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Subsurface Containment Assurance Program: Key Element Overview and Best Practice Examples

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Abstract
The goal of Subsurface Containment Assurance is to ensure that no environmental damage, damage to operated assets, or impacts on well operations (drilling or production) are incurred by leakage of production or injection fluids from their intended zones. Subsurface Containment Assurance involves the integrated efforts of the subsurface (reservoir and overburden characterization), the wells (planning, construction, well integrity and abandonment) and the operations (process and well operations and management of change) teams. Disciplines must act together to develop and implement a surveillance plan to proactively monitor containment during well and injection operations.

The paper will describe the elements of a Subsurface Containment Assurance Program that are required for business units operating across the entire life cycle from exploration to mature developments. The program is designed to be comprehensive yet flexible, and focuses on the critical elements and risks for individual operating units. A consistent framework has been created and implemented that draws from existing tools for reservoir and overburden characterization and field management, and combines these tools to reduce the risk of unintended subsurface fluid containment loss. Specific assessment criteria and ranking approaches and tools for qualitative and quantitative estimation of containment risks will be reviewed. Lastly, practices for deepwater subsurface containment and implications for the oil and gas industry will be discussed.

Introduction
Containment of produced or injected fluids within their intended wellbores or geologic zones in oil and gas fields is widely recognized as a critical part of exploration and production in both conventional and unconventional prospects and reservoirs. The consequences of containment loss to an operator or partner can be large, including both direct and indirect costs (e.g., clean-up cost, loss of production, and damage to reputation), even for small events. On the other hand, effective containment assurance programs can minimize drilling and operational risk and enhance a company's reputation as a safe and prudent operator or partner.

This paper focuses on **Subsurface Containment Assurance**, which is defined herein as the identification and mitigation of those elements of hydrocarbon exploration and production (E&P) that could lead to a potential loss of containment of subsurface fluids. Subsurface containment assurance encompasses wellbore integrity, subsurface integrity, and aspects of deepwater and surface facilities that are directly relevant to upstream E&P operations. While upstream operations are the focus of this paper, ExxonMobil's onshore pipeline rupture that discharged ~1,500 barrels of crude oil into the Yellowstone River, Montana, in July 2011 (NBC News, 2011) and Tesoro's onshore pipeline rupture that leaked more than 20,000 barrels of crude oil into wheat fields near Tioga, North Dakota in September 2013 (Peixe, 2013) demonstrate the critical importance of containment assurance to downstream or integrated oil and gas companies. These and other upstream incidents, as described below, also underscore the need for effective monitoring and response systems within the company as part of a larger containment assurance strategy. Unexpected events in the subsurface sometimes occur in the oil and gas industry, and key learnings from high-reliability organizations that minimize or prevent impacts from unexpected incidents in high-risk environments (e.g., Weick and Sutcliffe, 2007; Lekka, 2011; Sutcliffe, 2011) can inform a subsurface containment assurance program.

Several definitions of risk have been applied to oilfield operations, including various combinations of safety, environmental, or process risk, involving estimation of event likelihood and consequence magnitude (e.g., Valeur and Petersen, 2013). In subsurface containment assurance, risk can be thought of as a combination of exposure of an asset to potential containment loss and the uncertainty in characterizing potential leakage mechanisms. There are many geomechanical similarities between hydrocarbon retention, a process that occurred over many millions of years, and oilfield operations that involve pore-pressure changes over much shorter timescales. As a result, much of the geological, geophysical, geomechanical, reservoir-engineering, drilling, and completions technical work on reservoir and overburden characterization that was done before production began, such as trap and seal analysis, can be leveraged to analyze potential or actual issues in containment science within a producing field.

In this paper, several of the key elements that can drive an effective subsurface containment program for upstream E&P activities will be described. First, the need for containment assurance will be demonstrated from examples in the industry. Next, an approach to subsurface containment assurance risking that contains the key elements will be outlined, followed by current practices for deepwater containment.

Examples of Subsurface Containment Issues in the Industry

Although most exploration and production activities within the oil and gas industry are conducted with a high degree of safety, losses of containment are documented in the open literature. Several of these are noted in this section according to the mechanism(s) of subsurface containment loss.

Well Integrity

Loss of well integrity can occur from several causes including repurposing, poor cement jobs, aging or abandoned wells, and overburden or reservoir deformation (e.g., Nagel, 2001; Ebitu et al., 2011). BP's Macondo deepwater containment loss in the Gulf of Mexico in April 2010 at the *Deepwater Horizon* rig demonstrates the importance of well integrity to subsurface containment assurance (e.g., Hopkins, 2012; Skogdalen and Vinnem, 2012). This incident in particular has elevated the visibility and priority of well integrity and containment assurance efforts within the industry.

Subsurface Integrity

Subsurface fluids may migrate out of their intended zones even if wellbore integrity is maintained due to unforeseen pathways in the subsurface, such as top-seal failure above a producing reservoir. Some of the risk factors that might be considered in subsurface containment assessments include: overpressuring relative to formation or top-seal strength; the frictional stability of major faults in a compartmentalized reservoir; the availability of conduits such as faults, fractures, and stratigraphy that might connect to freshwater aquifers, the sea floor, or the ground surface; and exceedence of specified limits on injected volumes, pressure, or voidage replacement ratios in the reservoir. Containment losses may therefore occur in the subsurface as a result of well integrity loss, subsurface integrity loss, or both (**Figure 1**).

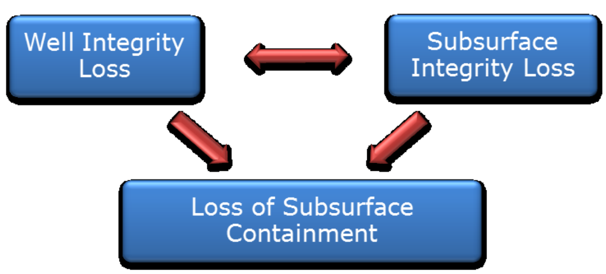

Figure 1. Leakage and migration of subsurface fluids can occur from a loss of well integrity, subsurface integrity, or both.

Leakage of bitumen through cracks in the overburden and onto the ground surface was documented at Canadian National Resources Limited's Primrose East (Energy Resources Conservation Board, 2013) and Primrose (Pratt, 2013) heavy-oil fields in eastern Alberta, Canada in January 2009 and July 2013, respectively. In these examples, the exposure of near-surface fields is related to non-catastrophic hydrocarbon and injected steam migration associated with uncertainties in overburden characterization; mitigation of future events involved specification of reduced steam injection volumes during production operations. The leakage events illustrate how consideration of subsurface integrity, in addition to wellbore integrity, motivates a key element of subsurface containment risking.

A necessary part of hydrocarbon production in many conventional and unconventional reservoirs, Cuttings and Wastewater Reinjection (CWRI) (e.g., Guo et al., 2006; Ronderos and Ovalle, 2010; Ochi et al., 2013) can contribute to localized losses of subsurface containment. Of 29 active CWRI wells on the Norwegian continental shelf alone, 13 wells have leaked crude oil and injected fluids to the seafloor between 1997 and 2010 (Klima- og forurensningsdirektoratet, 2010). CWRI into undercompacted weak Cenozoic marine sedimentary shales and mudrocks in the overburden above ConocoPhillips Company's Ekofisk field (Nagel and Strachan, 1998) triggered a large moment-magnitude M_w = 4.1–4.4 seismic event in May 2001 (Ottemöller et al., 2005). The event may have resulted from sudden unstable shearing along pre-existing normal faults and/or bedding planes in the overburden sequence as a result of the locally elevated pore pressures, highlighting the potential importance of faults and potential fluid migration pathways away from a wellbore in subsurface containment risking.

Subsurface Geologic Barriers

Stratigraphic units such as shales that have sufficiently low values of permeability, and more ductile deformation properties, can serve as effective top seals for subjacent reservoirs; top seals comprise one of several key elements in subsurface containment risking. As noted by Davison et al. (2013) and others, excessive formation or bottom-hole injection pressures can give rise to dilatant ("tensile") failure of the overlying top-seal formations. Leakage of crude oil or mixtures of subsurface fluids to the sea floor offshore Norway near Statoil's Tordis field (Eidvin and Øverland, 2009) in May 2008, offshore China at ConocoPhillips's Bohai Bay field in June 2011 (Bertrand, 2012), and offshore Brazil at Chevron's deepwater Frade field in November 2011 (Asher, 2012), illustrate how subsurface containment assurance should explicitly integrate production operations and geomechanical assessments of formation and top-seal mechanical strengths. Additionally, companies in such situations are expected to investigate and understand the potential causes of the containment losses and to initiate steps to mitigate the risks of future accidents.

Near-Surface Caprock

Production of hydrocarbons under very shallow conditions requires a careful balance between operating pressures and the strength of the near-surface overburden. In many reservoirs such as the Suban wet-gas field in Sumatra, Indonesia (Hennings et al., 2012) or in deepwater environments where shallow-water flow is apparent (e.g., Winker and Stancliffe, 2007a, b), stratigraphic units within a few hundred meters of the surface can be poorly consolidated; in conjunction with typically small magnitudes of the *in situ* stresses, injection pressures or large gradients can potentially pose a containment risk. Shallow depth, overburden strength at appropriate pressure and temperature conditions, pressure gradients, and *in situ* stress state might be considered to be appropriate risk elements for sufficiently shallow fields.

At Total's Joslyn Creek heavy-oil field in Alberta, Canada, steam injection associated with steam-assisted gravity drainage (SAGD) hydrocarbon production that exceeded specified injection-pressure limits led to explosive release of gas, rock projectiles, and dust leaving a crater 125 m by 75 m across in the Clearwater Shale caprock in April 2006 (Energy Resources Conservation Board, 2010). Mechanical analysis of such overburden systems by Chin et al. (2012) demonstrates that the shear strength of a caprock may be at least as critical an element in determining caprock strength as its tensile strength, reinforcing the importance of frictional stability in subsurface containment risking (e.g., Ingram and Urai, 1999; Nygård et al., 2006; Energy Resources Conservation Board, 2010).

Fluid Injection and Microseismicity

Extensive previous work has demonstrated that fluid withdrawal can induce microseismicity and/or faulting within or near a reservoir (e.g., Yerkes and Castle, 1976; Segall, 1989; Grasso and Wittlinger, 1990; Teufel et al., 1991; Segall et al., 1994; Segall and Fitzgerald, 1998; Zoback and Zinke, 2002). Wastewater injection into hydrocarbon reservoirs can, under certain conditions, also induce microseismicity (Zoback, 2012; Kim, 2013) and perhaps induce slip on nearby pre-existing faults if those faults are already close to failure from the pre-production *in situ* tectonic stress field and injection volumes are sufficiently large (Frohlich, 2012). Stimulation of unconventional reservoirs by hydraulic fracturing can also induce microseismicity (e.g., Zoback et al., 2012; Busetti et al., 2013).

Undocumented Wellbores

Production operations in areas that have seen historical oil and gas operations are sometimes impacted by the presence of abandoned or undocumented wellbores. Shell's onshore natural gas operations in Tioga County, Pennsylvania were halted in June 2012 by a containment loss that resulted in a 10-m-high geyser of methane and water. The cause of the geyser was related to an unmapped wellbore that was abandoned ~70 years before (Detrow, 2012). This and similar events highlight the importance of including knowledge of abandoned or the potential of undocumented wellbores, local government regulations, and a rapid and effective response system in a subsurface containment assurance program.

An Approach to Subsurface Containment Assurance

Subsurface containment assurance involves the integrated efforts of the subsurface (reservoir and overburden characterization), the wells (planning, construction, well integrity and abandonment) and the operations (process and well operations and management of change) teams. In general, the potential risks to subsurface containment loss need to be identified for a given field, followed by the development and implementation of appropriate risk mitigation strategies. A "defense-in-depth" approach in which the effectiveness of multiple risk-mitigation elements is considered and assessed represents a key learning from recent containment incidents such as Macondo (Hopkins, 2012, p. 17). These mitigation strategies may include both "soft issues" (i.e., personnel training, staffing, identification and communication of key learnings; e.g., Bunn et al., 2010; Vinnem and Røed, 2013) and "hard issues" (i.e., revised pressure limits and alarms for field operations). A subsurface containment assurance program may layer a variety of both soft and hard issues in an attempt to mitigate multiple potential leak causes identified within a "defense-in-depth" or "Swiss Cheese" model of accident causation (Reason, 1997) in which holes in the cheese correspond conceptually to a sequence of failures of defenses, barriers, or safeguards. Near-miss incidents can provide important learning opportunities and motivation for improving the layering process and further reducing containment risk (Cooke and Rohleder, 2006).

In some sense, each field is unique in having its own set of geologic characteristics and production histories. Although a unique subsurface containment assurance program could be created for each field individually, such an approach might become excessively burdensome and difficult to manage for a large number or variety of assets. An alternative approach that utilizes a limited number of broad categories (as done for example in a geological engineering rock-mass classification scheme; Bieniawski, 1989) or elements can, if thoughtfully designed and executed, encompass a wide range of field types. An example of the latter type of approach is described in this paper. Applicable to both prospects and producing fields, six key elements can contribute to a subsurface containment assurance program that incorporates both "soft" and "hard" issues (**Figure 2**).

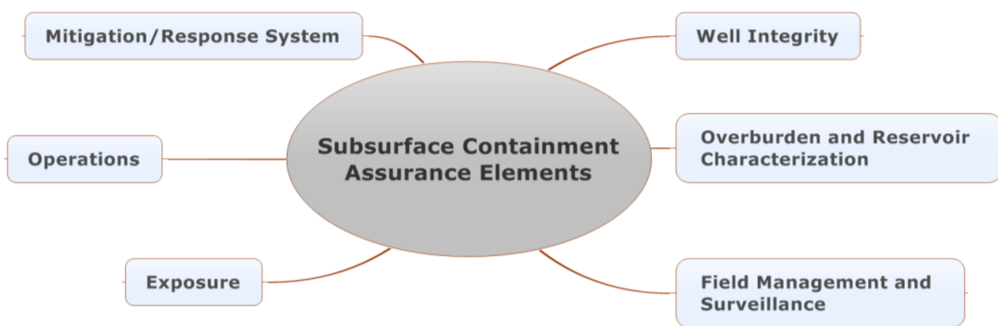

Figure 2. Principal elements of a subsurface containment assurance program.

- The *Exposure* element assesses the position of the asset within its life-cycle (e.g., prospect appraisal or producing field), the occurrence of existing or planned injection and withdrawal operations, abandoned or undocumented wellbores, and the degree to which well integrity or out-of-zone issues might exist. Exposure can also include an estimate of value at risk if an issue were to arise.
- The *Well Integrity* element involves those aspects of well planning, construction, and operation that have a bearing on subsurface containment.
- The *Overburden and Reservoir Characterization* element can help assess pre-production baselines, collection and archiving of geologic, geophysical, geomechanical, pore-pressure, fracture pressure, and production data that could inform containment analyses (e.g., Balasubramanian et al., 2013). Aspects of trap analysis that involve the mechanical strengths of top seals, faults, and fractures, and properties of stratigraphic units relevant to fluid flow and reservoir performance, may be contained in this element.
- The *Field Management and Surveillance* element can establish hard controls such as pressure and volume limits for individual wells along with more integrated assessment of injector and producer clusters. Various production and geophysical monitoring approaches (e.g., Ebitu et al., 2011; Gu et al., 2011) that may shed light on containment form an important part of reservoir surveillance and can inform field management decisions.
- The *Operations* element ties shorter-term, more day-to-day decisions to the wider context of field management, sometimes with explicit communication and feedback loops between operators and engineers. The objective is to

ensure that operating parameters remain within both well-design limits and geomechanical (stress and rock strength) limits.

- The *Mitigation/Response System* element incorporates soft issues such as communications, long-term planning, assessment, capture of key learnings, response training, and continuous improvement of a subsurface containment assurance program, along with articulation with governmental regulations applicable to a particular field or asset type. A management-of-change process can incorporate these aspects to help refine the subsurface containment assurance program.

In order to facilitate subsurface containment assurance, the various disciplines must work together to develop and implement a surveillance plan to monitor containment during well and injection operations. Such a process may be *proactive*, defining a process to be used to assure subsurface containment over the life-cycle of a field, or *responsive*, specifying actions to take and perhaps technical work required to address a suspected or identified containment issue. Either of these approaches may benefit from the use of screening, risking, or analytical tools (e.g., Skogdalen et al., 2011; Vinnem et al., 2010; Amendt et al., 2013a, b; Davison et al., 2013) that could help to inform and document the decision-making process. Reduction of the risk of containment loss may occur through a series of stages, or levels, defined by successively greater reduction of uncertainty in the key elements described in this section. The desired target level may be associated with the well-known ALARP (As Low As Reasonably Practicable) principle (e.g., Valeur and Petersen, 2013) as defined within an oil and gas company.

A useful way to illustrate a subsurface containment assurance program is by using the "bow-tie" model (e.g., Markowski and Kotynia, 2011; Hopkins, 2012, p. 62; Ramsden et al., 2013). The approach was developed for offshore risk assessment by Shell (Primrose et al., 1996; Trbojevic, 2008). This approach relates risks and consequences of a potential loss event to multiple barriers, commonly comprising elements of a decision tree (**Figure 3**). Although the bow-tie model is widely used in process and facilities safety risk assessment in the oil and gas industry, its application to subsurface containment assurance can illustrate how the key elements interact to minimize risk of containment loss.

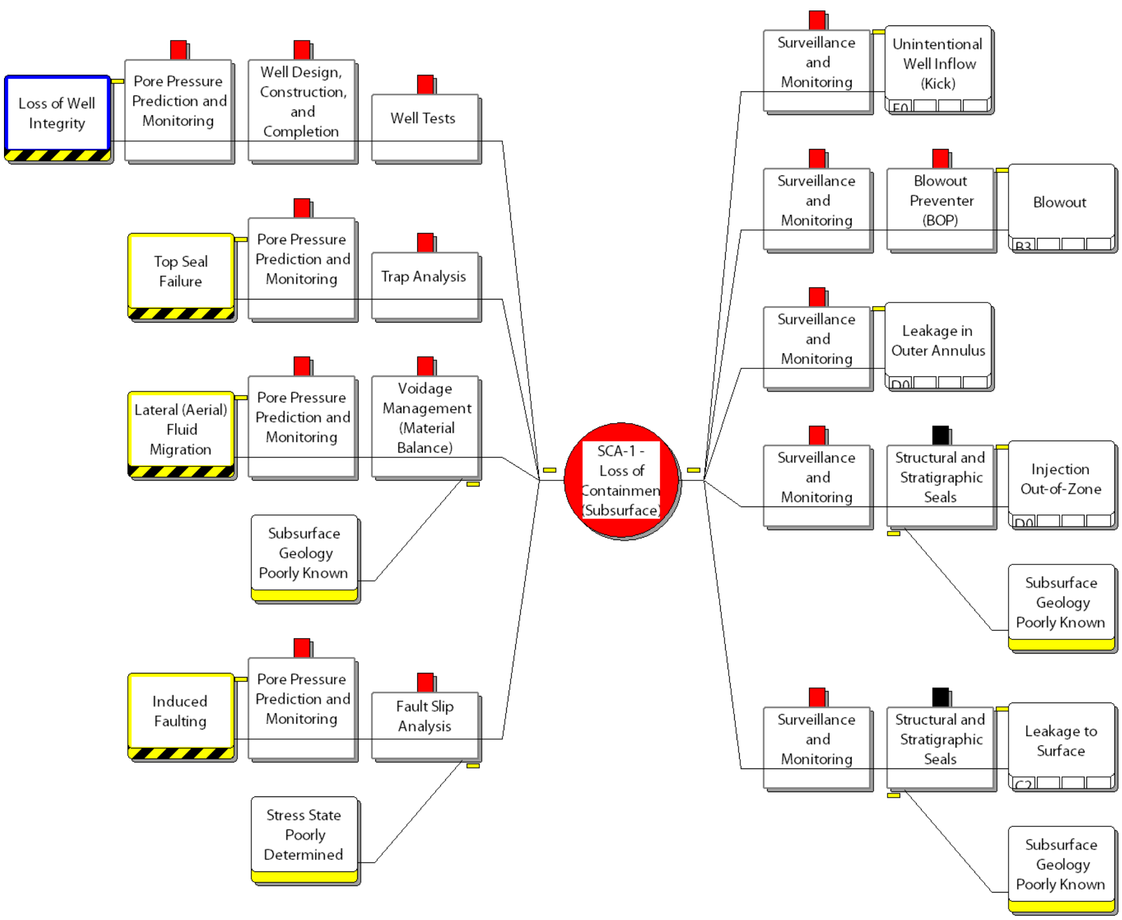

Figure 3. Conceptual bow-tie model of a subsurface containment assurance program. The model is schematic and may not be comprehensive or indicative of specific workflows. Red flags above panels denote required factor (barriers); blue panel outlines, operations factor; yellow, environmental factor; black-and-yellow stripes below panels, threats (risks, left-hand side of diagram).

The schematic subsurface containment bow-tie diagram shown in Figure 3 depicts the flow of a subset of potential risks to containment loss and the multiple independent barriers that can be installed on either side of an unexpected containment loss event. Each barrier and activity may be concretized by one or more technical workflows. In practice, a minimum of two independent barriers should be in place for a subsurface containment assurance program to be considered reliable. As noted by Book (2012), bow-tie diagrams can identify areas needed for continuous improvement including both hard and soft issues.

Practices for Deepwater Containment

With high-pressure, high-temperature (HPHT) fields being explored and produced in offshore settings such as the Gulf of Mexico, South America, Africa, North Sea, Australia, New Zealand, India, and southeast Asia (e.g., McLean et al., 2010; Shadravan and Amani, 2012), operating under deepwater conditions presents challenges of interest to subsurface containment assurance (e.g., Leffler et al., 2011). Deepwater plays and reservoirs have been variously defined as those located in offshore areas with water depths exceeding, for example, 305 m (1,000 ft) or 500 m (1,640 ft) for deepwater and 2,000 m (6,562 ft) for ultra-deepwater (Carré et al., 2002), corresponding to locations approximately beyond the continental shelf. Myers (2008) additionally defines hyper-deepwater conditions as water depths greater than 3,657 m (~12,000 ft), or beyond the (then-) current technological limit for riser height. Following Wood Mackenzie (www.woodmacresearch.com), we adopt depths exceeding 400 m (1,312 ft) for deepwater and 1,500 m (4,920 ft) for ultra-deepwater assets in this paper, but utilize the term deepwater herein to denote water depths exceeding 400 m for brevity.

In many deepwater environments of interest such as the Gulf of Mexico, rapid deposition has led to the accumulation of fine-grained, low-permeability sediments intercalated to various degrees with reservoir sands. As a result, formation (pore) pressures can exceed hydrostatic values which, in combination with small values of least-principal stress S_3 (corresponding to S_{hmin} in a normal-faulting tectonic regime), define a narrow drilling window (given at the specified depth by S_3 minus pore pressure) (e.g., Heppard et al., 1998; Smith et al., 1999; Shadravan and Amani, 2012). Narrow drilling windows are especially troublesome when drilling deviated and long-reach wells in deepwater environments, where changes in the magnitudes and orientations of the local stress state near salt bodies, shales, and other subsurface geological heterogeneities can potentially lead to wellbore enlargement and lost circulation, as documented, for example, at Shell's Ursa field (Gradishar et al., 2013).

Shallow seafloor sediments can be weak, given small values of effective stress, and plastic, leading to time-dependent creep and liquefication in some cases (Winker and Stancliffe, 2007b) along with landsliding on gentle continental slopes (e.g., Kvalstad et al., 2001). Seafloor slumps can be mapped by using sonar. Many of the physical properties of the sediments, including grain size, clay-rich mineralogies, high cohesion, and low friction that contribute to their intrinsic weakness and plastic deformation response can be measured by, for example, cone penetration tests (e.g., Boggess and Robertson, 2011). The attendant low bearing strength at the seafloor is important in siting and anchoring drilling structures such as tension-leg platforms (e.g., Kumar and Sonawane, 2004; Evans, 2011); stabilization of the sediments near the wellbore can be addressed by setting jet pipe.

Overbalanced drilling with a riser may lead to loss of circulation (if the fracture gradient is exceeded), whereas underbalanced drilling without a riser can promote shallow-water flow and sand production into the wellbore (Winker and Stancliffe, 2007a, b). In the former case, formation damage may compromise casing cement or lead to fracturing near a casing shoe, which could then either propagate up to the surface or laterally to connect closely spaced wells, leading to local subsidence of the overburden. In the latter case, reduction of mud weight by dilution with seawater (e.g., the pump-and-dump strategy) can lead to unfavorable chemical reactions with salt bodies and wellbore enlargement (Akers, 2011); the returns to the seafloor can undermine the ability of the seafloor to support foundation pilings, as for tension-leg platforms, by eroding near-surface sediments (Winker and Stancliffe, 2007b). Narrow drilling windows and prevention of lost circulation are currently being addressed by a variety of solutions including wellbore-strengthening technology (i.e., chemically activated cross-linking polymers that can limit mud loss into more permeable formations), dual-gradient and managed-pressure drilling (Smith et al., 1999; Myers, 2008), flat-rheology (i.e., temperature-insensitive) synthetic drilling mud, and improved monitoring of the drilling process (McLean et al., 2010).

The multiple borehole instability and lost circulation issues identified for the Ursa A–10 well by Gradishar et al. (2013) illustrate the diversity of potential failure mechanisms that might be encountered in deepwater environments. Shear failure (i.e., faulting) of a fractured shale occurred by invasion of higher-pressure synthetic drilling mud into the existing fractures, decreasing the effective stress and triggering faulting. In such cases, the bulk shear strength of the fractured shale can be predicted by its unconfined compressive strength and friction, which may be comparable to or less than the fracture gradient of an unfractured shale (e.g., Finkbeiner et al., 1998). Existing natural fractures in other stratigraphic layers were dilated by drilling mud, locally reducing the effective fracture gradient and drilling window. Stress cycling that can occur in association with swab-and-surge pressures, barite sag (separation and settling of weighting minerals such as barite from the drilling mud), and mud-weight corrections can lead to fatigue weakening and eventual failure of the wellbore.

The overview of geotechnical challenges and practices related to deepwater E&P by Evans (2011) highlights a suite of both hard and soft issues identified by BP's operations in the Caspian Sea, Angola, and West Nile Delta. Many of these influence either foundation stability or wellbore stability as discussed above, and several strategies were noted for geotechnical data acquisition, geohazard risk identification and mitigation, and allocation of costs over particular phases of the asset life cycle. Evans (2011) emphasized several soft-issue challenges including resourcing geotechnical engineers and integrating them on deepwater teams, an under-appreciation of geotechnical risks in deepwater environments, and sometimes *ad hoc* standards or guidelines for new deepwater projects within a company. Similar themes were echoed by Hill et al. (2011a, b) in their descriptions of BP's offshore Angola concessions. There, the identification of pockmarks on the seafloor, which are craters perhaps hundreds of meters wide by tens of meters deep formed by upward expulsion of fluids or shallow gas, could indicate migration pathways to the seafloor from faults or salt-sediment contacts in the subsurface. Shallow polygonal faults systems (e.g., Cartwright, 2011) as well as deeper normal-fault systems in offshore Angola were noted as potential sources of seismically generated ground accelerations that, if activated by production operations, could affect the design or stability of engineered deepwater structures.

On the basis of the preceding discussions, subsurface containment assurance practices for deepwater operations might include:

- A baseline assessment of containment exposure, such as characterization of pre-existing surface seeps and background seismicity, and important subsurface uncertainties, monitored, reviewed, and updated over the life of the field;
- Identification of shallow-water flow and other potential impacts of overpressured weak stratigraphy on drilling and well construction;
- Characterization of the *in situ* stress state and pore pressure conditions of reservoir and overburden to define initial drilling windows;
- Adequate characterization of the mechanical and geotechnical properties of reservoir and overburden layers including methane gas hydrates that are potentially both hazardous and lucrative;
- Assessment of the presence and importance of structural heterogeneities, such as faults, fracture sets, and stratigraphic contacts that could contribute to pore-pressure communication, reduced zonal pressure isolation, and/or shear failure at stress values lower than the local fracture gradient;
- Definition and deployment of a field management plan that specifies operating envelopes (e.g., pressure and strength limits), effective interaction between operators and longer-term field management engineers, and strategies for field surveillance and monitoring;
- Knowledge sharing and data archiving designed to facilitate communication of key learnings within the asset team, the business unit, and the company; and
- Clear definition and deployment of a response system and mitigation strategy that is communicated to, and articulated with, partners and operators as appropriate.

Discussion and Implications for Industry Practice

The subsurface containment assurance program outlined in this paper is predicated on risk identification and mitigation by using a defense-in-depth (multiple independent barrier) approach. The program appears to be generally consistent with others in the oil and gas industry, based on available information, such as ExxonMobil's Operations Integrity Management System (ExxonMobil, 2009), including the shared elements of risk assessment and mitigation, operations, archiving and documentation of key information, response systems, continuous improvement, and consistent application across a company's asset portfolio. An independent assessment of 10 integrated international or national oil and gas companies (including data for ConocoPhillips through 2011) by Yousefi and Aldeanueva (2013) shows that the general goals of subsurface containment assurance as described in this paper are being addressed in many of these companies by using a variety of distinct organizational strategies. Mellat Parast and Adams (2012) demonstrate the critical role that top management must play to facilitate quality-management practices such as subsurface containment assurance. The program described in this paper emphasizes a heightened focus on subsurface containment exposure and risks as an integrated part of day-to-day and longer-term E&P activities.

In an influential and ground-breaking study, the accidental loss of containment of subsurface fluids in the oil and gas industry could potentially be interpreted from this point of view as an inevitable occurrence in industries that are characterized by large, highly complex, fast-moving, and tightly interconnected technical and management systems (e.g., Perrow, 1984). Continued investigation of this thesis in other industries suggests, however, that such unexpected events may instead be reduced or eliminated in organizations that can successfully manage risk (Lekka, 2011). These "high-reliability organizations" (e.g., Weick et al., 1999; Roberts and Bea, 2001; Hopkins, 2007; Sutcliffe, 2011) are described by several characteristics including what is known as "resilience" (Costella et al., 2009), in which companies can survive and return to normal operation despite accidents by focusing on processes and practices that foster improvement toward a higher state of reliability. Examples cited of high-reliability organizations include air-traffic control centers, fire-fighting units, nuclear power plants and aircraft carriers, health care, and NASA (U.S. National Aeronautics and Space Administration). Following Roberts and Bea (2001), Costella et al. (2009), Lekka (2011), and Sutcliffe (2011) many high-reliability organizations:

- Aggressively seek to "know what they don't know" by allocating resources that enable them to anticipate and respond appropriately to minimize the risk of unexpected events. Accidents and near-misses are acknowledged and analyzed to reduce uncertainty and improve mitigation procedures.
- Effectively balance safety with profits by empowering and training employees to make collaborative decisions that mitigate the occurrence of unexpected events.
- Maintain a focus on the "bigger picture" in all its complexity and nuances while facilitating rapid access to appropriate subject-matter expertise when required. Both proactive and responsive procedures are well defined and employees know when and how to use them.
- Develop and maintain resilience to continue operations, including an organizational culture of safety and proactivity both prior to and during unexpected events.

As noted by Hopkins (2007), integration of high-reliability organization concepts into the oil and gas industry has been hindered by a prior focus in the literature on technological complexity rather than on organizational behavioral characteristics such as those noted for high-reliability organizations in this paper. The development and deployment of effective subsurface containment assurance programs such as those described by ExxonMobil (2009) and in this paper can potentially benefit from the experiences of high-reliability organizations. However, the intent of the subsurface containment assurance program described in this paper goes further by noting that losses of subsurface containment, of any frequency or magnitude, are neither inevitable nor acceptable.

The International Organization for Standardization (ISO) 14000 family of environmental management standards (http://www.iso.org/iso/home/standards/management-standards/iso14000.htm; http://en.wikipedia.org/wiki/ISO_14000) can also inform or supplement elements of a subsurface containment assurance program. These standards were created to assist organizations identify and improve their management processes in order to minimize environmental impacts, comply with applicable regulations, and continuously improve in this area (e.g., Jackson, 1997; Szymanski and Tiwari, 2004). The process commonly involves conducting a gap analysis that compares the characteristics of a given project or asset relative to the ISO 14001 requirements, with subsequent installation of processes and workflows that could potentially lead to certification. Some upstream and downstream operations have adopted, or in some countries were required to follow, this approach (e.g., Petrobras in Brazil: Amaral, 1998; Enppi in Egypt: Shaarawi, 1999; Shell Nigeria: Onianwa et al., 2002; Qatar, Saudi Arabia: Anonymous, 2007) although it is not required for a subsurface containment assurance program such as that described in this paper (e.g., Onianwa et al., 2002).

Conclusions

This paper outlines a subsurface containment assurance process that specifies and layers a suite of soft and hard issues with the aim of mitigating multiple potential leakage mechanisms in wells and the subsurface, thereby reducing the risk of a containment loss in the subsurface. Subsurface containment assurance is seen to be an industry-wide issue that potentially affects all types of assets including conventional and unconventional, onshore and offshore. Because the consequences of containment loss to an operator or partner can be significant, an effective subsurface containment assurance program can form an integral part of an oil and gas company's operating strategy. Deepwater E&P activities pose a suite of challenges that invite close articulation with a subsurface containment assurance program. The development and deployment of effective subsurface containment assurance programs such as that described in this paper can potentially be enriched by knowledge transfer from resilient, high-reliability organizations with the fundamental caveat that losses of subsurface containment, of any frequency or magnitude, are considered to be neither inevitable nor acceptable.

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