



The Development History and Latest Progress of Deep-Sea Polymetallic Nodule Mining Technology

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Abstract: Deep-sea polymetallic nodules are a mineral resource with potential for commercial development. Due to the unique deep-sea environment in which they are found, specialized technology and equipment are required for their extraction. In this paper, firstly, the development of deepsea polymetallic nodule mining technology is classified into three stages, and its characteristics are summarized. Moreover, the results from research into deep-sea polymetallic nodule mining technology are analyzed, including proposals for mining systems, research into key technologies, basic scientific problems, and proof of technical feasibility from sea tests. Secondly, the testing of the collector prototype and the environmental impact assessment study of Global Sea Mineral Resources NV, as well as the progress of the deep-sea polymetallic nodule mining test project in China, are introduced. On this basis, the opportunities and challenges brought by the fast-growing demand for electric vehicles to the development of deep-sea polymetallic mining technology is analyzed, and a possible technical scheme for a mining system and the trends in its development towards high reliability and high standards of environmental protection according to the requirements of commercial exploitation are explored. This provides a reference for the research and development of high-efficiency technology and equipment for the mining of deep-sea polymetallic nodules.

Keywords: deep-sea mining; polymetallic nodules; extraction technology; hydraulic transportation; pilot mining tests

1. Introduction

Deep-sea polymetallic nodules are an enormously large mineral resource. The nodules, several centimeters in size, form at the sediment surface at 4000–6000 m in water depth. They are rich in the metals used in new energy batteries, such as nickel (1.25–1.5%), cobalt (0.2–0.25%), manganese (27–30%), and copper (1–1.4%), and have tremendous potential for commercial development [1,2]. However, these minerals are found in extreme environments with particular conditions and particular requirements for environmental protection. As a result, the mature extraction technology methods, technology, and equipment from the terrestrial mining industry cannot be applied to nodule mining directly there. In addition, the methods and techniques for nodule mining are clearly different from those used in marine oil and gas extraction.

For decades, people have been exploring and studying mining technology and equipment for harvesting deep-sea polymetallic nodules. They have put forward technical solutions and mastered some key technologies, but they also faced many technical problems. Nevertheless, some new developments are underway. This paper reviews the history of research into nodule extraction, summarizes the results from research at every stage, analyzes the current state of research, introduces the latest developments in research, and looks ahead to future trends and developments.



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2. The Development History of Deep-Sea Polymetallic Nodule Mining Technology

Deep-sea polymetallic nodules were discovered more than 140 years ago. However, surveys and evaluations of the resources, as well as research into extraction methods, began in the 1950s due to commercial interest. In 1972, the Japanese conducted mining trials using a "continuous line bucket system" at a depth of 4500 m. These were discontinued due to unsolvable technical problems [3]. In 1979, the French proposed the concept of a "free-shuttle mining system"; however, research could not be continued because financial research deemed the costs to be too high [2]. This research has had a limited role in the development of nodule extraction technology. Those who developed these proposals later gave up moving forward with their development and turned instead to research in other proposals. Those former research horizons, subsequently, slowly disappeared [4]. The 1970s were a period of progress when sea trials for the mining of deep-sea polymetallic nodules were conducted by several international consortia, thereby establishing the foundations for nodule extraction technologies. Subsequently, pioneer investors enabled the development of key technologies to continue to be tackled.

2.1. Pilot Tests by the International Consortia in the 1970s

In the 1970s, due to the demand of the metal markets and estimations of terrestrial mineral reserves at that time, attention started to be paid internationally to the commercial exploitation of deep-sea polymetallic nodules. Lead by the US, companies from industrial nations such as Germany, Japan, Canada, Belgium, etc. formed several international consortia and stepped up their research into nodule mining, and each of them developed a series of trials for the harvesting of nodules at a depth of 5000 m in the Clarion-Clipperton Zone (CCZ) in the Pacific Ocean.

In the summer of 1978, Ocean Management Incorporated (OMI) completed the world's first successful deep-sea polymetallic nodule pilot mining tests (PMTs) in the CCZ. The system trialed by OMI consisted of three parts, namely, a nodule collector that collects nodules on the seafloor, a surface mining vessel, as well as a lifting system that transports the nodules collected by the nodule collector from the seabed to the surface mining vessel through a vertical riser pipe [5]; see Figure 1. The surface mining vessel SEDCO 445 in the test system was converted from a standard drilling ship. Two lifting systems were tested in this trial: an air lift system and a pump lift system. The air lift system injected compressed air generated by an air compressor on the surface mining vessel into the riser pipe in order to lift the nodules (see Figure 1a), whereas the pump lift system transported the nodules through a series of hydraulic submersible pumps on the riser pipe (see Figure 1b). The German company KSB provided the submersible pumps for the trial. Three nodule collectors were tested in the trial. Two of these used hydraulic power to collect the nodules and were developed by Deep Ocean Mining Company Ltd. (DOMCO) in Tokyo, Japan. The other nodule collector used a mechanical collection method. All three nodule collectors were passively towed along the sea floor by conveyor risers attached to surface mining vessels. The mining trials were conducted in three cruises in succession, recovering approximately 800 tons of nodules from a depth of 5200 m and transferring them to the surface mining vessel. A total of 650 tons was recovered through the pump lift method and 150 tons were recovered through the air lift method. The maximum extraction capacity exceeded 40 tons/hour.

In October of the same year, another consortium, Ocean Mining Associates (OMA), carried out trials for nodule extraction at a depth of 5500 m in the CCZ using a mining system similar to OMI's air lift system. In 18 h, it collected 550 tons of nodules, with a maximum extraction capacity of 50 tons/hour [6].



Figure 1. OMI pilot mining system configuration (a) air lift system (b) pump lift system.

In February 1979, Ocean Minerals Company (OMCO) in Maryland, USA carried out sea trials of a nodule mining system in the Pacific Ocean. OMCO's system also employed the air lift method. However, its nodule collector was outfitted with Archimedes screw drives to enable it to crawl over the soft sediment. In addition, this system also had a buffer station installed on the end of the riser pipe. An ore storage bin and an adjustable feeder were installed within the buffer. The goal of this was to create a buffer to even out the quantity of nodules transported through the pipe during times of high variation in the quantity of nodules collected by the nodule collectors on the seabed. It was also believed that suspending a buffer weighing dozens of tons onto the lower end of the riser pipe would help stabilize the thousands of meters of pipe in the turbulent ocean environment [7,8]. The results of the sea trials showed that this system could collect nodules from the seabed and lift them to the surface mining vessel.

The systems in these mining trials all used 5000 m riser pipes to transport the nodules from the seabed to the surface and, therefore, were also called pipe-based lifting deep-sea mining systems. The successful test of these systems verified the technical feasibility of deep-sea polymetallic nodule mining and proposed a technical scheme for the development of nodule extraction technology.

2.2. Research by Pioneer Investors after the 1980s

In 1982, The United Nations Convention on the Law of the Sea (UNCLOS) was adopted [9]. A "pioneer investors" system was also proposed allowing signatory states who invested in international seabed activities over given thresholds, or entities controlled by such states, to be registered as "pioneer investors". These were granted "pioneer areas" that did not exceed 150,000 km² of the seabed. The pioneer investors enjoyed exclusive rights to carry out "pioneer activities" in their pioneer areas. These activities included the survey and evaluation of resources and R&D and tests of the related mining equipment [10]. Seven nations or entities, including India, South Korea, Japan, China, France, Russia, and the IOM (Interoceanmetal Joint Organization), registered in this system as pioneer investors. They were granted pioneer areas and began work in prospecting and

developing mineral resources. In 2000, the International Seabed Authority (ISA) brought in the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area. Each of these pioneer investors signed contracts with the ISA for the exploration of polymetallic nodules and, thus, became contractors for the exploration. They began feasibility studies for the exploitation of nodules in accordance with the terms of their contracts. Unlike the consortia of the 1970s, the research by these pioneer investors (or contractors) was essentially carried out with the dedicated support of their respective states, so that the states could store strategic mineral resources and develop their technologies. Therefore, on the basis of the aforementioned research of nodule extraction technologies, the pioneer investors started to pay even more attention to tackling the key mining technologies for the goal of the commercial exploitation of nodules.

2.2.1. Studies on the Scale of the Commercial Exploitation of Deep-Sea Polymetallic Nodules

In 1987, the UN Ocean Economics Technology Branch proposed a production capacity index for the annual commercial extraction of 3 million dry tons of nodules over 20 years of development [11]. Thereafter, the provisions of the contract area in the Exploration Regulations by ISA were also determined based on this [12]. Most of the pioneer investors also assumed this extraction capacity as a basic standard in their research [13]. In 2008, the ISA workshop analyzed and recognized a preliminary cost model (a 20-year production cycle, 1.5 million tons per year) for a nodule mining and processing venture [14]. In current ISA exploitation regulation formulation discussions, the commercial exploitation scale of nodules is set at 3 million tons of dry nodules, but it is recommended that this is realized through two mining systems, each with an annual output of 1.5 million tons of dry nodules [15,16]. Considering sea conditions and the time it takes to maintain these systems, calculations were usually based on 250 working days per year. The production output of each system is 250 dry tons of nodules per hour. According to results from explorations, the moisture content has been calculated to be 30%, which results in a total of 360 wet tons of nodules per hour. From this, it is known that the maximum extraction capacity of the OMI and OMA systems is, in reality, only slightly above 1/10 of the scope of commercial extraction systems.

2.2.2. Research into Nodule Vertical Pipeline Lifting Technology

Comparative studies were carried out in the early stages into two methods of vertically transporting the minerals: air lift and pump lift. Results showed that in the air lift system schemes with an air compressor installed on the surface mining vessel, there were no moving components under the water. The system had a simple structure, and it had a good reliability and maintainability. However, the efficiency of transport was much less than that of pump lift systems. Furthermore, according to conclusions from research stating that there is no capacity for the transport of solid particles when annular flow is generated during pneumatic transport in vertical pipes [17], in order to realize a target of 360 wet tons per hour of nodules at 5500 m, the inner diameter of the riser pipe in the systems had to be greater than 1 m. However, at that time, the corresponding concentration of nodule particles transported through the system was only 3-4%, and the efficiency of the transport system was under 15% [18]. The resulting excessively low transport concentration and transport efficiency were not very acceptable and, furthermore, with their excessively large dimensions, the pipes further added to the weight and bulk of the pipe system, increased the difficulty of operating this system, and even exceeded the stacking space that could be provided on the decks of the surface mining vessels. On the other hand, in the abovementioned conditions for commercial extraction systems, the internal diameter of the pipe in pump lift schemes could be contained to within 0.4 m, the optimum particle transport concentration was 12–15%, and the transport efficiency could reach 40% or more. Therefore, the mining system schemes proposed by the pioneer investors all employed pump lift systems.

Using this as a basis, some institutions in Japan [19,20], the China Ocean Mineral Resources Research and Development Association (COMRA) [21–23], the Korea Institute of Ocean Science and Technology (KIOST) [24–26], etc., all developed pump lift systems with submersible electronic pumps. Although the pumps in the basic proposals were all based on the prototype KSB pumps used in the OMI system, a series of research developments were achieved with the upgraded flow channel design of the lifting pumps for transporting large particles, the development of excellent hydraulic models, etc. In addition, a large amount of theoretical and experimental research was carried out in the hydraulic transport of deep-sea nodules through vertical pipes. IOM carried out a nodule hydraulic pipeline lift test, testing the transport performance of nodules of different shapes and sizes at different volume concentrations and flow speeds [27]. COMRA [28] even used abandoned mine shafts to carry out experimental research simulating this transport and investigated the techniques and parameters of hydraulic pipe transport.

2.2.3. Research into Nodule Harvesting Technology on the Seabed

The harvesting of nodules consists of two stages, picking the nodules up off the seafloor and transferring them to the nodule collector. There are also two aspects to consider in its design concept: high collection efficiency, namely, picking up the highest possible amount of nodules from the seafloor, and low disturbance, namely, minimizing disturbance to the sediment and minimizing the displacement of sediment in plumes caused by collection activity. Various design proposals were put forward to address these. The compound hydraulic-type used by COMRA used two rows of high-pressure water jets, one to blow the nodules up from the seabed, and the other to propel them to the nodule collector [29,30]. India National Institute of Ocean Technology (NIOT) used a mechanical type using a composite comb-like shovel to scoop the nodules from the seabed and transport them onto a conveyor [31]. The KIOST design was a hybrid hydraulicmechanical-type where nodules were blown upwards by high-pressure water from nozzles. They were then diverted by a back plate and carried onto the nodule collector by a conveyor with a scraper [32–34]. Prototypes of each proposal were developed and tested in laboratory ponds and in shallow seas. The basic considerations of these proposals were that there were few moving components in fully hydraulic collection equipment, their structure was simple, and there was no need to carry sediment onto the nodule collector during collection. However, they expended a comparatively large amount of energy, and their collection efficiency was relatively low. On the other hand, the mechanical type collection methods had problems such as fragile mechanical components and nodule collection heads that were prone to blockage by sediment. However, there have not yet been sufficient comparative analyses and trials to confirm these considerations, and there lacks the unanimous common knowledge of assessments of the various collection methods.

2.2.4. Research into Traveling Methods of Nodule Collectors on the Seafloor

In order to realize high productivity in the commercial extraction of nodules, the nodule collectors must collect nodules across a relatively large range on the seabed. Furthermore, in order to not waste resources in the mining area, targets for collection rates can be proposed. To achieve this, nodule collectors must not only move along the seabed, but must also have a high capacity to control the paths they take. They must not leave behind many areas where nodules are not collected and must not repeatedly attempt collection where they have previously collected nodules. As mentioned, OMI and OMA nodule collectors are passively moved along the seafloor on sleds towed via a 5000 m riser pipe by the surface mining vessel. There are obvious difficulties in controlling paths with high precision using this method. The OMCO nodule collector employs an Archimedes screw propulsion mechanism to achieve self-propelled travel [35]. In theory, this should have a certain level of path controllability. However, it has also been suggested that the grooves of the screw when traveling on the soft cohesive sediment are easily filled with sea mud, causing skidding and making it relatively difficult to turn [36].

In order to resolve these problems, the pioneer investors started to investigate the feasibility of nodule collectors using a crawler track-based self-propelled mechanism on the seabed. South Korean [37–39], Indian [40], and Chinese teams [41–43], among others, carried out in-site surveys of the seabed and laboratory simulations of the geotechnical characteristics of the sediment. They began studies in the maneuverability, anti-slip and anti-sinking capacity, and the structural parameters and design of a tracked heavy-duty vehicle to travel on the exceptionally soft cohesive soil. They also conducted research into the controllability of the path and positioning of the nodule collector in the deep-sea environment. The research showed that with the self-propelled crawler track mechanism, the width of the crawler track and the shape of the grousers could be used to adjust the bearing surface area and shearing force of the crawler track, as well as provide good controllability [44]. Combined with advanced submarine navigation systems, this would allow for high-performance, stable travel and path tracking on the exceptionally soft sediment. Over the past few years, South Korean, Indian, and Chinese teams have carried out testing and research in shallow seas into travel on the seabed, and they demonstrated the good maneuverability and controllability of their nodule collector prototypes. Figure 2 shows COMRA trials conducted in 2018 of a nodule collector prototype walking on the seafloor and its path taken. This trial was conducted at 514 m in water depth, and the maximum single distance traveled by the prototype tested in the trials was 2881 m. It traveled the entire planned route and achieved an underwater positioning precision of 0.72 m [45].



Figure 2. Seabed walking test of collector prototype of COMRA. (**a**) The collector test prototype of COMRA (**b**) The travel path of the test prototype on the seabed [44]. (The abscissa represents longitude and the ordinate represents latitude. In this trial, the combination of ultra-short baseline and long baseline was used for navigation. The blue dots in Figure 2 represent signals collected from ultra-short baselines, while the red and green dots represent signals collected from long baselines.).

2.2.5. Shallow-Sea Trials of Key Sub-Systems

In order to assess and verify the nodule mining equipment they developed, pioneer investors conducted a series of shallow-sea trials of single equipment or key subsystems [4, 30,37,38,40,44–49], summarized in Table 1.

Year	Country/Organization	Depth/m	Subject of Testing
1997	Japan/TRAM	2200	Seabed nodule collection by towed nodule collectors
2001	India/NOIT	410	Nodule collector seabed extraction
2001	China/COMRA	135 (lake trial)	Traveling and collection by nodule collectors, lifting pumps
2006	India/NOIT	460	Traveling and collection by nodule collectors, lifting pumps
2009	South Korea/KIOST	100	Nodule collector travel
2010	South Korea/ KIOST	100	Lifting pumps
2013	South Korea/KIOST	1370	Nodule collector travel and artificial nodule collection
2015	South Korea/KIOST	1200	Pump and pipe-based transport system
2016	China/COMRA	304	Pump and pipe-based transport system
2018	China/COMRA	514	Nodule collector travel and artificial nodule collection
2018	India/NOIT	890	Nodule collector travel

Table 1. Shallow-sea trials of key sub-systems conducted by pioneer investors in 1982–2018.

These trials achieved a certain level of success, and some problems were also found. For example, in the lake test of COMRA, there was no walk at the bottom of the lake because of the track skid [44], and the navigation system failed due to the noise interference of the collector. The trials played a very good role in the development of research into deep-sea polymetallic nodule extraction technology.

2.2.6. Proposal for a Deep-Sea Polymetallic Nodule Commercial Mining System

By integrating the above studies, a deep-sea nodule commercial mining system was essentially proposed. Figure 3 shows the system scheme suggested by COMRA [50]. In this system, the lifting pumps are multistage centrifugal pumps, and the nodule collector is self-propelled on the seabed using crawler tracks. The technical proposals for commercial mining systems put forward by the Koreans [49], Japanese [51], and teams [27,52] from other nations were identical.



Figure 3. COMRA proposal for a deep-sea nodule commercial mining system [50].

NIOT also proposed a system using hydraulic pipes to lift the minerals; however, they considered using a soft pipe for their entire riser pipe, and positive displacement pumps were used instead of centrifugal pumps to lift the minerals [53]. French pioneer investors

(Ifremer) proposed the concept of a mining system that also used the pump lift mode and a self-propelled collector; however, its mining ship was a semi-submersible surface platform [54]. In addition to the above air lift and pump lift systems, a team of Russian pioneer investors (Yuzhmorgeologia) proposed a lift system for feeding the seawater into the undersea mud pump through another pipeline by using a mounted pump on a mining ship [52].

2.3. Research by EU Businesses and Institutions in the 2010s

Over the turn of the century, the increased demand for metals such as cobalt, nickel, and copper in the development of new energy technologies resulted in an increase in the attention paid to the exploitation of deep-sea polymetallic nodules. In 2006, the Federal Institute for Geosciences and Natural Resources (BGR) in Germany signed an exploration contract with the ISA and was granted a contract area for the exploration of nodules on the international seabed. In 2013, UK Seabed Resources Ltd. (UKSR) and Global Sea Mineral Resources NV (GSR) from Belgium applied for a contract area on the international seabed as an exploration contractor [55]. Unlike the previous group of pioneering investors who were national or governed state-owned enterprises, most of the new contractors were private companies after the 2010s, and the commercial purpose of developing deepsea mineral resources was very clear. Meanwhile, the exploitation of deep-sea mineral resources would be an important facet of the "Blue Growth" [56] plan formulated by the European Union. They hoped to make use of the advantages of EU countries and businesses in marine engineering to assume a favorable position in the exploitation of deepsea mineral resources and the research and development of equipment to that end. Through the "Blue Mining" [57] and "Blue Nodules" [58] plans, they would arrange and support the research and development by companies in the EU into technology and equipment for exploiting deep-sea mineral resources. Meanwhile, awareness and standards of the international community regarding environmental protection were continually increasing, as did concerns and questions about the environmental disturbance caused by deep-sea mining. Minimizing the effect of mining activities on the marine environment inevitably became an objective and requirement in the research and development of nodule mining technology and equipment.

Compared with the Blue Mining Project, which strove for the sustainable development of the exploitation of deep-sea mineral resources throughout the entire process from exploration to extraction to smelting, the Blue Nodules Project focused even more attention on "research and innovation to develop a deep-sea mining system for the harvesting of polymetallic nodules from the seafloor with minimum environmental impact" [58]. Fourteen major companies and research organizations from nine EU countries participated in this project. As can be seen in the conceptual proposals for nodule extraction systems put forward by this project, similar to Figure 3, the systems used a "hydraulic lifting system + tracked self-propelled nodule collector" prototype [57,58]. The clear difference was that a return water pipe was also installed on the surface mining vessel to transport the processed water back to the seabed after the dewatering process of the slurry mixture [58]. This concept of returning wastewater to the seafloor and discharging it there had actually already been proposed before this, and it had already become a basic common consideration in designing mining systems based on riser pipes [59,60]. In 2018, an MIT research team carried out a one-time sea trial to study the turbulent sediment plumes that mining vessels could potentially release into the ocean [61]. Furthermore, some performance targets for the nodule collectors were also clearly proposed for the system. These included a nodule collection efficiency of 80% for the nodule collection head, the separation of nodules and sea sludge in the nodule collector, and a minimum environmental impact [58]. With the guidance and support of these projects, some universities and companies in the EU also launched several studies into the disturbance in the environment of the seabed during collection, ways to curb plumes in the sediment, and the pollution of the ocean environment during the lifting of minerals and the discharge of wastewater. They put forward several

new proposals and designs for new equipment pertaining to gathering and traveling by nodule collectors, the lifting of minerals, and the discharge of wastewater in order to reduce their impact on the environment. For example, the Delft University in the Netherlands proposed a conceptual design that "mitigates the impact of turbidity during deep-sea nodule harvesting" [62]. The Technology University of Bergakademie Freiberg built a 136m high vertical delivery test system, among other things [63]. A research program for collector prototype testing was established in the Blue Nodule Project, and a subgroup of the Blue Mining consortium also participated in the study [57,64]. In reference four, it is mentioned that the Royal IHC of the Netherlands is developing a tracked vehicle prototype and that they carried out trials at 300 m in water depth in 2018 and 2019. Meanwhile, as a contractor, GSR also developed a prototype for a seabed nodule collector. In 2018, it applied to the ISA to carry out collection tests and assessments of the environmental impact in their contract area [65]. At the general assembly of the ISA in 2017, a Dutch delegation submitted the proposal "Development of Environmentally Responsible Mining Technologies: Towards an Approval Process for Mining Equipment" [59]. Paying attention to concern by the international community regarding environmental protection, it drafted the establishment of a future technical threshold for commercial exploitation and demonstrated the goals and confidence of the EU and the companies there in developing deep-sea mining systems with a high capacity for environmental protection.

3. Recent Progress in the Development of Deep-Sea Nodule Mining Technology

3.1. GSR's Collector Test and Environmental Impact Assessment Study

In 2013, GSR signed a contract with the ISA for the exploration of polymetallic nodules and was granted an exploration area in the CCZ. They began resource exploration work and put forward research plans for the development of mining technology and the assessment of the environmental impact [65]. According to their plans, GSR would trial prototypes of nodule collectors in three different stages with three generations of machines: a tracked soil testing device (TSTD), a pre-prototype, and a prototype. In their contract area, they began testing the performance of nodule collectors and researching the impact of nodule mining activity on the environment.

The TSTD was also named the "Patania I". There was no nodule collection head and, therefore, it could not collect nodules. Its main role was to carry out tests of the terramechanical performance of the crawler track traveling mechanism on the sediment. In May 2017, GSR began to test the walking function of Patania I in situ in the contract area of the CCZ. Between June 19 and June 24, Patania I was deployed four times to the seabed, reaching a maximum depth of 4571 m. There, they completed trials and tests relating to, for example, traction and speed, sinking and slipping, soil mechanical properties and turbidity [66]. After sea trials of the TSTD were completed, GSR began the development and testing of its pre-prototype, Patania II. Based on the TSTD research, Patania II continued to use two crawler tracks as a self-propelled traveling mechanism. Furthermore, Patania II also had a hydraulic nodule collection head with adjustable ground clearance and was able to undergo seabed nodule harvesting performance trials. In terms of the scale of the Patania II, the nodule collection head had a width of 4 m, the maximum traveling speed reached 1 m/s, and its weight in the air was 35 tons.

In February 2018, GSR and BGR notified the ISA that they planned to jointly carry out trials of their mining machine components in their respective contract areas and would begin related environmental monitoring [65]. Tests would be carried out using Patania II with two objectives. The first objective was to test the seabed travel and nodule collection of the pre-prototype nodule collector and test its performance to verify the feasibility of the design proposal. The second objective was to combine the pre-prototype trials to gather data relating to the disturbance caused by the mining activities to the environment in order to assess the environmental impact. These data would be used as a basis to research and propose environmental management and monitoring plans.

In April 2019, GSR started trials as scheduled, but was interrupted due to fiber cable failure [67]. In April 2021, GSR once again began trialing Patania II. On May 20th, GSR announced that this six-week sea trial was successfully completed [68,69]. During this trial, twenty-three scientists from eight institutions conducted independent environmental monitoring of the test impact on another ship far away from the test site, collected data on the drift and settlement of sediment plumes generated from the collector test, and measured sediment concentration in the water column.

3.2. Progress of the Deep-Sea Polymetallic Nodules Mining Test Project in COMRA

After sea trials by several international consortia were concluded in the 1970s, due to the sluggishness of the international metal market at that time and changes in the international seabed area systems, these consortia did not continue further research. As mentioned, the research of the pioneer investors in the 1990s into nodule mining technology was focused on key technologies such as seabed nodule collectors and underwater vertical transport systems. Although sea trials were launched into key sub-systems and single-unit equipment, no complete mining trials had been carried out of mining systems.

In 2016, under the guidance of a National Scientific Research Program led by COMRA and with the participation of enterprises such as the China Minmetals Group and research institutions such as the Central South University in China, a "Deep-sea Polymetallic Nodule Mining Test Project" was launched. The objective of this project was to complete a full-system linked trial of the extraction of deep-sea polymetallic nodules. The test system used the "hydraulic pipe-based lifting + tracked self-propelled nodule collector" prototype put forward by COMRA (Figure 3). It was designed to be carried out at 1/10 of the scale of commercial extraction and operate at a depth of over 1000 m.

According to project plans, they designed and developed a pilot nodule collector [44,45]. This nodule collector was self-propelled using dual crawler tracks and collected nodules using hydraulic power. It had the capacity to separate and crush nodules, and in order to adapt to the strong interference in the operation of the nodule collector in the deep sea, it used a navigation and positioning system combining inertial navigation and mobile acoustics. A hydraulic pipe-based transportation sub-system was designed and developed. This included a multistage centrifugal pump with a coarse particle passage capacity [70,71], a buffer station with the capacity to adjust the concentration of the nodule slurry [72], a rigid riser for transport, quick connectors, and flexible hoses. It also included related technology such as anti-clogging technology for the pump flow and technology to inhibit the vortex-induced vibration of the riser pipe. A transport vessel was converted into a mining trial vessel. The scheme of heave compensation and launch and recovery for the subsea system was studied and the corresponding equipment was developed. A nodule recovery scheme was designed, and a shipborne dewatering system was developed. A power system and operating system were developed according to the requirements of the mining testing of subsea system, as well as power distribution units and a central monitoring system for mining operations. Investigations were carried out to select a suitable test area. The distribution of nodules and engineering geological properties in the relevant areas were investigated, which provided the original parameters for the design of the pilot collector. Two marine areas with fundamentally similar environments were defined (1 km \times 1 km). One area was designated as the trial area and the other area was designated as the reference area. Surveys were carried out into the geology, chemistry, physical oceanography, and biological environment of the trial area and the reference area to gather information for an environmental baseline and to collect samples.

In 2020, each key equipment development and performance evaluation was performed. The assessment of the walking and harvesting performance of the test collector was conducted in the laboratory pool where simulated seabed sediment was arranged at the bottom of the pool and artificial nodules were spread at an average abundance of 10 kg/m² with a maximum particle size of less than 100 mm. The result achieved from the assessment was a maximum walking speed greater than 1 m/s and a maximum nodule harvesting capacity of 41 kg/h. The test lifting pump was assessed for its performance in the transport of clean water and mineral slurry [73,74]. The main results of the slurry transport performance evaluation are presented as follows: the maximum particle size of artificial nodules d = 20 mm, the working flow $Q_w = 468.3 \text{ m}^3/\text{h}$, the volume fraction of polymetallic nodules $C_V = 10\%$, the head $H = 97.14 \text{ mH}_2\text{O}$, and the productivity of wet polymetallic nodules W = 49.35 t/h.

In June–July 2021, a preliminary feasibility test of launch and recovery as well as wholesystem extraction operations were carried out in the South China Sea, with a maximum test depth of 1306 m. During the test, the test collector walked approximately 1.6 km along a predetermined path and had a maximum deviation from the path of less than 1 m. A feasibility verification test of the whole nodule extraction process from nodule collection and crushing, pumping, and pipeline lifting to deck dewater and mineral storage was carried out. A total of 1166 kg of nodules were collected and transported onto the surface mining vessel and the feasibility of the system was verified. However, due to the limited abundance of nodules at the test site, an extraction capacity test was not performed. Meanwhile, a three-dimensional monitoring of the environmental impact was carried out throughout the entire workflow of the trial. Data were acquired from the assessment of the environmental impact of deep-sea nodule mining. Figure 4 shows photographs of the mining test ship and the test collector. This test system by COMRA was designed and developed at 3500 m in test water depth, and further mining sea tests will be conducted as planned.



(a)



(b)



4. The Outlook of Deep-Sea Polymetallic Nodule Mining Technology

Sea trials carried out 40 years ago had already proved the feasibility of technology for exploiting deep-sea polymetallic nodules. Continuing studies and developments in related industries have enabled technologies for the collection and transport of deep-sea polymetallic nodules to continually improve. The increasingly stringent requirements for evaluating the environmental impact are a challenge that must inevitably be faced during the development of deep-sea polymetallic nodule extraction technologies. The demand for the metals used in new energy batteries may speed up the development of technologies for deep-sea polymetallic nodule extraction and the course of its commercial exploitation. Deep-sea polymetallic nodule extraction technologies are, at this moment, facing a new stage of development.

4.1. Facing the Development Opportunities

The demand for metals used in new energy batteries is a driving force behind the accelerating development of deep-sea polymetallic nodule mining technology. A report by the World Bank has indicated that, in order to satisfy the ever-increasing demand for clean energy technologies, the production of minerals (such as graphite, lithium, and cobalt) may increase by approximately 500% by 2050 [75]. BNEF (Bloomberg New Energy Finance) predicts that the demand for nickel for batteries may increase sixteen-fold by 2030, and the demand for cobalt will grow cumulatively at a rate of 11.6% over the next ten years [76]. Nodules are rich in nickel, cobalt, and other metals required for new energy batteries. Since 2011, a batch of private enterprises have applied for polymetallic nodule mining areas on the international seabed and to survey the resources [55]. Recently, the companies DeepGreen (Vancouver, BC, Canada) and Sustainable Opportunities Acquisition Corporation (NYSE: SOAC) co-founded the Metals Company (British Columbia, BC, Canada) and hope to begin commercial mining in 2024 [77]. Over recent years, the US [78], the EU [56], Japan [79], and China [80] all announced policies supporting the exploitation of deep-sea mineral resources. Deep-sea polymetallic nodule mining technologies will inevitably become a focus for research and development, and they will undergo considerable development thanks to the driving forces of commercial interest and national strategies.

4.2. Recent Mainstream Technology Scheme

Corresponding to the demand for a high production capacity and high efficiency in commercial exploitation, air lifting systems require pipes with large diameters, and they have low transport efficiencies, which are problems that have still not been resolved. Over the past few years, some companies have put forward proposals for a mechanical lifting system consisting of winches, cables, and skips [81]. However, it has to achieve the high demand for the winch load and the speed required for the production capacity necessary for commercial extraction, and anti-twisting measures for the cables have yet to be tested and verified. On the other hand, in the sea trials in South Korea and China, the track self-mining collector showed good mobility and a high-precision path control performance [37,38,45], and the multi-stage centrifugal pump and hydraulic pipeline transport scheme also achieved good research results [24,73]. Therefore, the "centrifugal pump and hydraulic pipe lifting + self-propelled tracked nodule collector" system will be the mainstream technical scheme of the deep-sea polymetallic nodule mining system for a period of time in the future.

4.3. A Low Environmental Disturbance

A large number of experts and organizations consider deep-sea mining to certainly have a lesser impact than terrestrial mining on the environment [81]. However, there are also many who consider the ecosystem and environment of the deep seabed to be extremely vulnerable. Many also believe that there is still a very limited understanding by humanity of the effect of deep-sea mining activities on the environment. Such people, therefore, oppose the development of deep-sea mining [82]. Protecting the ocean environment is a main principle of the United Nations Convention on the Law of the Sea, and the ISA is also currently formulating guidelines for assessing the environmental impact of exploiting deep-sea mineral resources [83]. Organizations such as the American Bureau of Shipping have begun to discuss the relevant international regulations and standards that deep-sea mining activities must abide [60]. Reducing the adverse effect of mining operations on the deep-sea environment is a basic requirement for deep-sea mining activities and will become an obligatory target in the research and development of deep-sea polymetallic nodule extraction systems and equipment. Equipment design and technological proposals geared towards a low disruption of the environment are, inevitably, a direction in which the development of nodule extraction systems are striving, and they are steadfast objectives.

4.4. Mutual Promotion of Deep-Sea Equipment and Material Development

The development of deep-sea polymetallic nodule extraction systems and the development of deep-water equipment, components, and materials will boost each other. Deep-sea polymetallic nodules are found at a depth of 4000–6000 m, and the depth of operations where they are extracted are greater than those of polymetallic sulfides and cobalt-rich ferromanganese crusts and even greater than the depth of current marine oil and gas extraction. The R&D and commercialization of deep-sea polymetallic nodule extraction systems will boost the development of deep-water equipment, components, and materials, which will in turn drive the engineering of and raise the extent of the commercialization of deep-sea polymetallic nodule technologies and systems.

5. Conclusions

Polymetallic nodules are rich in cobalt, nickel, copper, manganese, and other metal resources urgently needed for new energy batteries and are the preferred target of deep-sea mineral resource development. The remarkable discovery of nodules has a history of more than 100 years, and its research and development have also been underway for decades. The development history and latest progress of nodule mining technology have been systematically summarized and analyzed in this paper.

According to the influence of the state of demand on the world metal markets and changes to the international seabed area system, the research on the mining technology of polymetallic nodules can be classified into three stages. The three stages of research exhibit their own characteristics. In the first stage, the research was directly based on actual mining tests in the mining areas, which verified the technical feasibility of deep-sea polymetallic nodule mining and formed the basic technical prototype of the pipe transportation mining system. In the second stage, most of the research was carried out, bestowing more attention to tackling key technologies. The third phase of research paid more attention to the environmental impact of mining technology and equipment and the capacity of commercial mining. The recent progress of GSR's collector test and the environmental impact assessment study and COMRA's deep-sea polymetallic nodule mining test project were introduced, indicating that the research on deep-sea polymetallic nodules mining technology will enter a new stage.

From the development trend, the "centrifugal pump and hydraulic pipe lift + selfpropelled tracked nodule collector" system is currently still the main proposal for deep-sea polymetallic nodule mining systems. A low environmental disturbance will become an important target of the deep-sea polymetallic nodule mining system. The development of deep-sea polymetallic nodule extraction systems and the development of deep-water equipment, components, and materials will boost each other. The high production capacity, high reliability, and high environmental protection requirements of commercial mining bring new challenges and opportunities to the research and development of deep-sea polymetallic nodule mining technology and systems. This will push the research and development of nodule mining technology to new heights.

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