

# Drilling hazard management: The value of risk assessment

**Part 2 of 3: Correctly interpreting drilling dynamics enables operators to make the right proactive decisions during operations.**

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Attaining success with drilling hazard management (DHM) depends on recognition of the project's risks. If executed effectively, the process yields a comprehensive awareness that provides a foundation not only to mitigate risk but also to optimize operations. Risk assessment can be conducted for any operation. This article presents a flexible, iterative process that allows evaluation of planned mitigations that may create further risks. The implementation of this process can be used to critically challenge each facet of the well design.

Risk assessment should be applied at the following stages of the well planning process:

- **Analysis:** Evaluating design alternatives for potential risks, hazards and benefits facilitates selection of the best approach.

- **Design:** The "basis of design" document provides specifics of the selected alternative and requires more focused evaluation.

- **Execution:** Risk assessments of all procedures, logistics, communications, etc., should be conducted to ensure that all risks are managed, to help minimize non-productive time and to sustain performance.

- For any change in the scope of the operation, the "management of change" document should be accompanied by a risk assessment of any new procedures, practices or technologies. (Within this article, we will deal only with risk of mechanical success and efficiency risk, not risks associated with health, safety and the environment.)

Three alternative responses succinctly sum up how risk can be managed: accept, mitigate or avoid. *Accepting* a risk means that the likelihood and consequence of the risk event actually happening ranks

so low that it is an acceptable risk to undertake. This likelihood is commonly referred to as "as low as reasonably practical" (ALARP). *Mitigating* means that the risk, as currently understood, is not acceptable and requires new or additional intervention. These new mitigations can come in the form of best practices, policies, procedures, techniques and technologies that better manage the risk. *Avoiding* usually requires revising the well design or mitigant in place or eliminating a step or task.

Using a risk matrix as a guidance tool enables the team to select any action that it determines to be reasonable and appropriate for the operation. A matrix provides a vehicle for documenting and organizing what is important to better understand the risk profiles of the operations and manage accordingly. Decisions are guided by company policies, rules or regulations, as well as those of the relevant regulatory authorities.

## PREPARATION

Factual information, a clear scope and well-defined objectives are needed to conduct a focused risk assessment. The first step of the process is to perform due diligence and collect all pertinent data available. Adequate data collection should include the most current information from all sources and stakeholders. Data can come from multiple sources including, but not limited to, local, regional and global well histories, reports, studies and personal experiences.

Risk assessment success depends on the quality and range of the participants' knowledge and experience. A broad knowledge base and a wide range of expertise produce better results. Drilling engineering peers and personnel of other disciplines, such as geoscientists and reser-

voir and production engineers, should be integral sources of input during discussion and planning. Providers of critical services should also be included in the process.

The degree of rigor applied to the risk assessment process should be commensurate with the complexity of the well. Although the process can be tedious, it begins by defining the scope of each separate risk assessment session, the sum of which make up the process. All stakeholders involved need to provide their expertise; it is important for the stakeholders of various disciplines to fully understand the impact of their own objectives, procedures and requirements and to be prepared to brainstorm on any given operational task.

Understanding the scope of each session allows the stakeholders to use their own experiences and knowledge to discern possible and probable risks and hazards. Asking "what if" opens the session to speculative scenarios. If, for example, the session scope is risk assessment of tripping the drillstring, the "what ifs" would include such risks as stuck pipe, loss of circulation and swabbing. Participants prepared to bring their experiences and knowledge to identify risks and hazards help the team use time efficiently, stay within the scope, and compile a comprehensive assessment.

## CONDUCTING RISK ASSESSMENT SESSIONS

The initial risk assessment session should be conducted in a multidisciplinary environment to collect risks and associated consequences from the stakeholders. All participants should be given an opportunity to identify their risks and consequences, which can be accomplished through simple brainstorming. Once the "what ifs" are identified, consequences can be determined by asking "so what."

Identification of potential risks and their consequences constitutes the risk register—i.e., the full list of “what ifs” and “so whats” associated with all operations.

Adherence to a few basic rules can help ensure an effective session. They include appointing an unbiased facilitator and an excellent scribe; reviewing the risk assessment tool and its capabilities; and defining and communicating the session’s scope before beginning. In addition, it is important to maintain reasonable time limits for sessions; experience suggests that anything over two hours can be counterproductive. The risk register should be completed offline by the engineer or another person responsible for the project or well. Do not debate or wordsmith the brainstorming session; simply allow each person to offer his or her ideas and record them in the register. Work out granularity and details offline. The idea of a brainstorming session is to record, simply and concisely, the risks and associated consequences that collectively constitute the risk register.

**RISK ASSESSMENT PROCESS**

The risk assessment process is dynamic and should be continually reviewed and updated with the most current information. Because a consequence can also become a new risk, the assessment process can be somewhat circular in nature. For example, if the risk is fluid loss and the consequence is stuck pipe, this consequence becomes a new risk that generates a new consequence, such as that the pipe becoming irretrievably stuck. The key to addressing circular issues is managing the worst-case risk event first. This approach usually resolves circular issues and the original risk itself. The risk then eventually becomes mitigated and thus managed.

Sometimes risk can be superfluous, or deemed so by some of the stakeholders. For example, a driller might be concerned about the risk of sticking a wireline tool given hole conditions, while a geologist might not think it is a problem. Nevertheless, these risks should always be recorded and evaluated. The process, particularly if the worst-case risk events are evaluated first, often removes the superfluous issues by default.

Another issue that sometimes arises focuses on the costs used to determine the risk-adjusted value of a new mitigant. This issue should be raised in the early, brainstorming risk assessment sessions, but only using rough numbers, since these sessions should be high-level discussions. Dwelling on minutia at this point leads to losing sight of the scope. If more granularity is required, a subsequent risk-assessment session can be scoped, communicated to all stakeholders, and conducted on that singular focus. Over time, granularity and objectivity improves, but keeping the multidisciplinary brainstorming sessions at a high level is necessary to establish an initial baseline.

The risk assessment process should also determine and justify tradeoffs among geoscientists, reservoir engineers, production engineers and drilling engineers. Accommodating stakeholders from each of these disciplines is fundamental to the process and one of the reasons why it is necessary to assess any risk mitigant. Total cost of ownership means that the various disciplines understand the tradeoffs that occur in well planning designs and, ultimately, execution of the well. For example, directional well targets in slimhole profiles have specific risks associated with hole cleaning. The geoscientists need to understand this issue and

how the associated risks impact the cost of the well. Risk assessments become a decision quality tool and therefore assist in evaluating alternative well models.

**The risk matrix.** Acceptable forms of risk matrices can range from a very simple categorization of risk by high, medium and low risk of occurrence to a more granular tabular matrix for probability on one axis and severity of consequence on the other. In general, the more granular the matrix, the more valuable it is in terms of defining, ranking and managing risks. Table 1 depicts a typical industry risk matrix.

The risk matrix can be adjusted for levels of likelihood or probability and costs. Identifying costs associated with consequences is important to evaluate the added value and risk-adjusted costs of any new mitigant. The only exception is for health, safety and environmental (HSE) risk, because it is not possible to monetize the value of human life. Adjustments to the matrix axis should be based on relevant best fits for any given project. For example, if an operation is in deep water, costs should be those that are relevant to the operation itself. Probabilities are more subjective, but percentages of occurrence should be based on the experience and knowledge of, and agreed to by, the team conducting the risk assessment.

In general, the same matrix should be used for successive operations at a given project or well, to provide continuity, so long as the relative values remain representative of the project or well over time. If these values change significantly, then a new matrix may be warranted.

**The risk assessment process tool.** It is important to capture risks in

**TABLE 1. Typical industry (success) risk assessment matrix**

Probability		Likelihood indices						
> 40%	1	Likely	6	5	4	3	2	1
20–40%	2	Occasional	7	6	5	4	3	2
10–20%	3	Seldom	8	7	6	5	4	3
5–10%	4	Unlikely	9	8	7	6	5	4
< 5%	5	Remote	10	9	8	7	6	5
< 1%	6	Rare	10	10	9	8	7	6
Consequence indices (examples can be adjusted for local costs)			Increasing consequence/impact					
			6	5	4	3	2	1
Consequence description (rig or equipment damage/downtime, mechanical damage/downtime)			Incidental	Minor	Moderate	Major	Severe	Catastrophic
			Half day lost (\$100K)	Day lost (\$100K–\$250K)	Loss of hole section (\$250K–\$1M)	Loss of more than 1 hole section (\$1M–\$5M)	Loss of well (\$2M–\$20M)	Loss of rig (> \$20M)

a tool that can be used to conduct and record the entire risk assessment process. The process must be auditable and sustainable. Table 2 represents a typical

industry risk assessment tool populated with step-wise aspects of the process. The table uses actual examples to illustrate key points.

**EXECUTION PHASE AND WELL LISTENING**

In the execution phase of well operations, DHM begins with understanding

**TABLE 2. Typical industry risk assessment tool**

Hole section 4: 12–14-in. section Risk 1: Fluid loss in hole section						
	1.01	1.02	1.03	1.04	1.05	1.06
<b>Consequences</b>	Non-productive time	Slight losses	Severe losses resulting in 4 days to cure, squeeze and drill out	Whole mud losses resulting in loss of hole section and requiring sidetrack	Well control	Blowout
<b>Existing mitigation(s) in place</b>	Mud program, lost-circulation procedures and materials, BOP equipment, pit drills	Mud program, lost-circulation procedures and materials, BOP equipment, pit drills, applied controlled drilling	Mud program, lost-circulation procedures and materials, BOP equipment, pit drills, applied controlled drilling	Mud program, lost-circulation procedures and materials, BOP equipment, pit drills, applied controlled drilling	Mud program, lost-circulation procedures and materials, BOP equipment, pit drills, applied controlled drilling	Mud program, lost-circulation procedures and materials, BOP equipment, pit drills
<b>Likelihood of occurrence with existing mitigation(s) in place<sup>1</sup></b>	100%	100%	40%	100%	10%	5%
<b>Likelihood (ranking 1–6)</b>	1	1	2	1	4	5
<b>Consequence (ranking 1–6)</b>	6	6	3	3	2	1
<b>Risk ranking factor<sup>2</sup></b>	6	6	4	3	5	5
<b>Risk response choice: accept, mitigate, avoid</b>	Accept	Accept	Avoid	Avoid	Mitigate	Mitigate
<b>Mitigation(s) needed<sup>3</sup></b>			Add pressure-while-drilling (PWD) for proactive ECD management	Add pressure-while-drilling (PWD) for proactive ECD management	Add pressure-while-drilling (PWD) for proactive ECD management	Add pressure-while-drilling (PWD) for proactive ECD management
<b>Cost of mitigation(s) needed</b>			\$500,000	\$500,000	\$500,000	\$500,000
<b>Likelihood of occurrence with mitigation(s) needed in place</b>			20%	5%	1%	1%
<b>Likelihood (ranking 1–6) with mitigation(s) needed in place</b>			3	5	6	6
<b>Consequence (ranking 1–6) with mitigation(s) needed in place</b>			3	3	2	1
<b>New risk ranking factor<sup>4</sup></b>			5	7	7	6
<b>Extra time if event occurs, hr</b>			96	96	96	73
<b>Extra cost if event occurs</b>			\$4 million	\$4 million	\$3 million	\$3 million
<b>Risked time, hr<sup>5</sup></b>			19.20	4.80	0.73	0.74
<b>Risked cost<sup>5</sup></b>			\$800,000	\$200,000	\$30,000	\$30,000
<b>Benefit-to-cost ratio<sup>6</sup></b>			1.60	7.60	0.54	0.24
<b>Comments</b>			This indicates that not only is the risk profile improved, but also, on a risk-adjusted basis, the cost of the new mitigant adds value to the operation.	This indicates that not only is the risk profile improved, but also, on a risk-adjusted basis, the cost of the new mitigant adds value to the operation.	This further justifies the new mitigant.	This further justifies the new mitigant.

<sup>1</sup> Probability percentage of occurrence based on data or experience.  
<sup>2</sup> Ranking from the risk matrix; risk response choice is suggested by color, and action is determined by the team.  
<sup>3</sup> With intent to reduce the probability of the risk occurring.  
<sup>4</sup> With needed mitigation(s) in place, based on lower probability of the risk occurring (consequence generally remains the same); not improvement in risk profile.  
<sup>5</sup> Risk-adjusted lost time and cost if the event still occurs (normally, total NPT off the critical path to the time on the critical path); associated costs are the total daily cost of operations.  
<sup>6</sup> Added value of the new mitigant represented by its discrete cost as a function of reduced risk; the value for the worst-ranked risk indicates that the mitigant has added value.

and making the correct proactive decisions regarding the totality of the drilling dynamics. The art of “listening to the well” involves simply recognizing, integrating and correctly interpreting all drilling dynamics—weight on bit, drillstring rotational speed, equivalent circulating density (ECD) and shale shaker cuttings—to assist in making the correct decision while executing drilling operations.

For example, indicators that the ECD is too low include the following:

**Unexpectedly high rate of penetration (ROP).** A mud weight that is too low can have the net effect of removing the force at the bit, allowing the formation being drilled to fail more easily, thus increasing ROP.

**Torque/drag increase.** Removal of mud weight force can cause the formation to collapse inward, thereby creating lateral forces on the bit, BHA and drillstring.

**Cavings (particularly concave or splintered).** Recognizing the types of cuttings over the shaker is critical to drilling data interpretation. Cuttings from a shale section where the wellbore is approaching failure will characteristically appear concave (the shape of the hole) or splintered.

**Flowrate increase.** Decreased force of the mud weight can create underbalanced conditions, allowing fluid influx into the wellbore.

**Shut-in drill pipe pressure and/or well control.** This is an obvious condition of well control events or formations trying to feed into the wellbore.

**Drilling break gas failing to “fall out” after circulating.** This indicates in situ gas feeding into the wellbore from a permeable gas horizon.

**BHA drift (principal stress vectors).** Pseudo-induced stress can be caused by tectonics, salt diapers, faults, etc. Stress can be quite different from pore pressure in magnitude and is a vector. This phenomenon can have the net effect of trying to force the BHA in a principal direction if not correctly balanced with mud weight. Recognizing the difference between stress and pore pressure while drilling is crucial to interpreting dynamic drilling data.

**Hole fill-up (sloughing or collapsing hole).** Hole collapse can result in fill when off bottom and is quite common in softer formations.

Indicators of excessively high ECD include the following:

**Unexpectedly low ROP.** If the mud weight is too high, it can have the net effect of adding confining force at the bit,

making the formation being drilled more difficult to penetrate; thus the ROP decreases with poor performance.

**High bit wear.** Extraordinary mud weight force creates more confining stress on the rock, making the rock more difficult to drill.

**Overly wet shale.** Mud weight that is too high increases the instability of the shale section. Shale is not permeable but does respond to wetting through ionic exchange, much the same as clay on the ground that cracks when dry, then swells when hydrated. Overly wet shale reduces the net effect of inhibition, regardless of the drilling fluid. Even oil-based systems are never 100% water free.

**Fluid loss.** Mud weight that is too high creates unnecessary fluid losses and differential sticking, and exacerbates the risk of fracturing softer formations.

Indicators of other hazards include the following:

**D exponents (changing drillability trends).** This quantity represents real-time drilling analogs of specific energy applied to the bit or formation drillability. This data is normally and routinely compiled in the mud log and can represent shifts in drilling trends from a normal to a stressed environment. Trend shifts are very reliable predictors of changes in the drilling environment. This data compiled with other interpretations can be a clear indicator of the need to increase mud weight, especially in light of other interpreted data.

A common misunderstanding in the industry is that D exponents have no value with fixed cutters, when quite the opposite is true. This engineering-specific energy algorithm is independent of bit type. Another value of these as trend predictors is that they can help forecast changes in wellbore stresses, which pressure-while-drilling (PWD) tools cannot. PWD tools measure only the net balance in the static and dynamic states.

**Elliptical hole (principal stress vectors).** An elliptical hole is normally an after-the-fact indicator, but recognizing this stress-induced hazard can help plan the next well to identify wellbore stability issues and assist in directional planning. This data can also be used to compare conventional pore pressure predictions to stress both in direction and in magnitude and to better deliver a reliable mud weight schedule and help improve predictions.

**Fluffy, wetted shales (chemical instability).** Chemical instability is common in shale. Cuttings characteristics can be exhibited as “fluffy” or, in the worst

case, gumbo. This phenomenon can happen in any mud balance condition and is exacerbated if the mud weight is too high. If wetting occurs with mud weight too high, reducing the mud weight can create further instability because wetted shale will relieve stress. Newly exposed shales undergo ionic exchange and are re-wetted. Once the applied mud weight is too high, it can be nearly impossible to correct this condition, as the hazard will compound itself.

## LIMITS OF REAL-TIME DATA

The advent of real-time technologies facilitates accurate decisions and best practices for any operation. However, the industry’s growing dependence on real-time data can foster a singular focus that sometimes results in misinterpretation of issues. For example, operators often respond to the commonplace occurrence of background gas by weighting up drilling systems arbitrarily. This reaction—or a reaction stemming from misinterpretation of any of the above dynamics—is counterproductive to performance and can also induce dangerous drilling conditions. Good drilling practices revolve around interpretation of the totality of the data to make the correct decision while drilling; singular interpretation of conditions associated with any of the drilling dynamics can be counterproductive to maintaining a safe and stable wellbore, as illustrated with the following examples.

**Ballooning (wellbore breathing).** Ballooning is a phenomenon that often occurs as a consequence of excessively high ECD. Resultant flowback when pumps are shut down can often be confused with influx caused by a pore pressure that is greater than mud balance. This interpretation is often further complicated by gas entrained in shale, common especially in mottled shale. “Weighting up” the mud to counter the shale gas can further complicate ballooning. Arbitrarily increasing mud weight in the presence of shale gas alone can result in the extension of natural fractures or fracturing of the formation below or at the shoe, sometimes with catastrophic consequences.

Failure to distinguish ballooning from a well control event is a common mistake made in drilling operations. It is also one of the leading causes of unnecessarily expending casing strings in narrow-margin drilling operations such as occur in high-pressure/high-temperature and deepwater environments.



In a typical case in an actual well, high ECD resulted in ballooning, and a subsequent increase of the mud weight resulted in the extension of existing fractures. The higher ECD further exacerbated wellbore instability by increasing the cyclic bleed-offs. Ultimately, the mud weight increase fractured the formation, and massive and unsafe fluid losses were sustained before control of the well was regained.

The sequence of events began with the setting of casing at 11,370 ft with 1.7-sg mud weight. This mud weight was arbitrarily increased in the shoe track to 1.9 sg before drilling ahead. ECD management became difficult, with frequent ballooning events. Frequently conducted flow checks showed no flow. All other drilling dynamics were normal; there was no torque or drag, and cuttings appeared normal.

As background gas increased in the shale interval, the mud was weighted up several times without conducting any flow checks. Gas alone is not a reason to increase mud weight; since shale does not have transmissibility but does have porosity, entrained gas is common and cannot be weighted out, especially in highly mottled shale. Entrained gas

always arrives with the cuttings and expands according to Boyle's law, no matter the mud weight.

Drilling in shale continued from 13,300 ft to 14,000 ft, with increasing background gas. The well was circulated and conditioned with no fill. The BOP was closed with no flow and no pressure observed, and control was circulated through the choke. No torque spikes, drag or fill were observed, and cuttings still appeared normal. Mud weight was increased to 2.0 sg while circulating on the choke.

The shut-in drill pipe pressure of 340 psi was bled back with no further flow or pressure. The BOP was closed with 340 psi, then opened. The well briefly had a small initial flow and then shut in with no pressure. The well was opened and found to be stable with no flow. Shut-in pressure was not measurable. The well was circulated and conditioned, and the mud weight was further increased to 2.3 sg, and later to 2.45 sg with immediate and massive fluid losses. Ballooning-induced fracturing occurred after the mud weight increase. Three days of circulating and conditioning back to 2.1 sg was necessary to stabilize the well.

**TABLE 3. Generic lost-circulation control methodology**

**Solution set**

1. Avoid applying excessive mud weight; improve hydraulics and overall ECD including improved hole cleaning and controlled drilling.
2. Flush or spot 1–3% fibrous and/or flaked LCM pill, or add 1–3% fibrous and/or flaked LCM to circulation mud.
3. Flush or spot 1–3% sized calcium carbonate pill, or add 1–3% sized calcium carbonate to circulation mud.
4. Spot and/or squeeze 8–12% LCM pill (mixture of fibrous, flaked and granular LCM).
5. Apply cement spot and/or squeeze.
6. Specialty techniques such as chemical pig or gunk squeeze.
7. Blind drilling.
8. Improve mud cake by adding asphaltic material.

**Application**

Type of loss	Type of formation							
	Congl.	Shale (or silty shale)	Sandstone				Coal	
			Low por.	Med. por.	High por.	Fractured	Small fissured	Fractured
Seepage only	1,2	1	1,3	1,3	1,3	1,3	1,8	1,8
Small losses	1,2	1,2	1,3	1,3	1,3,2	1,3,2	1,8,2	1,8,2
Medium losses	1,4	1,4	1,3,6	1,3,2,5	1,3,2,5	1,3,2,4,5	1,2,4	1,2,4,5
High losses	1,4,5	1,7,4,5	–	1,3,5,6	1,3,5,6	1,4,5,6	1,4,5	1,4,5
Uncontrolled losses	1,7,4,5,6	1,7,4,5,6	–	–	1,7,4,5,6	1,7,4,5,6	1,4,5,6	1,4,5,6

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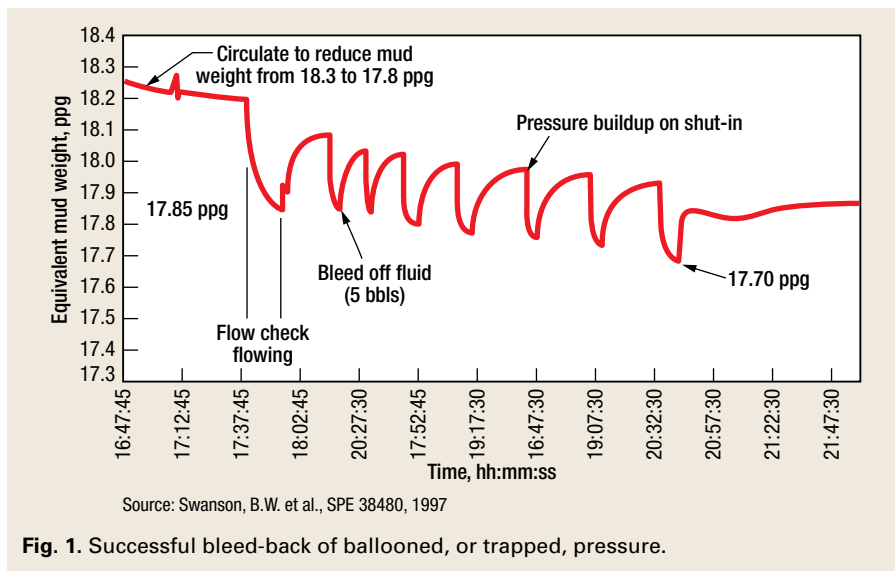


Fig. 1. Successful bleed-back of ballooned, or trapped, pressure.

A decision was made to run liner once the well was stable. The pore pressure/fracture gradient curves were observed to be normal. It was determined that, other than background and connection gas, which bled off, there had been no reason initially to increase the mud weight.

In this well, properly managing ECD and recognizing ballooning as a consequence of high ECD could have allowed the well section to be drilled deeper. The misinterpretation of ballooning required the setting of a liner before planned and caused the loss of a casing point. The consequences could have been much worse—wellbore collapse or even a shallower formation influx from an underbalanced formation.

When ballooning is recognized, care must be taken to avoid unnecessarily weighting up. Instead, trapped pressure must be bled back. Figure 1 represents an actual case where ballooned pressure was recognized and successfully bled back.

**Fluid loss.** Fluid losses can range from slight to catastrophic and result in wellbore failure or well control events. They primarily occur because the ECD is outside the safe drilling margin defined by the overburden fracture gradient on the high side and the in situ pore pressures and stress of the formations on the low side. These boundaries can be exceeded as a result of ballooning or, in porous formations, because an unnecessarily high mud weight is applied. Maintaining the ECD low enough to ensure fluid volume integrity yet high enough to maintain wellbore integrity is critical, and requires well listening.

Sometimes losses can be acceptable and sustained. In these cases, recognizing

the types, relative volumes, classes of lithology, and placement of proper lost-circulation material (LCM) is critical to the successful management of fluid losses.

The best practice and first line of defense is to avoid overweighting the hole and thereby prevent ballooning events. Typical fluid loss decision tree processes can and should be created. Table 3 is an example of the foundation of a fluid-loss control application process.

**Stuck pipe.** Stuck pipe is a drilling hazard that can be associated with ballooning and fluid losses. Recognizing and avoiding stuck pipe requires some of the same well listening techniques as used for other hazards. Generally, stuck pipe is avoidable if drilling margins are honored and listening guidelines are observed.

Some causes of stuck pipe that might have little to do with the drilling margin are coal sections; shale welling (gumbo); hole packoffs around the BHA; under-gauge hole; wellbore geometry (such as hole restriction in highly permeable sections with high fluid loss); collapsed casing; cement blocks; junk; green cement; cuttings beds or buildup, especially in high-angle holes; and salt, causing plastic flow. Prevention of stuck pipe in each of these scenarios requires an awareness of overall hole conditions; of course, some are unavoidable, such as unknown collapsed casing. Nonetheless, they should all be considered as potential risks and assessed.

The best practices to avoid stuck pipe are much the same as for ballooning and fluid loss—recognizing the conditions within the drilling margins and events and reacting correctly. Other factors that should be considered include BHA and

drillstring configuration, as well as the inhibitive characteristics of the formations being drilled.

## NEXT INSTALLMENT

Part 3 addresses the integration of mitigation into the well design. Managing drilling hazards requires understanding how practices and technologies can improve the risk profile and add value—i.e., demonstrate a positive cost-benefit balance from a risk-adjusted perspective. Any new mitigant must decrease the likelihood of the risk event occurring, and the risk adjusted cost should be financially beneficial to the overall operation. It is therefore important to understand how various technologies can improve the ability to mitigate and manage risk and improve the ultimate value of the well. **WO**

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