Wood 2009). Wells are boreholes drilled in the Earth's crust to provide controlled access to deep subsurface formations. A properly functioning well isolates the formations along its depth, preventing the upward migration of formation fluids along the wellbore (International Organization for Standardization 2017).

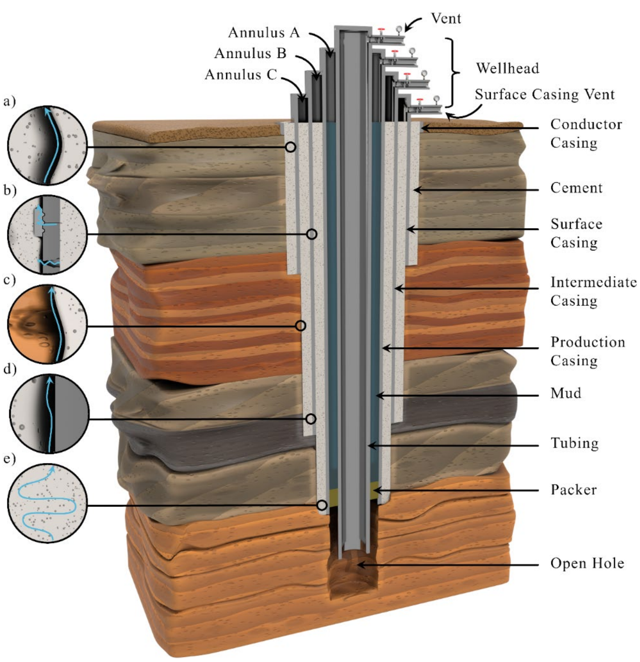

Fig. 1 Sketch of a borehole and potential leakage pathways as shown in Gasda et al. (2004). The conductor casing is a short pipe that is driven into the ground to avoid the collapsing of shallow sediments if necessary. The next inner casing is called the surface casing. The innermost casing is the production casing. All casings between the surface and production casing are intermediate casings. Inside the production casing lies the tubing - a slim steel pipe that channels reservoir fluids to the surface. The space between the tubing and the production casing (annulus *A*) is filled with fluid instead of cement, so the tubing can be exchanged when corroded. A seal (the packer) is placed at the bottom of the *A* annulus to prevent reservoir fluids from entering this annulus. Note that the commonly used term "tubular" covers any steel pipe in the well, including all casings and the tubing. The fluid leakage pathways shown are: **a** fractures or mud channels in the cement, **b** casing corrosion and thread leak, **c** microannulus between rock and cement, **d** microannulus between cement and steel, and **e** cement matrix flow. Gas migration can, for example, happen through a combination of **b**) and **d**)

Well integrity ensures that fluids are contained within the well and do not leak into the surrounding environment by maintaining the condition of components such as casings and cement (Colborn et al. 2014; Kiran et al. 2017). According to the NORSOK D-010 standard, achieving well integrity involves implementing technical, operational, and organizational measures to minimize the risk of uncontrolled release of formation fluids throughout the entire lifespan of the well (Norwegian Oil Industry Association and Federation of Norwegian Manufacturing Industries 2021). Ensuring the integrity of oil and gas wells will continue to be crucial for maintaining a strong and reliable energy infrastructure, even with an expected decrease in natural gas and oil consumption. Subsurface energy applications are essential for reducing emissions through geologic carbon storage, compressed air storage and hydrogen storage as well as geothermal energy, which all require well integrity management (Carroll et al. 2016; Bai et al. 2016; Iyer et al. 2022; Ugarte and Salehi 2022; Wood 2024). The sealing components of wells used in these operations will be exposed to fluids and subsurface conditions that pose multiple potential leakage risks.

Fig. 1 depicts the components of a drilled well with four casings. Casings are steel pipes placed in the drilling phase to stabilize the borehole and isolate formations. The spaces between these casings are called annuli. They are typically fully or partially filled with cement, except for the innermost annulus (Fig. 1). The cement is placed to seal the annulus and avoid unwanted fluid flow. Annuli are named from the inside out, starting with *A* for the innermost annulus, *B* for the next annulus, and so on. Also shown in Fig. 1 are different types of structural failures in the well's sealing system that may become a potential conduit for leakage of the reservoir fluids. While Fig. 1 represents a typical well design, configurations vary significantly depending on geological conditions and operational requirements, with notable differences between land wells and deepwater wells (Wan 2011; Jiang 2021; American Petroleum Institute 2006). For example, some wells have more or fewer casings, and annuli may only be partially cemented, with the upper sections filled with mud.

It is estimated that there are approximately six million active and inactive oil and gas wells in the United States and Canada alone (WellWiki 2021; WellDatabase 2025). Managing the integrity of these wells, along with millions of others worldwide, is a major challenge. While there are many methods for testing the integrity of a well, jurisdictions with regional well integrity management programs typically rely on operators to report the occurrence of sustained casing pressure (SCP). This phenomenon refers to the buildup of annular pressure from leaking well components and is an indicator of integrity issues (Yao and Wojtanowicz 2017). By definition, SCP rebuilds after it has been vented, distinguishing it from operator-induced pressures and those caused by temperature fluctuations (American Petroleum Institute 2006). When the annulus between casings is open to the atmosphere, SCP cannot build up. Instead, the gas flows out of the annulus, which is known as surface casing vent flow (SCVF). Both SCP and SCVF result from undesirable gas leakage through a well annulus and can lead to various problems. Pressure buildup associated with SCP is particularly concerning, as it can cause failure of the casing shoe or head, potentially resulting in catastrophic well blowouts, especially in offshore wells (Kinik and Wojtanowicz 2011). For onshore wells with lower pressures, SCP can lead to the contamination of aquifers: If there is a leakage path that causes gas to escape from the well to the surrounding subsurface, this is referred to as gas migration (Lackey et al. 2022). Gas migration (GM) can pollute aquifers, surface waters, and the atmosphere (Ingraffea et al. 2014; Jackson and Dusseault 2014; Wisen et al. 2020; Morais et al. 2024). In contrast, SCVF leads to direct greenhouse gas (GHG) emissions into the atmosphere, exacerbating global warming. This also applies when SCP is released on detection to avoid the aforementioned risks. Sherwin et al. (2024) estimated that, on average, 3% of the produced methane is lost from oil and gas wells in the USA. Fugitive emissions from the oil and gas sector contributed 4% of global greenhouse gas emissions in 2016 (Ritchie 2020). Although it is difficult to estimate the share from specific sources, such as SCP/SCVF from leaking wells (Boettcher et al. 2019), Bowman et al. (2023) quantified emission rates from abandoned wells in Canada. Since SCP and SCVF are both indicators for integrity issues and can lead to severe issues, regulatory monitoring and testing requirements can be effective risk reduction tools.

Regulations regarding SCP and SCVF differ from country to country, and industry guidelines are commonly used as best practices. This study focuses on SCP and SCVF regulations and guidelines of countries with the highest combined oil and gas production. This includes the USA, Russia, China, Canada, Norway, and Australia, as well as Saudi Arabia, Iran, the United Arab Emirates, Iraq, and Qatar. This study provides a comprehensive overview of current regulations, methods, and problems related to SCP and SCVF in these countries with large oil and gas productions and suggest improvements.

Background

Causes of well integrity failure

Potential leakage pathways in a well include fractures and mud channels in the cement (Fig. 1a), casing corrosion (Fig. 1b), thread leaks (Fig. 1b), micro-annuli between rock and cement (Fig. 1c), micro-annuli between cement and steel (Fig. 1d), and flow through the cement (Fig. 1e). Leakage pathways can develop due to physical, chemical or biological reasons (Kiran et al. 2017).

Physical or mechanical factors that compromise cement integrity include inadequate cementing, poor compaction, rough surfaces or wellbore inclination. For example, modulus differences between cement and surrounding rock can promote fracture formation and plastic deformation (Gray et al. 2009). Cement contracts during cooling, potentially causing debonding fractures. Thermal expansion can increase annular pressures, leading to cement and casing fractures. Casings are also affected by dynamic loading, variable flow rates, and leak-off tests. Fractures in the cement, casing or their interfaces can enable unwanted gas flow and create localized stresses (Nygaard and Lavoie 2010; Nygaard et al. 2014). These localized stresses may further initiate fractures in the system, resulting in high wellhead pressures or gas release to the atmosphere.

Additionally, chemical reactions can degrade well integrity. Common factors include cement degradation, casing corrosion, and sealant weakening (King and Valencia 2016; Ahmed and Salehi 2021; Taleghani and Santos 2023). Well cement, primarily composed of calcium and silicon oxides, can react with CO_2, leading to cement degradation. Calcium can interact with lime, aluminum from hydrated ferrite, and sulfate from H_2S, forming ettringite or gypsum (Zivar et al. 2021; Perera 2023). The resulting expansion causes internal stresses within the cement matrix (Sun et al. 2019, 2022).

In subsurface environments, microorganisms can cause biological corrosion (Javaherdashti 2008). Their metabolic processes produce byproducts that lead to biofilm formation on metal surfaces, which influences interfacial chemical and electrochemical reactions (Liu and Cheng 2018). This type of corrosion affects not only natural gas and oil wells but also underground hydrogen and carbon storage wells (Ugarte and Salehi 2022).

Observed occurrence of well integrity failure

Reports of SCP and SCVF issues have been consistently documented in oil and gas wells worldwide. Davies et al. (2014) concluded that 1.9–75% of wells experience barrier element failure, with 6.3% of wells in Pennsylvania affected. High frequencies of SCP have been documented in offshore wells. In the Gulf of Mexico, up to 30% of wells exhibited SCP in some areas (Bourgoyne et al. 1999). In Norway, well integrity issues were documented in up to 18% of the offshore wells (Vignes and Aadnoy 2008) and 31.3% of all wells on the Northern Continental Shelf (Rød 2017).

The occurrence of SCP and/or SCVF occurrence varies widely in onshore wells. Lackey et al. (2021) identified integrity problems in wells across Colorado, New Mexico, and Pennsylvania. Testing for SCP and SCVF is mandatory for all wells in Pennsylvania. While compliance issues have been identified in this state, it is estimated that 14.1% of Pennsylvania wells tested prior to 2018 experienced SCP and/or SCVF (Lackey et al. 2021; Fig. 2). The percentage of wells that exhibited SCP varied between 0.2% and 26.5% among five regions considered in Colorado and New Mexico.

Similar trends have been observed in Canada. In British Columbia, a study of 21,525 wells found that 10.8% (2,329 wells) experienced leakage during their operational lifespan (Wisen et al. 2020). In Alberta, 4.9% of wells experienced SCVF, while 0.7% showed GM (Bachu 2017). Seymour et al. (2024) estimated that 2.8% of wells in Alberta and 12% of wells in British Columbia exhibited SCVF. Despite testing requirements for 58.2% of wells in Alberta, only 6.2% had reported SCVF data, indicating compliance issues (Abboud et al. 2021). These studies center on SCP and SCVF because detecting and measuring GM outside the well casing is more challenging than measuring gas inside the casing, as it disperses over a large area in the shallow subsurface around the well (Bachu 2017).

Studies estimating GHG emissions from SCP and SCVF have mainly focused on Canadian jurisdictions. In British Columbia, SCVF emissions are estimated at approximately 75,000 tons per year, though the actual number is likely higher due to underreporting (Bowman et al. 2023). In 2022, about 11,100 wells in Alberta reported emissions, releasing an estimated 39,000 tons of methane (Seymour et al. 2024). Methane emissions from wells in Alberta and British Columbia range from 23,000 to 176,000 tons, representing 1.7–11.4% of methane emissions from the upstream sector. These values are likely underreported, as direct measurements of methane emissions from 238 abandoned wells in Alberta found SCVF in 32% of those wells (Bowman et al. 2023).

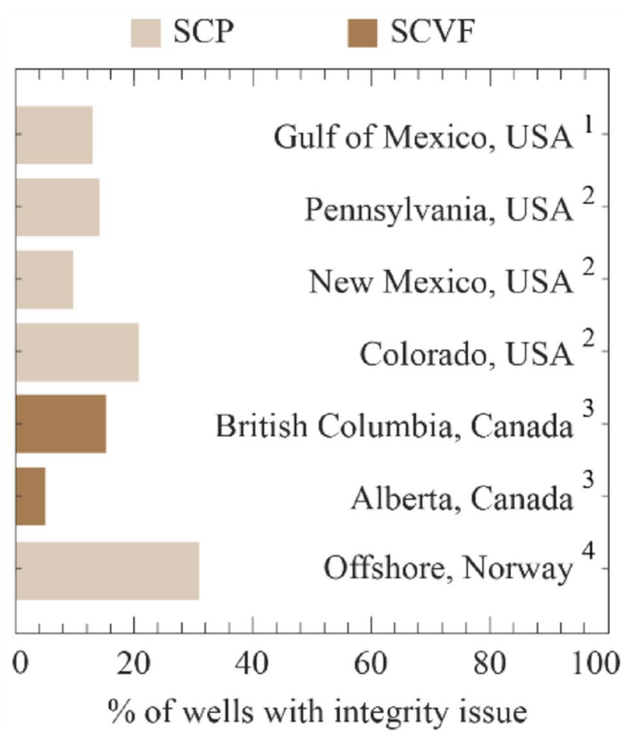

Fig. 2 The percentage of wells showing SCP was up to 30% in some locations of the Gulf of Mexico, e.g. the Mississippi Canyon ([1] Bourgoyne et al. 1999), while 20.8% of wells in Colorado, 9.8% in New Mexico, and 14.1% in Pennsylvania showed SCP or casing vent flow ([2] Lackey et al. 2021). The percentage of wells with SCVF in Alberta and British Colombia are 2.8% and 12%, respectively ([3] Seymour et al. 2024). However, Bowman et al. (2023) estimated that 32% of the abandoned wells in Alberta show SCVF based on 238 wells. Norway has well integrity issues in 31.3% of the wells ([4] Rød 2017)

National regulations and guidelines

Overview

This section discusses procedures for managing annular pressure and vent flow as described in legally binding regulations and non-legally binding industry guidelines as of 2024. The legally binding regulations are defined by authorities, whereas industry guidelines are issued by oil and natural gas business associations, e.g., the American Petroleum Institute (API). Regulators in some jurisdictions also inspect wells for SCP and/or SCVF during routine compliance inspections; however, practices for these inspections vary widely.

This study identifies four major aspects of regulations and guidelines pertaining to SCP/SCVF testing: (1) monitoring, (2) diagnostic testing, (3) pressure or flow rate thresholds, and (4) barrier classification. Monitoring is the routine measurement of annular pressure for SCP or flow for SCVF. Changes in pressure or flow detected during monitoring may indicate well integrity issues or result from other factors, such as temperature variations. Diagnostic testing is required to differentiate between potentially harmful well integrity issues and harmless effects, such as temperature variations due to production rate changes. The difference between monitoring and diagnostic testing can be subtle and subjective. For example, flow rate measurements may be considered diagnostic testing because measuring a constant flow rate over a specified time period diagnoses SCVF. Note that this study classifies pure flow rate measurements and similar assessments as "monitoring" when performed routinely and as "testing" when conducted intermittently.

In addition to monitoring and diagnostic testing, some regulations and guidelines mention allowable pressure or flow rate thresholds in different annuli. An SCP threshold can, for example, be defined as the maximum pressure that can occur in an annulus without risking groundwater contamination or damage to well components. Exceeding this threshold indicates a potentially severe integrity issue. Some guidelines classify wells based on the integrity of both barriers, independent of diagnostic test results (Table 1, Column 4; Online Resource 1). Likewise, the barrier classifications aim to mitigate undesired accidents and events. In Table 1, the presence of monitoring, diagnostic testing, pressure thresholds, and barrier classification in regulations and guidelines of different countries are summarized.

Jurisdictions in the USA and Canada, as well as Russia, have SCP and SCVF management regulations (Fig. 3). In the USA and Canada, these regulations vary between jurisdictions. In addition to these state-level regulations, U.S. federal regulations cover SCP for offshore wells in federal waters, and onshore regulations apply to wells on land owned or managed by the federal government. Online Resource 2 provides a detailed analysis of regulations by jurisdiction in the USA and Canada. While SCP and SCVF are not regulated directly in China, Australia, and Norway, they are indirectly controlled through guidelines and regulations. In China, guidelines of state-owned companies are used. In Australia, there are both national regulations and state-level regulations, similar to those in the USA, but with a risk-based approach. For example, in Western Australia, well integrity hazards (including SCP) must be controlled. A well management plan is required, including the standards that are followed (Government of Western Australia 2015).

Table 1 Different countries' SCP and SCVF regulations and guidelines, sorted by gas production in 2023 (× indicates a topic is covered in a regulation or guideline and– suggests the topic is not covered)

Country	Reference	Document Type	Monito-ring	Diagnostic testing	Thresholds	Classi-fication
USA	Bureau of Safety and Environmental Enforcement (2010)	Regulation (offshore)	×	×	×	–
	American Petroleum Institute (2006)	Guideline (API RP 90, offshore)	×	×	×	–
	American Petroleum Institute (2016)	Guideline (API RP 90−2, onshore)	×	×	×	–
	State regulations	Regulation	State-dependent (Online Resource 2)			
Russia	Ростехнадзор (2020)	Regulation	×	×	–	–
China	China National Offshore Oil Corporation (2018)	Guideline (state-owned company)	×	×	×	×
	China National Petroleum Corporation (2022)	Guideline (state-owned company)	×	×	×	×
Canada	Alberta Energy Regulator (2022)	Directive[a]	–	×	×	–
	Government of British Columbia (2023)	Regulation	–	×	×	–
	British Columbia Energy Regulator (2023)	Regulator Guideline[b]	×	×	×	–
	Other provinces have further regulations (Online Resource 2)					
	Energy Safety Canada (2022)	Guideline	×	–	–	–
Australia	Office of Parliamentary Counsel, Canberra (2023), NOPSEMA (2020a, b), Government of Western Australia (2015), Queensland Government (2004)	Regulation	–	–	–	–
Norway	Petroleum Safety Authority Norway (2023a, b, c)	Regulation (offshore)	×	–	–	–
	Norwegian Oil Industry Association and Federation of Norwegian Manufacturing Industries (2021)	Guideline (offshore)	×	–	×	–
	Norwegian Oil and Gas Association (2017)	Guideline (offshore)	×	×	×	×
International	International Organization for Standardization (2014, 2017)	Guideline	×	×[c]	×	–

[a]Although not formal regulations, directives are authoritative and must be followed. [b]While not a regulation itself, the Oil and Gas Activity Operations Manual is issued by the regulator as a guideline containing recommended practices to ensure compliance with the regulations. [c]Bleed-down/build-up tests are suggested but not described. Instead, the American Petroleum Institute (2006) is referenced for a testing description

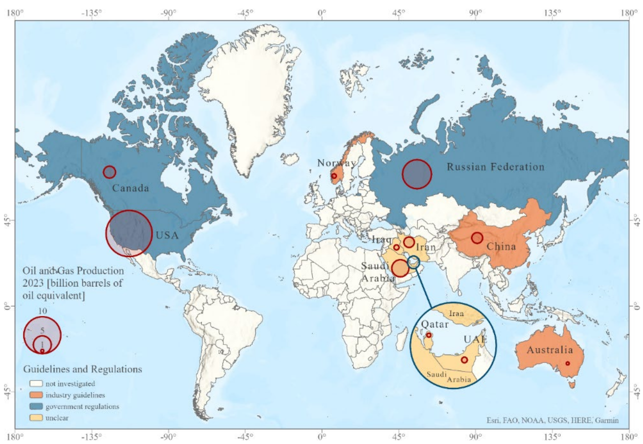

Fig. 3 World map showing countries with guidelines and regulations for SCP and SCVF. Oil and gas production data from Enerdata (2024), shapefiles from Esri (2022). Mercator projection

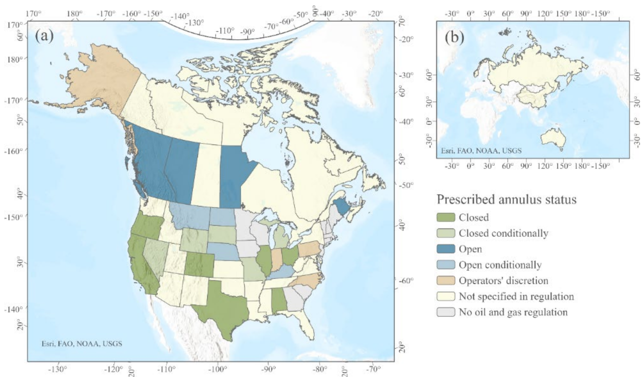

Fig. 4 Map of annulus management requirements as outlined in regulations of (**a**) the USA and Canada and (**b**) Norway, Russia, China and Australia. Shapefiles from Esri (2017), Esri (2022) and Statistics Canada (2023). Projections: (**a**) Albers equal-area conic, (**b**) Mercator

Norwegian regulations follow a similar risk-based approach (Petroleum Safety Authority Norway 2023a, c, b). Unfortunately, the authors found no information describing regulations in Middle Eastern countries.

Annulus management

An annulus can be configured as either open to the atmosphere or closed at the wellhead, and each approach has advantages and disadvantages. With closed annuli, a leak that causes fluids to migrate upwards within the annulus is contained, preventing methane from being emitted into the atmosphere by retaining it within the wellhead. If cement is injected at the bottom of the annulus, SCP buildup can stop gas leakage through the cement and lead to a steady state if the annular pressure at the wellhead becomes sufficiently high (Xu and Wojtanowicz 2017; Lackey and Rajaram 2019). However, closed annuli not sealed from the bottom with cement– a common configuration for onshore wells– will continuously build SCP, displacing fluid from the annulus as the gas headspace grows. If SCP exceeds the formation's hydrostatic pressure and entry pressure at the bottom of the casing, GM into the surrounding subsurface will occur. Conversely, open annuli prevent pressure buildup at the wellhead, thereby mitigating the buildup of unsafe pressures and protecting aquifers from SCP-induced GM. However, open annuli can lead to direct GHG emissions in case of a subsurface leak that causes SCVF.

In Canada and the USA, the status of an annulus (open/closed) is often prescribed in regulations (Fig. 4). In British Columbia, Canada, the surface casing annulus has to be open to the atmosphere (Government of British Columbia 2023). However, SCVF emissions of natural gas have to be kept below 100 m³/day for each well. Similarly, Alberta also requires open annuli (Alberta Energy Regulator 2022). The surface casing annulus has to be open to the atmosphere unless production rates and well depth are limited, there is no H_2S involved, and there is no SCVF. In contrast, USA regulations require annuli to be closed in seven states (Fig. 4). Jurisdictions with conditionally closed wells in the USA only require annuli of certain well types (e.g., wells with uncemented annuli) or the A annulus to be closed. Jurisdictions with conditionally open annuli only require open annuli during hydraulic fracturing operations, except in Kentucky. In Kentucky, open annuli are only prescribed for temporarily abandoned wells drilled through coal seams. Other jurisdictions, like Pennsylvania, leave annulus management to the operator's discretion.

Monitoring

Monitoring for SCP and SCVF is another important aspect of well integrity management, as it can detect issues early and reduce the risk of potential impacts. Most regulations and guidelines include annulus pressure or flow monitoring (Table 1). The USA offshore regulations describe specific annular monitoring requirements based on the well type (Bureau of Safety and Environmental Enforcement 2010). Monitoring of all annuli is mandated in fixed platform wells. Subsea wells only require monitoring of the *A* annulus. Hybrid wells (subsea wellhead but surface completion) require monitoring of the *A* and *B* annuli. The recommended monitoring frequency is daily to monthly. Compared to this regulation, the API RP 90 offshore guideline suggests monitoring all annuli monthly to semi-annually (American Petroleum Institute 2006).

Onshore regulations in the USA are state-dependent and apply to offshore wells located within 12 nautical miles (~22 km) of the shore in state waters (Fig. 5). Annulus pressure monitoring for onshore wells is mandatory in 18 states and on some federal lands (Online Resource 2). Some states require monitoring of specific annuli, whereas others require monitoring of all annuli. Figure 5 summarizes the state-wise monitoring frequency. Often, monitoring is only prescribed during specific phases like hydraulic fracturing or stimulation. Arkansas, Colorado, New Mexico, Pennsylvania, and Texas are the only jurisdictions in the USA that require routine annular pressure monitoring. Flow rate monitoring is only prescribed in California and Pennsylvania. Overall, either pressure or flow monitoring, or both, are required in 38% of U.S. states.

Russian regulations require routine annulus pressure monitoring during production; however, frequencies are not specified. After abandonment, annual annulus pressure monitoring and air monitoring for hydrogen sulfide are prescribed (Rostekhnadzor 2020).

China's guidelines suggest real-time pressure monitoring of the A annulus and a daily inspection of the records (China National Offshore Oil Corporation 2018; China National Petroleum Corporation 2022).

Canadian regulations do not prescribe routine annulus pressure monitoring. In British Columbia and New Brunswick (15% of provinces and territories), routine flow monitoring is necessary (Online Resource 2). In British Columbia, GM should also be monitored when detected (British Columbia Energy Regulator 2023). The Canadian IRP 27 guideline suggests monitoring SCVF and annulus pressures during and after remediation (Energy Safety Canada 2022).

Australia does not prescribe pressure or flow monitoring during well operation. However, annulus pressure reporting is required at well abandonment (NOPSEMA 2020b).

Norway's regulations mandate pressure monitoring of all annuli in surface-completed wells and the innermost annulus in subsea-completed wells (Petroleum Safety Authority Norway 2023c). Additionally, pressure monitoring of the next outer annulus is required in the case of hydrocarbon flow in an annulus. Norwegian guidelines recommend the monitoring of all accessible annuli (Norwegian Oil and Gas Association 2017; Norwegian Oil Industry Association and Federation of Norwegian Manufacturing Industries 2021).

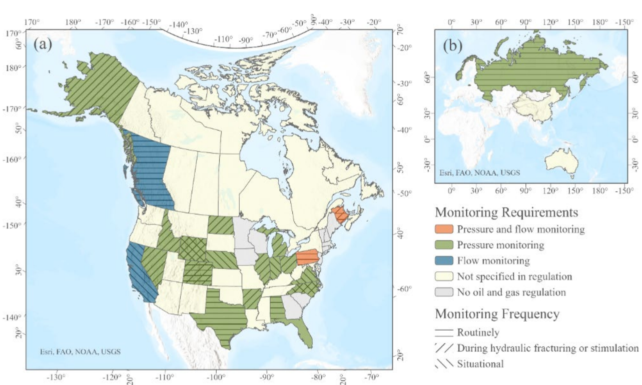

Fig. 5 Monitoring requirements as outlined in regulations of (**a**) the USA and Canada and (**b**) Norway, Russia, China and Australia. Shapefiles from Esri (2017), Esri (2022) and Statistics Canada (2023). Projections: (**a**) Albers equal-area conic, (**b**) Mercator

Diagnostic testing

Diagnostic testing identifies and distinguishes well integrity issues from pressures caused by temperature variations or other effects. Diagnostic testing is initiated at time periods specified by the regulator or when SCP or SCVF is suspected. Depending on the diagnostic testing method, more detailed information about the leak severity and source can be obtained.

In the USA, diagnostic testing practices vary for offshore and onshore wells. Federal offshore regulations prescribe diagnostic testing if annular pressure is detected and specify reporting requirements (Bureau of Safety and Environmental Enforcement 2010). These regulations state that operators should follow the diagnostic testing recommendations in the API RP 90 guideline (American Petroleum Institute 2006). According to API RP 90, diagnostic testing has to be conducted whenever the annulus pressure exceeds 6.9 bar to determine whether the pressure is sustained (i.e., rebuilds after it has been bled off) due to a constant leak source in the annulus or transient due to thermal effects (Bureau of Safety and Environmental Enforcement 2010). The diagnostic test recommended by API RP 90 is the Bleed-Down/Build-Up (B/B) test (Fig. 6). In this test, gas is released from the annulus being tested through a half-inch needle valve until the pressure reaches zero, a predetermined quantity of liquid fluid is recovered, or a specified amount of time has elapsed. Subsequently, the valve is closed, and the pressure is monitored. After B/B tests, further diagnostic actions like analyzing recovered fluids are suggested. The guideline defines three scenarios derived from B/B test results:

(1) No leak: When bled down to zero, the pressure does not build up within 24 h, indicating it was likely thermally induced.
(2) Minor leak: The pressure builds up to the original pressure or lower within 24 h after bleeding to zero. In this case, continuous monitoring and periodic re-evaluation are required.
(3) Major leak: The annulus pressure does not bleed to zero or there is pressure communication between annuli. In this scenario, the leak source has to be identified, repairs may be required, and the Maximum Allowable Operating Pressure (MAWOP) has to be recalculated (further explained in "Pressure and flow thresholds" Sect.).

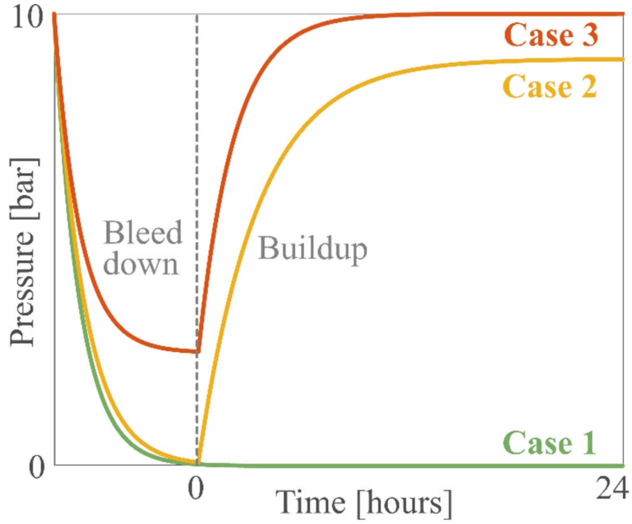

Fig. 6 Different cases for Bleed-Down/Build-Up tests performed at the wellhead by releasing pressure from an annulus and observing the pressure development for 24 h. Case 1 represents an annulus with a thermally induced or anomalous non-sustained pressure; no pressure buildup is observed. Case 2 is a moderately leaking scenario; Case 3 represents a severe leak. Modified after Kazemi and Wojtanowicz (2022)

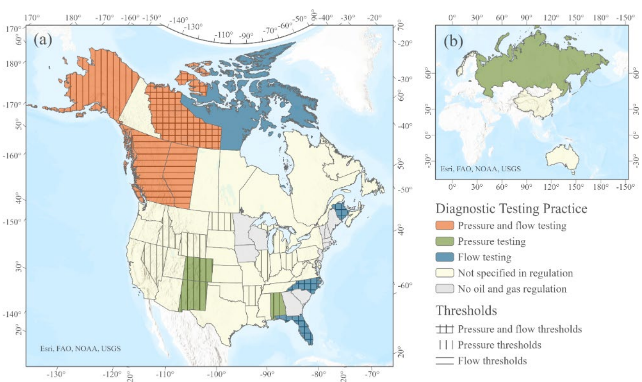

Fig. 7 Map of diagnostic testing requirements ("Diagnostic testing" Sect.) and thresholds ("Pressure and flow thresholds" Sect.) as outlined in regulations of (**a**) the USA and Canada and (**b**) Norway, Russia, China and Australia. Shapefiles from Esri (2017), Esri (2022) and Statistics Canada (2023). Projections: **a** Albers equal-area conic, (**b**) Mercator

In contrast to the USA's offshore regulations for federal waters, onshore wells and wells in state waters are regulated by individual states and vary considerably (Fig. 7). Diagnostic pressure testing procedures are mentioned in only five states, usually for all annuli. In Alabama, Alaska and New Mexico, B/B test variations are required, with differing pressure recording practices, bleed-down times, and build-up times between states. Colorado requires the most detailed testing: tubing and casing pressures are recorded; the annulus valve is opened; a fluid sample is taken, if possible; and the tubing and casing pressures are recorded at five-minute intervals for 30 min. At the end of the test, the annulus is shut in, and the instantaneous pressure is recorded. An end-of-test fluid sample is collected, and the procedure is repeated for all annuli. Reporting requirements also vary between states, and reports often have to be filed if certain thresholds are exceeded. In Alaska, Florida and North Carolina, diagnostic flow testing is prescribed, which involves flow rate measurements. Overall, either pressure or flow testing, or both, are required in 12% of U.S. states. More information and references for state regulations are compiled in Online Resource 2.

China's guidelines suggest a test similar to the API RP 90 B/B test (China National Offshore Oil Corporation 2018; China National Petroleum Corporation 2022). Russian regulations also prescribe diagnostic testing through annulus pressure manipulation (Rostekhnadzor 2020). This test involves pressurizing the annulus with drilling fluid or air. If the annular pressure drops by more than 0.5 MPa within the following 30 min, the annulus is considered not tight. However, it is not stated explicitly, whether an annulus exhibiting a pressure drop of more than 0.5 MPa during the test is considered to experience SCP. Leaks have to be repaired before abandonment, stimulation, or any other treatment close to the borehole. If any annular pressure due to leaks (SCP) is detected, well operation has to be stopped. The operator is then responsible for identifying and eliminating the causes of SCP and making decisions regarding further well operation.

In Canada, operators must vent the surface casing annulus to prevent pressure build-up and protect groundwater. Consequently, Canadian regulations focus on SCVF rather than SCP. The provinces of Alberta and British Colombia recommend multiple diagnostic tests for SCVF, including bubble tests (Alberta Energy Regulator 2022; British Columbia Energy Regulator 2023). During a bubble test, one end of a hose is connected to the surface casing annulus vent while the other end is submerged in water. The water is then observed for 10 min. If bubbles are detected, the flow rate through the surface casing vent and the shut-in surface casing pressure have to be determined. The suggested bubble test frequency for new wells is yearly (Alberta Energy Regulator 2022). In Alberta, flow rate determination and measuring the shut-in pressure are suggested for diagnostic testing as well. In British Columbia, the flow rate, stabilized shut-in pressures, and buildup pressure have to be recorded after positive bubble tests. British Columbia and Alberta also require operators to test wells for GM. According to the British Columbia Energy Regulator (2023), GM can be observed as bubbles in a pond, stressed vegetation, or unusual gas odours. For GM testing, soil samples are taken 6 m around the well to measure gas concentrations. Both provinces require SCVF and GM testing at specific times, such as before abandonment. In both Alberta and British

Columbia, if SCVF is detected, testing must be repeated in the following years (Alberta Energy Regulator 2022; British Columbia Energy Regulator 2023). Testing for SCVF is also required in the Northwest Territories, Nunavut and New Brunswick at specific stages in the lifecycle of a well, such as prior to suspension and abandonment (Fig. 7). Overall, 38% of the Canadian provinces and territories require diagnostic testing. The Energy Safety Canada IRP 27 guideline (Energy Safety Canada 2022) also addresses aspects of SCVF testing, focusing on source identification through methods such as carbon isotope data analysis, and it describes remediation techniques.

In Norway, regulations do not require diagnostic testing. However, such tests are suggested by the 117 Offshore Norge guideline (Norwegian Oil and Gas Association 2017). According to the industry guideline, annular pressures correlate with temperatures when they are thermally induced. If well temperatures and annular pressures do not correlate, SCP is indicated. Once SCP is suspected, it is recommended to identify the leak path by manipulating the annulus pressure. For pressure manipulation, bleed down and pressure application are recommended; however, they are not described further. The document also suggests measuring leak rates, maximum stabilized annular pressure, and the volume of flammable hydrocarbon in annuli. Mitigation and remediation techniques are explained as well. The guideline recommends establishing a maximum allowable pressure change criterion and advises ceasing normal operations if barriers fail or are impaired or if allowable pressure limits are exceeded. In cases of barrier failure, barrier restoration is recommended before resuming further operations.

In Australia, the regulations do not contain information on diagnostic testing. The International Standard ISO 16530-1 recommends source identification in case of a high annulus pressure by reviewing the well history, performing B/B tests, or manipulating the neighboring annulus pressures (International Organization for Standardization 2017). This standard does not allow leaks to the surface, subsurface, or a well barrier that cannot withstand the new pressures.

Pressure and flow thresholds

Pressure thresholds are recommended or prescribed pressure values that can be safely applied to an annulus. For offshore wells, these thresholds are usually based on the strength of the weakest well component and incorporate a safety factor. The components included in the threshold calculation vary from country to country.

The API RP 90 offshore guideline from the USA considers only the strength of tubulars, such as casings and tubings (American Petroleum Institute 2006). The guideline recommends calculating the strength of an annulus's inner, outer, and next outer tubular and then multiplying these values by a safety factor of less than 1. The lowest of the calculated values is defined as the Maximum Allowable Wellhead Operating Pressure (MAWOP). The Bureau of Safety and Environmental Enforcement (2009) uses the same MAWOP calculation. In contrast, the API guidelines for onshore wells (API RP 90−2) consider not only tubular strength but also wear and corrosion, wellhead failure, completion equipment failure, and formation fracturing at the casing shoe in their MAWOP calculation (American Petroleum Institute 2016).

The API RP 90−2 guideline also recommends establishing upper and lower diagnostic thresholds (DT) as a warning system to provide time to respond to pressure changes before they reach critical levels. The upper DT should be set below the MAWOP to leave enough response time for a bleed off. The lower DT is recommended to be lower than the sum of the operator pressure and thermal effects, yet high enough to ensure a prompt response to communication between annuli.

In the USA, pressure thresholds are specified in the onshore regulations of 14 states (28%) and on public lands. In four states, the threshold is based on the strength of well components, whereas five other states use absolute pressure values. For example, in Colorado the annular pressure threshold is defined as 30% of the true vertical depth of the surface casing. This well-specific approach maintains annular pressures below the hydrostatic gradient in the formation at the bottom of the surface casing to prevent GM and protect groundwater. If the annular pressure threshold is exceeded, diagnostic testing must follow. There are no flow thresholds in states that require open annuli. However, Florida, North Carolina and New Mexico require remediation or further testing if fluids leak from annuli or if loss of well integrity is discovered (Online Resource 2). This can be considered a qualitative flow threshold.

In Canada, regulations of two jurisdictions include pressure thresholds: In New Brunswick, when the pressure exceeds 25 bar, hydraulic fracturing must stop. The Northwest Territories use a qualitative threshold: if SCP is detected in any annulus other than the surface casing and the A annulus, operations must be suspended, and remediation is required (Online Resource 2).

Additionally, Canadian regulations classify SCVF and GM based on their escalation potential, effectively establishing thresholds. In Alberta and British Columbia, SCVF is categorized as either serious or non-serious, with mostly identical criteria (Alberta Energy Regulator 2022; British Columbia Energy Regulator 2023). A serious classification applies when the flow rate exceeds 300 m^3/day or if qualitative criteria are met, such as a public safety risk or casing failure. However, in British Columbia, SCVF must also not exceed 100 m^3/day (Government of British Columbia 2023).

The criteria for serious GM are similarly based on the proximity of the well to a sensitive receptor in both provinces. If these conditions are not met, SCVF or GM is classified non-serious. In Alberta, serious SCVF or GM have to be repaired within 90 days. In British Columbia, the regulator has to be contacted for repair work, and serious cases require repair as soon as possible. For non-serious SCVF and GM, repair work can be deferred until abandonment. Similar requirements are outlined in the regulations of New Brunswick and the Northwest Territories (Online Resource 2). Overall, either pressure or flow thresholds, or both, are defined in 31% of Canadian provinces and territories.

Compared to the USA, other countries use similar methods for the calculation of MAWOPs or Maximum Allowable Annulus Surface Pressures (MAASP). Typically, the strength of well components is included, as outlined in Chinese guidelines (China National Offshore Oil Corporation 2018; China National Petroleum Corporation 2022). The ISO 16530-1 and 16530-2 standards additionally include fluid and rock pressure gradients (International Organization for Standardization 2014, 2017). Norway's guideline 117, as well as ISO 16530-1 and 16530-2, also recommend setting DTs (Norwegian Oil and Gas Association 2017). According to Norway's 117 Offshore Norge guideline, leak rates in an annulus of up to 0.42 m³/day are acceptable (Norwegian Oil and Gas Association 2017). In contrast, the Norwegian NORSOK D-010 guideline only accepts leak rates of zero (Norwegian Oil Industry Association and Federation of Norwegian Manufacturing Industries 2021).

Improved interpretation and remediation methods

Modeling for SCP and SCVF interpretation

Measurements of SCP and SCVF alone are limited in the insights they provide. Typical diagnostic testing methods ("Diagnostic testing" Sect.) can only detect a leak and, depending on the method used, quantify the leak rate. Some guidelines therefore suggest additional practices such as geochemical analyses of annular fluids to gain deeper insights into their characteristics and origins. However, there are more elaborate methods that can provide additional insights from annular testing, such as flow simulations using theoretical and numerical models and experimental approaches for predicting SCP behavior (e.g. Xu and Wojtanowicz 2001; Lackey and Rajaram 2019; Klose et al. 2021). While they are too complex to be used routinely for all wells, these methods can support routine SCP and SCVF testing if necessary. For instance, transient gas flow models can identify the leak depth, extent, and source formation gas pressure (e.g. Huerta et al. 2009; Tao et al. 2011; Zhu et al. 2012; Xu and Wojtanowicz 2017).

Xu and Wojtanowicz (2001) published the first mathematical SCP buildup model specifically designed to identify the leak mechanism. They expanded their original model by incorporating gas flow in the mud in addition to gas flow in the cement (Xu and Wojtanowicz 2003). These models were later adapted for various other applications, for example emission predictions. Kinik and Wojtanowicz (2011) used the previous model by Xu and Wojtanowicz (2003) to analyze B/B tests quantitatively and determine the maximum possible emissions from well annuli. They also emphasized the importance of considering both casing head failure and casing shoe failure as crucial criteria. This is essential because, depending on the well, casing shoe failure might be reached before casing head failure, and vice versa. Yao and Wojtanowicz (2017) also estimated emissions based on the Kinik and Wojtanowicz (2011) model. They observed 19 wells that can be bled down to 0 bar to show that 3–5 wells would still release large volumes of gas into the atmosphere in case of a wellhead failure. Another model application is the quantification of permeabilities. Tao and Bryant (2014) assessed SCP and SCVF data from more than 300 wells based on the model by Xu and Wojtanowicz (2003) and could identify wellbore permeabilities from 0.01 to 10 millidarcy. They also developed a model to estimate the SCVF rate. The model by Xu and Wojtanowicz (2003) was also progressed and adapted by Lackey and Rajaram (2019) for groundwater contamination of onshore wells with SCP or SCVF. Based on this study, Qiao et al. (2023) modified the earlier models to simulate the simultaneous flow of gas and liquid along the cement. Huerta et al. (2009); Tao et al. (2010a, b, 2011) modified the model from Xu and Wojtanowicz (2001) for the leakage of CO_2 sequestration wells.

Casing pressure prevention and remediation

Preventing integrity issues is less costly and presents fewer environmental risks than remediation. Avoiding SCP and SCVF involves efficient post-cementing techniques for complete zonal isolation (Landry et al. 2015). These techniques address the early deterioration of the cement sheath's integrity due to gas invasion and channeling after the cementing operation, which may lead to the development of integrity issues. Foam cementing (Stewart and Schouten 1988), the use of self-healing cement (Landry et al. 2015; Arif Khattak et al. 2015; Shadravan and Amani 2015), expandable cement system (Tanoto et al. 2016), and site-specific cementing procedures are explored for SCP and SCVF prevention (Ezani et al. 2021). Apart from cementing operations, casing expansion (Kupresan et al. 2014; Sukhachev et al. 2022) and casing patching (Saltel et al. 2015) are suggested preventive SCP and SCVF techniques involving the casing. Casing rotation also prevents early gelation of the cement slurry and the loss of downhole pressure in the cement column by keeping the slurry in motion with the casing string's motion (Rankin and Rankin 1992). An alternative method of cement vibration (Haberman and Wolhart 1997) was developed (Manowski and Wojtanowicz 1998; Wojtanowicz et al. 2002; Chimmalgi and Wojtanowicz 2005) and successfully implemented in the field operations (Dusterhoft et al. 2002). While foam cementing is widely used, the other methods are less common or still experimental (Mahmoud et al. 2024). Despite preventive treatments, SCP development is common. Hence, there is still a need to advance both SCP prevention and remediation technology.

Remediation of gas leakage through annular cement channels and cracks is difficult. Downhole intervention methods employ workover rigs to access and seal off the leaking annulus at depth from within the well. This is expensive and not always effective. Cement can be squeezed to decrease porosity and permeability by perforating the production casing and forcing cement slurry through the holes. However, the success rate is below 50% and the perforation poses another integrity hazard (Bourgoyne et al. 1999). Biomineralizing fluids, resin-based solutions or nanocomposites can also be squeezed to seal micro annuli (Ali et al. 2022; Hiebert et al. 2022; Olayiwola et al. 2023; Alam et al. 2024). Another technique is milling out a section of the inner casing and placing a cement plug to intercept gas flow (Obodozie et al. 2016). This remediation technique is more effective than squeeze cementing; however, it is unreliable in wells with eccentric inner casings due to the unknown size of the milling tool (Milanovic and Smith 2005). A more proven and reliable technique involves cutting and removing the upper section of the inner casing to replace the whole column of leaking cement. Although effective, this technique can only be used in wells with no cement sheath outside the upper section of the inner casing (Milanovic and Smith 2005). A combination of these techniques was successfully used for SCP removal in 12 wells in the Gulf of Mexico (Soter et al. 2003). This suggests that a site-specific remediation approach is necessary.

Another approach to SCP repair is the wellhead intervention method, which involves replacing the well's annular fluid above the cement top by injecting sealant or heavy fluid into the casing head (Horton et al. 2004). The fluids are injected through a hose in an annulus to plug it off or increase hydrostatic pressure, decreasing gas movement. A simplification of this concept is the buoyant displacement technique, where a hydrophobic fluid based on brominated organics is injected directly into the casinghead's valve. As the heavy fluid settles by buoyancy, it displaces the lighter annular fluid, thereby balancing the pressure at the cement top (Demirci et al. 2017). Pilot and field-scale experiments on this technique were successful (Demirci and Wojtanowicz 2018, 2023).

Discussion and recommendations

Direct and indirect regulations

The studied countries regulate SCP and SCVF using two different approaches: (1) Direct regulations with specific requirements, as in the USA, Canada, and Russia, and (2) indirect regulations that outline risks to be avoided, as in Australia and Norway, without specifying mitigation measures. China follows an intermediate approach, as the guidelines of state-owned companies are not official regulations.

Direct and indirect approaches each have advantages and disadvantages. Direct regulations establish clear rules and boundaries that operators have to follow. They ensure a minimum standard for all wells in a jurisdiction, some containing hundreds of thousands of wells. Direct requirements can also enforce uniform reporting of SCP/SCVF monitoring and testing results, which can be compiled into public databases that facilitate well integrity management. However, some wells may require a more customized approach, necessitating deviations from direct regulations.

Indirect regulations do not apply requirements widely to all wells. The Australian approach requires operators to design a well operations management plan and present it to the regulator for approval. This indirect approach allows for more regulatory flexibility, as regulators can tailor their requirements to individual wells. Thus, tighter regulations can be enforced in specific cases, which is not the case for general, direct regulations. However, the Australian approach leaves room for human error and subjectivity and may not be feasible in jurisdictions that manage large numbers of wells. Norwegian regulations place responsibility on the operator, based on the assumption that they have the optimal expertise to handle specific well integrity challenges. This reliance on industry knowledge is common across many jurisdictions and has led some to adopt industry guidelines as official regulations. For example, U.S. federal offshore regulations have directly incorporated the API RP 90 guideline.

Considering the benefits and drawbacks of direct and indirect approaches, this study proposes a directly regulated minimum standard workflow for SCP and SCVF management ("Suggested minimum standard workflow" Sect.). This workflow allows for deviations in consultation with regulators to ensure flexibility. The direct workflow shall be combined with a general requirement to avoid risks to human health and the environment, as done in indirect

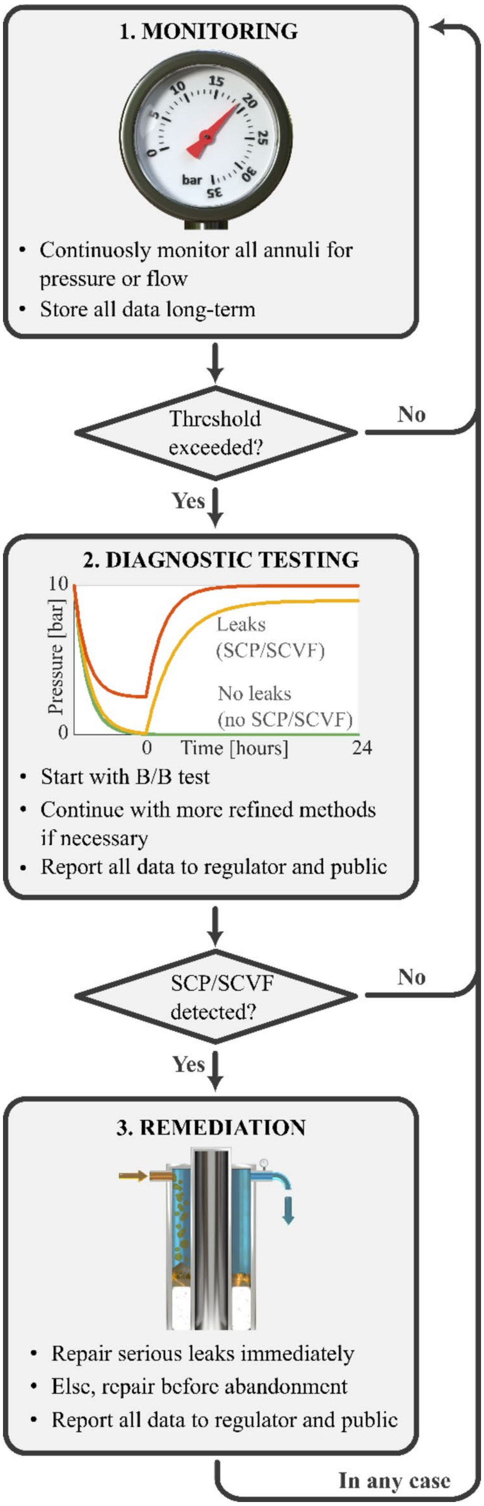

Fig. 8 Recommended minimum standard workflow for SCP/SCVF management, including (1) monitoring, (2) diagnostic testing, and (3) remediation

regulatory approaches. This addition of broader environmental requirements serves as a safety net in cases where the prescribed workflow does not cover specific scenarios. With different regulatory approaches based on history, local phenomena, and evolving research, regulations should continually be updated to improve SCP and SCVF identification and diagnosis.

Suggested minimum standard workflow

As discussed, directly regulating well monitoring and testing offers considerable advantages. Thus, this study suggests a minimum standard workflow, as illustrated in Fig. 8. Continuous monitoring of all annuli throughout the well's lifecycle is recommended with recorded data (continuous electronic recording preferred) and an early warning system based on threshold values. Analog pressure gauges should be used for safety redundancy and reviewed periodically. Regulators should establish a pressure or flow threshold that triggers diagnostic testing when exceeded. Routine diagnostic testing is also recommended for all wells, at least annually. If a threshold is surpassed or routine diagnostic testing detects pressure, B/B tests can serve as a starting point for identifying well integrity issues, with further testing or modeling depending on the test results. When SCP is detected, operators should communicate with regulators to discuss remediation options. Monitoring for GM is equally important, and can be done by a visual inspection for distressed vegetation as a starting point. If GM is detected, diagnostic testing (e.g. soil testing) and remediation should follow as they would for SCP. Mandatory reporting requirements for all testing data to regulators are also recommended. Additionally, regulators may choose to either require operators to provide monitoring data upon request or mandate the direct submission of such data, depending on the number of wells within a given jurisdiction. Flow rate data are especially important for the estimation of emissions in the context of SCVF (Bowman et al. 2023; Seymour et al. 2024). This study also suggests that regulators establish a database for monitoring and testing data that is accessible to the public, comparable to the Netherlands Oil and Gas Portal (Geological Survey of the Netherlands n.d.). This ensures transparency, reduces the risk of data loss, and supports environmental and well integrity research.

Similar workflows that cover monitoring and diagnostic testing are suggested in API RP 90 (American Petroleum Institute 2006). Designed for direct field use, these API workflows include explicit threshold values and require MAWOP recalculations in case of pressure communication between annuli. However, they do not address reporting or remediation directly; instead, wells that do not bleed down to 0 bar during testing are handled on a case-by-case basis.

In contrast, the suggested workflow outlines the minimum requirements for safe annulus pressure and flow management: monitoring, diagnostic testing, and remediation. It is designed to be applicable across most jurisdictions, particularly those without a mandatory or complete SCP/SCVF workflow.

Since the workflow covers minimum requirements, it can be adjusted and expanded based on the specific characteristics of a jurisdiction or serve as a foundation for a more tailored or optimized workflow. For example, regulators might choose to mandate geochemical sampling of annular fluids alongside diagnostic testing or require continuous electronic monitoring. As suggested by Kinik and Wojtanowicz (2011) and Kazemi and Wojtanowicz (2022), the B/B test could also be refined in a more optimized workflow. For instance, removing the 24-hour time limit and allowing both bleed-down and buildup pressures to reach steady states would capture the true minimum and maximum pressures. Otherwise, if an annulus cannot be bled down to zero bar, it is unclear whether this is due to a major leak or simply because the bleed-down was halted prematurely. Moreover, the standard B/B test procedure does not consider that a pressure buildup stabilizing at a value lower than the initial SCP may indicate pressure loss due to potential subsurface leakage. Thus, an optimized workflow could include a more in-depth examination of these cases.

Open and closed annuli

A key decision in well integrity and pressure management involves balancing the uncontrolled release of gases through SCVF in open annuli with the risk of harmful SCP in closed annuli. Ideally, effective monitoring would detect issues early enough that the choice of annular management approach is of lesser importance. However, to combine the benefits of open and closed annuli, this study suggests closed annuli with emergency release valves where feasible. The valves can be installed at the wellhead and contain trigger springs that would release gas only if a certain pressure is reached, such as the maximum allowable pressure.

In the case of open annuli, quantifying leakage rates for SCVF wells is crucial for understanding their contribution to global oil and gas sector emissions, and to estimate effective cement and system permeabilities. Furthermore, gaining a deeper understanding of the integrity issues experienced by a well can enhance the chances of successful remediation. To support this, recording the flow rates during the depressurization phase of B/B tests can provide additional data for further analysis.

Abandoned wells

The regulations and guidelines discussed primarily apply to active wells and often do not specify SCP, SCVF, or GM monitoring requirements for abandoned wells. However, studies have shown that abandoned wells can also lose integrity after plugging (Cahill et al. 2023). A long-term perspective (> 100 years) can benefit the cement-plugged abandoned wells that may not remain impermeable indefinitely. Abandoned wells leaking into the subsurface can lead to pore pressure changes in and around the reservoir, causing subsidence or even seismic events. To mitigate these risks, this work recommends diagnostic testing and remediation before abandonment, as required in British Columbia and Alberta. This study also suggests long-term monitoring of abandoned wells. Understanding emissions from abandoned wells remains an area of ongoing research (O'Malley et al. 2024), making the development of practical long-term monitoring solutions a valuable subject for future research.

Conclusions

Wells are crucial for subsurface energy extraction and usage. Sustained casing pressure (SCP) and surface casing vent flow (SCVF) are unintended pressure development at the wellhead or fluid flow to the atmosphere, respectively. Both are common problems caused by loss of well integrity that can compromise the safety of wells or lead to aquifer pollution and greenhouse gas emissions. 10–30% of wells in major oil and gas-producing regions show SCP and SCVF. Therefore, this study reviews SCP and SCVF government regulations and industry guidelines for major oil and gas-producing countries like the USA, Russia, China, Canada, Australia, and Norway. The main conclusions are:

1. There are considerable differences in the regulations. Some countries, like the USA, Canada, and Russia, have clearly defined, direct regulations. Others, such as Norway and Australia, take an indirect approach, leaving operators responsible for managing annular pressures and flows. China also does not regulate SCP directly; instead, guidelines from state-owned companies are followed. In the USA, regulations vary widely between jurisdictions. Similarly, Canadian regulations differ by jurisdiction but focus more on SCVF than SCP, as operators are often required to keep well annuli open to the atmosphere.
2. Pressure or flow monitoring, involving routine data recording and assessment, is required by regulation in 38% of U.S. states, 15% of Canadian provinces and territories, as well as in Norway and Russia. China and

Australia do not mandate monitoring by regulation. In the regulations of 12% of U.S. states, 38% of Canadian provinces and territories, and Russia, diagnostic testing is included to determine whether abnormal pressures or flow are harmless or indicate an integrity issue. China, Australia, and Norway do not specify such testing. While 28% of states in the USA and 31% of Canadian provinces and territories prescribe specific thresholds, in Russia, China, Australia, and Norway, they are only suggested through guidelines. These variations highlight an opportunity to enhance regulations, particularly by incorporating monitoring and testing requirements to enable early issue detection.

3. Based on these circumstances, this study proposes a workflow as a minimum regulatory standard for SCP/SCVF, starting with routine monitoring throughout all stages of a well's lifecycle. Diagnostic testing should follow when unexpected pressure or flow is detected. There are simple diagnostic B/B- or bubble-tests that can be supported by methods such as leak rate quantification and evaluation or numerical models. The authors also recommend testing wells for SCP/SCVF before abandonment and performing remediation when test results are indicating a leak. Lastly, comprehensive documentation and reporting of SCP/SCVF data are crucial to prevent the loss of information that is essential for understanding a well's history.

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Declarations

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