Conceptual Study on Coring Systems to reach the Earth's Mantle and retrieve Core Samples

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ABSTRACT

The deep-sea drilling vessel (*D/V*) *Chikyu* is a riser-equipped, dynamically positioned scientific drill ship owned and operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and built for the purpose of scientific research and exploratory expeditions. The vessel is designed to access scientific targets deeper than previously attempted, to depths of 7000 m below the seafloor, in order to recover core samples in the deep oceanic crust. A wireline retrievable coring system has been adopted for more efficient operations, i.e., the inner core barrel including the core sample is retrieved through the drill pipe by a wireline. The core samples are then investigated for scientific analysis to elucidate the factors affecting global environmental change, earthquakes, biospheric conditions below the seafloor, and the mechanisms involved in volcanic eruptions. The *D/V Chikyu* is, thus, employed in exploratory expeditions which aim to drill to depths never before possible while also constantly optimizing operations, upgrading equipment and developing advanced technologies in deep sea drilling in order to attain the breakthrough goal of eventually reaching the earth's mantle.

Innovations and improvements of the drilling systems will be vital in order to withstand such extreme environments as temperatures of over 250 deg C and pressures greater than 1000 atm. Efforts are also focused on the development of new types of core barrels including a turbo corer, motor-driven core barrel (MDCB) and core bits as part of research into key technologies of national strategic importance. Constant calibration and improvement of equipment such as the core barrel parts will be carried out for efficient operations. This study introduces the present status in development as well as new conceptual designs and technological work being carried out for coring systems that can achieve high performance and efficiency even under extreme drilling environments.

1. INTRODUCTION

The deep sea drilling vessel (*D/V*) *Chikyu* (**Figure-1**) was completed in July, 2005 and measures 210 m in overall length, 38 m in breadth, and has a gross tonnage of approximately 57,000. The top of the derrick is located approximately 121 m above sea level. The vessel has been built for the purpose of scientific research and can carry out deep sea drilling up to a depth of 7000 m below the seafloor to recover core samples in deep underwater formations. The core samples are investigated for scientific analysis in elucidating the factors involved in environmental change, earthquake outbreak mechanisms, and deep biosphere and solid earth cycles below the seafloor (Kyo *et al.,* 2000). Our work is also part of multinational investigations in these areas under an international scientific effort called the Integrated Ocean Drilling Program (IODP). The *D/V Chikyu* is equipped with a riser subsea system and riser-pipes, currently of 2500 m and, in the future 4000 m, and two heave compensation systems, i.e., passive and active, which allow stable drilling and coring under rough sea conditions. Presently, the *D/V* Chikyu can drill to a vertical maximum depth of 9500 m (in 2500 m water depth) while aiming to eventually reach up to 11000 m (4000 m water depth).

Scientists have recently found remarkable differences in the kinds of rocks present within the upper mantle. While typical mantle rocks appeared in one of the holes, the other yielded mantle rock in combination with a significant amount of gabbro, a rock that makes up the lower layer of the ocean crust. Gabbro forms from molten rock, or magma, that rises out of the mantle and hardens deep within the crust. The finding of this rock in the mantle has led researchers to believe they have penetrated a fossilized conduit through which mantle magma rose into the crust. Researchers have also drilled a major hole into the gabbro rocks of the deep crust (Monastersky, 1993). The *D/V Chikyu* is, thus, involved in groundbreaking work to reach deep into the earth's crust with the eventual goal of reaching the earth's mantle and, in order to carry out this goal, improved and new drilling technologies are presently under development.

Figure 1: Deep-sea Drilling Vessel *Chikyu*

2. PRESENT CORING EQUIPMENT

The wireline coring system was adopted for more efficient operations onboard the *D/V Chikyu*. The inner core barrel including the core sample is retrieved through a drill pipe by a wireline. For the IODP expeditions, several kinds of wireline coring systems were deployed according to variations in formation hardness or strata. Currently, the temperature capacity of the coring equipment is still only 150 degree Celsius (deg C) since the rubber seals and o-rings are still unable to withstand such high temperatures as 250 deg C without distortion.

The Rotary Core Barrel (RCB) system (**Figure-2**) was designed for core retrieval in medium to hard formations. It is the simplest and yet most advantageous of the various coring systems and is configured to cut a core sample up to 9.5 m long with a diameter of 58 mm. A shorter core length often provides better core recovery, however, at the cost of longer expedition times due to the necessity for more frequent core-retrieval. The outer core barrel with bit is used both to trim the core and drill the hole for the bottom hole assembly (BHA). A modified version of a standard inner core barrel provides a non-rotating core tube to transfer the core sample into a clear plastic liner (Shinmoto *et al*., 2009). Previously, for shallow formations of less than 1000 meters below the seafloor, the roller cone bit was employed to recover the core samples. Presently, in scientific drilling with *Chikyu*, a 10-5/8" polycrystalline-diamond-compact (PDC) core bit is employed to enhance core recovery and quality. Using this 10-5/8" PDC bit, the borehole annulus can be enlarged and effective hole cleaning carried out to prevent clogging. However, with regard to bit design, it may be more suitable for hard formations. In any case, analysis of the core recovery as well as sample conditions (core quality) is significant not only for scientific purposes but for further improvement and development of the coring systems.

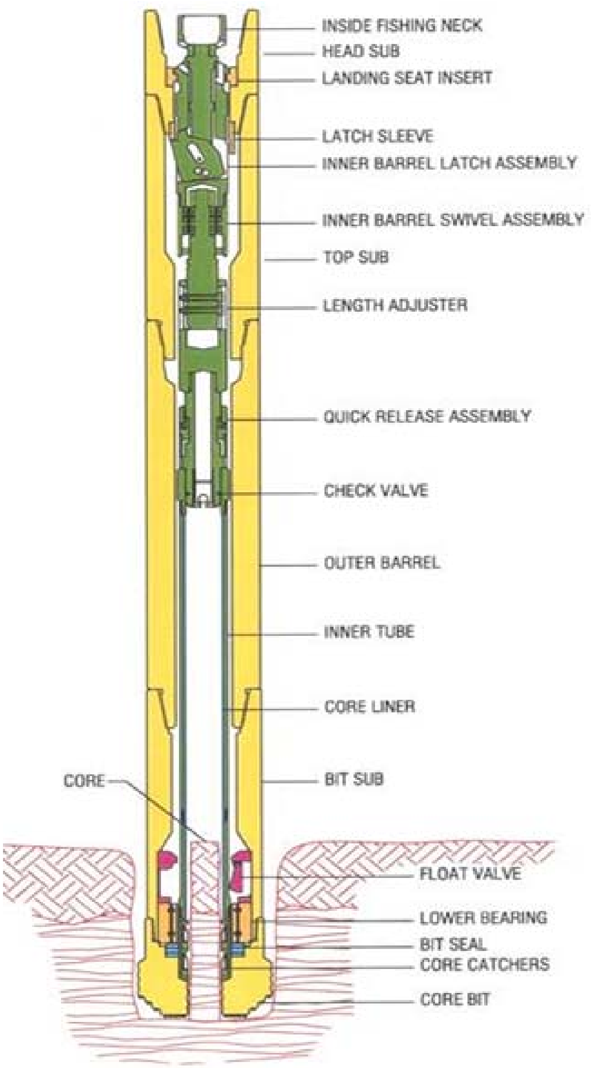


Figure 2: Rotary Core Barrel (RCB)

3. DEVELOPMENT OF NEW CORING SYSTEMS TO REACH THE EARTH'S MANTLE

Innovations and improvements of the drilling systems will be vital in order to withstand such harsh environments as mud circulating temperatures of over 250 deg C and pressures greater than 1000 atm during continuous drilling to reach the earth's mantle. We are finding that assumptions, practices and designs that had served us well in the past are no longer valid or suitable for operations in High Temperature/High Pressure (HT/HP) wells. The redesign of existing downhole equipment in order to develop improved or new equipment will be carried out using modern design aids to limit the risk of unexpected problems during product development and initial field application. An improved coring system for applications in deep ocean drilling that can withstand a HT/HP environment, such as a more efficient turbo corer and motor driven core barrel (MDCB), is now in the stage of conceptual design and testing. The target performance of such coring systems is shown in **Table-1**.

Table 1: Target Performance of the Coring Systems

	Turbo Corer	MDCB
Depth(m-bsf*)	0 ~ 7000	0 ~ 7000
Formation Type	Soft ~ Hard	Hard
Core Size (mm)	61.1~83.0	61.1
Core Length (m)	4.5	4.5
Core Bit Size (in.)	8-1/2"~10-5/8"	8-1/2" (3-3/4")**
Operating WOB (kN)	50~100	5~15
Operating Torque (N-m)	2000~3500	1000~2000
Rotary Speed (rpm)	100~200	200~600
Max. Temp. (degC)	250	250
Max. Pressure (MPa)	150	150
Flow Rate (l/min)	600 ~ 1100	600~950(150~300)**
Mud Weight (g/cm^3)	1.0 ~ 1.8	1.0 ~ 1.8

m-bsf *: meters below sea floor, MDCB( )** :for thruster section

3-1 Turbo Corer

When drilling to extreme depths, drill pipes will encounter much more friction so that drill bit efficiency will be lost as power from the surface Hydraulic Power Swivel (HPS) system lessens. Thus, more power at the bottom of the borehole will be required for extremely deep underwater formations. A RCB is no longer effective when coring at extreme drilling depths in vertical holes of over 7000 m-bsf. A conceptual design for a powerful and effective turbo corer is now being developed, as shown in **Figure-3**. This turbo corer consists of a power section (turbine, reduction gear), transmission section (spline coupling, shaft), and bearing section. There are 40 turbine stages on our newly developed turbo corer and the reduction gear has been adapted from Japanese automobiles. Basically, the bottom section such as inner core barrel is the same as the RCB. A turbine motor was found to be better for high temperature conditions and extended use compared to a positive displacement motor (PDM) which uses rubber components to prevent vibrations while turning but only have a maximum temperature capacity of 150 ~ 175 deg C and are, thus, prone to friction, melting and bending out of shape (Saito. *et al*., 2000). Although most turbo corers do not have reduction gear, our turbo corers have been developed to control and maintain appropriately high torque for efficient drilling. There are several types of turbo corers. With commonly used hollow type turbine corers (Tiraspolsky, 1985), the turbine motor section is located in the outer core barrel and is non-retrievable, remaining downhole even when damaged. Thus, development of a corer which allows retrieval of the turbine motor section and reduction gear have enabled constant maintenance and repair at the surface during coring operations.

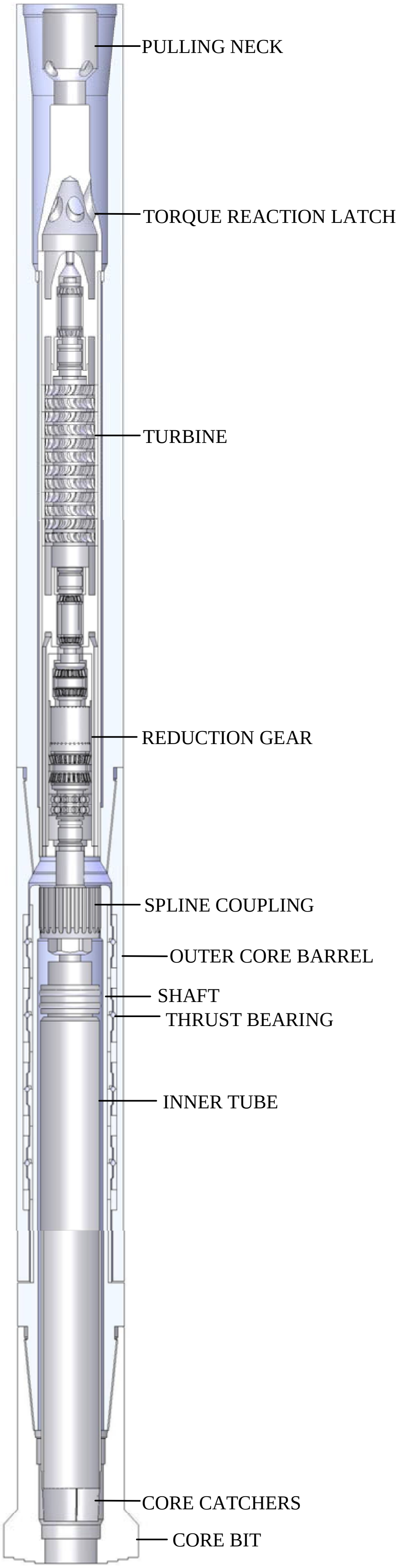
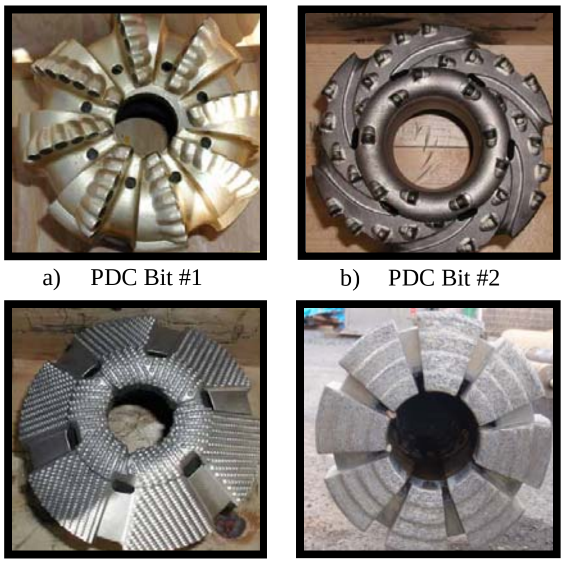


Figure 3: Schematic Design of the Turbo Corer

3-2 Core Bits

Drilling and coring in the deep ocean poses several challenges which limit the performance capabilities of currently used coring equipment and systems. Currently used coring bits are prone to damage and wear when drilling in extremely hard formations of a vertical intermediate section. Hard formations in a deep vertical section create a drilling environment subject to the risk of increased vibrations, which even in soft formations is capable of catastrophic damage to the BHA components, bit cutting structure and core sample quality (Karasawa *et. al.*, 1994). Several core bits have been developed specifically for deep sea scientific and exploratory drilling, i.e., for soft to hard formations. A traditional approach in core bit selection involves the recording of the actual bit performance as well as core recovery conditions. Careful and detailed analysis of the core bits and their performance under various conditions will be vital in order to achieve high core recovery and quality from mantle formations. Our newly developed core bits are shown in **Figure-4.** Two types of PDC core bits (a & b in **Figure-4)**, surface set diamond bit (SDB) (c in **Figure-4**) and the impregnated diamond bit (IDB) (d in **Figure-4)** are designed particularly for hard formations at extreme seafloor depths. The size of the PDC bits are 8-1/2”, 9-7/8”, 10-5/8” for PDC, 8-1/2”~9-7/8” for SDB and 8-1/2” & 7-1/4” for IDB. Currently, we have two types of core bits with differences in shapes for the cutters, matrix body and number of diamond tips and total flow area, depending on the different formation strata as well as hardness.



a) PDC Bit #1 b) PDC Bit #2

c) SDB d) IDB

Figure 4: Present Core Bits

3-3 MDCB

In addition to the turbo corer, an novel and more effective MDCB (**Figure-5**) is presently being developed. This is a wireline-retrievable coring system designed to improve recovery in formations that are difficult to core (e.g., hard, fractured crystalline rock, interbedded hard/soft formations, and friable conglomerate and reef materials) with a conventional wireline rotary core barrel (RCB). However, the MDCB can only be used to recover core for intermittent short intervals (a few to approximately 4.5 m of core) due to the long handling time to prepare the tool for consecutive coring runs. It must, therefore, be used in conjunction with a conventional core barrel such as the Small-Diameter RCB (SD-RCB). The MDCB consists of a motor section, thruster section, inner core barrel section, and core bit. The motor section is powered by the hydraulic force of fluid pumped down the drill string, causing the motor to rotate. The thruster section uses hydraulic force to provide appropriate weight on bit (WOB) and advance the inner core barrel. The inner core barrel section has a 4.5 m core tube with a core bit at the bottom. Compared to the RCB coring system, the MDCB is designed for higher revolutions per minute (rpm) with lower WOB and uses surface-set diamond or impregnated diamond core bits to recover cores from friable, laminated hard/soft and crystalline formations (IODP USIO 2005). The improved MDCB will apply less drilling stress to the formation and reduce rotational torque, improving core quality and recovery. The hydraulic force is translated into the WOB and interchangeable nozzles to optimize the WOB at various flow rates.

3-4 Core Barrel Components withstanding HT/HP

In order to reach the mantle, future projects will aim to expand drilling into deep formations of over 11,000 m total vertical drilling. This program targets the development of technologies allowing greater efficiency in operations at high temperatures of over 250 deg C so that the core barrel components are being designed for HT/HP endurance, e.g., by placing aluminum core liner along each tool. The bearings, seals and coring components are also being individually developed for extremely high temperature (250 deg C) and pressure (150 MPa) conditions.

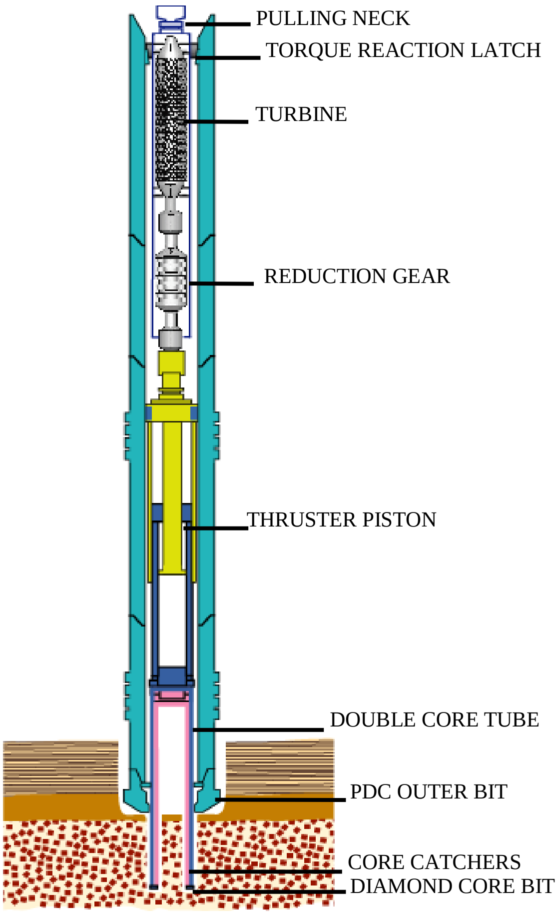


Figure 5: Schematic Drawing of the MDCB

4. COMPONENT TESTS

Present coring systems still need to be greatly improved to achieve the objectives of this project so that the capability and performance of the various components are also constantly evaluated for their feasibility and drillability through hard deep sea formations under extreme HT/HP conditions.

4-1 Turbo Corer

Turbo corer tests were carried out to estimate its capability for maintaining the required torque and how much drilling fluid pressure can be reduced with the turbine reduction gear as well as other tests to fine tune the smaller components.

4-1-1 Model Experiment

A model of the turbine motor which is a 1/2 scale size of the actual turbo corer is shown in **Figure-6**. The conceptual design has 40 turbine stages of rotors and stators. However, the component tests were carried out for just 5 stages using this scaled model which includes the reduction gear and spline coupling to estimate the performance of an actual size turbine motor. The mud weights in the tests were 1.35 g/cm^3.

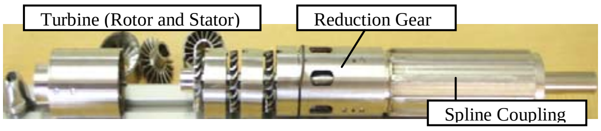


Figure 6: 1/2 Scale Turbine Motor

The actual operating torque required is 3500 N-m with a rotary speed of 100 rpm for the turbine motor including reduction gear. The fluid flow rates into the turbine stages were as high as 600 ~ 1100 l/min which are about the same flow rates for a RCB coring system and is, thus, effective for borehole stability and bringing the formation cuttings to the surface. The reduction gear was assembled with the spline coupling connected to the shaft to generate appropriate torque which is then measured by a torque meter.

4-1-2 Results of the Model Experiment

The 1/2 scale size experiments were carried out in order to obtain the performance curves for the power section. The actual turbine motor power, efficiency factor and torque can be converted using the equation below. A specific speed for the waterwheel formula can convert the 1/2 scale size test to the actual turbine motor performance curves. The following equation (1) can calculate the specific speed of the turbine while equation (2) is used to calculate torque and power in the full size turbine.

$$N = \frac{\Delta P^{\left(\frac{5}{4}\right)}}{P_t^{\left(\frac{1}{2}\right)}} N_s \qquad *** (1)$$

$$P_t = \frac{\pi}{30} * T * \left(\frac{N}{1000}\right) \qquad *** (2)$$

N_s: Specific speed of turbine (N_s = 66.7)

N: Rotation (rpm) of 1/2 scale turbine

P_t: Power by one stage of turbine

ΔP: Pressure drop of turbine.

T: Torque

The characteristic curves of the turbine motor are shown in **Figure-7**, as plotted using the equations. The curves indicate the performance for power P_t, torque T, efficiency factor η and pressure drop ΔP. The turbo corer is designed for 100 rpm, thus at the moment, 3500 N-m torque can be generated.

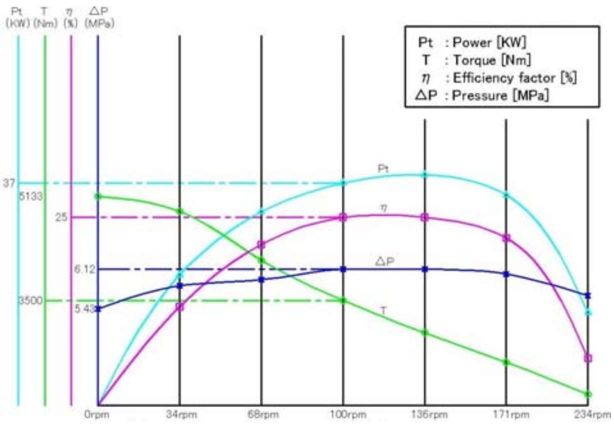


Figure 7: Characteristic Curves of the Turbine Motor

4-2 Core Bits Land Drilling Test

In order to evaluate core bit adoptability for various formations as well as to investigate core sample recovery and quality, land drilling tests were carried out. The field tests for instrumented drilling were carried out in Salt Lake City, U.S and Hitachi-Omiya City, Japan. A total of 53 rock samples were cored using RCB systems.

4-2-1 The Coring Equipment

Core bit land drilling tests were carried out using the core bits under development (Figure-3) assembled with the currently used core barrel (RCB). The instrumented drilling system used at the site is shown in **Figure-8**. Such factors as the rate of penetration (ROP), WOB, torque on bit T, rotary speed of pipe R, flow rate of drilling fluid Q, and pump pressure of drilling fluid P were recorded. The unit houses a computer as well as data logger. The data scan rate is 100 msec. All of the drilling parameters can be monitored on a display. The typical height of a sample rock is approximately 1 m with a width of 70 cm.

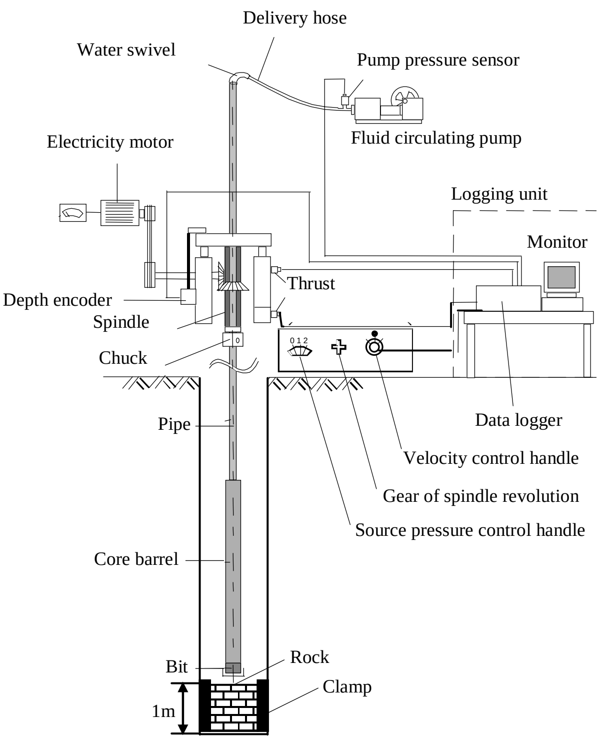


Figure 8: System of Land Drilling Test

4-2-2 Rock Properties

Table-2 shows the rock sample properties from the tests. The rock properties are classified according to their characteristics. The dry bulk density, porosity and unconfined compressive stress (UCS) are measured by a conventional geotechnical method based on Japanese Industrial Standards (JIS). The UCS of the sample rocks ranged from 7 ~ 492 MPa.

Table 2: Rock Properties for Land Drilling Test

Rock Name	Dry Bulk Density (g/cm^3)	Porosity (%)	UCS (MPa)
John Day Basalt	2.909	N/A*	492
Carthage Marble	2.667	N/A*	141
Colton Sand Stone	2.352	12.5	88
Castlegate Sandstone	1.951	27.2	19
Austin Chalk	1.974	27.3	25
Oya Green Tuff	1.370	38.5	7
Teppei Andesite	2.032	18.6	27

*N/A: Not Applicable

4-2-3 Results of the Tests

Figure-9 shows an example of a core sample (Teppei Andesite) using a RCB, PDC #1 bit and also presents such drilling parameters as the ROP, WOB, T, R, Q, and P versus depth. The ranges for the parameters were as follows: ROP: 1~3 mm/s, WOB: 40 ~ 50 kN, P: 1.0 ~ 2.0 MPa, Q= 950 l/min, R: 30 ~ 120 rpm, T: 1~2 kN-m, and similar to typical RCB operations drilling parameters.

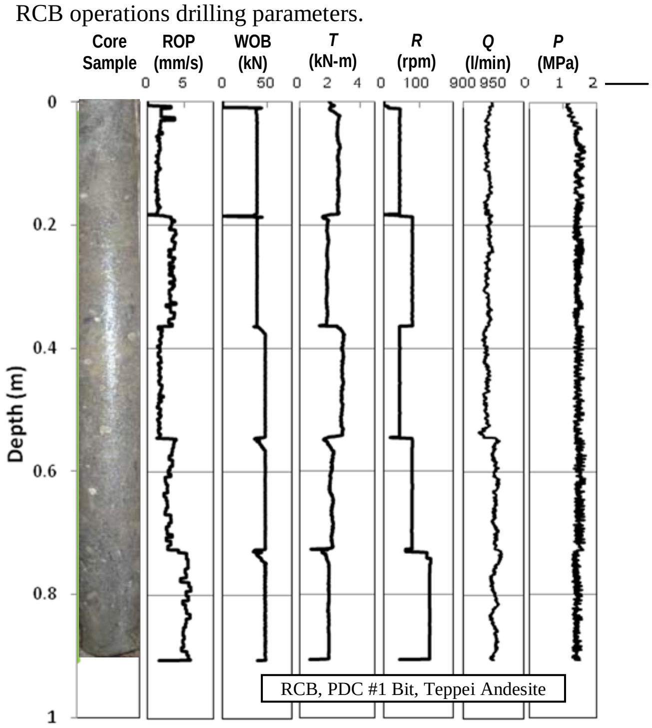


Figure 9: Core Sample and Drilling Parameter

4-2-4 Investigations on Core Quality

During the land drilling tests, a total of 53 core samples were successfully obtained by the newly developed core bits including the Roller Cone Bit (RC). The results were as follows: 13 core samples by PDC #1, 16 core samples by

PDC # 2, 6 core samples by RC, 7 core samples by SBD and 11 core samples by IDB. Efficiency and durability of the core bits are important factors, however, high core sample recovery and quality are the most essential points in their selection. Core quality was evaluated on a scale of 0 to 10. The scale definitions are shown in **Table-3** which also covers the core recovery rate or factors. 0 (zero) means no core.

Table 3: Core Quality Scale and Definitions

Core Quality	Definitions
10	Full size core, no surface imperfections
9	Full size core with marks on the surface
8	Full size core with a fracture within 2.5 cm
7	(not used)
6	Under size core, no surface imperfections
5	Under size core with marks on the surface
4	Under size core, with a fracture within 2.5 cm
3	Biscuits
2	Discs
1	Rubble
0	No core

The averaged core sample quality scales using the various core bits (PDC # 1 and #2, SDB, IDB) as well as the roller cone (RC) core bit, all with regard to the UCS, are shown in **Figure-10**. The UCS can identify formation hardness. IDB is more effective in terms of obtaining good core quality than RC for drilling in hard rock (UCS>140 MPa). Also, different types of PDC were adopted for different UCS. PDC#1 could core better quality samples than PDC #2 while SDB showed the ability to obtain high quality core in harder rock.

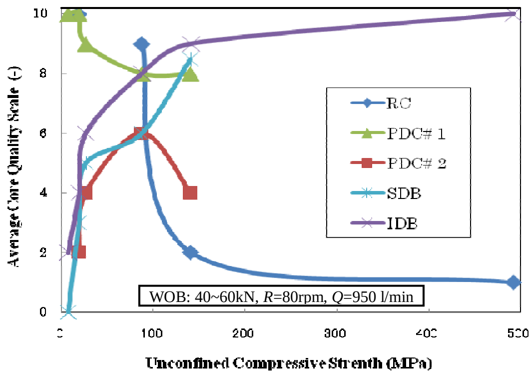


Figure 10: Core Sample Quality with regard to UCS

4-3 Thruster Section of MDCB

Since the improved motor driven core barrel (MDCB) applies less drilling stress to the formation, core quality and recovery in friable, fractured or crystalline formations can be enhanced. When the WOB can be controlled to provide a more uniform application of the weight to the bit, the diamond bit life and core recovery are significantly improved. Component development and testing were carried out for the muddy water drive-type core barrel, especially the flow quantity adjustment areas, to obtain performance data. The flow quantity was approximately 200 l/min from the thruster section. An improved special thruster section is also under development and tests were carried out to obtain the speed of the thruster section as well as the actual piston thrust which can be converted to WOB for efficient drilling operations.

4-3-1 Equipment

Test components of 1/1 size scale were manufactured and tests carried out. The piston rod distance was set at 2 m. The pressure sensors were installed both above and below the piston section. Pressure sensor P3 is located above the thruster section and the P2 sensor is below the thruster section, as shown in **Figure-11**.

Figure 11: Thruster Section Function Test

4-3-2 Results of the Experiments

The following equation was used to measure the thrust force from the hydraulic force into the piston rod.

$$F = \frac{P_3 - P_2}{A}$$

F: Thrust of the piston rod

P_3: Fluid pressure below the piston

P_2: Fluid pressure above the piston

A: Area of the piston rod

The results of the thrust force with regard to the flow rate are shown in **Figure-12**. Tests carried out with three types of mud weight (M.W). The thrust range was from 0.5 ~ 1.5kN which sufficiently meets the required specifications. The thrust did not depend on changes in the M.W.

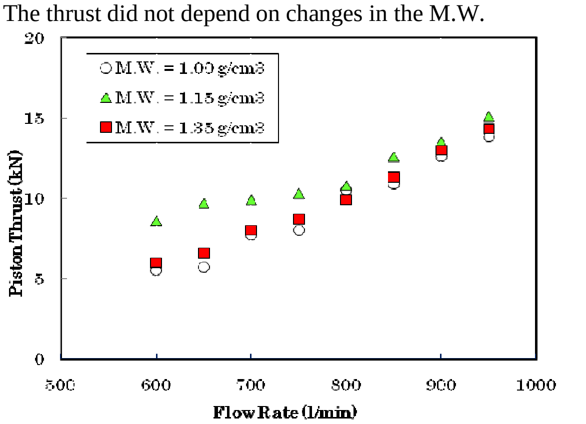


Figure 12: Thrust Force with regard to the Flow rate

4-4 O-rings

Newly developed rubber products were developed to withstand HT/HP conditions and heat resistant performance tests were carried out to examine their durability.

4-4-1 Equipment

The container used for the HT/HP tests is shown in **Figure-13**. The O-ring and backup ring are installed in the cylinder tube. The system can generate a temperature of 300 deg C as well as 68 MPa pressure conditions inside the container.

4-4-2 Test Conditions

Measurements of the temperature and pressure under HT/HP conditions inside the container are shown in **Figure-14**. From 11 hr to 83 hr, the temperature and pressure are almost stable (temperature tolerance 1 deg C and pressure tolerance 2~3 MPa). Testing was conducted for a total of 72 hours under HT/HP conditions, however, after 14 hours, the container top was opened and the o-rings removed to observe their condition as well as measure their diameter and hardness as compared to the accepted standard.

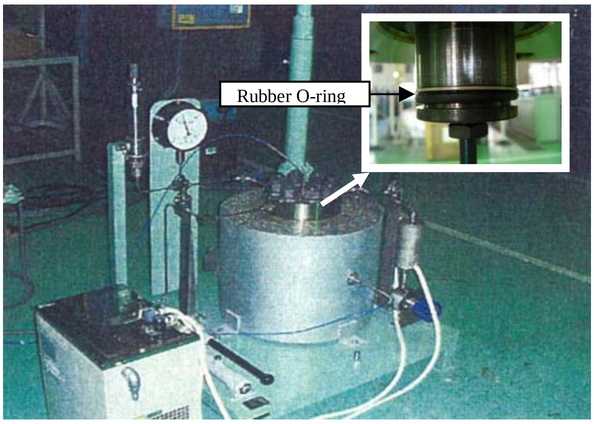


Figure 13: High Temperature (300 deg C) Test Equipment for the O-rings

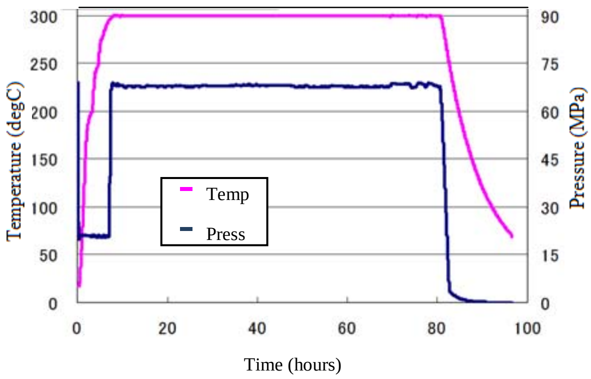


Figure 14: Simultaneous Pressure and Temperature Test at 68 MPa and up to 300 deg C

4-4-3 Results

Two types of o-rings were newly developed, i.e., O-ring A & B in **Figure-15**. The O-ring A showed good performance under HT/HP conditions while O-ring B was broken and the diameter highly distorted. For O-ring A, the rubber components were, thus, considered to be applicable for our project. These high temperature tests also showed that it was possible to design and build a HP/HT coring tool using rubber o-rings and seals specifically designed for high temperature environments of over 250 deg C.

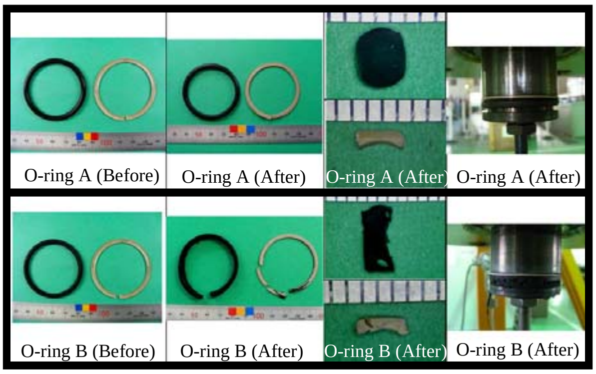


Figure 15: Results of O-ring HT (300 deg C) Testing

5. CONCLUDING REMARKS

This paper presents an overview of the technological developments being carried out in our coring systems and equipment as well as an outline of a conceptual study for deep sea drilling to retrieve core samples from the Earth's mantle.

1. The turbo corer is presently under development for more power under high temperature conditions. Tests were carried out on a 1/2 scale size model and results were obtained to estimate the power, efficiency factor and torque required for efficient drilling operations.

2. Coring tests using several types of core bits according to variations in rock formation hardness were carried out as represented by Unconfined Compressive Stress (UCS) to characterize core quality.

3. A motor-driven core barrel using a turbine motor is also under development. Component testing against extreme deep sea drilling conditions were carried out in order to clearly define the required improvements and modifications. A specially developed thruster section was also evaluated.

4. Material testing of the O-rings and other rubber components under HT/HP conditions was carried out and the 300 deg C capable O-ring was found to be applicable. Such components as the O-rings and seals are the most easily damaged in the core barrel assembly.

SI Metric Conversion Factors

Pressure	atm x 0.10	MPa
Length	in. (") x 2.54	cm

Nomenclatures

BHA	Bottom Hole Assembly
WOB	Weight on Bit
RPM	Revolutions per minute
HT/HP	High Temperature / High Pressure
UCS	Unconfined Compressive Strength
ROP	Rate of Penetration
RCB	Rotary Core Barrel
SD-RCB	Small-Diameter Rotary Core Barrel
MDCB	Motor Driven Core Barrel
PDC	Poly-Crystalline Diamond Compact
IDB	Impregnated Diamond Bit
SDB	Surface Set Diamond Bit
RC	Roller Cone
MW	Mud Weight

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