smaller structural-casing strings have been maintained effectively reducing the hydraulics.

Operationally, when the structural casing is spudded, the mud pumps are turned off or rolled at a very slow rate to keep the bit nozzles from plugging. Progress is made by virtue of the SOW alone. At a nominal value of SOW (5 to 10 kips), the pump rate is increased. The pump rate continues to increase with depth until a maximum planned flow rate is reached. The depth at which maximum flow rate is targeted is on the basis of broaching history of the area, but is usually before 150 ft BML. As the casing approaches its final depth, pump rate is sometimes decreased for the last 10 to 15 ft to add assurance the sediments near the structural-casing shoe are not washed out, which could result in casing subsidence.

**Sweeps.** Because the drilling fluid used in the jetting process is seawater, the fluid has low cuttings carrying capacity. Sweeps are used to enhance hole cleaning and remove cuttings from the annulus. Viscous sweeps are periodically pumped to sweep the hole of accumulating cuttings. Sweeps are usually composed of seawater with guar gum or prehydrated bentonite. With annular capacities of greater than 1 bbl/ft, large sweeps are required to prevent sweep stringing and dispersal.

Sweeps are important throughout the jetting process. When jetting is commencing, hole cleaning is compromised by the low flow rates used to establish skin friction and prevent broaching. Sweeps provide additional hole cleaning assistance to the limited flow rates. As jetting progresses and flow rate is increased, the swepst assist in removing larger and more cohesive pieces of formation. As a minimum, sweeps are pumped at connections and mid-stand. On jetting jobs with undersize bits, sweep frequency can be increased as frequently as every 15 to 20 feet.

**Reciprocation.** Reciprocation of the structural-casing string while jetting is a polemic subject with differences of opinion existing even within organizations and drill teams. Reciprocation of casing is the vertical movement of the casing string. As progress is being made during the jetting operation, the formation creeps in behind the casing connectors and begins to fill the void and develop skin friction with the casing. Reciprocation pulls the casing and its connectors back through this disturbed area. The wiping action reduces the developing skin friction and results in less required slack-off weight to make forward progress. Reciprocation does not assist in hole cleaning since cuttings are removed through the casing by BHA annulus. Reciprocation does not lead to broaching since the fluid flow will follow the path of least resistance, which should be inside the casing. Reciprocation will reduce the level of flow resistance of the soils outside the casing that resists broaching. Broaching is caused by a restriction inside the casing such as a packoff around the jetting BHA or a plugging of the exit ports in the wellhead and running tool. It is the restriction inside the casing that makes the alternative path outside of the casing to become the path of least resistance.

Reciprocation should only be used to maintain the WOB schedule. The length of reciprocation can vary from a few meters to as much as the entire stand, depending on the experiences of the personnel involved. Smaller lengths of reciprocation have proved equally effective in many locations. Some drill teams prefer to jet with a locked compensator to allow vessel heave to be transmitted through the drillstring to the structural casing. Hence, the string is jetted with a continuous stroke of the amount of the vessel heave. Caution must be observed such that the instantaneous SOW caused by the heave does not exceed Euler buckling force.

**Post-Jetting Considerations**

Once a structural-casing string has been jetted successfully to final depth, the casing annulus must be cleared of cuttings and the running tool/jetting BHA released from the wellhead. A large viscous sweep, 100 to 500 bbl, has proven most effective in removing any cuttings remaining in the annulus. Excessive circulation at TD should be avoided because of the risk of washing out the formation at TD and inciting subsidence.

Once the cuttings have been removed, a period of “soak” time is employed to allow the skin friction to increase and improve the soil to casing adhesion. During the soak period, no circulation is to occur and the hookload should be the same as the final slackoff hookload. The running tool or drill ahead tool (DAT) should not be manipulated in any fashion during the soak period. A soak period of one to two hours is prudent insurance against casing subsidence after running tool release.

| TABLE 2—TIME SPENT IN STRUCTURAL CASING X JETTING BHA ANNULUS BY CUTTINGS AT VARIOUS FLOW RATES |
|---|---|---|---|---|---|---|
| Time Spent by Cuttings in 300 Feet of Annulus With Zero Slip Velocity (min) |
| Flow Rate (gal/min) | 200 | 400 | 800 | 1,000 | 1,200 | 1,400 |
| 30 in.-casing x 8 in. DC’s | 40.7 | 20.3 | 10.2 | 8.1 | 6.8 | 5.8 |
| 30 in.-casing x 9½ in. DC’s | 39.1 | 19.5 | 9.8 | 7.8 | 6.5 | 5.6 |
| 36 in.-casing x 8 in. DC’s | 62.7 | 31.4 | 15.7 | 12.5 | 10.5 | 9.0 |
| 36 in.-casing x 9½ in. DC’s | 61.1 | 30.6 | 15.3 | 12.2 | 10.2 | 8.7 |

| TABLE 3—BBL’S OF CUTTINGS IN STRUCTURAL CASING X JETTING BHA ANNULUS AT VARIOUS ROP’S AND CIRCULATION RATES |
|---|---|---|---|---|---|---|
| bbls of Cuttings in Annulus While Jetting (36 in. x 8 in. DC Annulus) |
| Flow Rate (gal/min) |
| ROP (ft/hr) | 200 | 400 | 800 | 1,000 | 1,200 | 1,400 |
| 0.33 | 199.1 | 99.5 | 49.8 | 39.8 | 33.2 | 28.4 | 180.0 |
| 0.5 | 132.7 | 66.4 | 33.2 | 26.5 | 22.1 | 19.0 | 120.0 |
| 1 | 66.4 | 33.2 | 16.6 | 13.3 | 11.1 | 9.5 | 60.0 |
| 2 | 33.2 | 16.6 | 8.3 | 6.6 | 5.5 | 4.7 | 30.0 |
| 3 | 22.1 | 11.1 | 5.5 | 4.4 | 3.7 | 3.2 | 20.0 |
| 4 | 16.8 | 8.3 | 4.1 | 3.3 | 2.8 | 2.4 | 15.0 |
| 5 | 13.3 | 6.6 | 3.3 | 2.7 | 2.2 | 1.9 | 12.0 |
TABLE 4—ECDS IN STRUCTURAL CASING X JETTING BHA ANNULUS AT VARIOUS ROPS AND CIRCULATION RATES (8.57 LB/GAL DENSITY SEAWATER)

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<tr>
<th>Equivalent Mud Weight (ppg) While Jetting 300 Feet of 36 in. x 8 in. DC Annulus</th>
<th>5,000 Feet WD</th>
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<td>ROP (min/ft)</td>
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<td>8.61</td>
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</table>

Other Operations Considerations

The remotely operated vehicle (ROV) on the drilling rig is essential to the jetting operation. The ROV allows the jetting team to observe the following key items:
- Bit stick-out/bits space-out.
- Returns emanating from wellhead and wellhead-running tool.
- Broaching at mudline.
- Final jetting depth (wellhead stick-up from the mudline).

Documentation of operational parameters is extremely valuable to assess jetting performance and provide guidance for planning of future wells. Operational parameters and ROP should be documented on a per unit length basis. Reciprocation and sweeps should also be recorded. ROV recordings are essential when attempting to evaluate a non-optimal jetting operation. Fig. 12 displays jetting data from a deepwater West Africa well in composite graphical form.

Case Histories

Five case histories are presented below containing lessons learned through incidence of non-productive time. The intent is to share these experiences and learnings with fellow operators to avoid similar occurrences in the future.

Case History 1. 36-in. casing was to be jetted with a 17¾-in. PDC bit and BHA. The bit had been run on previous wells with excellent results and used for jetting one other well. A near-bit stabilizer had been planned, but left off the jetting BHA at the advice of the directional-drilling service provider. The casing was run and hung off in the moonpool. The BHA was run and the drill-ahead tool landed in the wellhead. The ROV was launched to check the bit space-out before tripping to the mudline and recorded an acceptable space-out. The drill-ahead tool was then cam-locked into the wellhead and the jetting assembly run to the mudline.

At the mudline, the ROV checked the space-out again but observed an increased bit stick-out from the jet shoe. It appeared most or the entire bit gauge was below shoe. Jetting was commenced, but broaching began almost immediately. Jetting was continued in the hope the broaching might bridge off, but the broaching continued. The operation was ceased and the jetting assembly was pulled. At the mudline, the ROV noted the PDC bit was pushed to one side with a PDC blade protruding beyond the OD of the casing. The inside of the structural casing was plugged off with clay/sediment. Fig. 13 shows an ROV photograph of the packed-off casing, while Fig. 14 illustrates the bit pushed past the OD of the casing.
In this case, the bit stick-out calculation had not considered the stem travel on the drill-ahead tool. When the cam is activated on the drill-ahead tool to lock the tool to the wellhead, the stem travels down by about 2 in. Hence, the bit stick-out appeared to be acceptable when checked at the rig, but when the tool was made up to the wellhead, the bit moved down by 2 in. Because the PDC bit only had 3 to 4 in. of gauge, the downward movement resulted in all of the gauge length sticking out below the jet shoe. The lack of a near-bit stabilizer completed the contributions to the event. With no near-bit stabilization, the bit was allowed to be pushed over to one side until the bit shank butted up against the casing. The PDC blade and nozzles were allowed to cut and jet outside the OD of the casing. This created a flow path outside the casing and further reduced flow and cleaning capacity inside the casing.

Lessons learned during this event include:

- Stem travel on the drill-ahead tool, cam-activated running tool must be considered in bit stick-out calculations.
- Bits with a short gauge section and an abrupt transition to the bit shank diameter, such as many PDC designs, have a more critical bit space-out. As a result, these types of bits are prone to be more problematic in this application.
- The use of a near-bit stabilizer in the jetting BHA helps keep the bit cutting and jetting action directly below the casing.

Case History 2. 36-in. casing was to be jetted with a 17½-in. tri-cone mill-tooth bit. Bit stick-out was 8½ to 9 in. per the well-program guidelines of 8 to 12 in. A connection was made with the jet shoe at 115 ft BML. After the connection was made, the ROV showed one port of the drill-ahead tool (DAT) was plugged off and fluid was no longer exiting the port. The DAT was equipped with six 3-in. ports and the 36-in. wellhead housing (WH) equipped with four 4-in. ports. After the cuttings cloud at the DAT/WH subsided, the ROV dove to the mudline. No broaching was observed at this point. The ROV returned to the DAT/WH and confirmed the cuttings cloud still enveloped the wellhead. The ROV made a second dive to the mudline and at this time, broaching was observed around the 36-in. casing. Jetting had progressed at this point to 160 ft BML. The ROV returned to the wellhead and ceased to observe returns coming from the wellhead circulating ports. The jetted depth, at this point, was 170 ft BML. The casing was jetted an additional 15 to 185 ft BML in hopes circulation from the wellhead ports might be re-established and the broaching would cease. The broaching continued and circulation was not re-established. The decision was made to pull out of the hole, and the trip out of the hole was made with no overpull. Once the casing was clear of the seafloor, the ROV could observe the casing-jetting BHA annulus was packed off with cuttings inside the jet shoe. Fig. 15 shows two of the ROV images.

The broaching was initiated by the obstruction of the fluid flow path in the casing by jetting BHA annulus, caused by the packoff of sediments in the annulus. No data was available to support a hypothesis that the soils in this area may have been more cohesive or sticky than soils in offsets wells. The packed-off sediments at the jet shoe, combined with pressure while drilling (PWD) data showing no build-up in the equivalent circulating density (ECD) suggesting a cuttings build-up, indicate either initial formation break-up and mobilization or hole cleaning in the lower part of the jetting BHA were major issues.

Lessons learned during the investigation of this incident include:

- The bit stick-out recommendation of 8 to 12 in. below the jet shoe was on the basis of experience with 30-in. casing by 26-in. bit
or 26- by 26-in. bits. A 17½-in. bit with a stick-out of 8 to 12 in. will have its nozzles below the jet shoe. Instead, the new guidelines provide guidance for both size bits. A 17½-in. bit stick-out is now suggested to be in the 4 to 8-in. range.

- ROP should be controlled with 17½-in. bits to limit cuttings in the annulus and to allow more time for the bit and jetting action to break up the formation.

- Flow rates should be increased when jetting a 36-in. casing string as compared to jetting 30-in. casing strings. A minimum of 1,200 gal/min should be used and full circulation rate should be achieved by 150 ft. BML. Still higher flow rates have potential to improve jetting performance.

- Increased sweep frequency and volume are needed in the larger annulus to avoid cuttings buildup. The cost of sweep material is small. Above 150 ft. BML, guidelines have been reinforced to pump 50 bbl sweeps at the middle of stand and before connection. Below 150 ft. BML, guidelines were increased to include pumping 50 bbl sweeps every 15 feet (eight sweeps totaling 400 bbl to TD).

Case History 3. 36-in. casing was to be jetted with a 26-in. bit to 290 ft BML. This planned depth was the same depth as the structural casings of the first two wells on the geologic structure. Progress was made to 210 ft BML with normal operational parameters. Below 210 ft BML, ROP began to decrease. The casing was reciprocated with 180 kips overpull to initiate movement. At 250 ft BML, ROP again slowed substantially. Reciprocation initiation took 200 kips overpull. Progress was made to 270 ft BML at a very slow ROP and another reciprocation was made, requiring 230 kips overpull to move the casing upward. This was the limit of overpull available on the drillstring being used. Any increase in skin friction would result in the casing and drillstring being stuck.

The drillstring and jetting BHA could be retrieved but the casing would be permanently stuck and the well junked. The casing and jetting assembly were pulled from the well and the casing saved. Examination of the 26-in. bit showed wear around the shirttail, indicating the bit was walking around the ID of the casing that aids formation breakup and removal. The casing was found to be clean, indicating hole cleaning was not a problem.

A second attempt was made at a location 40 ft from the original hole. The targeted jetting depth was reduced from 290 to 270 ft BML on the basis of the results of the first attempt. 26-in. bit stick-out was increased in the hope to increase hole washing to some extent. Jetting during the second attempt proceeded. Despite increased reciprocation, jetting ROP decreased and overpulls required to reciprocate the string increased. At 205 ft BML, the overpull required to work the pipe reached the tensile limit of the drillstring. Again, the casing and jetting BHA were retrieved from the well.

The third attempt used the same casing and jetting BHA configuration. The drillstring was changed out for a heavier string with greater overpull margin. In addition, it was decided to jet with a locked heavy compensator to impart vessel motion to the string and have a faster response during string pickup. The adjustment allowed more room to work the pipe at the top of a stand. Jetting with a locked compensator was possible because of the mild weather conditions prevalent at the time.

Jetting progressed at a new location 30 ft from the first two attempts with similar results to the second attempt. However, jetting did not cease once pickup overpulls reached 230 kips. The pipe was reciprocated and jetting continued with progress being made to the final depth.

Lessons learned during this incident include:

- Select a drillstring with sufficient overpull for jetting. The standard design overpull for drillstrings while drilling or running casing is 100 kips. This is not a sufficient design criterion for jetting. Further, the drillstring should be recently inspected to ensure it could deliver expected overpulls.

- Use of a locked compensator was considered one of the keys to success on the third attempt. The pinned compensator allowed a rapid pickup and a longer stroke during the reciprocation.

Case History 4. 30-in. casing was successfully jetted with a 17½-in. tri-cone mill-tooth bit to 260 ft BML in two hours. Bit stick-out was reported as 7.6-in. per the well program. Partial returns outside of the casing were continuous during the jetting operation from the mudline down to 165 ft BML. The casing was never reciprocated because of low slack-off weight employed in reading TD. The casing was allowed to soak for two hours to allow skin friction to build. The wellhead-running tool (drill-head type) was then torqued to release from the wellhead. The tool would not release. While working and applying torque to the running tool, pumps were run at varying flow rates up to 1,000 gal/min for approximately one hour. While attempting to release the tool, returns were observed around the outside of the casing. When the tool finally released, the casing sank 7 ft. The BHA was tripped to the surface while allowing skin friction to regain strength. However, when the new BHA was run to TD, returns continued outside the casing. The casing could not be retrieved, and the well was ultimately respud 50 ft away.

The principal lessons learned during the investigation of this incident were:

- Minimize/stop pumping while attempting to release running tool.

- The rapid jetting, low WOB, lack of need for reciprocation, and partial returns outside the casing were all signs of very low shear-strength soil. When such conditions are encountered, soak time to rebuild skin friction should be increased beyond standard procedures.

Case History 5. 36-in. casing was to be jetted with a 26-in. bit to 270 ft BML. This planned depth was the same depth as the structural casings of the first three wells on the geologic structure. Jetting progressed without incident with connections made at 62 and 157 ft BML. A third connection was made at 250 ft BML. During the connection, the ROV ascertained a further 23 ft remained to be jetted. Following the connection, approximately 20 more feet were jetted with visibility eventually being lost because of the cuttings cloud. The pumps were turned off for 10 minutes to allow the cuttings cloud to dissipate and check the mudmat position for a final check of distance to jet. The ROV determined an additional 6 ft of jetting was required to position the top of the wellhead and the mudmat properly. When picking up on the casing, it was found that the casing was stuck. The casing would not pick up with 230 kips over string weight and would not jet downward with maximum allowable slack-off and full-jetting pump rate. The bending moment loading on the casing was unacceptable and the wellhead sat too high for the subsea development, the running tool was released, the BHA retrieved, and the casing string abandoned in place.

The loss of the structural casing on this well left the drill team with the following lessons learned:

- Do not stop pumping unless there is a connection being made. Static casing allows skin friction to build and increases the risk of sticking casing at an undesired depth.

- Clearly mark structural casing with distances from mudmat nut for the last 60 feet. Markings should consist of a yellow line around the circumference of the pipe and four large clear distance numbers at 90° intervals.

- Plan drillpipe space-out such that no connection is required in the last 60 ft of jetting. The distance markings should be visible at the mudline and skin friction should not yet be approaching the maximum values observed near final depth.

- Remaining distance to jet should be confirmed during last connection and an ROV video record of the distance be made. This distance should be jetted without stopping. Should the distance to jet fall into question, jetting should continue until the mudmat lands on the mudline. This situation is preferable to sticking the casing high.

Conclusions

The following concepts and practices have been found key to jetting success:
1. Jetting structural casing to final depth is achieved through a combination of applying increasing SOW to the formation while removing formation from the casing path through a combination of bit action and hydraulic washing.
2. Development and adherence to a jetting SOW plan/plot assures the structural casing remains straight while jetting and should not subside when released from the running tool.
3. Reciprocation is used to break skin friction and transfer applied SOW to the bottom of the jetting string. Reciprocation is an effective tool when used in a judicious manner.
4. Pump rate and sweeps are used to clean the jetting BHA by structural casing annulus. When the annulus is clean, the chance of broaching is minimized, as the annulus remains the path of least hydraulic resistance.
5. Drillstrings used for jetting should be designed for overpulls much higher than typical drillstring design practices. The jetting BHA should be well stabilized and robust. Connections should have been recently inspected.
6. Use of larger OD casing poses new challenges in hole cleaning during jetting. These challenges are exacerbated by well plans using slim-hole bits and DATs, but can be overcome with proper use of reciprocation and sweeps.

**Nomenclature**

\[ A_s = \text{side surface area of structural casing, ft}^2 \]

\[ BF = \text{buoyancy factor, dimensionless} \]

\[ BW_{Ca} = \text{buoyed weight of casing at depth } x, \text{ lbm} \]

\[ BW_{C+JA} = \text{buoyed weight of casing plus jetting BHA at depth } x, \text{ lbm} \]

\[ c = \text{undrained shear strength of the soil at the point in question, lbm/ft}^2 \]

\[ D = \text{intermediate depth of interest, ft} \]

\[ D_{FP} = \text{depth below mudline to fixed point (casing may move/rotate only above this depth), ft} \]

\[ D_{MASOW} = \text{depth at which MASOW occurs, ft} \]

\[ D_{MASOW} = f_s = \text{depth at which MASOW = buckling force limit, ft} \]

\[ E = \text{modulus of elasticity for steel } = 29 \times 10^6 \text{ psi} \]

\[ f = \text{unit skin friction capacity, lbm/ft}^2 \]

\[ F_B = \text{buckling force limit at intermediate depth(s), lb} \]

\[ F_{BE/FP} = \text{buckling force limit at fixed point, lb} \]

\[ F_{os} = \text{factor of safety for undrained shear strength data} \]

\[ I = \text{casing moment of inertia, in.}^4 \]

\[ ID = \text{inside diameter of casing, in.} \]

\[ l_C = \text{total length of casing, ft} \]

\[ L_{stickup} = \text{length of casing above mudline when jetted to final TD, ft} \]

\[ MASOW = \text{maximum allowable SOW, lbm} \]

\[ MW = \text{density of drilling fluid, lbm/gal} \]

\[ OD = \text{outside diameter of casing, in.} \]

\[ Q = \text{ultimate bearing capacity, lbm} \]

\[ Q_f = \text{skin friction resistance, lbm} \]

\[ SF_B = \text{buckling safety factor, dimensionless} \]

\[ SF_s = \text{buckling safety factor, dimensionless} \]

\[ TD = \text{jetting total depth, ft} \]

\[ W_C = \text{weight of casing, lbm/ft} \]

\[ W_{JA} = \text{weight of jetting assembly, lbm/ft} \]

\[ x = \text{unit of length along the axis of the structural casing, ft} \]

\[ \alpha = \text{dimensionless factor to account for disturbance of the soil by jetting (always<1.0)}. \]

\[ \pi = \text{constant pi} = 3.14159 \]

\[ \rho_s = \text{density of steel, lbm/gal} \]

**Acknowledgments**

Thanks to the ExxonMobil Development Company and members of its deepwater drill teams for permission to publish this paper.

**References**


**Appendix—Calculations for Development of the Planned SOW Profile**

A typical planned SOW guideline is shown below in Fig. A-1. The X-axis is SOW and the Y-axis is depth.

Below mudline (in reverse order).

1. Buoyancy factor,

\[ BF = 1 - \frac{MW}{\rho_s} = 56.45 \]  \hspace{1cm} (A-1)

2. BML buoyed weight of casing at 130 ft BML,

\[ BW_{C130} = BF \times W_c(lbm/ft) \times 130 \]  \hspace{1cm} (A-2)

3. BML buoyed weight of casing+jetting assembly at 130 ft. BML,

\[ BW_{C+JA130} = BF \times (W_c + W_{JA})(lbm/ft) \times 130 \]  \hspace{1cm} (A-3)
4. Maximum allowable SOW,

\[ \text{MASOW} = SF_x \times BW_{casing} = SF_x \times BF \times (W_c + W_d)(\text{ppf}) \times L_c \]  
(A-4)

5. Depth at which MASOW = BML, buoyed weight of casing + jetting assembly,

\[ D_{MASO} = SF_x \times L_c \]  
(A-5)

6. Jetting TD,

\[ TD = L_c - L_{Stickup} \]  
(A-6)

Calculations required for defining maximum available set-down weight:

7. Casing moment of inertia,

\[ I = \frac{\pi}{64} \times (OD^4 - ID^4), \text{in.}^4 \]  
(A-7)

8. Buckling force limit at fixed point,

\[ F_{Buck} = SF_x \times \frac{\pi^2 EI}{(4 \times 12^2 \times L_c)^2} \]  
(A-8)

Depth at which MASOW = buckling force limit,

\[ D_{MASO} = SF_x \times \left( \frac{\pi^2 EI}{(4 \times 12^2 \times L_c)^2} \right)^{0.5} \]  
(A-9)

9. Buckling force limit at intermediate depth(s), D_c

\[ F_{B} = SF_x \times \frac{\pi^2 EI}{(4 \times 12^2 \times L_c = D + D_{Stickup})^2} \]  
(A-10)

Notes:

- From the mudline to the point of full lateral stability (generally found at 100 to 150 ft BML—value of 130 ft BML used in the appendix equation): Setdown weight equal to the lesser of the buoyed weight of the structural casing below the mudline or the maximum setdown weight on the basis of the buckling force. Normally, this is sufficient to provide an adequate penetration rate and will minimize the risk of casing deviation.
- From the point of full lateral stability to structural casing TD: Setdown weight equal to the lesser of the buoyed weight of the combined structural casing and jetting assembly below the mudline or the maximum setdown weight based on the buckling force. The maximum allowable setdown weight is equal to 90% of the buoyed weight of the combined structural casing and jetting assembly. Final orientation of the casing will have been established by this depth and will not change regardless of the amount of setdown weight applied.

### SI Metric Conversion Factors

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*Conversion factors are exact.

Jay Akers has been a drilling and subsurface engineer for ExxonMobil Development Company for 23 years. Akers has experience in drilling, completion, and workover operations in the United States, Norway, Nigeria, Angola, and Brazil. He holds a BS in chemical engineering from Texas A&M University and a MS in petroleum engineering from The University of Texas at Austin. He is also a member of SPE.