

## Article

# Research on Key Technologies of 260 °C/210 MPa Ultra-Deep Logging Equipment

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**Abstract:** Deep and ultra-deep oil, which are unconventional oil reservoirs have become an important field for increasing reserves and production in China's oil and gas exploration and development, and pose higher requirements for ultra-deep logging technology and equipment. For addressing the technical challenges faced in the development of 260 °C/210 MPa ultra-high temperature and high-pressure logging equipment, based on the CPLog fast and imaging series instruments, this article originally proposes key core technologies and solutions such as 260 °C/210 MPa electromechanical sensors, 13,000 m cable communication, and large borehole correction processing. Through the design indoor testing of a BS-PT-based ultra-high temperature acoustic transducer, 260 °C/210 MPa instrument pressure-bearing housing components, and field testing of large borehole environment testing and 13,000-m cable 8000-m deep well data transmission, it will help develop a prototype of 260 °C/210 MPa ultra-high temperature and high pressure logging equipment. The key technology research of 260 °C/210 MPa logging equipment has laid the foundation for the development of ultra-deep logging equipment and provided technical support for the exploration and development of ultra-deep oil and gas at a depth of 10,000 m.

**Keywords:** calibration of large wellbore environment; CPLog; deep and ultra-deep; 13,000 m cable communication; 260 °C/210 MPa ultra-high temperature and high pressure



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## 1. Introduction

As the difficulty of discovering shallow and medium-depth oil and gas resources in China increases, the exploration and development of deep and ultra-deep oil and gas resources have become crucial for China's future growth in oil and gas reserves and production [1,2]. In recent years, significant discoveries in deep and ultra-deep layers have been made in basins such as the Tarim, Sichuan, Junggar, and Songliao. For example, in the Tarim Basin, resources buried at depths of 6000 to 10,000 m account for 83.2% of its total oil and 63.9% of its total natural gas, with ultra-deep oil and gas resources comprising about 19% of the global total [3–5]. Since the “12th Five-Year Plan”, the number of deep and ultra-deep wells in China's oil industry have gradually increased. The number of deep wells at a depth of 4500 m have increased by more than 20% annually, the number of ultra-deep wells at a depth of 6000 m have increased by more than 15% annually, and the number of ultra-deep wells at a depth of 8000 m have doubled annually. The number of key exploration wells such as Round Exploration 1 and Round Exploration 3 have exceeded 8500 m. In 2023, China National Petroleum Corporation (CNPC) deployed two 10,000 m deep wells, “Shen Di Chuan Ke 1” and “Shen Di Ta Ke 1”, in the Tarim Oilfield and Southwest Oilfield, respectively. These wells are designed to exceed 10,000 m in depth, with the expected bottom-hole temperatures and pressures reaching up to 225 °C and 175 MPa. This marks the official entry of China's oil and gas exploration into ultra-deep layers. The high-temperature and high-pressure environment, along with the complex wellbore

structures in these ultra-deep layers, pose significant challenges and higher requirements for the stability of logging equipment performance and the reliability of process safety.

This paper introduces the key technologies of ultra-deep measurement logging equipment, including high-strength mechanical structure, pressure-sealing capabilities, low-power high-integration circuit systems, 13,000 m long cable communication, and ultra-high temperature and pressure transducers. It also presents the solutions for developing 260 °C/210 MPa ultra-deep logging equipment.

## 2. Current Status of the Key Technologies for Ultra-Deep Well Logging Equipment

Leveraging advanced chip and detector manufacturing technologies, Schlumberger, Halliburton, and other logging companies' well logging technologies and equipment lead the field in high-temperature and high-pressure applications [6]. Schlumberger's high-temperature and high-pressure slim-hole Qstring series has an outer diameter of 76 mm, with temperature and pressure ratings reaching up to 260 °C and 206.9 MPa. This series is complemented by the Tuffline30000 high-strength high-temperature cable system, which has a maximum tensile strength of 30,000 pounds (lbs) and can withstand temperatures up to 232 °C for 24 h. Additionally, it features an ultra-strong cable drum capable of holding 131,000 m of cable, all of which are custom-made for overseas ultra-deepwater projects. Halliburton's Hostile slim-hole logging series includes tools with outer diameters of 70 mm and 79.4 mm, with maximum temperature and pressure ratings of 260 °C and 137.9–206.8 MPa, respectively.

China's ultra-high-temperature and high-pressure well logging services largely rely on imported instruments, which, due to cost considerations, are only used in a few exploratory wells and key development wells, failing to meet the production needs of numerous domestic development wells. In response to this situation, several Chinese companies have started developing high-temperature and high-pressure slim-hole instruments. CNPC has independently developed the "230 °C High-Temperature High-Pressure Slimhole Logging Series" based on conventional instruments. This series overcomes technological bottlenecks such as high-temperature high-integration design based on MCM circuits, high-temperature pressure-bearing structure design and processes, and slim-hole instrument environmental calibration. The resulting high-temperature high-pressure slim-hole (Φ76 mm) logging equipment can withstand temperatures and pressures up to 230 °C and 170 MPa, suitable for minimum borehole diameters of 100 mm. In August 2024, this series successfully completed the fourth phase of the Shendi Ta Ke 1 well project, fully validating the stability and reliability of 13,000 m long cable remote transmission communication, ground collection and downhole instruments, and ultra-deep well logging power skids, setting an Asian record with a logging depth of 9889.63 m. CNOOC's ESCOOL ultra-high-temperature logging system (ESCOOL system) has capabilities for cable logging at 235 °C/175 MPa and imaging and coring sampling at 205 °C/140 MPa. To date, it has completed logging operations in over 260 wells, with a maximum pressure of 163 MPa, highest temperature of 206 °C, and deepest well depth of 8835 m, covering full-size operations from surface large boreholes to ultra-deep slim holes. The high-temperature high-pressure series instruments produced by Jereh have a maximum outer diameter of 80 mm and have completed over 180 ultra-deep well operations exceeding 8000 m, with the highest records being a maximum vertical well depth of 9300 m, highest well temperature of 191 °C, and maximum pressure of 179 MPa.

To better ensure the quality of ultra-deep well logging tasks, CNPC Logging is leveraging its existing CLog rapid and imaging series instruments to continuously tackle the core key technologies. These include 260 °C/210 MPa logging sensors and mechanical structures, fully enclosed compact 260 °C circuit systems, 13,000 m cable ultra-deep well communication and storage, ultra-deep well logging borehole correction processing, and fine interpretation and evaluation. The aim is to quickly develop 260 °C/210 MPa ultra-deep well logging technology equipment to achieve comprehensive and accurate data collection in ultra-high-temperature and high-pressure wells.

### 3. Research on Key Technologies of Ultra-High-Temperature and High-Pressure Logging

#### 3.1. 260 °C/210 MPa Ultra-High Temperature and Pressure Logging Sensors

##### 3.1.1. Acoustic Transducer

Given the urgent need for high-temperature piezoelectric acoustic logging transducers for ultra-deep oil and gas exploration in China, it is necessary to develop BS-PT-based piezoelectric ceramic materials and transducers capable of withstanding operating temperatures up to 260 °C. This development aims to provide the core components for high-end acoustic deep well detection instruments that are independently controllable. BS-PT-based piezoelectric ceramics possess piezoelectric properties comparable to PZT-based piezoelectric ceramics, with a Curie temperature nearly 100 °C higher than that of PZT. Therefore, the safe operating temperature limit of BS-PT-based piezoelectric ceramics is above 300 °C, meeting the high-temperature environmental requirements for the current and future ultra-deep well exploration [7].

##### (1) BS-PT-Based High-Temperature Piezoelectric Ceramic Formulation

Research on the effects of doping with transition elements or rare earth elements on the dielectric, ferroelectric, and piezoelectric properties, and their stability at high temperatures, is necessary. This research aims to clarify the relationship between the compositional modification, phase transition behavior, and temperature stability of high-temperature BS-PT piezoelectric ceramics [8,9].

As shown in Figure 1a, at 260 °C, the piezoelectric constant  $d_{31}$  of BS-PT is approximately 320 pC/N, which is greater than the piezoelectric constant  $d_{31}$  of PZT-5 (approximately 205 pC/N) at the same temperature, indicating that BS-PT material exhibits higher temperature stability. The value of  $d_{31}$  varies with temperature, and piezoelectric ceramic materials undergo depolarization at temperatures above their Curie temperature, resulting in a decrease in the piezoelectric constant  $d_{31}$  and a significant reduction in their material performance. The depolarization temperature  $T_d$  of BS-PT ceramics is approximately 400 °C, which is much higher than that of PZT-4, PZT-5A, and PZT-8 ceramics, with  $T_d$  values of 180 °C, 360 °C, and 275 °C, respectively (test standards refer to “Static Test Method for the Measurement of Piezoelectric Charge Constant  $d_{33}$  of Piezo-Ceramic Materials” [10]). Compared to the temperature resistance of traditional PZT, BS-PT material can maintain both high temperature resistance and high piezoelectric performance in environments of 260 °C.

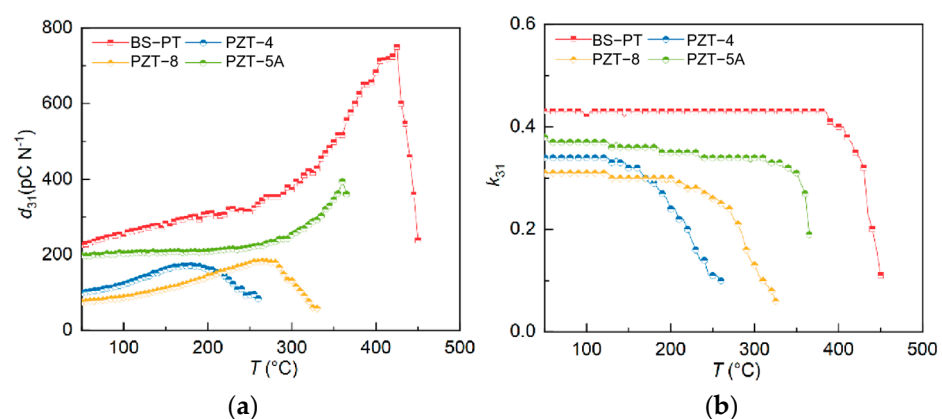


**Figure 1.** (a). The trend of the piezoelectric strain constant ( $d_{31}$ ) of BS-PT and PZT-based piezoelectric ceramics with temperature. (b). The trend of the electromechanical coupling coefficient ( $k_{31}$ ) of BS-PT and PZT-based piezoelectric ceramics with temperature.

Figure 1b illustrates the temperature dependence of the electromechanical coupling coefficient  $k_{31}$ . The results show that the  $k_{31}$  of BS-PT ceramics remains stable over a wide temperature range of 30 to 400 °C, whereas the  $k_{31}$  of all PZT ceramics gradually decreases

with increasing temperature. This indicates the better stability of BS-PT ceramics under high-temperature conditions.

## (2) Production Process of BS-PT-Based Piezoelectric Ceramics

To meet the demand for ultrasonic transducers in deep well detection, especially large-sized high-temperature piezoelectric ceramics, it is crucial to develop the engineering and production processes for BS-PT-based piezoelectric ceramics. This includes addressing the challenges related to the forming and sintering processes of large-sized BS-PT-based piezoelectric ceramics and ensuring performance consistency.

The production process of piezoelectric ceramics generally involves the following steps: raw material handling, raw material processing, the synthesis of electronic ceramic materials, forming, sintering, and surface processing.

In regard to the bonding process, the impact of different high-temperature adhesive amounts and bonding methods on the bonding strength was studied. Tests were conducted to measure the bonding strength of ceramic pieces and metal plates in a high-temperature environment of 260 °C. Based on the test results, the high-temperature adhesive and its encapsulation process were selected.

## (3) 260 °C Ultra-High Temperature Acoustic Transducer Prototype and Performance Testing

### (a) 260 °C Ultra-High- Temperature Acoustic Transducer Prototype

As shown in Figure 2, the prototype of the 260 °C ultra-high-temperature dipole acoustic transducer is presented.

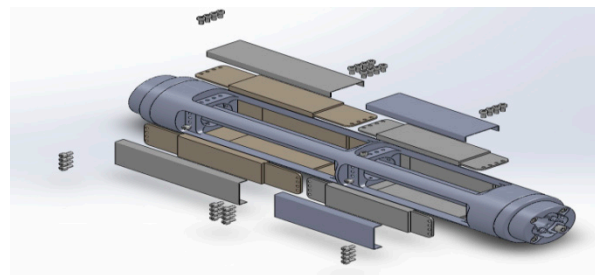


**Figure 2.** Dipole emission transducer.

### (b) Performance Testing of the 260 °C Ultra-High-Temperature Acoustic Transducer

Figure 3 shows the acoustic performance test of the ultra-high-temperature acoustic transducer acoustic measurement station. The test results show that the sensitivity of the multipole receiving transducer based on PT type piezoelectric ceramics can reach over  $-20$  dB. In the operating frequency range, the receiving sensitivity is higher than that of conventional PNB-type material transducers (the testing standard refers to the “Testing Method for Performance Parameters of Piezoelectric Ceramic Materials” [11]).

The ultra-high-temperature acoustic transducer has passed the 235 °C @ 4 h high temperature test, with effectively improved insulation resistance and performance indicators meeting the design requirements. It not only verifies the potential of BS-PT-based high-temperature piezoelectric ceramic materials for ultra-high-temperature logging applications, but also provides an effective means for the 260 °C ultra-high-temperature acoustic logging technology, which helps to further promote the application and development of 260 °C ultra-high-temperature acoustic logging technology.

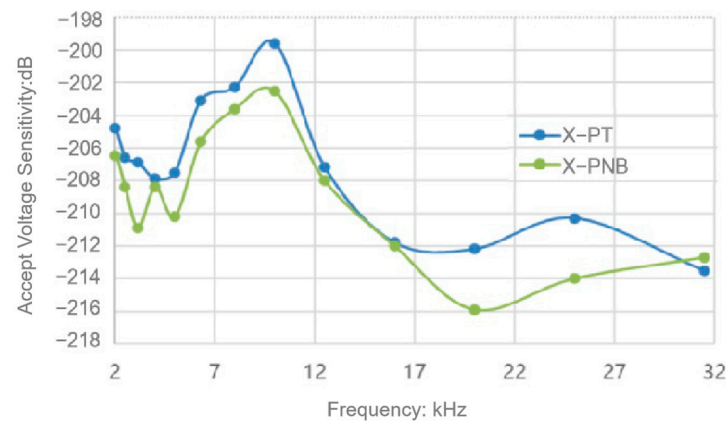


**Figure 3.** Acoustic performance testing of acoustic metrology station.

### 3.1.2. Lateral Electrode System

The electrode system is the sensor of the array lateral logging tool, as shown in Figure 4. As a core component, its high-temperature and high-pressure performance directly determines the instrument's application range and logging effectiveness. According to the instrument's structure and the 260 °C/210 MPa temperature and pressure requirements, the electrode system is composed of a mandrel, metal electrode rings, PEEK insulating sleeves, pressure-sealing joints, and pressure balance components. The metallic parts are made of TC18 material, with an outer diameter of 92 mm and an inner diameter of 60 mm.

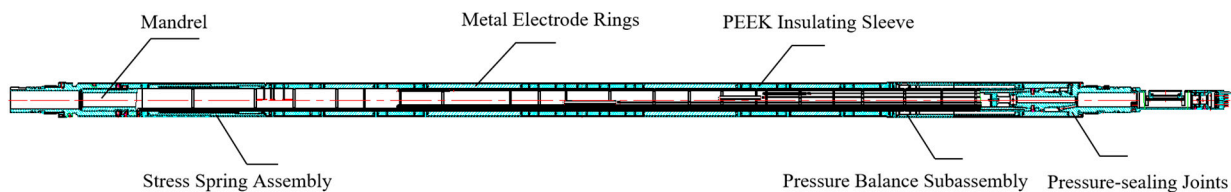


**Figure 4.** Array lateral electrode system.

The pressure bearing and sealing of electrode systems in high-temperature environments are critical factors affecting their performance and are currently the focus of technical research.

- (1) Pressure Bearing Issues and Solutions: based on the overall layout and structural characteristics of the electrode system, the following structures have been designed to address pressure bearing issues:
  - ① A Stress Spring Assembly is designed between the upper and lower parts of the A1U electrode to add a pre-tightening force to the integrated structure of the electrode ring and insulating sleeve, making the connection surface tighter and reducing the risk of looseness and failure.
  - ② A piston balancing structure is designed in the connection structure between the electrode, insulating sleeve, and metal mandrel to enhance the ability of the electrode and insulating sleeve structures to adapt to external environments.

As shown in Figure 5, a pressure balance subassembly is designed between the A1L Lower Electrode Ring and the A1L Upper Electrode Ring. The balance piston separates the inner and outer chambers, with the outer chamber connected to the formation through a Mud Channel, and the inner chamber filled with high-temperature-resistant silicone oil. The balance piston can move left and right under the action of the silicone oil in the inner chamber and the formation fluid in the outer chamber, achieving pressure balance between the inside and outside of the instrument. A Balance Spring is designed in the outer chamber to cushion and limit the movement of the piston. When the pressure inside the instrument

is greater than the external pressure, the balance piston will slowly compress the Balance Spring and move outward. When the sealing position of the piston exceeds the Drain Port, the Drain Port connects with the silicone oil in the inner chamber, allowing oil to escape and release pressure, thereby protecting the instrument. A Pre-Tensioning Spring applies a small initial pre-pressure to the silicone oil in the inner chamber, making the silicone oil distribution in the inner chamber more uniform and filling it more fully, thereby improving the overall balancing effect of the instrument and the sensitivity of pressure transmission.

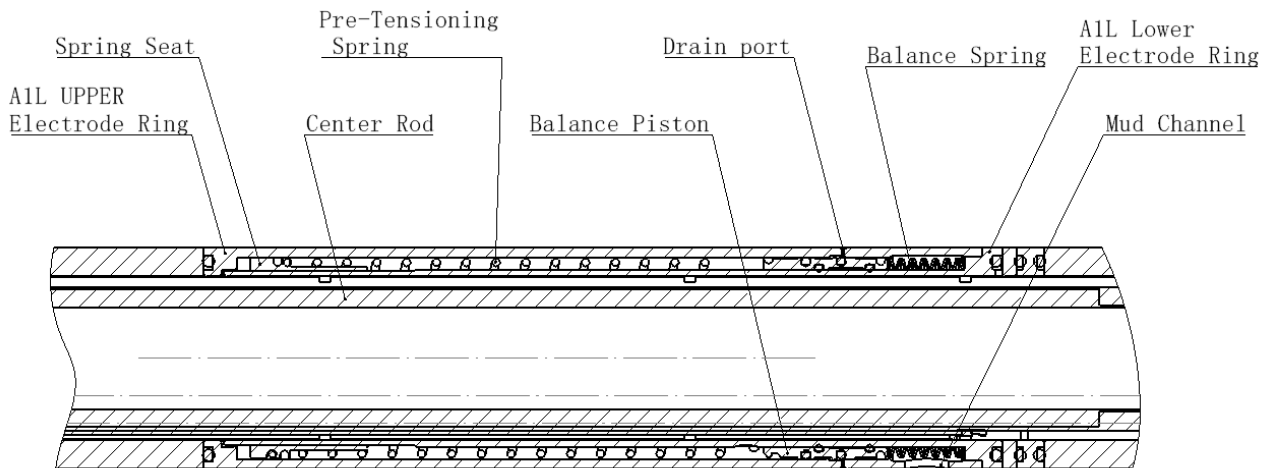


**Figure 5.** Pressure balance structure.

- (2) **Sealing Issues and Solutions:** Sealing is the core technology of ultra-high temperature and high-pressure lateral instruments. The sealing effect determines the insulation performance between electrodes and is crucial for the instrument's ability to measure effectively. To enhance the sealing performance, the following measures were taken:
- ① In terms of material selection, perfluoroether rubber material with a temperature resistance of 300 °C was chosen as the sealing component to ensure excellent sealing performance even at extreme temperatures.
  - ② In the overall structural design, as shown in Figure 6, the metal electrode rings and insulating sleeves were sequentially mounted on the insulating mandrel to form a sealed space filled with high-temperature silicone oil. The sealed space was connected to the inner chamber of the pressure balance structure shown in Figure 5. Under the action of the balance piston, the pressure inside the sealed space remains balanced with the external pressure, thereby improving the instrument's overall temperature and pressure resistance. To enhance the sealing reliability between the electrode and the insulating sleeve, the conventional lateral electrode end-face sealing was replaced with a new shaft-hole sealing design, as shown in Figure 7a,b. This improvement ensures that the sealing effect is no longer affected by the pre-tightening force between the electrode and the insulating sleeve end face. At the same time, it increases the compression of the sealing ring, improves the reliability and pressure resistance of the sealing, and prevents external media such as mud, water, and gas from penetrating into the sealed space, which could otherwise reduce the system's insulation value. This ensures that the electrode system remains in good insulation condition at all times.

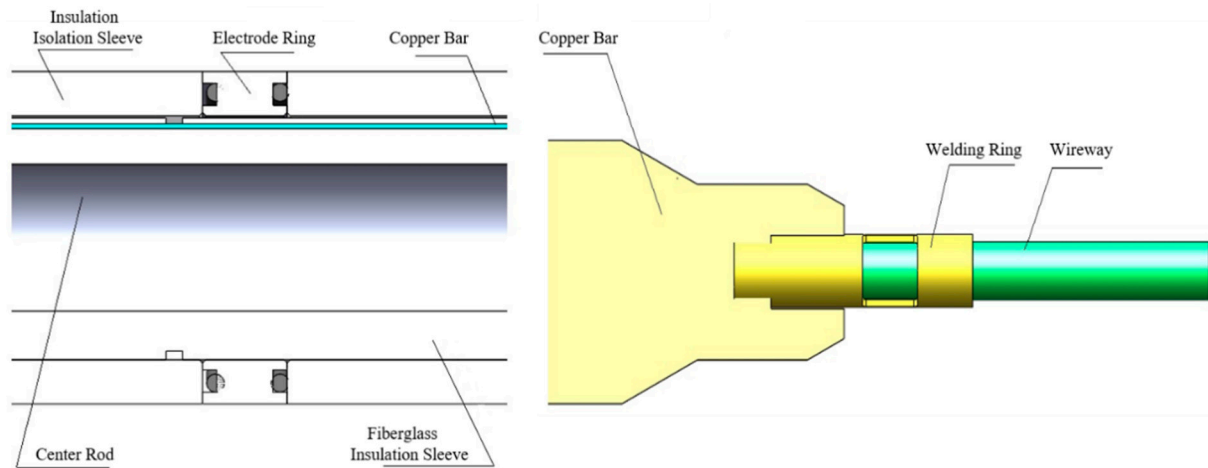


**Figure 6.** Installation diagram of the mandrel, insulating material, copper strip, and wires.

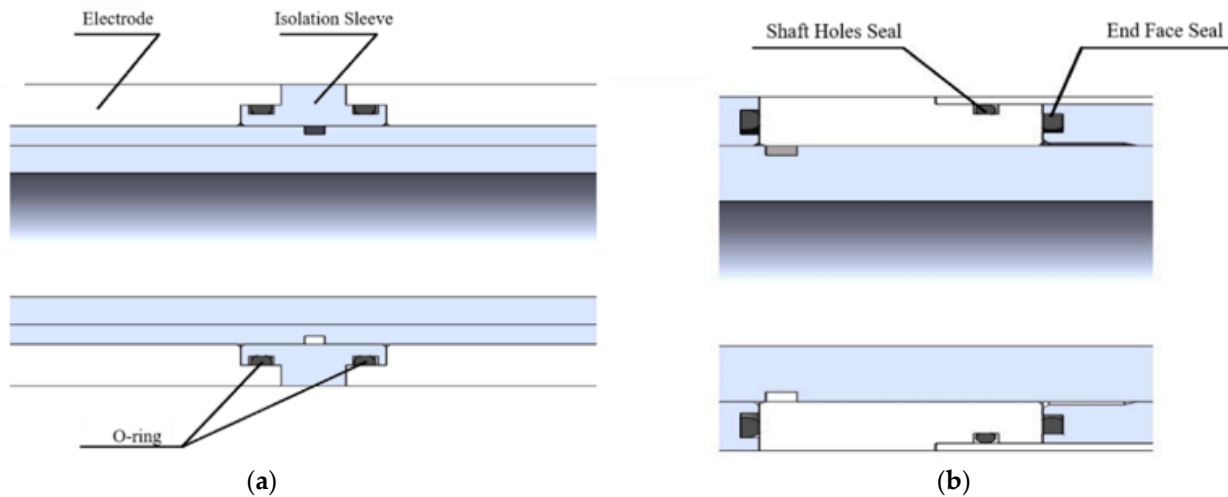


**Figure 7.** (a) End-face seal and shaft-hole seal structure; (b) Improved shaft-hole seal structure.

- (3) **Issues and Solutions for pressure-bearing sealing plugs:** The pressure-bearing sealing plug is a core component connecting the instrument's circuit system and sensors, serving as the channel and carrier for system power supply and signal transmission. The pressure-bearing sealing plug separates the circuit system from the sensor acquisition system, with one end enduring high temperatures and pressures from the formation while the other end protects the circuit from external temperature and pressure influences, maintaining it in a normal temperature and pressure environment, as shown in Figure 4. The maximum temperature and pressure rating for commonly used sealing plugs (pressure-sealing joints) is 230 °C/180 MPa. To meet the system design requirements, the project team, in collaboration with professional manufacturers and research institutions, successfully developed a series of pressure-bearing sealing plugs with temperature and pressure ratings of 260 °C/210 MPa using ceramic sintering and metal brazing technologies. After testing in a high-temperature and high-pressure autoclave, the high-temperature and high-pressure electrical conductivity and insulation performance of the pressure-bearing sealing plugs met the design requirements, laying a solid foundation for the successful design of the system.

### 3.1.3. Induction Coil System

The coil system is the detector part of the array induction logging tool, as shown in Figure 8. It consists of a central joint sealing assembly, beryllium copper tube assembly, coil

array assembly, outer tube of the coil system, lower sealing assembly, and pressure balance subassembly.

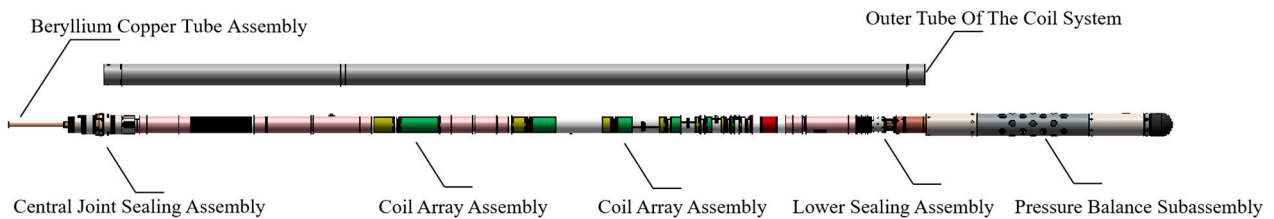


**Figure 8.** MIT1531 array induction tool.

The coil array consists of one transmitter coil and multiple sets of receiver coils. The receiver coils are distributed with source distances of 06, 10, 16, 24, 39, 60, and 94 inches, covering a detection depth range of 0.25 to 3.0 m longitudinally. The source distances of the coil sub-arrays increase sequentially, and the signal response relationship, as shown in Figure 9, illustrates the one-dimensional radial differential geometric factor response relationship. The resolution and detection depth are controlled by the spacing between the primary receiver and transmitter coils of the sub-arrays. Short spacing results in a high resolution but shallow detection depth, while long spacing results in deep detection depth but a low resolution. Maintaining consistent coil array spacing, the balance between the internal and external oil chambers of the coil system, and stable electrical characteristics of the coil system are the foundation for the accurate measurement of the induction logging tool based on the principles of electromagnetic wave logging.

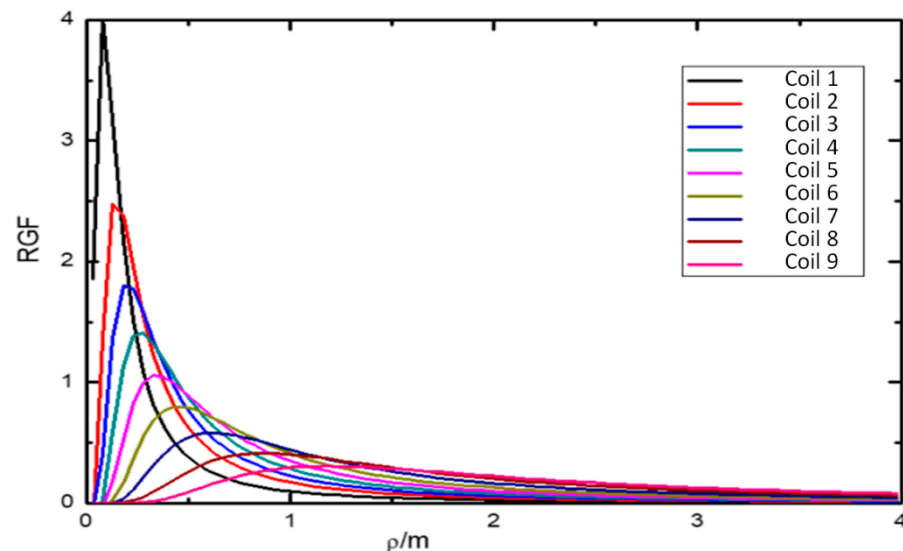


**Figure 9.** One-dimensional radial differential geometric factor.

The induction logging tool's coil array components must withstand temperatures of 260 °C and pressures of 210 MPa and need to be made from non-metallic, non-magnetic materials. For material selection, the coil array framework uses ceramic with minimal deformation at high temperatures to reduce the changes in coil magnetic flux due to thermal deformation across a wide temperature range. The insulating sleeves between coils are made of polyether ether ketone (PEEK), which has a load-bearing thermal deformation capability of up to 318 °C and can operate for extended periods at 260 °C. The insulating outer tube of the coil system uses glass-reinforced plastic (GRP) rated for 280 °C. The central joint and lower joint sealing assemblies use multiple 260 °C/210 MPa multi-core sealing plugs for wiring. The beryllium copper tube assembly uses 32.2 × 11.225 mm

C17200 beryllium copper tubes as the support structure and wire conduit for the coil array components, meeting the 260 °C/210 MPa temperature and pressure requirements.

The gap between the coil system outer tube and the coil array components is filled with silicone oil, and the pressure balance subassembly contains an adjustable oil chamber supported by springs, internally connected to the coil system's oil circuit to achieve pressure balance inside and outside the GRP tube in high-temperature and high-pressure environments.

The technical challenges and solutions for electromagnetic interference and sealing in high-temperature environments are as follows:

- (1) Multi-Core Pressure Sealing Plug Solutions for the Central Joint and Lower Joint: The pressure sealing plug uses a five-core structure, with four sets distributed circumferentially in the central joint to accommodate the seven sets of receiver coil array wires. In the lower joint, two sets are axially distributed to accommodate the transmitter and temperature probe wires. Physical separation of the transmission and reception lines solves the issue of crosstalk between the transmitter signal and the receiver lines. The five-core pressure bearing connector is a multi-pin connector with ceramic as the insulating material, and uses metal pins and ceramic sintering technology to meet the insulation requirements of 500 MΩ under a temperature and voltage resistance of 260 °C/210 Mpa.
- (2) The GRP (glass-reinforced plastic) outer tube for the coil system is made by bonding fiberglass cloth and synthetic resin as the base materials. The selected synthetic resin can withstand temperatures above 280 °C. Test specimens of GRP tubes are being processed to conduct long-term adhesive strength tests of fiberglass cloth and synthetic resin in a 260 °C environment.

### 3.2. 260 °C/210 MPa Low Power Consumption High-Integration Circuit System

As the number of high-inclination wells and long horizontal wells continue to increase, the demand for memory logging modes is rapidly growing. Dual-mode logging, which combines cable and memory logging, will become the primary form of logging in the near future. The basic requirements for the logging circuit system are low power consumption and high integration design. The key characteristics include an independent power supply, independent communication, independent storage, and independent pressure resistance.

#### 3.2.1. Power System Design

There are two main methods for downhole instrument power supply. The first method is to supply power to the downhole power conversion subassembly using AC power from the surface, converting AC to DC to power various instruments. The second method is to use downhole battery packs to directly power various instruments, achieving dual-mode AC and DC power supply. This approach changes the early working mode where each instrument converts AC to DC and then from DC to DC, improving the conversion efficiency from 70% to over 85%. Additionally, each instrument now includes current limiting protection to enhance the system power supply safety.

#### 3.2.2. Low Power Consumption Design of Acquisition and Processing Circuits

When designing the downhole logging instrument system, priority is given to reusing acquisition and processing circuit systems. For instance, common instruments such as four parameters, continuous inclination, caliper, dual laterolog, and digital acoustic instruments are designed using a single circuit board, while spectral, neutron, and density instruments use a different circuit board. The basic functions such as analog detection and signal sourcing are implemented through hardware virtualization, and low-power-consumption components rated for 175 °C are selected to meet the requirements for acquisition control and weak signal processing for different instruments, as shown in Figure 10.

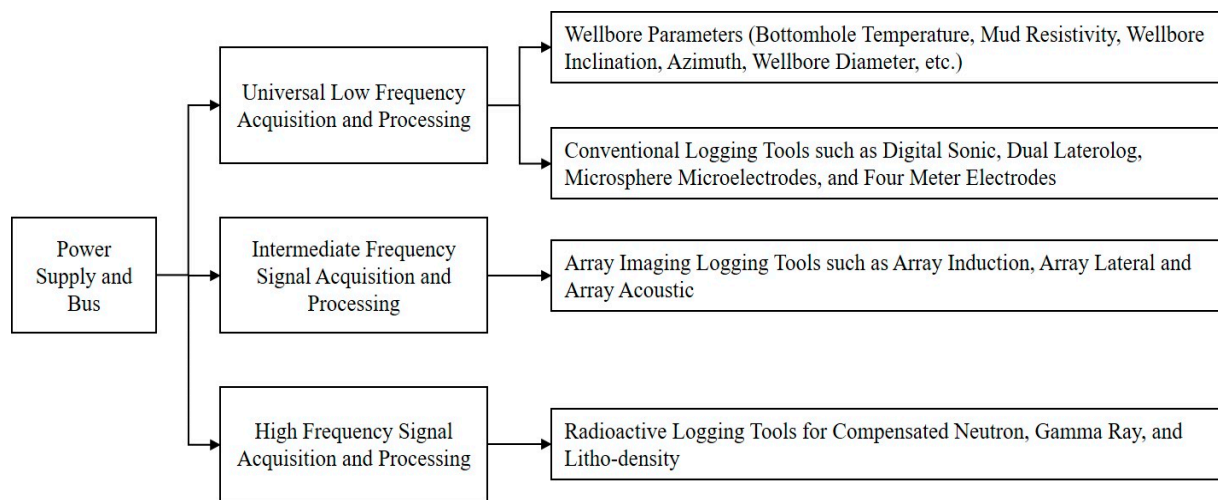


**Figure 10.** Reuse of acquisition and processing circuit systems.

The acquisition and processing circuit system achieves high-precision downhole signal acquisition across a broad frequency range, meeting the measurement needs of various instruments. This is accomplished through technology streamlining, chip selection, design simulation, and functional verification. Based on the circuit design and simulation, and according to the specific design functions of different instruments, combined with the requirements for acquisition accuracy, control, computing power, and communication, the system ensures high-precision signal measurement for different types of instruments.

### 3.2.3. Thermal Insulation System Design

To achieve a 260 °C ultra-high temperature circuit system in downhole logging instruments, given that the existing electronic components have temperature ratings below 210 °C, a combination of low-power-consumption circuits and high-power thermal insulation is necessary. Currently, downhole instrument thermal insulation bottles include independent thermal insulation bottles and pressure-bearing thermal insulation bottles. Independent thermal insulation bottles are compact, flexible in design, relatively mature, and frequently used. They typically come in single-end and double-end opening designs. Pressure-bearing thermal insulation bottles are used less frequently in logging instruments. Although they allow the further utilization of instrument cavity space, the weld points present certain unreliability in high-temperature and high-pressure environments, necessitating overall process improvement. At the same time, in order to increase the working time of the thermos in high-temperature environments, insulation paint is sprayed on the inside of the thermos to prevent external heat from entering the interior of the thermos. This series of instruments adopts a double-end-opening independent thermal insulation bottle design, as shown in Figure 11. The efficiency of the heat absorber depends on the composition of the heat-absorbing material, the material of the connectors, the vacuum effect, and the environment to be tested. The length of the heat absorber correlates with the power of the circuit board: the higher the power and the longer the required working time, the longer the heat absorber needs to be.

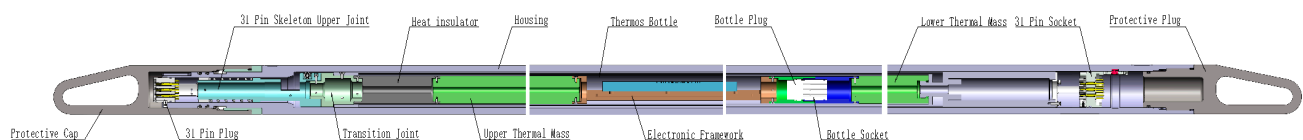


**Figure 11.** Double-end-opening thermal insulation bottle structure.

To ensure the quality of the logging data (related to the circuit driving of acoustic and electrical instruments) and construction safety, while also ensuring the reliable operation of

the downhole instrument circuit for a long time, the heat-absorbing agent capacity of the instrument should not be too much (which would increase the length of the instrument) nor too little (leading to a short insulation time). Through theoretical calculations and experimental testing, when the ambient temperature is 260 °C and the circuit power loss is 5 watts, to ensure 30 h of continuous operation of the instrument with the temperature inside the thermos not exceeding 175 °C, using the metallic heat-absorbing agent, the required capacity of the heat-absorbing agent is approximately 2.5 L. Following this principle, the structure of the thermos can be designed according to the specific needs and working durations to meet the actual logging requirements for ultra-deep wells.

### 3.3. 260 °C/210 MPa Ultra-High-Temperature-and-Pressure Mechanical Structure

The existing domestic logging instruments are generally rated for 175 °C/140 MPa and 230 °C/170 MPa. Instruments meeting the 260 °C/210 MPa specifications are used mostly in the overall design and core component testing stages, and there are currently no industry standards for validation in a high-temperature and high-pressure environment exceeding 260 °C/210 MPa. Below, we will present the design of the pressure-bearing outer casing components and universal parts that meet the 260 °C/210 MPa requirements through theoretical calculations.

Design parameters: outer diameter—92 mm, inner diameter—60 mm, material—TC18, yield strength at 260 °C ( $\sigma_{0.2}$ )—820 MPa.

The Thick-Walled Cylinder Pressure Calculation Formula is as follows:

The stress in each direction at any point on the pressure-bearing structure of a thick-walled cylinder is:

$$\text{Radial stress } \sigma_r = -\frac{Pr_2^2}{r_2^2 - r_1^2} \left(1 - \frac{r_1^2}{r^2}\right) \quad (1)$$

$$\text{Hoop stress } \sigma_\tau = -\frac{Pr_2^2}{r_2^2 - r_1^2} \left(1 + \frac{r_1^2}{r^2}\right) \quad (2)$$

$$\text{Axial stress } \sigma_z = -\frac{Pr_2^2}{r_2^2 - r_1^2} \quad (3)$$

In the formula,  $P$  is the external environmental pressure, MPa;  $r$  is the radius of the pressure point, mm;  $r_1$  is the radius of the inner hole of the instrument, mm;  $r_2$  is the inner radius of the outer surface of the instrument, mm [12].  $\sigma_r$  is the Radial stress at the bearing point, MPa;  $\sigma_\tau$  is the Radial stress at the bearing point, MPa;  $\sigma_z$  is the Radial stress at the bearing point, MPa;

When  $r = r_1$ , the stresses reach their maximum values. By substituting  $r = r_1$ ,  $k = \frac{r_1}{r_2}$  into the above formula and simplifying, we obtain:

$$\sigma_1 = \sigma_r = 0 \quad (4)$$

$$\sigma_2 = \sigma_\tau = -\frac{2P}{1 - k^2} \quad (5)$$

$$\sigma_3 = \sigma_z = -\frac{P}{1 - k^2} \quad (6)$$

According to the mechanics of materials and the fourth strength theory, the maximum combined stress on the inner wall is [12]:

$$\sigma_s = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (7)$$

$$\text{Allowable stress } [\sigma] = \sigma_{0.2}/n \quad (8)$$

In the formula,  $n$  is the safety factor [12]. The pressure safety factor  $n$  of logging instruments is generally  $\geq 1.25$ .

Substituting the design parameters into Equations (4)–(7), we obtain:  $\sigma_s = 635$  (MPa)  
The Allowable stress of the material is:  $[\sigma] = 820/1.25 = 656$  (MPa)

For  $\sigma_s < [\sigma]$ , the instrument's pressure-bearing outer casing structure and material parameters are reasonable.

The pressure-bearing outer casing components were processed and successfully passed the pressure testing at 230 °C/180 MPa. The next step is to prepare for pressure testing in an environment of 260 °C/210 MPa.

### 3.4. Data Transmission over Ultra-Long Cables

The high-reliability data transmission system for 10,000 m cables overcomes the communication challenges of a 15,000 m ultra-long seven-core cable, achieving an uplink data rate of  $\geq 200$  kbps and a downlink command rate of  $\geq 20$  kbps.

For the measurement of ultra-long cable characteristics, the attenuation characteristic parameters of 6500 m and 13,000 m seven-core cables were measured, and the actual measurement data and attenuation curves are shown in Table 1 and Figure 12. Based on these data, the following conclusion was drawn: the usable cable bandwidth frequency for the 13,000 m ultra-long cable is a maximum of 100 kHz. The measurement waveform is shown in Figure 13. The green signal represents the 100 kHz, 4 Vpp input waveform at the cable's input end, the blue signal represents the output waveform at the cable's output end, and the center line represents the Fast Fourier Transform (FFT) frequency amplitude waveform. The attenuation test comparison data indicated that over the 13,000 m ultra-long cable, the receiving end of 1 kHz signal is 1200 mV, while the receiving end of 90 kHz signal is 50 mV. The amplitude ratio of the two signals is 24 times. In addition, the group delay at the receiving end of the 90 kHz signal is quite large, which may lead to signal distortion or delay. When the frequency is further increased, the frequency and phase of the received signal cannot be resolved through FFT algorithm.

To ensure reliable data transmission within this frequency band, the following key technologies are utilized: time-division half-duplex working mode, RS forward error correction coding and decoding technology, frequency pre-emphasis technology, real-time modulation constellation allocation technology, PID synchronization for clock signals, and channel characteristic evaluation statistics.

#### (1) Time-Division half-duplex working mode

The original megabit remote transmission system used a frequency-division full-duplex mode, where uplink data and downlink commands were transmitted simultaneously along the cable. This required isolating the uplink data and downlink commands in frequency. Downlink commands used a cable bandwidth of 2–18 kHz, uplink data used 40–205 kHz, and the 18–40 kHz frequency band was left unused for isolation. For the 15,000 m ultra-long cable, the communication signal frequency range was 4–100 kHz. The transmission mode has been modified to a half-duplex time-division transmission mode, utilizing the 18–40 kHz bandwidth. This way, during any unit of time, either data or commands can use the entire cable bandwidth exclusively, increasing the bandwidth utilization and effectively improving the data transmission rates and quality.

#### (2) RS forward error correction program design

In the previous generation of telemetry systems, RS forward error correction (FEC) processing was used for uploading data. However, since the FPGA's used downhole (Field-Programmable Gate Array) was an ACTEL high-temperature-resistant device, and the company did not provide a free RS decoder IP core, the downlink commands lacked forward error correction functionality and only had CRC checksum functionality. This meant that it could only detect errors but not correct them, resulting in a higher bit error rate for command reception when the cable was long [13], and a significant loss of downlink commands. To improve the accuracy of the downlink telemetry command reception, an RS(24,16) decoder was designed within the ADSP21060 chip of the downhole telemetry

instrument. When the number of errors does not exceed four bytes, all errors can be successfully corrected, enhancing the reliability and stability of the downlink commands.

**Table 1.** Attenuation test data for 6500 m and 13,000 m seven-core cables.

| $V_{in}$ |                | $V_{out-6500\text{ m Cable}}$ |                    |                    | $V_{out-13,000\text{ m Cable}}$ |                    |                    | $V_{out-s}/V_{out-l}$ |
|----------|----------------|-------------------------------|--------------------|--------------------|---------------------------------|--------------------|--------------------|-----------------------|
| F<br>kHz | $V_{in}$<br>mV | $V_{out-s}$<br>mV             | $V_{out-s}/V_{in}$ | $V_{in}/V_{out-s}$ | $V_{out-l}$<br>mV               | $V_{out-l}/V_{in}$ | $V_{in}/V_{out-l}$ |                       |
| 1        | 5000           | 2000                          | 0.400              | 2.50               | 1200                            | 0.240              | 4.17               | 1.67                  |
| 2        | 5000           | 1950                          | 0.390              | 2.56               | 1000                            | 0.200              | 5.00               | 1.95                  |
| 5        | 5000           | 1900                          | 0.380              | 2.63               | 500                             | 0.100              | 10.00              | 3.80                  |
| 10       | 4500           | 1400                          | 0.311              | 3.21               | 300                             | 0.067              | 15.00              | 4.67                  |
| 20       | 4000           | 1000                          | 0.250              | 4.00               | 200                             | 0.050              | 20.00              | 5.00                  |
| 30       | 4000           | 800                           | 0.200              | 5.00               | 150                             | 0.038              | 26.67              | 5.33                  |
| 40       | 4000           | 750                           | 0.188              | 5.33               | 145                             | 0.036              | 27.59              | 5.17                  |
| 50       | 4000           | 690                           | 0.173              | 5.80               | 110                             | 0.028              | 36.36              | 6.27                  |
| 60       | 4000           | 590                           | 0.148              | 6.78               | 90                              | 0.023              | 44.44              | 6.56                  |
| 70       | 4000           | 500                           | 0.125              | 8.00               | 75                              | 0.019              | 53.33              | 6.67                  |
| 80       | 4000           | 400                           | 0.100              | 10.00              | 60                              | 0.015              | 66.67              | 6.67                  |
| 90       | 4000           | 380                           | 0.095              | 10.53              | 50                              | 0.013              | 80.00              | 7.60                  |
| 100      | 4000           | 300                           | 0.075              | 13.33              | 45                              | 0.011              | 88.89              | 6.67                  |
| 110      | 4000           | 240                           | 0.060              | 16.67              | 40                              | 0.010              | 100.00             | 6.00                  |
| 120      | 4000           | 200                           | 0.050              | 20.00              | 30                              | 0.008              | 133.33             | 6.67                  |
| 130      | 4000           | 160                           | 0.040              | 25.00              | 25                              | 0.006              | 160.00             | 6.40                  |
| 140      | 4000           | 130                           | 0.033              | 30.77              | 20                              | 0.005              | 200.00             | 6.50                  |
| 150      | 4000           | 110                           | 0.028              | 36.36              | 15                              | 0.004              | 266.67             | 7.33                  |
| 160      | 4000           | 100                           | 0.025              | 40.00              | 10                              | 0.003              | 400.00             | 10.00                 |
| 170      | 4000           | 80                            | 0.020              | 50.00              | 5                               | 0.001              | 800.00             | 16.00                 |
| 180      | 4000           | 65                            | 0.016              | 61.54              | 4                               | 0.001              | 1000.00            | 16.25                 |
| 190      | 4000           | 55                            | 0.014              | 72.73              | 3                               | 0.001              | 1333.33            | 18.33                 |
| 200      | 4000           | 45                            | 0.011              | 88.89              | 2                               | 0.001              | 2000.00            | 22.50                 |

Note: F is the frequency of the input signal;  $V_{in}$  is the voltage of the input signal;  $V_{out-s}$  is the output voltage attenuated by a 6500 m seven-core cable;  $V_{out-l}$  is the output voltage attenuated by a 13,000 m ultra-long seven-core cable.

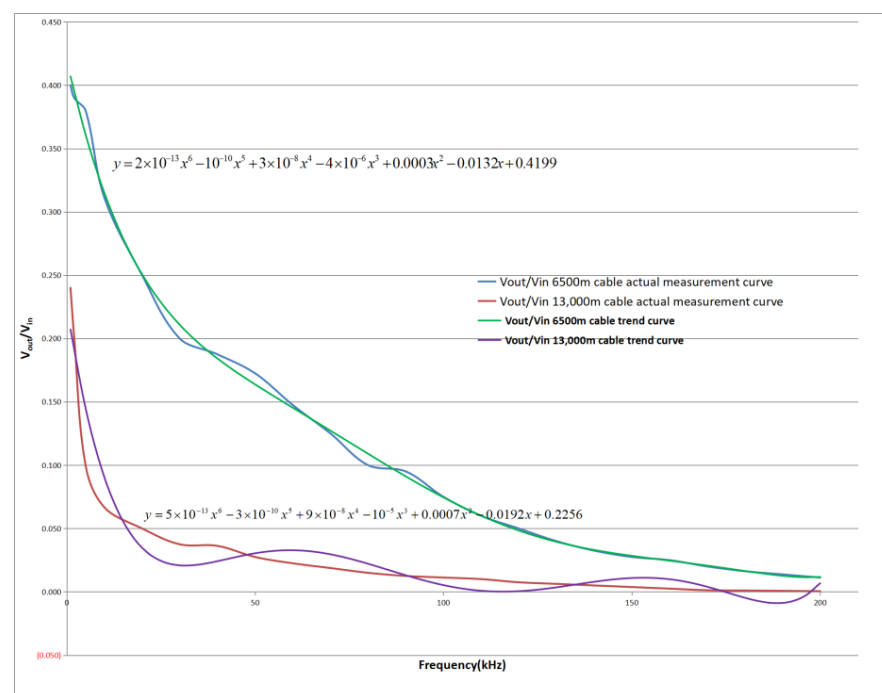


**Figure 12.** Attenuation test curves for 6500 m and 13,000 m seven-core cables.

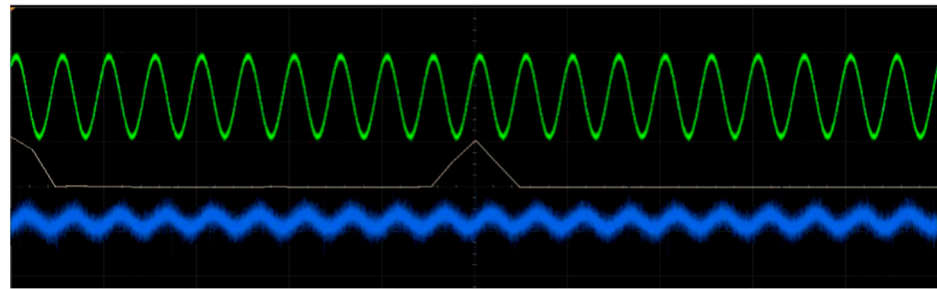


**Figure 13.** Test waveform of the 13,000 m cable at 100 kHz input (green), output (blue) and FFT frequency amplitude waveform (midline).

### (3) Frequency pre-emphasis technology

Given the inherent characteristics of seven-core cables, which exhibit varying attenuation properties for OFDM high-frequency signals—specifically, lower attenuation at lower frequencies and higher attenuation at higher frequencies—pre-emphasis processing has been designed for both downhole and surface modulation signals to compensate for the frequency-dependent attenuation. The digital component multiplies the digital signal by an exponentially varying coefficient based on the frequency of the transmission signal. This serves as a signal compensation mechanism during the transmission of analog signals within the cable's bandwidth [14,15], enabling the automatic gain control (AGC) circuit at the receiver to have more adjustment ranges. Simultaneously, the relevant peak intervals are statistically analyzed to automatically adjust the pre-emphasis parameters.

### (4) Real-time modulation constellation allocation design

Signals are transmitted using the 6–85 kHz range, with different dimensional modulation signals allocated to different carriers in real-time based on the cable characteristics to improve the signal transmission reliability and balance during high-speed transmission. For lower-frequency sub-carriers with better channel characteristics and less signal attenuation, a higher-dimensional 64 QAM modulation mode is used to increase the data transmission speed. For higher frequency sub-carriers, where the signal attenuation varies, lower-dimensional 16 QAM and 4 QAM modulation modes are selected in real time to enhance the transmission reliability, achieving a high-speed remote transmission rate of 300 kbps [16].

### (5) PID synchronization for clock signals

The ground clock synchronization algorithm was improved from the original minimum error adjustment algorithm [17–19] to a proportional-integral-derivative (PID) algorithm. This algorithm not only minimizes errors but also incorporates real-time error variation parameters (derivative) and historical variation parameters (integral), allowing the ground clock to more stably track the changes in the downhole clock. This ensures more stable clock adjustments and enhances the reliability of the system data transmission.

### (6) Channel characteristic evaluation statistics

By continuously evaluating and statistically analyzing the channel characteristics, the system can dynamically adjust transmission parameters to optimize the data integrity and transmission efficiency under varying conditions.

A 13,000 m long cable communication indoor test was conducted, with a downlink speed of 51.2 kbps and an upload speed of 268.8 kbps. The 13,000 m long cable was successfully operated in an 8000 m deep well at Deep Taco 1 well. The logging instrument included seven types (seven nodes), with 1516 words of valid data uploaded per frame, a CAN interrupt interval of 160 ms, a measurement speed of 370 m/h, and a smooth communication process.

### 3.5. Large Borehole Data Processing

In logging environments, factors such as borehole diameter, mud density and salinity, mud cake, borehole roughness, mud invasion zones, formation temperature and pressure, the surrounding rock, and instrument outer diameter and clearance can inevitably influence various logging curves. Especially in the cases of poor borehole and mud quality, these non-formation factors can cause severe distortion in the logging curves. In ultra-deep wells, the impact of these non-formation factors is even more pronounced due to the multiple openings, particularly when there are large boreholes in the first or second openings. Therefore, it is necessary to establish a comprehensive set of borehole environment correction charts for the instrument series to ensure the accuracy of the measurement data.

The process and method for calculating reservoir parameters in ultra-deep wells are similar to those for conventional reservoirs, with differences mainly in two areas: the calibration of logging by rock physics experiments and the evaluation of reservoir effectiveness and accurate fluid identification under deep high-temperature and high-pressure conditions. For the former, the measurement parameters under confining pressure conditions should be used to calibrate the logging curves. For the latter, an improved evaluation system is needed. Through in-depth research on deep high-temperature and high-pressure reservoirs, the currently adopted evaluation system (as shown in Figure 14) includes the following:

1. Calculation of the reservoir parameters based on conventional logging data.
2. Evaluation of reservoir levels near the borehole using imaging logging.
3. Identification and evaluation of fractures, the analysis of formation anisotropy, and provision of engineering data using array sonic data.
4. Evaluation of fracture development near the borehole using far-field sonic detection.

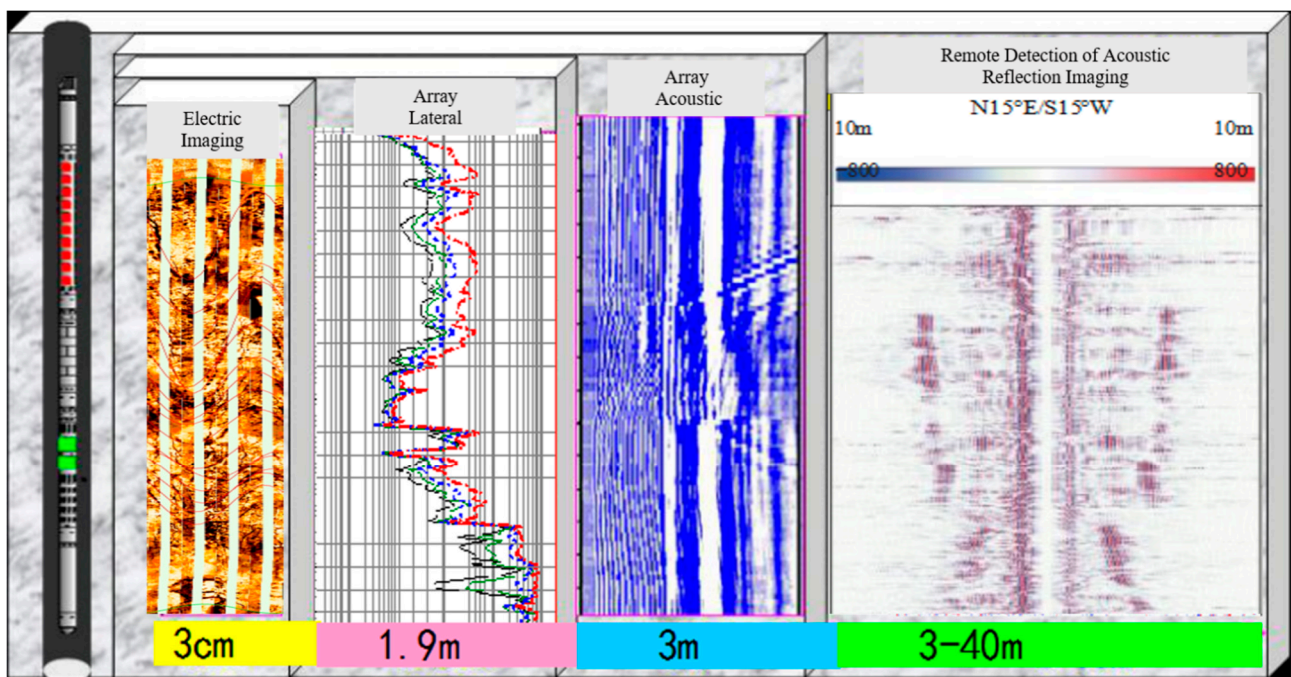


**Figure 14.** Evaluation system for the effectiveness of dual-porosity medium reservoirs and accurate fluid identification under deep high-temperature and high-pressure conditions.

Among them, 3 cm represents the radial detection depth of the electric imaging instrument, 1.9 m represents the radial detection depth of the array lateral instrument, 3 m represents the radial detection depth of the array acoustic instrument, and 3–40 m represents the radial detection depth of the remote detection of acoustic reflection imaging instrument. The black, green, blue, and red lines in the third column represent the resistivity

curves HALT1, HALT2, HALT3, and HALT4, respectively, corresponding to different radial detection depths in array lateral logging.

Figure 15 shows the application results of the above evaluation system in the Dagang XX well. The well was drilled to a depth of XX70 m with a bottom hole temperature of 216 °C. After successfully obtaining the data, reservoir effectiveness evaluation and fluid identification were carried out. Firstly, the porosity and resistivity spectra derived from micro-resistivity imaging logging data were inverted to obtain the vertical distribution of porosity near the wellbore (Track 10). Vertically, Layer 213 exhibits relatively developed porosity. Subsequently, conventional curves were used to calculate the lithology profile (Track 8) and porosity values (yellow-filled section in Track 7) near the wellbore, while resistivity invasion relationship information (Track 6) was also obtained. Layer 213 remains a relatively high-quality reservoir within this interval. Then, the bulk modulus and Poisson's ratio near the wellbore, calculated from the array acoustic data, overlapped (Tracks 11 and 12), revealing gas-bearing responses in Layers 213, 214, 216, and 218, with Layer 213 showing the most significant gas-bearing response. Finally, fractures near the wellbore were detected using far-detection techniques, revealing a set of fractures near Layer 216, approximately 28–30 m away from the wellbore. In summary, Layer 213 is considered the best and is evaluated as a Class II reservoir, while Layers 214, 216, and 218 are evaluated as Class III reservoirs.

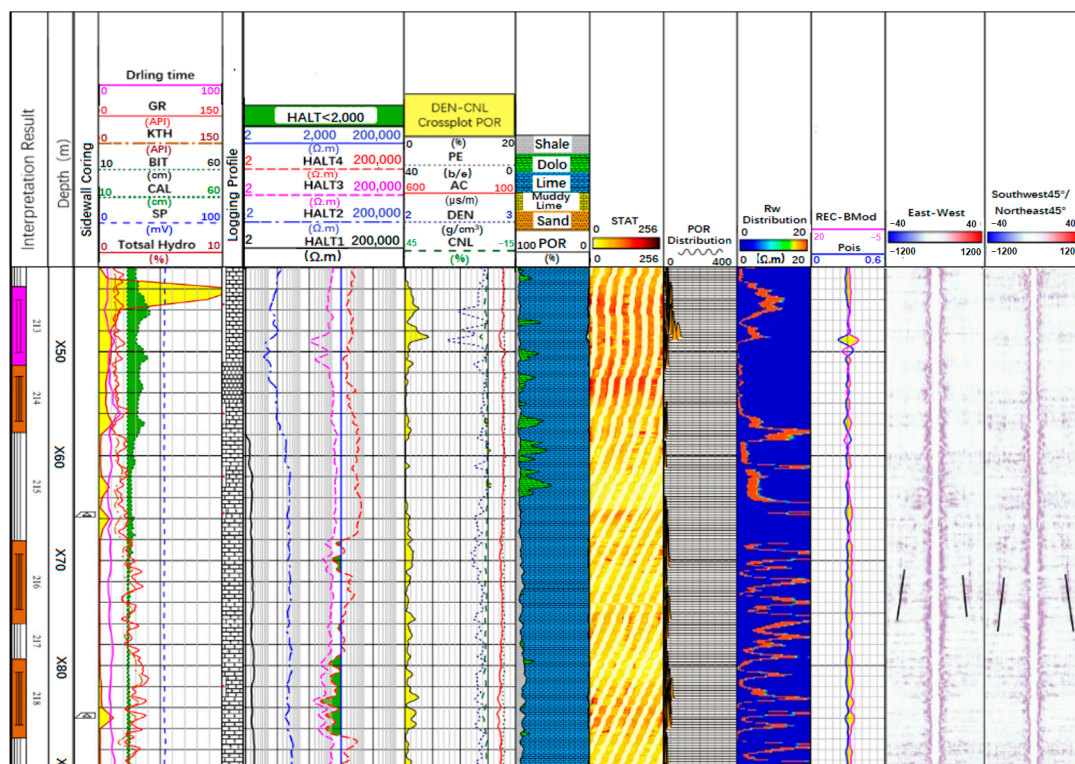


Figure 15. Evaluation results of the deep reservoir in Dagang Oilfield XX well.

#### 4. Conclusions

- (1) Verification has shown that the development of 260 °C/210 MPa ultra-high temperature and high-pressure logging equipment can be achieved by using BS-PT-based ultra-high-temperature acoustic transducers, modifying the mechanical structure of the lateral electrode system and using 300 °C Perfluoroether rubber material as the sealant, selecting non-magnetic non-metallic materials for the induction coil system, and incorporating a dual-mode power supply, reusable acquisition and processing circuit systems, double-end independent thermal insulation bottle structures, and through 18 months of engineering, the development of a prototype of 260 °C/210 MPa

can be achieved. It is recommended that all the key technologies be tested and validated under extreme indoor and field environments. For instance, the BS-PT-based ultra-high-temperature acoustic transducer, seals, pressure-bearing housings, and other components should undergo extensive and repeated testing at 260 °C/210 MPa within a 300 °C/300 MPa high-temperature and high-pressure autoclave through specially designed test setups. This would ensure the reliability and stability of the equipment under extreme conditions.

- (2) Cable communication employing the six key transmission technologies has overcome the significant signal attenuation differences at high- and low-frequency points, achieving reliable transmission in deep wells up to 8000 m with 13,000 m cables. It is recommended that in the later stages, real-well verification be conducted in two 10,000 m scientific exploration wells in China, with a focus on the relationship between the cable extension length and signal amplitude attenuation, bit error rate, transmission rate, etc. This will further optimize the transmission technology to ensure reliable communication in wells deeper than 10,000 m.
- (3) Through experimental validation, establishing a comprehensive set of borehole environment correction charts for ultra-deep wells can more accurately reflect the actual formation conditions. Using measurement parameters under confining pressure conditions to calibrate logging curves and improve the evaluation system, successful data acquisition, reservoir effectiveness evaluation, and fluid identification were achieved in the Dagang XX well. It is recommended to conduct test verification in the ultra-large borehole environments of two 10,000 m scientific exploration wells in China, and to compare and validate the results with geological data such as well logging, in order to further improve the accuracy of the calibration chart for large boreholes.
- (4) Developing 260 °C/210 MPa logging technology and equipment and achieving the independent control of the key core technologies are crucial for overcoming the bottlenecks in domestic logging instruments. This approach effectively addresses the challenges of efficient and reliable data acquisition in ultra-high-temperature and high-pressure complex conditions, enhances the evaluation capabilities for complex reservoirs such as clastic rocks, carbonates, and unconventional oil and gas, and meets the need for high-efficiency and low-cost development in oilfields under the new norm of low oil prices. Additionally, this equipment can completely replace imported equipment, significantly reducing the introduction costs and providing strong technical support for the deep exploration projects.

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