

# A Literature Review of Recent Advances and Future Trends in Modern Drilling and Completion Technologies

Hongyuan Fu\*

School of Petroleum Engineering, Xi'an Shiyou University, Xi'an, China

\*Corresponding Author: Hongyuan Fu

## ABSTRACT

In recent years, CNPC's operating companies have carried out intensive R&D programs to address key bottlenecks that limit drilling efficiency and well construction performance, including rate-of-penetration (ROP) improvement for horizontal wells, deep-well drilling, casing-exit sidetracking for mature wells, and wellbore strengthening and loss-circulation control. Through targeted technology breakthroughs and systematic integration of mature practices, a series of distinctive, field-proven technology packages has been developed. The main advances reviewed in this paper include: (i) one-run drilling enabled by an integrated "four-in-one" bottom-hole assembly (BHA); (ii) deep formation ROP improvement technologies for the Cambrian and Changcheng (Great Wall) formations; (iii) "aggressive drilling" practices for ROP optimization; (iv) 3D horizontal-well profile design and the "pre-separation" anti-collision methodology for large pad drilling; (v) casing-window milling and sidetracked horizontal-well drilling and completion; (vi) drilling and completion for super-long horizontal laterals in tight-gas reservoirs; (vii) nitrogen drilling; (viii) wellbore pressure management (managed pressure drilling, MPD) techniques; (ix) slim-hole super-long horizontal drilling; and (x) specialized drilling-fluid systems. After several rounds of technological evolution, an integrated R&D framework characterized by a coordinated "process–tools–fluids" approach has been established. Looking forward, further efforts should be devoted to automation and intelligent drilling/completion, cost-effective development of tight and shale reservoirs, deep and ultra-deep drilling technologies, continuous upgrading of specialized drilling-fluid and environmental compliance technologies, and the development of integrated geo-engineering decision-making workflows. These innovations will support safe, efficient, and high-quality growth of China's oil and gas industry.

## KEYWORDS

Drilling; Completion; Drilling and Completion Technologies; Technology Advances; Development Recommendations; CNPC.

## 1. INTRODUCTION

As hydrocarbon development is expanding from conventional targets to unconventional reservoirs such as tight gas and shale oil, well types are increasingly characterized by factory-style pad drilling, super-long horizontal laterals, and deeper objectives (e.g., Cambrian and Changcheng formations). Consequently, drilling and completion operations face a set of compounded challenges, including ROP limitation in hard formations, simultaneous risks of wellbore instability and losses in extended open-hole sections, pressure management within narrow mud-weight windows, anti-collision and obstacle avoidance in clustered wells, reuse of mature-wellbores, and stricter environmental compliance for fluids and cuttings handling.

To meet the requirements of high-quality capacity build-up and economic development, a number of distinctive technologies and field applications have emerged in recent years, covering ROP improvement, trajectory control and geosteering, wellbore pressure management, sidetracking and stimulation-oriented well reconstruction, and drilling-fluid systems and solid-waste management. A systematic review of these outcomes helps consolidate best practices, identify remaining gaps, and provide guidance for technology selection and well design optimization across different blocks and well types.

Accordingly, this paper synthesizes recent publications and engineering reports on key drilling and completion technologies, summarizes their mechanisms and field performance, and discusses future development trends and needs. The paper is organized as follows: Section 2 reviews key ROP-improvement technologies and 3D horizontal-well practices; it then covers casing-exit sidetracking, super-long laterals in tight gas, slim-hole super-long laterals, nitrogen drilling and pressure-management technologies, and specialized drilling-fluid solutions. Section 3 presents a technology outlook and recommendations.

## 2. MAJOR ADVANCES IN DRILLING AND COMPLETION TECHNOLOGIES

### 2.1. Key Technologies for ROP Improvement

#### 2.1.1. One-run drilling with an integrated “four-in-one” BHA

Directional-well construction typically includes a vertical section, build-up, hold, turn/azimuth adjustment, and drop sections. Under conventional practices, different sections often require different BHAs, resulting in frequent trips and low operational efficiency. By optimizing key equipment and tools—such as rapid rig-walk systems, customized PDC bits, high-power mud motors, MWD inclination sensors, and wear-resistant stabilizers—this approach integrates multiple functions into a flexible “four-in-one” BHA. Together with a strongly inhibitive, low-solids drilling-fluid system, it enables fast one-run (one-trip) drilling for clustered directional wells and has become a core technology in regional directional drilling.



**Figure 1.** Integrated “four-in-one” BHA

Key features of one-run drilling include: efficient vertical drilling with effective deviation control, proactive anti-collision capability in pad drilling, strong azimuth-holding performance in rotary–slide composite drilling, and adjustable build rate as needed[1-3]. The approach leverages the advantages of PDC bits while reducing tripping time. For tight-gas horizontal wells, the technology has achieved a target of 1,500 m one-run drilling in the horizontal section. Supporting nano/micro plugging and wellbore-strengthening water-based fluids provide favorable rheology and strong inhibition and plugging performance; high-temperature/high-pressure (HTHP) fluid loss is controlled below 6.0 mL, meeting the requirements of high-performance drilling fluids and offering reliable support for one-run drilling.

The technology has been widely deployed, with over 20,000 directional oil wells and more than 2,000 directional gas wells reported. Overall one-run success rates exceed 90% (approximately 85% for

directional oil wells). Minimum drilling cycles as short as 1.83 days have been achieved in some oil wells; for gas wells, a two-run success rate of 78% was reported, including 20 wells completed in one run with a minimum drilling cycle of 6.75 days. Wellhead spacing in large pads has been reduced to 4–5 m, and the mid-target semicircle has been narrowed to 15–20 m. Large well pads (e.g., up to 73 wells in a single platform) and extended-reach wells (e.g., displacements above 1,500 m) have been successfully executed.

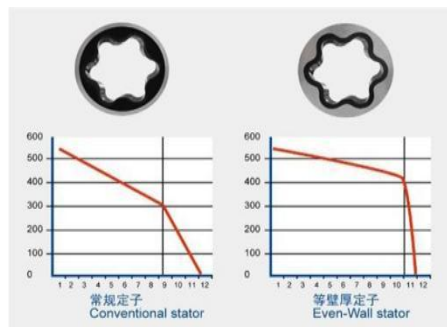
### 2.1.2. Deep-formation ROP improvement for the Cambrian and Changcheng formations

Based on lithology analysis and drillability evaluation of the Cambrian and Changcheng formations, bit design/selection and tool matching were optimized to establish three ROP-improvement modes: (i) impregnated diamond bit + turbine, (ii) impregnated PDC bit + high-speed mud motor, and (iii) uniform-wall-thickness high-speed mud motor + hybrid bit. These packages increase footage per bit and improve drilling efficiency in deep hard formations[4].



**Figure 2.** ROP-improvement tool packages

Field trials reported the following results: in Well Gutian-1 (Changcheng), the “turbine + impregnated diamond bit” package increased average footage per bit from 31 m to 137 m. The “impregnated PDC + high-speed motor” package achieved an average footage per bit of 50 m with an average ROP of 0.52 m/h. In Well Li-34 (Changcheng), the “uniform-wall motor + hybrid bit” package achieved an average footage per bit of 48 m and an ROP of 1.02 m/h, increasing footage by 8 m and ROP by 64.5% compared with the “impregnated PDC + turbine” configuration.



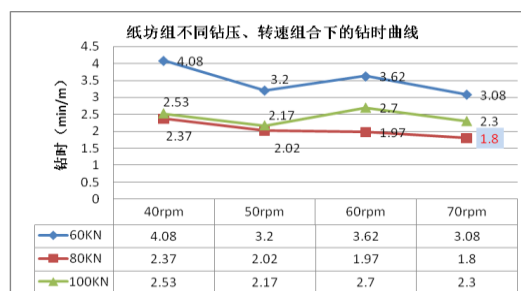
**Figure 3.** Comparison of conventional and uniform-wall-thickness stators

**Table 1.** BHA combinations and ROP-improvement performance

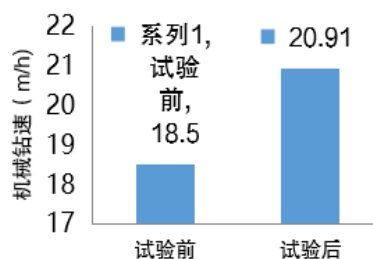
Bit type	Bit model	Power section	Interval (m)	Formation	Footage (m)	Time (h)	ROP (m/h)
PDC bit	8 1/2 KPM1642A RT	9/10-lobe high-temperature mud motor (PDM)	4734–4785	Cambrian	124	82	1.51
PDC bit	8 1/2 KPM1642A RT	9/10-lobe high-temperature mud motor (PDM)	4787–4860	Cambrian	124	82	1.51
PDC bit	8 1/2 KPM1642A RT	9/10-lobe high-temperature mud motor (PDM)	4883–4960	Changcheng (Great Wall) Fm.	77	66	1.17
PDC bit	8 1/2 KPM1642A RT	7/8-lobe high-temperature mud motor (PDM)	5017–5038	Changcheng (Great Wall) Fm.	21	30	0.70
Impregnated diamond bit	KMI13162 T (Jiangzuan)	Turbine (Jiangzuan)	4860–4883	Changcheng (Great Wall) Fm.	23	30	0.46
Impregnated diamond bit	K507 (Smith)	Turbine (Halliburton)	4960–5017	Changcheng (Great Wall) Fm.	57	100	0.57

2.1.3. “Aggressive drilling” for ROP optimization

To further increase drilling speed, high-quality PDC bits and multi-stage high-power mud motors were selected. Drilling parameters were optimized according to motor power characteristics, yielding a parameter template that applies weight-on-bit via incremental pump pressure/torque, optimizes flow rate to balance hole cleaning and wellbore stability, and sets rotary speed based on BHA safety limits. Reported results include a 27% increase in rock-breaking energy, an 18% increase in sliding efficiency, and a 13.0% increase in ROP.



**Figure 4.** Sensitivity testing of drilling parameters versus ROP



**Figure 5.** ROP comparison for aggressive drilling in shale-oil laterals

This approach emphasizes optimization in three dimensions: rig–pump matching, tool matching, and drilling-parameter design. For different rig and pump configurations, liner sizes were optimized to maximize hydraulic efficiency. Sensitivity tests of ROP versus parameters in different formations informed optimized parameter combinations. Tool matching was achieved through selection of high-power motors and high-performance PDC bits.

Field applications show that aggressive drilling increased ROP in tight-gas horizontals from 10.36 m/h to 13.22 m/h (+27.64%)[5], improved shale-oil lateral ROP from 18.5 m/h to 20.91 m/h, and increased ROP in the upper sections of Gaogiao directional wells from 14.5 m/h to 21.5 m/h (+32.7%). In areas with relatively stable formations (e.g., above the Liujiagou Formation), large-displacement drilling with “PDC + motor” and high annular return velocity ( $\geq 1.8$  m/s) has also significantly improved ROP[6].

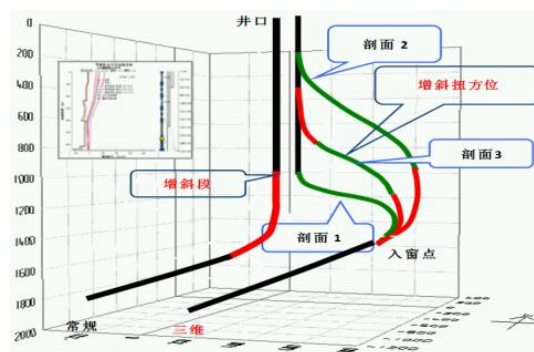
By adopting a “two-highs-and-one-large” parameter philosophy (higher WOB, higher rotary speed, and larger flow rate), drilling intensity was strengthened by 40–50%, hydraulic power increased by 34%, and mechanical rock-breaking power increased by 2.2 $\times$ , leading to another step change in drilling speed. During 2019–2020, the technology was applied to 516 wells, delivering an average ROP increase of 17% and driving key tools such as motors and bits toward higher power and longer service life.

## 2.2. 3D Horizontal-Well Technologies

### 2.2.1. 3D horizontal-well profile design

3D horizontal wells are a dominant well type for factory-style horizontal drilling in certain blocks[7]. Typical challenges include gravel layers at key stratigraphic interfaces, severe bit wear in hard formations such as the Liujiagou Formation, and wellbore instability/caving risks in formations such as the Shiqianfeng and Shihezi formations, which increase operational difficulty.

For parallel lateral planning within a well pad, large-offset 3D horizontal wells are often required. By trial optimization of “high–medium–low” kick-off points, a seven-section 3D profile was selected—“low inclination for displacement build, steady inclination for azimuth turning[8], and inclination build for landing into the window”—together with multiple landing modes adapted to different reservoir dips.

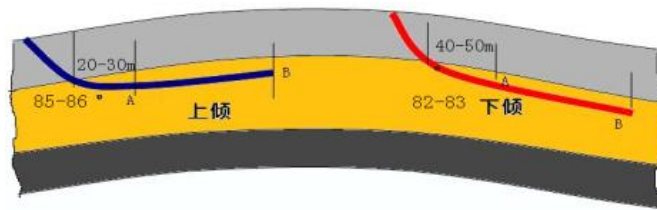


**Figure 6.** Schematic evolution of 3D horizontal-well trajectories

This method provides efficient, templated trajectory correction control and improves sliding efficiency during azimuth turns with small inclination changes. More than 600 3D horizontal wells with offsets exceeding 600 m have been drilled using this approach, with a maximum reported offset of 1,266 m.

**Table 2.** Template-based correction control

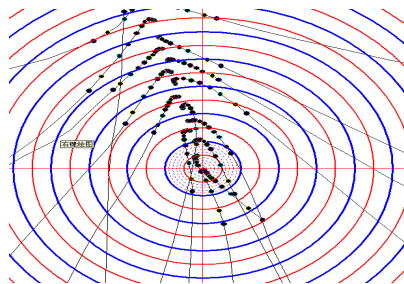
Distance to target	Correction mode	Angle between target body and correction azimuth
Short	Correction by extending the effective distance-to-target	Greater than 90°
Long	Correction by consuming the effective distance-to-target	Less than 90°
Medium	Deviation reduction with the effective distance-to-target unchanged	Equal to 90°



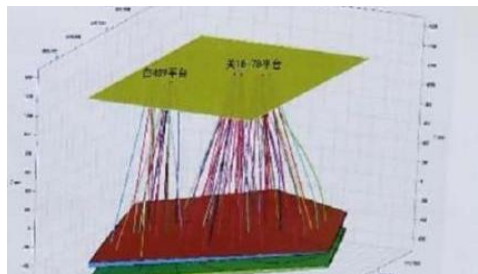
**Figure 7.** Landing-window control for different reservoir strike directions

### 2.2.2. The “pre-separation” anti-collision method

The “pre-separation” anti-collision and obstacle-avoidance method controls wellbore azimuth toward directions favorable for collision avoidance while keeping inclination within limits, producing a fishbone-shaped set of trajectories in clustered wells. The method shifts the strategy from passive obstacle avoidance to proactive separation, addressing the challenges of large well pads with many wellheads, small spacing, and high collision risk, and thereby improving construction efficiency.



**Figure 8.** Fishbone-shaped anti-collision example using the pre-separation method



**Figure 9.** Example of clustered well trajectories on a platform

Key elements include: preliminary well-network grouping by quadrant, sorting wellheads by stratigraphic target from shallow to deep, “pre-separated” sliding to realize fishbone distribution, and staggered kick-off points for separation.

The method has been applied in more than 100 large well pads with 20+ wells each. Reported cases include a platform with 73 oil wells and a minimum wellhead spacing of 4 m, as well as a gas-well

pad with 23 wells. In a representative factory drilling project comprising vertical, directional, conventional horizontal, and 3D horizontal wells, the integration of the pre-separation method, 3D profile optimization, trajectory control, and a tailored drilling-fluid system increased average ROP to 9.68 m/h (+18.19%) and shortened average drilling cycle to 55.67 days (-8.82%)[9].

### 2.3. Casing-Exit Sidetracked Horizontal-Well Drilling and Completion

With the increasing number of low-rate, low-efficiency wells and frequently shut-in wells, casing-window milling and sidetracking with integrated reconstruction has been tested and promoted. Key enabling technologies include ECD control (equivalent circulating density) and small-diameter BHA trajectory control, which support the recovery of remaining oil and gas and the revitalization of mature assets.

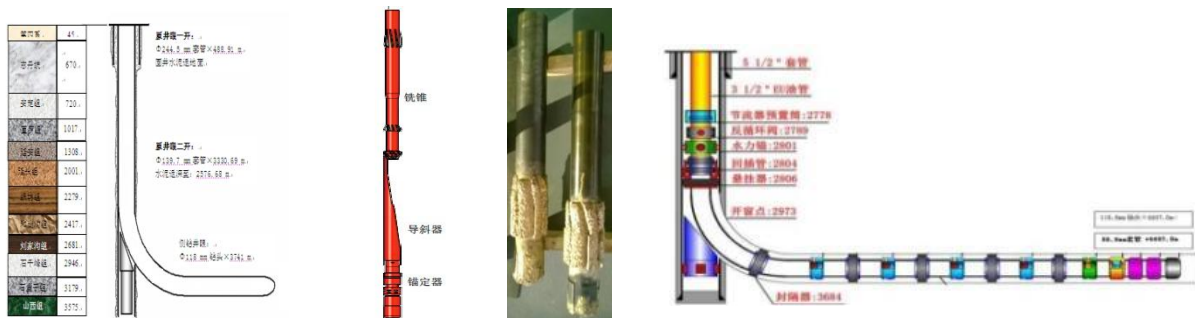


Figure 10. Schematic of six key technologies

(1) The practice combines optimized legacy wellbore preparation, efficient window milling and sidetracking, and optimized selection of downhole tools and instruments. A strongly inhibitive, low-density CQSP-4 drilling-fluid system, together with ECD control and small-diameter BHA trajectory control, is used. Casing-exit sidetracked horizontal wells in 5-1/2 in casing have been executed (54 wells), with an average lateral length of 733 m and an average drilling cycle of 32.19 days; a minimum cycle of 15.67 days was reported. In 7 in casing, five sidetracked horizontal wells were completed; a record maximum inclination of 81.02° for whipstock-based window milling and an upward casing exit were also reported.

Table 3. Statistics of 5-1/2 in casing-exit sidetracked horizontal wells

Year	Wells	TD (m)	Total footage (m)	Lateral (m)	Drilling cycle (d)	Well construction cycle (d)	Monthly footage (m/rig·mo)	ROP (m/h)
2021	11	4423	1709	850	34.33	62.18	1332	4.18
2020	26	4309	1672	768	26.60	44.00	1316	4.80
2019	10	4238	1430		33.69	70.42	891	4.33
2017	3	4156	1664	620	68.77	91.90	641	2.23
2012	1	4236	1319	600	29.13	65.67	1022	3.44

(2) In low-pressure, low-permeability tight-gas settings, some conventional wells lose economic viability. Applying  $\phi$  139.7 mm casing-exit sidetracked horizontal-well technology can restore production potential. Key challenges include lubrication and anti-sticking, shale sloughing in the lateral, and losses in narrow annuli. A strongly inhibitive and strongly plugging CQSP-4 drilling-fluid system was developed and evaluated. Laboratory results showed a 95.63% cuttings hot-rolling recovery at 100°C for 12 h; after 24 h hot rolling at 100°C, API fluid loss was 2.8 mL and HTHP fluid loss was 13.2 mL. The fluid also demonstrated strong resistance to cuttings contamination.

Drilling-fluid and operational practices for window milling, open-hole drilling, solids control, loss prevention, drag reduction, and hole cleaning were optimized. As of December 2022, 18 wells had been applied in the field, reducing drilling cycles by 69.58% compared with 2017–2018 and

increasing ROP by 102.82%. The average drilling cycle decreased from 80.5 days to 24.49 days, demonstrating clear ROP and efficiency gains and offering reference for similar wells in other regions[10-12].

## 2.4. Drilling and Completion for Super-long Horizontal Laterals in Tight-Gas Reservoirs

Tight-gas fields in the Ordos Basin are typically characterized by greater burial depth, poorer reservoir quality, and heterogeneous distribution. Such reservoirs often exhibit low pressure, low permeability, low productivity, and low abundance, which have long constrained efficient development[13][14]. Super-long horizontal laterals can increase the drainage area and support effective development of tight-gas reservoirs.

Key technical challenges include long open-hole sections with poor stability, difficulty in trajectory control, complex loss-control in the lateral, and challenges in running completion strings. Through optimization of trajectory control, selection of rotary steerable systems, development of high-performance water-based fluids, and optimization of buoyancy-assisted casing-running techniques, an integrated technology package for super-long tight-gas laterals has been established[15].

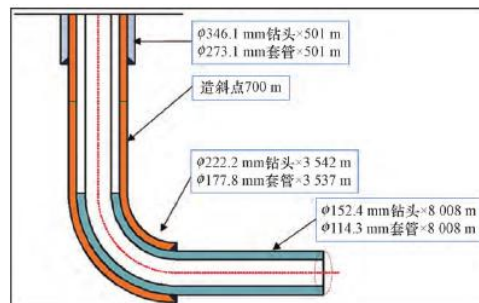


Figure 11. As-drilled wellbore structure of Well Jing 51-29H1

With continuous process optimization, multiple milestones have been achieved in super-long lateral drilling and completion, including laterals of 3,321 m, 4,088 m, and 4,118 m in different wells. Ongoing field trials targeting 5,000 m laterals indicate further breakthroughs are possible, providing new solutions for tight-gas development both domestically and internationally.

## 2.5. Nitrogen Drilling

Gas drilling is considered an effective approach to eliminate water-blocking damage in certain formations[17]. To better evaluate reservoirs in natural-gas exploration wells, nitrogen drilling trials have been conducted, resulting in four key technology elements: formation evaluation during nitrogen drilling, safe drilling practices for reservoirs, equipment and surface-system integration, and optimization of BHA and drilling parameters.

Nitrogen drilling features minimal formation damage, enables while-drilling evaluation, and can reveal true deliverability and petrophysical properties[18][19]. Reported ROP improvements are

significant—typically 3–5 times that of conventional mud drilling—and the method can also mitigate severe losses and improve loss-control performance.

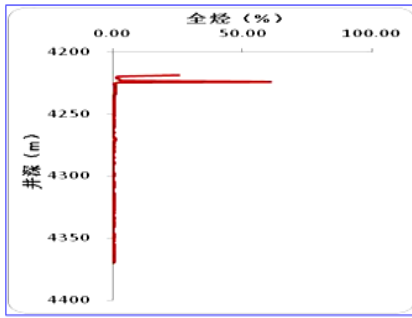


Figure 12. Well Li 17 (conventional mud drilling)

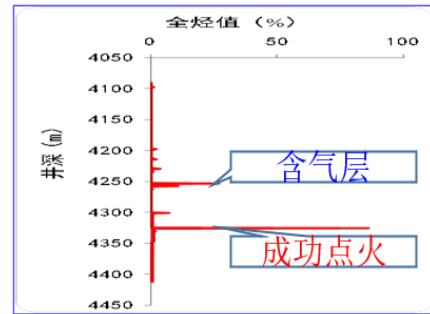


Figure 13. Well Li 16 (nitrogen drilling)

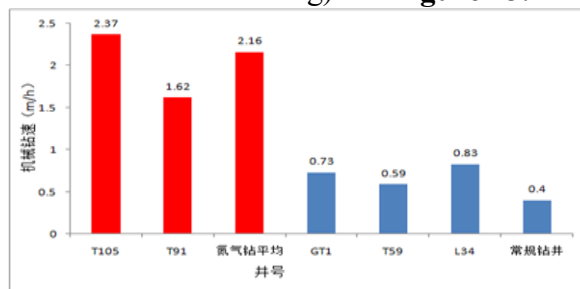


Figure 14. ROP improvement in deep formations during nitrogen drilling

Six field trials accurately evaluated multiple reservoirs and identified 15 gas-bearing intervals, achieving successful ignition. In deep Cambrian and Changcheng formations, ROP increased by more than 4× compared with conventional drilling and by more than 1× compared with impregnated-bit + turbine configurations, providing technical support for risk exploration and improved understanding of original reservoir properties.

## 2.6. Wellbore Pressure Management (MPD)

In certain injection-then-production areas where formation pressure is uncertain and required kill-mud density is high, managed pressure drilling (MPD) has been implemented. A rotating control device (RCD) is installed before the second hole section, and a rotating head is installed before reaching the water-bearing layer. A diversion and backpressure control scheme is used to drill to total depth under controlled pressure, followed by centralized weighting-up. This workflow mitigates issues such as high water influx, high kill-mud density, repeated well-control cycles, reduced ROP after killing, and high sticking risk, thereby shortening the drilling cycle.

Key features include using an XK28-7/14 RCD, automatic backpressure control during MPD circulation, backpressure compensation during connections, continuous pumping while pulling out of hole, and pressure-assisted tripping. The system also supports early warning for abnormal conditions.

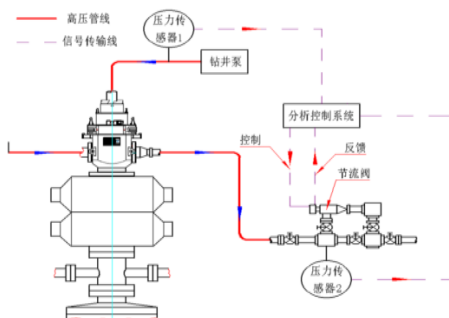


Figure 15. MPD circulation workflow

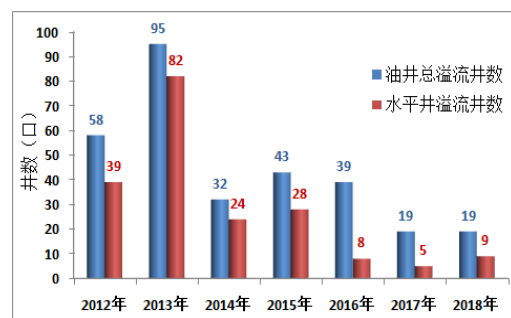


Figure 16. Yearly statistics of kick incidents

The pressure-management technology has been applied to more than 200 wells. By controlling backpressure at 1.5–2 MPa and maintaining drilling-fluid density based on the water-layer pressure, average drilling cycles were shortened by about 1 day[20][21]. The technology family includes MPD in waterflood areas and nitrogen underbalanced drilling, which helps mitigate well-control risk associated with pressure anomalies in mature fields. Diversion MPD has been applied in 177 wells, reducing kick incidents by ~30% and shortening drilling cycles by ~13%.

## 2.7. Slim-hole Super-long Horizontal Drilling

For slim-hole super-long horizontals, typical challenges include difficult trajectory control, reduced reservoir contact ratio, low ROP, wellbore collapse risk, and frequent losses. Technologies developed to address these issues include rotary-steerable intelligent trajectory control, near-bit azimuthal gamma imaging, engineering-parameter monitoring, bit selection optimization, and nano-film-forming plugging water-based drilling fluids. Together, they enable precise trajectory control, higher reservoir contact ratio, improved downhole safety, and higher ROP[22].

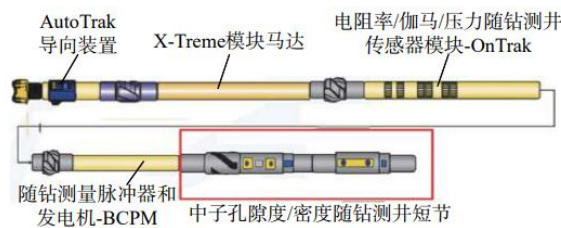


Figure 17. Schematic of a rotary steerable system

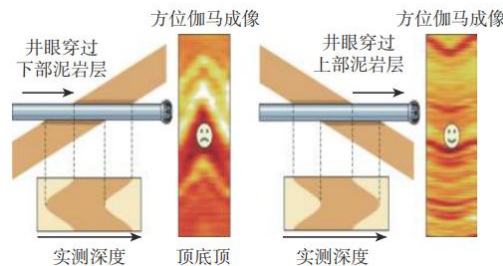


Figure 18. Schematic of near-bit azimuthal gamma imaging

A representative application reported safe and efficient drilling of a well with a 4,466 m horizontal section and a total measured depth of 8,008 m, achieving a reservoir contact ratio of 96.6% and setting records for the deepest well and the longest onshore horizontal section in the Asia–Pacific region. Field results indicate strong application value and scalability.

Rotary-steerable intelligent control enables accurate trajectory control in super-long laterals and maximizes lateral extension. Near-bit azimuthal gamma imaging and engineering-parameter monitoring further improve reservoir contact and drilling safety. Nano-film-forming plugging water-based fluids and optimized PDC bits are critical enabling technologies and provide reference for similar wells in other oilfields.

Compared with international practices in geosteering for super-long horizontals, further optimization is still needed, particularly in integrated geo-engineering workflows.

## 3. TECHNOLOGY OUTLOOK

Globally, drilling and completion technologies and equipment are continuing to evolve toward automation and intelligence. Capabilities such as advanced detection, precision guidance, closed-loop control, and data-driven decision-making can substantially improve drilling success and reservoir contact while enhancing safety and cost efficiency. To meet the needs of large-scale, cost-effective

development of unconventional resources and deep complex exploration targets, oilfield operators are building innovation ecosystems that integrate multidisciplinary R&D teams, ROP-improvement tools (e.g., efficient rock-breaking, downhole measurement and control, drag-reduction, and near-bit steering), and testing and qualification platforms, thereby promoting the coordinated “process–tools–fluids” approach. Future R&D should focus on key bottlenecks such as cost-effective tight/shale development, high-risk deep frontier exploration, sidetracking-based rejuvenation of mature wells, effective development of low-permeability large well pads, and underground gas storage projects.

From a technology roadmap perspective, oilfield operators should strengthen fundamental research and multidisciplinary integration (engineering, geology, chemistry, mechanics, information science, materials, and automation) and leverage big data and digital platforms. Priority directions include: (i) automated and intelligent drilling/completion systems and equipment (near-bit intelligent steering, intelligent rigs, real-time multi-parameter downhole acquisition and optimization, digital monitoring software, smart drill pipe/bits, and intelligent decision systems); (ii) integrated technology packages for tight and shale reservoirs (drilling–logging–mud logging–testing integration, deep long laterals and super-long laterals, 3D drilling for ultra-large pads and large offsets, efficient casing/open-hole sidetracking, slim-hole and second-section horizontal wells); (iii) safe and efficient drilling in deep/ultra-deep and high-temperature/high-pressure conditions (while-drilling reaming and expandable tubulars, ROP tools, high-strength lightweight corrosion-resistant drillstrings, high-temperature drilling fluids, high-performance loss-control materials and integrated plugging, and ultra-high-pressure well-control equipment); (iv) continuous upgrading of specialized drilling fluids and environmental compliance technologies (loss mechanisms, intelligent gels and biomimetic plugging, multi-pressure open-hole pressure-bearing plugging, low-density anti-sloughing systems, environmental testing standards, cuttings recycling/resource utilization, and environmentally friendly surface-hole loss-control methods such as dry drilling and casing drilling); and (v) integrated geo-engineering decision-making (geological modeling, model updating and dynamic trajectory adjustment, joint technical taskforces, remote expert support, rotary steerable and LWD measurements, downhole information acquisition and transmission, and a surface data collection–analysis–feedback closed loop). Overall, sustained R&D investment and technology integration are needed to balance ROP improvement with controllable risk and to support high-quality development.

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