Journal of Power Sources 187 (2009) 253–260

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Practical application of a sea-water battery in deep-sea basin and its performance

Masanao Shinohara[a,*], Eiichiro Araki[b], Masashi Mochizuki[c], Toshihiko Kanazawa[a], Kiyoshi Suyehiro[b]

[a] Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[b] Japan Agency for Marine–Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan
[c] Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

ARTICLE INFO

Article history:
Available online 6 November 2008

Keywords:
Sea-water battery
Deep-sea application
Deep-sea basin
Sea floor long-term observation

ABSTRACT

Stable power supply is essential for various long-term sea floor geophysical observations. Due to a simple structure and a large energy capacity, sea-water batteries have been developed and used for such observations. However, the characteristics of sea-water batteries have not been well known in the case of installations at depths more than 5000 m in deep-sea basin. In 2000, a sea floor borehole broadband seismic observatory was installed in the northwestern Pacific basin where the water depth is 5577 m. For electric power supply, a Sea-Water Battery (SWB) system with monitoring and control was developed and used. The SWB system consists of four sea-water battery cells, a DC/DC converter, the Power Control System, the Data Logger, and an accumulator. The conditions of the SWB system were recorded more than 1 year, and the monitoring data was recovered. The SWB system generated enough power for the observation system consuming power of 6 W in average and continued to supply power for at least 5 years. From the monitoring data, the SWB can supply up to the long-term average of at least 13 W. The energy density is estimated to be 318 Wh kg^{-1}. The sea-water battery is useful for application of long-term power consumption even in the deep-sea basin.

1. Introduction

Stable and sufficient supply of electric power is one of the major difficulties for various geophysical observations on the sea floor. Therefore, power consumption of an observation system is limited by the power availability such as provided by a large amount of lithium batteries. In the case of observations with a period more than 1-year, the quantity of batteries becomes huge even using low-power instruments. Therefore, a large pressure vessel containing batteries is needed, because a normal battery cannot be exposed to sea-water. The energy capacity of present battery power system is not enough to meet the requirements for a long-term observation on the sea floor.

A slow-discharge sea-water battery is one of the solutions for long-term sea floor observations. The idea of sea-water batteries have been known for a long time [1–7]. Most of sea-water batteries used metal anodes and sea-water as an electrolyte with cathodes. The SWB600/1200 were developed by Kongsberg Simrad AS, Norway [8] and used in shallow water depth. The principle of the SWB600/1200 is described in Hasvold et al. [9]. Its energy comes from electrolytic dissolution of the magnesium anode. The SWB600/1200 has a magnesium rod anode, and a cathode composed of carbon fibers. The advantages of the SWB600/1200 are high energy density, low cost, safety characteristics and an infinite storage capability [8,9].

There are a few studies for the sea-water battery for deep-sea application. Wilcock and Kauffman [10] carried out a deep-water test in the NE Pacific where water depth is 2200 m using magnesium–graphite and magnesium–copper batteries. They showed the output voltage from cell of sea-water battery decreased in deep-water in comparison with that in shallow water depth. Watanabe et al. [11] improved the SWB600 for deep-water depth more than 6000 m and found that single cell of the SWB600 generated an electric power of 2 W at the depth of about 700 m.

In 2000, a sea floor borehole broadband seismic observatory (WP-2) was installed in the northwestern Pacific basin during Ocean Drilling Program (ODP) Leg 191 [12] to obtain data for a study of the Earth's interior. The WP-2 is located in the northwest Pacific ocean east of Japan (Fig. 1) and the water depth is 5577 m. The data from WP-2 were acquired autonomously in the data module that was recovered using a Remotely Operated Vehicle (ROV). For stable electric power supply for the WP-2 system, a Sea-Water Battery (SWB) system with a power control and monitoring system was developed to be based on the SWB1200 by Kongsberg Simrad AS [8] and the results of Watanabe et al. [11]. The WP-2 continued a seismic observation for approximately 5 years and 436 days of

* Corresponding author. Tel.: +81 3 5841 5794; fax: +81 3 5841 8265.
E-mail address: mshino@eri.u-tokyo.ac.jp (M. Shinohara).

0378-7753/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2008.10.105

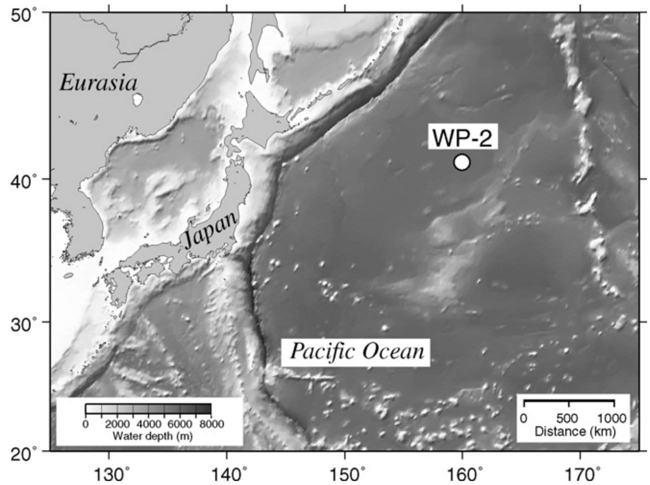

Fig. 1. Location map of the WP-2 where the Sea-Water Battery system was installed on the sea floor as a power source for a borehole boardband seismic observation system. Water depth of the WP-2 site is 5577 m.

continuous seismic data were recovered in total [13]. This was one of the first practical application of the sea-water battery in deep-sea basin. The conditions of the SWB system were recorded by the monitoring system which was developed for the WP-2 system. The objectives of this paper are to describe the SWB system we developed and to evaluate system performance using the data from the monitoring system of the SWB installed in deep-sea basin.

2. The WP-2 sea floor borehole broadband seismological observatory

We outline the system of the borehole broadband seismic observatory WP-2 (Fig. 2). The details of the WP-2 observatory system are

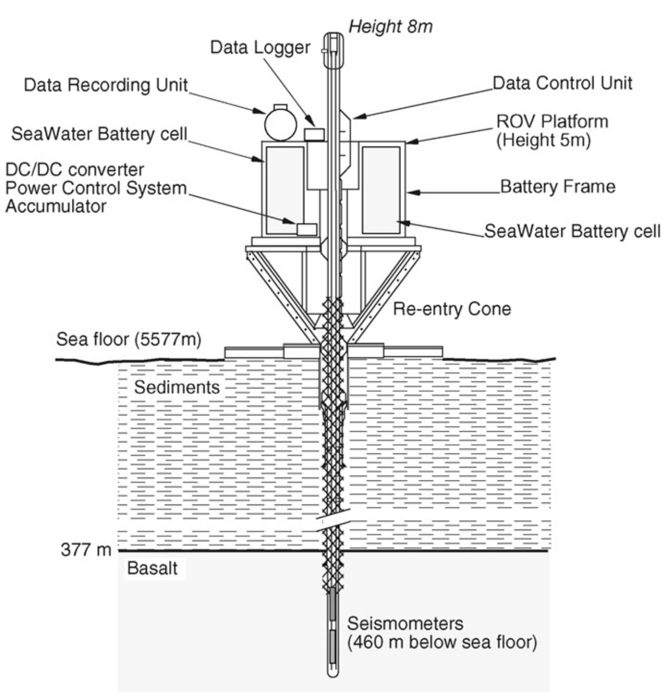

Fig. 2. Schematic diagram of the system of the WP-2 borehole seismological observatory. The four sea-water battery cells are positioned on the re-entry cone. The Data Logger is put on the top of the Battery Frame.

described in Shinohara et al. [14]. The observatory was designed to last for many years as a stand-alone system with its own batteries and recorder. The two seismometers were placed near the bottom of the hole, each housed in a separate pressure vessel. Both sensors were feedback-type broadband seismometers (Güralp Systems Ltd., CMG-1T). Two separate cables are required to connect the sensors uphole. The signals are digitized in the sensor packages and sent in digital form to the sea floor packages. The depth of the seismometers is approximately 460 m below the sea floor [12].

The Data Control Unit (DCU) on the sea floor combines the digital data from the two seismometers into a single serial data stream. It also distributes power to the individual seismometers. The data are stored in digital format in a Data Recording Unit (DRU) after being sent via an RS232C link. The DRU has hard disks capable of storing more than six channels of 1.5-year long continuous data of 24 bits dynamic range at 100 Hz sampling rate. The seismometers are emplaced in the borehole permanently; they are cemented into the hole as required to assure good coupling. The DCU accepts commands and software upgrades through the DRU which has to be replaced by an ROV or submersible before the hard disks become full. The DRU provides a communication link to the borehole system while the station is being serviced by the ROV. The DRU can send part of the data to the surface across a serial link to check the health of the system.

To know the exact power consumption of the system is important for the design of the power supply system. We evaluated the system power consumption of the WP-2 system before the installation. When all the seismometers are running, we expect the power consumption of the whole system over a long period to be 9.1 W. Because two seismometers are identical (one is back-up), operating one seismometer is enough for a seismic observation. In such case, the power consumption of the total system reduces to about 6 W. The power management program in the DCU is designed to turn off one seismometer in the case that capacity from the power supply becomes less than 9 W.

The WP-2 observatory was activated in October 2000 using the ROV *KAIKO* of the Japan Agency for Marine–Earth Science and Technology (JAMSTEC). In August 2001, the *KAIKO* re-visited the WP-2 site, and retrieved 92 days of continuous data. The *KAIKO* visited the WP-2 site again in June 2002, and 330 days of continuous data were recovered. The *KAIKO* visited the WP-2 site at the end of July 2005, and 14 days of continuous data were recovered. In total, 436 days of continuous broadband data were recovered [13].

All the necessary power is supplied from the SWB system which was developed for the WP-2 system based on the SWB1200 system by Kongsberg Simrad AS [8]. Designed output power of the SWB system for the WP-2 system was expected to be up to 24 W. The conditions of the SWB system are monitored by the Power Control System (PCS), and data from the PCS are recorded in the Data Logger (DL). In addition, the PCS controls the power switch and will turn the switch off for the protection of the system under certain SWB conditions.

3. Sea-Water Battery system and monitoring data

3.1. The SWB cells

The power for the WP-2 system is supplied by the SWB system. The SWB system consists of four SWB1200 cells [8,9], a DC/DC converter, the PCS, the DL, and an accumulator (Fig. 3). The cell is a magnesium/oxygen battery based on a magnesium anode, which uses sea-water as the electrolyte and oxygen dissolved in the sea-water as the oxidant [8].

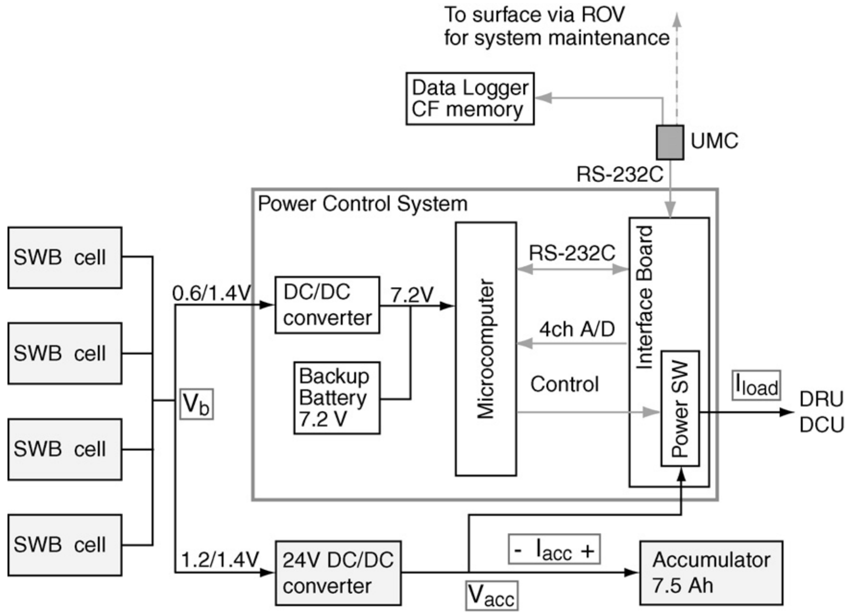

Fig. 3. Schematic diagram of the SWB system. The SWB system consists of four SWB1200 cells [8,9], a canister containing the 24-V DC/DC converter and the Power Control System, and the canisters of the accumulator and the Data Logger (DL). The DL is connected to the PCS using an underwater mateable connector (UMC). The PCS can be accessed using a remotely operated vehicle (ROV). The PCS consists of the interface board, the microcomputer, the DC/DC converter, and the backup battery. The PCS controls the power to DRU and DCU. The voltages (V_b and V_{acc}) are directly measured by an A/D converter on the PCS. The currents (I_{acc} and I_{load}) are estimated by measurement of the voltage drop of a resistor with a small value, which is serially connected to the power line.

The chemistry of the cell is the dissolution of magnesium at the anode and consumption of oxygen at the cathode, which is written in form

$$2Mg + O_2 + 2H_2O = 2Mg(OH)_2.$$

A calcareous deposit results from the formation of an alkaline product at the cathode,

$$4Ca^{2+} + 4HCO_3{}^- + 4OH^- = 4CaCO_3 + 4H_2O.$$

The alkaline reaction products need to be removed from the cathode surface by the sea current because the calcareous formation disturbs the second reaction at the cathode [9].

The anode is a magnesium alloy rod with a diameter of 0.184 m and length of 2.2 m [8], and needs to be replaced once it is consumed. The replacement of the anode is designed to be handled by an ROV or submersible. The cathode elements surround the anode and the cathode frame is made from titanium. The weight in air of the anode and the titanium cathode frame are 120 and 40 kg, respectively. The cathode element consists of a titanium wire and carbon fiber elements [9]. The cathode collector lead (titanium wire) is connected to the titanium frame, which is also part of the cathode. Because the titanium frame is designed to allow sea-water to pass easily, the cell so that oxygen-rich sea-water is supplied to the cathode and the products of the cell reactions are removed.

The cell voltage is approximately 1.6 V, although the cell voltage largely depends on the conductivity of the sea-water, which varies with the temperature and salinity [8,9]. In order to produce the designed output of 6 W for each cell, a minimum circulation of 20 mm s^{-1}, an oxygen concentration of 3 ppm, and a salinity of 20 was expected [8]. Because the isolation between cells is low, the cells are connected in parallel (Fig. 3).

The DC/DC converter [8] transforms the low cell voltage (1.6 V) into the output voltage (24 V). The output of the DC/DC converter is connected to the accumulator, which averages the power demand on the DC/DC converter and the cells. The DC/DC converter is inactive until the cell voltage becomes larger than 1.41 V. After the cell voltage is higher than 1.41 V, the DC/DC converter takes power from the cells and charges the accumulator as long as a sufficient cell voltage which is larger than 1.41 V is available. If the cell voltage becomes smaller than 1.20 V, the DC/DC converter becomes inactive until the cell voltage rises to 1.41 V.

The accumulator consists of multiple lead acid cells with a voltage of 2 V and an energy capacity of 7.5 Ah [8]. The accumulator cell is electric float-charged by the DC/DC converter output (Fig. 3). When the voltage of the accumulator becomes 25.7 V, the accumulator cell is fully charged and has no charging from the DC/DC converter [8]. A 6500-m depth-rating pressure vessel contains the accumulator. The SWB cells, DC/DC converter and accumulator have been originally developed by Kongsberg Simrad AS [8] based on Hasvold et al. [9].

3.2. Power Control System

It is difficult to estimate the performance of the sea-water battery prior to deployment in a deep-sea basin, because the performance of the sea-water battery strongly depends on the sea-water environment. And, there are few chances of system maintenance on the sea floor using an ROV or submersible due to its depth. Voltages and currents of each part of the system are indispensable information to estimate a performance of the SWB system. In addition, the SWB system must be protected from over-discharge which may cause a complete damage of the SWB system at any conditions. Because the recovery of the whole SWB system from the WP-2 site is very difficult, we must avoid malfunction of the SWB system. For a use of the sea-water battery as power supply of the seismic observation system, we add the functions of monitoring the system condition and control of supplying power to an existing sea-water battery.

The PCS is one of the developed parts for the WP-2 system. The purposes of the PCS are to monitor the voltages and currents of the SWB cells, the accumulator, and the output of the SWB system and to control the power switch of the SWB system to protect the accumulator from over-discharge. The DC/DC converter and the PCS are contained in the same capsule.

The PCS monitors the conditions of the SWB using A/D converter, and time information is added to the monitoring data. The data are sent to the DL by an RS232C connection. Because the Underwater Mating Connector (UMC) is used for the connection between the PCS and the DL, we can check and control the PCS directly using an ROV by establishing a link of the PCS and a computer on a mother ship of the ROV.

A microcomputer, an interface board, a small DC/DC converter, and a backup battery compose the PCS (Fig. 3). The PCS monitors the input voltage to the DC/DC converter and all the output voltage and current distributed from the accumulator. The microcomputer has a four-channel A/D converter to measure voltages and currents. The A/D converter in the microcomputer samples the voltage of the SWB cells (V_b), the voltage of the accumulator (V_{acc}), the current for the load (I_{load}), and the current of the accumulator input (I_{acc}) (Fig. 3). The direction of electric current to the accumulator is also monitored, in other words, we can find whether the accumulator is charging or discharging. The sampling interval can be changed by sending commands to the microcomputer by the RS232C link.

The microprocessor controls the power switch on the interface board. The microprocessor immediately turns off the power switch to protect the accumulator, when the voltage of the accumulator is smaller than 18 V. The PCS also turns off the power switch when the accumulator voltage is smaller than 20.8 V and the current runs less than 0.5 A for 20 min, continuously. When the voltage of the accumulator becomes larger than 26.5 V for 20 min, continuously, the PCS turns on the power switch again. The power is supplied by a small DC/DC converter to the PCS from the SWB cells. The DC/DC converter for the PCS is the same as that for the accumulator, however, the active voltage differs. When the voltage from the SWB cells becomes larger than 1.4 V, the PCS DC/DC converter is active. When the voltage of the SWB cells becomes small than 0.6 V, the PCS DC/DC converter stops the work. The PCS has a backup battery and a lifetime of the backup battery is more than 250 days. The PCS samples the data every 60 s in defaults mode and transmits the data via an RS232C with asynchronous procedure. After the transmission of the data, the PCS makes decision of turning the external load switch on or off according to the voltage and current limits.

A setting of the PCS can be changed through an RS232C link. A sampling interval of the data can be changed and voltages and current can be read at any time through an RS232C link. The power switch is also controlled by sending a command to the PCS. A real-time clock can be read and set through an RS232C link.

3.3. Data Logger

The DL is also developed for the WP-2 system. The DL consists of a single card computer with a serial interface and a Compact Flash (CF) memory as a storage device. Lithium batteries supply the power to the DL. When the PCS starts sending data over a serial communication line, the DL receives the data from the PCS and saves them to the CF memory. The data consist of current and voltage readings (V_b, V_{acc}, I_{acc}, I_{load}) from the DC/DC converter and the accumulator with time. The status of the power switch in the PCS is also included in the data. When the CF memory has reached its data-storage capacity, logging of data from the PCS is stopped. The recording period of the DL depends on capacity of the CF memory and a CF memory with 10 MB can be stored more than 160 days data at sampling interval of 60 s. The DL accepts a CF memory with capacity of up to 64 MB. The DL is housed in a pressure vessel with a 6500 m depth-rating. The vessel is retrieved by an ROV because the DL and the PCS are connected using the UMC.

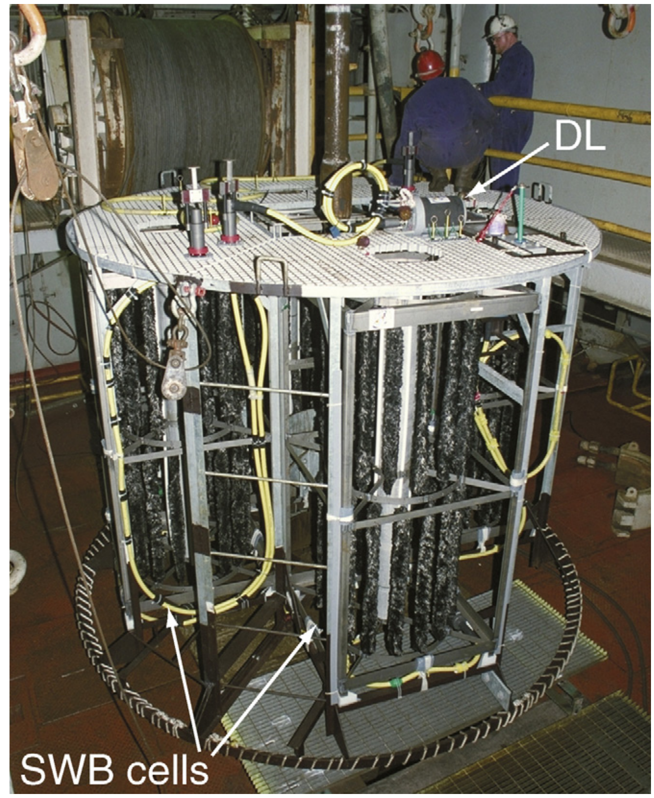

Fig. 4. Photograph of the Battery Frame in the moonpool area of the drilling vessel *JOIDES Resolution* (August, 2000).

3.4. Mounting frame for the SWB

The cylindrical frame (BF) is developed for mounting of the SWB system (Fig. 4) and is sitting on a re-entry cone of the drilling hole. Four SWB cells [8,9] are positioned in concentric positions. The BF is made of steels coated with zinc, and base of the BF is also coated with tar epoxy paint to protect from corrosion. The titanium frame of the SWB cell, the stainless steel pressure housings for the DC/DC converter, and the accumulator are mounted on the BF with polyvinyl chloride insulators. The top of the BF is covered with fiber-reinforced plastic drain-board and has holes to access the SWB anodes. The top panel is also used as the ROV platform. The diameter of the top panel is 3.2 m, and the diameter of the bottom of the BF is 3.66 m, which corresponds to the diameter of the re-entry cone. The SWB cells are lifted in order to improve the seawater circulation through the cells. On the top panel, the UMC from the SWB system for the DL or connection to an ROV is mounted. The DL is deployed on the top panel of the BF (Fig. 4).

3.5. Installation of the SWB system and data recovery

The installation of the WP-2 system was performed in August, 2000. After fixing seismometers at the bottom of the deep borehole by cementing, the BF was assembled onboard. Then the BF was lowered through the moon pool on drilling deck of the D/V *JOIDES Resolution*. When the BF reached the re-entry cone, the BF was disconnected from the ship using an acoustic release system. The WP-2 system was deployed at the water depth of 5577 m. The DL started the recording just before deployment of the BF.

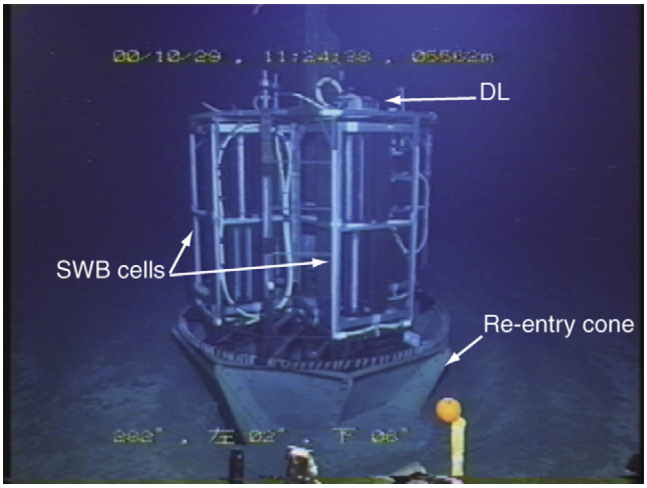

Fig. 5. An ROV view of the Battery Frame on the re-entry cone at the WP-2 (October, 2000).

The WP-2 observatory was activated in October 2000 using the ROV *KAIKO* (Fig. 5). Since the performance of the SWB system depends on the environment around the deployed position, there was a possibility that SWB could not generate enough power for the whole observation system. Therefore, we decided to operate WP-2 using only lithium batteries during the first observation period as the preliminary observation. We recovered the DL on the top of the BF by using the *KAIKO*. In addition, we deployed a moored buoy near the WP-2 in order to measure sea-water current on sea floor for 1-day.

In August 2001, the *KAIKO* re-visited the WP-2. During the second visit, it was confirmed that the SWB system continued working properly by using the ROV link. Therefore, our long-term observation using both the SWB and backup lithium battery system was started. We also deployed the DL to monitor the SWB. When the SWB generates an enough electric power for the observation system, the power is supplied to the observation system from the SWB system. If the SWB cannot generate the power, the backup lithium battery system supplies the power to the observation system. The *KAIKO* recovered the monitoring data of the SWB system during the third visit in June 2002. Consequently, we obtained the monitoring data of the SWB system for two period; the first monitoring period is from August 2000 to October 2000, the second monitoring period is from August 2001 to June 2002.

3.6. Recovered data

For the first monitoring period, we obtained the continuous data for about 66 days (Fig. 6). The data include the period of the WP-2 installation. For most period of the data, the SWB had no electric load. At the end of the first period, the seismometer system was powered up to evaluate a performance of the SWB system (Fig. 7). The SWB cell started voltage generation immediately when the SWB cell went to the sea, and constant cell voltage was observed for most of the period. At the end of the period, we deployed a current meter near the SWB system. Sea-water current can be compared with the SWB cell voltage (Fig. 8).

During the second monitoring period, the WP-2 observation system worked properly through the whole period. Only one of two seismometers was powered up in order to reduce power consumption. In addition, hard disks were spin up every day to write the data of the seismometer (Fig. 9). Maximum current reached 0.8 A during the disk writing. Average current is 0.6 A for writing the data

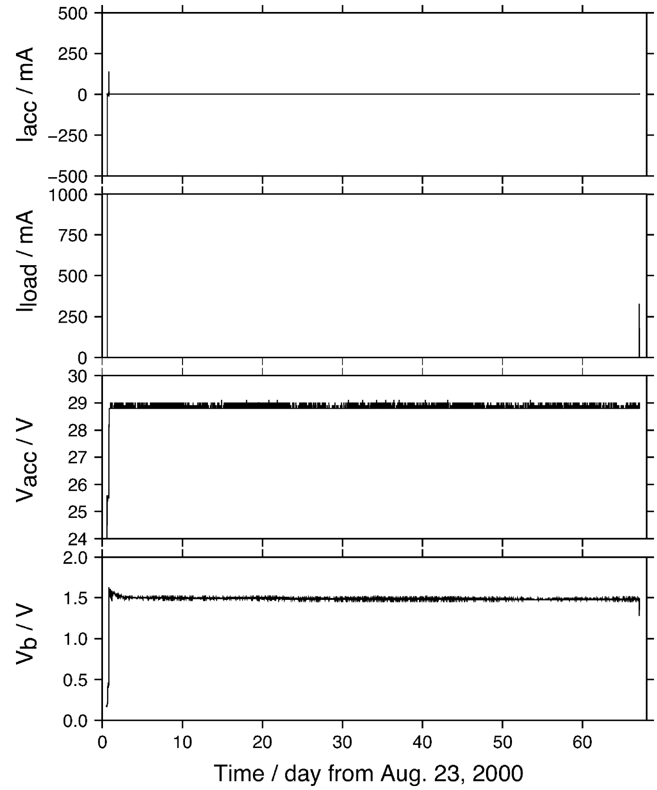

Fig. 6. Records from the PCS at the WP-2 during the first observation period (August–October, 2000). The data were stored in the DL. During most of this period, no power was supplied from the SWB system. Without a power load, a stable cell voltage (V_b) of 1.5 V was observed during all the period.

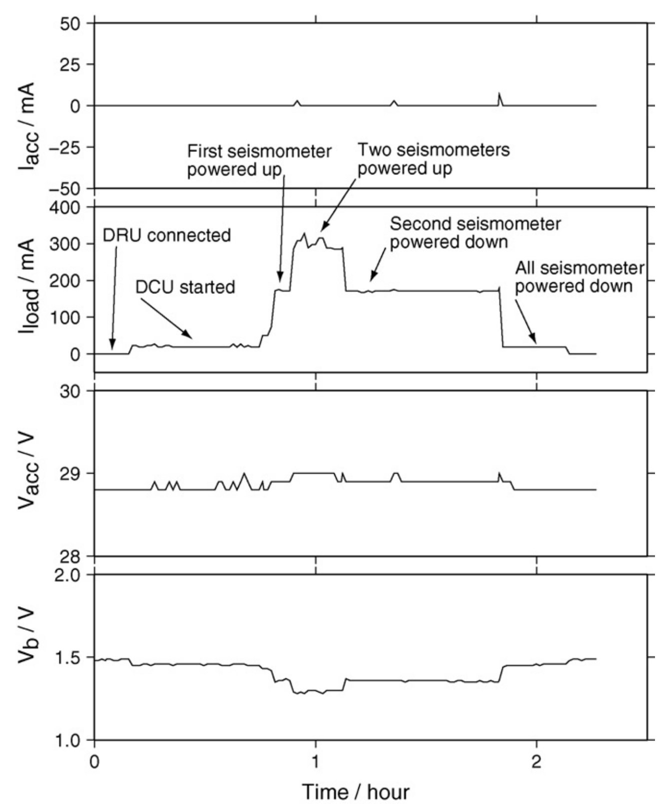

Fig. 7. Results of the performance test on the deep-sea floor carried out at the end of the first observation period. During the test, no current from/to the accumulator was observed. The cell voltage is inversely correlated to consuming power.

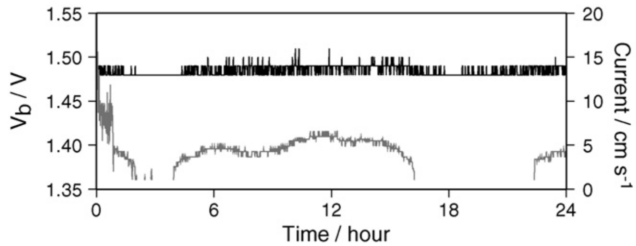

Fig. 8. Comparison the sea-water current with the voltage of the SWB cell. Black line and grey line indicate the cell voltage and the sea-water current, respectively. The sea-water current meter was installed close to the WP-2 and cannot measure currents with speed of less than 1.1 cm s^{-1}. A strong correlation between the cell voltage and the sea-water current was not observed.

to the disk, and an output voltage from the SWB system downed to approximately 24 V (Fig. 10). In addition, sometimes the cell voltage became less than 1.2 V. When the cell voltage becomes less than 1.2 V, the DC/DC converter stops working. This means that the electric power was sometimes supplied from the accumulator only during the disk writing. Duration of the writing the data was about 40 min. After finishing the disk writing, the accumulator still supplied the power to the system due to a low voltage from the cell. After the disk writing, the output voltage of the SWB cell gradually increased in some cases. Then 6 h later from a finish of the disk writing, the cell voltage became stable and the accumulator was full-charged. However, the SWB system always supplied the power to the WP-2 system, because the PCS never switched off the power switch during all the period of the observation.

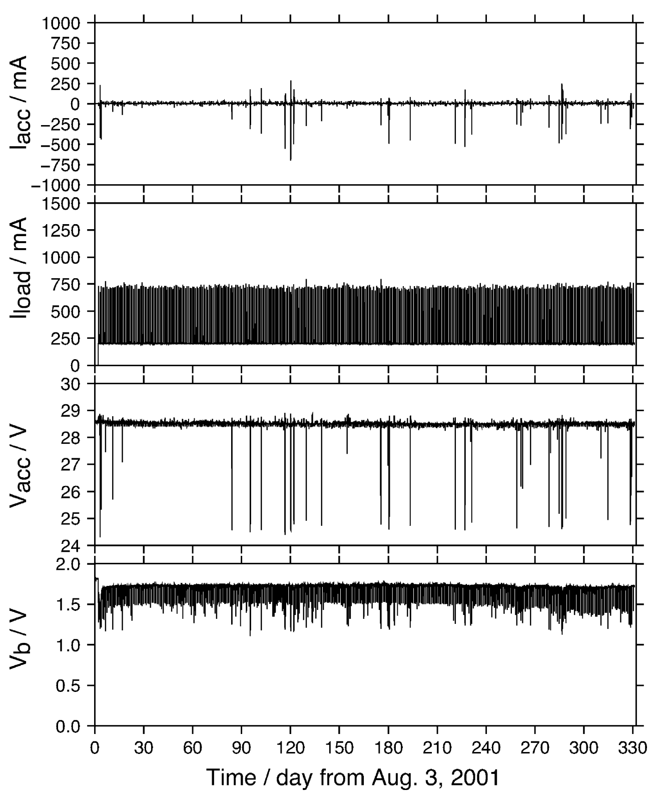

Fig. 9. Records from the PCS at the WP-2 during the second observation period (August, 2001–June, 2002). Voltages and currents are smoothed with 10 min running mean. During the second period, power for the WP-2 system was supplied from the SWB system, and the cell voltage (V_b) increased to approximately 1.7 V in average.

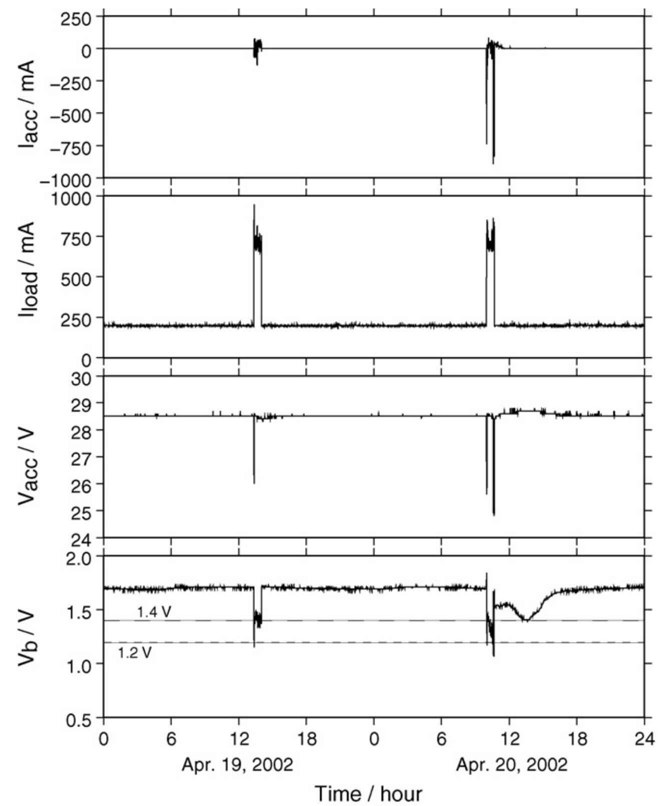

Fig. 10. Variation of voltages and currents in the SWB system for two days in the second observation period. Large currents corresponded to spinning up of the hard disk of the DRU, and the cell voltages decreased during large power consumption.

4. Discussion

From the first period measurement, the SWB cells were confirmed to generate the electric power even in the deep-sea basin where sea-water depth is more than 5000 m. Watanabe et al. [12] complied a vertical profile of dissolved oxygen up to 4000 m in the northwestern Pacific from the database of Japan Oceanographic Data Center. The minimum dissolved oxygen is observed at a depth of about 800 m. Below this depth, the density of dissolved oxygen increases gradually with depths. At the depth of 4000 m, the density of the dissolved oxygen reaches 3 ml l^{-1}. The water depth of the WP-2 is 5577 m. It is estimated that the density of the dissolved oxygen is enough for the SWB cell. In addition, the SWB needs water current for generation of the power. We compare the cell voltage with the sea-water current observed at the sea floor by a current meter. However, there is not a strong correlation between the sea-water current and the cell voltage (Fig. 8). Note that our current meter could not measure the current with a speed of less than 1.1 cm s^{-1}. This indicates that the small sea-water current may be useful for the SWB cell in the deep-sea basin circumstance.

At the end of the first observation period, we carried out a performance test for the SWB system at the WP-2. For the WP-2 system, each part of the system can be powered up separately. Therefore we turned on each part to observe the performance of the SWB system (Fig. 7). An electric current from/to the accumulator could not observed during the test. This means that we measured the performance of only the SWB cell and the DC/DC converter. The total output power is inversely correlated to the cell voltage (Fig. 11). When we consumed the electric power of 9 W, the cell voltage was 1.25 V. When the cell voltage is smaller than 1.2 V, the DC/DC

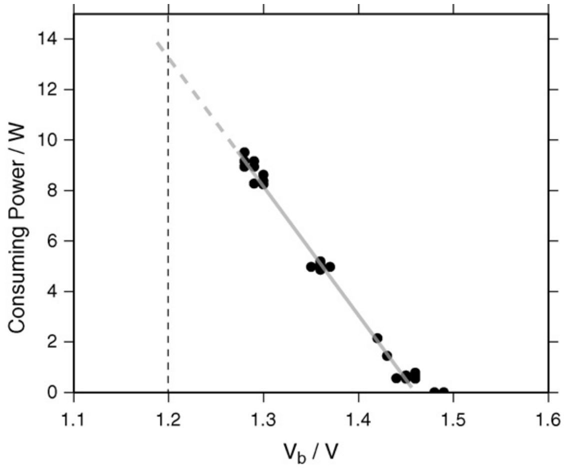

Fig. 11. Variation of supplied power with the cell voltage during the first observation period. The total output power is inversely correlated to the cell voltage. Because the 24 V DC/DC convert stops working at 1.2 V of input voltage, the SWB seems to be able to supply the average power of at least 13 W.

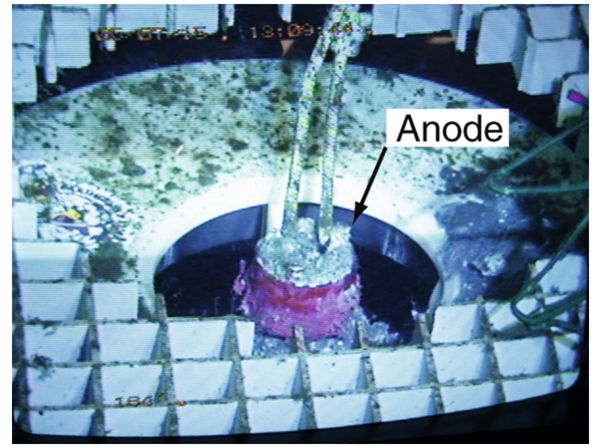

Fig. 12. Photograph of the anode in the WP-2 system (July, 2005). The SWB spent about 5 years in the deep-sea basin. Most of the anode was dissolved.

converter stops working. The cell voltage of 1.2 V is estimated to correspond to the power of 13 W. From this observation, we conclude that the long-term average of a consuming power should be less than 13 W for our system. In other words, the SWB at the WP-2 can supply the average power of at least 13 W. Because the maximum power consumption of our seismometer system is approximately 9 W, the SWB system generates the enough power for the seismic observation system.

For the second monitoring period, the WP-2 seismometer system took power from the SWB system. The long-term average power consumption of the WP-2 system could be found to be 6.14 W by the monitoring data. This power consumption included one seismometer, the DRU and the DCU. Another seismometer was powered down in order to reduce power consumption. The DRU contained four 3.5-in. Hard Disks (HDs) which were power-on every day. A duration of power-on was 40 min. The average power consumption during the HDs were powered up was 20.0 W. Form the result of the performance test, the DC/DC converter was estimated to be stopped working when output power is more than 13 W. From the monitoring data of the DL, the output voltage of the SWB sometimes dropped to approximately 24 V and the current from the accumulator was observed. After the data writing was finished, the current from/to the accumulator fluctuated for a next few hours. We interpret that the power was sometimes supplied from the accumulator when the HDs in the DRU were powered on. After the writing, the power consumption of the WP-2 system became small, however, the accumulator needed the power for charging. Because the cell voltage sometimes dropped to less than 1.2 V due to the charging of the accumulator, the scatter of the current from/to the accumulator was observed. After finishing the charging of the accumulator, the current form/to the accumulator and the cell voltage became stable.

Average voltages of the SWB cell differed for the first observation period (1.5 V) and the second observation period (1.7 V) (Figs. 6 and 9). Hasvold et al. [9] reported an increase of the cell voltage from 1.3 to 1.6 V around 15 days after the deployment at sea-water depth of 180 m. Wilcock and Kauffman [10] also observed the increase of cell voltage with a time. Our SWB system kept the cell voltage of 1.5 V more than 60 days from the deployment, and the average cell voltage of 1.7 V was observed almost 1 year after the deployment. Although a mechanism of this increase of the cell voltage should be the same as the observation of Hasvold et al. [9] and Wilcock and Kauffman [10], it seems to take longer time for the increase of the cell voltage in application of the deep-sea basin. The performance test was carried out during the period when the cell voltage was 1.5 V. Unfortunately, we did not carry out a performance test during the high cell voltage period, however, there is a possibility that a maximum power output became more than 13 W after 1 year from the deployment.

The WP-2 system continued the observation until July 2005 with the SWB system. After the second monitoring period of the SWB system, we do not have monitoring data from the SWB system. However the WP-2 seismometer system recorded its own power consumption for system monitoring. From the data stored by the DL and the data of the system monitoring in the WP-2 seismometer system, the SWB supplied the power of 203 kWh in total from August 2001 to July 2005. Because the weight of the anode and the cathode are 120 and 40 kg for one cell of the SWB, we estimate the energy density is 318 Wh kg^{-1} for our SWB system. This energy density of the SWB system is comparable with that of a primary lithium battery (585 Wh kg^{-1}) and is larger than that of an alkaline battery (150 Wh kg^{-1}). For estimation of the energy densities of a lithium battery and an alkaline battery, the weight of a battery itself is taken into consideration. Pressure vessels are needed to use such kinds of batteries in the deep-sea. Therefore the actual energy densities as battery systems are expected to become much smaller for a lithium battery and an alkaline battery.

In July 2005, we discontinued the observation at the WP-2. During the last visit of the *KAIKO* to the WP-2, the anode was observed by the *KAIKO* (Fig. 12). Because most of the anode disappeared, the anode should be exchanged to continue the power generation. The SWB continued to supply the power for approximately 5 years without exchange of the anode.

5. Conclusions

In 2000, a sea floor borehole broadband seismic observatory (WP-2) was installed in the northwestern Pacific basin where the water depth is 5577 m. For stable electric power supply, the Sea-Water Battery system with a monitoring system and a power control was developed and installed as a part of the system. The SWB system consists of four SWB cells, a DC/DC converter, the Power Control System, the Data Logger, and an accumulator. The PCS monitors the condition of the SWB system and controls the power switch of the system. The DL records the monitoring data captured by the PCS and is recovered by using an ROV. The SWB system generated the enough power for the WP-2 seismometer system which consumed the power of 6 W in average and continued to supply the power for at least 5 years. A sea-water current did not seem to affect largely the performance of the SWB cell. From the monitoring data from the PCS, our SWB can supply the power of the long-term average of at least 13 W. The energy density is estimated to be 318 Wh kg^{-1} for the SWB system. Because it is difficult to estimate a performance of the sea-water battery in the deep-sea basin before deployment and an environment should change after deployment, it is important for stable power supply using the sea-water battery that the system is sophisticated. Under a suitable design of the system, the sea-water battery is useful for application of long-term power consumption even in the deep-sea basin where the water depth is more than 5000 m.

Acknowledgments

We thank Drs. William W. Sager, Carlota Escutia, Mike Storms, and many people from the Ocean Drilling Program, who made the installation of the WP-2 station successful. We are obliged to the captain and crew of R/V *KAIREI*, JAMSTEC, for success in the observations. We are grateful for the skillful maneuvers of the ROV by the *KAIKO* team, JAMSTEC. We thank Drs. Kenji Hirata, Yuka Kaiho, Hajime Shiobara for fruitful discussions and active support in this study. We also thank Messrs. T. Imabori and H. Sekino, Japan Drilling Co. Ltd. for information of the SWB. This study was partly supported by the Ocean Hemisphere Project from the Ministry of Education, Culture, Sports, Science and Technology of Japan from 1996 to 2002. Most of the figures were created using GMT [15].

References

[1] N.S. Lidorjenko, V.A. Naumjenko, A.T. Kopjov, L.P. Esajan, D.V. Kurygitsa, Russ. Patent SU-5,509,307 (1976).
[2] C.L. Opitz, US Patent 3,401,063 (1968).
[3] M.A. Walsh, US Patent 4,522,897 (1984).
[4] Ø. Hasvold, Norweg. Patent 164,324 (1988).
[5] E. Buzzelli, J. Jackovitz, J. Lauer, Sea Technol. 32 (1991) 66.
[6] B.M.L. Rao, J.T. San Giacomo Jr., W. Kobasz, D.S. Hosom, R.A. Weller, A.A. Hinton, Sea Technol. 33 (1992) 63.
[7] P.K. Shen, A.C.C. Tsueng, C. Kuo, J. Power Sources 47 (1994) 119.
[8] Kongsberg Simrad AS, SIMRAD SWB 1200 SEA WATER BATTERY, Supplier Final Documentation LEG191, 2000.
[9] Ø. Hasvold, H. Henriksen, E. Melvæe, G. Citi, B. Johansen, T. Kjønigsen, R. Galetti, J. Power Sources 65 (1997) 253–261.
[10] W.S.D. Wilcock, P.C. Kauffman, J. Power Sources 66 (1997) 71–75.
[11] T. Watanabe, M. Mochizuki, H. Shiobara, T. Kanazawa, Bull. Earthq. Res. Inst. 74 (1999) 287–299.
[12] T. Kanazawa, T. Sager, W.W. Escutia, C., et al., Proc. ODP, Init. Repts., 191 [CD-ROM], Available from: Ocean Drilling Program, Texas A&M University, College Station, TX 777845-9547, USA, 2001.
[13] M. Shinohara, T. Fukano, T. Kanazawa, E. Araki, K. Suyehiro, M. Mochizuki, K. Nakahigashi, T. Yamada, K. Mochizuki, Phys. Earth Planet. Inter. 170 (2008) 95–106.
[14] M. Shinohara, E. Araki, T. Kanazawa, K. Suyehiro, M. Mochizuki, T. Yamada, K. Nakahigashi, Y. Kaiho, Y. Fukao, Ann. Geophys. 49 (2/3) (2006) 625–641.
[15] P. Wessel, W.H.F. Smith, Eos, Trans. Am. Geophys. Union 79 (1998) 579.