Conveyance—Down and Out in the Oil Field

Well productivity can be greatly enhanced by drilling high-angle wells or by directing the wellbore into multiple targets. In such wells, traditional methods for conveying evaluation, remediation and intervention tools are no longer practical. In response to the challenges presented by complex well trajectories, service companies have developed numerous innovations for accessing and evaluating these complicated wellbores.

You can't push a rope. Many a frustrated wireline engineer has uttered those words when logging tools failed to reach the bottom of a well, especially in high-angle wells. But the source of that frustration has been overcome—at least in some respects—by the introduction of new conveyance methods. These developments enable evaluation, completion and remediation not only in high-angle wells but also in long horizontal wellbores, environments that previously presented insurmountable challenges to traditional logging methods.

In the days when most wells were vertical, delivering logging tools to total depth and back was a relatively straightforward task. A truck-powered winch containing a spool of cable ran the tools in and retrieved them from the well. The tools were pulled to the bottom of a well by gravity. The cable was also used to communicate with the tools, provide power and send information about the downhole environment back to the surface. This method of conveyance sufficed for openhole logging, cased hole evaluation and running mechanical services, which included perforating. But today, gravity is not the only means of getting tools to the bottom of the well, and cables are not the only means of delivering data to the surface; tool delivery, data transmission and equipment deployment methods abound.

This shift in techniques and methodology has developed in large part to meet the needs of wells drilled at high angles. Whereas TD once implied the deepest point in the Earth reached by a well, the measured depth of horizontal wells often far exceeds their true vertical depth (TVD). In 2010, more than 16,000 horizontal wells were drilled worldwide. This number does not include thousands more wells drilled directionally to reach targets far from the surface entry point or reach multiple zones separated by great lateral distances.

With today’s technology, drilling engineers can create such complex wellbore geometries that delivering downhole tools to a targeted formation becomes a challenge. These wells require evaluation information when they are drilled, and they will also require some means to access the reservoir for future evaluation and intervention.

A number of technologies have been developed to address the difficulties created by complex wellbore trajectories. Whereas in the past, the primary consideration was simply which tools to run, today, engineers must also consider how to optimally evaluate, access and perform remedial work for the life of a well. Fortunately, the restrictive reliance on gravity to pull logging tools attached to a cable has been replaced by an expanding battery of methods, equipment and techniques. Petrophysicists and engineers now have a plethora of choices. This article reviews some of these methods and also looks at recently introduced technologies that offer greater flexibility in data acquisition choices.
Conveyance consists of more than the mechanisms of pulling and pushing tools downhole. Its greater purpose is to address the challenges created by wellbore environments. These challenges include deploying tools at the surface, overcoming frictional forces, maneuvering past obstacles and adapting to unforeseen downhole conditions. Flexibility and adaptability are important factors that engineers consider when deploying tools downhole, but their tool choices often dictate the method of conveyance.

Conveyance methods can be grouped into two basic types: cable conveyed and pipe conveyed (above). Within both categories are variations and hybrid solutions that blend elements of the other. The various methods come with trade-offs, strengths and weaknesses, so there is rarely a perfect solution.

Cable conveyed tools have a long history. The first electric log, acquired at Pechelbronn field in Alsace, France, on September 5, 1927, was run on a cable. The survey instrument was lowered 300 m [980 ft] into the well, and subsurface measurements were plotted by hand as the tool was slowly retrieved using a manually operated winch (next page, top right). For the next 50 years, the logging industry remained tethered to a cable, even as logging tools evolved to include extremely complex measurements that demand high data rates. Surface units used for acquisition also became more and more sophisticated. But the well logging landscape experienced its most dramatic transformation in the 1980s with the introduction of logging-while-drilling (LWD) tools.

LWD tools are an integral part of the drill-string bottomhole assembly (BHA). In the early days, measurements were fairly basic; they included gamma ray and resistivity, followed by the addition of porosity measurements. The tools communicate via a series of pressure pulses transmitted through the circulating drilling mud to convey commands downhole and deliver data to the surface. These pressure pulses are encoded with data about well conditions, the status of the BHA and the formations encountered by the bit.

Mud pulse telemetry transmits data at rates that are several orders of magnitude lower than those achieved using logging cables; but, given the time required for drilling operations, this method has generally proved to be sufficient. Other transmission methods are available; for example, electromagnetic telemetry is used as an alternative to mud pulse telemetry in air or foam drilling. And more recently, wired drillpipe, which can send data using an imbedded transmission cable, has been introduced.

Wired drillpipe promises high data rates: 57,000 bits per second compared with 10 bits per second with mud pulse telemetry. Commercial transmission systems, such as the IntelliServ Broadband Network, are currently available, although this technology has yet to replace mud pulse telemetry as the method of choice for service companies and operators. Whichever method is used, the ability to acquire real-time data from near the bit not only offers a substitute for wireline logging, but also has led to a revolution in the application of rotary steerable drilling systems, ushering in a new age of horizontal and extended-reach drilling. Using real-time information provided by LWD tools, directional drillers can remotely steer and guide the bit to specific targets, making precise corrections in wellbore trajectory.

As well trajectories shifted from vertical to horizontal, LWD data, in many cases, supplanted traditional wireline logging for formation evaluation. Meanwhile, the quality and scope of LWD data have improved, and sophisticated tool offerings are now available while drilling. For instance, the EcoScope multifunction LWD service offers resistivity, porosity, azimuthal density, ultrasonic caliper, capture spectroscopy and azimuthal

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<table>
<thead>
<tr>
<th>Conveyance Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>Wireline-gravity conveyance</td>
<td>• Suitable for both formation evaluation and production services</td>
<td>• Gravity dependent</td>
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<tr>
<td></td>
<td>• Largest selection of tools</td>
<td>• Vulnerable to hole irregularities</td>
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<tr>
<td>Downhole tractors</td>
<td>• Compatible with wireline, slickline and coiled tubing conveyance</td>
<td>• Not suitable for every well</td>
</tr>
<tr>
<td></td>
<td>• Highest operational efficiency for horizontal intervention</td>
<td>• Primarily a cased hole service</td>
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<tr>
<td></td>
<td>• Requires minimal number of field personnel</td>
<td>• Retrieval risks with horizontal intervention</td>
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<td></td>
<td></td>
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<td>Pumpdown conveyance</td>
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<td>• High operational efficiency</td>
<td>• Limited applicability</td>
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<td>Slickline</td>
<td>• Highest operational efficiency of all conveyance methods</td>
<td>• Primarily cased hole intervention</td>
</tr>
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<td>• Low cost</td>
<td>• Gravity dependent</td>
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<td>Coiled tubing conveyance</td>
<td>• Suitable for a variety of logging, stimulation, perforating and</td>
<td>• Primarily cased hole and producing well intervention</td>
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<td></td>
<td>mechanical services</td>
<td>• Limited reach due to helical lockup</td>
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<td></td>
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<td>Drillpipe combined with wireline</td>
<td>• Highest success rate in difficult conditions</td>
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</tr>
<tr>
<td></td>
<td>• Gravity independent</td>
<td>• Time-consuming</td>
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<td></td>
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<td>• Limited reach in very difficult conditions</td>
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<td>• Not suitable for fragile tools</td>
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<td></td>
<td>• Maintains well control</td>
<td>• Complications due to presence of logging cable</td>
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<tr>
<td>Drillpipe-LWD</td>
<td>• Highest chance of success in difficult conditions</td>
<td>• Not suitable for cased hole or intervention in producing wells</td>
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<tr>
<td></td>
<td>• Gravity independent</td>
<td>• Expensive</td>
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<td></td>
<td>• Maintains well control</td>
<td>• Smaller selection of tools compared with wireline</td>
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<tr>
<td>Drillpipe-wireless</td>
<td>• High success rate in difficult conditions</td>
<td>• Limited tool offering</td>
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<td></td>
<td>• Gravity independent</td>
<td>• Limited logging time</td>
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<td></td>
<td>• Highest efficiency among drillpipe conveyance methods</td>
<td>• Relatively slow</td>
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<tr>
<td></td>
<td>• Maintains well control</td>
<td>• Expensive downhole equipment</td>
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Conveyance methods.
gamma ray measurements in one compact tool (below right). Instead of a chemical radioactive source for neutrons, the tool uses a pulsed neutron generator powered by a turbine, which is driven by circulating mud. The tool also includes a variety of sensors that provide information to improve drilling operations.

Logging companies can perform advanced services such as seismic, acoustic and magnetic resonance logging while drilling. Pressure measurements and sampling, which have long been exclusively in the wireline logging domain, can now be carried out with LWD tools as well.

Engineers developing log evaluation programs, however, have more to consider than measurement technology when deciding on which services to run. For example, temperature and pressure limits are generally lower for LWD tools. And there are size limitations because LWD tools are designed for specific ranges of borehole diameters, whereas wireline tools can be used in a much broader range. There are also higher costs associated with deploying LWD equipment for long periods of time during the drilling process compared to logging with wireline tools.

Although the gap between wireline and LWD offerings continues to narrow, there are some services that are not available while drilling. These include high-data-rate services, such as the FMI formation microimager tool, tools requiring high power, such as sidewall coring tools, and other technologies that have yet to migrate to LWD platforms.

Eventually, the rig moves on to drill the next well, and LWD tools can no longer be used for data transmission. Even if they were available, LWD tools were not developed to perform cased hole services. Wireline tools are needed to evaluate and access the reservoir, although getting them to the bottom of horizontal and high-angle wells is problematic. Thus, alternative means of conveyance have been developed to deliver these tools.

### Holding on or Cutting the Wire

Drillers can negotiate high-angle and difficult wellbores because drillpipe is stiff and heavy. This is not the case with tools at the end of a wireline. In the past, when TD could not be reached with logging tools because of well conditions, engineers developed and attempted various methods to get past obstructions. Operators have welded chains to the bottom of tools hoping that the chain would pile up on a ledge and eventually fall off and pull the tool downhole. Weight bars, friction-reducing wheels and rollers have...
Carrier conveyed logging. Special logging tools can be conveyed inside a protective carrier and run in hole on drillpipe. Once the desired depth is reached, the tools are ejected through the bottom of the drillpipe. The tools then acquire data, which are stored in memory, as the drillpipe is pulled out of the hole. At surface, data are read and merged with a depth-time reference log. Conventional depth-based logs are generated from the merged data. The tools must have small diameters to fit inside the carrier; one example, the 2 1/4-in. Multi Express service provides a triple-combo toolstring plus a sonic tool option. This carrier conveyance system permits fluid circulation and pipe rotation while running into the well and while logging.

Tough logging conditions. Before LWD tools were widely available, the TLC system conveyed wireline tools via drillpipe. Logging tools are attached to the drillpipe using a crossover adaptor with a wet-connect device. Tools are run in the hole to the bottom of casing, and a mating connector, attached to the logging cable, is threaded through a side entry sub and pumped down the drillstring until it engages the downhole connector. Once communication and power are established, the tools are pushed out into open hole and down to the bottom of the well. Because the cable is exposed above the side entry sub, it is not allowed to exit the bottom of casing for fear of damage to the cable, and extreme care must also be exercised while running in the hole to avoid crushing the cable. The logging tools, which are at the end of the drillpipe, are also at risk of being damaged in open hole. Most wireline logging tools can be run using this system.

A modified technique, logging while fishing (LWF), uses a concept similar to the TLC system. Should a conventional wireline logging tool become stuck in the well while logging, a cut-and-thread fishing operation is performed to engage the stuck tool with a grapple attached to the end of drillpipe. The severed cable is reconnected at surface to provide power and communication to the downhole tools, and then data are acquired as the pipe and tools are pulled out. This operation has been performed when crucial data were needed but hole conditions made logging impossible.

Both TLC and LWF methods are still in use today, offering the capability to acquire information that would otherwise be unobtainable. However, the process of running in the hole and logging can be slow. Perhaps more significant, the operator has little control over the tools at the end of the drillpipe during TLC operations. Drillers must also take precautions to avoid damaging the exposed logging cable and the tools while running them in the hole. Compared with drillpipe and BHAs, the relatively fragile logging tools can be easily crushed or damaged. Engineers have designed specialized hardware and protective equipment as accessories to protect the tools, but a risk associated with pushing exposed tools through open hole remains.
Even with protective hardware, openhole logging tools may encounter ledges, bridged sections of open hole and large washed-out wellbores, making it impossible to push the tools to bottom. Drillers often attempt pipe rotation to get around obstructions, which is not an option when tools are attached with TLC operations.

A recent adaptation of the TLC concept has been developed that uses drillpipe to convey logging tools. The main differences are that the tools are protected inside a carrier while they are being run in the hole and no logging cable is required (previous page, top right). Once the drillstring reaches the logging depth, the field engineer uses an ejection mechanism to deploy battery-powered tools. Extended beneath the bottom of the drillpipe, these tools acquire downhole data, which are stored in memory while the drillpipe is being pulled out of the hole. Pipe movement is recorded versus time during retrieval. At surface, the time-based data from downhole are recovered using a laptop computer and then merged with the depth data from pipe movement to generate conventional depth logs. A logging truck is not required.

Because they are deployed inside drillpipe, the tools must have a smaller diameter than conventional logging equipment. The recently introduced Multi Express slim, multiconveyance formation evaluation platform is an example of a set of tools that can be deployed using the protective drillpipe carrier. With a 23/4-in. [5.7-cm] diameter, these tools fit inside the 5-in. [12.7-cm] OD carrier with enough clearance to circulate mud downhole. The ability to circulate is an important feature for running drillpipe into the well, especially in long horizontal openhole sections in which cuttings can accumulate.

The Multi Express platform includes induction, Litho-Density, sonic, audio-temperature, spherically focused resistivity and induction resistivity tools. The sonic tool includes a cement bond logging option and the telemetry cartridge includes a casing collar tool.

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The Multi Express platform includes induction, Litho-Density, thermal and epithermal neutron porosity and array acoustic tools (above). The induction tool acquires data at two depths of investigation—deep and medium resistivity—and an optional tool section can acquire shallow SPL, spherically focused resistivity data. The density tool has an articulated pad and caliper to provide good borehole contact. The compact telemetry–neutron–gamma ray section can acquire both thermal and epithermal neutron porosity data. It includes a casing collar locator for depth correlation, which can be used with cement bond logging. The sonic tool can be run in openhole mode for borehole-compensated sonic data or in cased hole mode for cement bond logging.

While developing this tool platform, engineers focused on minimizing tool length and weight. A triple-combo toolstring—induction, density and neutron tools—consists of three devices of approximately 3 m [10 ft] each and is 9.75 m [32 ft] long when fully assembled. The 4.3-m [14.4-ft] sonic tool can be included as well. The Multi Express family of tools was designed to be handled by one person; the heaviest tool weighs 40.8 kg [90 lbm].

The Multi Express tools are ideal for logging small wellbores, shallow wells and air-filled holes. The platform includes the tools mentioned above plus an audio-temperature tool, which supplies important measurements in coalbed methane and shallow air-drilled tight gas wells. These
types of wells can be difficult to evaluate with conventional logging units because the wells have small drilling pads and the rigs move quickly from wellsite to wellsite.

Logging engineers can access wells for both openhole logging and cement bond logging using fit-for-purpose logging trucks with integrated masts, such as the Blue Streak high-efficiency unit (left). Drilling and workover rigs are not required when engineers use these small, self-contained logging units. Monocables—logging cables with a single conductor—are generally used instead of multiconductor cables that are common with conventional logging tool systems.

With the memory recording option, the Multi Express tools can also be run with cables that have no conductor. This adds the capability of using slickline units for openhole logging, although there is no surface readout using this method. Data acquisition and quality are confirmed after the tools have returned to the surface and the stored information is retrieved.

Smart Iron

Conveyance at the end of pipe is not limited to LWD and TLC operations; pipe-conveyed methods include coiled tubing (CT) logging (below left). This proven system of tool deployment, introduced in the mid-1980s, is often used for production logging (PL) and perforating. CT units may include a cable inside the tubing to provide power to downhole tools and relay real-time measurements to the surface. In the absence of an integrated wire, logging can be performed in memory mode using tools that store data for retrieval once they return to the surface. Perforating, as with conventional tubing-conveyed perforating (TCP) operations, can be initiated with surface-applied pressure to activate guns, but the integrated wire gives greater control and offers engineers the option of sending power from surface to fire guns sequentially.

A major limiting factor in using CT is that it ceases to make progress, or locks up, beyond about 900 m (3,000 ft) of horizontal section. Lockup occurs because the tubing assumes a helical shape as it comes off the reel, resulting in increased friction between the casing and the tubing. When frictional forces reach a critical point, more tubing can be injected into the well, but the end of the string cannot be pushed deeper into the wellbore. Several options can be employed to extend this limit: CT straighteners reduce residual bend and friction, filling the tubing with nitrogen can provide added buoyancy, friction reducers may extend length capability.
and larger diameter tubing can often go deeper but requires much larger surface equipment.\(^6\)

ExxonMobil, in developing the Sakhalin Island land-based offshore Chayvo field in Russia, tested a hydraulically actuated CT tractor to extend the reach of operations.\(^3\) The field is located offshore, but drilling and production facilities are located on land. To access their wells, ExxonMobil engineers needed to increase the CT range beyond that possible with existing hardware. Although much of the equipment was standard for CT units, engineers made several modifications to accommodate a 35,006-ft \([10,670-m]\) reel of 2\(\frac{3}{4}\)-in. OD coiled tubing.

This hydraulic CT tractor was powered and controlled by differential pressure between the tubing and the annulus. The assembly was tested prior to job commencement and had 9,700 lbm \([43,148 \text{ kg}]\) of pull and nominal operating speed of 950 ft/h \([290 \text{ m/h}]\). During the job, a 31,938-ft \([9,735-m]\) well was successfully logged with PL tools and 1,050 ft \([320 \text{ m}]\) was perforated with \(3\frac{1}{8}\)-in. \([8.57-\text{cm}]\) casing guns.\(^8\)

Although the operation was a success, engineers discovered that using coiled tubing for frequent PL runs was not viable. Excessive wear experienced by the coil, high cost and poor data quality at low flow rates led to the eventual abandonment of the CT technique for PL logging in the field.\(^7\) For routine operations, the industry needed an alternative to logging with a CT unit.

**Going Around the Bend**

In 1988, Elf Aquitane made one of the first recorded attempts to log a cased horizontal well with PL tools.\(^3\) The operator was developing the Rospo Mare pilot project offshore Italy to produce viscous oil trapped in a karst formation. The company drilled three pilot wells: a vertical, a high-angle deviated and a horizontal well. The horizontal contacted more than 600 m \([1,970 \text{ ft}]\) of formation. The horizontal well provided essential information for further field development.

The complex nature of the design required to run the PL tool underscores the challenges of evaluating, completing and performing remediation of wells with horizontal and high-angle trajectories. Few operators have the luxury of running dual tubing strings just to acquire production logs, but in the late 1980s there were not many alternatives.

This dearth of options for accessing horizontal wells was first addressed with the introduction of wired CT units. As ExxonMobil discovered in the Chayvo field, PL logging on coiled tubing can be expensive, and data quality can suffer. Downhole wireline tractors, developed in the 1990s, provided an alternative to CT units, adding flexibility, efficiency and cost savings to cased hole evaluation and intervention in horizontal wells. Within 10 years of Elf’s pumpdown logging experiment, operators were routinely using tractors for the majority of their well interventions in horizontal and high-angle wells.\(^11\)

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Pulling a Rope

Although earlier attempts were recorded, downhole tractors successfully arrived in the oil field in the mid-1990s. In 1996, a device to access horizontal boreholes performed the first tractor service on a well in Norway. Developed to perform well interventions without the high cost associated with CT services, downhole tractors dramatically changed the way North Sea operators planned and managed their fields.

Prior to 1996, interventions had been performed almost exclusively by CT units. By 2009, approximately 80% of the interventions performed by one operator had shifted to wireline tractors. Not only did this reduce costs, it expanded both the frequency and scope of interventions.

Tractor types. Service companies have developed many different topologies for downhole tractors. Continuous drive units (left) have wheels, tracks and even corkscrew drives. Reciprocating units (right) use locking devices and imitate an inchworm’s motion with an anchor, extend, release and re-anchor movement.

Climbing the borehole. Engineers designed the reciprocating, gripping mechanism of the MaxTRAC tractor based on rock-climbing gear. The cams located on the extended arms (inset) rotate into position and grip the inside of the casing or borehole. Once the cams are securely locked, the tractor can move forward, but backward movement is nearly impossible.
Service companies offer a variety of downhole tractors. They include tractors with rotating wheels, motorized tracks and corkscrew designs (previous page, top). In a departure from these systems, Schlumberger engineers developed a reciprocating gripping mechanism for the MaxTRAC downhole well tractor system (previous page, bottom). This 2 1/8-in. [5.4-cm] diameter tool has a maximum pull of approximately 4,448 N [1,000 lbf] while exerting 13,335 N [3,000 lbf] maximum force on the casing or borehole wall. It can advance at 670 m/h [2,200 ft/h] while pulling 2,224 N [500 lbf] and operates in hole sizes that range from 2.44 in. [6.20 cm] to 11.3 in [28.7 cm]. It has the ability to log in forward direction or, with some specific limitations, in reverse while being retrieved by wireline.

The reciprocating grip system uses cams to grip the inside of the casing or borehole. This design is similar to devices used to secure ropes during rock climbing: Once the cam is in position, backward pull causes it to expand and lock more securely in place. It can easily be pushed forward, but it is almost impossible to pull backward. The tractor requires at least two gripping sections, but more can be added as needed. With each power stroke, the tool moves forward in inchworm fashion (above). The MaxTRAC tractor has been deployed in a number of openhole and cased hole applications and, with the TuffTRAC cased hole services tractor, holds a number of

Loss of power to the tool is not the only concern when engineers design a tractor job. With continuous forward motion, the equipment can eventually reach a point that exceeds the capability of the logging unit to retrieve the tool using the cable. To ensure successful return to surface, the field engineer can model the downhole forces with job-planner software (below). Using information that includes deviation, pushing force, friction and job variations, modeling software provides a go–no-go determination (next page, top right). The planner also determines the number of drive sections needed and helps establish the weakpoint for cable release in the event the tool becomes stuck downhole. The field engineer can fine-tune the model with real-time data.

Although downhole tractors were originally developed for cased hole intervention, operators have used the MaxTRAC tractor system to run a variety of openhole services. For instance, the FMI tool is often combined with the tractor system for fracture identification. Horizontal wells drilled through fractured reservoirs are difficult to evaluate with LWD services alone because of the high data density required for imaging the fractures. The FMI tool can help identify the optimal intervals for production along the horizontal section. The MaxTRAC tractor has also been used in openhole completions to deploy PL tools and to deploy Multi Express tools in both open and cased wells.

**Table 2**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>World’s longest openhole tractor pass</td>
<td>4,238 m (13,904 ft)</td>
</tr>
<tr>
<td>Two descents for a total of</td>
<td>8,476 m (27,808 ft)</td>
</tr>
<tr>
<td>World’s deepest PL on tractor</td>
<td>8,650 m (28,380 ft)</td>
</tr>
<tr>
<td>Most cumulative distance traversed using a tractor in a single well</td>
<td>85,987 m (282,109 ft)</td>
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^MaxTRAC-TuffTRAC records.

Prejob planning. From well data, tractor job planner software provides operational limitations and critical go–no-go analysis before the job commences. The planner can then be updated with downhole data while the tractor is operating. The well profile data (top left) includes deviation and dogleg severity—a measure of how rapidly the wellbore trajectory is changing per unit of distance. Modeled cable tension at the surface indicates whether tension will exceed safe operation limits (top right). The forces acting on the tractor are also modeled (bottom left) to ensure the limitations of the tractor are not exceeded. A pseudo-3D profile, created from client-provided deviation and inclination data, helps visualize borehole geometry (bottom right). The wellbore path (red) is presented versus TVD (blue), surface location (magenta) and north departure (green).
Tackling a Giant

Saudi Aramco has been instrumental in developing tractor technology.\(^\text{15}\) For the Ghawar field, the largest onshore oil field in the world, engineers have increasingly turned to horizontal, extended-reach and multilateral wellbores as part of the ongoing development program. The expense of using CT units, as well as the difficulty of accessing complex completion geometries for conveying diagnostic and surveillance tools, has led Aramco to investigate alternatives.\(^\text{15}\)

Aramco, which extensively tested various downhole tractors, views them as an enabling technology for intervention services. The company has determined that tractors can effectively log horizontal wells, far exceed the reach of conventional CT units, provide significant cost benefits and offer safer operations compared with complex CT mobilization and deployment.\(^\text{15}\)

However, Aramco’s earlier experience with openhole logging, starting in 2004, was not as positive as with cased hole tractor operations. Aramco and Schlumberger engineers determined that the cams used with the MaxTRAC system could successfully grip in formations with unconfined compressive strength (UCS) greater than 5,000 psi \([34.5\text{ MPa}]\). Below that cutoff, the cams would dig into the formation and lose gripping force. Engineers working with field operations staff developed an add-on kit to distribute the force more uniformly, which maximized the gripping force in soft formations (below right).\(^\text{18}\)

The newly designed gripping assembly was first tested in a 6\(\frac{1}{8}\)-in. wellbore completion in a formation with a high UCS. A 5,072-ft \([1,546\text{-m}]\) horizontal openhole section was successfully logged with a PL toolstring. Eight more openhole wells in high UCS formations were successfully logged before engineers attempted operations in a soft formation. The soft formation candidate, with a 7,553-ft \([2,300\text{-m}]\) lateral section, was then logged with PL tools to determine oil entry points and establish a flow profile along the lateral section. The job was successfully completed and the well evaluated using the new design.\(^\text{18}\)

Openhole tractors are not suitable for every well, particularly those with long washed-out sections or irregularly shaped boreholes. However, Aramco determined that the use of openhole tractors can deliver significant cost savings over conventional CT logging. Tractors have a much longer reach than CT units and require fewer personnel and less hardware on location. Today, openhole tractors are in use not only in Saudi Arabia but also in several other locations in the Middle East.

\(^\text{15}\) AL-Amer et al, reference 6.
\(^\text{16}\) AL-Amer et al, reference 6.
\(^\text{17}\) AL-Amer et al, reference 6.
When the Going Gets Tough

Logging is not the only operation that takes place in horizontal wells. Initial completion operations often use drilling or workover rigs to run TCP guns, which can traverse extremely long intervals. However, after the rig has moved on, remedial perforating in horizontal wells can be difficult to perform. CT units are an option for this task but they have depth limitations. Tractor tools have been used to run and position perforating guns, but the shock that the downhole equipment can receive—up to 20,000 g—can damage sensitive electronic and mechanical components.

Recognizing the need for a more robust tractor for perforating services, Schlumberger engineers designed the TuffTRAC cased hole services tractor. Tool movement is accomplished using mechanically powered wheels (above). The TuffTRAC tool is bigger and stronger than the MaxTRAC tractor and has a much simpler design; it has minimal downhole electronics. Maximum running speed is 975 m/h [3,200 ft/h] and maximum pulling force is 10,676 N [2,400 lbf]. It is designed primarily for perforating and cement evaluation. The TuffTRAC system also offers traction control, which dynamically adjusts the gripping force while the tractor is in forward motion.

The TuffTRAC equipment is currently the only tractor qualified for perforating that can reverse out of the well. This has proved beneficial in horizontal well sections where guns were trapped by debris in the wellbore. On at least one occasion, surface-applied tension was not sufficient to free the guns because the high angle of the well prohibited pulling force from being transmitted to the tools. By moving in reverse, the tractor was able to free the guns, which were then retrieved without a costly fishing operation.

Although perforating can damage electronics and mechanical components, the TuffTRAC service has demonstrated that properly engineered solutions can mitigate some of the effects of high explosives (left). Tested to extreme limits, this new tractor design has been field qualified. In one North Sea well that had initially been com-

<table>
<thead>
<tr>
<th></th>
<th>Pickup Truck</th>
<th>TuffTRAC (8 drives)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of unit</td>
<td>2,560 kg [5,645 lbm]</td>
<td>277 kg [610 lbm]</td>
</tr>
<tr>
<td>Additional radial force</td>
<td>0</td>
<td>4,448 N [1,000 lbf] per wheel</td>
</tr>
<tr>
<td>Weight per wheel</td>
<td>640 kg [1,411 lbm]</td>
<td>522 kg [1,152 lbm]</td>
</tr>
<tr>
<td>Size of wheel</td>
<td>76 cm [-30 in.]</td>
<td>7.6 cm [3 in.]</td>
</tr>
<tr>
<td>Towing capacity</td>
<td>44,927 N [10,100 lbf]</td>
<td>106,757 N [24,000 lbf]</td>
</tr>
<tr>
<td>Towing force</td>
<td>4,448 N [-1,000 lbf]</td>
<td>10,676 N [2,400 lbf]</td>
</tr>
</tbody>
</table>

^ TuffTRAC pulling power. The TuffTRAC tractor can use up to eight drive wheels (right). In the maximum pull configuration, it has 106,757 N [24,000 lbf] of pulling capacity. For comparison, the pickup truck shown has a towing capacity of 44,927 N [10,100 lb].

^ Qualification testing. The TuffTRAC tractor was designed to withstand the rigors of perforating. The tool was attached to loaded casing guns, which were fired at the surface, shown here, without significant damage to the tool. The design-for-purpose and qualification testing resulted in a robust system that has been proved in the field.

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completed as a commingled oil producer from two separate zones, only water was being produced. Engineers ran the TuffTRAC system to set two plugs, ran 73.1 m [240 ft] of 2%-in. high shot density guns in four runs and made six trips to retrofit sand screens. For this single intervention, the tractor traversed 22,500 m [73,819 ft] without incident. The procedures resulted in resumption of oil production without a costly workover and recompletion.

In another North Sea horizontal well, an operator needed to perforate approximately 1,250 m [4,100 ft] of reservoir section for a water injection project. One objective was to achieve a particular perforation hole size in heavy-wall 6 5/8-in. liner with one shot every 7 m [23 ft]. The plan called for perforating in two phases across separate intervals (above). The two phases included 90 holes per interval for a total of 180 shots.

Because of logistics and cost, it would have been difficult to justify perforating with TCP guns using a CT unit—180 shots would have required at least 1,250 m [4,101 ft] of gun stock. For limited-entry perforation operations such as this, engineers at Schlumberger Rosharon Completions Center (SRC), in Texas, USA, have developed an addressable-switch perforating system that uses radio-safe detonators and allows up to 40 single-shot carriers to be run in a single descent. The system requires surface power to communicate with and detonate each shot. Because the TuffTRAC tractor is combinable with the addressable-switch system, field engineers were able to run as many as 20 single-shot carriers per descent to perforate the Phase 1 interval and as many as 33 single-shot guns for the Phase 2 interval. During the execution of the job, the tractor traversed a total of 8,670 m [28,450 ft] in the course of 12 descents. Although CT perforating was an option, using more than 1,250 m of gun stock to perforate 180 holes was neither cost-effective nor an efficient use of resources. Another option would have been multiple runs—perhaps as many as 60—with a conventional switched-gun system. The application of this new technology greatly reduced the number of runs, equipment wear and the time on location for personnel.

**Change Brings Opportunity**

Game-changing technology often creates a bridge to better methods of operation and offers a wider range of choices. For instance, in many developing countries, telephone service providers are investing in cellular phone systems rather than traditional landline infrastructures. The benefits to consumers include smart phones and wireless Internet access, which go far beyond eliminating the inconvenience of being tied to a telephone cord.

In a similar fashion, LWD tools have changed the way operators approach drilling. Memory logging has changed the way data acquisition is carried out while simultaneously offering a broader range of opportunities. In the near future, wired drillpipe promises to provide even greater opportunities.

Wireless downhole communication may become more readily available to the oil and gas industry, and there are already commercial systems that communicate with downhole tools via radio waves. Depth and data limitations for wireless systems exist at present, but controlling downhole devices and receiving data without the use of cables and wires open new possibilities and applications for operators and service companies.

LWD tools, coiled tubing and downhole tractors create opportunities in drilling, completions and production that previously did not exist. The oil and gas service industry continues to develop new methods that reduce costs, decrease equipment requirements and minimize the number of personnel on location.

As conveyance techniques evolve, they introduce opportunities to improve production and, in general, function more efficiently than earlier methods. If you can’t push a rope, you may be able to pull it. Or perhaps, in the future, it may be easier just to cut the rope completely. —TS

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**Well profile for North Sea injector. The operator perforated this well in two stages. Together the stages covered approximately 1,250 m. Holes were spaced approximately 7 m apart across the intervals. A total of 180 shots were attempted. Only one shot failed to fire. During the course of 12 descents, the tractor tool traversed 8,670 m.**