WORKSHOP ON

POLYMETALLIC NODULE MINING TECHNOLOGY- CURRENT STATUS AND CHALLENGES AHEAD

BACKGROUND DOCUMENT

Jointly organised by

The International Seabed Authority (ISA)

&

Ministry of Earth Sciences of the Government of India.

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INTRODUCTION

1. Exploration, mining and processing technologies for developing polymetallic nodule resources in the Area, have long since been recognized as key components in their commercialization. In January 1994, the Preparatory Commission for the International Seabed Authority and for the International Tribunal for the Law of the Sea convened a meeting of a Group of Technical Experts to review the state of deep seabed mining and make an assessment of the time when commercial production might be expected to commence.[1] In discharging its mandate, the Group of Technical experts took into account information notes submitted by five of the registered pioneer investors (India, IFREMER, Yuzhmorgeologiya, DORD and IOM)[2], the annual periodic reports submitted by the six pioneer investors and publicly available information on the state of land-based mining, the world's metals markets and its future prospects, and the relative role in the future world metal market of the two sources of supply.

2. In its report to the Preparatory Commission, the Group of Technical Experts made, inter alia, the following observations:

i. In the field of exploration, direct sampling devices – both visual and acoustic – have been adequately developed and are used by various companies and institutions; they are commercially available. However the technology needs to be upgraded to support the commercialization of the deep seabed polymetallic nodule programme.

ii. In the field of deep seabed mining, two of the basic design concepts have been abandoned or shelved: the continuous line-bucket dredge and the shuttle system. The system envisaged and developed in parts includes the collection of polymetallic nodules by either a towed or a self-propelled collector, and the lifting of nodules through a 5-km-long vertical riser pipe utilizing a centrifugal pump or an air lift. The collector system to be operational in a high pressure and low-temperature environment while operating on soil of poor strength, demands special equipment components and material which needs to tested in the actual deep seabed environment. However, an integrated mining system, even on a pilot scale of long duration, has not yet been demonstrated.

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[1]Report of the Group of Technical Experts to the General Committee of the Preparatory Commission for the International Seabed Authority and for the International Tribunal for the Law of the Sea. LOS/PCN/BUR/R.32 1 February 1994

[2] "Current status of deep seabed mining and its future prospects" Department of Ocean Development (India); "Status and perspectives of the exploitation of deep seabed deposits" IFREMER/AFERNOD (France); "Analysis of present status and future perspectives of deep seabed mining and its future prospects" (Russian Federation); State of deep seabed mining and its future prospects" DORD (Japan), and a submission by the Ministry for the protection of the Environment, Natural Resources and Forestry (Poland).

iii. In the field of extractive metallurgy, metal extraction has been achieved by hydro-metallurgy as well as by pyro-metallurgy. A large number of processing routes have been developed for recovery of the three as well as the four metals contained in polymetallic nodules. However, these processes have been tested on a rather small scale, varying from tens of kilograms to hundreds of kilograms per batch. While there does not appear to be any major gap in the processing technology, the results available are not adequate for up scaling and use in feasibility study estimates.

iv. Capital and operating costs of deep seabed mining have sometimes been considered too high to allow early development of such deposits. However, when compared to a land-based mining operation, a polymetallic nodule project has to be separated into two distinct operations – one producing nickel, cobalt and copper and the other producing manganese. If the expected revenue from the manganese operation is credited to the total production cost, the balance of the total production cost can be comparable to the cost of a land-based lateritic nickel operation.

3. The Group of Technical Experts noted that political and economic changes at the time "have already had an important impact on the supply and demand balance of all the metals contained in polymetallic nodules. As a consequence, there has been a sharp decline in the prices of those metals. In countries which had a centrally planned or controlled economy, production costs often did not reflect the true costs and could not be considered competitive in the long term in a market -oriented economy." The Group also noted that "there will also be an impact on the cost of many operations as many countries adopt regulations based on their social and environmental policy objectives"

4. As concerns regulatory regimes, the Group of Technical Experts stated that "When making an investment decision, investors will need to carefully evaluate the implications of conducting exploration and development under the relevant regulatory regime. Considerations would include such factors as taxation/revenue sharing, the complexity of the regulatory regime, and the potential for delay and uncertainty." In the case of the deep seabed mining regime, it noted that "the entry into force of the Convention adds certainty to the situation, and that the process for registration and approval of the claims of the pioneer investors by the Preparatory Commission seems to be efficient and helps to promote confidence in the administration of the regime." It also drew the attention of the Preparatory Commission to "the importance of the environmental protection provisions of modern regulatory regimes. In the case of land-based mining, the approach to integrating environmental and economic objectives in a

regulatory regime is cited by the mining industry as a significant factor that influences their investment decisions."

5. In conclusion, the Group of Technical Experts stated that, *inter alia*, "as regards the time when commercial production may be expected to commence, it is certain that commercial deep seabed mining will not take place before 2000, and is also unlikely before 2010." The Group of Technical Experts also concluded that an assessment of the time when commercial production from deep seabed mining may be expected to commence can be made with further precision "when in the future, large-scale feasibility studies and deep-sea tests for a sustained period are undertaken".

6. In the 14 years since the report of the Group of Technical Experts was published, a number of developments of a legal, structural, economic and technical nature have occurred. With regard to the legal framework, first was the entry into force of the United Nations Convention on the Law of the Sea of 1982 and the Implementation Agreement on its Part XI, and the establishment of the International Seabed Authority. Second was the adoption by the Assembly of the international Seabed Authority of a legal framework for exploration for polymetallic nodule deposits in the Area in 2000[3], and third was the conclusion of exploration contracts between the pioneer investors and the International Seabed Authority of 15-year duration.[4]

7. With regard to structural developments, first was the discovery of the Voisey's Bay nickel deposits in Labrador, Canada[5], and second the break up of the Union of

[3] Regulations on Prospecting and Exploration for polymetallic nodules in the Area. ISBA/6/A/18

[4] The Government of India – registered on 17 August 1987. The contract was signed on 25 March 2002; Institut français de recherché pour l'exploitation de la mer / Association française pour l'étude et la recherche des nodules (IFREMER/AFERNOD) of France – registered on 17 December 1987. The contract was signed on 20 June 2001; Deep Ocean Resources Development Company (DORD) of Japan – registered on 17 December 1987. The contract was signed on 20 June 2001; State Enterprise Yuzmorgeologiya of the Russian Federation – registered on 17 December 1987. The contract was signed on 29 March 2001. China Ocean Mineral Resources Research and Development Association (COMRA) of the People's Republic of China – registered on 5 March 1991. The contract was signed on 22 May 2001; Interoceanmetal Joint Organization (IOM), a consortium formed by Bulgaria, Cuba, Czech Republic, Poland, Russian Federation and Slovakia – registered on 21 August 1991. The contract was signed on 29 March 2001; The Government of the Republic of Korea – registered on 2 August 1994. The contract was signed on 27 April 2001; The Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany – approved during the 11th Session in 2005. The contract was signed on 19 July 2006.

[5]One of the richest nickel-copper-cobalt finds in the world, the Voisey's Bay deposits are located approximately 35 kilometres southwest of Nain in northern Labrador, Canada. They consist of a series of individual nickel-copper-cobalt deposits known as Reid Brook, Discovery Hill, Ovoid and Eastern Deeps. The Ovoid is close to the surface and presents a classic opportunity for open pit mining. The other deposits are deeper, requiring conventional underground mining techniques. The Ovoid has proven ore reserves of almost 32 million tonnes consisting of 2.83 per cent nickel, 1.68 per cent copper and 0.12 per cent cobalt. The other deposits are estimated to contain at least 118 million tonnes of indicated and inferred reserves. Additional exploration, including underground assessment, will be required to determine the full extent and value of these resources.

Soviet Socialist Republics and the introduction of mineral resources/metals from this geographic area to the world's metal markets.[6]

8. With regard to economic developments, the market for metals began to rebound in 2002 and 2003, based almost exclusively on demand associated with the modernization of China and the growing Chinese economy. Chinese demand is today, and is expected to continue to be, the biggest single influence on the global minerals market. Copper consumption in China has more than tripled since 1998 and it is now the biggest consumer of copper in the world. China is also the world's largest consumer of nickel.

9. The new demand has driven commodity prices up. Market prices for copper have more than tripled since 2002, for nickel and cobalt have risen six-fold since 2001, and for manganese have more than doubled. Technological developments in the offshore oil and gas industries, in particular as they relate to deep water oil and gas, particularly in relation to risers (the pipes which connect the drilling platforms to the well) , that now go to water depths of over 10,000 feet, have rekindled interest in polymetallic nodules as reserves of nickel, copper, cobalt and manganese.

10. The workshop will address the possible impact of these developments on the commercialization of polymetallic nodules and encourage collaboration among contractors and between contractors and technology developers from related fields such as the oil and gas industry. It will also attempt to obtain an estimate of the costs of production (mining and processing) as currently envisaged, to provide the members of the Authority with a yardstick for when these deposits might be commercialized.

NODULE DEPOSITS OF COMMERCIAL INTEREST IN THE AREA

11. Polymetallic nodule deposits of commercial interest occur at deep depths (4500-5500 m), miles away from shore. Nodules are porous, concretionary objects of various sizes and shapes, found in thin discontinuous layers on the floor of the ocean, and contain, in some cases, economically attractive quantities of cobalt, nickel, copper and manganese (and possibly molybdenum, vanadium and titanium).

12. The environment in which mining operations will take place is unique. The terrain of the ocean floor is uneven, abounding in seamounts, hills, ridges, troughs, scarps, outcrops, boulders and other irregularities and obstacles. Generally the sediments on which the nodules rest are soft, fine-grained, water- saturated, clay or ooze. The sea surface is affected by waves, ocean swells, currents, and sometimes storms and cyclones. Different types of currents are encountered at various depths of the water

[6] Russia's MMC Norilsk Nickel Company has been the world's leading producer of nickel. In 2005, it accounted for 19 per cent of world mine production.

column. Such conditions present a very difficult environment for mining operations dependent on remotely controlled mechanical apparatus.

MINING TECHNOLOGY DEVELOPMENT

13. During the 1970s and 1980s, initial undertakings were carried out by four multinational consortia composed of companies from the United States, Canada, the United Kingdom, Federal Republic of Germany, Belgium, the Netherlands, Italy, Japan, and two groups of private companies and public agencies from France and Japan.[7] Three publicly sponsored entities from the USSR, India and China also undertook some work.

14. In developing the design of a mining system, technology developers had to address basic questions of how to pick up the nodules from the ocean floor and bring them up to the surface facility with maximum efficiency. With regard to the capacity of the mining system, it was determined that for a nodule mining venture to be economic, an amount of no less than 3 million metric tons of dry nodules needs to mined annually for a period of up to 20 years. Three basic design concepts for deep sea mining technology were pursued. Picking up nodules with a dredge –type collector, and lifting them through a pipe (the hydraulic mining system), picking up nodules with a bucket-type collector and dragging up the bucket with a rope or cable (the continuous line bucket mining system), and picking up nodules with a dredge-type collector and having the collector ascend by the force of its own buoyancy (the modular or shuttle mining system).

15. The Hydraulic mining system has drawn the most attention among deep seabed mining technology developers. This system uses the principles of hydraulics in lifting the nodules to the surface ship. The system envisaged and developed in parts includes the collection of nodules by a towed or self-propelled collector mechanism linked to the end of a 5-km-long vertical lift (riser) pipe close to the bottom of the ocean,

[7] The consortia were the **Kennecott Consortium or KCON**, comprising Kennecott Corporation (US), RTZ Deepsea Enterprises Ltd (UK), Consolidated Goldfields, PLC (UK), BP Petroleum Development Ltd (UK), Noranda Exploration Inc (Canada), and the Mitsubishi Group (Japan); **Ocean Mining Associates or OMA**, comprising Essex Minerals Company (US), Union Seas Inc (Belgium), Sun Ocean Ventures (US), with Deepsea Ventures, Inc its service contractor; **Ocean Management Incorporated or OMI**, comprising Inco Ltd (Canada), AMR (Arbeitsgemeinschaft Meerestechnisch Rohstoffe) of the Federal Republic of Germany, SEDCO Inc (US), and Deep Ocean Mining Company Ltd (DOMCO) of Japan; **Ocean Minerals Company (OMCO)** comprising Amoco Ocean Minerals Company (US), Lockheed Systems Company, Inc (US), and Ocean Minerals, Inc (Netherlands); **Association Française pour L'Etude et La Recherche des Nodules(AFERNOD)** of France, comprising Centre National pour L'Exploitation des Oceans (CNEXO), Commissariat a L' Energie Atomique (CEA), Société Métallurgique Le Nickel (SLN), and Chantiers de France-Dunkerque, and **Deep Ocean Resources Development Company Ltd** of Japan, with a composition that included, C. Itoh and company Ltd, Marubeni Corporation, Mitsubishi Corporation, Mitsui and Company Ltd, Nichimen Company Ltd, Nissho Iwai Corporation, Sumitomo Corporation, Mitsubishi Metal Corporation, and Sumitomo Metal Mining Company, Ltd.

and the lifting of nodules through the pipe utilizing hydraulic pumps fixed to the pipe, or sucking up the nodules though the pipe by means of compressed air injected into the pipe (air lift).

16. Of the four multi-national consortia, Ocean Mining Associates (OMA) tested an air lift system with a towed collector during 1977 and 1978. Approximately 500 tons of material was recovered with a system with a design capacity of 1,200 tons per day. Ocean Management, Inc. (OMI) conducted tests with both hydraulic pumps and air lift, and towed collectors in early 1978, and recovered 1000 tons over a few days. Ocean Minerals Company (OMCO) tested an[8] air lift system with a remotely controlled self-propelled collector in 1978 and 1979. The French group, Association Française pour L'Etude et la Recherche des Nodules (AFERNOD) participated in tests of the CLB system (the two-ship system) from 1970 until 1979. In 1980, a free shuttle system mining system was studied in which free unmanned submersibles to gather nodules of the seabed and lift them to sea surface was envisaged. However this system had inherent difficulties. Later the programme was reoriented to a hydraulic lifting system with a motorized collector able to be manoeuvred on the seafloor from the 5000 m pipe string. (1984-89). A vehicle PLA-2 6000 was designed and built to test the use of Archimedes screws for travelling on the soft bottom sediment and a collector device to harvest nodules.

17. However, all the tests pointed to some engineering problems in each system that needed to be worked out. Improvements or changes in designs were needed to achieve better system performance. Also, all the above at-sea tests were conducted with small scale experimental or pilot systems for short lengths of time. A commercial scale venture, however, requires design and operation of a much larger (perhaps by an order of magnitude) mining system.

18. Up until now, an integrated mining system, even on a pilot scale has not yet been demonstrated. Development of an integrated mining system operational in deep seabed environment on a sustained basis is demanding both in terms of time and effort and requires substantial financial inputs and technological advancement.

MINING TECHNOLOGY DEVELOPMENTS SINCE THE GROUP OF EXPERTS REPORT

19. **IKS Germany** worked independently and later in collaboration with India till the early 1990s. The modules that it worked on included: a nodule collector mounted on a well propelled crawler; a flexible hose for the hydro transport of solids with high pressure inlet at the mining system, and a satellite mining system consisting of a number of small mining units and one mother ship. It later conceptualized an advanced mining

[8] United Nations/Ocean Economic and Technology Branch. Analysis of Exploration and Mining Technology for manganese nodules. Seabed Minerals Series; V.2, Graham and Trotman Ltd., 1984.

system with mining unit consisting of a crawler, collector, crusher, slurry pump, floating hose and flexible cable.

20. **DORD (Japan)** tested a collector system around a seamount in 1997. It was supported with five sledges and equipped with four units of suck-up and intake devices between sledges. The test was carried out on a terrace like feature on a seamount at 2200 m depth and achieved around 87% efficiency.

21. **COMRA (China):** Since 1990, (COMRA) has been working on a special mining system for collecting and lifting nodules in its exploration area. An hydraulic principle-based hybrid collector was developed based on earlier research experience comprising a pick up device, double jets and baffle plates, coanda nozzle and transporting channel, and an outlet with a grid for the separating sediments from nodules. The system works with a single power unit, is reported to have a high pick up rate and low sediment content. The system was tested under simulated conditions. COMRA also designed a self propelled crawler consisting of a caterpillar tread, a driving wheel, a guide wheel, a support wheel, power supply and a frame. The caterpillar tread is composed of rubber with a high involutes grouser. The crawler is hydraulically driven and can move forward, backward, turn and brake easily. COMRA carried out tests of the hydraulic system using a concentrated jet pump and a circular jet pump.

22. **KORDI (Korea)** has been engaged in R & D activities for nodule mining since 1993. The first phase of its programme consisted of three stages: a feasibility study on mining technology; a concept design of a suitable seabed mining system, and a basic design of selected core subsystems. The performance and efficiency of the deep seabed collector has been determined to be the primary factor for successfully producing nodules at commercial scale by Korea. Korea has also selected the nodule pick-up device as core technology and is developing a hybrid pick-up device consisting of a hydraulic lifter and a mechanical conveyor. A pair of water jets combined with baffle plates loosen and separate nodules from the sediment without mechanical contact. A rotating fin-scraper then recovers only nodules from sediment plume and transports them to the collector. Several model tests on this system were conducted. Korea has also been working on link and motion control for the pick-up device and for the collector vehicle.

22. **Department of Ocean Development (India)** initiated work on mining technology in 1990. The collector module for its seabed mining system consists of a crawler vehicle, a mechanical screw type collecting head, a bucket elevator to transport the nodule to the hopper, a crusher to size the nodules and a pump to transport the nodule-water mixture to the riser module. The crawler has two independently run tracks, powered by two rotary vane types hydraulic motors run by a variable displacement type axial piston pump. The collector head has two screw conveyors to sweep the scattered nodules lying on the seafloor and to gather them below the elevator

so that they can be scooped to the crusher via the hopper. The crusher has two rotary drums in which the nodules are crushed to 10 mm and below. Crushed nodules are then fed to the riser module through a flexible pipe. This system was evaluated in a specially constructed shallow basin.

PROCESSING TECHNOLOGY FOR POLYMETALLIC NODULES

23. Polymetallic nodules are potential sources of copper (Cu), nickel (Ni), cobalt (Co) and manganese (Mn). Since the Cu, Ni and Co in the nodules are in oxide forms and they associate in the lattices of iron and manganese minerals, for extraction of these metals, the lattices are broken either by hydrometallurgical reduction or by reductive pyro-metallurgy. Based on this, nodule processing methods have been broadly divided into two categories - pyro-metallurgical treatment followed by hydrometallurgical processing and purely hydrometallurgical processing.

24. Metal extraction of nodules will be governed by the physical-chemical properties of nodules. Manganese dioxide and iron oxide phases in nodules are enriched with the metals. The particle sizes of these phases are so small, about 100 Angstrom units and hence it is not possible to employ physical separation methods. Nodules also have very high porosity which results in higher costs for processes involving drying of nodules. Also, nodules are fragile and need more energy in crushing and grinding. Since valuable metals of nodules are present as integral part of iron-manganese oxides, it is required to release them by disintegrating the matrix of Fe-Mn lattice in order to achieve high recovery of nodules. This can be done subjecting the nodules to reducing conditions. In Pyro-metallurgy, such reduction is done by roasting with gaseous, solid or liquid reductions, while in hydro-metallurgy; this is done by leaching with reducing agents.

25. Pyro-metallurgical methods- A number of processes such as chlorination, sulphation, smelting etc. have been tried to extract metals from nodules.

26. Hydrometallurgical Processes: These include mainly acid and alkali leaching with or without reducing agents. From Eh-pH diagrams, it is evident that metals from nodules are soluble in acidic media particularly under reducing atmosphere. Simple sulphuric acid leaching at 100°C leaching gives good recovery. To enhance the kinetics of leaching, pressure leaching at higher temperature has been adopted.

WORK OF THE CONSORTIA

27. Several consortia worked on processing nodules up to 1990 and their work is documented in the form of patents.

28. The Kennecott Consortium cuprion process, like the caron nickel process operated in Nicaro, Cuba, is based on ammonium carbonate leaching of nickel. In the caron process, laterite ore is dried and pre-reduced at high temperatures with gases. The cuprion process was developed to eliminate this energy- intensive stage and instead to carry out the reduction during leaching by means of cuprous ions. In the process, wet ore is ground and then slurried in a mixture of sea water and recycled process liquor which contains dissolved copper and ammonium carbonate. The slurry passes through a series of reaction vessels into which carbon monoxide is introduced. Cuprous ions are produced which subsequently catalyze the reduction of the manganese iron oxide matrix. Valued metals dissolve and are separated from the reduced residues by counter current washing. Ammonia and carbon dioxide are recovered and recycled by stream stripping residues. Electro-won nickel and copper are extracted from the leach liquor using a mixture of LIX64N in kerosene. By precipitating the raffinate with hydrogen sulphide, cobalt is recovered in the form of an impure sulphide which forms part of the feed to a separate cobalt extraction circuit. This precipitate can be treated in different ways to recover the cobalt. Though the processes may vary in detail, typically they would include a re-leaching of the sulphide, solvent extraction to remove copper and nickel, as well as zinc and molybdenum if present, and electrowinning of the cobalt from the raffinate.

29. Kennecott did not indicate any intention of recovering manganese from leached tailings. However, flotation testing by Kennecott reportedly produced manganese concentrates of commercial grade and quality from leach tailings.

30. The cuprion process has a number of factors to recommend it. Firstly, all the steps in the process take place at ambient temperatures and pressure. Second, energy consumption is relatively low. Third, most of the reagents used in the process are relatively inexpensive or recyclable, and fourth, there is only limited use of corrosive and highly toxic reagents[9]

31. The Ocean Mining Associates Process. Deep sea Ventures the Service Contractor for OMA used the chloride and sulphate based routes. Direct leaching of nodules in Hydrochloric acid has been described in the literature.[10] The acid is sufficiently reducing in nature to reduce manganese to soluble divalent state there by releasing the Cu, Ni, Co from its lattice. The liquor is enriched with CO, Ni and Cu Fe and Mn. The sulphate based process manganese is selectively converted to $MnSO_4$ by reacting nodules with SO_2 in absence of oxygen in fluidized bed reactor. Reacted ore is counter-currently leached in water to produce manganese sulphate solution from which

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[9] United Nations/Ocean Economics and Technology Branch. Analysis of processing technology for manganese nodules.- (Seabed Mineral Series vol3) Graham and Trotman Ltd. 1986.

[10] (Kane and Cardwell 1974)

Mn can be electrowon. Residue containing Cu, Ni and Co is leached in water in presence of air and O_2 mixture to produce sulphate solutions of metal.[11]

32 The Métallurgie Hoboken- Overpelt Process also uses strong hydrochloric acid as a leachant for polymetallic nodules. However, as opposed to the Deep-sea ventures process, the chlorine generated from the leaching reactor is passed to the end of the process, where it is used to oxidize manganous chloride solution after proper pH control. The Métallurgie Hoboken process involves solvent extraction and precipitation routes for the recovery of valuable metals.

33. The International Nickel Company Process (INCO) separates out manganese and iron initially from other metals by smelting. Nodules are reduced at 1000°C in a rotary kiln so as to convert almost all Ni, Cu, Co and part of Fe to metal. This is followed by smelting at 1400°C in an electric furnace under reducing atmosphere to produce Mn rich slag and an alloy containing almost all of Cu, Ni and Co.

EXPLORATION CONTRACTORS WITH THE AUTHORITY

34. The International Seabed Authority has signed exploration contracts with eight seabed entities. Seven of the contractors have completed the first phase (five years) of their contract periods. Amongst these contractors, COMRA, KORDI, IOM, India and to some extent Yuhzmorgeologia are actively engaged in R & D on nodule processing technologies. Of the remaining, IFREMER has not been actively working on Nodule processing while DORD, Japan had an active program in the 80s and 90s but presently they are assessing the route to follow. The status of their work on development of mining and processing systems is described below.

INTEROCEANMETAL JOINT ORGANIZATION (IOM)

Mining technology

35. The main objectives envisaged under the first phase of IOM's contract with the Authority in relation to mining technology were:

i. Analysis and assessment of existing and potential designs for nodule development technology.

ii. Collection of data for preparation of technological fundamentals for basic components of a nodule mining system.

iii. Development of a conceptual design for a future mining system and

[11] (Patents Cardwell and Kane, 1975)

iv. Design and laboratory modelling and testing of a lifting subsystem.

36. To firm up the basic components of the mining system, IOM collected geotechnical and geological conditions of polymetallic nodule distribution. Preparatory initial characteristics of expected mine site and oceanographic, meteorological and other factors of sea environment also have been analyzed.

37. To select a conceptual design for a nodule mining system, including the design of the collector, and the transport system, IOM decided that first, work on the power supply system, and the mining control and management system had to be initiated. As regards the nodule collector, IOM reports that a scientific and technical scheme of collectors with neutral buoyancy and the design of a collector-tracked carrier have been prepared. It also reports that a hydraulic system involving suction of water-sediment-nodule mix, with sediment collection being intensified by employing hydraulic hydro-magnetic devices that ensure vertical integration of sediment and nodules has been selected. It also reports that computer simulations have been carried out of the control process, and to assess the effects of the mining complex on the environment. According to IOM, preliminary results of the simulation showed that stress in the collection system's riser pipes did not exceed acceptable levels. It also reported that laboratory work has been conducted with the purpose of estimating slip velocity and experimental verification of nodules vertical flow on selected lifting sub-systems.

Nodule processing

38. IOM's work on nodule processing technology during the first five- year period of its contract was focussed on

- Optimization of existing technological schemes for extraction

- Development of basic technological scheme for polymetallic nodule processing.

39. IOM reassessed the variants of technological schemes for polymetallic nodule processing by both hydrometallurgical and pyro-metallurgical processes. It reported that an optimization of the hydrometallurgical process through the use of sulphur dioxide leaching lead to an extraction efficiency of 98.2-98.7% for Ni, 90.1-92.6% for Co and 98.2-99.4% for Mn .

40. It also reported that options for precipitating copper, nickel, cobalt, and manganese concentrates using solid precipitation reagents were worked out. A new method for copper extraction from product solution was developed and patented. This method is based on copper precipitation by powdered elemental sulphur in the presence

of reducing agent. IOM stated that it had developed a technological regime for the extraction of electrolytic manganese of 99.74% purity grade at 55% efficiency.

41. IOM indicated that its research on pyro/hydrometallurgical technology included developing the basic principles of the technology, including drying by reducing combustion, smelting, slag drainage and granulation of the complex alloy. Optimal temperature conditions for the same have also been ascertained. Optimal composition of furnace load was determined in large scale laboratory smelting for processing Mn-containing slags into silico-manganese.

42. With regard to a hydrometallurgical method of smelting IOM reported that the method employed by IOM results in selective concentration of copper in non-soluble residue, with more than 50% copper. It reported that the extraction of nickel and cobalt was carried out using sulphide precipitation in the form of mixed concentrate of nickel and cobalt content in excess of 30%. It also reported that it reviewed the existing options for nodule processing by liquid smelting, and that to increase the efficiency of nodule processing and the amount of base metals extracted from the nodules, work was carried out to investigate non traditional applications.

43. IOM has informed the Authority that it will continue working on both hydrometallurgical and pyro-metallurgical processes during the next 5 years. In this regard, it will analyze existing plant capacity and assess its capability for industrial scale processing. It will also commence work on an assessment of the environmental impact of setting up a nodule processing plant.

COMRA – CHINA

Mining technology

44. During phase I of its contract, COMRA finalized a mining system for a pre-pilot deep sea mining test based on technologic and economic analysis. The system consists of self-propelled collector with track, hydraulic lifting pipes and a surface vessel. The design was completed during the first year of the contract period.

45. COMRA conducted trial mining in a lake in an area with partially simulated deep-sea conditions. The system collected artificial nodules spread on the floor of the lake and transported them to the surface using a flexible hose subsystem. COMRA reports that the test was completely successful. Also, the environmental studies conducted on the trial site indicated that lake test had a tiny influence on the floor and water layer in the area.

46. COMRA informed the Authority that it is preparing for sea trial mining of polymetallic nodules. The collector system and the lifting system are the two major

components. It also says that the virtual reality testing of the mining system has also been performed. The R & D program on deep sea mining was revised and adjusted during 2005. Laboratory tests of its collector and lifting system have been performed.

EXTRACTIVE METALLURGY TECHNOLOGY

47. During the first five years of its contract, COMRA reports that it undertook 14 research projects on extractive metallurgy in 7 institutes involving around 60 scientists. Two processing units of 100-500 kg/day were set up and pilot tests conducted during 2004 and 2005. Pilot tests of reductive ammonia leaching for optimization of the process were carried out. Studies to increase the reaction rate and in turn to enhance leaching extraction were continued and an optimum zeta potential of reductive reaction was arrived at. To improve cobalt extraction from ammonia leaching, the effect of additives was tested. In the presence of additives, COMRA reports that the variation of cobalt ion in the range 0-2.5 g/l has little influence on the leaching extraction. COMRA further reported that the pilot tests were run for more than 2 months in 2004. A healthy extraction of 90% cobalt and 98% each for Copper and Nickel was achieved. Additionally, 84% of zinc and 96% of Mo were leached from nodules.

48. COMRA reported that the second set of pilot tests were conducted on the process 'smelting – oxidative leaching-SX'. It informed the Authority that satisfactory parameters were arrived at during the tests, and that metal recoveries from this process were Ni 91.94 per cent, Cu 94.28 per cent, Co 89.29 per cent, Mn 82.39 per cent, and Fe 91.45 per cent respectively.

49. COMRA also compared metallurgical processing tests of nodules collected from different locations, initiated studies on alternate utilization of nodules directly as catalysts of chemical reactions, for treatment of industrial wastes etc.

50. In the ensuing years, COMRA's program will include,

- Continuation of laboratory research on mining technology, and
- Expanded metallurgical experiments.

YUHZMORGEOLOGIA- RUSSIAN FEDERATION

Mining technology

51. As part of research activities under its contract, Yuhzmorgeologia modernised its existing deep towed equipment, re-engineering its data transfer unit and sonar data digital recorder. A prototype of equipment for in-situ measurement of the mechanical properties of sediments in nodule fields was developed. The sea trials of the seabed probe station UGI were carried out in Yuhzmorgeologiya's exploration site in a water depth of 6,000 m. Its deep-sea measurement technique was refined in multiple re-positioning modes to record the following parameters of bottom sediment properties in their natural state: shear strength (to 0.2 m depth), and penetration resistance (to 0.6 m depth).

52. Yuhzmorgeologia does not have an active nodule processing technology programme. However during the next five years it proposes to collect nodules for a nodule processing laboratory and pilot scale plants.

MINISTRY OF EARTH SCIENCES - INDIA

Mining technology

53. Since concluding its exploration contract with the Authority, India has been working on a crawler based mining system along with a flexible riser system for mining. Trials were conducted on the Indian research vessel ORV Sagarkanya. The Crawler was tested in 2000 at depths of 410 m. After modifications to the system following the trials, the vessel was also refurbished with the addition of a dynamic positioning system and a Launching and Recovery System (LARS). In 2006, India dummy tested the crawler and the LARS and found them to be working satisfactorily. The crawler was tested in the Angria bank region on the west coast of India during 2006. The system was tested underwater for 3 days. Coordination between crawler and vessel was achieved and long term underwater testing was completed. The performance of many indigenous components like an ambient pressure transducer, data acquisition and control system with pressure packing was tested during the trials and found to be working satisfactorily.

54. The Collector and crusher system will be tested at depths of around 500 m by spreading artificial nodules on the seafloor. A scaled down model of a crusher was tested using charcoal and nodules. Procurement of major sub-systems for artificial nodule laying systems is completed and the design of an experimental collector and crusher is also complete. India reports that it has developed an in-situ soil tester for measuring soil properties in the Central Indian Ocean Basin. The system was successfully tested at depths of 5000 m. India also reports that it is developing a

Remotely Operated Submersible (ROSUB), to be operated to depths of up to 6000 m. In this regard, it reports that the conceptual design of the system has been completed. It also reports that a Tether Management System (TMS), a suspended subsea station is being developed, and has been tested at an acoustic test facility. India further reported on different subsystems that it is developing, including a data telemetry system, a control system for its Remotely Operated Vehicle (ROV), a high voltage-high frequency converter, and thrusters for the movement of the ROV.

55. During the next 5 years, India reports that the tasks it intends to undertake are:

i. Design and development of a new crawler capable of operation at 6000 m depth

ii. Development of small semi submersible floating station
iii. Testing of its Remotely Operated Submersible;

iv. Conducting in-situ soil testing and micro level demarcation of its mine site to isolate sites of very low soil bearing strength, and

v. Undertaking studies on material behaviour in Hyperbaric and low temperature conditions for long-term operations.

Processing technology

57. India undertook trials of 15 metallurgical processing routes at different institutes. Out of these, three process routes were chosen for scaling up operations. Process one was the reduction roast ammonia leach route based on the Caron process for lateritic nickel ore. This process allows selective dissolution of Co, Ni and Cu as ammine complexes while precipitating iron and manganese in the residue. It is a combination of pyro and hydro-metallurgical methods. Metal recoveries were found to be 90% for Cu and Ni and 60% for Co. Process two was the reduction leaching of nodules in an ammonical medium. In this process, sulphur oxide is used as a reducing agent followed by two stages leaching under pressure. Both Fe and Mn remain in the leached liquor. After removal of Mn and Fe, the leached liquor is subjected to a solvent extraction electro-winning treatment for recovery of Cu, Ni and Co. The precipitates are then dissolved in acid under pressure. The final solution is treated for the recovery of Ni, Co and Zn. This process was chosen for scaling up to a 500 kg/day plant. Process three was sulphuric acid leaching of nodules at elevated temperature and pressure. Under these conditions, iron becomes insoluble and most of it separates out in the residue. The process consists of pre-leaching, pressure leaching, impurity removal and solvent extraction-electro winning.

58. India has set up a demonstration plant (500kg/day capacity) for processing nodules. India is working on developing a techno-economically feasible process for extracting metals from nodules. The objective is to develop a complete engineering flow sheet for a commercial polymetallic nodule plant in phases. During Phase I, six campaigns were completed by August 2004. Based on the inputs from the plant's operation, the original flow sheet was modified to eliminate the second stage leaching. This helped to reduce the time required and money without sacrificing recovery efficiency. The recovery percentages of nickel and cobalt exceeded the design values. Average recovery efficiency during Phase I was Cu 92%, Ni 96% and Co 82%. Validation of processes developed by the different laboratories was taken up from 2004 in 3 further campaigns. Testing of the flow sheets that were developed was done in a separate campaign. Due to problems in recovery, a new flow sheet had to be developed for the recovery of nickel and cobalt. The new process is being tested. R & D activities on metal processing technology continue in different laboratories. A total of 12 activities are in different stages of development in 2 laboratories. In the next 5 years, India proposes to develop a process for extracting metals from nodules through the smelting route, through the high pressure acid leach route, to work on the recovery of molybdenum and other valuable metals from nodules, to work on the discharge of effluents from PMN processing, and to test and develop a process for the production of metal powder through Hydrogen reduction.

59. India reports that it will try to optimize its pilot plant to further enhance the leach pulp density from 15% to 18%. It also reports that its campaigns have helped to increase the pilot plant's capacity from 500 kg/day to 900 kg/day. In addition to the activities at the pilot plant, the R & D activities continue at the two laboratories for improving cobalt extraction in ammonical solution and recovery of metals from leach liquor by the bulk sulphide precipitation-chloride leaching route.

KORDI (KOREA)

Mining technology

60. KORDI has developed an integrated computer simulation programme which carried out non-linear time domain analysis of the coupled dynamics of a collector vehicle and flexible hose on the seafloor. KORDI has also developed a sensor fusion algorithm. The basic design of the test collector for at sea tests has been completed. KORDI has also established a deep-seabed mining laboratory, for research on collector and integrated mining operation technology. A test miner was constructed along with an operations console for sea testing. KORDI is also working on developing a commercial lifting technology. The experiments and results from previous efforts enabled it to modify the impeller and guide vane.

61. As part of its processing technology development, KORDI continued to work on the hydro-metallurgical processes/ leach technology to increase the efficiency of the operation. KORDI also continued collaborative efforts with India in the reduction smelting process. The project will run till 2008. Korea reports that it has also worked on solvent extraction for separation of cobalt and nickel in a continuous system with mixer-settlers. During the next 5 years, KORDI proposes to take the nodule processing technology program to the engineering conceptual design and experimental scale.