

Article

The Design and Application of a New Wireline Pressure Coring System for the Guangzhou Marine Geological Survey Methane Hydrate Expedition in the South China Sea

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Abstract: Natural gas hydrate is widely distributed, shallow-buried, clean, and pollution-free and has enormous reserves, it is regarded as the alternative clean energy source in the oil and gas field with the most potential. Pressure coring is the only way to drill for gas hydrate core on the surface under in situ conditions, which is of great value for analyzing its occurrence conditions and reserves comprehensively. Based on this, a new wireline pressure coring system (WPCS) with a ball valve seal was designed and developed in this paper; it was applied in the deep sea for the first time in the South China Sea hydrate survey voyage of the Guangzhou Marine Geological Survey (GMGS). A total of 15 runs of deep-sea gas hydrate drilling and coring applications were carried out, and they tested well. The experimental water depth was 1700–1800 m, and the coring depth below the seafloor was about 100–150 m. The formation consisted of sandy hydrate and argillaceous hydrate. The results showed the following. (1) The success rate of ball valve turn-over could reach almost 100% in the argillaceous hydrate reservoir, although there are some isolated cases of pressure relief. Meanwhile, drilling in the sandy hydrate reservoir, the success rate was only 54.55%. (2) When drilling in the argillaceous hydrate reservoir, the core recovery rate could reach 80%, while in the sandy hydrate reservoir, it was almost 0%. In practice, the sandy formation with gas hydrate is stiff to drill compared to the performance in argillaceous formations. After our analysis, it was believed that the ball valve and core tube could be easily plugged by sand debris during the sampling of sandy hydrate formation. Moreover, the sandy core is easily plugged into the core liner because of the high friction of sand grains in clearance. (3) The pressure-holding effect of the core drilling tool was related to the formation of hydrate, the sealing form of the ball valve, and the environmental pressure. Sandy hydrate formations often caused the ball valve to jam, while the muddy hydrate formation did not. The research results of this paper have reference value for the further optimization of the WPCS structure, the optimization of drilling parameters, and the design parameters of the ball valve structure, which could be better used for the pressure coring of gas hydrate and subsequent research work in the future.

Keywords: natural gas hydrate; pressure coring; structure design; ball valve seal; core recovery rate

1. Introduction

Natural gas hydrate is a kind of crystalline solid substance formed by gas molecules (mainly methane) and water under certain temperature and pressure conditions; it is

commonly known as “combustible ice” [1,2]. Its occurrence environment is mainly under permafrost in high latitudes and in the continental shelf extending to the sea at a depth of several hundred meters [3]. And natural gas hydrate is widely distributed, shallow-buried, clean, and pollution-free and has enormous reserves, it is regarded as the alternative clean energy source in the oil and gas field with the most potential. At present, more than 100 exploration sites in the world have discovered natural gas hydrate [4]. The amount of natural gas resources contained in natural gas hydrates in the world is about $2 \times 10^{16} \text{ m}^3$ [5,6], and the organic carbon content converted from this reserve is about twice that of existing fossil fuels (coal, oil, and natural gas) [7,8]. At the same time, gas hydrate is considered to be an alternative resource of fossil fuel with great potential because of its good accumulation and chemical conditions. Therefore, in recent years, natural gas hydrate has been a research hotspot in the scientific community and oil–gas industry [9]. Among such research topics, how to safely, economically, and efficiently extract natural gas from hydrates is a very key technical problem [10]. At present, the development technology of natural gas hydrate in oceans mainly includes the pressure reduction method, solid fluidization method, heat injection method, chemical injection inhibitor, and carbon dioxide replacement method [10,11]. Each of these technologies has its advantages and disadvantages, and scientists around the world have also conducted numerous experiments on these technologies. Countries around the world have also carried out marine gas hydrate test mining many times. Among such countries, in 2020, China conducted its second test production using a series of advanced technologies including the horizontal well and pressure reduction method. This test production has created two world records for a total gas production of $86.14 \times 10^4 \text{ m}^3$ and an average daily gas production of $2.87 \times 10^4 \text{ m}^3$, realizing a major leap from “exploratory test production” to “experimental test production” [12].

In the study of gas hydrate, the most direct and effective research method is to obtain complete and undisturbed *in situ* samples of gas hydrate in the seabed and carry out further experimental analyses [13]. When the hydrate is obtained by conventional means, due to the decrease in pressure and the increase in temperature, natural gas hydrate decomposition will occur during or after the core collection process, and gas expansion will destroy the complete structure of the hydrate core. Therefore, the pressure coring system is the only method from which a core is retrieved to the surface in an *in situ* condition [14,15].

To sample gas hydrate over a complete gas hydrate stability zone (GHSZ), a number of downhole, wireline-operated pressure coring tools have been developed, such as a PCS (Pressure Core Sampler), a PTCS (Pressure Temperature Core Sampler), an FPC (Fugro pressure corer), a PCTB (Pressure Corer Tool Ballvalve), and so on [16,17]. After pressure coring is completed, the core barrel and the core inside are pulled into the pressure chamber by lifting the wireline. The lower end of the pressure chamber is usually sealed with a specially designed flapper valve or ball valve [18].

The first successful wireline pressure coring tool, which was a PCS, was developed by the ODP (Ocean Drilling Program) for the drilling vessel JOIDES Resolution [19,20]. By using the PCS, gas-rich or gas hydrate-bearing sediments were successfully retrieved in 1995 and 2002 at Blake Ridge on ODP Leg 164 and at Hydrate Ridge on ODP Leg 204. However, the core diameter of the PCS was limited, and the core could not be removed from the system without releasing the pressure from the sample [21]. Hence, two developments of a new wireline pressure coring tool were initiated in response to the perceived limitations of the PCS on Leg 164. The PTCS was invented in 1998 and was upgraded in 2004 by Aumann & Associates Inc. and the Japan National Oil Corporation, which was designed to retrieve longer, larger cores than the PCS and to provide a temperature control system. And two types of wireline pressure coring tools, the FPC and HRC (HYACE rotary corer), with the former also known as FRPC (Fugro rotary pressure corer), were developed in the European-funded Hydrate Autoclave Coring Equipment project (HYACE) in late 1997. These wireline pressure core tools were designed to recover hydrate cores in liners that

were to be subsequently transferred into a Pressure Core Analysis and Transfer System (PCATS) [22,23].

Later, the Hybrid PCS was developed from PTCS, designed mainly by a combined design of PCS and PTCS for the drilling vessel Chikyu, and fitted to PCATS, which included core handling and an analysis system [24,25]. In 2012, the Hybrid PCS was successfully used in the Nankai Trough offshore Japan expedition 802 and obtained 18 pressure cores [20,26,27], as shown in Table 1.

Table 1. Coring summary of expedition 802.

Number of Cores		
Hybrid PCS cores	16 × 3 m + 2 × 1.5 m	
Hybrid PCS	Recovery rate	34.99/51 m, recovery rate 69%
	Pressure condition	
Pressure-conserved cores (≥ 12 MPa)	8 cores	17.08 m
Partially pressure-conserved cores (≥ 5.5 MPa)	4 cores	11.6 m
Pressure lost (< 5.5 MPa)	6 cores	6.31 m

Based on the Hybrid PCS and the PCATS, Geotek has further developed the PCTB. The PCTB has been widely used in China, India, Japan, and the United States to recover a large number of pressure-holding core samples, while the PCATS has been instrumental in processing and analyzing the cores [28–30].

Pressure coring that maintains the in situ hydrostatic pressure is a critically important technical issue. As shown in Table 1, it could be found that it was very difficult to make the cores conserve their original formation pressure after coring. Specifically, more than half of the cores failed to conserve their original pressure. To achieve this goal, the pressure chamber must seal the core and be able to withstand the hydrostatic pressure at the coring depth using a sealing mechanism (flapper or ball valve) when lifting to the surface. As shown in Table 2, the ball valve and flapper valve were the main types for sealing, and the Hybrid PCS was the most active pressure coring tool.

Table 2. Summary of available pressure coring techniques [13].

	Drill Pipe Diameter (in)	Core OD (in)	Max Core Length (m)	Max Pressure (MPa)	Sealing Mechanism	Active
PCS	5 or 5 ¹ / ₂	1.575	1	69	ball valve	No
FPC		2.125	1	25	flapper valve	No
HRC		2	1	21	flapper valve	No
PTCS	6 ⁵ / ₈	2.625	3.5	24	ball valve	No
Hybrid PCS/PCTB	5 or 5 ¹ / ₂	2	3.5	35	ball valve	Yes

The presence of the gas hydrates can be inferred through the utilization of geophysical tools, yet the sole direct method for ascertaining the in situ concentration of the natural gas embedded in this gas hydrate is to core the formation while meticulously maintaining the constant in situ pressure [5]. To obtain a more comprehensive and minimally perturbed sample of seafloor gas hydrate in situ pressure, a novel wireline pressure coring system (WPCS), which is rooted in the ball valve sealing mechanism, was successfully devised and deployed during the Guangzhou Marine Geological Survey (GMGS) expedition conducted in the South China Sea in 2023.

2. Design of WPCS

2.1. Methodology

The technical scheme for the novel WPCS was crafted based on the following fundamental principles:

- (1) The WPCS was designed as a rotary wireline coring system, similar to the Extended Coring System (ECS) for the drilling vessel JOIDES Resolution. It features a maximum outer diameter of 96 mm, compatible with 5-inch and 5½-inch drill strings to optimize operational efficiency. The pressure chamber within the WPCS sustains pressures up to 35 MPa (5000 psi). Core samples collected by the WPCS measure 2 inches in diameter, with a maximum length of 3.5 m [31,32].
- (2) In accordance with the gas hydrate phase equilibrium principles, the WPCS is designed to maintain in situ pressure upon retrieval from the formation. Post-recovery on deck, the pressure chamber is detached from the WPCS via a quick link system. This process controls temperature rise in the vertical cryogenic mousehole and facilitates connection to the newly designed Pressure Core Analysis Transfer System (PCATS) for pressure core transfer and analysis, ensuring pressure containment is maintained without release.
- (3) Continuous monitoring of temperature and pressure profiles throughout the operation enables assessment of gas hydrate stability within the WPCS core, distinguishing between stable and dissolved states.

Figure 1 illustrates the structural configuration of the WPCS, which was composed of an inner barrel assembly and an outer barrel assembly, viewing from the inside to the outside. The WPCS inner barrel assembly was suspended and connected inside the outer barrel assembly and integrated into the BHA (Bottom Hole Assembly) (The abbreviations are listed in Abbreviations). With an inner latch and outer latch, the inner barrel and outer barrel could be locked in place to cut and shape the core into the plastic liner with the cutting shoe during the coring process. The WPCS is segmented into three primary subassemblies from top to bottom: (1) the wireline running tool and the wireline retrieving tool; (2) the upper barrel system composing the outer latch barrel and the inner latch barrel; (3) the lower barrel system housing the pressure chamber section with an internal plastic core liner. Notably, the upper and lower barrel systems are interconnected via a quick link system, facilitating efficient assembly and disassembly within a vertical cryogenic mousehole to manage the temperature fluctuations. Additionally, the pressure chamber system is equipped with pressure and temperature recorders positioned atop the core liner. These instruments monitor and record the in situ pressure and temperature data throughout the coring recovery process.

2.2. Working Mechanism

The WPCS is structured into three principal subassemblies (Figure 1). (1) The upper barrel assembly encompasses the running and retrieving tools. (2) Situated centrally is the pressure control assembly, housing a pressurized reservoir. (3) At the base lies the lower barrel assembly, designed for the sample autoclave.

This configuration facilitates efficient operation and ensures the integrity of core samples during retrieval. Each subassembly plays a crucial role in maintaining operational stability and preserving the quality of recovered geological samples. The integration of a pressurized reservoir within the middle assembly enhances the system's capability to manage pressure differentials encountered during coring operations.

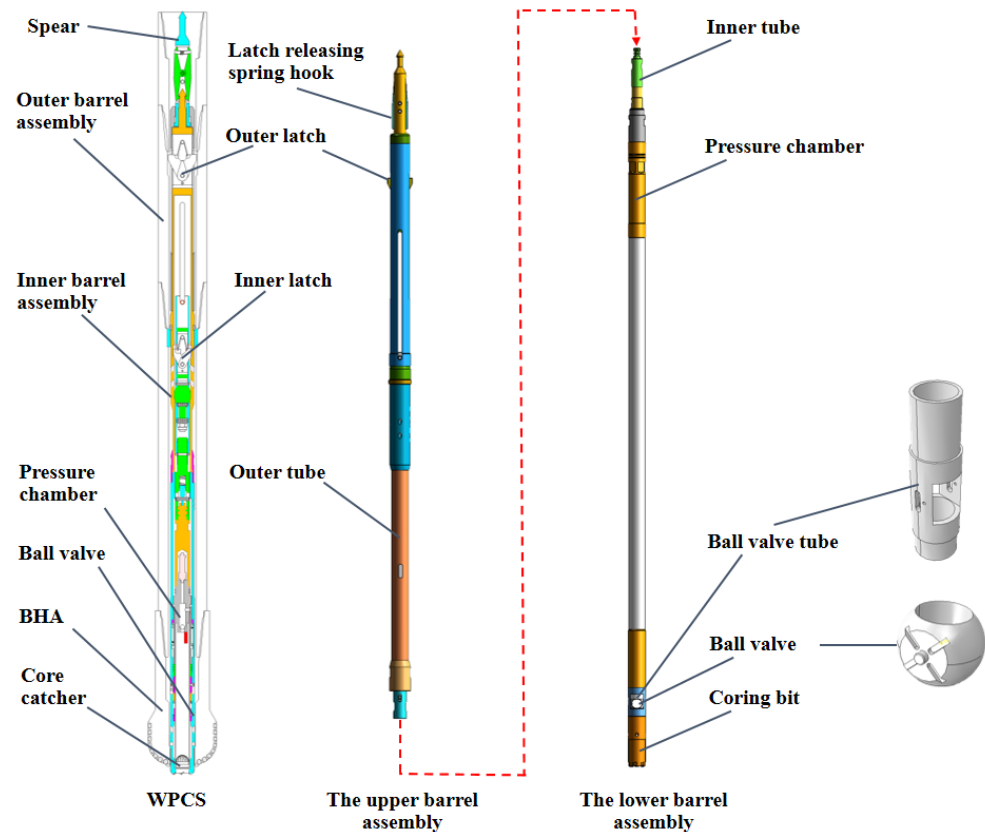


Figure 1. The structure of WPCS.

In practical operation, the WPCS is deployed using a wireline running tool which is lowered through the drill string to engage with the BHA. Once the WPCS is securely latched onto the BHA at the bottom of the borehole, the connection between the wireline running tool and the WPCS can be automatically disengaged. Subsequently, upon retrieval of the wireline running tool on the deck, the WPCS undergoes rotation facilitated by the top drive mechanism, utilizing the latch and BHA drill string. Throughout the coring operation, the drilling mud is circulated down the drill string by the drilling mud pump. This serves the dual purposes of maintaining borehole stability and facilitating cooling and lubrication of the coring drill bit. To safeguard the integrity of the gas hydrate cores, a plastic core liner is employed. This liner is supported by a core liner bearing within the inner barrel assembly, ensuring both the core liner and core catcher remain stationary. This approach minimizes any potential disturbance to the core samples during retrieval.

After completing the coring process, the wireline retrieving tool was deployed to engage the WPCS, initiating the release of the outer latch releasing sleeve. Upon lifting the sleeve, several sequential actions were observed. Firstly, the wireline tension caused the release of the inner latch, allowing the inner barrel to ascend. Secondly, the lower ball valve of the pressure chamber promptly closed upon the plastic core liner being drawn into the autoclave section, driven by the thrust spring force of the valve (Figure 2). Subsequently, the outer latch was disengaged, followed by the closure of the upper seal of the pressure chamber. (4) Finally, the retrieval of the WPCS proceeded similarly to other wireline coring tools, as shown in Figure 3. These procedures ensure the systematic retrieval of geological core samples while maintaining the integrity of the samples for subsequent analysis.

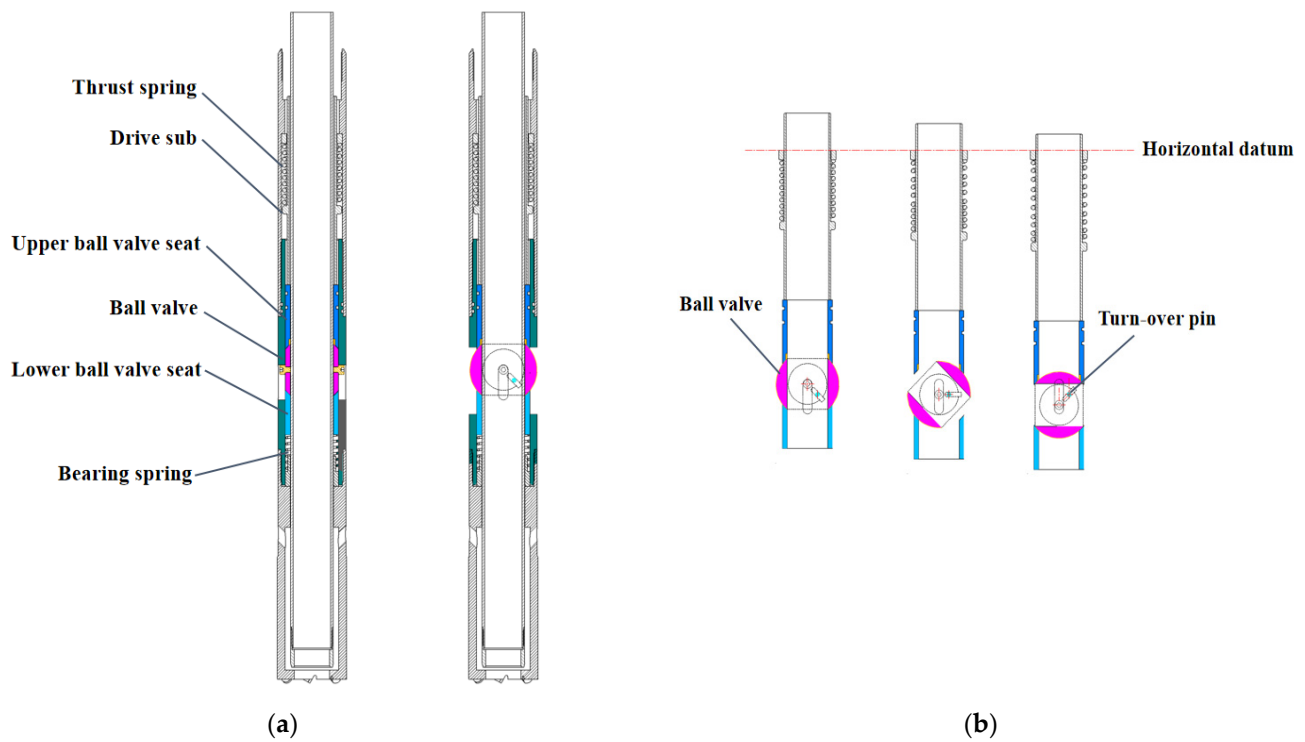


Figure 2. The position and schematic diagram of the ball valve: (a) the comparison of ball valve before and after turning; (b) the process of turn-over sealing of the downward motion unit.

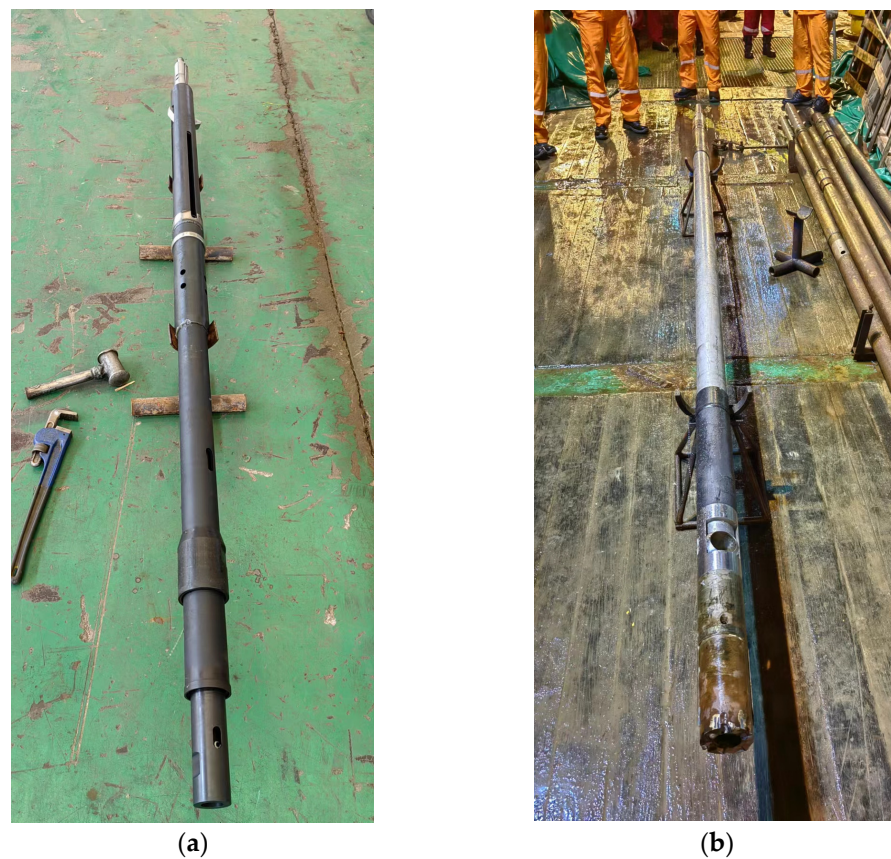


Figure 3. The physical diagram of section connection of the WPCS: (a) the upper barrel assembly of WPCS; (b) the lower barrel assembly of WPCS.

Upon recovery of the WPCS onto the deck, the pressure chamber was detached from the WPCS via the quick link system. Subsequently, it was connected to the newly designed PCATS for transfer and analysis of pressure cores without releasing pressure (Figure 4). Throughout the coring recovery process, pressure and temperature data were continuously recorded by the pressure/temperature recorder positioned atop the core liner with the pressure chamber system.

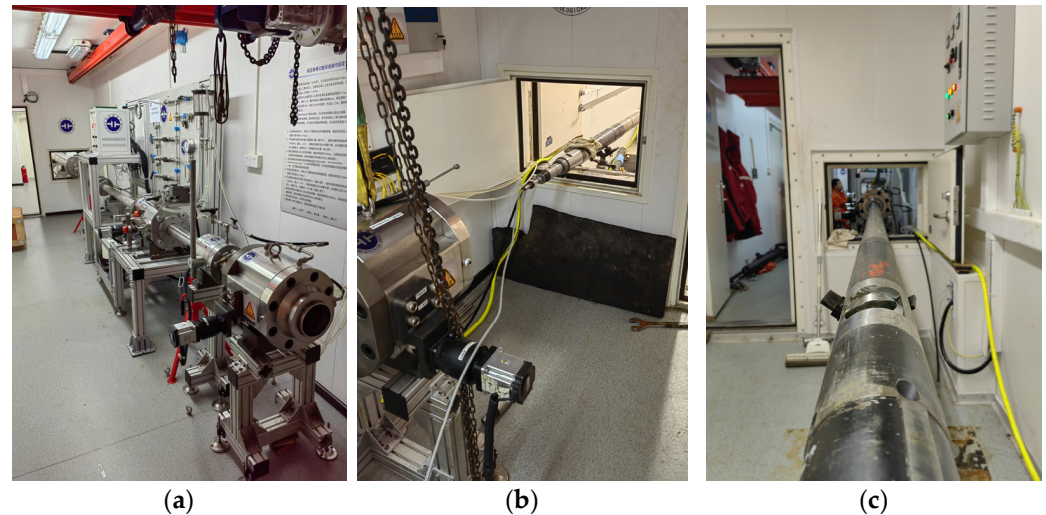


Figure 4. The Pressure Core Analysis Transfer System: (a) the main part of the Pressure Core Analysis Transfer System; (b) pressure measurement of the hydrate core inside the autoclave before transfer; (c) transfer of the hydrate core inside the core tube with pressure holding.

3. Application and Results

From 11 May to 22 June 2023, the GMGS conducted a hydrate survey voyage in the South China Sea with China National Offshore Oil Corporation (CNOOC)'s "Offshore Oil 708", and carried out the first application of the WPCS designed in this paper in the deep ocean. The specific application conditions and test results are shown in Table 3.

As indicated in Table 3, the investigation involved conducting a total of 15 pressure coring tests across six boreholes, with operations conducted at a seawater depth ranging from 1751.2 m to 1769 m. And the drilling depth ranged from 76.5 m to 168.4 m during the submarine pressure core drilling. Furthermore, the penetration depth of individual core drilling ranged from 0.8 m to 2.5 m.

Among the 15 core drilling tests conducted, 10 of them had a single-return penetration depth of 1.5 m~2.1 m, with a maximum penetration depth of 2.5 m and a minimum penetration depth of 0.8 m. The above single penetration depth was less than the maximum coring length that WPCS could carry out, that is, 3.5 m. In addition, the core recovery rate is a very important index for evaluating core quality. The core recovery rate refers to the ratio of core recovery length to penetration length. That is, the core recovery rate $P = L_c / L_p \times 100\%$. Analysis of the fifteen core drilling tests revealed that only three achieved a core recovery rate exceeding 90%. Additionally, six tests yielded recovery rates ranging from 45% to 90%, while the remaining six tests resulted in recovery rates below 45% (Figure 5).

During the pressure-holding core drilling operations across the above six specified boreholes, the in situ pressure at the bottom of the hole ranged from approximately 18 MPa to 20 MPa. Analysis presented in Table 3 illustrates notable disparities among the results from 15 pressure-holding seal tests and their impact on core recovery rates. Among these tests, 10 runs achieved different degrees of pressure-holding sealing, and the success rate of pressure-holding sealing was 66%. Notably, runs 13 and 14 successfully maintained in situ pressure-holding seals. Throughout the coring and retrieval operations, careful measures were taken to ensure the inner tube core barrel remained within the stable temperature and pressure regime of the gas hydrated stability zone. As depicted in Figure 6, the temperature

and pressure curve was recorded during the whole coring process of the WPCS in run 13, and the phase equilibrium curve of gas hydrate proves that the gas hydrate could be kept stable using WPCS. However, affected by other factors (such as hard sandy hydrate), the core recovery rate was 0. The other eight runs of tests only achieved partial pressure-holding sealing and failed to maintain the temperature and pressure stability region of hydrate. Additionally, there were five test runs that failed to achieve the pressure-holding sealing effect. Practical implications of drilling in sandy gas hydrate formations were evident, highlighting increased drilling complexities compared to clay-rich formations. Sandy cores exhibited heightened friction among grain particles, frequently resulting in blockages within the core liner.

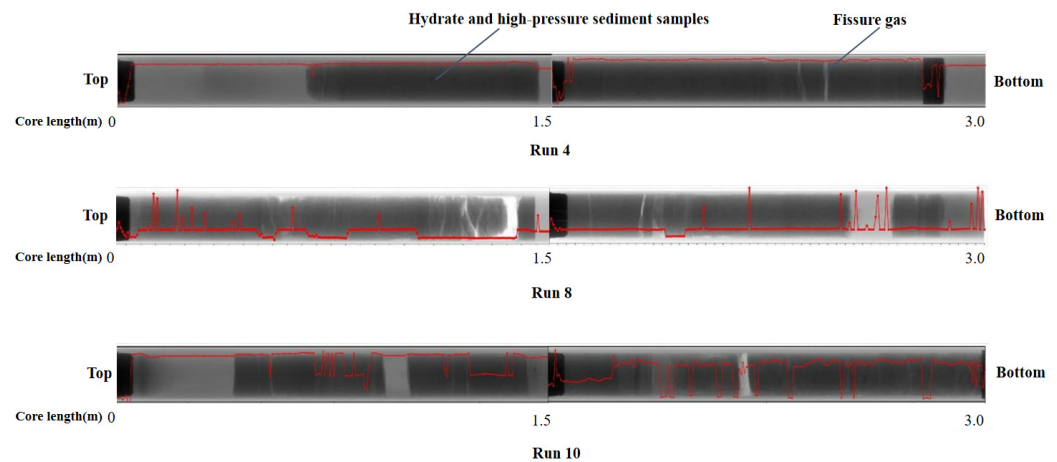


Figure 5. X wave and P wave scanning picture of several typical runs.

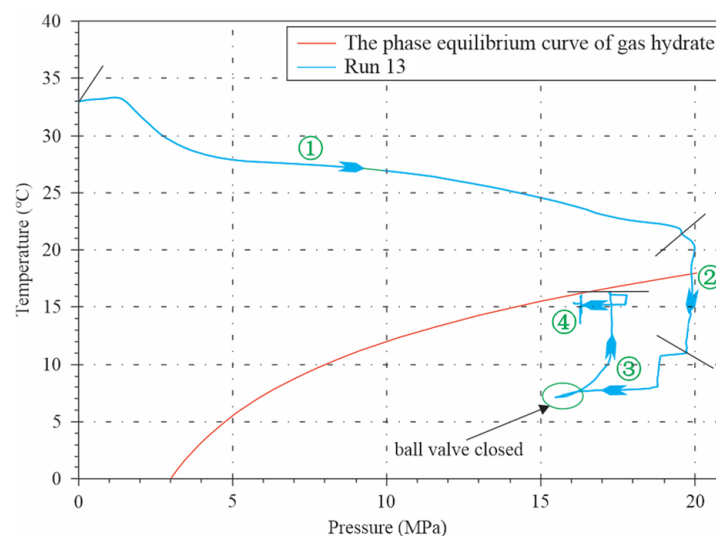


Figure 6. The temperature and pressure curve of the WPCS in run 13 (the critical line is the phase equilibrium curve of gas hydrate). ① Lowered through the drill string to latch in the BHA; ② coring; ③ retrieved; ④ pressure core transferred.

The temperature and pressure profiles depicted in Figure 7 exhibit consistent trends throughout the entire operational sequence. In the preparation stage before lowering the drill string, elevated temperatures on the deck caused a gradual increase in temperature, while pressure remained unchanged. (1) In the stage of lowering through the drill string to latch in the BHA, with the increase in the descending depth, the pressure gradually increased and the temperature gradually decreased. At this time, the changes in pressure and temperature were relatively linear. (2) During coring operations, due to the slow increase in depth, the temperature and pressure basically did not change. But due to the rotation of the

drill string, the temperature and pressure had a certain pulsation change. (3) Upon retrieval, initial stages maintained stable temperature and pressure levels. However, delayed closure of the ball valve during later retrieval stages caused a reduction in confining pressure, resulting in temperature elevation and subsequent hydrate destabilization. This led to increased pressure within the hydrate core in the pressure chamber. (4) During pressure core transfer operations, both temperature and pressure remained relatively constant.

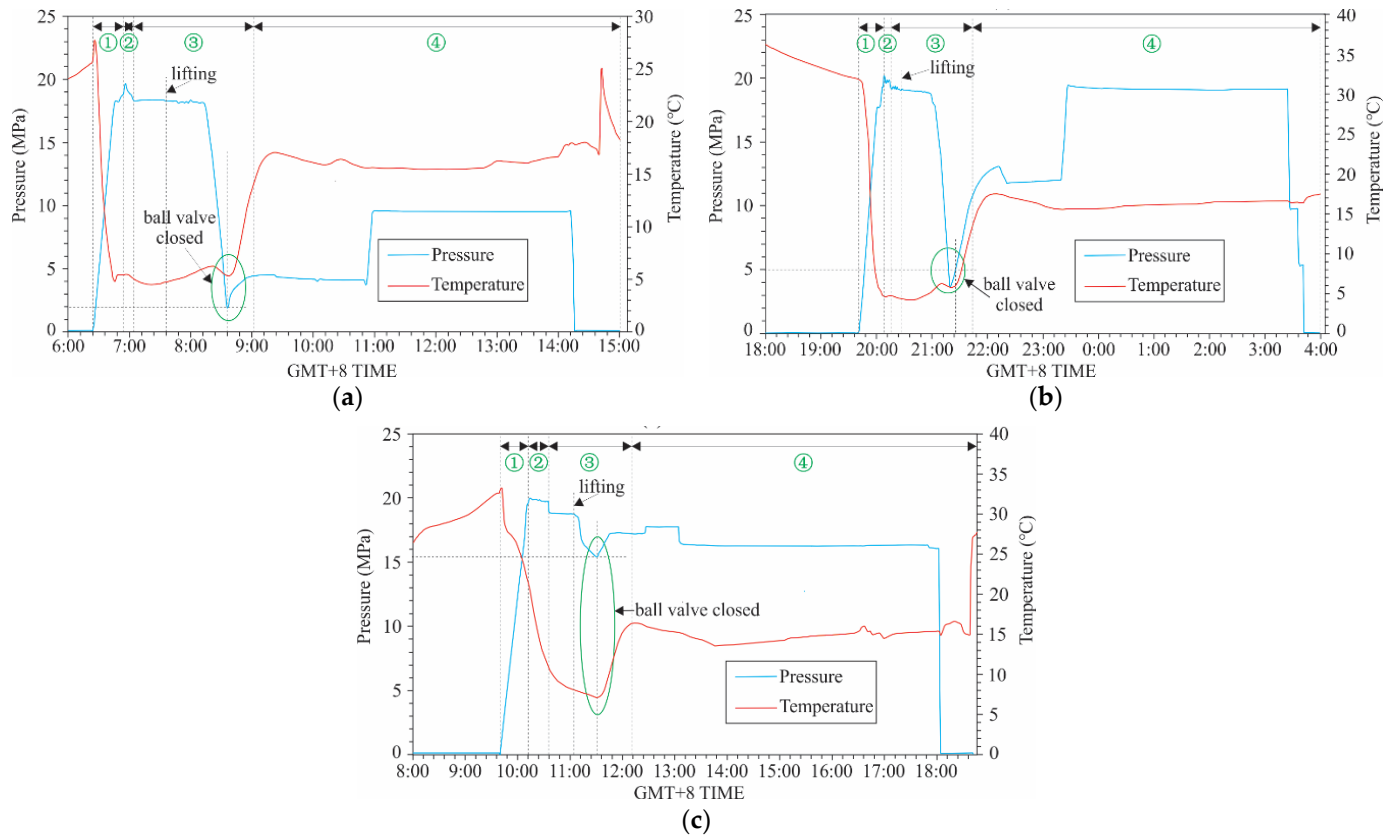


Figure 7. The temperature and pressure curve of the WPCS recorded over time during the whole coring process: (a) run 8; (b) run 9; (c) run 13. ① Lowered through the drill string to latch in the BHA; ② coring; ③ retrieved; ④ pressure core transferred.

According to the design requirements of WPCS, the sequence involves raising the inner pipe assembly above the ball valve, followed by the activation of the ball valve drive sub and drive spring to facilitate its overturning and subsequent sealing. However, during three specific runs (run 8, run 9, run 13) detailed in the data, the depth of turn-over of the ball valve was recorded, respectively, at 198.92 m, 496.85 m, and 1580.03 m, as indicated in Figure 7. Delays in the closure of the ball valve during the retrieval of the drilling tool resulted in a reduction in confining pressure within the pressurized core. This unintended consequence led to an increase in temperature, thereby compromising the stability of the hydrate and resulting in its decomposition. Concurrently, analysis of pressure data, depicted in Figure 7, indicates that the hydrate continued to decompose after the ball valve closure, resulting in a continuous increase in the pressure of the hydrate core within the pressure chamber.

Table 3. Summary of results from pressure coring.

Run	Hole	Water Depth (m)	Coring Depth (m)	Core Interval (m)	Recovery Rate (%)	Holding Pressure (MPa)	Reservoir Type	Remarks
1	Hole A	1769.0	135.0–137.5	2.5	100	1.7	Sandy gas hydrate layer and Clay layer	
2	Hole A	1769.0	136.7–138.2	1.5	0	2	Sandy gas hydrate layer	Sand plugging at the entrance of core tube
3	Hole A	1769.0	138.2–139.7	1.5	0	10	Sandy gas hydrate layer	Sand plugging at the entrance of core tube
4	Hole B	1766.4	125.7–127.2	1.5	77	2.15	Clay layer	
5	Hole B	1766.4	130.8–133.3	2.5	87	0	Sandy gas hydrate layer and Clay layer	BHA stuck and failed to retrieve
6	Hole B	1766.4	132.5–133.3	0.8	0	0	Sandy gas hydrate layer	Sand plugging at the entrance of core tube; Sand block at ball valve
7	Hole B	1766.4	133.3–134.5	1.2	100	0	Sandy gas hydrate layer and Clay layer	
8	Hole C	1751.2	76.5–78.6	2.1	90	4	Clay layer	
9	Hole C	1751.2	95.7–97.8	2.1	52	4.6	Clay layer	
10	Hole C	1751.2	141.0–143.0	2.0	85	10	Sandy gas hydrate layer and Clay layer	
11	Hole C	1751.2	143.0–144.5	2.0	45	0	Sandy gas hydrate layer	BHA stuck and failed to retrieve
12	Hole D	1769.0	135.0–137.0	2.0	45	0	Sandy gas hydrate layer	BHA stuck and failed to retrieve
13	Hole E	1769.0	166.4–168.4	2.0	0	18.9	Clay layer	
14	Hole F	1769.0	126.0–127.5	1.5	0	17.8	Sandy gas hydrate layer	Sand plugging at the entrance of core tube
15	Hole F	1769.0	127.5–128.3	0.8	0	1.9	Sandy gas hydrate layer	Sand plugging at the entrance of core tube

4. Discussion

4.1. Factors Affecting Recovery Rate

Based on the data presented in Table 3, of the fifteen core drilling test results, five runs achieved a core recovery rate exceeding 80%, whereas six runs resulted in a core recovery rate of 0%. It was concluded that the results were closely related to the structural characteristics of the drilling tool and the geological characteristics of hydrate occurrence.

The sealing structure of the ball valve of WPCS required a large lip area of the bit (as shown in Figure 8a). In the process of drilling in the hard sandy hydrate formation, it would be difficult to penetrate due to the high formation hardness. On the other hand, because the rock breaking section of WPCS was too large, the concentration of cuttings

near the core tube was too high, which easily caused sand blocking of the core tube. The drilled core could not enter the core liner effectively, and even caused the problem of core hydration loss and hydrate decomposition. Despite the designed maximum core length of 3.5 m for WPCS, actual operational constraints in hard, sandy hydrate formations typically reduce this to approximately 2.5 m. And it is further shortened due to the actual drilling conditions. For instance, in run 2, run 3, run 6, run 14, and run 15, there were obvious sand blocking phenomena in the process of drilling, which eventually led to the core recovery rate of 0%.

In addition, the BHA experienced three incidents of sticking during run 5, run 11, and run 12, resulting in failure of core recovery. It was believed that this was caused by the damage of the inner latch releasing the sleeve of the WPCS. As shown in Figure 8a, the drill bit had a large rock breaking area. In order to prevent the drilling fluid from scouring the core during drilling in the sandy hydrate formation, the pumping volume was relatively low, resulting in a high concentration of cuttings near the drill bit. The condition exacerbated the downhole complexities, such as water blockages and sticking (Figure 8b).

In contrast, three out of the four runs of the pressure-holding core drilling in the muddy reservoir achieved a better recovery rate, which was much better than the overall coring effect in the sandy reservoir.

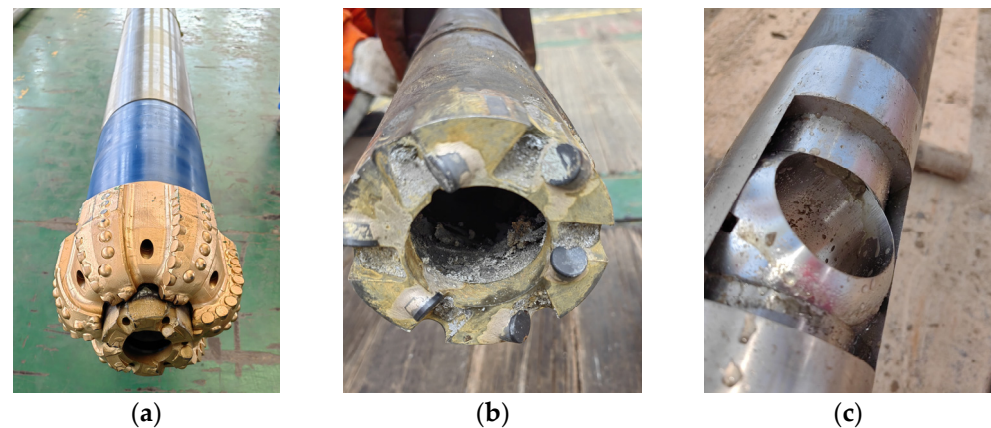


Figure 8. The physical picture of WPCS: (a) pressure-retaining core bit and BHA; (b) the water tunnels of core bit plugged by sand; (c) pressure-retaining ball valve turned over with sand.

4.2. Factors Affecting Pressure Holding

As can be seen from the application results in Table 3, the pressure-retaining effect of WPCS was closely related to the type of hydrate reservoir and operational feasibility of closing and sealing the ball valve in situ.

In the case of drilling operations within muddy reservoirs, all four runs achieved a certain degree of pressure holding. On the other hand, the success rate of ball valve turn-over and sealing in the sandy reservoir was only 54.55%. This disparity can be attributed to two primary factors identified through analysis. Firstly, during the sealing process, the ball valve was blocked by falling sand (Figure 8c), which was a common issue contributing to ball valve sealing failure [33,34]. Secondly, elevated concentrations of rock cuttings resulted in the jamming of the inner pipe assembly, rendering retrieval attempts futile.

As shown in Figures 1, 2 and 8c, in the process of the ball valve turn-over sealing, the ball valve drive nipple, the upper ball valve seat (including the ball valve seal), the ball valve, and the lower ball valve seat (collectively known as the downward motion unit, DMU) made a downward movement as a whole, and the ball valve turned over due to the presence of the turn-over pin and the keyway on the ball valve. Therefore, the key to the ball valve turn-over was to achieve the overall downward movement and complete the 90° flip. In the process of the downward movement, the downward component forces included (1) the force driven by the thrust spring; (2) the gravity of DMU. The upward component forces included (1) the thrust of the bearing spring; (2) the buoyancy of the DMU; (3) the

friction resistance at the side sealing ring of the upper ball valve seat (Figure 9). Notably, the buoyancy force and gravity of the moving unit were also constant. At the same time, the specifications of the driving spring and the bearing spring used in the 15 cycles were consistent, and the downward and upward forces generated in the initial state of the two remained constant. Therefore, the key to determining whether the downward motion unit could move downward was the resistance at the sealing ring on the upper ball valve seat. The friction resistance was significantly affected by the type and the lubrication method of the sealing ring. With the increase in sampling depth, the ambient pressure increased and the temperature decreased, resulting in varying degrees of increase in the viscosity of the lubricating medium, and this also led to changes in friction resistance. During runs 1 to 12, butter lubrication was employed for the side sealing ring of the upper ball valve seat, while runs 13 to 15 utilized a combination of oil and butter. It was observed that run 13 and run 14 successfully achieved in situ pressure-retaining ball valve turn-over sealing. (Figure 10).

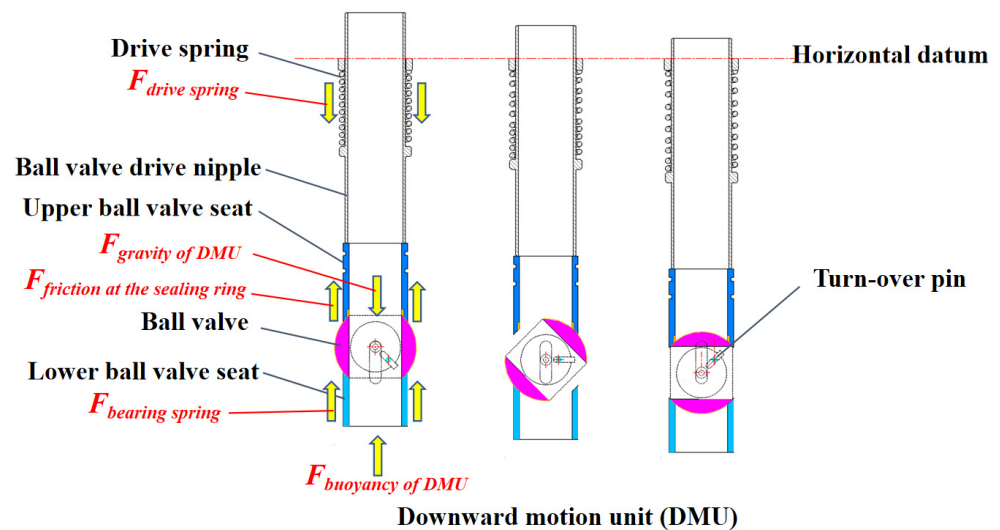


Figure 9. Force analysis near DMU.

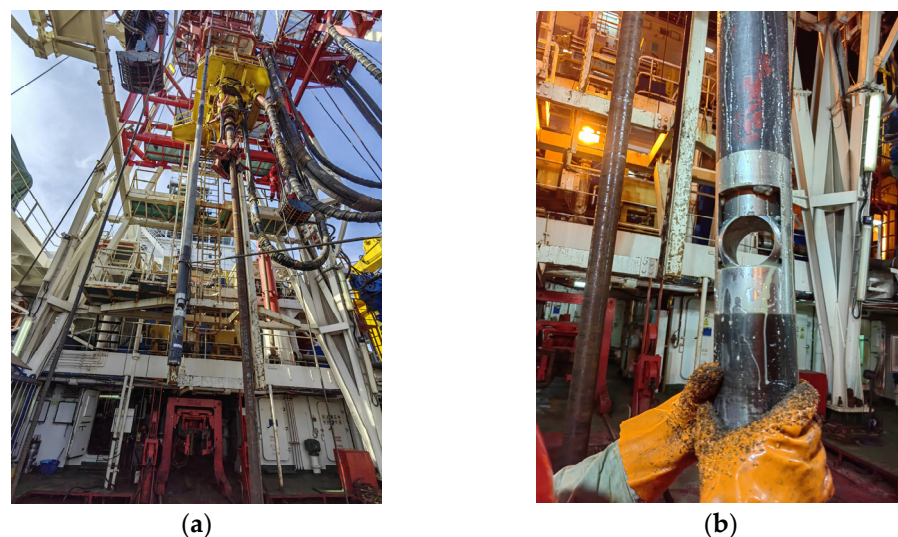


Figure 10. Several cases of ball valve turn-over sealing: (a) the unsuccessful case with no ball valve turn-over; (b) the successful turn-over sealing case of the ball valve.

As can be seen from the application results in Table 3, the pressure-retaining effect of WPCS was closely related to the type of hydrate reservoir and whether the ball valve could be closed and sealed in situ.

Upon raising the inner tube assembly above the ball valve, the DMU began to move downward, initiating the ball valve's interaction with the flip pin for support. Since the support reaction force of the flip pin does not pass through the ball valve's center of mass, so that the ball valve has a flipping trend, the flipping torque generated by the flip pin must be greater than the friction torque between the upper and lower ball valve seats and the ball valve. Among them, the friction resistance between the ball valve seat and the ball valve was determined by the normal pressure (or supporting force) of the ball valve seat, and the force was significantly affected by the environmental pressure of the ball valve seat. For instance, the supporting force on the lower ball valve seat was influenced by the difference between the buoyancy and downward gravity of the lower ball valve seat, which was directly related to the normal component force at the ball valve contact surface. While the buoyancy and gravity remained constant, the hydrostatic pressure increased with the sampling depth, consequently increasing frictional resistance. Similarly, the friction resistance between the upper ball valve seat and the ball valve also increased with the increase in the sampling depth. Therefore, the static friction resistance before the ball valve was increased with the increase in sampling depth. So as depicted in Figure 10a, the ball valve did not turn over at the bottom of the hole. But with the increase in the sampling mechanism, the hydrostatic pressure on the ball valve seat reduced, and the static friction resistance during turn-over was correspondingly reduced. So the reversing seal was realized at a certain height from the sampling position. The successful turn-over sealing case of the ball valve is shown in Figure 10b.

When testing the WPCS in an atmospheric environment, the friction resistance between the ball valve and the ball valve seat was determined only by the coefficient of static friction, the gravity of the downward unit, and the tension of the driving spring and the bearing spring. So the force required for the ball valve to turn over was much less than that required for the submarine coring condition. In addition, when testing in an atmospheric environment, the ambient temperature and pressure of the seals outside the upper ball valve seat would be much lower than the seabed coring conditions, and the difficulty of movement deformation and the viscosity of the lubricating medium would be correspondingly lower than the seabed conditions. Therefore, the driving force of the downlink unit would be greater than the seabed conditions.

5. Conclusions

According to the work performed above, the following conclusions could be drawn:

- (1) A new WPCS core drilling tool was designed and applied for the first time in the deep sea during the hydrate survey voyage in the South China Sea of Guangzhou Marine Geological Survey, and good application results were obtained.
- (2) The core recovery rate was closely related to the structure of the core drilling tool and hydrate formation. In the process of core drilling in the sandy hydrate formation, because the rock breaking surface of the drill tool was too large, the concentration of cuttings near the core bit was too high, which facilitated the complex situation of core pipe plugging, water hole plugging of the drill bit, and the interaction of the inner and outer pipes.
- (3) The pressure-holding effect of the core drilling tool was related to the formation of hydrate, the sealing form of the ball valve, and the environmental pressure. Sandy hydrate formations often caused the ball valve to jam, while the muddy hydrate formation did not. The sealing form of the ball valve affected the effective driving force of the ball valve turning down, and the ambient pressure increased the friction resistance between the ball valve and the upper and lower ball valve seats.
- (4) In order to improve the application effect of WPCS, the coordination between WPCS and BHA should be further optimized. To maintain a clean and cool environment near the drill bit, the drilling fluid should be improved. In addition, the interaction between the drive spring and the environmental pressure should be quantified as much as possible.

- (5) Gas hydrates remain stable in a low-temperature and high-pressure environment. According to the phase equilibrium curve of gas hydrate, the main safety and security of WPCS operation is to control the temperature rising, to avoid pressure rising rapidly in the pressure chamber system of WPCS due to the pressure core dissolving.
- (6) The WPCS needs to develop abundant security measures to improve reliability, such as BHA being stuck and failing to retrieve.

6. Patents

The work in this manuscript resulted in three patents for the WPCS. Among them, one of the patents is pending, and the patent application number is 202211133818.1. The other two have been granted, and the patent license numbers are ZL201910651361.5 and US10, 822, 903 B2.

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Abbreviations

A list of acronyms defining all the abbreviations alphabetically has been added in the table.

BHA	Bottom hole assembly
CNOOC	China National Offshore Oil Corporation
DMU	Downward motion unit
ECS	Extended coring system
FPC	Fugro pressure corer
FRPC	Fugro rotary pressure corer
GMGS	Guangzhou Marine Geological Survey
HRC	HYACE rotary corer
HYACE	Hydrate autoclave coring equipment
ODP	Ocean drilling program
PCATS	Pressure core analysis and transfer system
PCTB	Pressure corer tool ball valve
PTCS	Pressure temperature core sampler
PCS	Pressure core sampler
WPCS	Wireline pressure coring system

References

1. Kvenvolden, K.A. Hydrocarbon gas in sediment of the Southern Pacific Ocean. *Geo Mar. Lett.* **1988**, *8*, 179–187. [[CrossRef](#)]
2. Kvenvolden, K.A. Methane hydrates and global climate. *Glob. Biogeochem. Cycles* **1988**, *2*, 221–229. [[CrossRef](#)]

3. Bazaluk, O.; Sai, K.; Lozynskyi, V.; Petlovanyi, M.; Saik, P. Research into Dissociation Zones of Gas Hydrate Deposits with a Heterogeneous Structure in the Black Sea. *Energies* **2021**, *14*, 1345. [\[CrossRef\]](#)
4. Brewer, P.G.; Orr, F.M.; Friederich, G.; Kvenvolden, K.A.; Orange, D.L. Gas Hydrate Formation in the Deep Sea: In Situ Experiments with Controlled Release of Methane, Natural Gas, and Carbon Dioxide. *Energy Fuels* **1998**, *12*, 183–188. [\[CrossRef\]](#)
5. Kvenvolden, K.A. Methane hydrate—A major reservoir of carbon in the shallow geosphere? *Chem. Geol.* **1988**, *71*, 41–51. [\[CrossRef\]](#)
6. Kvenvolden, K.A. Potential effects of gas hydrate on human welfare. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 3420–3426. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Koh, C.A.; Sloan, E.D.; Sum, A.K.; Wu, D.T. Fundamentals and Applications of Gas Hydrates. *Annu. Rev. Chem. Biomol. Eng.* **2011**, *2*, 237–257. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Kvenvolden, K.A. Gas hydrates as a potential energy resource—A review of their methane content. *US Geol. Surv. Prof. Pap.* **1993**, *1570*, 555–561.
9. Lin, Z.; Su, M.; Zhou, H.; Su, P.; Liang, J.; Wang, F.; Yang, C.; Luo, K. Deposition processes of gas hydrate-bearing sediments in the inter-canyon area of Shenhu Area in the northern South China Sea. *J. Oceanol. Limnol.* **2023**, *41*, 740–756. [\[CrossRef\]](#)
10. Hou, L.; Yang, J.; Liu, Z.; Jiao, J. Current status and suggestions on development of marine gas hydrate technologies in China. *World Pet. Ind.* **2021**, *28*, 17–22.
11. Klymenko, V.; Ovetskyi, S.; Martynenko, V.; Vytiaz, O.; Uhrynovskyi, A. An alternative method of methane production from deposits of subaquatic gas hydrates. *Min. Miner. Depos.* **2022**, *16*, 11–17. [\[CrossRef\]](#)
12. Ye, J.; Qin, X.; Xie, W.; Lu, H.; Ma, B.; Qiu, H.; Liang, J.; Lu, J.; Kuang, Z.; Lu, C.; et al. The second natural gas hydrate production test in the South China Sea. *China Geol.* **2020**, *3*, 197–209. [\[CrossRef\]](#)
13. Abid, K.; Spagnoli, G.; Teodoriu, C.; Falcone, G. Review of pressure coring systems for offshore gas hydrates research. *Underw. Technol.* **2015**, *33*, 19–30. [\[CrossRef\]](#)
14. Sun, J.; Ning, F.; Lei, H.; Gai, X.; Sanchez, M.; Lu, J.; Li, Y.; Liu, L.; Liu, C.; Wu, N.; et al. Wellbore stability analysis during drilling through marine gas hydrate-bearing sediments in Shenhu area: A case study. *J. Pet. Sci. Eng.* **2018**, *170*, 345–367. [\[CrossRef\]](#)
15. Li, X.; Xie, W.; Liu, A.; Yu, Y.; Xiong, L.; Yu, P.; Xiong, Z.; Feng, X.; Cui, S.; Zeng, J. New Research of Borehole Wall Protection Technology in Ocean Scientific Drilling. *Mar. Technol. Soc. J.* **2023**, *57*, 72–87. [\[CrossRef\]](#)
16. Schultheiss, P.J.; Francis, T.J.G.; Holland, M.; Roberts, J.A.; Amann, H.; Parkes, R.J.; Martin, D.; Rothfuss, M.; Tyunder, F.; Jackson, P.D. Pressure coring, logging and subsampling with the HYACINTH system. *Geol. Soc. Lond. Spec. Publ.* **2006**, *267*, 151–163. [\[CrossRef\]](#)
17. Liu, X.; Ruan, H.; Zhao, Y.; Cai, J.; Chen, Y.; Liang, T.; Li, C.; Liu, H.; Deng, D. Progress in research and application of the pressure-temperature core sampler for marine natural gas hydrate. *Drill. Eng.* **2021**, *48*, 33–39. [\[CrossRef\]](#)
18. Schultheiss, P.J.; Aumann, J.T.; Humphrey, G.D. Special session-gas hydrates: Pressure coring and pressure core analysis developments for the upcoming Gulf of Mexico Joint Industry Project Coring Expedition. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 3–6 May 2010.
19. Abegg, F.; Hohnberg, H.J.; Paper, T.; Bohrmann, G.; Freitag, J. Development and application of pressure-core-sampling systems for investigation of gas- and gas-hydrate-bearing sediments. *Deep Sea Res. Part I Ocean. Res. Pap.* **2008**, *55*, 1590–1599. [\[CrossRef\]](#)
20. Kubo, Y.; Mizuguchi, Y.; Inagaki, F.; Yamamoto, K.; Schultheiss, P.; Grigar, K. A new hybrid pressure coring system for the drilling vessel Chikyū. *Proc. Integr. Ocean Drill. Program* **2014**, *17*, 37–43. [\[CrossRef\]](#)
21. Holland, M.E.; Schultheiss, P.J.; Roberts, J.A. Gas hydrate saturation and morphology from analysis of pressure cores acquired in the Bay of Bengal during expedition NGHP-02, offshore India. *Mar. Pet. Geol.* **2019**, *108*, 407–423. [\[CrossRef\]](#)
22. Lee, Y.J. Gas Hydrate Exploration by using PCS (Pressure Core Sampler): ODP Leg 204. *Econ. Environ. Geol.* **2005**, *38*, 165–176.
23. Heeschen, K.U.; Hohnberg, H.J.; Haeckel, M.; Abegg, F.; Drews, M.; Bohrmann, G. In situ hydrocarbon concentrations from pressurized cores in surface sediments, Northern Gulf of Mexico. *Mar. Chem.* **2007**, *107*, 498–515. [\[CrossRef\]](#)
24. Inada, N.; Yamamoto, K. Data report: Hybrid Pressure Coring System tool review and summary of recovery result from gas-hydrate related coring in the Nankai Project. *Mar. Pet. Geol.* **2015**, *66*, 323–345. [\[CrossRef\]](#)
25. Guo, D.; Xie, H.; Chen, L.; Zhou, Z.; Lu, H.; Dai, L.; Wang, D.; Wang, T.; Li, J.; He, Z.; et al. In-situ pressure-preserved coring for deep exploration: Insight into the rotation behavior of the valve cover of a pressure controller. *Pet. Sci.* **2023**, *4*, 2386–2398. [\[CrossRef\]](#)
26. Yamamoto, K.; Inada, N.; Kubo, S.; Fujii, T.; Suzuki, K.; Nakatsuka, Y.; Ikawa, T.; Seki, M.; Konno, Y.; Yoneda, J.; et al. A Pressure Coring Operation and On-board Analyses of Methane Hydrate-bearing Samples. In Proceedings of the Offshore Technology Conference 2014, OTC 2014, Houston, TX, USA, 5–8 May 2014.
27. Guo, D.; Xie, H.; Gao, M.; Li, J.; He, Z.; Chen, L.; Li, C.; Zhao, L.; Wang, D.; Zhang, Y.; et al. In-situ pressure-preserved coring for deep oil and gas exploration: Design scheme for a coring tool and research on the in-situ pressure-preserving mechanism. *Energy* **2024**, *286*, 129519. [\[CrossRef\]](#)
28. Humphrey, G.; Holland, M.; Schultheiss, P. Wireline Coring and Analysis under Pressure: Recent Use and Future Developments of the HYACINTH System. *Sci. Drill.* **2009**, *7*, 44–50. [\[CrossRef\]](#)
29. Freudenthal, T.; Wefer, G. Drilling cores on the sea floor with the remote-controlled sea floor drilling rig MeBo. *Geosci. Instrum. Methods Data Syst.* **2013**, *2*, 329–337. [\[CrossRef\]](#)

30. Dickens, G.R.; Wallace, P.J.; Paull, C.K.; Borowski, W.S. Detection of methane gas hydrate in the pressure core sampler (PCS): Volume-pressure-time relations during controlled degassing experiments. *Proc. Ocean Drill. Program Sci. Results* **2020**, *164*, 113–126. [[CrossRef](#)]
31. Li, X.; Li, K.; Zhang, Y.; Wang, Z.; Shi, S. Development of Marine Gas-hydrate Pressure and Temperature Core Sampler. *Drill. Prod. Technol.* **2021**, *44*, 72–75.
32. Li, X.; Xiong, L.; Xie, W.; Gao, K.; Shao, Y.; Chen, Y.; Yu, Y.; Kou, B.; Lu, Q.; Zeng, J.; et al. Design and Experimental Study of Core Bit for Hard. Rock Drilling in Deep-Sea. *J. Mar. Sci. Eng.* **2023**, *11*, 306. [[CrossRef](#)]
33. Lu, C.; Zhang, T.; Xu, J.; Qiao, M.; Blinov, P.A.; Zhang, S.; Merzliakov, M.U. Development and experiment of pressure core sampler for marine natural gas hydrates. *Drill. Eng.* **2023**, *50*, 18–26.
34. Li, W. Design and Finite Element Analysis of Pressure Maintaining Coring Ball Valve. *Sci. Technol. Innov.* **2023**, *12*, 1–4.

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