New Aspects of Multilateral Well Construction

Multiple drainholes that diverge from a main wellbore maximize reservoir contact. In addition to providing more drainage area than a single-bore well, these multilateral completions potentially reduce overall drilling risk and total cost. To meet specific field-development objectives in today's demanding oil and gas applications, operators require reliable junctions between primary casing in the main borehole and liners in lateral well branches.

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In the pursuit of optimal production, cost reduction and maximum reserve recovery, operating companies in the petroleum industry are placing increasing emphasis on multilateral completions—separate drainholes, or branches, drilled from a single primary borehole. More than 10% of the 74,000 new wells drilled each year are candidates for these types of completions. Multilateral technology is also used for reentry drilling applications in existing wells.

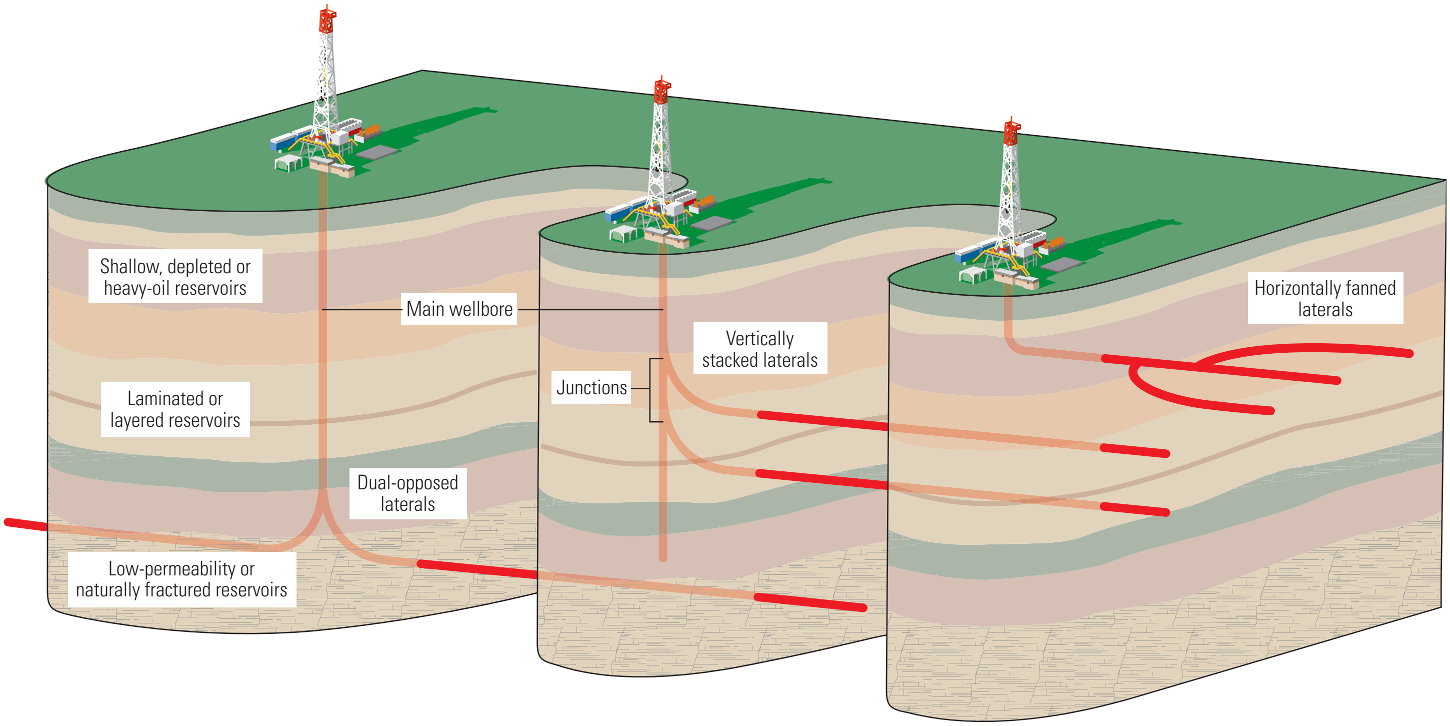
Basic forms of multilateral wells have been around since the 1950s, but early drilling methods and completion equipment were suitable in only a few applications. Improvements in well-construction techniques during the 1990s allowed operators to drill and complete an increasing number of wells with multiple lateral branches.[1] Today, main wellbores and laterals can be drilled vertically, at high angles or horizontally to address various subsurface conditions.

Multilateral well configurations range from a single drainhole to multiple well branches in horizontal-fanned, vertical-stacked or dual-opposed arrangements (next page). Laterals are completed as openholes and with uncemented or cemented "drop-off" liners—casing that is not connected to the main wellbore. Other completion designs use mechanical assemblies to provide a strong connection, pressure integrity and selective access at junctions between lateral liners and the primary casing of a main wellbore.

Like any other well completion, multilateral liners often include external casing packers to ensure zonal isolation or mechanical screens for sand control. Production from individual laterals can be commingled or flow to surface through separate tubing strings. Today, wells also may incorporate advanced completion equipment to monitor and control flow from each lateral branch. Accordingly, drilling and completion risks vary with well configuration, junction complexity, well-completion requirements and downhole equipment.

Multiple laterals increase productivity by contacting more reservoir than a single-bore well. In some fields, multilateral technology offers advantages over other completion techniques, such as conventional vertical and horizontal wells or fracture stimulation treatments. Operators use multilateral wells to target several formations or more than one reservoir and to tap bypassed reserves with a single main wellbore. Multilateral technology often provides the only economical means to produce isolated reservoir compartments, outlying satellite fields and small reservoirs containing limited reserve volumes.

Multilateral wells are particularly suited for connecting vertical and horizontal features, such as natural fractures, laminated formations and layered reservoirs. Multiple high-angle or horizontal drainholes intersect more natural fractures and often enhance production better than single-bore horizontal wells or hydraulic fracturing. A multilateral well should be considered in settings where directional or horizontal wells are appropriate. Directional, horizontal and multilateral wells optimize wellbore contact with a reservoir and allow higher flow rates at lower pressure drops than single-bore vertical or horizontal wells.



^ Basic multilateral configurations. Horizontally spread laterals in fork, fan or spine-rib arrangements target a single zone to maximize production from shallow low-pressure or heavy-oil reservoirs and fields with depleted pressure. Vertically stacked laterals are effective in laminated formations or layered reservoirs; commingling several horizons increases well productivity and improves hydrocarbon recovery. In low-permeability and naturally fractured formations, dual-opposed laterals can intersect more fractures than a single-bore horizontal well, especially if stress orientation is known, and can also reduce flowing friction pressure during production.

But there are limits to how long a single horizontal section can be before borehole and pipe, or casing, friction limit well outflow. Multilateral wells reduce frictional pressure losses during production by spreading inflow across two or more shorter lateral branches. For example, dual-opposed laterals reduce flowing friction pressure compared with a single-bore horizontal well that has the same reservoir exposure and production rate (see "Key Design Considerations," *page 68*).

Multilateral wells require additional initial investment in equipment, but potentially reduce total capital expenditures and development costs as well as operational expenses by decreasing the number of required wells. This technology reduces wellhead, platform-riser and subsea-completion requirements, which decreases cost and optimizes slot utilization on offshore platforms or subsea templates. Multilateral wells also minimize the size, or footprint, of surface locations and mitigate environmental impact onshore. Fewer main wellbores reduce repeated exposure to shallow drilling risks.

Lateral junctions are a critical element of multilateral completions and can fail under formation stresses, temperature-induced forces and differential pressures during production. Junctions are divided into two broad groups: those that do not provide pressure integrity (Level 1, 2, 3 and 4), and those that do (Level 5 and 6). Multilateral success depends on junction durability, versatility and accessibility.

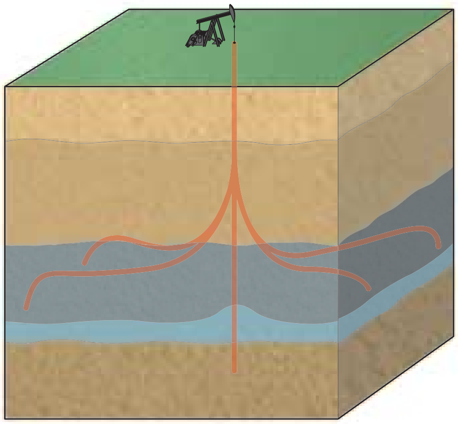
Level 3 and Level 6 systems have emerged as preferred multilateral junctions.[2] Level 3 junctions incorporate a liner tieback and mechanical connection to the primary casing that permit selective access and reentry of lateral branches. Level 6 junctions are an integral part of the primary casing string that provides pressure integrity and lateral access.

New junction-construction techniques allow the use of multilateral wells in a wider range of subsurface conditions for a growing number of reservoir applications. However, more complex equipment and well configurations create technical obstacles, operational risks and economic concerns that operators and service companies must address. This article reviews multilateral applications and classifications. We also discuss junction systems and installations through test-well results and field examples from the USA, Canada, Venezuela, Brazil, Nigeria and Indonesia.

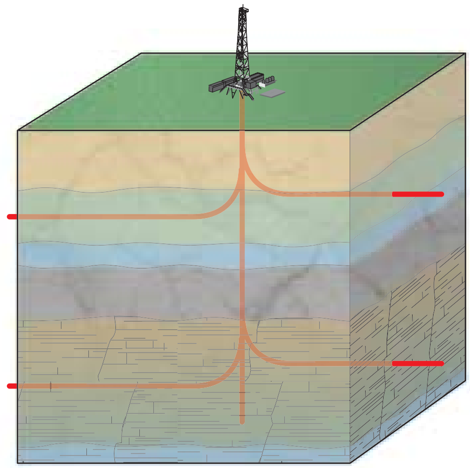
Reservoir Applications

Multilateral wells replace one or more individual wells. For example, a dual-opposed multilateral well replaces two conventional horizontal wells, each drilled from surface with separate casing strings and wellheads. For areas with shallow drilling hazards, deep reservoirs or fields in deep water, a single main wellbore eliminates the risk and high cost of drilling to total depth (TD) twice. Onshore, this reduces the number of wellheads and the size of surface locations. Offshore, multilateral wells conserve platform and subsea template slots, and reduce surface-facility and deck-space requirements.

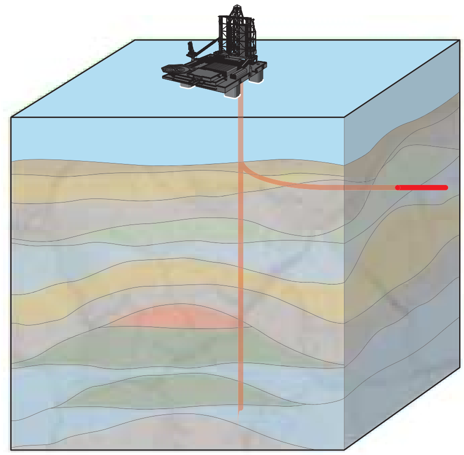
A primary advantage of multilateral wells is maximum reservoir contact for increased productivity or injectivity, and improved recovery factors. Several lateral drainholes intersect and connect heterogeneous reservoir features, such as natural fractures, streaks of higher permeability, laminated formations or layered reservoirs and isolated pockets of oil and gas. Maximizing reservoir contact increases wellbore drainage area and reduces pressure drawdown, which mitigates sand influx and water or gas coning more effectively than do conventional vertical and horizontal wells.



^ Heavy-oil reservoirs. In addition to improving steam injection, horizontally spread laterals maximize production and improve recovery from heavy-oil deposits and thin, shallow or depleted reservoirs by increasing wellbore drainage area. In reservoirs with thin oil columns, horizontal laterals mitigate premature water and gas breakthrough, or coning.



^ Low-permeability or naturally fractured reservoirs. Horizontal laterals improve the likelihood of intersecting natural fractures and completing an economic well in naturally fractured formations with unknown fracture orientation. If stress orientation is known, dual-opposed laterals optimize wellbore contact with the reservoir.

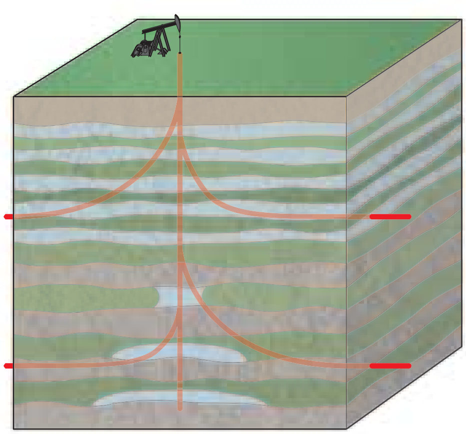


^ Satellite fields. Multilateral wells are an effective and economical means of producing outlying fields and small reservoirs containing limited hydrocarbon volumes.

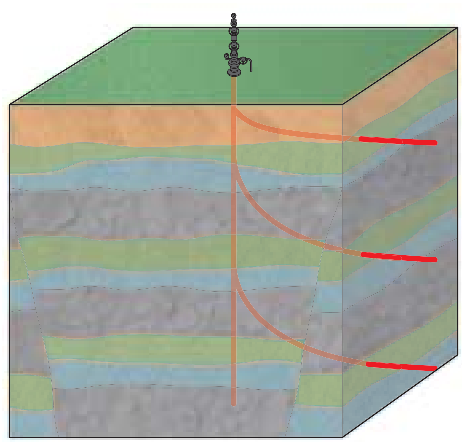
Any new technology has elements of risk and technical complexity, so both advantages and disadvantages must be addressed.[3] Loss of a main multilateral wellbore results in lost production from all the branches. Multilateral completions are mechanically more complex than conventional wells and depend on new tools and downhole systems. Well control during multilateral drilling or completion operations can be difficult. Also, there are greater risks related to long-term wellbore access for remedial well work or reservoir management.

After consideration of positive and negative aspects of multilateral technology as well as its long-term impact on field development, several reservoir applications become evident. Wells with multiple laterals are particularly suited for fields with heavy-oil reserves, low permeability or natural fractures, laminated formations or layered reservoirs, bypassed hydrocarbons in distinct structural or stratigraphic compartments and mature production or depleted reservoir pressure.[4]

Economic development of heavy-oil reserves is limited by low oil mobility, steam-injection sweep efficiency and recovery factors (see "Heavy-Oil Reservoirs," *page 30*). For heavy-oil or other low-mobility reservoirs, lateral drainholes offer advantages similar to hydraulic fracturing treatments in low-permeability gas zones. Increased wellbore contact with a reservoir stimulates oil production. Horizontal laterals also reduce pressure drops across the completion face, mitigate water coning and improve steam injection in these reservoirs (above left).



^ Laminated formations or layered reservoirs. In layered reservoirs, several vertically stacked laterals contact more of the reservoir than a single-bore vertical well and can tap multiple productive formations. Varying lateral inclination and vertical depth of each drainhole can drain multiple thin formations.



^ Isolated reservoir compartments. Multilateral wells often are more efficient than individual wellbores for tapping bypassed hydrocarbons in distinct reservoir compartments or as a result of partial reserve depletion.

Low-permeability and naturally fractured reservoirs are frequently associated with limited productivity, so formation anisotropy is a factor in designing multilateral wells. Hydraulic fractures lie parallel, not perpendicular, to natural fractures. As a result, wells produce as if propped fractures were much shorter than in a homogeneous reservoir. Horizontal laterals drilled perpendicular to natural fractures significantly improve well productivity by intersecting more fractures (above middle).

In laminated zones and layered reservoirs or heterogeneous formations, wells with vertically stacked laterals improve productivity and reserve recovery by connecting multiple pay intervals separated by vertical barriers or permeability contrasts and gradations (bottom left). Simultaneously producing multiple zones helps keep production rates above the economic limit of surface facilities or offshore platforms and prolongs the economic life of wells and fields.

Multilateral wells can tap and produce bypassed reserves in distinct reservoir compartments created by depositional environments, formation diagenesis and sealing faults (left). When reserve volumes in individual blocks do not justify a dedicated single-bore well, multilateral completions can connect several reservoir compartments. Reservoir compartmentalization also occurs as aquifer or injected water sweeps past low-permeability areas, leaving pockets of bypassed oil and gas that can be recovered by drilling and completing multilateral wells.

In a similar fashion, multilateral wells allow development of small reservoirs and outlying satellite fields that are not feasible to produce with conventional vertical, high-angle or horizontal wells (previous page, top right). Operators also use multilateral wells to exploit low-pressure and depleted reservoirs, particularly for infill and reentry drilling.[5]

In mature fields, multilateral wells improve infill drilling by targeting areas that are not economic to produce with a dedicated wellbore. During plateau production, drilling lateral branches from existing wellbores taps additional hydrocarbons without abandoning current production. This strategy improves the flow rate from a well and increases recoverable reserves, allowing mature reservoirs to be produced economically.

Wells with multiple branches help modify reservoir drainage in tertiary water- or steam-injection projects. Lateral branches sidetracked from existing wells control inflow location and improve flood patterns as sweep efficiency changes over time. Producing previously bypassed hydrocarbons and realigning injection patterns with lateral well branches eliminate the need to push reserves toward existing production wells.

Multilateral wells also assist with reservoir conformance to control gas and water inflow. Multiple lateral branches drilled with variable lengths in different layers improve hydrocarbon vertical sweep and reserve recovery. Horizontal laterals mitigate gas and water coning in some reservoirs, especially those with thin oil zones, gas caps or bottom-waterdrive. Multilateral wells improve recovery during gas-cap depressurization late in the field life cycle and also improve deliverability in gas-storage projects.[6]

Operators even use multilateral wells for exploration to sample horizontal reservoir quality and areal extent, and appraise stratigraphic traps. Another role is reservoir delineation. By planning two or more laterals from one main wellbore, a larger area can be probed directly from a single surface location. This approach increases flexibility during field delineation by allowing each lateral to be planned based on knowledge gained from drilling the main borehole and preceding laterals.

In addition to selecting multilateral configurations to address specific reservoir applications, engineers must determine the degree of mechanical and hydraulic integrity at lateral junctions that is required to optimize production and maximize recovery (below).[7] Schlumberger offers multilateral solutions from reentry drilling and openhole laterals to advanced RAPID Reliable Access Providing Improved Drainage junctions that provide connectivity, strength, sand exclusion and pressure integrity.

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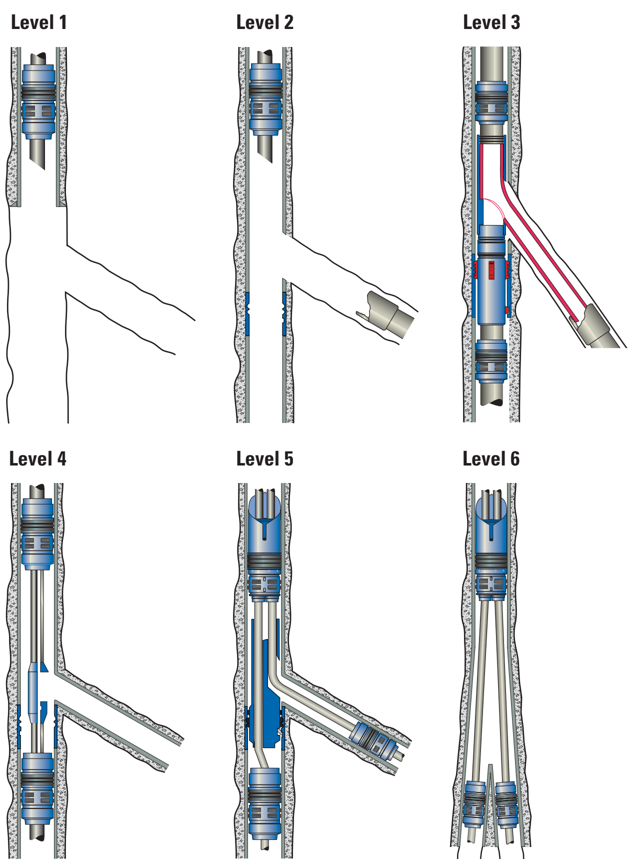


Level 1 – Openhole sidetrack or unsupported junction.

Level 2 – Cased and cemented main wellbore with openhole lateral or drop-off liner.

Level 3 – Cased and cemented main wellbore with uncemented lateral liner mechanically connected to the main wellbore (red).

Level 4 – Cased and cemented main wellbore with cemented lateral liner mechanically connected to the main wellbore.

Level 5 – Cased and cemented main wellbore and uncemented or cemented lateral liner with hydraulic and pressure integrity provided by additional completion equipment inside the main wellbore—packers, seals and tubulars.

Level 6 – Cased and cemented main wellbore and uncemented or cemented lateral liner with hydraulic and pressure integrity provided by the primary casing at the lateral liner intersection without additional completion equipment inside the main wellbore.

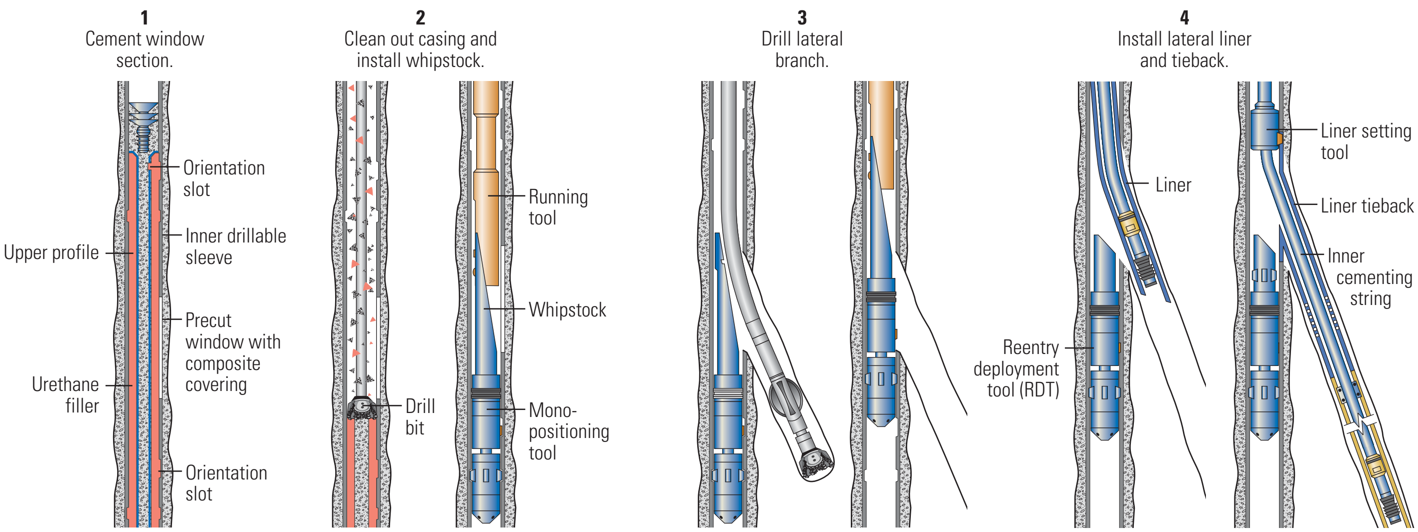
^ Junction classifications. Multilateral wells are characterized according to definitions established in the Technical Advancement of Multilaterals (TAML) Forum held in Aberdeen, Scotland, July 26, 1999 and recently updated in a July 2002 draft proposal. These standards classify junctions as Level 1, 2, 3, 4, 5 or 6 based on degree of mechanical complexity, connectivity and hydraulic isolation.

Precut Windows and Junction Connectivity

The prefabricated RapidTieBack nonmilling multilateral drilling and completion system uses casing-exit windows machined in advance and covered with a drillable internal sleeve to construct closely spaced laterals in new wells (below). This junction system can be installed quickly with minimal rig downtime in wells with inclination angles up to horizontal. A key system advantage is the capability to complete quad—up to four—laterals at right angles with adjacent casing windows as close as 6 ft [1.8 m].

RapidTieBack quad junctions are designed to locate junctions within a reservoir and drill high-angle drainholes using short-radius drilling assemblies. This multilateral system also can be set above the reservoir, which reduces angle build-rates and lateral inclination to minimize stress on junctions.

By eliminating milling operations, precut windows provide fast and consistent casing exits, avoid steel-cuttings debris and reduce the risk of casing damage. Drill bits with hole-opening gauges further reduce risk while drilling out

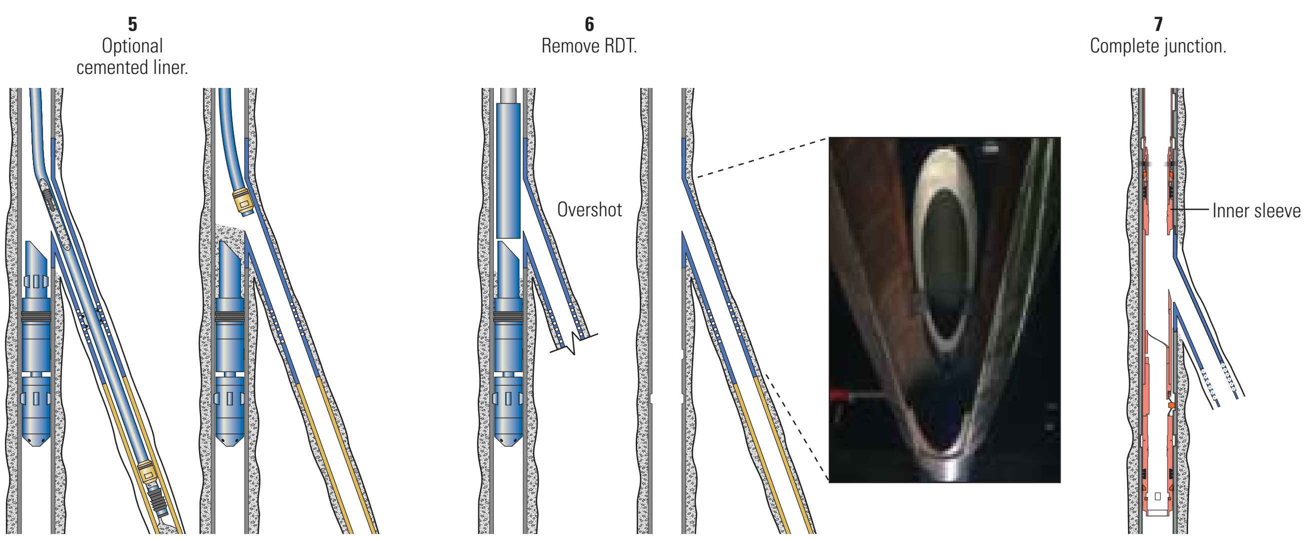


1 – Install junction at proposed depth. Orient windows based on gyroscopic measurements and cement primary casing.

2 – Drill out internal sleeve and cement. Set retrievable whipstock and monopositioning tool in profile below window section. Retrieve running tool.

3 – Drill lateral borehole and remove drilling assembly. Reorient whipstock to drill opposing lateral. Retrieve whipstock and monopositioning tool. Clean out main wellbore.Repeat for next set of windows.

4 – Set liner assembly, reentry deployment tool (RDT) and monopositioning tool in profile below window. Shear assembly off of RDT and run liner into lateral. Set liner setting tool in upper profile and lock liner tieback into precut window.



5 – Release liner setting tool and lift inner cementing string. Cement liner using dual-wiper plugs. Retrieve liner setting tool and inner cementing string.

6 – Wash over RDT with overshot, release monopositioning tool and retrieve RDT.

7 – Install inner template sleeve to hold lateral liner in place.

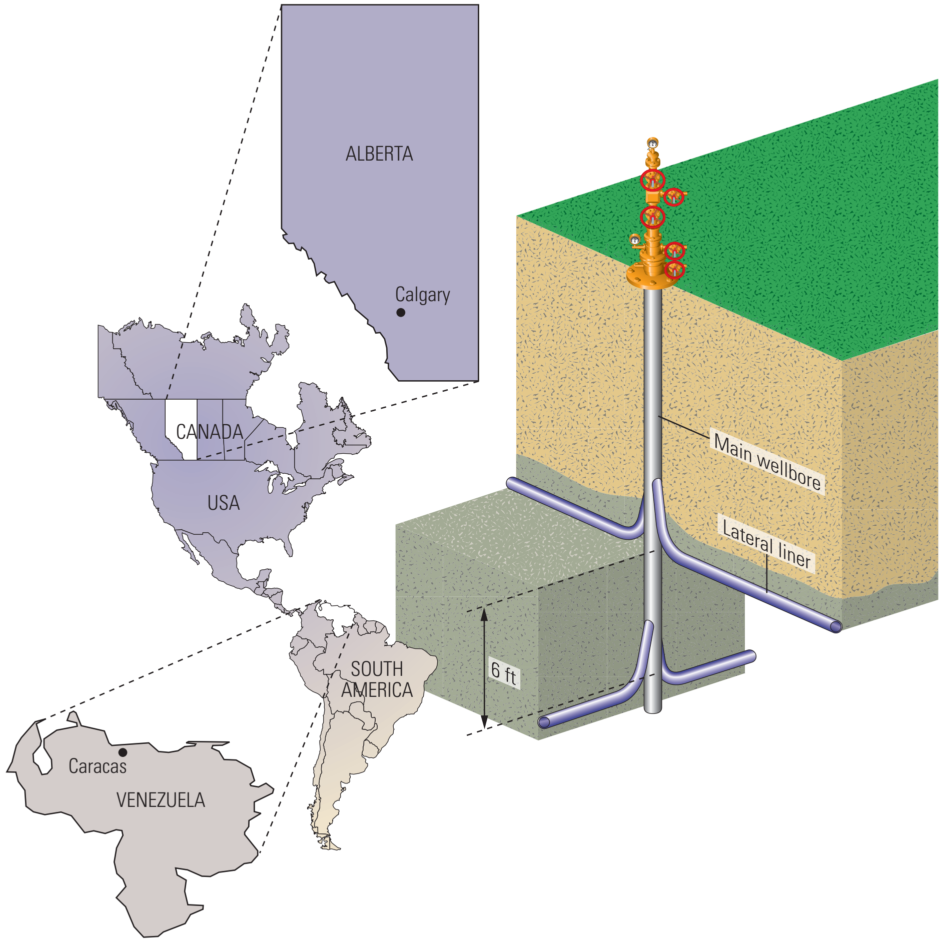
^ Precut casing windows. Applications for RapidTieBack quad junctions include new wells that require fullbore junctions in shallow heavy-oil reservoirs, low-permeability or naturally fractured formations and mature fields with depleted pressure. This system requires no milling of steel casing, connects liners to the primary casing of a main wellbore and allows cementing of liners.

cement and the temporary urethane-filled sleeve. A specially designed wash tool with an orientation key confirms that RapidTieBack profile nipples in the main casing are clear of debris.

Installation of a mechanical tieback sleeve connects lateral liners with the parent casing for added stability and provides selective reentry access to well branches for remedial work. Laterals can remain openhole or be completed with uncemented or cemented casing, slotted liners and sand-exclusion screens for additional borehole stability. A large internal diameter through the liner tieback in the main wellbore accommodates bigger completion hardware, high-volume artificial-lift equipment and reentry tools for future well operations.

A large internal bore allows completion tools and equipment with larger outside diameters, such as high-volume electrical submersible pumps and hydraulically or electrically operated tubing and slickline-retrievable flow-control valves, to pass through RapidTieBack quad junctions. Placing artificial-lift equipment deeper increases pressure drawdown for additional productivity and decreases ultimate abandonment pressure, which improves reserve recovery.

RapidTieBack quad systems have been used extensively for heavy-oil applications, but they are also applicable for multilateral-well completions in low-permeability, naturally fractured and depleted reservoirs to improve well productivity and reserve recovery by increasing wellbore drainage area and reducing pressure drop across pay intervals.



^ Quad-lateral completions. Operators have installed more than 220 RapidTieBack quad junctions in Venezuela and Canada *(left)*. Setting precut windows in a short tangent section improves the junction-construction process and facilitates lateral access. This system provides the option of completing up to four laterals openhole or with liners connected to the main wellbore by a mechanical tieback sleeve for added strength and stability at junctions *(right)*. An oriented diverter set in a reference profile provides selective access to reenter lateral branches for remedial well interventions.

RapidTieBack Quad: Canada and Venezuela

Thermal processes for enhanced oil recovery (EOR) inject steam to heat formations, reduce heavy-oil viscosity and promote flow. Multiple lateral branches maximize reservoir contact and improve productivity for cyclic steam injection and production, a process historically called "huff and puff." This technique typically involves at least two months of steam injection and possibly a shut-in and "soak" period followed by six or more months of production.

Although about four times more costly than single-bore wells in these applications, quad-lateral wells typically increase well productivity more than sixfold. These multilateral completions also limit environmental impact by reducing the number of wells, which also minimizes surface facilities such as steam lines and gathering lines. During the past six years, RapidTieBack quad systems have been used successfully to construct more than 220 multilateral junctions for steam-soak radial wells in Canada and cyclic steam stimulation (CSS) wells in Venezuela (above).[8]

The RapidTieBack quad junction allows laterals to be initiated and drilled through closely spaced exit windows in a short section of primary casing, which facilitates horizontal steering before reaching the bottom of a productive interval. Operators use this system to drill directional laterals by exiting the primary casing above a reservoir and turning horizontal after entering productive zones.

Combining EOR processes with multilateral-well technology is extremely effective. In most cases, production economics and reserve recovery exceed expectations, so operators in Canada and Venezuela plan to continue drilling and completing multilateral wells over the next few years. Operators in North and South America also are considering RapidTieBack quad systems for well-completion applications other than heavy-oil reservoirs.

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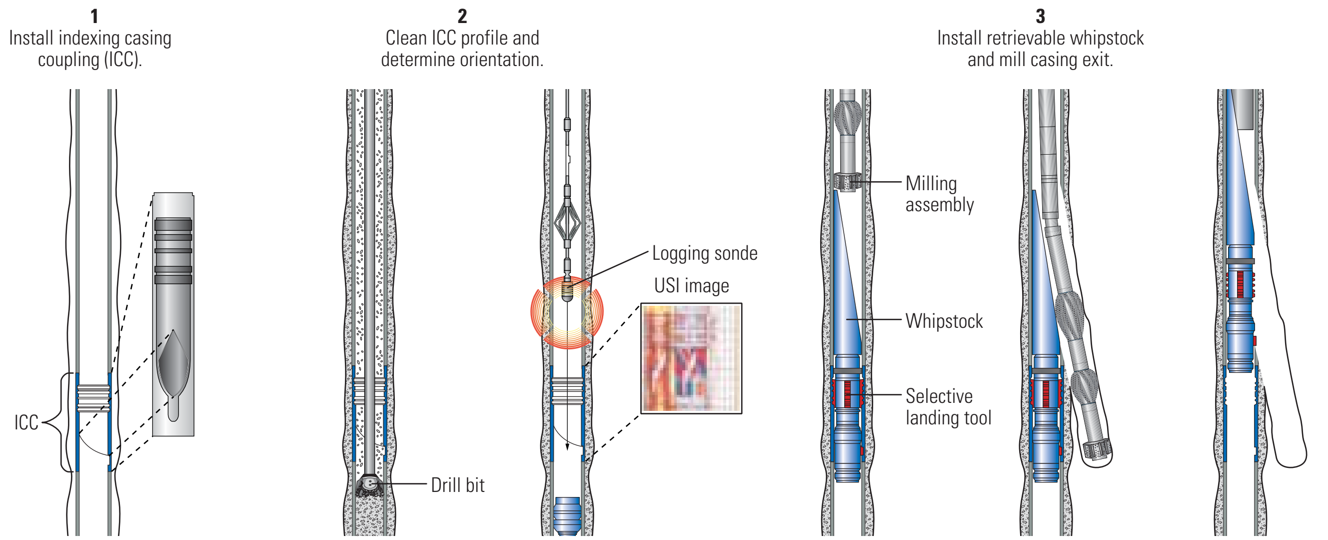
Milling Oriented Windows

The RapidAccess multilateral completion system providing selective drainhole access helps orient milled casing-exit windows for openhole laterals, drop-off liners and more complex junction installations (below). It also provides selective lateral access for reentry operations. This simple, low-cost window-milling technique uses a specially designed profile nipple, or indexing casing coupling (ICC), installed in parent casing strings to orient commercially available retrievable whipstocks. Using an ICC eliminates the need to orient precut windows by turning and positioning a string of casing from the surface.

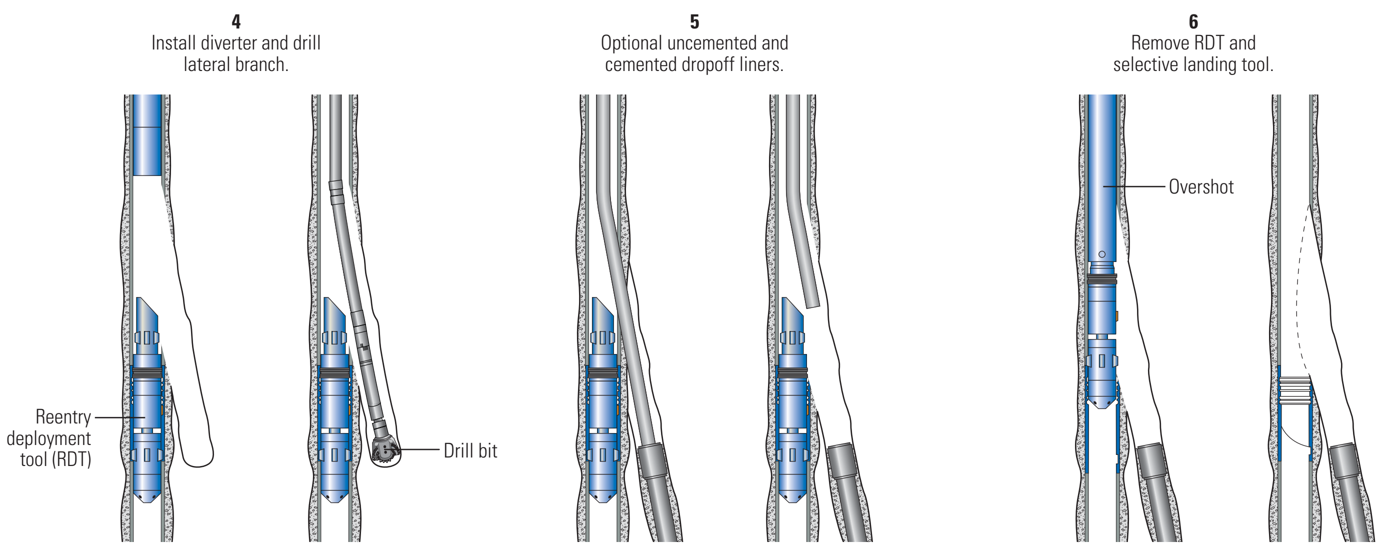
The fullbore ICC provides a permanent datum for milling casing windows and drilling laterals from 7- and 9⅝-in., or other standard size, primary casing strings. Installing more than one ICC supports construction of several lateral junctions and allows multiple reservoir penetrations for optimal field development. Five different profiles



1 – Place ICC in casing below proposed lateral depth and cement casing. The ICC is not oriented in advance. Cement casing.

2 – Drill out cement. A proprietary coating prevents cement from sticking to an ICC profile. Wiper plugs typically clean the ICC, but a jetting tool is available to clean ICC profiles. Determine ICC orientation with USI UltraSonic Imager log measurements acquired during a USI and CBT Cement Bond Tool evaluation.

3 – Attach retrievable whipstock and selective landing tool to milling assembly. Lock selective landing tool with orienting key adjusted to properly position tools in ICC profile. Shear off of whipstock and mill window through casing. Remove milling assembly and retrieve whipstock.



4 – Clean out main wellbore. Set reentry deployment tool (RDT) and selective landing tool in ICC to divert drilling assemblies and logging tools through casing window. Drill lateral borehole.

5 – Install liner on drillpipe guided by RDT for borehole stability and zonal isolation. Pump cement through drillpipe and liner into liner-borehole annulus to a point below the polished-bore receptacle (PBR) on top of the liner. Release drillpipe from liner and retrieve running tool before cement hardens.

6 – Retrieve RDT and selective landing tool.

^ Milling casing windows. The RapidAccess system uses a profile nipple called an indexing casing coupling (ICC), installed in the primary casing to mill exit windows for openhole laterals. The ICC serves as a permanent depth and directional orientation reference for drilling and reentry operations. This system provides fullbore access in 7- and 9⅝-in. casing, and is a key component of RapidConnect and RapidExclude junctions.

provide for additional kickoff points and selective access to laterals for optimal well-construction, completion and production flexibility. The ICC profiles can be installed in any sequence and at any depth to verify tool orientation throughout the life of a well.

The ICC does not require special installation or operational procedures. An ICC is installed and run like a short joint of casing. This integral design with standard American Petroleum Institute (API) tubular dimensions simplifies logistics and allows conventional cementing operations. The ICC does not restrict internal wellbore diameter or limit casing reciprocation and rotation during cementing, which helps ensure an adequate cement bond.

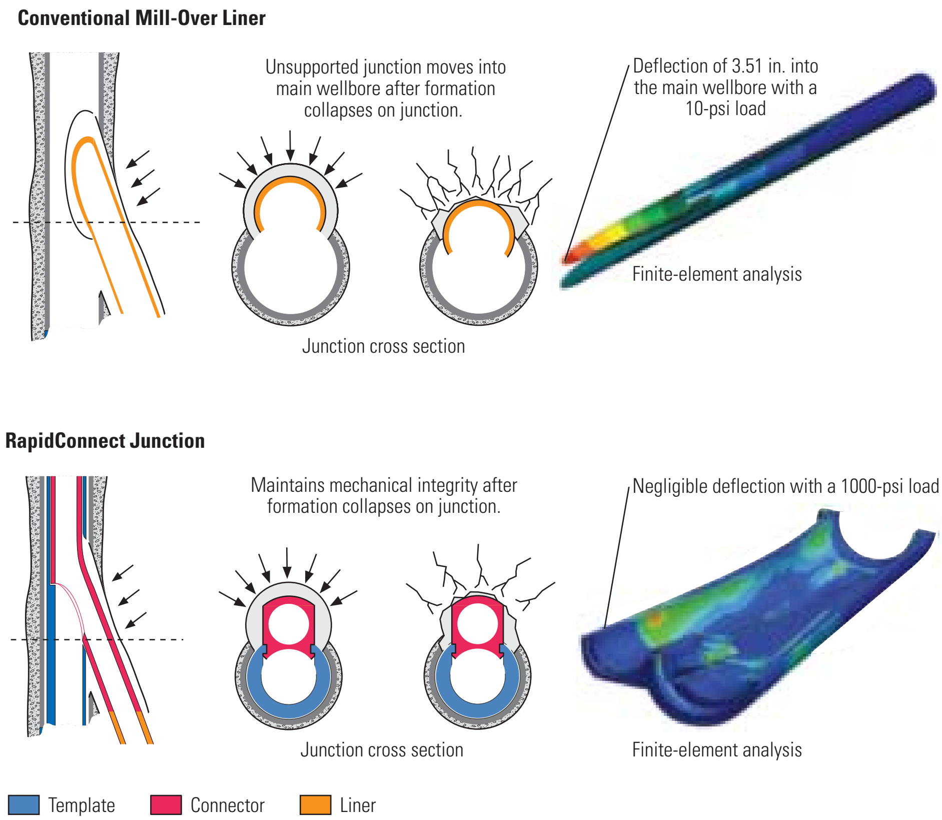
After the casing is cemented, wireline or measurements-while-drilling (MWD) survey tools determine ICC depth and directional orientation so that a selective landing tool can orient a whipstock and milling assembly in a specific direction at the chosen depth. The ICC position also can be determined from USI UltraSonic Imager log data often acquired during CBT Cement Bond Tool evaluations, which eliminates an extra logging run.

Previous casing-exit techniques required installation of a temporary packer to serve as a reference and platform for milling casing windows. With packer-based systems, depth and directional orientation are lost after retrieving the packer. Future access to the lateral is extremely expensive, if not impossible. Now, the ICC concept provides positive verification of tool orientation and added confidence during the multilateral well-construction process.

A casing window can be milled up to 90 ft [27 m] above an ICC. Two or three windows can be indexed off of the same ICC at different orientations as long as they are within the 90-ft spacing. Redundant tool-retrieval features ensure access to lower laterals. Positioning an ICC at the proper depth is the primary consideration during installation.

A two-stage process using a whipstock followed by a special reentry deployment tool (RDT) further improves window milling and junction construction compared with systems that just use a whipstock. The RDT outside diameter is smaller and thus easier to retrieve than standard equipment, which minimizes debris and tool-retrieval problems after drilling.

The ICC is an important element in multilateral-well maintenance, long-term field-development planning and reservoir management. Setting an oriented diverter in the ICC allows selective access at a junction for lateral reentry. By providing a permanent reference point and support



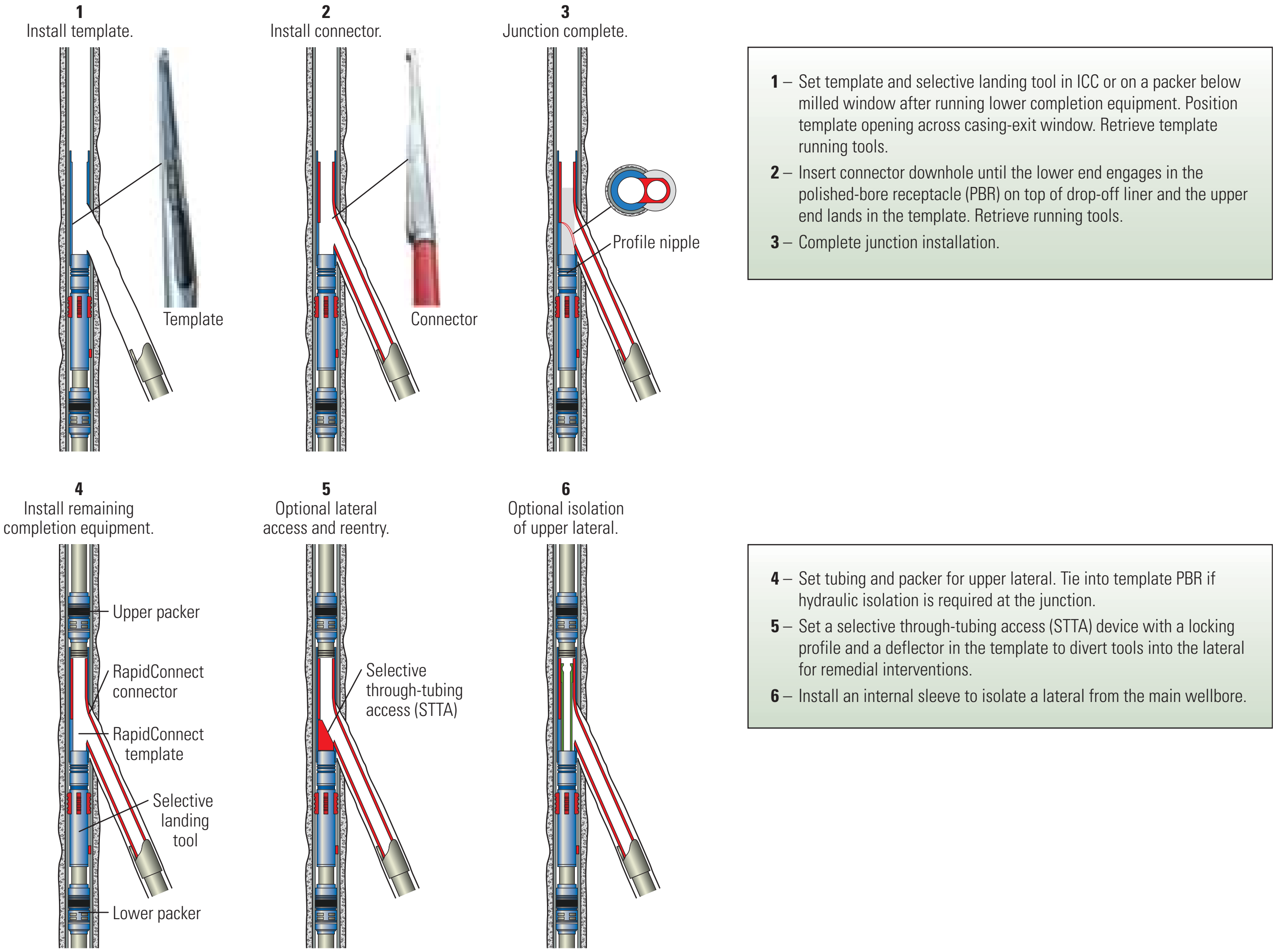
^ RapidConnect junction versus mill-over liner. Constructing a lateral junction by milling over the top of a liner that extends into the main wellbore has several disadvantages *(top left)*. Formation forces eventually push liners back into the main wellbore, restricting access below that point or collapsing the junction completely. RapidConnect and RapidExclude connectors and templates improve junction mechanical integrity and reliability *(bottom left)*. These junctions withstand pressures 100 to 150 times greater than a mill-over junction. Loads on the junction are transferred to the primary casing by the connector and template interlocking profiles. Finite-element analysis verified structural integrity of the RapidConnect system. A load of 10 psi [69 kPa] on a mill-over junction results in more than 3.5 in. of deflection in $9\frac{5}{8}$-in. casing *(top right)*. However, a 1000-psi [6.9-MPa] load on a RapidConnect junction results in negligible deflection *(bottom right)*.

for through-tubing lateral access, the ICC reduces the cost and risk of future remedial work and junction construction. RapidAccess openhole junctions are applicable in shales and competent, consolidated formations. The ICC also provides the foundation for Schlumberger RapidConnect multilateral completion system providing selective drainhole access and connectivity and RapidExclude multilateral junction for solids exclusion (see "Junction Connectivity and Stability," *below*, and "Junction Strength and Sand Exclusion," *page 63*).

Junction Connectivity and Stability

In early multilateral junctions, maintaining selective branch access was possible only with precut windows or more complex junctions. This made planning for future laterals difficult because junction depth had to be determined in advance. In addition, precut windows with drillable sleeves limited casing integrity. Building on RapidAccess window-milling solutions, RapidConnect and RapidExclude junctions create a structural connection between lateral liners and the primary casing that allows selective access to well branches and the main wellbore. Each well branch is cased, but typically only the main wellbore is cemented.

Conventional anchoring systems with mechanical liner hangers or latching mechanisms often extended into the main wellbore, preventing access to laterals and the main wellbore. Mill-over liners provided temporary access to the lateral and main wellbore, but these junctions eventually collapse under loads caused by formation temperatures and stresses, pressure depletion, subsidence and high pressure differential when high-volume electrical submersible pump are used. In contrast, RapidConnect and RapidExclude designs provide mechanical integrity at a junction in the event of formation instability and movement over the life of a well (above).



^ Junction connectivity and strength. The RapidConnect and RapidExclude systems use RapidAccess ICC profiles to construct junctions that connect lateral liners to milled exit windows in primary casing strings. A high-strength junction is constructed in the well, not prefabricated. Two main components are assembled downhole to close dimensional tolerances without precut windows and orienting the casing from surface. The first component, a template with precut window and guide rails, is set across a milled window. The second component, a connector, physically anchors lateral liners to the template.

These two systems achieve connectivity at milled casing windows by assembling junction components downhole to close dimensional tolerances. The resulting high-strength connections are suited to multilateral applications in unstable, unconsolidated, weakly consolidated or incompetent formations. There are two main components of these systems, a template and a connector, that fit together to provide consistent junction connectivity.

The template with a precut window and guide rails is placed next to a milled casing-exit window. These rails match profiles on a connector. The template is installed in an ICC as part of the main wellbore completion, and the precut window is oriented adjacent to the previously milled casing window for a lateral. Using ICC profile nipples allows precise tool orientation during installation.

The interlocking guide rails and connector profiles orient and divert the liner and connector through the template window into a lateral. The top of the connector then locks into place in the upper section of a template to resist liner movement. The concept is similar to tongue-and-groove connections.

This technique creates a strong structural connection. The RapidConnect junction achieves a collapse-strength rating of 1500 psi [10 MPa]. The smooth transition from main wellbore to lateral facilitates subsequent reentry and remedial operations. Integral through-tubing lateral access and selective isolation simplify future operations and facilitate production control.

An optional ICC installed in advance at minimal cost allows the flexibility to drill and complete other lateral branches in the future. Unlike precut windows, the ICC provides complete casing integrity until an exit window is milled. If unplanned laterals are required in a wellbore where there is no ICC, the RapidConnect system can be installed using a conventional packer as the reference datum and tool platform.

Schlumberger evaluated RapidConnect and RapidExclude equipment and procedures in an experimental well at the Gas Technology Institute (GTI) facility in Catoosa, Oklahoma, USA, to validate the junction-construction process for milled casing windows (above). This full-scale testing was in addition to conventional component, subassembly and system-level qualification tests performed during the standard product-development process. The system installation and junction construction were successful, and the system was fully functional after retrieval from the test well. Several

RapidConnect field installations and a full-scale RapidExclude junction test at the Catoosa site confirmed junction performance and deployment procedures.[9]

RapidConnect Junction: Nigeria

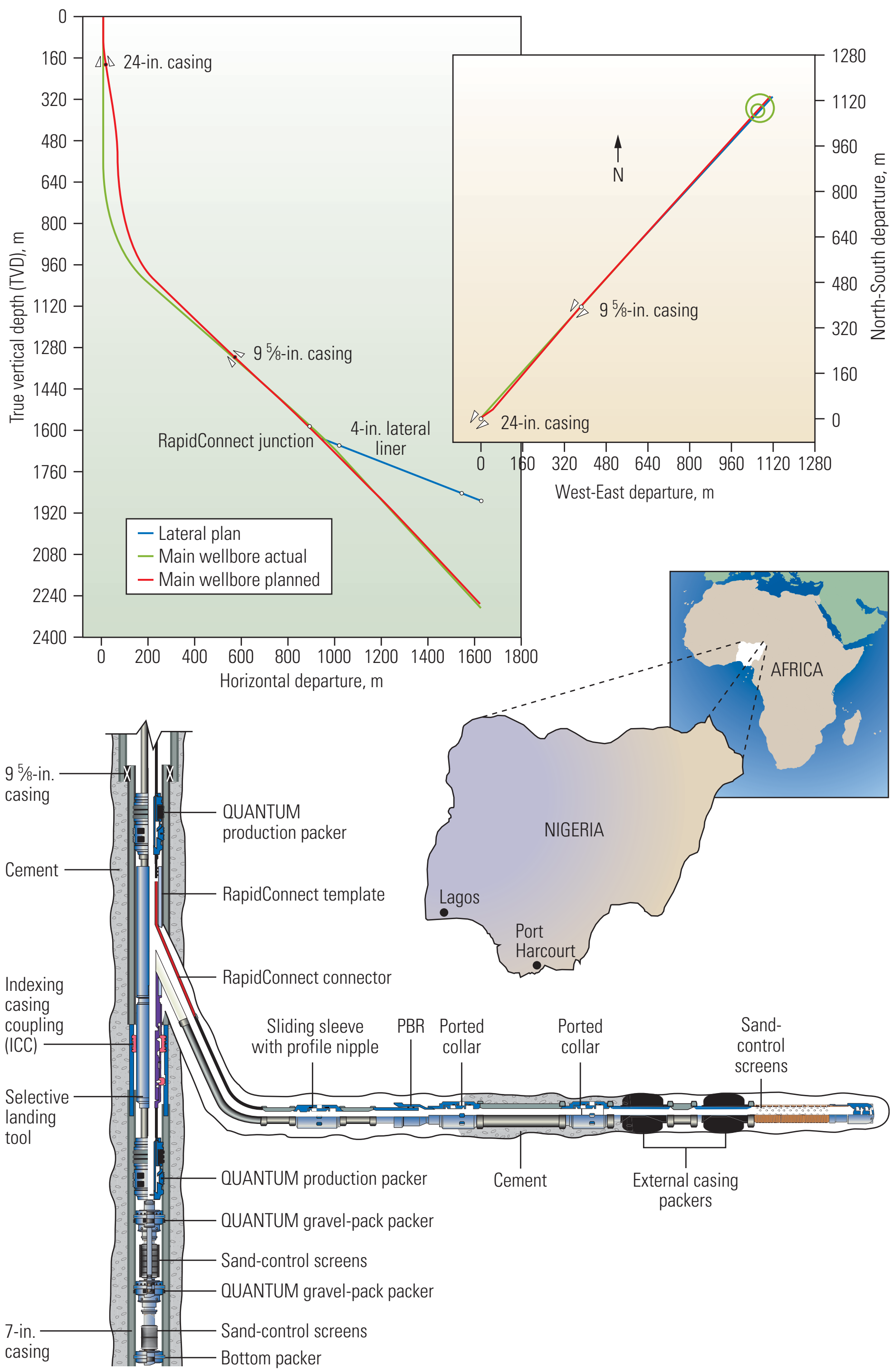
In March 2000, TotalFinaElf ran the first 7-in. RapidConnect junction in Ofon 26, a new well located offshore Nigeria (right).[10] The main borehole penetrated two productive intervals, while a single lateral branch targeted a fault-isolated section of the upper zone. The well design called for a cased and cemented main wellbore with a cased lateral liner mechanically connected to the primary casing, but not cemented at the junction.

Prior to drilling and completing the upper lateral, TotalFinaElf individually gravel packed the two producing zones in the main wellbore below the proposed lateral. An isolation packer between the two screen assemblies allowed selective production from either interval. To support multilateral equipment and completion operations, the 7-in. production casing of the main wellbore, which was set at 2883 m [9459 ft], included an ICC for depth reference and directional orientation.

The operator oriented a commercially available whipstock in the ICC, milled a window in the 7-in. casing between 1916 and 1920 m [6286 and 6299 ft] and drilled a 6-in. lateral drainhole to 2730 m [8957 ft]. Maintaining formation stability and lateral connectivity at this junction depth and high angle was a major concern.

A lower 4-in. drop-off liner attached to an upper 4½-in. temporary liner was run into the 6-in. lateral. The upper liner prevented loss of borehole diameter or hole collapse between the 7-in. casing window and the drop-off liner during cementing operations. Stand-alone sand-exclusion screens without a gravel pack controlled sand influx and stabilized the productive interval sufficiently, but a water zone above the screen depth had to be isolated from the junction. The operator chose external casing packers to isolate the sandface before cementing. Ported collars allowed cement to be placed in the annulus across from the water zone.

The 4-in. liner assembly included standard wire-wrapped screens for sand control, a primary and a backup ECP, two ported collars, a polished-bore receptacle (PBR) for a subsequent tieback liner and a quick disconnect to release the 4½-in. liner. A 2⅜-in. internal washpipe facilitated fluid circulation and cementing. A sliding sleeve in the 4½-in. liner provided a way to circulate cement out of the annulus below the junction.



^ Nigeria offshore multilateral completion. TotalFinaElf installed a RapidConnect system to complete the Ofon 26 well in Nigeria, West Africa *(middle)*. The trajectory of the main wellbore targeted two productive zones; a single lateral branch tapped a fault-isolated section of the upper zone *(top)*. The two lower zones were completed with standard sand-exclusion screens and gravel packed individually. The operator ran a drop-off liner consisting of stand-alone wire-wrapped screens, a primary and a backup external casing packer (ECP) to isolate the sandface before cementing, two ported collars, a polished-bore receptacle (PBR) and a disconnect to release the running string and a temporary 4½-in. liner to stabilize the lateral during completion operations *(bottom)*. A 4-in. tieback liner then was set in the PBR of the drop-off liner and locked into the RapidConnect template.

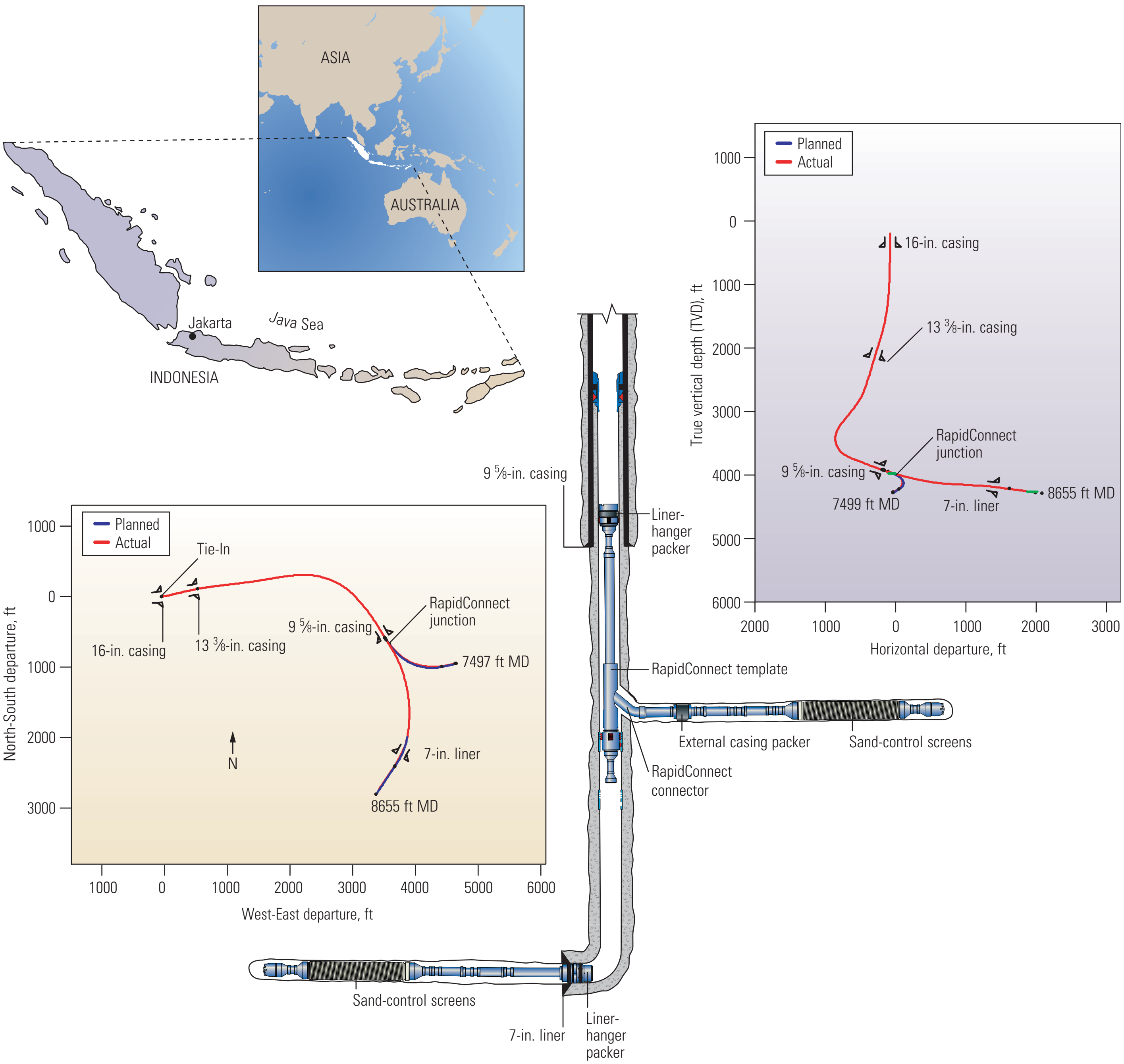
9. Ohmer H, Brockman M, Gotlib M and Varathajan P: "Multilateral Junction Connectivity Discussion and Analysis," paper SPE 71667, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 30–October 3, 2001.

10. Ohmer et al, reference 9.

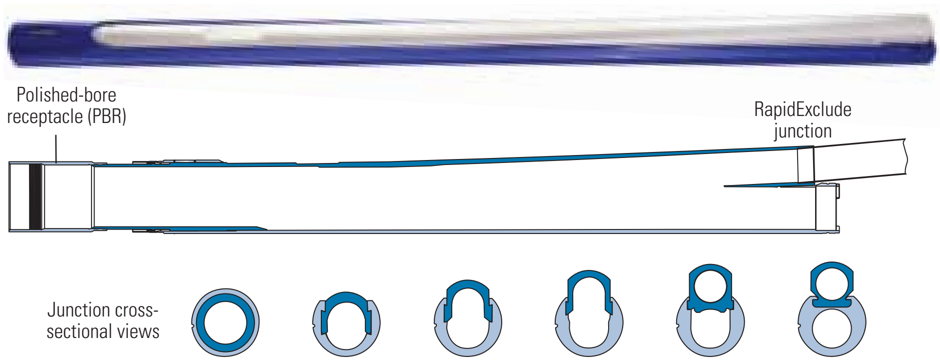
The workstring tubing, 4½-in. liner and 2⅜-in. washpipe were retrieved after cementing the drop-off liner and cleaning out excess cement above the 4-in. lateral tieback PBR. This left the 4-in. drop-off liner in the 6-in. openhole, 18 m [59 ft] from the 7-in. casing window. The junction was deployed in two runs: the first to place a RapidConnect template adjacent to the 7-in. milled casing window; the second to tie back into the drop-off liner and complete the junction with a RapidConnect connector.

On the first trip, the template was seated in the upper isolation packer below the junction. The second trip stabbed a seal assembly on the tieback liner into the 4-in. PBR on the drop-off liner and locked the connector into the template. A sliding sleeve located in the RapidConnect stinger and shifted by coiled tubing allowed special conformance-control chemical gels to be pumped into the annulus to further seal the junction and prevent water influx.

Production tubulars and completion equipment for the upper main wellbore completion were connected into the top of the RapidConnect template, and an isolation sleeve was run across the RapidConnect junction to isolate the lateral. Multilateral technology increased productivity and extended the economic life of this well by allowing selective production from multiple zones.



^ Indonesia multilateral completion. Repsol YPF, now China National Offshore Operating Company (CNOOC), installed a RapidConnect system to complete East Rama field Well AC-06 in the Java Sea, Indonesia *(upper left)*. Each lateral branch targeted two pay intervals *(left and right)*. The lower 6-in. lateral was completed with a liner consisting of a 4-in. Weatherford expandable sand screen (ESS) and expandable isolation sleeve (EIS) assembly and 4½-in. blank pipe below a 7-in. liner packer at 2406 m [7894 ft] MD. The upper 6-in. lateral was completed with a liner assembly comprising 4-in. ESS, 22 m [72 ft] of 4-in. EIS, 4½-in. blank pipe and a 4½-in. TAM International external casing packer (ECP) that was connected to the main wellbore and RapidConnect template by a tieback liner and the RapidConnect connector *(middle)*.



^ High-strength junctions and sand exclusion. The RapidExclude system is based on RapidAccess and RapidConnect designs. A modified guide-rail profile excludes sand and provides additional mechanical integrity. This system resists junction loads up to 2500 psi [17 MPa] and excludes particles as small as 40 microns. This profile view shows engagement between the template and connector of a 9⅝-in. RapidExclude system *(top)*. Left to right, these cross sections represent slices from top to bottom of the assembly *(bottom)*. The two components begin as concentric pipes and then diverge until there are two separate bores.

RapidConnect Junction: Indonesia

Developing outlying offshore fields in Southeast Asia adds substantial oil production and recoverable reserves for the region. These types of fields, however, often are located beyond existing development patterns. Operators install small platforms with minimal facilities to reduce cost, but this limits the available slots for development and infill drilling.

For example, the East Rama field platform in the Java Sea, Indonesia, had eight wellhead slots and limited weight capacity (previous page). Six slots were already in use when two "sacrificial" vertical wells drilled by the Schlumberger multipurpose service vessel (MPSV) *Bima* identified an untapped block of oil reserves. Optimal field development and reserve drainage required five wellbore entry points in the reservoir.

Repsol YPF, now China National Offshore Operating Company (CNOOC), decided that two multilateral wells were the best solution. Acting as the primary contractor, Schlumberger collaborated with Diamond Offshore Drilling, M-I Drilling Fluids, TAM International and Weatherford on this project. Each of the two laterals for East Rama AC-06, the first multilateral well, targeted two pay intervals. This completion did not require hydraulic isolation at the junction, so the operator chose the RapidConnect system.

In January 2002, a RapidConnect junction was installed to complete Well AC-06.[11] After cementing 9⅝-in. intermediate casing at 1875 m [6152 ft] measured depth (MD) and 1196 m [3924 ft] true-vertical depth (TVD), Diamond Offshore Drilling drilled a directional 8½-in. borehole to 2430 m [7973 ft] MD, just above the reservoir. The rig contractor then cemented a 7-in. casing string that included a primary and a backup ICC with different profiles. The first ICC was at 1890 m [6201 ft] MD; the second ICC was placed 19 m [62 ft] deeper as a contingency.

The first 6-in. lateral was drilled directionally to 2608 m [8557 ft] MD using an M-I Drilling Fluids synthetic oil-base drill-in fluid and Schlumberger VISION475 4¾-in. MWD/logging-while-drilling (LWD) system. After TD was reached, the lateral liner with a 4-in. Weatherford expandable sand screen (ESS) and expandable isolation sleeve (EIS) assembly and 4½-in. blank pipe was installed below a 7-in. liner packer at 2406 m [7894 ft] MD.

After the liner packer was set and the ESS and EIS assembly were expanded, a 7-in. QUANTUM gravel-pack packer with a plug was set in the main wellbore at 1920 m [6300 ft] MD to isolate the first lateral and lower completion during drilling and completion of the upper lateral. A high-viscosity fluid was circulated on top of the isolation packer as a debris barrier.

A selective landing tool run in conjunction with the Schlumberger VISION475 system accurately determined the downhole orientation of the upper ICC. The next run set the selective landing tool and a Weatherford whipstock in the upper ICC at 1890 m MD. A 7-in. casing window was milled from 1880 to 1884 m [6168 to 6181 ft] MD in less than 2½ hours using a Schlumberger PowerPak XP extended power steerable downhole motor. The upper 6-in. lateral was directionally drilled with the same type of drill-in fluid that was used in the lower lateral.

A 7-in. QUANTUM packer and temporary liner were run above 78 m [256 ft] of 4-in. ESS, 22 m [72 ft] of 4-in. EIS, 4½-in. blank pipe and a 4½-in. TAM International external casing packer, which was set at 6300 ft MD. The ESS and EIS sandface completion were expanded and the ECP was inflated with cement. The liner disconnect was released, and the upper QUANTUM packer and temporary liner were retrieved. The whipstock and QUANTUM packer plug were retrieved from the wellbore.

Installation of a RapidConnect template and connector on a tieback liner connected the upper lateral completion assembly with the main wellbore and completed the Level 3 junction. An electrical submersible pump set in 9⅝-in. casing above the 7-in. liner hanger finalized the completion; production from each lateral branch was commingled. From start of drilling to first production, this well was completed in a record 36 days.

At a stabilized oil rate of 874 m^3/d [5500 B/D] and 128,864 m^3/d [4.5 MMscf/D] of gas, Well AC-06 produces three to four times more oil than the best conventional wells in the field. This multilateral well also achieved the highest productivity level—32 B/D/psi [0.74 m^3/d/kPa]—for East Rama field. Well AC-02 and Well AC-03 single-bore completions produced at 7 and 12 B/D/psi [0.16 and 0.28 m^3/d/kPa], respectively. The productivity improvement demonstrated by this well proved that multilateral technology is cost-effective for developing satellite fields and bypassed reserves.

Junction Strength and Sand Exclusion

Multilateral junctions can experience connectivity problems because of unstable formations and high mechanical loads that adversely affect their mechanical integrity. In formations that are prone to sand production, solid particles entering through junctions cause serious problems. Schlumberger developed a multilateral system to construct junctions that exclude sand and better support the loads that are created by formation instability.

Based on proven RapidAccess and RapidConnect concepts, the RapidExclude multilateral junction for solids exclusion prevents sand influx (above). This system is an additional completion tool for layered, faulted and compartmentalized reservoirs, including wells that

11. Caretta F, Drablier D and O'Rourke T: "Southeast Asia's First Multilateral with Expandable Sand Screens," *Offshore Engineer* (April 2002): 55–56.
Tanjung E, Saridjo R, Provance SM, Brown P and O'Rourke T: "Application of Multilateral Technology in Drilling an Offshore Well, Indonesia," paper SPE 77829, presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Melbourne, Australia, October 8–10, 2002.

penetrate different pressure regimes. Continuous engagement between a modified template-locking rail and connector profile excludes formation grains and solid particles. The RapidExclude system controls sand influx in unconsolidated or weakly consolidated reservoirs. This high-strength junction also provides junction stability in unstable shales or formations with high stresses.

Most conventional junctions exhibit collapse resistance in the 10 to 100 psi [0.07 to 0.7 MPa] range and have an open gap of more than 1 in. [2.5 cm]. This enhanced junction exhibits collapse strength that exceeds 2500 psi [17 MPa], and excludes formation sand grains and solid particles as small as 40 microns.

A 9⅝-in. RapidExclude system was qualified in June 2002 at the GTI Catoosa facility in Oklahoma. A test well was completed with 9⅝-in. casing that included a RapidAccess ICC. Field-proven procedures from previous RapidConnect installations were used to mill the casing-exit window and construct a junction at 970 ft [295 m] in a shaly sand. Junction components were retrieved as part of this full-scale qualification test to evaluate installation reversibility.

The connector was retrieved with a conventional spear by applying straight pull. Next, the template was retrieved, again by straight pull. Both components were in good condition and fully functional. The selective reentry deflector, intervention tools and an isolation sleeve were run and retrieved successfully by a slickline unit to complete the system qualification. The RapidExclude system performed as expected and was qualified for commercial installation. In November 2002, Schlumberger successfully installed a RapidExclude junction in Venezuela.

Junction Pressure Integrity

The prefabricated RapidSeal multilateral completion system providing selective drainhole access and connectivity with a pressure-sealed connection forms a high-strength symmetrical junction with hydraulic integrity between two adjacent laterals and the main wellbore. This system was developed through a joint research and development project between Agip, a division of Eni, and Schlumberger.

Early Level 6 junctions consisted of two full-size liners attached to a joint of primary casing. This configuration simplified junction construction, but required a large borehole that resulted in loss of two or more intermediate casing sizes. The sudden jump from large parent casing to smaller lateral liners was also a limitation.

Schlumberger and Agip addressed these limitations by developing a novel metal-forming technology. Unlike the RapidConnect and RapidExclude systems, which are assembled downhole, a RapidSeal junction is manufactured in advance as one piece. Currently, this system combines two 7-in. outlets below 9⅝-in. casing or two 9⅝-in. outlets below 13⅜-in. casing to form a junction.

The manufacturing process reduces initial outside diameter of the system by plastically compressing the two lateral outlets to less than their expanded diameters in a special mechanical press. This ensures even stress distributions, consistent system geometry and accurate dimensional tolerances and allows a compressed junction to pass through the preceding casing string, which minimizes wellbore telescoping.

The unique hybrid design of this dual-outlet junction increases resistance to both internal burst and external collapse pressures. Two outlets are welded onto a stiffener, or structural member, made of high-strength material. Only the ductile outlets, not the stiffener, sustain plastic deformation. A proprietary process ensures full weld penetration along the stiffener-outlet interface.

The RapidSeal system uses a combination of strong, ductile components to reduce failures and tubular stresses in the outlets, and maintain the strength of a junction after it is compressed and reformed. When this system is deployed at the proper depth, a wireline-conveyed expansion tool reforms the outlets to their original size and cylindrical shape in a single trip (next page). Compared with systems that use a mechanical swedge, this technique greatly reduces installation time.

The reforming process, which takes about 45 minutes, is monitored and controlled in real time on the surface. This procedure ensures a smooth expansion and confirms that final outlet geometry meets API specifications for internal pipe dimensions. Pistons in the two saddles of the expansion tool apply force to simultaneously open and reform both outlets symmetrically. Electric power from the wireline operates a pump in the tool that provides sufficient hydraulic pressure to develop 1.5 million lbf [6.6 million N] of force in a 13⅜-in. RapidSeal junction.

An adapter provides a smooth transition from a single bore to the two outlets and connects the outlets to the main junction bore. The bottom of the junction assembly is a steel frame inside a fiberglass guide that functions as a standard guide shoe and protects the outlets during installation. The steel structure also acts like a whipstock to guide tools out of the junction outlets during drilling and completion of each lateral branch.

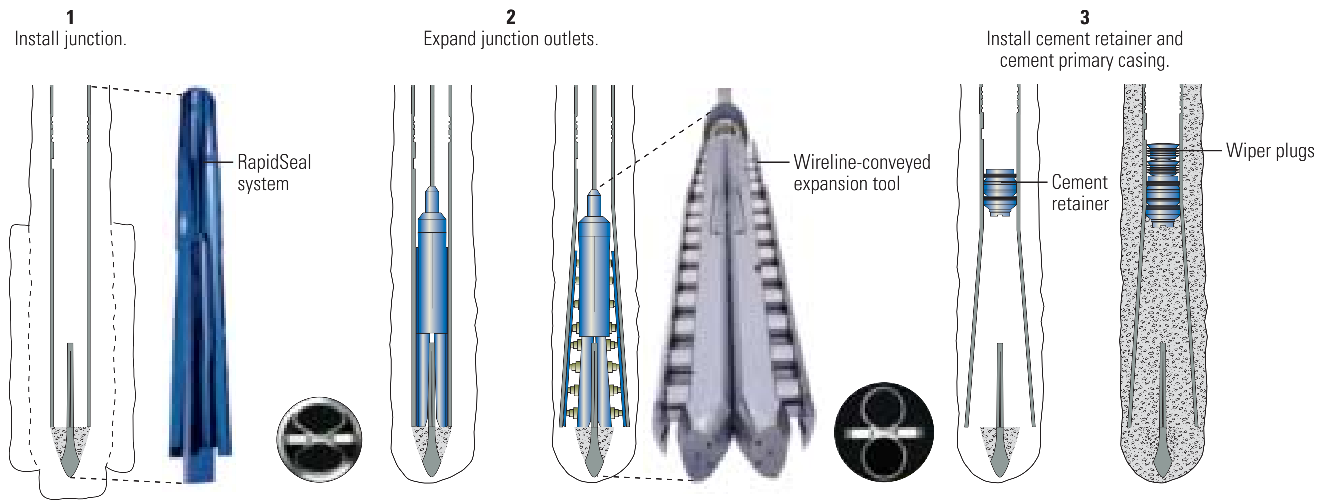
The symmetrical design of RapidSeal junctions ensures a smooth transition from the main wellbore to each branch, allowing standard drilling tools and completion assemblies to pass through the junction. Service-pressure ratings for 9⅝-in. and 13⅜-in. RapidSeal junctions are 1200 psi [8 MPa] and 2200 psi [15 MPa], respectively.

After extensive laboratory testing, a RapidSeal junction with 9⅝-in. parent casing and two 7-in. outlets was installed, expanded and cemented successfully in a deviated experimental well at the GTI Catoosa test facility in Oklahoma.[12] Two 6⅛-in. directional branches were drilled out of the junction. The first branch was completed with an uncemented 4-in. liner; the second branch was completed with a cemented 4-in. liner. The test objective was to evaluate the RapidSeal system before the first commercial field installation. Components, tools and procedures performed successfully during this test installation. The 13⅜-in. RapidSeal system has been qualified in laboratory tests.

RapidSeal Junctions: Brazil, Nigeria and Indonesia

Petrobras installed the first commercial RapidSeal system in an onshore well at Macau, Brazil. This 9⅝-in. junction was oriented and installed above the reservoir at 518 m [1700 ft] MD. The two outlets were expanded to original round geometry within API dimensional tolerances and cemented in place. The expansion process required 6 hours, including trip time, with only 30 minutes of nonproductive time. The operator directionally drilled two 7-in. lateral branches using a PowerPak XP

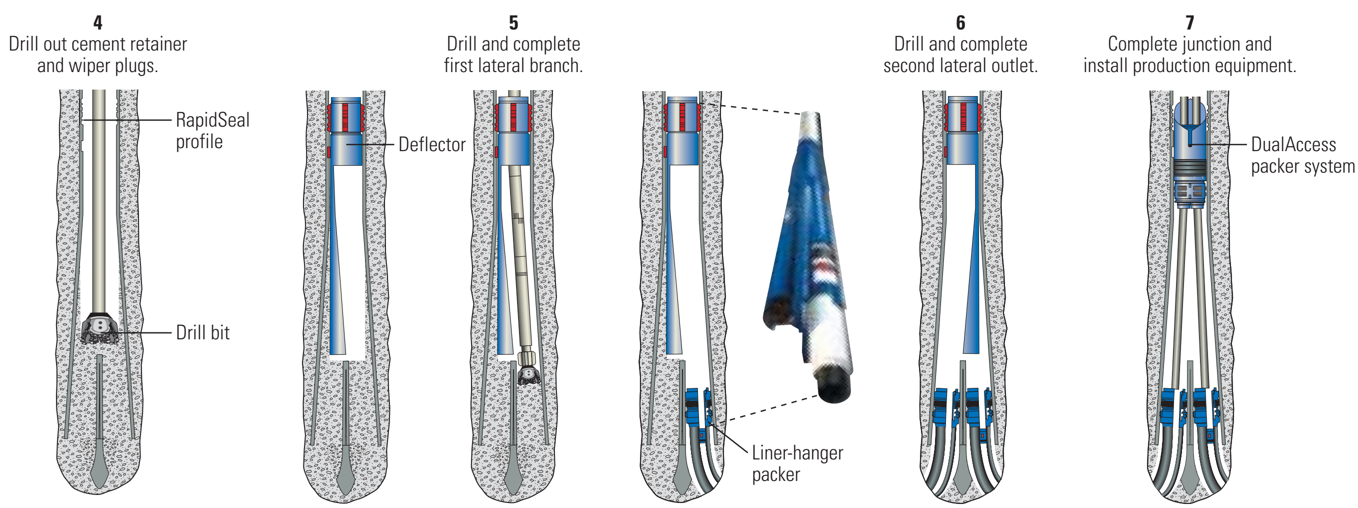
12. Ohmer H, Follini J-M, Carossino R and Kaja M: "Well Construction and Completion Aspects of a Level 6 Multilateral Junction," paper SPE 63116, presented at the SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 1–4, 2000.



1 – Drill main borehole. Under-ream and enlarge openhole section across junction location. Set RapidSeal system on primary casing.

2 – Position wireline-conveyed expansion tool saddles in RapidSeal outlets. Verify junction directional orientation to ensure proper expansion of outlets. Real-time process control and monitoring at surface confirm simultaneous expansion and final geometry of outlets. Retrieve expansion tool.

3 – Using the RapidSeal profile for depth verification, set wireline-conveyed cement retainer above junction to prevent a pressure differential and increase reliability. Cement junction.



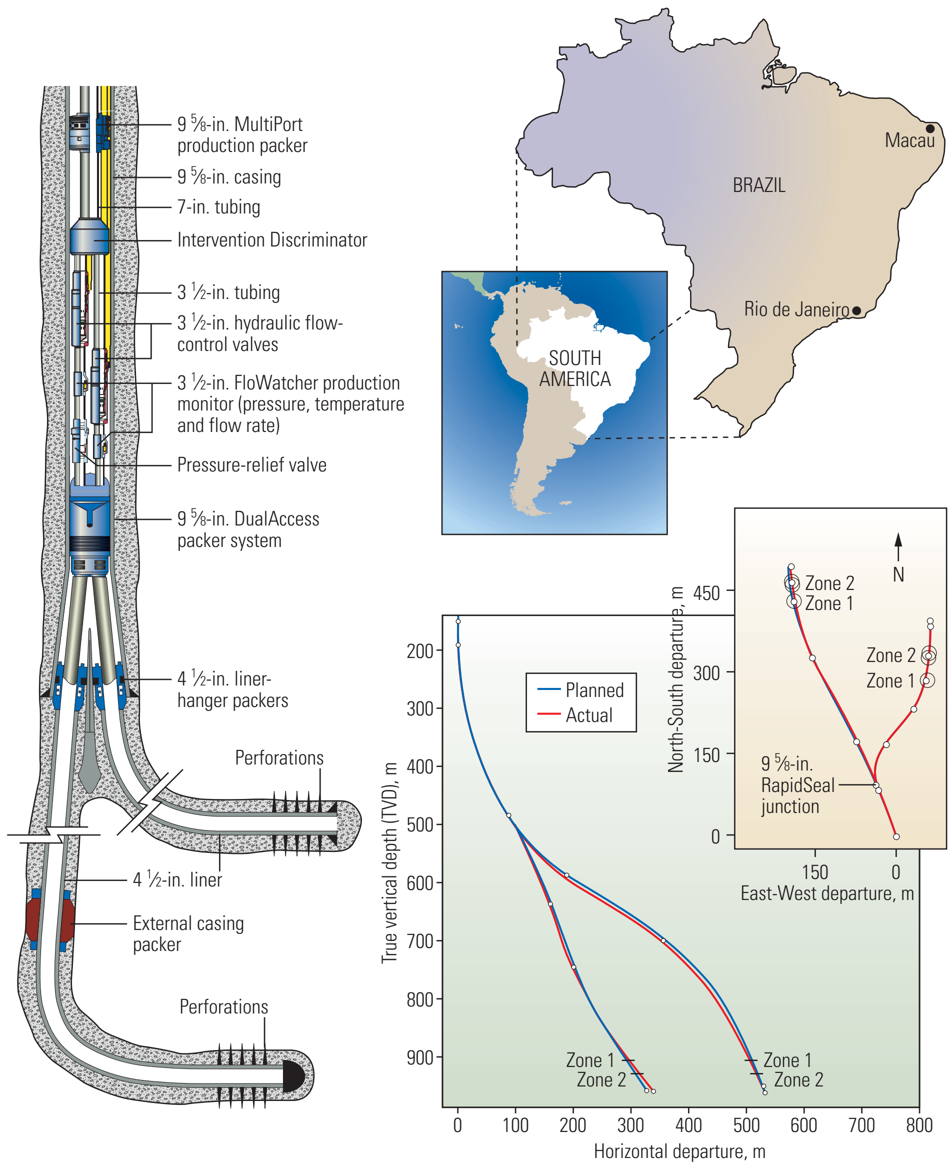
4 – Clean out main wellbore to top of junction outlets. The RapidSeal profile provides a positive depth indicator.

5 – Set and orient deflector in RapidSeal profile to divert drill bit and liner assembly into first outlet. Clean out cement and drill first lateral borehole. Run liner-hanger packer and casing. Install slickline plug in profile nipple below liner hanger to isolate lateral. Retrieve deflector.

6 – Set and orient a deflector in the RapidSeal profile oriented to divert bit and liner assembly into second outlet. Clean out cement and drill second lateral borehole. Run liner-hanger packer and casing in second lateral branch. Install slickline plug in profile nipple below liner hanger to isolate lateral. Retrieve deflector.

7 – Set DualAccess system in main wellbore to complete both lateral branches.

^ Junction pressure integrity. The RapidSeal system is manufactured in advance, not constructed downhole, to achieve pressure integrity. This TAML Level 6 system includes a prefabricated section of parent casing with two smaller outlets. The symmetrical outlets are compressed to pass through the preceding casing and then reformed to original geometry by a wireline-conveyed modular expansion tool. The expansion process is controlled and monitored from surface in real time and performed in a single trip.



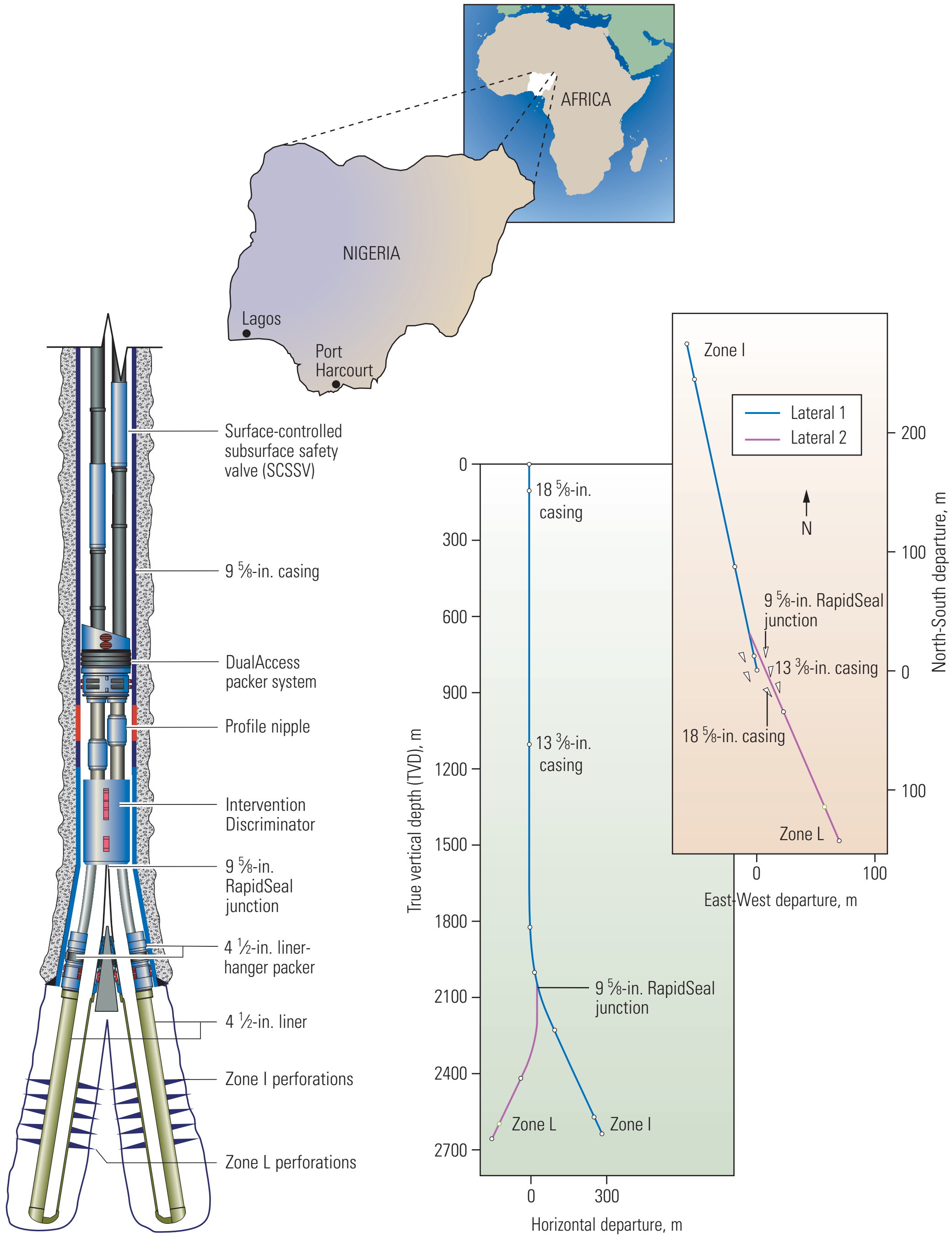
^ Brazil Level 6 multilateral field test. The first commercial installation of a 9⅝-in. RapidSeal system was performed onshore for Petrobras in Macau, Brazil *(upper right)*. Each lateral targeted two productive intervals *(lower right)*. A DualAccess completion system was installed temporarily for extensive testing and evaluation of advanced flow-control and monitoring equipment *(left)*. This system consists of tubing strings with seal assemblies for each lateral liner, a packer to isolate the annulus between production strings, and the primary casing and an Intervention Discriminator to selectively access each lateral.

positive-displacement motor (PDM) and 6-in. by 7-in. eccentric, bicentered polycrystalline diamond compact (PDC) bits (above).

The first branch with a cemented 4½-in. liner for zonal isolation down to the reservoir extended 644 m [2112 ft]. The second branch with a cemented 4½-in. liner extended 568 m [1864 ft]. A DualAccess system with isolation packers set in each lateral and a multiport production packer in the main wellbore was hydraulically connected by separate tubing strings to an Intervention Discriminator and a MultiPort bypass packer with multiple porting above the laterals. Hydraulic flow-control valves allow selective isolation or production of upper and lower lateral branches. FloWatcher integrated permanent production sensors monitor pressure, temperature and flow rate from each well branch.

The DualAccess system is retrievable for access to the main wellbore and reentry of both branches. After extensive and successful testing of both laterals for pressure integrity and accessibility, DualAccess completion equipment was retrieved to perforate and complete the well. The first lateral branch was completed with 3½-in. production tubing and a progressing cavity pump (PCP). The second lateral branch was completed with 3½-in. tubing and an electrical submersible pump.

Petrobras and Schlumberger are collaborating together to develop procedures for offshore installation and operation of a 13⅜-in. RapidSeal



^ Nigeria Level 6 multilateral completion. Agip drilled two lateral branches using a RapidSeal junction in the onshore Idu ML 11 well *(top)*. The first branch extended 693 m [2274 ft]; the second lateral extended 696 m [2283 ft] *(right)*. Each outlet was tied back to surface independently using a DualAccess packer system *(left)*.

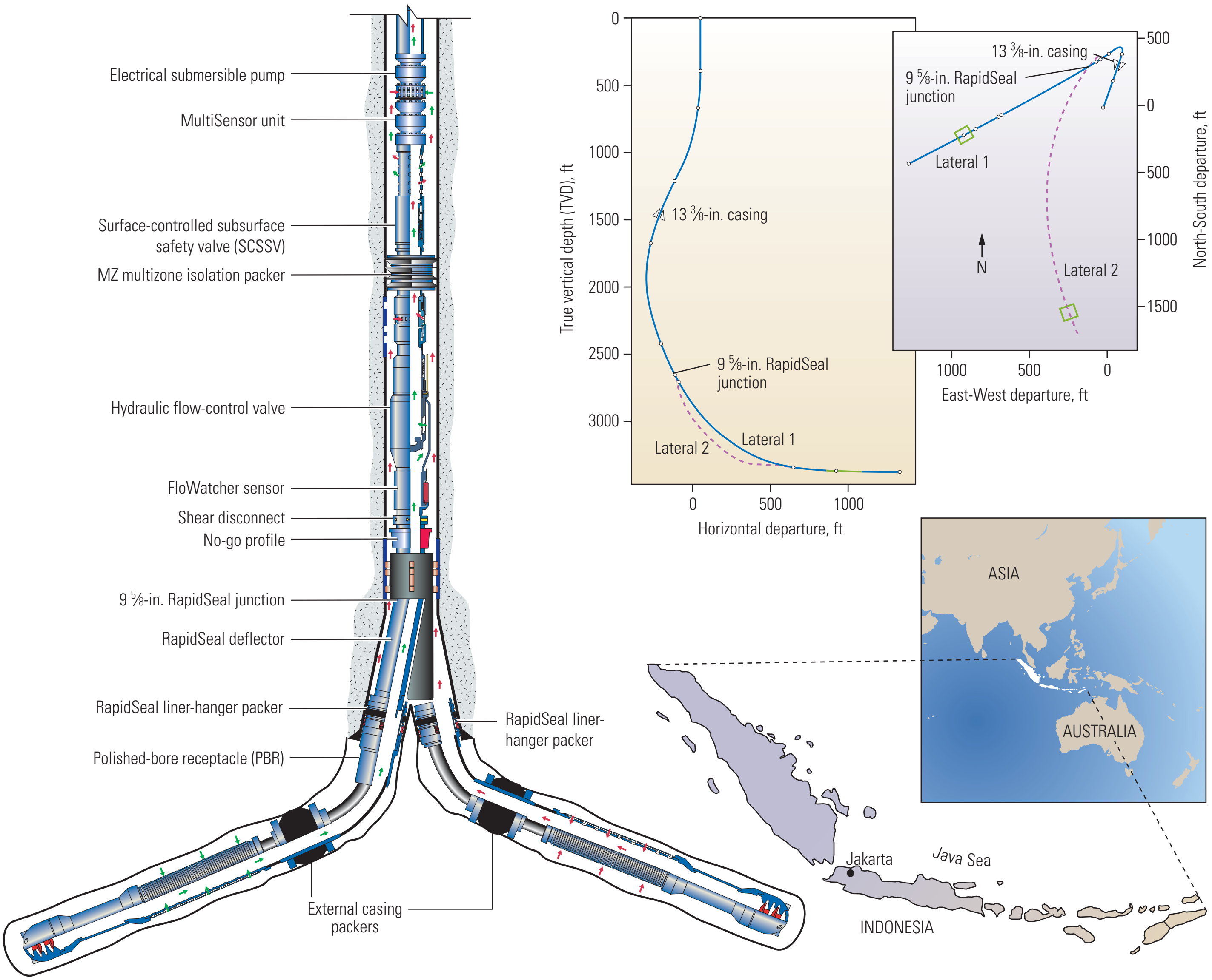
system in Brazil. Schlumberger has also installed RapidSeal systems in Nigeria for Agip, and in Indonesia for CNOOC.

Agip recently installed a Level 6 junction to complete the Idu ML 11 well in Idu field onshore Nigeria. The objective was to produce two separate intervals—Zones I and L—with two lateral branches from a single main wellbore. Agip drilled to the proposed junction depth at 2000 m [6562 ft] and under-reamed the hole to 17½-in. for RapidSeal system expansion.

The junction was oriented before expanding the outlets and cementing the primary casing. The operator drilled both lateral branches with 6⅛-in. PDC bits using synthetic oil-base mud (OBM) and cemented 4½-in. liners in place. The first lateral extended 693 m [2274 ft]; the second lateral extended 696 m [2283 ft]. Each outlet was tied back to surface independently using a DualAccess packer system (above). At initial rates of 2250 BOPD [358 m^3/d] from Zone L and 2000 BOPD [318 m^3/d] from Zone I, this well is producing better than originally forecast and more like two separate directional wells.

Advanced, or intelligent, completion components are evolving to meet operator needs, and multilateral completions are becoming increasingly sophisticated. Many wells now include downhole equipment to monitor production, selectively control flow from lateral branches and manage reservoirs more efficiently.

CNOOC recently drilled and completed the first TAML Level 6 multilateral well in Indonesia



^ The world's first intelligent Level 6 multilateral completion. CNOOC recently drilled and completed the NE Intan A-24 well, the first TAML Level 6 multilateral in the Java Sea, Indonesia *(lower right)*. After orienting, expanding and cementing the 9⅝-in. RapidSeal junction at 2770 ft [844 m] MD in place, the operator drilled two lateral branches *(upper right)*. The first branch extended 1655 ft [504 m] MD; the second lateral extended 2335 ft [712 m] MD. Each lateral was completed with an external casing packer and sand-control screens. An orienting device, or deflector, ensured correct insertion of completion equipment in junction outlets. Advanced completion equipment—hydraulic flow-control valves and sensors to measure pressure, temperature and flow rate for each well branch, a Schlumberger electrical submersible pump with a downhole Phoenix artificial-lift monitoring system and a variable-speed drive on surface—made this the first "intelligent" Level 6 multilateral well *(left)*.

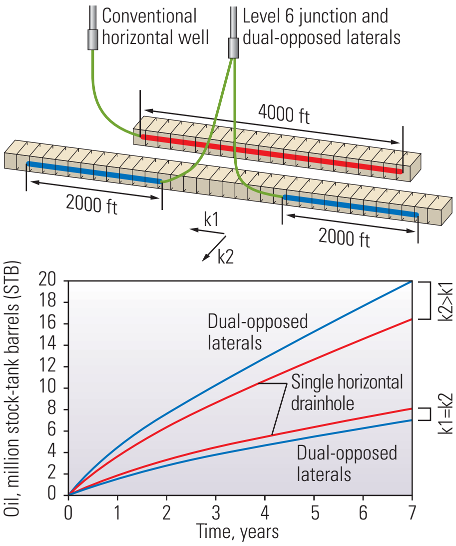
and the world's first Level 6 intelligent completion to increase recoverable reserves and reduce well-construction costs. A RapidSeal junction was installed to complete the NE Intan A-24 well in the Java Sea (above). This well in 23 m [75 ft] of water required less time to drill—just 25 days—and cost about $1 million less than the AC-06 well, a Level 3 multilateral completion in East Rama field drilled to about the same depth with similar lateral lengths.

After the 9⅝-in. RapidSeal junction was oriented, expanded and cemented in place at 2770 ft [844 m] MD, both lateral branches were drilled with M-I Drilling Fluids synthetic OBM. The first lateral extended 1655 ft [504 m] MD and was drilled with a 6⅛-in. PDC bit. The second lateral extending 2335 ft [712 m] MD was drilled with a 6-in. by 7-in. bicentered bit using a PowerPak PDM that had a 1.83° bent housing. CNOOC completed the first lateral with 3½-in. premium sand-control screens. The second lateral utilized 4½-in. premium sand-control screens. Each branch included an ECP for zonal isolation.

Advanced well-completion equipment installed above the junction included downhole hydraulic valves to control flow and sensors to measure pressure, temperature and flow rate for each well branch. A Schlumberger electrical submersible pump with a downhole MultiSensor well monitoring unit for submersible pump completions and a variable-speed drive at the surface lifts hydrocarbons to the surface through 4½-in. tubing. A surface control and data acquisition (SCADA) system and multiphase flow meters on surface monitor pump parameters and well performance, and transmit data to CNOOC in real time via the Web.

Key Design Considerations

The first factor to consider when planning a multilateral completion is whether it is a new or existing well. New wells offer engineers the freedom and flexibility to design multilateral wells from the bottom up. NODAL production system analysis and reservoir modeling help establish optimal lateral length and tubing size, which determines primary and intermediate



^ Reservoir simulation and multilateral-well modeling. Using ECLIPSE reservoir simulation software and a coarse, structured grid, this example compares a conventional horizontal well that has a single 4000-ft [1220-m] lateral section with a Level 6 multilateral well that has two dual-opposed 2000-ft [610-m] laterals *(top)*. Cumulative production from a dual-lateral well greatly exceeds the output of a single-bore horizontal well when horizontal permeability (k) varies *(bottom)*. To accurately predict production inflow, the area around a wellbore must be modeled in detail. Each discrete wellbore segment has individual local pressure and fluid properties. The ECLIPSE simulator also uses a fine and unstructured grid to model wellbore segments and reservoir flow around complex multilateral trajectories.

casing sizes. Completion options and well configurations are more limited for existing wells, but many older wells are candidates for reentry using multilateral technology.

Another consideration is junction type, which depends on the required degree of mechanical integrity and pressure integrity at each lateral, formation stresses, and the need for reentry access to individual branches. An openhole lateral without junction connectivity may be sufficient when lateral production is commingled, junctions are in competent formations or lateral access is not required. A Level 6 system may be more appropriate if selective production or injection in each lateral is desirable, if the junction is located in a weakly consolidated formation or if lateral access is required.

Reservoir knowledge is crucial when planning multilateral wells. In exploration or early development wells, there may not be enough information to plan a complex well trajectory. In this situation, operators can drill a low-cost vertical well with contingency plans for one or more laterals, depending on information obtained while drilling and completing the main wellbore. Horizontal and multilateral wells also are used at this stage to better delineate the reservoir from a single surface location. In latter stages of field development, a considerable amount of reservoir information is available, so more complex well trajectories can be designed to target specific formations, reservoir compartments or bypassed reserves.

In economic terms, multilateral wells do not represent two or more wells for the price of one. In a few cases, multilateral completions double well output, but based on industry averages, increases of 30 to 60% are more likely. Historically, for multilateral wells to be profitable, capital expenditures should increase by no more than 50%. This means that overall well-construction economics should improve by about 40%. Optimal multilateral completions are based on economic evaluation of several alternatives that rely on forecasts of reservoir performance.

In many situations, numerical simulation using a single-well or field-wide model is required to provide an accurate forecast on which to base project economic analysis. Numerical simulation requires more knowledge of the reservoir, takes longer to set up and requires more computational time than analytical models. However, numerical models can account for effects such as multiphase flow and gravity, complex reservoir geometry and heterogeneous reservoirs. The multisegment well module in ECLIPSE reservoir simulation software models fluid flow and frictional-pressure losses through wellbores, annuli, lateral branches and well-completion valves.[13] This advanced modeling capability provides more realistic estimates of multilateral-well performance (above left).

Evolving Technology, Increasing Acceptance

Following a trend similar to acceptance of horizontal wells in the early 1990s, operators in the late 1990s began to ask, "Why not drill a multilateral well?" Today, rather than asking if a multilateral well is applicable, the question often is, "What type of well configuration and multilateral system is best suited to meet field-development and production requirements?" Multilateral wells are not just an accepted technology, but an essential tool for developing hydrocarbon reserves worldwide.

Exploiting reservoirs with multilateral wells is a viable means of reducing total capital expenditures and field-operating expenses, and significantly improving production in today's most challenging petroleum arenas. As confidence in multilateral technology grows, smaller reservoirs like satellite fields currently under consideration for development in the North Sea, and frontier fields in the Gulf of Mexico, Southeast Asia, West Africa and the Middle East will be developed with multilateral wells.

Multilateral-completion systems vary in complexity. RapidConnect and RapidExclude junctions provide enhanced strength and sand exclusion for added durability and more reliable reentry access to lateral well branches in both new and existing wells. RapidSeal systems offer the flexibility to optimize flow from each lateral for production and conformance control, to produce separate reservoirs with different initial pressures or to inject in one lateral while producing from the other.

There is an increasing trend toward minimizing conventional rig interventions. Using standard coiled-tubing equipment, for example, the Discovery MLT multilateral tool system provides selective access to lateral junctions. A flow-activated bent-sub controls tool orientation, while pressure feedback provides real-time confirmation at surface that the correct well branch has been entered. The acid-resistant tool allows placement of well-treatment fluids. This system facilitates reentry, cleanout and stimulation operations in openhole laterals, drop-off liners or junctions constructed in existing wellbores.

Multilateral completions were one of the key oilfield technologies to emerge during the past decade. It is extremely important to screen and select well-completion systems for multilateral wells within the context of reservoir conditions, field-development requirements, total cost and overall risk.[14] These techniques serve production companies best when thorough risk-reward analysis is performed. An integrated, multidisciplinary team is required to plan, design and implement multilateral wells properly.

Today, service companies continue to invest in research and new product development to provide operators with more reliable tools and systems for installing multiple drainage points in reservoirs. In the near term, two challenges remain: further optimization of equipment and installation consistency. This technology is still evolving, but as long as improving net-present-value is a primary business objective, multilateral technology will continue to be a leading source of economic gains throughout the oil and gas industry. —MET

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