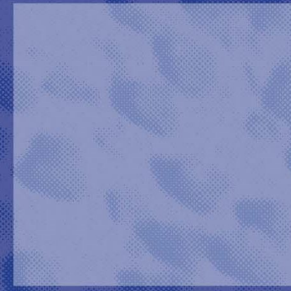
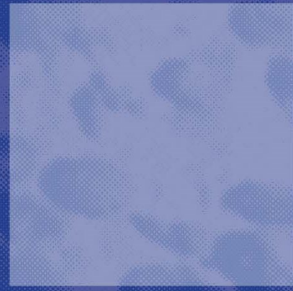
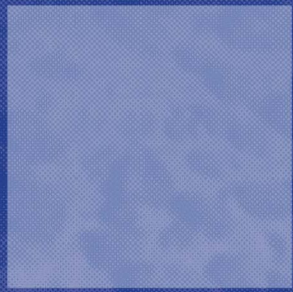


# POLYMETALLIC NODULE MINING TECHNOLOGY CURRENT TRENDS AND CHALLENGES AHEAD



# **POLYMETALLIC NODULES MINING TECHNOLOGY: CURRENT TRENDS AND CHALLENGES AHEAD**

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Proceedings of the Workshop jointly  
organized by The International Seabed  
Authority and the  
National Institute of Ocean Technology, Chennai,  
[Ministry of Earth Sciences], Government of India  
18 to 22 February 2008

*International Seabed Authority, Kingston, Jamaica*

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NATIONAL LIBRARY OF JAMAICA CATALOGUING –IN –PUBLICATION DATA

Polymetallic nodule mining technology – current trends and challenges ahead : proceedings of the Workshop jointly organized by the International Seabed Authority and the Ministry of Earth Sciences, Government of India, National Institute of Ocean Technology, Chennai, India 18-22 February 2008.

p. ; cm  
ISBN 978-976-8241-08-5 (pbk)

1. Ocean mining 2. Ocean engineering

622.295 - dc 23

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# Opening Statements

## **Welcoming Remarks and Workshop Objectives**

*Ambassador Satya N. Nandan, Secretary-General, International Seabed Authority*

I am pleased to be here this morning and to see you attending this important workshop. Exploration, mining and processing technologies for developing polymetallic nodules resources in the Area have long been recognized as key components in their commercialization.

We have assembled here in this beautiful city of Chennai for a workshop to take stock of the present status of the mining technology and the challenges that lie ahead.

Last year when I visited NIOT and later had discussions in Delhi with Dr. P. S. Goel, Secretary, Ministry of Earth Sciences and Dr. S. K. Das, advisor to the ministry and former member of the LTC and an active contributor to the work of the Authority, the idea of a workshop on technology development was raised. Since then we agreed to hold this meeting.

I thank the government of India for inviting the International Seabed Authority to hold this workshop in India, and particular in Chennai, and for agreeing to host the event at NIOT. It is the untiring efforts of the Ministry of Earth Science and the group at the NIOT which have resulted in this workshop becoming a reality.

I would like to thank the Minister of Earth Science, Dr. Kapil Sibal; the Secretary of the Ministry, Dr. P. S. Goel; Dr. S. K. Das and their colleagues in Delhi and here at the NIOT. I would like to thank Dr. Kathioli, whom you just heard, he is the Director of the National Institute Of Ocean Technology; also Dr. M. A. Atmanand, he is in charge of technology development of seabed mining and their colleagues at NIOT. All of them have contributed to making this workshop possible.

Ladies and gentlemen this is not the first time we have met to discuss the state of seabed mining technology. In January 1994 the preparatory commission for the ISA 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 to make an assessment of the time when commercial production might be expected to commence.

In discharging its mandate the group of technical experts took into account information notes submitted by five of the registered pioneer investors at that time: India; IFREMER of France; Yuzhmorgeologiya (of the Soviet Union at the time), now Russia; DORD of Japan; IOM - Inter Ocean Metal - based in Poland. We took into account the annual periodic reports submitted by the six pioneer investors at the time and the publicly-available information.

The Committee was of the view that the developments in the field of visual and actual sampling for nodules have been adequate to assess the resources. However, the technology needs to be adequately upgraded to get to the commercialization stage.

The experts also concluded that 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 two systems that were being envisaged and developed in parts, included the collection



of polymetallic nodules by either a towed system or self-propelled collector system and the lifting of nodules through a 5 km long vertical riser pipe utilizing using centrifugal pump or airlift.

The collector system, to be operational in a high pressure and low temperature environment, while operating on soil of poor strength demanded special equipment components and material which needed to be tested in the actual deep seabed environment. However, it was noted that an integrated mining system, even on a pilot scale of long duration, has not yet been demonstrated. The expert committee also took stock of the nodule processing technology and concluded that though the progress in hydro and pyrometallurgy is noteworthy, results available are not adequate for upscaling and use in feasibility study.

The group of technical experts noted that political and economic changes at the time already had an important effect on the supply and demand on balance of metals contained in the 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 cost often did not reflect the true cost and would 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.

In conclusion the group stated that, *inter alia*, "As regards to 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.

It has been 14 years since that group reported. A number of developments of legal, structural, economic and technical nature have occurred since.

With regard to the legal framework, first was the entry into force of the 1982 United Nations Convention on the Law of the Sea and the implementing agreement of 1994 which dealt with some of the outstanding issues relating to party levels which is the deep seabed mining regime part of the Convention.

In 1994 also we saw the establishment of the International Seabed Authority.

Third was the conclusion of exploration contracts between pioneer investors and the International Seabed Authority for a period of 15 years.

With regard to economic developments the market for metals began to rebound in 2002/3 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.

New demands, not only from China, but also from other growing economies like Brazil, India and others have driven commodity prices very high. Market prices for copper have more than tripled since 2002. For nickel and cobalt prices have risen almost six-fold since 2001 and for manganese the prices have doubled.

Technical developments in offshore gas and oil industries, in particular as they relate to deep water oil and gas, particularly in relation to risers, (these are pipes which connect the drilling platforms to the wells that now go to depths of over 10,000 ft.) have rekindled interest in polymetallic nodules as reserves of nickel, copper, cobalt and manganese.

These are positive developments for all of us. We have been waiting to see deep seabed mining become a reality.

It is not surprising, therefore, that there is growing attention being given to seabed mining and minerals. Our pioneer investors were in the main government-supported entities. In recent times there has been interest shown by some private enterprises. In fact we expect some of them, at least, to apply for a license very shortly. The interest of private sector is very important in that those who have shown interest are already in mining on land or in offshore areas. They would bring with them the skilled personnel and expertise and of course, their experience. All this augurs well for the future development of seabed mining.

Two inhibiting factors in the development of seabed mining have been the prices of metal and the development of mining technology. As regard to the prices of metals I have already indicated the record prices they have reached and likely to continue. If that proves to be so then that should generate interest in the development of technology in order to harness the resources that lie there.

The present workshop will therefore address the possible impact of these developments on the commercialization of polymetallic nodules. This is also an opportunity for all the technology developers to come on a single platform and take stock of the developments. We hope this will also 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, that is, mining and processing as currently envisaged, to provide the members of the Authority with a yardstick for when these deposits might be commercialized. I am very happy as I said earlier that the workshop is to be inaugurated by Dr. Harsh Gupta, former secretary of Department of Ocean Development, who signed the contract on behalf of Government of India.

As we can see from the agenda there are very interesting topics relevant to this issue that is to be discussed. I hope we will have fruitful and constructive deliberations during this week. We are also looking forward to the visit to the Indian Research vessels which is on the programme.

I once again thank the Government of India for hosting this workshop. On behalf of the International Seabed Authority I welcome you all and wish you a successful workshop.

## **Opening Remarks**

*Mr. Nii A. Odunton, Deputy to the Secretary-General, International Seabed Authority*

Good morning. Mine is a very brief set of remarks. I was asked yesterday to give participants an idea of what we expect from the workshop. I believe with your registration package each of you has the Agenda for the workshop.

We were trying to get up to about 17 papers presented on the various facets of polymetallic nodule development. We managed to get 14 experts who are very well versed in their areas of work. These include outside experts and also representatives of the contractors. There are other experts who will talk about the other areas of technology development that could come to bear on nodule development.

We are going to spend the first three days hearing these presentations. On the third day we would then like to have three working groups established. We know, based on the report of the technical experts, that up until now no large-scale tests of equipment have taken place. As a result, we recognise that this may be a burden on trying to get some kind of handle on production costs.

I have been involved in this exercise from 1975. There have been periods of time when we have been told the orders of magnitude by which metal prices have to rise for seabed mining to take place. The assumption is that there was some knowledge of the cost of production, even in the absence of successful large-scale tests of whatever technology had been developed up until that time.

It would be useful, I believe, if at the end of work of the three working groups; one on exploration and mining, another on processing, and a third on a cost model of deep seabed mining, we could come out with some idea about the cost of production.

We see, and the Secretary-General mentioned it, that metal prices keep going up. We also have a situation where demand will increase not only from the countries that the Secretary-General mentioned, but in terms of other uses of the metals to be found in nodules. The metals should not be seen in isolation; they are tied into other issues that confront the international community. We are talking about carbon emissions, global warming, all of which have to do with the uses of resources; some uses which could be replaced with the metals to be found in nodules. It would be useful if at the end of the deliberations of the working groups we can come up with an idea of what we are presently talking about with regard to any kind of production coming from nodules.

After the working groups have reported to us, as mentioned earlier, there will be visits to labs of the Indian research vessels and we will all have an opportunity to see some of the very good work being done by India. I was fortunate enough to have come here last year.

I would like to close by thanking all the good friends whom I see and all the experts we have invited to come. I think we have the possibility of an excellent workshop.

Thank you very much.

## **Inaugural Address**

*Padmashree Dr. H. K. Gupta, Former Secretary, Department of Ocean Development  
(Now Ministry of Earth Sciences), Government of India*

Good morning everybody. It is always a pleasure to get back to the Institute of Ocean Technology and especially today when I have my good friend, Mr. Satya Nandan, Secretary-General, International Seabed Authority here and we have participation from almost all countries involved in polymetallic nodule development

We have with us today, Mr. S. K. Das, we also have Dr. Ravindran who pioneered many things I see in this institute. We had wonderful overviews of the entire polymetallic nodules scenario by the talks delivered by Dr. Kathioli who covered what exactly is happening and a kind of overview by Mr. Nandan, who told us what are the crucial areas, how things have moved and what is expected of this workshop. Finally, in his well projected viewpoints Mr. Nii Odunton told us way the workshop is structured and the kind of outcome which is anticipated from this workshop. When I think back there is not a more appropriate time to have this workshop because as he said the prices of metals have skyrocketed.

I have just returned from the launch of the International Year of Planet Earth in Paris which was a global event and all questions related to what was going to happen to the future of the globe were addressed. It is a tough situation; because we want to live comfortably in the world. At the same time we want to minimise the effect of whatever we do to the health of the globe. So in that direction the kind of programmes that are being taken up under polymetallic nodules, especially estimating of the environmental impact – whatever will happen after you mine the Area, are extremely important.

I would like to cover another important aspect from the point of view of my own country, India. We started this polymetallic nodule programme way back in 1981. As a matter of fact it is coincidental that at the beginning of Department of Ocean Development, two major programmes were taken up; one was the work on polymetallic nodules and the other was the Antarctic programme.

Success stories may be told about both of them. Over the last two and half decades we have invested almost US\$600 million in this programme. Also for the current five year plan; which is 2007-2012, there is a budget of US\$150M for the polymetallic nodules programme. This does not include the amount put in *ORV Sagor Kanya*, the ship dedicated to oceans, which has done a lot of work. We have just now commissioned *ORV Sagor Nidhi*, which cost us almost US\$60M. You may ask why I am giving you all these numbers. It is simple. Any programme that the government takes up has to go through a parliamentary process and they ask questions like; what are the benefits of this programme to our country? When it will become productive then we will see the end results.

Keeping that in view, I think it is very appropriate that in this workshop you have designed interaction among all interested parties and plan discussions on very specific issues so that at the end of the workshop there will be some guesstimates to see where we are and what holds for us in the future.

While we take into account polymetallic nodules, one very important issue which I think will be facilitated by this workshop is the possibility of the exchange of expertise. This is something we have talked about for a very long time. In my last discussion with Mr. Satya Nandan we talked about setting up a time frame where people share their experiences, not only in this forum, but transferring it to the necessary party so that we can take benefit. That way you can make it much more cost effective instead of each country or interested party investing on their own on every issue.

I must say a few words about this institute. I have always felt pride in it.

You have surface water, which is about 27°C-28°C which you can flush in cool conditions and then you can bring cold water from down below to condense it to make potable water. This concept is decades old, but I am happy to tell participants that during Ravindran's time and then Dr. Kathioli this concept was converted into a reality. India succeeded in establishing a 100,000 litres per day low temperature, thermal desalination plant at Kavaratti which has been operating very efficiently.

Kavaratti is a small island of about 10,000 people. They collect about 10 litres per person and as a result visits to hospitals have dropped to less than a half, because most the diseases on the island are water-borne diseases. This is a technique which is very suitable for tropical countries and there are several extensions of this device. We waste a lot of hot fluids in all kinds of production. It is notable that hot fluid can be re-used using the same principle to produce good water. Again, I must say on 26 December 2004 we had a devastating tsunami caused by the second-largest earthquake ever recorded, namely the Sumatra earthquake, and several countries thought of putting up a tsunami warning centre. India has just succeeded in doing that and NIOT played a very important role in planting the ocean bottom pressure recorders in 2 key zones. This entire system, which was completed in record time of about 30 months at a cost of US\$30m, is totally operational. The acid tests were the earthquakes of 12 September 2007 and the accompanying tsunamis which were forecasted. The system came through within 10-15% which is a remarkable achievement.

We are also working on gas hydrates with a totally new approach. Again, what we are trying to do is trying to get gas hydrates to the surface of the water from water depths of 2-3km. We are developing techniques where we can drill from the ocean bottom and have a ROV to sample the hydrates. What I am trying to say is that the requirements are there, but there are new approaches. All these things tell us what the ocean has in store for us in the future.

I wish you a very pleasant stay in Chennai and an excellent workshop. Thank you very much.

## **Vote of Thanks**

*Dr. M. A. Atmanand, Project Director, National Institute of Ocean Technology*

Good morning respected chief guest of the workshop, Padmashree Dr. H. K. Gupta, former secretary, Department of Ocean Development, Government of India; Ambassador Satya N. Nandan, Secretary-General, International Seabed Authority; Mr. Nii Odunton, Deputy to the Secretary-General, International Seabed Authority; our Director, Dr. Kathirolu; senior officials from the International Seabed Authority and Ministry of Earth Sciences; delegates and my dear colleagues, it is my pleasure to propose the Vote of Thanks on behalf of the organising committee of this workshop.

First of all, I would like to thank Dr. H. K. Gupta for accepting to be the chief guest of this function. We are grateful to him for spending his valuable time with us. The Secretary-General of the Seabed Authority, Mr. Satya N. Nandan, has taken a lot of pains in order to hold this workshop at NIOT. A special thanks to him for all the efforts taken in this regard. Even though not present at this occasion, the Secretary, Ministry of Earth Sciences, Dr. P. S. Goel was a major force behind conducting this workshop at NIOT. I offer our sincere gratitude to him.

In order to hold the workshop at NIOT, our Director, Dr. Kathirolu, has played a major role in motivating us. I would like to thank him on behalf of the committee for all his efforts in making this workshop a success.

Dr. S. K. Das, Adviser at the Ministry of Earth Sciences has helped us in various ways in conducting this workshop.

I should thank the Deputy to the Secretary-General of the International Seabed Authority, Mr. Nii Odunton; Dr. Wakdikar, Ministry of Earth Sciences; Dr. Vijay Kodagali, International Seabed Authority; and the other members of the ISA and MOES for their contribution to making this workshop a success.

This function has been made successful with the cooperation of the delegates of various countries. I thank them, their respective parent organisations and the various ministries concerned for their support.

Thanks to the delegates from various constituent institutions of the polymetallic nodules programme under the MOES.

I cannot leave out Professor Ravindran, our former Director and former LTC member who laid the foundation for many of the activities at NIOT. I would like to thank Dr. Sudhakar of the National Centre of Antarctic Research and Mr. Rajshekhar of vessel management, NIOT for their efforts in ensuring that the research ships, *ORV Sagar Kanya* and *ORV Sagar Nidhi*, which you will be visiting will be made available at Chennai Port for the technical visit of the delegates.

This function would not have been a success but for the support from the various groups of NIOT. I would like to thank all the team members who worked behind the scene in this regard. And also the team for efforts the various administration, purchasing, catering and other related activities.

I would like to thank Ms. Vijay Laxmi and her team for their excellent support given at this function hall and other estate-related activities. I thank Dr. Dilsha and his able team whom you would have seen at the airport almost 24 hours working on receiving the delegates and all the logistics support arrangement for this workshop.

Our gratitude to Dr. Lata for the support given at the various meeting rooms and for providing WiFi and other multi-video systems for this workshop.

I would like to thank the security and the housekeeping staff for their efforts.

I would be failing in my duties if I left out my own brethren, who shouldered various responsibilities. I thank all my team members who have put forward their sincere efforts for the past 10-15 days in the various activities connected with the workshop. It would be a long list if I read out the names. I would like to thank one and all.

Like the photo of the rising sun that you see here; the photo was taken at the Central Indian Ocean Basin when we were there in 2006. Let us hope that this workshop will pave the way for mining of the manganese nodules in the near future.

I would like to wish all the delegates a pleasant, fruitful stay in Chennai.

Thank you.

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# Executive Summary

A preliminary cost model for a deep seabed polymetallic nodule mining and processing venture (a 20-year, 1.5 million ton per year operation) was developed at the Authority's eleventh workshop on 'Polymetallic nodule mining technology – Current Status and challenges ahead', jointly organized by the Authority and the Ministry of Earth Sciences of the Government of India, at the National Institute of Ocean Technology, in Chennai, India, between 18 and 22 February 2008.

Inputs to the model came from 16 technical and legal presentations made by participants. The majority of the inputs were, however, developed in the three working groups that were established to discuss exploration, mining and processing technology and the current economics of a polymetallic nodule mining.

There were 48 participants at the workshop, with representatives of six of the eight exploration contractors for polymetallic nodule development in the Area (China, Germany, India, the Republic of Korea, Poland and the Russian Federation) presenting papers that, inter alia, described the status of their efforts to develop a cost-effective configuration of technology to facilitate exploration and mining for polymetallic nodules, and their processing into copper, nickel, cobalt and manganese.

Contractors were also requested to provide estimates of production costs based on their selected configurations and production scales, and to identify those areas of activity where collaboration could enhance the viability of their ventures. Nine other presenters focused on: an analysis of mining technologies developed in the 1970s and 1980s; model mining units envisaged in the 1970s and 1980s; project economics and cost models that had been developed for deep seabed mining (Flipse (1980), Nyhart (1980), Hillman (1981), Ingham (1985) and MIT (1985); the economic and technical considerations underpinning the pioneer regime and the ISA regulations for prospecting and exploration for polymetallic nodule deposits in the Area; possible applications of technology developed for space to deep seabed mining; the status of lift systems for polymetallic nodule mining; advances in nickel laterite processing and possible applications to polymetallic nodule processing; technology development for polymetallic sulphides and possible applications to nodule mining; and advances in riser technology for oil and gas and their possible applications to nodule mining.

Three working groups were formulated at the workshop addressing the following issues: Working Group 1 provided capital expenditure (CAPEX) and operating expenditure (OPEX) for polymetallic nodule mining ventures that would recover 1.2 million and 1.5 million wet tons of nodules a year from a site approximately 6,000 nautical miles from a land-based processing facility.<sup>1</sup> The Group estimated that the CAPEX for a passive collector system (e.g. mining ship, and mining system) would be approximately US \$552 million; approximately US \$562 million for a tracked collector system; approximately US\$ 372.6 million for a system designed around the Chinese collector system; and approximately US\$ 416 million for a system utilizing the Indian flexible riser. With regard to the OPEX, the Group estimated US\$ 94.5 million for the passive hydraulic collector

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<sup>1.</sup> An operating expenditure (OPEX) is an on-going cost for running a product, business, or system. Its counterpart, a capital expenditure (CAPEX), is the cost of developing or providing non-consumable parts for the product or system.

system, US\$ 95.7 million for the tracked collector system, US\$69.5 million for the Chinese collector system, and US\$ 89.9 million for the Indian flexible riser system.

The cost of the transportation system (three vessels leased each year) was estimated at US\$ 76.7 million per year and at US\$ 495 million if the vessels are purchased. The estimate provided by the Government of India was US\$ 600 million if the vessels were purchased. The Group estimated the annual OPEX for the transportation system at US\$ 93.2 million, compared to the estimate of US\$ 132.7 million provided by the Government of India.

Working Group 2 provided CAPEX and OPEX for a polymetallic nodule processing plant with an annual capacity of 1.5 million tons, producing nickel, copper, cobalt and manganese. To facilitate comparison with nickel laterite processing plants, both the CAPEX and OPEX were reported on a nickel equivalent basis.<sup>2</sup> The Group estimated the capital cost/kg of nickel equivalent as US\$10-14 /kg. For a 1.5 million ton capacity polymetallic nodule processing plant, the capital cost was estimated as US\$ 750 million (CAPEX), and the estimated cost of processing/kg of nickel equivalent was US\$ 3.9 /kg, resulting in an OPEX of US\$ 250 Million.

To initiate its work, Working Group 3 reviewed models of first-generation polymetallic nodule mining systems (Texas A&M University; the US Bureau of Mines; the Australian Bureau of Mines; the Massachusetts Institute of Technology) that were developed in the 1970s and 1980s, and selected the 1984 Massachusetts Institute of Technology report, 'A pioneer deep ocean mining venture' as the base upon which to assess systems proposed by participants in Working Groups 1 and 2. The Group evaluated trends in metal prices, taking into account increasing demand for nickel and the other metals in nodules from China, India and the Russian Federation, and decided to use a range of prices rather than attempt a single projection.<sup>3</sup> The range of cost estimates from Working Groups 1 and 2 and the MIT model were incorporated into the ISA model along with metal prices representing the lower and upper values in recent years. The range of mining operations, from 1.2 to 3 million short tons per year for a 20-year mine life was also incorporated into the model. Internal rates of return (IRR) for 12 alternative scenarios produced outcomes ranging from a low of 14.9 per cent to a high of 37.8 per cent.

Working Group 3 noted that the IRRs provided a measure for comparison with land-based mining operations for ore of the respective metals. The Group further noted that an IRR is used to set a threshold which potential mineral development projects must surpass before they receive serious consideration and investment. In this regard, it was brought to the Group's attention that Antam, an Indonesian state-owned mining and metals company that produces nickel ore and processes ore into ferronickel, has established an IRR of 15 per cent as a lower limit. The Group found that, with the exception of a scenario whereby the lowest metal prices and highest costs were used, the cases evaluated exceeded the cutoff value, with some resulting in IRRs of about 30 per cent. Indeed, the Group pointed out that it is only the scenarios whereby a mining operation requires three transport vessels to convey ore from the mine site to a land-based processing plant

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<sup>2</sup> To obtain the nickel equivalent of the nodule ore, the recovered tonnages of nickel, cobalt, copper (for a three metal recovery process) and manganese (for a four metal recovery process) are multiplied by the price ratio of the recovered metal and nickel to obtain the nickel equivalents.

<sup>3</sup> The lower bound of the range was determined by indexing the metal prices from the MIT report using the consumer price index, and the upper bound by using 2007 metal prices that are seen as the peak price year.

to recover only nickel, copper and cobalt (and not manganese) from nodules, combined with low metal prices that fail to exceed the 15 per cent cutoff.

Finally, Working Group 3 noted that metal prices, particularly nickel prices, are a major factor in the profitability and attractiveness of deep seabed polymetallic nodule mining ventures. The Group also noted that industrialization in large developing countries, demand from China and India, and the reindustrialization of the Russian Federation will drive demand upwards for decades to come. Further noting that there are no large deposits of nickel sulphides to be developed, it emphasized that oxide ores (laterites and polymetallic nodules) are the future source of nickel that could meet demand.

The presentations during the workshop focused on three themes: the economic, technical and legal framework for the development of polymetallic nodule resources in the Area; the current status of technology development by contractors for polymetallic nodule exploration with the Authority; and possible application of technology developed for other marine resources to deep sea mining. A brief summary of each one of the presentations is given in the following pages.

## **The economic, technical and legal framework for the development of polymetallic nodule resources in marine areas beyond the limits of national jurisdiction**

### ***Analysis of mining technologies developed in the 1970s and 1980s***

Mr. James A. R. McFarlane, Vice-President of Sound Ocean Systems of Redmond, Washington, USA (and formerly with International Submarine Engineering, Ltd., a sub-contractor to Ocean Management Inc.), presented an updated review of the costs of the pilot scale deep ocean mining system designed and tested in 1978, by the Ocean Mining Incorporated (OMI) consortium headquartered in Bellevue, Washington, USA. Mr. McFarlane was a consultant to the team that 'mined' an 800 ton bulk sample of manganese nodules in 5,200 m of water at a candidate commercial mining site in the mid-Pacific Ocean. The co-authors of the presentation were participants in the OMI programme (Mr. Frank H. Brockett, President of Sound Ocean Systems, Inc. and Mr. Jack P. Huizingh, Naval Architect/Marine Consultant). Mr. McFarlane informed participants that this bulk sample was later processed into a Ni-Cu-Co matte. He pointed out that although these tests were conducted in the 1970s, the basic mining system and lessons learned are for the most part still relevant today. He noted that he was unaware of similar mining efforts of comparable magnitude and success subsequent to those tests, and had therefore used that mining system and related economic analyses as a starting point for generating a rough cost estimate for a mining system that might be developed today.

Mr. McFarlane said that during the lead up to the mining test, a total of eight collector designs were manufactured and tested, including three different design styles (passive, hydraulic and mechanical). Initially, testing was done at a land-based site and finally the tests were carried out in the deep sea. Mr. McFarlane described the mining vessel, the riser system, the collector system, seafloor-riser interface, control system and the different instrumentation involved with the entire system. Of the three pilot mining test voyages, Mr. McFarlane said that the second voyage was the most successful, yielding over 800 tons of nodules at a collection rate exceeding 40 tonnes/hour. With regard to commercial mining systems, Mr. McFarlane said that in his opinion the mining system would have to produce 1 million metric tonnes (mt) of dry nodules annually (or 1.5 million mt of wet nodules) with a minimum of 270 working days per year, and with a daily production rate of around 5,500 tons. He also said that in his opinion, a second-generation commercial mining system could be developed based on the system tested by OMI in 1978. He estimated that currently, the capital cost of the mining system would be approximately US\$ 551 million, with an annual operating cost of approximately US\$ 105 million. He also said that current metal prices should encourage commercialization of deep seabed nodule mining in the foreseeable future

Mr. McFarlane emphasized that the cost estimates he had provided were for the mining system and suggested that they should only be used in preliminary assessments of whether a potential polymetallic mining project merits further development. He noted that the integration of the exploration, logistics, re-supply, transport, processing, engineering design, prototype testing, preconstruction, preproduction, indirect and numerous related project costs could be subjects for other workshops. He stated that subsequent economic feasibility analyses and projections for commercial viability would require credible estimates of nodule grades, processing recovery rates, product prices and markets.

In response to a question as to whether a passive or an active collector would be preferable, Mr. McFarlane said that the active collector would be complex, costly and require an intensive maintenance programme. He pointed out that since nodules normally lie on the abyssal seafloor, a passive system should be employed. However, it was noted that no one collector system would meet all mining requirements; just as there is no universal aircraft or automobile, the attributes of the system are mission-driven. When asked why OMI had selected a rigid riser system rather than a flexible riser, Mr. McFarlane said that a rigid riser coupled with a flexible part at the bottom was the configuration utilized. He stated that the collector system utilized in the tests could handle seafloor slopes of up to 10 degrees. Finally, in response to a question about how long it would take to upgrade the OMI system to a commercial system, Mr. McFarlane said that the time required to build the mining ship would be the only time-consuming part of the upgrade, and that other system components could be scaled up within a short period.

### **Model mining units of the 1970s (production requirements, area requirements and vertical integration)**

Dr. Tetsuo Yamazaki, Senior Researcher at the National Institute of Advanced Industrial Science and Technology (NAIST) in Japan prepared and presented a paper on this topic. His talk covered: model mining units for nodules developed in the 1970s; improvements in the 1980s and 1990s; economic validation analyses of nodule mining; sensitivity analyses of nodule mining; and the current technological feasibility of nodule mining.

Dr. Yamazaki gave an historical perspective of nodule mining technology development since the 1970s and the different concepts tried out over the years. He also provided an account of the 30- and 200-meter lift experiments carried out by Japan, and of a nodule collection experiment in 2,200 m of water along a seamount slope. Dr Yamazaki detailed the previous ocean economic feasibility studies for polymetallic nodule mining. He presented the results of his economic validation analysis for polymetallic nodules and cobalt-rich ferromanganese crusts. According to Dr. Yamazaki, the investment required for a commercial nodule mining system (with an annual production of 2.2 million tonnes of wet nodules) would be approximately US\$ 1.316 billion. He estimated that the project's annual operating cost would be US\$ 203 million, and that the IRR of the project at current metal prices would be approximately 23 per cent with a payback period of 5.7 years.

Dr. Yamazaki also presented an evaluation of existing processing technologies. During subsequent discussion, Dr Yamazaki said that in order to reduce the effect of heave on the mining system, the mining vessel should be kept as small as possible. He also stated that a three-metal route would be best, indicating that too much manganese would be introduced to the metal market if a four-metal route were followed.

### **Project economics and cost models during the 1980s, and updates based on current metal prices**

Dr. Caitlyn Antrim, Executive Director of the Rule of Law Committee for the Oceans of the United States, presented a paper on cost models developed during the 1980s for deep seabed polymetallic nodule mining. She was one of the authors of the Massachusetts Institute of Technology (MIT) model. She began her presentation on the generalized components of a deep

seabed polymetallic nodule mining venture, and reviewed some of the models developed during that period. She pointed out that all of the models: addressed the recovery and processing of polymetallic nodules; assumed that a ship-based slurry lift system would be utilized in mining; assessed economics in terms of the IRR of the project; and had three phases (pre-investment, construction and operation). Pointing out major differences in the models, she said some assumed that three metals (copper, nickel and cobalt) would be recovered from nodules, while others assumed that a fourth metal (manganese) would also be recovered. Ms. Antrim said that in some models the mine life was taken to be 20 years, while others assumed a 25-year mine life. She said that the models also showed differences in factors such as debt and taxation regulation.

Dr. Antrim explained the MIT model in greater detail and spoke about its preparation, construction and operation. She described the model as a tool for understanding metal markets, and to help in public education on marine mining ventures. She said that in 1982 the National Oceanic and Atmospheric Administration of the United States Department of Commerce (NOAA) commissioned Texas A&M University (TAMU) to improve technical and economic models of deep seabed polymetallic nodule mining to support the NOAA's regulatory mission. She provided details of TAMU models 1 and 2. She also said that in 1985, the US Bureau of Mines developed another model, and also presented the Australian Bureau of Mines and MIT Pioneer models. The MIT pioneer model envisaged a capital investment of US\$ 1162 million, annual operating costs of US\$ 217 million and annual returns of US\$ 415.6 million in a 3 million short ton polymetallic nodule mining operation that would last for 20 to 25 years. She concluded by saying that it is time to update the models to reflect the advances in technology and likely development schedules.

During the discussions, Dr. Antrim explained trends in metal prices over the previous 5-6 years and the influence of markets in countries such as the Russian Federation, China and India.

## **The legal framework**

Mr. Baidy Diène, a member of the Authority's Legal and Technical Commission, presented a paper on the economic and technical considerations underpinning the Pioneer regime and the regulations for prospecting and exploration for polymetallic nodules. He provided an historical perspective of the manganese nodule discovery and exploration programmes, and the background for the creation of the Pioneer regime under the United Nations Convention on the Law of the Sea. He also talked about the geological, environmental, regulatory, technological recovery and mining factors underpinning the Pioneer regime, and the lack of knowledge of many of these factors. Mr. Diène presented an overview of the regulations for prospecting and exploration adopted by the Authority and the responsibilities of contractors. The ensuing discussions highlighted the importance of the environmental factors in mining ventures. The Secretary-General also provided further insight into the pioneer regime.

## **The current status of technology development**

There are currently eight contractors with the Authority for polymetallic nodule exploration in the Area. These are: the Government of India; Institut français de recherche pour l'exploitation de la mer / Association française pour l'étude et la recherche des nodules (IFREMER/AFERNOD) of



France; the Deep Ocean Resources Development Company (DORD) of Japan; the State Enterprise Yuzmorgeologiya of the Russian Federation; the China Ocean Mineral Resources Research and Development Association (COMRA) of China; the Interoceanmetal Joint Organization (IOM), a consortium formed by Bulgaria, Cuba, the Czech Republic, Poland, the Russian Federation and Slovakia; the Government of the Republic of Korea; and The Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany. All, except for IFREMER/AFERNOD and DORD, made presentations on their achievements with regard to polymetallic nodule technology development to date.

## **The Government of India**

### ***Mining Technology***

Dr. Atmanand of the National Institute for Ocean Technology (NIOT) presented a paper on the status of polymetallic nodule mining technology development in India. His presentation covered the underwater mining system that is being developed, including the results of a shallow water sea trial of its proposed collector-crusher system. He provided information on the in-situ soil testing system developed and tested, and the several facilities that India has established to test different components of its marine technology. Dr. Atmanand informed participants that India is working on a crawler based mining system with a flexible riser. He discussed the advantages of the flexible riser system, and also described the crawler and pump systems. He informed the workshop of modifications that have been made to India's research vessel, *ORV Sagarkanya*, to enable it to cater to the demands of testing its underwater mining system. He also informed participants of the new dedicated technology demonstration vessel, *ORV Sagar Nidhi* that was commissioned in February 2008. He explained with figures, the mining system tests carried out at a 410 meter depth, and listed the areas where collaboration between contractors would be possible.

The discussions following the presentation were mostly on the advantages and disadvantages of the flexible riser system. Responding to a question on the number of crawlers that could be attached to the flexible riser system, Dr. Atmanand explained that up to 20 crawlers could be attached, but they would not all be launched simultaneously. The importance of defining how many crawlers would be deployed was raised. It was pointed out that the number of crawlers would have a major impact on the vessel chosen, and would require a different cost model.

### ***Processing technology***

Dr. P.K. Sen, Professor of Metallurgy at the Indian Institute of Technology (IIT) in Kharagpur, presented a paper on the status of the Government of India's nodule processing development activities. He informed participants that India had tested three possible nodule processing routes: the hydrometallurgical route based on ammonia leaching; the pyrometallurgical pre-treatment followed by leaching route; and the reductive acid leaching route.

With regard to India's selected hydrometallurgical process route, Professor Sen said that the Government of India spearheaded a pilot plant with a 500 kg/day capacity which was readily modified to treat 1 ton of nodules per day through alteration of initial process parameters. Details of the plant flow sheet were discussed. Professor Sen informed participants of the various process route modifications undertaken during the course of the pilot plant operations over 5 years. He also

showed participants figures on comparative metal recoveries using different operating conditions, such as pulp density and residence time. The figures met the stipulated process guarantees of the plant designer. Professor Sen informed participants that Indian laboratories have also successfully tested two additional process routes at large scale, namely a pyro-metallurgical pre-treatment/leaching route and reductive acid leaching route. Recovery of copper, nickel and cobalt were also reported to be high for both these process routes.

Dr. Sen provided a preliminary economic analysis of one of India's processing routes and made a comparison between this plant and a land-based lateritic nickel processing operation. According to Dr. Sen, polymetallic nodule processing without manganese recovery would entail a specific capital expenditure/annual kg of nickel equivalent which would be almost double that of lateritic nickel processing. If manganese is recovered, the specific capital expenditure would be of the same order of magnitude as that of laterite processing. Professor Sen said that the upward trend in metal prices should favour deep seabed polymetallic nodule mining. The estimated rate of return on the Indian processing route is likely to be around 14.6 per cent. He concluded his presentation by saying that the next phase in India's development work would be the enhancement of process recovery at demonstration plant scale and studies of various schemes to reduce processing plant operating costs. During discussions, Professor Sen observed that the processing plant could turn a profit within 8 to 10 years of operation.

## **Interoceanmetal Joint Organization**

### ***An overview of Interoceanmetal's deep-sea technology development: mining and processing***

Dr. Valcana Stoyanova, Deputy Director-General of the Interoceanmetal Joint Organization (IOM), presented a summary of IOM's mining and processing technology efforts, as well as information on seafloor topography in the IOM exploration area. Dr. Stoyanova said that the IOM technology development strategy aimed to: address the recovery and processing of polymetallic nodules; model the production of three metals (copper, nickel and cobalt); utilize a ship-based slurry lift system; assess the economics of their mining operation in terms of its internal rate of return; and establish the phases of pre-investment, construction, and operation. Ms. Stoyanova also said that IOM's conceptual design included: a mining vessel or floating platform; a seabed nodule collecting miner; a buffer or platform for the temporary storage of nodules placed in front of the vertical transport system; a control and management system; and an energy subsystem. She reported that these are all at the conceptual stage.

Dr. Stoyanova also presented a preliminary economic assessment of metallurgical schemes under consideration by IOM and indicated that the total estimated CAPEX for its nodule processing system is US\$ 414 million. On behalf of IOM, Dr. Stoyanova called for increased cooperation among the contractors in the area of polymetallic nodule technology development.

During the discussions that followed Dr. Stoyanova's presentation, participants pointed out that environmental protection considerations should be incorporated into the design of mining technology. The metallurgical segment of Dr. Stoyanova's presentation also evoked discussion amongst participants, in particular the topics of energy consumption and the production of concentrates rather than metals in the IOM scheme.

## Republic of Korea

### ***Developing the mining technology for polymetallic nodules (Korea Ocean Research and Development Institute/Korea Institute of Geosciences and Mineral Resources)***

Dr. Sup Hong, Senior Researcher at the Korea Ocean Research and Development Institute (KORDI) presented a paper prepared with colleagues from his institute and the Korean Institute of Geosciences and Mineral Resources.

Dr. Sup Hong said that Phase I of the Republic of Korea's work was limited to feasibility studies and some fundamental research, and that in phase II of the work, technology development and at sea tests would be undertaken. He said that the Government is also pursuing a flexible riser system like the Government of India. He said that at-sea tests at water depth of 100 m are planned during Phase II, and he presented a comparison between the test system and the proposed commercial system. Dr. Sup Hong said that the government had developed an ROV, an underwater launcher, and a support vessel.<sup>4</sup> He also said that the government is working on underwater telemetry and developing high-pressure hyperbaric chambers. With regard to technology development, Dr Sup Hong said that the government is utilizing model and simulation techniques.

Dr. Sup Hong stated that design methods have been established through systematic fundamental research, such as the dynamic simulation method for analysis of the mechanical feasibility of the total system; experiments on collecting operations devices such as pick-up, seafloor driving and slurry transport; multidisciplinary design optimization (MDO) for developing a self-propelled miner; and two- and three-phase slurry pipe flow analyses. He described the Government's large scale test facilities, namely its Deep-Sea Mining Laboratory and Lifting Test Laboratory, and informed the workshop that a self-propelled test miner at 1/20 scale of commercial production capacity has been developed. Finally, Dr Sup Hong said that the test miner and the flexible nodule transport system would be subjected to a sea-test in nearshore waters in 2009.

The discussions following the presentation centered on buffer storage in the flexible riser and the weight of the buffer. Dr Sup Hong replied that at present, no buffer storage is provided for but that should it be utilized, it might weigh up to 200 tons. He also said that the mining operation that was envisaged would be a one-riser and one-crawler system for a 1.5 million tons/year operation.

## The Federal Republic of Germany

### ***The status of exploration for polymetallic nodules in the German licence area***

The status of exploration work in Germany's contract area was presented by Dr. Rühlemann of the German Federal Institute for Geosciences and Natural Resources (BGR). Recalling that Germany only recently obtained its exploration license, he described the original data obtained by

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<sup>4</sup> Remotely operated underwater vehicles (ROVs) are unoccupied, highly maneuverable underwater robots operated from aboard a surface vessel. They are linked to the ship by a group of cables that carry electrical signals back and forth between the operator and the vehicle.

BGR from Preussag, the original German company that prospected the area. He also described in detail the nodule deposits in two eastern blocks and one western block of the exploration area.

Dr. Rühlemann informed the workshop that Germany is preparing an inventory of the benthic community in its contract area, proposing an exploration cruise during the latter part of 2008, and has started to analyse trace metals in the nodules found there. He said that pilot projects on the economic feasibility of mining, exploration technology, and innovative concepts for mining and processing nodules are being planned by the Government.

During discussions, Dr. Rühlemann pointed out that BGR is working on developing technology for acoustic imaging of the seafloor. He said that Germany's scheme for processing electronic metals is still at developmental stage, and that processing trace metals in nodules would be an expensive proposition.

## **China**

Professor Yang Ning of Changsha Research Institute of Mining and Metallurgy of China, made a presentation on the development of polymetallic nodule mining technology by the China Ocean Mineral Resources Research and Development Association (COMRA) of China. He said that COMRA had worked on a tracked miner and an Archimedean screw miner. He said that COMRA had also worked on hydraulic and mechanical collectors, and air and hydraulic lifting. Professor Yang also said that COMRA is working on a rigid riser system with a self propelled miner. He presented details of the technical components of the pick-up device, the miner and the riser. He informed participants that COMRA had carried out a successful trial of the system in a lake environment, and declared that the required modifications have been made to carry out tests in the 1,000-meter water depth range. In this regard, he said that the necessary model and simulation tests have been completed.

Professor Yang informed participants that the results of COMRA's studies indicate that deep seabed polymetallic nodule mining is technologically feasible. He said that this was especially the case if polymetallic nodule mining was compared to cobalt-rich ferromanganese crusts and polymetallic sulphides mining. He noted that with the help of technology from the offshore oil industry, deep sea mining should be economically feasible.

With regard to cooperation in technology development among contractors, Professor Yang suggested sharing data and participation in tests, joint environmental investigation and exploration, exchange of data and comparison of results.

During discussions, Professor Yang clarified that the depth of the lake where COMRA's test trial was conducted ranged between 5 and 8 meters. On the processing routes proposed by COMRA, the workshop was informed that COMRA had recovered molybdenum from nodules in addition to nickel, copper, cobalt and manganese. Participants wanted to know how COMRA proposed to obtain carbon monoxide in large quantities. There was also a discussion of the mining system proposed by COMRA, in particular the number of pumps which it would use. In response, participants were informed that there would be two pumps used.

## **The State Enterprise ‘Yuzhmorgeologiya’ of the Russian Federation**

Dr. Valery Yubko, Deputy Director of the State Enterprise Yuzhmorgeologiya of the Russian Federation made a presentation on the concept of engineering and technological support for the mining and processing of polymetallic nodules from the Russian exploration area. Dr. Yubko presented the Yuzhmorgeologiya study on the size and operational parameters of the mining vessel, and the technical requirements for the proposed collector and other mining sub-systems. He also talked briefly about the Russian Federation’s processing technologies. He reported the recovery of molybdenum from nodules, as well as nickel, copper, cobalt and manganese. With regard to project economics, he said that a profit of US\$ 20,270 million had been projected from a 25-year deepsea mine. During discussions, Dr. Yubko said that Yuzhmorgeologiya is monitoring the progress being made by other contractors. He suggested that Yuzhmorgeologiya was of the view that if any of the contractors were to start mining others would follow. He also said the activities of Nautilus are being monitored for any possible impact on deep seabed polymetallic nodule mining.

### **Other technological developments**

Five presentations were made on the theme of the application of technologies developed in other fields to those required for deep seabed polymetallic nodule mining and processing – the last theme of the workshop.

Dr. Piotr Jasiobedzki of MDA Space Missions in Brampton, Canada, made a presentation on space robotics and its possible application to deep seabed polymetallic nodule mining. At the outset, he said that the challenges of space exploration and deep seabed mining of polymetallic nodules are comparable as both occur in remote and unknown environments. He said that space technologies have been used in a number of terrestrial applications, including three dimensional (3D) sensing and computer vision, autonomous navigation and hazard detection, robotic manipulators, vehicles and tools for extreme environments, sensor-guided robotic operations and task planning, and autonomous execution and monitoring.

Dr. Jasiobedzki explained that MDA Space Missions has applied space robotics to the medical and nuclear sciences. He said that space technology can be applied to, inter alia, mapping the seafloor using a moving rover, and underwater detection to provide autonomy for mining vehicles. Dr. Jasiobedzki then presented in detail the challenges of space technology. He said that space technology is complex, time consuming and costly. He explained the different project phases in space technology programmes, concluding that the processes developed for planning and executing space programmes could be used for deep seabed polymetallic nodule mining.

During discussions, participants enquired about the type of cameras used in space and visualization delays. Dr. Jasiobedzki explained that space objects may not always be in the line of sight and hence real-time monitoring may not be possible, and that a slight delay would be inevitable. He also said that there are issues of inner space versus outer space. He said that the delay may range from 1-7 seconds or up to 20 minutes in certain cases. A participant stated that the ultra short base line (USBL) gives 1 per cent of depth accuracy in underwater application and that this, along with a baseline method using subsea transponders, enables accurate monitoring.

## **Status of lift systems for deep seabed polymetallic nodule mining**

Dr. John Halkyard of Halkyard Associates, who worked for the Kennecott Consortium (KCON) in the 1970s, made a presentation on lift systems for polymetallic nodule mining, covering trends in deepwater riser technology, subsea pumping, and commercial lift system pump comparison. He summarized the advances in the oil industry by showing the increase in productivity from deeper wells. He said that the extensive use of risers in floating oil platforms has meant technological advancement in risers, and that this advancement could be employed in deep seabed polymetallic nodule mining.

Dr. Halkyard provided details of drilling riser joints in the oil industry. He also presented information on the flexible risers first used offshore Brazil, and subsea mud pumps. According to Dr. Halkyard, the nodule pumping options are submerged pumps and airlift pumps.

Dr. Halkyard concluded his presentation stating that the offshore oil industry is operating at depths approaching those of future polymetallic nodule mines in the Area; riser hardware for deepwater and harsh environments is mature; subsea power systems and pumps of the magnitude required for mining are now used routinely; and that as long as functional designs for deep seabed mining are ready, equipment would be available.

The discussions following Dr. Halkyard's presentation focused on the use of mud pumps.<sup>5</sup> He stated that a mud pump could be a good tool to use for nodule pumping. He said that lift systems could operate for 20 to 30 years without any problem.

## **Frontier advances in processing nickel oxide ores**

Mr. Julian Malnic, the Chief Executive Officer of Direct Nickel Pty Ltd (DNi), Australia, made a presentation on frontier advances in processing nickel oxide ores. He informed participants that within 20 months, Direct Nickel would demonstrate a 5 ton/day capacity plant that would be a new, simple and efficient method for processing nickel from laterites. He said that the new patented method is likely to revolutionize lateritic nickel extraction. He also said that the process involves low CAPEX and OPEX.

Mr. Malnic said that a 5,000 ton per year plant producing nickel from laterite ore would involve CAPEX of US\$ 150 to US\$ 170 million. He also discussed the trends in nickel prices over the last 50 years. He described laterites as the untapped world resource of nickel, which might yield up to 161 million tons of the metal. He said that this would be enough to cater to world demand for 100 years.

Mr. Malnic said that polymetallic nodule processing could also be carried out using Direct Nickel's processing route. He showed initial results from work carried out on marine deposits. During discussions, Mr. Malnic pointed out that with DNi's new process, CAPEX would be comparatively low, hence small processing capacities could be favourably entertained. He added that the process

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<sup>5</sup> Mud pumps are used in the oil and gas drilling industry for circulating drilling fluids, which are commonly and collectively referred to as 'mud'. Mud pumps are positive displacement type pumps that include pistons mounted on reciprocating rods within cylindrical sleeves or liners.

did not include manganese recovery. To pointed queries on the type of reagents used (chloride- or sulphur-based) he said he could not provide an answer as the process is being patented. He also said that even though the DN<sub>i</sub> method could process nickel ores as low as 0.5 per cent, the ideal grade should be a minimum of 1.1 per cent.

## **Nautilus Minerals - Technology development for seafloor polymetallic sulphides mining: Applications from oil and gas, and dredging technology**

Mr. Michael Johnston, Vice President of Nautilus Minerals Inc., made a presentation on its technology development process for the commercial mining of seafloor polymetallic sulphides. Mr. Johnston informed participants that Nautilus has been a spectacular success story, raising over US\$ 349 million in 18 months, with three major resource groups as share holders, and plans to start commercial operations by 2010 in the waters of Papua New Guinea. He informed the workshop of the major advantages of seafloor mining over land-mining ventures. He said that Nautilus had pioneered new drilling and aeromagnetic survey techniques. He presented a short video clip of rock cutting carried out at a depth of 1,600 m, and showed the preliminary results of drilling and other geophysical surveys carried out recently by the company.

Mr. Johnston elaborated on the proposed mining system and metallurgical test work to determine if valuable metals and products could be won from the recovered sulphides ore. He also informed the workshop that environmental impact assessment tests were underway and were likely to be completed by the end of 2008.

Most participants expressed keen interest in the rapid strides made by Nautilus in commercializing ocean mining of polymetallic sulphides. Asked how much the mining system would weigh, Mr. Johnston said it would be around 300 tons. He said that the 16-18-meter long cores collected were all vertical cores and that no horizontal coring was done. He also said that Nautilus planned to crush ore at the seafloor and to bring up material of constant size.

## **Advances in riser technology and possible application in deep sea nodule mining**

Ms. Tricia Hill, Sales Manager for Wellstream International Ltd, Houston, USA, made a presentation on flexible riser systems used in the offshore oil and gas industry, and their possible application in deep seabed polymetallic nodule mining. She pointed out that there are over 2,000 flexible risers in service worldwide and gave background information on the history and design parameters of flexible risers. Ms. Hill explained that the minimum bend radius of the flexible riser is determined by the extension limit of the interlocking metal layers and the strain limit of the polymer layers. She also compared stepped risers with the free-hanging risers. She stated that the flexible risers are advantageous in that they enable staged pumping by connecting pumps in line between segments of the flexible riser. She pointed out that power cables could also be connected to a flexible riser.

Ms. Hill said that the major advantages of flexible risers are: reduced top tension requirements for the surface vessel and robust design for 25-year service; the capability of emergency abandonment in severe weather; the ability to retrieve and reinstall the riser from a

surface vessel; the quick disconnect of the riser from a surface vessel; the fact that the riser is submerged below the depth of weather action; the flexible pipe is not fatigue limited; it is equipped with a technology enabler for ship-shaped platforms (FPSOs); it does not require VIV strakes; and it exhibits less drag compared to a steel riser with VIV strakes.<sup>6</sup>

Ms. Hill offered to collaborate with interested contractors to develop a flexible riser system for deep seabed polymetallic nodule mining. Participants actively took part in the discussions that followed the presentation, seeking details of, inter alia, the type of material used, and the diameter and length of pipe. It was pointed out that with the flexible riser, axial vibrations will be almost negligible.

## **Reports of the Working Groups**

### **Working Groups**

Working Groups were formed to examine possible areas of collaboration among contractors and technology developers from the oil and gas services and space applications industries to facilitate nodule development in the Area. The possible areas of collaboration were in mining, processing and transport (estimated to comprise 30, 50 and 20 per cent of capital and annual operating costs, respectively).

Working Group 1 on exploration and mining technology was to address, inter alia, the current status of deep ocean mining technology for the recovery of polymetallic nodules from the deep ocean floor, and to estimate the capital and operational expenditure for a commercial scale operation.

Working Group 2 on processing technology addressed, inter alia, resource requirements for three- and four-metal plants with a view to ascertaining possible methods to reduce the overall cost of processing, including the feasibility of designing a processing plant so that at modest incremental investment it can be converted to process land-based nickel laterite ores, the feasibility of designing the processing plant to operate on blended nodules and laterite ores, and the feasibility of converting an existing nickel laterite facility to accept nodules.

Working Group 3 on the current economics of a polymetallic nodule mining venture formulated, inter alia, a cost model for such a venture, including scenarios of a non-integrated venture comprising a nodule mining venture and a nodule/laterite processing venture to receive nodules from a nodule miner.

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<sup>6</sup> A floating production, storage and offloading vessel (FPSO; also called a 'unit' and a 'system') is a type of floating tank system used by the offshore oil and gas industry and designed to take all of the oil or gas produced from nearby platform (s), process it, and store it until it can be offloaded onto waiting tankers, or sent through a pipeline.



## ***Working Group 1***

Working Group 1 was chaired by Mr. James A.R. McFarlane and included Dr. M.A. Atmanand, Dr. S.K. Das, Mr. C.R. Deepak, Dr. John Halkyard, Mr. Robert Heydon, Ms. Tricia Hill, Dr. Sup Hong, Dr. Piotr Jasiobedzki, Mr. Michael Johnston, Dr. S. Kathioli, Professor Li Li, Mr. Lui Shaojun and Dr. Valcana Stoyanova.

At the outset, the Group decided to break down the technology for mining into sub-components, namely the collector, riser, surface vessel, and transport vessel(s). The Group also made some assumptions for its costing efforts regarding operational days for mining (inclusive of downtime for mechanical failures, lost days due to weather conditions, and travel time and days for dry-docking). It also noted that current material costs were very volatile, so the prices used were as of February 2007, and that the costs of fuel and steel were changing rapidly. To ensure that the actual capital and operational expenses are valid when the business model is explored for commercialization the Group recommended a review of its costing. It counted 270 operational days per year for mining, and stated that no research was undertaken to determine the weather conditions in the mining area, and the time that would be lost as a result of weather conditions.

### ***The collector***

Observing that different technologies have been researched and tested by contractors and earlier consortium members, it became apparent during discussions that no appropriate universal collector design was available because of varied bottom topography. The Working Group identified the basic collection philosophies such as the passive hydraulic – towed and self-propelled collectors. It described the passive hydraulic collector as utilizing the surface support vessel's power to maneuver the unit across the seafloor. In addition to surface propulsion, the group said the collector would have a small onboard electric motor providing hydraulic water flow to release the nodules. Once the nodules are off the sea bed, they would run across the collection plate and extraneous materials and misshapen nodules would be removed. The Working Group described the self-propelled seafloor collector as based on existing ROV technology. It said that the major difference between this vehicle and an ROV is the addition of the nodule collection mechanism. It also noted that numerous collection head designs have been proposed, as with passive systems. It acknowledged that the required technology exists for most, if not all of the subsystems to build and deploy a commercial collector.

### ***Risers***

The Group noted that risers are required to recover polymetallic nodules from the seafloor to the surface. In addition to the recovery of the nodules, the Group further noted that risers have numerous other operational responsibilities. The Group identified rigid, flexible and hybrid riser designs which all have different attributes. It emphasized that evaluation of these attributes and identification of other technical requirements must be completed in order to finalize overall system design. The Group identified some of the inputs to system design as: total weight; floatation requirements; current load; flow requirements; instrument integration; lift pumps/motors; deployment/recovery operations; and a shipboard storage area.

Working Group 1 agreed that the type of collector and mining support ship utilized would have an impact upon the riser selected, and noted that rigid risers cannot be used alone without slip joints and complex heave compensation equipment. The Group noted further that flexible riser systems have matured considerably since the first full scale deep sea oil and gas production (extending to deep water) operations were undertaken in the late 1970s. It cautioned, however, that using a flexible riser for deep ocean polymetallic nodule mining is a new application and additional research will be required to understand all associated technological issues. The Group suggested that consideration be given to the operational methodology utilized in a flexible riser system. The Group noted that the riser, deployed from large reels of approximately 1 km each, must be stored and that considerable deck space is required for these reels. It recommended that a more permanent deployment of this system needs to be investigated. A possible solution suggested was the addition of a remote docking mechanism at the end of the riser and an interface on the collector. It noted that there are flexible riser systems that decouple from the surface vessel in the event of rough weather. Noting that hybrid riser systems are utilized with towed passive nodule collectors and can also be used with self-propelled systems, the Group suggested that by utilizing this methodology, optimization of system design could be realized. Finally, it noted that the integration of lift pumps is more easily realized in a rigid riser, while the interface with the seafloor collector is optimized with the use of a flexible riser.

### ***Surface vessels***

The Group noted that capitalization of ships would be the largest single expense followed closely by ore transportation vessels. It further noted that this type of vessel could also be leased but that the total cost would be very similar in the end.

### ***Mining ship***

The Group observed that the 'mining' ship favoured by the majority of the participants was based on an oilfield drill ship, approximately 750 ft, or 230 m, in length. It also took note of a proposal which envisioned using a semi-submersible platform as a base of operations.

### ***Transportation of nodules to a land-based processing facility***

The Group agreed that the selection of transport vessels for moving nodules from the mining site to the shore-based processing facility is important as it would have a major operational cost impact. The Group said that the size and number of vessels would be directly affected by the mine site and the location of the processing facility. It also noted that the amount of available onboard nodule storage on the mining ship would also need to be considered in its calculations. No consideration was given during the Working Group session to using the transport ship as the fuel supply vessel to help cut costs.

## ***Collaboration***

Noting that there are numerous groups worldwide working on separate deep seabed polymetallic nodule mining projects, and that all of them have finite resources to create an operational system capable of collecting polymetallic nodules from the deep ocean seafloor, some in the Working Group suggested that a joint development plan be agreed to by contractors. If this was to be realized, it was suggested that a separate engineering firm could be engaged to oversee the programme and provide management and integration services. Others expressed reservations about the recommendation, stating that some contractors might wish to develop their own technology and operate independently.

## **Operational considerations**

### ***Site survey***

The Group agreed that to have efficient mining operations it is imperative to have accurate high-resolution data of the location and the extent of nodule fields in a contract area. It also agreed that using different platforms would allow cost-effective data collection. It noted that the typical systems employed for seafloor mapping are side scan sonar, sub-bottom profilers, AUVs and ROVs.<sup>7</sup> The Group further noted that each of these systems has different attributes that help to fulfill different needs in data collection efforts to map the mine sites. The entire high resolution survey would not need to be completed at the outset of the programme. The actual mining ship operation provides a very solid operational base for AUV operations. This would provide a highly cost-effective solution for the continued collection of high resolution data without the additional cost of another shipboard operation.

### ***Mining operations***

The Group agreed that once all components for the system were selected and manufactured, the operation could begin in earnest. It observed that some time (1 to 4 months) would be required for vessel and collector operators to become efficient in nodule recovery operations. The Group felt that the system would have to go through a break-in period and that lessons would be learned about which components meet the demands of the harsh operational environment. The Group emphasized that this educational period would be required regardless of the final configuration of technology selected. The Group suggested test programmes to help the system and its associated technology to mature but stated that there is no substitute for real mining experience.

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<sup>7.</sup> An autonomous underwater vehicle (AUV) is a robot which travels underwater. In military applications, AUVs are also known as Unmanned Undersea Vehicles. Remotely operated vehicles (ROVs) are the most widely used underwater vehicle, serving a range of military, commercial, and scientific needs. Power and control data are sent to the vehicle and video and sensor data are returned. An umbilical cable connects the ship to the vehicle. ROVs provide virtually unlimited bottom time and have high bandwidth for high-resolution video and data transmission. These systems have precise navigational control and tracking which makes them ideal tools for conducting underwater research.

### ***Transportation of recovered nodules***

The Working Group was of the opinion that timely transportation of recovered ore material was required to ensure seamless mining operations; ensuring that selected vessels are cost-effective is imperative to manage costs; and that a managed cost of the raw ore is required to make the operation competitive with land-based mining efforts.

### ***Environmental considerations***

Finally, the Group noted that environmental issues needed to be taken into account in any endeavour. It emphasized that any group that undertakes polymetallic nodule mining in the deep ocean will need to be sensitive to the environment. It noted that the involvement of appropriate scientific teams from the outset of any venture would assist in understanding and mitigating any issues or concerns that may arise.

### ***CAPEX and OPEX for a deep seabed polymetallic nodule venture in the Area***

Table 1 summarizes the Group's findings with regard to the CAPEX and OPEX for ventures collecting 1.2 million and 1.5 million wet tonnes of nodules a year from a site approximately 6,000 nautical miles from a land-based processing facility.<sup>8</sup> The table comprises the Working Group's estimate for 'typical operations' utilizing passive and tracked collectors and estimates based on the Chinese collector, and the Indian system utilizing a flexible riser.

***Table 1: CAPEX and OPEX for operations using different collectors and a flexible riser***

<b>Estimated cost of assorted collector operations</b>					
	<b>Passive hydraulic</b>	<b>Tracked collector - group</b>	<b>China Collector</b>	<b>Russian collector</b>	<b>India flexible riser mining</b>
<b>Capital expenditure</b>	<b>Cost ('000 USD)</b>	<b>Cost ('000 USD)</b>	<b>Cost ('000 USD)</b>	<b>Cost ('000 SD)</b>	<b>Cost ('000 USD)</b>
Mining ship	\$400,000	\$400,000	\$210,000		\$200,000
Owner-furnished ship	\$50,000	\$50,000	\$50,000		\$50,000
Owner-furnished mining	\$50,000	\$50,000	\$50,000		\$50,000
Subtotal – mining ship	\$500,000	\$500,000	\$310,000		\$300,000
Mining system					
Undercarriage					\$1,000
Riser/pipe (steel #1, flexible #2, 3 & 5)	\$16,000	\$20,000	\$20,000	\$1,000	

<sup>8.</sup> The facility is assumed to be located in China. The Group selected China since it was considered that it would be the most likely consumer of refined nodules. Other site locations, such as Mexico, are much closer to mining sites and therefore the transport costs of the raw ore would be lower.

	Passive hydraulic	Tracked collector - group	China collector	Russian collector	India flexible riser mining
Operating expenditure	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)
Riser hose winches					\$250
Submersible pump/motor	\$16,000	\$16,000	\$16,000		\$500
	(annual)	(annual)	(annual)	(annual)	(annual)
Interfaces	\$2,000	\$4,000	\$4,000		
Crusher					\$60
Buoyancy					\$500
	(annual)	(annual)	(annual)	(annual)	(annual)
Ballast	\$500	\$500	\$500		
Propulsion	\$0	\$750	\$750		
Navigation	\$200	\$200	\$200		
Power	\$200	\$500	\$500		
Control	\$250	\$500	\$500		\$250
Instrumentation	\$200	\$300	\$300		
Manipulators	\$350	\$350	\$350		
Collector mechanism	\$1,000	\$3,000	\$3,000		
Umbilical	\$1,500	\$2,000	\$2,000		\$1,000
Winch	\$1,500	\$1,500	\$1,500		\$1,000
Seafloor collector total	\$6,300	\$10,600	\$10,600		
Instrumentation and navigation	\$12,000	\$12,000	\$12,000		\$20,000
Subtotal – mining system	\$52,300	\$62,600	\$62,600		\$6,060
Cost of 16 mining systems (Indian case study)					\$96,960
Total – capital cost	\$552,300	\$562,600	\$372,600	\$500,000	\$416,960
Mining ship					
Amortization (10 yr)	\$50,000	\$50,000	\$31,000		\$30,000
Insurance (1.5%)	\$7,500	\$7,500	\$4,650		\$4,500
Personnel & travel	\$11,200	\$11,200	\$11,200		\$10,080
Fuel oil	\$11,500	\$11,500	\$11,500		\$18,000
Maintenance and supplies	\$5,000	\$5,000	\$5,000		\$7,500
Catering/hotel	\$800	\$800	\$800		\$2,400
Subtotal – mining ship	\$86,000	\$86,000	\$64,150		\$72,480
Mining system					
Riser/pipe	\$1,600	\$2,000	\$1,000		
Submersible pump/motors	\$1,600	\$1,600	\$500		

	Passive hydraulic	Tracked collector - group	China collector	Russian collector	India flexible riser mining
Operating expenditure	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)
Interface	\$1,000	\$1,000	\$500		
Seafloor Collector	\$1,200	\$2,000	\$1,000		
Instrumentation	\$1,000	\$1,000	\$200		
Nodule conditioning	\$2,120	\$2,120	\$2,120		
	(annual)	(annual)	(annual)	(annual)	(annual)
Subtotal – mining system	\$8,520	\$9,720	\$5,320		\$14,440
Total – operating cost	\$94,520	\$95,720	\$69,470	\$100,000	\$89,920
<b>Ore transport costs</b>	<b>Group estimate</b>				<b>Indian costing</b>
	<b>Cost ('000 USD)</b>				
Transport ships - 3 leased per year					
Transport vessel – 3 purchased	\$495,000				\$600,000
<b>Estimated cost for assorted collector operations</b>					
Transport vessel					
Amortization (10 yr)	\$49,500				\$60,000
Insurance (1.5%)	\$7,425				\$9,000
Personnel & travel	\$5,000				\$15,000
Fuel oil	\$15,000				\$40,000
Maintenance and supplies	\$7,500				\$7,500
Catering/hotel	\$1,200				\$1,200
Subtotal – transport vessels	\$85,625				\$132,700
<b>Transport ocean going tug &amp; barge</b>					
Total tug daily rate	\$1,095				
Total barge rental	\$750				
Personnel & travel	\$1,000				
Fuel oil	\$4,000				

	Passive hydraulic	Tracked collector - group	China collector	Russian collector	India flexible
Operating expenditure	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)	Cost ('000 USD)
Maintenance and supplies	\$500				
Catering/hotel	\$200				
Total	\$7,545				
<b>Assumptions</b>					
Recovery Rate Case 1 - 4	1,500,000 wmt per year				
Recovery Rate Case 5	1,200,000 wmt per year				
Operations	270 days per year				
Travel distance from mine site to processing (the processing plant is assumed to be in China)	6,000 nm				

In summary, the Working Group estimated that CAPEX for the passive hydraulic collector system (mining ship and mining system) would be about US\$ 552 million. It also estimated a CAPEX of about US\$ 562 million for the tracked collector, about US\$ 372.6 million for a system designed around the Chinese collector, and about US\$ 416 million for a system utilizing the Indian flexible riser. The Group estimated an OPEX of US\$ 94.5 million for the passive hydraulic collector system, US\$ 95.7 million for the tracked collector system, US\$ 69.5 million for the Chinese collector system, and US\$ 89.9 million for the Indian flexible riser system.

The cost of the transportation system (three vessels leased each year) was estimated at US\$ 76.7 million per year and at US\$ 495 million if purchased. The estimate provided by the Government of India was US\$ 600 million if the vessels were purchased. The annual OPEX for the transportation system was estimated at US\$ 93.2 million by the Group, compared to US\$ 132.7 million by the Government of India.

## **Working Group 2**

Working Group 2 was chaired by Professor P.K. Sen and consisted of Ms. Shashi Anand, Mr. Julian Malnic, Ms. Irena Ponomareva, Mr. Michael Johnston, Dr. Valcana Stoyanova, Mr. Avram Avramov, Dr. MK Ghosh, Dr. Bansi Dhar Pandey, Dr. T.B. Singh, Mr. Ramesh Gurllhosur, Mr. Liu Shaujun, Mr. Gao Yuqing and Mr. Jiang Xunxiong.

The Group initially focused on an assessment of the status of the polymetallic nodule processing technologies being developed by contractors and then went on to discuss:

- The financial resource requirements for three- and four-metal plants;
- Technological developments and possible methods for reducing the overall cost of processing;

- The steps to be taken to establish the feasibility of designing a process plant based on the model proposed by the contractors;
- The compatibility of technology developed for nickel laterite ore processing with polymetallic nodule processing.

### ***Contractors' processing routes***

The Group identified the preferred processing routes of contractors, as well as the routes which could benefit from further assessment and up-scaling. The Working Group also discussed the similarities with earlier piloted technologies for which indicative costs were available; the scales at which present technology has been demonstrated; metal recovery from different routes; the improvements over generic technology; and the final product form. Table 2 summarizes the information obtained.

*Table 2: Contractors and their nodule processing routes*

<b>Aspect</b>	<b>IOM pyro/hydro</b>	<b>IOM, hydro</b>	<b>COMRA, smelting</b>	<b>COMRA, hydro</b>	<b>IMMT (India), hydro</b>	<b>NML (India), pyro- hydro</b>
Similarities with earlier piloted technologies	INCO improved	SO <sub>2</sub> leach, new precipitation	INCO improved	CUPRION improved	New process	Similar to Kennecott
Technology demonstrated at	100-150 kg/day	100-150 kg/day	100 kg/day	100 kg/day	1 ton/day	100-150 kg/day
Metal recovery from different routes (%)	Cu Ni Co Mn	Cu Ni Co Mn	Cu Ni Co Mn	Cu Ni Co Mn	Cu Ni Co Mn Mo	Cu Ni Co Mn
Improvements over generic technologies	Novel alloy dissolution	TSNIGRI, (patented)	Novel ally dissolution (patented)	Additive to activate leach (patented)	Novel process concept (patent applied)	Activated leaching (patented)
Final product form	Cu conc. Co-Ni conc. Si-Mn alloy	Cu conc. Co-Ni conc.	Cu, Ni-cathode Ni cathode Co oxide Mn as Si-Mn	Cu cathode Ni cathode Co oxide MnCo <sub>3</sub>	Cu, Ni, Co – as cathode Mn as Si-Mn	Cu, Ni, Co – as cathode Mn as Si-Mn



The Group noted that the presentation by NIAIST, Japan, brought out the salient aspects of earlier efforts during 1993, optimal conditions were chosen for ammonium sulphate leach and reduction smelting followed by chlorine leaching. Subsequently, the later process was piloted. The data reported cites 90 per cent cobalt, 97 per cent nickel and 94 per cent copper leaching efficiency attained during the smelting-chlorine leaching route. The Group recommended, however, that the ammonium sulphate leaching route and the high pressure sulphuric acid leaching route should be re-evaluated. It noted that recovery values under these routes have not been cited.

The Group noted that in general, the processing routes pursued by the contractors contained improvements in certain process steps over the generic technologies cited in the table. Some of the contractors' processing routes indicated a totally novel approach. It was also noted that the products for all the processes are not always metals, but sometimes compounds, which have market value. The Group concluded that the contractors are generally aware of the permissible and potential revenues from different products that help to lower the cost of production. The Group also made the observation that while all the contractors' processes are designed to recover four metals (nickel, copper, cobalt and manganese), COMRA and the Yuzhmorgeologiya reported the recovery of molybdenum in their processing endeavours.

### ***Estimation of resource requirements***

The Group thought that the four-metal recovery option has been chosen by contractors in order to minimize the capital requirements of the full-scale plant. It agreed that manganese recovery contributes substantially to the overall revenues generated from processing. It noted that the incremental capital requirements for manganese recovery in a four-metal processing route compared to a 3-metal processing route were small enough to enable lowering the processing plant operating capacity to 1.5 million tons per year, as compared to a 3.0 million ton per year plant. The Group noted that the capital requirements of processing were substantially reduced for the lower capacity operation.

The Group acknowledged that discussions during the presentations had raised the necessity of generating large-scale data to attain the engineering goal of process scale up. The Group noted that the capital and operating costs would be based on demonstration plant data as well as estimates using available data at smaller scales of operation. It therefore pointed out that the accuracy of its cost estimates is to be considered variable.

The Group reported that IOM had provided estimated operating costs for a 1.5 million ton per year nodule processing plant following a smelting route that produced manganese-bearing slag and a complex alloy of copper, nickel and cobalt. The intermediate product was then subjected to sulphuric acid leaching for the selective recovery of metal sulphides. IOM's operating costs were estimated at US\$ 414 million using an input price of US\$ 97 per ton for nodules. The raw material and feed stock accounted for 58 per cent of the total costs whereas power and fuel costs amounted to about 33 per cent (capital costs were not available for the purposes of comparison). The other processing routes (hydrometallurgical ) of IOM at the same processing capacity and producing various metal-bearing concentrates, resulted in an estimated US\$ 7 million profit (capital costs were not available for this process, either).

Working Group 2 reported that the NIAIST processes presented in the workshop (smelting, chloride leaching route and ammonium sulphate leach/ SCL) reported capital costs of US\$ 380 to

US\$ 410 million for 1995-1999. The corresponding operating expenditure for a three-metal system was reported at about US\$ 50 million. The processing plant capacity was reported as 1.39 million tons per year. With the recovery of manganese the estimated capital and operating costs for the SCL route are US\$ 475 million and US\$ 155 million, respectively.

The Group reported that the preliminary Indian cost estimates for a 1.5 million ton per year processing plant utilizing the reductive ammonia leaching route are US\$ 700 million (CAPEX) and US\$ 235 million (OPEX) for a four-metal plant. At 2006 US dollar values, the Japanese and the Indian estimates were not considered by the Group to be widely different.

The Group also reported that Yuzhmorgeologiya provided current (2006 dollar) estimates of capital and operating costs for a four-metal plant operating at 3.0 million tons per year capacity. The estimates were US\$ 1,650 million (CAPEX) and US\$ 400 million (OPEX) for a pyrometallurgical smelting reduction route; and costs of US\$ 1,000 million (CAPEX) and US\$ 400 million (OPEX) for a sulphuric acid/SO<sub>2</sub> leach system. These estimates, when scaled down to a 1.5 million ton per year capacity plant, were not considered to be markedly different from the Japanese and Indian estimates.

The Group informed the workshop that no cost estimates had been provided by COMRA; since one of COMRA's generic processes is the Cuprion process, the Group assumed the Hillman & Gosling estimates at current dollar rates scaled down to 1.5 million tons per year capacity.

The Group concluded that the IOM operating expenditure estimates are on the high side, noting however that they include estimates for the cost of nodules. It noted that without taking into account the cost of nodules, the operating costs would be around US\$ 270 million. The Group once again pointed out that this estimate is of the same order of magnitude as the Japanese and Indian estimates.

In the absence of further details, the Group estimated average CAPEX and OPEX costs for a four-metal processing plant as US\$ 750 million and US\$ 250 million, respectively, for a 1.5 million ton per annum processing plant.

### ***Probable cost-cutting technologies that could be used***

The Group noted that a major part of operating expenditure is represented by energy, a fact that has been raised specifically by IOM in its analysis of operating expenditure. Because of the similarity between nodule processing and the processing of land-based nickel laterite ore, the process operating costs are dominated by fuel costs. The fuel serves both as reductant and process energy supplier. The high temperature reduction process can be substituted by sulphuric acid leaching as in laterite processing, but fuel costs still dominate a sizable portion of total operating costs.

The Working Group suggested that contractor efforts should be specifically directed towards flow sheet design to minimize energy costs.<sup>9</sup> The Working Group observed that such

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<sup>9</sup> The Group said that many of the processes being developed employ an ammonia medium. It noted that recycling the ammonia consumes energy. It suggested that energy requirements for recycling (involving separation of the reagent) would be better understood by considering the ammonia recovery step for processes based on ammonia

considerations would come to the fore once large scale trials have established the basic engineering parameters for accurate estimates of energy requirements. The Group noted that at present, no contractor data has been reported for such studies.

The Working Group agreed that obtaining multiple products from polymetallic nodules would increase the economic viability of the processing operation. It noted that nodule processing operations have been traditionally limited to three or four metal production options. The Group suggested that recovery of additional values from the core processing technology would also permit profitable operations at lower capacity and would lower investment requirements. The Working Group reported that COMRA and Yuzhmoregeologiya had reported recovery of molybdenum from nodules in addition to the four metals. It further reported that BGR has suggested combined pyro-hydrometallurgical processing for optimized recovery of the major elements (Ni, Co, Cu, Zn, Pb, Mn<sup>10</sup> with special focus on electronic elements (Ge, Ga, In, Se, Te, Mo<sup>11</sup> ) Other than molybdenum, (around 1,000 ppm<sup>12</sup>), the Group noted that other elements are present in average concentrations of less than 100 ppm, and would require specific recovery methods. It also noted that another approach using a hydrocarbon-bearing reducing agent for the reduction of nodules and the production of smelter gas containing hydrogen (in addition to metal-bearing alloys and a manganese-bearing slag) offers interesting possibilities. The Group observed that the production of smelter gas containing hydrogen represented another product that could be traded, yielding additional revenues. Finally, the Group made the observation that these concepts based on preliminary data are yet to be reported at larger scales to quantify the assessment of benefits.

### ***Compatibility of technology developed for nickel laterite ore processing***

The Working Group observed that it would be useful to compare the specific investments for laterite ore and polymetallic nodules to understand the barriers to mobilizing substantial capital that does not yield returns commensurate with the risk involved. It noted that the capital and operating costs (in terms of dollars per kg nickel) for laterite processing are available for such plants. In the case of polymetallic nodules, the Group indicated the need to report capital expenditure in units of nickel equivalent; the recovered tonnages of nickel, cobalt, copper (for a three-metal recovery process) and manganese (for a four-metal recovery process) are multiplied by the price ratio of the recovered metal and nickel to obtain the nickel equivalents.

The Group reported that Direct Nickel provided data on processing laterite ores. For a laterite plant, based on estimates provided by Direct Nickel, the CAPEX was 9.5 US\$/kg Ni, whereas the OPEX was 2.2 US\$/kg Ni for a 50,000 tons per year nickel production facility; it is to be noted that these are values for 1.5 per cent nickel ore. The Group also estimated the capital cost/kg of nickel equivalent to be 10 to 14 US\$/kg for a 1.5 million ton per year polymetallic nodule processing plant, where the capital cost is US\$ 750 million; the estimated operating cost/kg of nickel equivalent is 3.9 US\$/kg without capital charges (operating expenditure: US\$ 250 Million average).

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leaching of nodules. Considering a base estimate of 7 tons of steam requirement for recovering 1 ton of NH<sub>3</sub> from aqueous solution, the energy for steam production for a leach solution containing 50 kg/m<sup>3</sup> ammonia leaching nodules containing 1.3 % Ni is as high as 400 M/kg of Ni recovered even for a 25 % pulp density of leach. It is thus essential to attain the highest permissible leach pulp density without violating solubility limits.

<sup>10.</sup> Ni – nickel, Cu – copper, Co – Cobalt, Zn – Zinc, - Pb – Lead and Mn - Manganese

<sup>11.</sup> Ge – Germanium, Ga – Gallium, In - Indium, Se – Selenium, Te – Tellurium and Mo =Molybdenum

<sup>12.</sup> Parts per million

The Group therefore concluded that the synergy of a laterite plant based on a DNi-type process with a nodules plant is immediately apparent. The Group said that the high nickel equivalents obtained by processing manganese should lead to an examination of options that did not include manganese production but production of metallic copper and cobalt in addition to metallic nickel. Since the DNi process produces a mixed metal hydroxide, it can be extended to metal production with incremental capital and operating expenditures. With copper and cobalt recovery, the nodules would easily be equivalent to a 1.5 percent nickel laterite ore. Thus the capital and operating costs / kg of nickel equivalent under the DNi process could match existing estimates of nodule processing plant costs.<sup>13</sup>

Working Group 2 concluded that metallurgical processing activities had advanced considerably. It also noted that estimates of processing costs among contractors are of the same order of magnitude. The Working Group identified the major outstanding issues as: engineering design for flow sheets and firming up cost estimates; enhancing revenues through multi-product recovery beyond the four-metal recovery approaches traditionally used; designing processes for maximum energy efficiency and minimum environmental burden (hitherto neglected in metallurgical processing); and working out collaborative arrangements among contractors and land-based laterite processing companies for rapid translation of technology developed to commercial scale.

### ***Working Group 3***

Working Group 3 was chaired by Dr. Caitlyn Antrim and included Ambassador Hasjim Djalal of Indonesia, Dr. Tetsuo Yamazaki, Dr. Carsten Ruhlemann, Dr. Sandor Mulsow, Dr. Valery Yubko, Ms. Tatiana Kalach, Mr. Baïdy Diène and Mr. Gritakumar E. Chitty.

The Working Group considered data from models of first-generation mining systems, reviewed 50-year trends in metal prices and projections for the future, defined a structure for financial evaluation of alternative mining system designs and evaluated the internal rate of return of alternative systems including systems proposed by Working Groups 1 and 2.

The Working Group reviewed information addressing past models of Deep Ocean mining (Texas A&M University, the US Bureau of Mines and the Australian Bureau of Mines). The baseline case used in the 1984 MIT report was selected as a base upon which to assess systems discussed by participants in the ISA-NIOT Workshop, particularly the information being developed in Working Groups 1 and 2.

A general model of deep ocean mining economics presented as a spreadsheet during the 2006 ISA Workshop on cobalt-rich ferromanganese crusts and polymetallic sulphides was selected as the structure for analysis, and was used to evaluate the data from the 1984 MIT report to confirm the model analysis. The Group also evaluated trends in metal prices, including projections of increasing demand by China and soon by India and the Russian Federation. The Group thought that the lower prices experienced between the end of the first wave of seabed mining interest and the beginning

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<sup>13</sup>. In real terms, this would imply that a process similar to the DNi process could target the production of either nickel from laterites or multi-metal from deep seabed polymetallic nodules. If the source material (nodules) cost is high, manganese recovery would need to be attempted.

of this decade had passed and the current issue was the rate at which metal prices would increase over the coming decades.

The Working Group decided to use a range of prices rather than attempt a single projection. Metal prices indexed from the MIT report using the consumer price index provided the lower boundary of prices, and prices in 2007 (viewed by some commodities experts as the peak price year) served as the upper boundary. Subsequent to the oral reports of the other two working groups, data from their presentations were incorporated into the computer model. A range of cost estimates drawn from the MIT Report, Working Group 1 on Mining Technology and Working Group 2 on Processing Technology were incorporated into the model along with the metal prices representing the upper and lower values in recent years.

**Expenses based on historic model**

To compare the results of the MIT model with the workshop model, the Group indexed the cost estimates and metal prices in that model to current prices using the US Producer Price Indices specific to the capital equipment and metals industry sectors.

The Group noted that the MIT pioneer operation consisted of two mining systems to recover 3 million dry tons of polymetallic nodules per year. Nodules were to be processed in a single ammonia leach processing plant and tailings<sup>14</sup> were to be disposed of onland.<sup>15</sup>

In order to maintain comparability between the estimates of the MIT report, (based on US short tons), and the estimates generated at the workshop (based on metric tons), the Group decided to index capital and operating costs using scaling factors that represent both the increase in capacity and savings from economies of scale.

The results of the Group’s work on the capital and operating costs reported in the MIT report are summarized in Table 3, with costs as reported in 1980 dollars and indexed to 2007.

*Table 3: Original and updated costs of MIT model of pioneer operation*

Sector	Capital	Costs	Annual operating Expenses	
	1980-1983 (million short tons)	2007-2013 (million metric tons)	1980-1983 (million short tons)	2007-2013 (million metric tons)
Prospecting & exploration: R&D	30.00	55.40	142.00	312.39
Mining	306.24	565.48	65.58	144.27
Transport	200.88	370.93	22.20	48.84

<sup>14.</sup> Tailings (also known as ‘slimes’, ‘tailings pile’, ‘tails’, ‘leach residue’ or ‘slickens’) are the materials left over after the process of separating the valuable fraction from the worthless fraction of an ore.

<sup>15.</sup> The cost estimates for the operation were based on designs produced by Texas A&M University (for sea systems design) and Dames & Moore (for the processing plant). Costs were calculated in 1980 dollars.

Sector	Capital	Costs	Annual operating	
Ore terminal	22.87	42.23	3.29	7.02
Onshore transport	36.65	67.67	7.68	16.90
Processing	449.10	829.27	99.60	219.12
Waste disposal	15.28	28.21	39.00	85.80
Marine support	1.80	3.32	4.88	10.74
General &	88.20	162.86	4.00	8.80
Continuing	0.00	0.00	6.00	13.20
Total	1,121.02	2,125.38	217.03	867.07
Capital costs are indexed by the Producer Index for Capital Equipment; Operating costs are indexed by the producer price index for metal industry costs				

The estimates provided by Working Groups 1 and 2 were summarized by Working Group 3 in Table 4:

*Table 4: Mining system cost estimates provided by WG1 (costs of single ship, US\$ millions)*

System	Capital cost	Operating cost
Passive hydraulic	552.30	44.52
Tracked collector	562.60	45.72
Chinese collector	372.60	38.47
India flexible riser	416.96	59.92

It was also noted that Working Group 1 prepared estimates of the cost of a system for transporting ore from the mine site to the processing plant. The estimates are presented in Table 5. The system proposed by Working Group 1 is based on three transport vessels carrying ore to a plant 6,000 miles away.

*Table 5: Sea transportation system cost estimates established by Working Group 1*

System	Capital cost	Operating cost
Leased transport	0.00	76.00
Owned transport	495.00	36.13
Indian transport	600.00	72.70

### **Assessment of revenue**

Working Group 3 agreed that the revenue of a mining operation is based on the production of ore, the metal contained in the ore and the market price of the metal. The Working Group updated the revenue estimates from the MIT model and its results are contained in Table 6.

**Table 6:** Original and updated revenue estimates (prices in US\$/pound: revenue in US\$/dry ton of nodules)

Metal	Metal Content (%)	Recovery (%)	Metal price (1980)	Revenue from metal (1980)	Indexed metal price (2007)	Indexed revenue from metal (2007)	Actual metal price (2007)	Actual revenue from metal (2007)
Nickel	1.50	95	3.75	119.86	9.45	301.93	17.12	547.20
Copper	1.30	95	1.25	34.63	3.15	87.22	3.35	92.80
Cobalt	0.24	60	5.63	18.18	14.18	45.81	30.20	97.54
<b>Total</b>				<b>172.67</b>		<b>434.96</b>		<b>737.54</b>

Several factors relevant to the assessment of revenue were presented in the reports of Working Groups 1 and 2.

- The metal content of the recovered nodules is assumed to be lower than that in the base case of the MIT model.
- The metal recovery of the processing systems has improved over the MIT pioneer operation. In the case of cobalt the change is significantly greater.
- Contractors participating in the Workshop are considering manganese production at a lower ore processing rate, in addition to the three-metal systems of the first wave of ocean mining development.

The revenue estimates per ton of ore reported by Working Group 3 are shown in Table 7.

**Table 7:** Revenue estimates per ton of ore, based on Working Groups 1 and 2 reports

Metal	Metal Content (%)	Recovery (%)	Indexed metal price (2007)	Indexed revenue from metal (2007)	Actual metal price (2007)	Actual revenue from metal (2007)
Nickel	1.30	95	9.45	257.22	17.12	466.00
Copper	1.10	94	3.15	71.79	3.35	76.34
Cobalt	0.24	90	14.18	67.51	30.20	143.77
Total three-metal recovery				396.52		686.11
Manganese	29	85	0.50	271.64	0.50	271.64
Total four-metal recovery				668.16		957.75

**Note:** The price of manganese is based on reports of the US Geological Survey contained in the 2005 USGS Minerals Yearbook. The alloy price is divided by manganese content at the price per pound of contained manganese.

A reference was made to Working Group 2’s emphasis that manganese should be produced in the form of silico-manganese or ferro-manganese, noting that silico-manganese has a metal content of about 70 per cent manganese. The Working Group noted that a single deep seabed polymetallic nodule mine producing 1.5 million metric tons could produce about 530,000 mt of

silico-manganese which constitutes approximately 10 per cent of world silico-manganese production, or 5 per cent of combined ferro-manganese and silico-manganese production (Table 8). The Working Group further noted that a single polymetallic nodule mine would probably have only a minor impact on prices for silico-manganese, but it would have a significant impact if manganese production were to occur at all licensed ISA exploration sites.

*Table 8: World production of ferro- and silico-manganese*

	2001	2002	2003	2004	2005
Blast furnace, ferro-manganese	941,000	991,000	917,000	778,000	739,000
Ferro-manganese	3,060,000	3,010,000	3,340,000	4,060,000	3,940,000
Silico-manganese	3,780,000	4,300,000	4,590,000	5,820,000	6,880,000
Total production (excludes US prod)	7,781,000	8,301,000	8,847,000	10,658,000	11,559,000

### **Financial analysis**

The Working Group decided to conduct a discounted cash flow (DCF) analysis of the polymetallic nodule mining venture because a DCF is a financial tool commonly used to measure the relative attractiveness of alternative investment opportunities in the hard minerals sector, and was also the method used to evaluate the development prospects of seabed mine sites in the 1970s and 1980s.

### **Methodology**

Working Group 3 applied a relatively simple spreadsheets-based model that schedules costs and expenses over the lifetime of a mining operation, calculates annual net cash flow and calculates the discounted sum of the annual cash flows. The spreadsheet model accounts for expenses and income in five categories: prospecting and exploration; research and development; capital investment; operating expenses; and sales revenues. These cash flows were scheduled over a seven year period consisting of two years of prospecting and R&D, two years of site exploration and three years of exploration and capital construction, followed by twenty years of commercial production. The model factored in a scale up to full production in the first three years of commercial production, and a US\$ 250,000 application fee paid to the International Seabed Authority at the completion of prospecting.

### **Key factors not included**

The model did not include inflation, national taxation, payments to the ISA or debt financing.<sup>16</sup>

<sup>16.</sup> *Inflation:* Long term inflationary pressures may have an effect on the economic attractiveness of a mine. In general, inflation will improve the economic outlook and deflation will cause it to fall. Projection of inflation effects was outside the terms of reference of the working group and was not considered. *National Taxation:* Payment of national taxes (or payments to the International Seabed Authority) would reduce the internal rate of return, but because of the complexity of national taxation systems and their variation among states, they are not included in the Working Group's model. Studies of potential first-generation mining systems suggests that development opportunities with projected before-tax returns of 18 per cent would see a reduction in internal rate of return of about 3 per cent under the United States tax code. *Payments to the International Seabed Authority:* The model does not include payments to the ISA that will be established in the rules for commercial exploitation, nor is the issue of whether such payments will be credited against national taxation addressed. *Debt Financing:* Debt financing of a mining operation allows investors to borrow funds at a rate lower than the rate of return on their investment. Key factors in an analysis are the fraction of the capital cost covered by borrowing and the interest rate charged on the loan. Past studies have indicated that debt financing could raise the internal rate of return by several per cent.



**Review of the original and updated MIT Pioneer Operation**

The Group reported that the assessment of the original MIT Pioneer Model using the simplified analysis model reported an internal rate of return of slightly more than 1.5 per cent greater than the return calculated by the original MIT model (Table 9). The Group attributed the difference to several simplifications, including the absence of the negative effect of US taxation and the positive effect of debt financing in the original model.

*Table 9: Analysis based on MIT Pioneer Model in 1980 (Scaling annual capacity of model from short tons to metric tons)*

Model conditions	IROR (%)
Baseline result based on 20-year production lifetime at 3 million short tons per year	10.74
Baseline model scaled to 3 million metric tons per year	11.68

Working Group 3 reported another analysis based on costs indexed to present day for two cases. The first case uses the metal content and cobalt recovery rate of the original pioneer model while the second uses a reduced content of nickel and cobalt and a high cobalt recovery fraction. The changes in the second case were used throughout the subsequent analyses of the Chennai variations (Table 10).

*Table 10: Analysis of MIT pioneer model indexed to 2007 costs and prices (updated estimates of metal content and cobalt recovery)*

Model conditions	IROR Indexed Prices (%)	IROR 2007 Prices (%)
MIT pioneer model with costs indexed to 2007	20.21	37.75
MIT pioneer model with costs indexed to 2007, content reduced and cobalt recovery increased:	17.19	35.85

**Review of workshop variations**

Working Group 1 reported on capital and operating costs for the mining and transportation components of a seabed mining operation and Working Group 2 reported on processing alternatives.

Working Group 3 acknowledged that the MIT Pioneer Model with costs indexed to 2007 would provide a framework in which estimates made by Working Groups 1 and 2 could be substituted for the corresponding elements in the model while retaining the cost estimates for sections not addressed by the Working Groups. It also noted that Working Group 2 stated that a three-metal recovery system needed to operate at higher annual capacities, with 3 million dry tonnes per year being a common standard. Four-metal systems, with additional costs and revenues coming from manganese production, can operate at half that capacity. All variations include the assumption made by Working Group 1 that ore would be transported to China for processing and that the lifetime of the mining operation would be 20 years of commercial production. Table 11 provides a summary of the results, including the variations.

*Table 11: Analysis of workshop variations on mining and transport systems*

Variation	Mining	Processing	Capital cost	Annual operating cost	IROR indexed Prices (%)	IROR 2007 Prices (%)
1	3 Passive collector	3-Metal, 3 million	3,285,460,000	531,270,000	12.64	28.54
2	3 Flexible riser	3-Metal, 3 million	2,879,440,000	577,470,000	13.08	28.70
3	3 COMRA	3-Metal, 3 million TPY	2,746,360,000	513,120,000	15.51	30.79
4	2 Passive collector (each 0% capacity increase over	3-Metal, 3 million TPY	3,031,402,000	510,790,800	14.11	28.88
5	1 COMRA (each with 50% capacity increase over WG1 design)	4-metal, 1.5 million TPY	2,149,889,866	433,874,981	21.04	30.40
6	2 COMRA (each with 25% annual capacity decrease below WG1 design)	4-metal, 1.5 million TPY	2,351,606,434	441,305,979	19.46	28.45

Variation 5 – the four-metal, single ship system – has the highest projected rate of return under moderate metal price assumptions and the second highest projected rate of return under optimistic prices, and it has the lowest projected capital and operating costs. While the three-metal, three-transport vessel of the COMRA design has the highest projected return under high price conditions, its return under lower nickel, copper and cobalt prices is significantly lower than for the four-metal system.

### **Conclusions of Working Group 3**

The financial outlook for deep ocean mining has changed for the better. This is due both to rising metal prices, driven in part by rising consumption in China, and to the more general effect of prices increasing significantly faster than the cost of capital equipment and its operation. The model indicates that an identical deep ocean mining system would return a significantly better financial return today than 25 years ago at the heyday of the first wave of interest in deep seabed mining.

Projections by the US Geological Survey indicate that demand for metals in manufacturing and other sectors of newly industrializing States, including China, India and the Russian Federation, will continue to grow faster than the world economy at large.

Opportunities to develop known high-value deposits or to expand current deposits on land have largely been implemented already. New production is moving to greenfield deposits of oxide ores of lower grade than those found in operations now in production.

Based on past analyses, current research and projected metal price trends, deep seabed mining for high nickel-copper-cobalt mine sites in the Clarion-Clipperton Zone meet the economic and investment criteria to be considered for investment and development.

Based on updated estimates of historic designs and estimates of mining, transport and processing systems prepared at the Chennai workshop, several designs demonstrate internal rates of return at the 15 per cent level used to identify land-based deposits worthy of consideration for development. At this time, the four-metal system looks particularly attractive relative to the 15 per cent minimum IRR.

At the present time and based on the estimated costs of manganese production from nodules, the profitability of the smaller four-metal design appears to offer less exposure to the risk posed by periods of lower nickel, copper and cobalt prices.

Additional work is required to assess design improvements that might contribute to lower costs in both the mining and processing sectors and the effects of less distant processing locations, and to prepare more definitive estimates of costs in the four-metal processing system.

## PART ONE

# The economic, technical and legal framework for the development of polymetallic nodule resources in the Area

### CHAPTER 1

Updated Analysis of the Capital and Operating Costs of a Polymetallic Nodules Deep Ocean Mining System Developed in the 1970s

*Frank H. Brockett, President, Sound Ocean Systems, Inc. Redmond, WA, USA ; Jack P. Huizingh, Naval Architect / Marine Consultant, Kaneohe, HI, USA; James A.R. McFarlane, Vice President, Sound Ocean Systems, Inc., Redmond WA, USA*

### CHAPTER 2

Model Mining Units of the Twentieth Century and the Economics (Production Requirements, Area Requirements and Vertical Integration)

*T. Yamazaki, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan*

### CHAPTER 3

Seabed Mining Economics: Lessons to be learned from old and dusty models

*Caitlyn Antrim, Executive Director, Rule of Law Committee for Oceans, Arlington, Virginia, USA*

### CHAPTER 4

Economic and Technical Considerations Underpinning the Pioneer Regime

*Baïdy Diène, Special Adviser, Ministry of Mining & Energy, BP.11841-Peytrin, Dakar, Senegal*

## **CHAPTER 1 Updated Analysis of the Capital and Operating Costs of a Polymetallic Nodules Deep Ocean Mining System Developed in the 1970s**

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### **Summary**

This paper will briefly describe the pilot scale deep ocean mining system that was designed and successfully tested during the mid-1970s by Ocean Management Incorporated headquartered in Bellevue, Washington State. The authors were part of the team that recovered an 800 ton bulk sample of polymetallic nodules in 5,250 m of water at a candidate commercial mining site in the mid-Pacific Ocean. This bulk sample was later processed into a Ni-Cu-Co matte. Although these tests were conducted over 30 years ago, the basic mining system approach and lessons learned are still relevant today. Since we are unaware of similar mining efforts of comparable magnitude and success subsequent to those tests, we have used that mining system and related economic analyses as a starting point to generate a rough cost estimate for a mining system that could be developed to commercially mine polymetallic nodules in the deep ocean. The cost estimates presented reflect only the mining system. The integration of the exploration, logistics, re-supply, transport, processing, engineering, design, prototype testing, preconstruction, preproduction, indirect and numerous related project costs are not included. These costs are the subjects of other workshop presentations and will be required to prepare an overall project cost estimate. Subsequent economic feasibility analyses and projections for commercial viability will also require credible assumptions of nodule grades, processing recovery rates, product prices and markets.

### **Introduction**

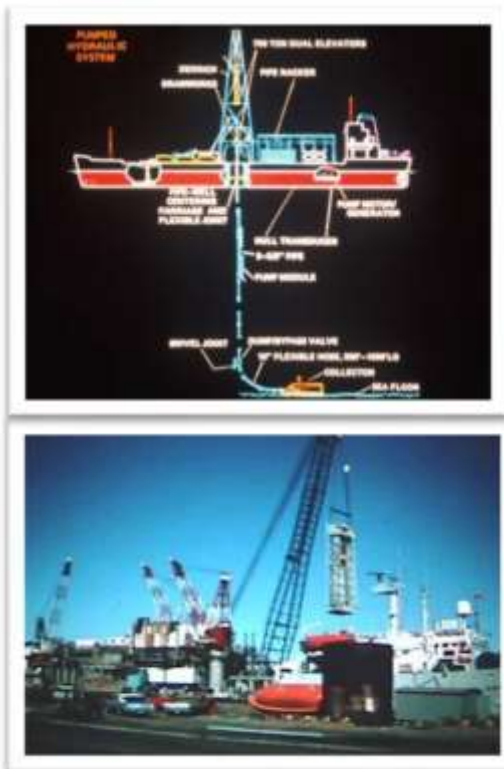
In early 1978 a consortium was created and led by the International Nickel Company (INCO) of Canada, and included AMR of Germany, DOMCO of Japan and SEDCO of the United States of America (USA).<sup>1</sup> The resultant company was Ocean Management Incorporated (OMI), which completed the world's first successful deep ocean pilot mining tests (PMTs) in the Eastern Equatorial Pacific. Three test cruises culminated a four-year research and development programme to determine the technical feasibility and economic viability of deep ocean mining. The PMT was conducted in more than 5,250 meters (m) of water in the nodule-rich belt located between the Clarion and Clipperton fracture zones roughly 1,000 nautical miles southeast of Hawaii. The OMI team, operating aboard the *SEDCO 445* drill ship, successfully recovered over 800 tons of nodules during these tests.

The developmental mining system tested during the PMTs was configured around the *SEDCO 445* drill ship. The configuration is illustrated in Figure 1. A riser pipe assembled with 9-5/8 inch diameter oil field casing extended from the gimbaled derrick floor to within 50 m of the seafloor. This gimbaled derrick provided a stable and efficient handling platform for the casing, submersible pumps, seafloor collectors and related equipment. The test sites were located in 5,250m of seawater. The resulting weight of the riser pipe, pumps, instrumentation and collector assembly was over 450 metric tons.

<sup>1</sup>. AMR (Arbeitsgemeinschaft Maerestechnisch-gewinnbare Rohstoffe) was owned by Metallgesellschaft AG, Preussag AG and Salzgitter AG, all of the Federal Republic of Germany; DOMCO (Deep Ocean Mining Company Ltd comprised of 23 Japanese companies.

During the PMTs, OMI tested a hydraulic submersible pump and an air injection lift system to raise the nodules from the seafloor to the surface. Three seafloor nodule collector designs were tested. The interface between the seafloor collector and riser pipe was a flexible hose which accommodated variations in seafloor bathymetry. Above the flexible section of the hose, a deadweight was installed to control riser pipe lift-off during towing operations and a dump valve to prevent nodule clogging in the riser pipe during mining shutdowns. A vacuum relief valve was also included in the lower assembly to prevent collapse of the flexible hose in the event the collector became jammed with nodules.

The primary function of the collector was to gather the nodules from the seafloor. The collector was also required to reject oversized and undersized nodules, eliminate unwanted sediment, and introduce the nodules into the riser system. In addition to providing a conduit for lifting the nodules to the surface, the riser pipe was used to tow and navigate the seafloor collector through the mine site. Once on deck, an air, water and nodule separator directed the nodules to conveyors. These conveyors were used to transport the nodules to the ship's hold and deck storage containers. Residual water and entrained sediment were returned to the ocean.



*Figure 1: OMI pilot mining system configuration*

### **Mobilization**

Mobilization of the PMT was conducted in a shipyard in Beaumont, Texas. During the mobilization, the *SEDCO 445* was converted from its standard drill ship configuration to one more suitable for deep ocean mining. Several significant modifications were implemented during the mobilization process. The major change was the removal of the fixed derrick and the installation of a gyro stabilized hydro-rig derrick shown in Figure 2.

*Figure 2: Installation of the hydro-rig gimbaled derrick onto the *SEDCO 445**

Modifications were also made in pipe string storage and handling equipment to accommodate the 9-5/8 inch riser pipe. Pipe storage racks and special pipe handling equipment were installed so the joints of the pipe could be efficiently moved from the storage hold to the derrick floor.

Deployment of the complete riser and mining system typically took two to three days. Retrieval times were similar, resulting in a round trip time of five to six days. Figure 3 shows the mechanized transfer of a joint of riser pipe.



*Figure 3: Pipe handling equipment aboard the SEDCO 445*

Four large in-line submersible pumps were stored in custom racks designed to support the vertically oriented pumps. Three large air compressors were also installed on deck to power the air lift system. The air, water nodule separator, conveyor and storage system was another installation on deck. A 40 foot shipping container that was outfitted to serve as the test communications and instrumentation center was

also secured on deck. Six instrumentation and pump cable winches were installed around the moon pool with sheaves to direct the cables to a hanging personnel basket for attachment to the riser pipe. Finally, the riser pipe, pumps, collectors, hose, valves, conveyors, storage bins and supplies were loaded and secured for transit to the mine site.

*Figure 4: Installation of mining system control room*



The mobilization phase included extensive dockside training and testing before the ship departed Texas for the trip through the

Panama Canal to the mine site. An important aspect of all phases of the early testing was the refinement of the procedures used to handle, launch, deploy, operate, and recover the elements of the mining systems. The dockside tests and the subsequent shallow water tests and sea trials also provided an opportunity to train ship and mining system crews.



*Figure 5: The SEDCO 445 off Honolulu, configured for deep ocean mining*

### **Seafloor collector system**

The ship, riser pipe, pumps, airlift and instrumentation systems were designed and assembled using known technologies and equipment. By contrast, continuous collection of nodules from seafloor and sediment removal represented a large unknown.

Performance of the seafloor collectors was crucial to the success of the project. As a result, OMI conducted an extensive collector development programme over the four years leading up to the PMT. This development effort was completed by three groups of engineers, designers and technicians located in Germany, Japan and the United States. The collector development team conceived, modeled, evaluated and manufactured several competing designs. Significant costs in ship and project time would be incurred should the collectors fail. Collector system reliability was ranked accordingly during the evaluation of the competing designs.

During this effort, numerous collector concepts were developed including both active and passive designs. A wide variety of each was tested in controlled laboratory environments using scale models of critical collector components. As shown in Figure 6, pilot scale collectors were built and tested in a specially constructed tow facility in Redmond, Washington. Simulated ocean bottom sediment with representative shear strength and bearing capacity and simulated nodules were developed and used during the land based testing programme. The sediment was installed in the bottom of the test bed and seeded with nodules. After installing the collector to be tested at one end the facility was filled with water. After each test the facility was drained so that the simulated seafloor could be inspected and an estimate of nodule recovery could be made. The bed was then prepared for the next test and the process repeated.



*Figure 6: Electro-hydraulic collector after test run in tow facility*

Evaluation of the tow test results eliminated some designs and yielded several promising concepts that were then selected for in-situ deep sea testing and evaluation. Two 'collector test' cruises were scheduled aboard the German Research Vessel (R/V) *Valdivia* in the summer of 1976. This same ship was used to conduct the extensive exploration programme required to delineate potential test sites and commercial claim sites. With its large existing A-Frame and stern ramp, the R/V *Valdivia* was ideally suited to the requirements of the collector test programme.

These initial at-sea tests used eight collector designs configured for testing on an umbilical tow cable system. The basic collector functions of each design were tested and compared by counting nodule throughput for each design.

*Figure 7: Dockside testing of collector launch and recovery procedures on the R/V Valdivia*

During the in-situ deep ocean testing, various collector concepts were tested including multiple variations of each of the three design styles, which were passive, hydraulic and mechanical systems. OMI had initially considered self-propelled collector concepts but had eliminated them as being unnecessary and unwarranted. The driving factors in making this decision were added complexity, added weight, added cost and potentially





added cost and potentially reduced reliability. At the end of the collector development effort, OMI selected one primary collector design, an elegant and simple, towed hydraulic design that utilized seawater as the means to collect, size, sort, reject, lift and transport nodules while simultaneously eliminating a majority of the unwanted sediment. A secondary system based on the cutter-blade-scraper concept was also chosen for evaluation during the PMT. Three collectors were fabricated and taken aboard the *SEDCO 445* for the PMT, including 2-metre and 3-metre active width hydraulic collectors and a 2-metre wide mechanical cutter-blade-scraper collector.



*Figure 8: Two-metre DOMCO hydraulic collector*

The primary two-metre and backup three-metre hydraulic collectors were designed by a team from the Sumitomo family of companies within the DOMCO group and were built in Seattle, Washington, and shipped to the PMT staging site in Texas. The hydraulic collector design was very simple and derived all of its nodule collection-related functions from a single 20 horsepower (hp) submersible electrical motor.

While seemingly under powered, this 20 hp design later proved up to the task, at times delivering more than 40 tons per hour of nodules.

### **Seafloor / riser interface**

As shown in Figure 9, the flexible hose was connected directly to the front of the collector using a commercially available hose clamp. A contra-helically wound armored cable was used to provide electrical power, asynchronous telemetry communications and data channels back to the surface from the collector. Soft ratchet clamps were used to attach all the cables to the hose and riser pipe. Typically, five to six cables were latched and unlatched to the riser pipe during deployment and retrieval.

*Figure 9: Two-metre hydraulic collector over moon pool with riser hose attached*

Approximately 150 m of flexible hose was used to connect the collector to the rigid portion of the riser pipe. The hose provided the flexible connection necessary to turn the corner from the vertically oriented rigid riser pipe to the horizontally oriented collector.



Similarly, it provided the flexible link that allowed the collector to follow the mining vessel as it made turns during the mining operation. The hose also provided the flexibility needed to accommodate the changes in water depth at the mining area without having to add or remove joints of the riser string.

Connected at the lower end of the riser pipe was a nodule dump valve. The dump valve was designed to remain closed when the lift system was operating and automatically open when the pumps or air lift system were shut down. The dump valve provided a means for falling nodules to escape the riser pipe and prevent clogging in the event of lift system shutdown or failure. The dump valve is shown in Figure 10 as it is being readied for installation on the rig floor.



*Figure 10: Dump valve being lifted to rig floor*

In addition to the dump valve, a large lead deadweight was installed at the bottom of the riser pipe. The deadweight controlled collector lift off during towing and maintained the riser pipe in a near vertical position. The lead donuts were installed around a short joint of 9-5/8 inch casing. A vacuum relief valve was also installed at the end of the riser pipe to prevent collapse of the flexible hose should a nodule clog occur at the collector. Although reinforced with

steel bands, the collapse strength of the hose was considerably less than the collector flow conduits and riser pipe.



*Figure 11: Deadweight being installed*

The riser pipestrung was comprised of 9-5/8 inch oil field casing made of high strength steel with welded-on threaded tool joints. The pipe bodies were made in Germany and the tool joints made and assembled in Texas. Completed joints measured 33 to 35 feet in length in the upper sections of riser and 40 to 43 feet in the lower sections. The pipe bodies were all made of S135 (135,000psi) high strength steel. The wall thicknesses of the pipe were tapered with respect to expected pipe loadings and location in the riser assembly. Tapering the pipe wall thicknesses reduced the overall weight of the riser pipe and associated loadings on the hydro-rig pipe handling system and derrick floor. Instrumentation subs were installed in the riser above the pumps and at the rig floor to monitor pipe stresses and loadings.

### **Lift system**

In-line submersible pumps were installed at a depth of 1,000 m below the water surface. The pumps were of mixed flow design powered with 1,000 horsepower motors. The pump motor

assemblies were installed in large diameter housings that directed nodule flows around the motors and carried the weight of the 4,300 m of riser and equipment suspended below. Typically two pumps were used during the mining tests. As seen in Figure 12, the pump motor housings were designed to transition to and from the 9-5/8 inch riser pipe and could be installed at any location in the riser pipe. Large armored power cables were strapped to the riser to power the pump motors.



*Figure 12: In-line submersible pump*

### **Instrumentation**

The instrumentation subsystem employed during the PMT was essentially an enhanced version of the system developed and used previously during the in-situ collector test cruises. Collector, riser/lift, pump motor, and shipboard sensor outputs and command and control signals were multiplexed to and from the control room via shielded twisted pair conductors in the umbilical cables. Commercially available computers, video monitors, and analog meters were used to monitor, control and record data from the various mining system components.

Instrumentation on the collector consisted of attitude sensors such as pitch, roll, heading, altitude, motor voltage, and a special impact sensor used to approximate nodule collection rate. The 'nodule counter' had been developed by Honeywell under

contract to INCO and utilized bender bar transducer technology to essentially count nodule impacts. By strategically placing the impact sensors in the nodule flow path within the collector, a reliable qualitative measurement of nodule throughput was achieved. Additionally, the collector was equipped with video, lights, and a hydrophone that also proved to be a qualitative backup measurement of nodule throughput. Several switch closure and position sensors were used to verify that specific command functions had in fact been executed.

*Figure 13: Command and control center*

Dedicated instrumentation 'subs' were constructed using heavy walled joints of casing and were integrated into the riser at specified locations along its length. These instrumentation subs typically measured pipe loads and stresses, pipe trail angles, accelerations, pressure differentials in the pipe and flow velocities. Ship motions, horsepower, speed and headings, weather conditions, hydro-rig behaviour, submersible pump horsepower and temperatures, air compressor horsepower



and pressures, solids flow measurements and navigational data were collected at designated points on the ship and directed to the instrumentation van and the mining system control center.



*Figure 14: Instrumentation sub being integrated into the riser*

The instrumentation van and the central control center presented real time data using an array of monitors. Each subsystem was assigned monitors, from which the project engineers and technicians could observe and analyze data and provide immediate status and advice to the mining test managers. Constant communication was maintained between the ship's Captain and bridge, the derrick floor and moon pool, the instrumentation van, and the mining control center.

## Results

A total of three PMT cruises were completed during the summer of 1978. The submersible pump system recovered approximately 650 metric tons of nodules while the air lift system recovered 150 metric tons for a total of 800 metric tons. Nodule throughput varied dramatically throughout the tests with the rate exceeding 40 tons per hour at times, causing the material handling systems and storage containers on the mining ship to overflow with nodules.



*Figure 15: Control system display*

The 800-ton bulk sample was shipped to INCO's Port Colbourne research facility for process testing and development. The sample was later processed into Ni- Cu-Co matte and distributed to the consortium partners for further evaluation.



*Figure 16: Transport conveyors overflowing with nodules*

The hydraulic collector design was successful at eliminating the majority of the sediment picked up with the nodules, resulting in entrained sediment concentration of less than 1 per cent by weight. At the surface, the cold water from the seafloor descended rapidly back toward the seafloor.

The mining system configuration used during PMT was judged by OMI to be a promising design for future commercial operations and was used as the basis for subsequent cost estimates and feasibility analyses. The PMT configuration, described above, was a passively towed hydraulic collector combined with a submersible pump lift system that has been used as the basis for this analysis and paper. The commercial system is described in detail in the following sections.

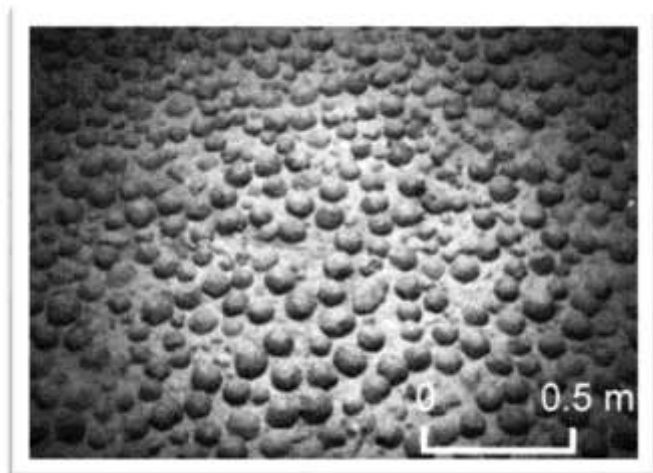
### **Description of commercial scale mining system**

In estimating the cost of a commercial mining system, a project of modest, achievable size for a first-generation operation is assumed and described below. The proposed mine site lies within the North Central Pacific Ocean in an area defined as the nodule belt, which is roughly bounded by the lines of 5° to 20° North Latitude and 110° to 160° West Longitude. Within this 5 km<sup>2</sup> nodule belt lie several mine sites with the potential for commercialization and a minimum mine site life of 25 years. The water depth in this nodule belt is typically 5,250 m. The seafloor is relatively flat with modest changes in depth and slope. Nodule concentration averages 2 pounds per square foot.

*Figure 17: High concentration of nodule covera*

### **Nodule grades**

Nodule grades in this Pacific nodule belt have been documented by several sources and are typically as indicated in Table 1.



*Table 1: Nodule grades*

<b>Metal</b>	<b>Content by weight (%)</b>
<i>Nickel</i>	1.40
<i>Copper</i>	1.10
<i>Cobalt</i>	0.21
<i>Manganese</i>	28.00

## **Metal production**

Assuming a project size of modest scale and yet within the parameters of reasonable production, product markets, operational and financial risk, we have assumed the following annual metal production:

<b>Metal Cathode I</b>	<b>Refined Product</b>
<b>Nickel</b>	25,000,000 lbs ( 11,340 mt)
<b>Copper</b>	20,000,000 lbs ( 9,070 mt)
<b>Cobalt</b>	3,250,000 lbs ( 1,474 mt)
<b>Manganese</b>	500,000,000 lbs (226,760 mt)

To meet the above metal production, approximately 1,000,000 dry metric tons of nodules must be delivered annually to the process plant. Converting from dry metric tons to wet metric tons for as-mined nodules, the mining system will have to recover 1,500,000 wet metric tons (wmt) per year. Assuming one mining ship, with a 270-day production year, a mining rate of 5,550 wmt per day will be required.

Our concept of a commercial-scale nodule ore mining system that could be employed today is based on the pilot scale system that we tested successfully in the mid-1970s. Subsequent extrapolations of that system provide the parameters and define the requirements for a commercial-scale system that could be used today. We have also reviewed the current state of the art in the offshore oil industry and equipment that is related to mining the deep ocean. Other than the costs and numerous technical improvements, the basic mining functions, system and equipment components are essentially the same as they were at that time.

## **Vessel requirements**

We have assumed one mining ship outfitted with a mining system capable of recovering 1,500,000 wmt per year. Operationally, the nodule ore will be pumped at sea from the mining ship to a trailing bulk carrier using a floating hose transfer system. The mining ship will be large enough to store a three day supply of nodules, roughly 16,500 wmt to allow for bulk carrier change outs and delays due to poor weather. Re-supply of the mining ships would be accomplished with a combination of ocean going supply/crew boats and backhauls using the bulk carrier transports. The mining ship serves as the central working platform for the offshore mining operation. The vessel is required to provide the following functions:

- Tow and manoeuvre the mining system through the mine site.
- Deploy and recover the subsea portions of the mining system.

- Provide secure stowage of the mining system.
- Provide buffer storage for nodule slurry.
- Provide nodule slurry processing for on-board buffer storage.
- Provide spare mining system components.
- Provide reliable power to all ship and mining system requirements.
- Provide maintenance facilities and spares.
- Provide accommodation, hotel and food services for personnel.

The majority of these requirements are easily met by modern day drill ships used in the offshore oil industry. These deep water drill ships are designed to provide a stable operating platform under extreme weather conditions. Their design also has the required power and dynamic positioning capabilities for efficiently navigating the mine site with the nodule recovery system deployed. These drill ships are fully equipped with the systems required to handle the mining riser pipe, handle heavy pump/motors and full-scale seafloor collectors. Modern deep water drill ships are also large enough to accommodate the necessary mining system spares and to provide sufficient nodule storage for several days of mining.

The parameters of a suitable size drill ship class for a first-generation, commercial deep ocean mining project typically would be:

Length	L	= 750'
Beam	B	= 125'
Depth	D	= 60'
Draft	d	= 40'
Displacement		= 87,000 mt
Horsepower		= 60,000
Nodule Buffer Storage		= 16,500 wmt
Dynamic Positioning		= DP – 3
Derrick		= 4,000K lbs
Accommodation		= 100



Figure 18: Drill ship Jack Ryan

Drill ships of this size and class were typically built between 1998 and 2001. Examples that meet deep ocean nodule mining requirements are Transocean’s *Deepwater Discovery*, *Frontier*, and *Millennium*, Pride’s *Africa* and *Angola*, and SanteFe Global’s *C.R. Luigs* and *Jack Ryan*. This class of drill ship was typically 700 to 750 feet in length. More recent designs are over 800 feet in length and considerably more costly.

We have assumed a 1998-2001 generation drill ship in our model. The cost of drill ships built between 1998 and 2001 of the size the mining project will require ranged between US\$250 to US\$300 million. Recent increases in oil prices have led to increased exploration and demand for deep water drill ships. As a

result, orders for construction of new drill ships have soared along with the construction costs. Typical construction costs for slightly larger 850-foot drill ships scheduled for delivery between 2007 and 2011 are now in the range of US\$600 to US\$700 million; roughly double the cost of only seven years ago.

The use of high-grade, high-strength oil field casing and tool joints for the riser pipestring was successfully tested during the PMTs. The design was comprised of 9-5/8 inch high-strength oil field casing with industrial tool joints for making and breaking down the pipe string. For the proposed mining system, we assume a riser pipe system of similar design, but with 13 – 3/8 inch diameter casing. The larger diameter casing is also an oil field standard size and is readily available in high-strength steel.

The overall weight of the 5,250 m subsea system comprised of riser pipe, pump / motor modules, various interface sections and the seafloor collector at the point just before touchdown is estimated at 900 mt (2,000,000 lbs). This weight can be carried using high-strength steels and industrial tool joints with shoulders that allow handling at the rig floor. Assuming a mix of standard 43 foot and 35 foot sections, some 400 joints are required to make up the complete 5,250m riser pipestring.

Similar to offshore drilling in areas of high currents, towing the mining riser / pipestring will create drag and vortex shedding. These dynamic forces can impart uncontrollable vibrations and increase associated riser / pipe stresses. The larger the riser pipe diameter, the greater is the chance of vortex shedding. Installing fairing on the riser pipe in the area of highest flow can suppress or deter vortex shedding and its associated problems. The riser pipe fairing will also reduce the drag forces from towing and reduce towing horsepower and fuel consumption. For this mining system, we have assumed that fairings would be installed on the sections of riser pipe that are above the pump motor modules and are likely to experience a combination of towing velocities and ocean surface currents.

For our cost estimates, we have assumed that the mining ship will have one riser pipe string in operation along with a second complete 5,250 m spare pipe on-board. We also assume that 1,600 m of spare joints will be on board to replace any joints that are damaged during deployment and retrieval. Similarly, two sets of riser pipe fairings are assumed for the section of riser pipe above the pump / motor modules.

In-line submersible pumps and motors were also successfully tested during the PMTs. Analysis of the pumps following the tests indicated small amounts of erosion; however the pump materials for the test had been selected for short-term use only. With upgrades of the various pump materials, a similar pump / motor system can be used in the commercial mining system. To accommodate the larger nodule throughput required, we have assumed a system of three in-line pump / motors. The pumps would be of mixed flow design with six to seven stages, 250 m head, driven with 3,000kw DC motors. This pump / motor system can easily lift the required 220 wmt on nodules per hour at a modest 5-7 per cent solids concentration.

Channeling the flow from the riser pipe around the motors and back into the riser pipe requires pump / motors be housed in large diameter, high-strength steel casings. These casings must also carry the weight of the riser pipe, interfaces and seafloor collector that lie below the pumps. In addition, each pump / motor requires a 3,000 foot power cable with connectors and ship board winches to transmit power to the motors.

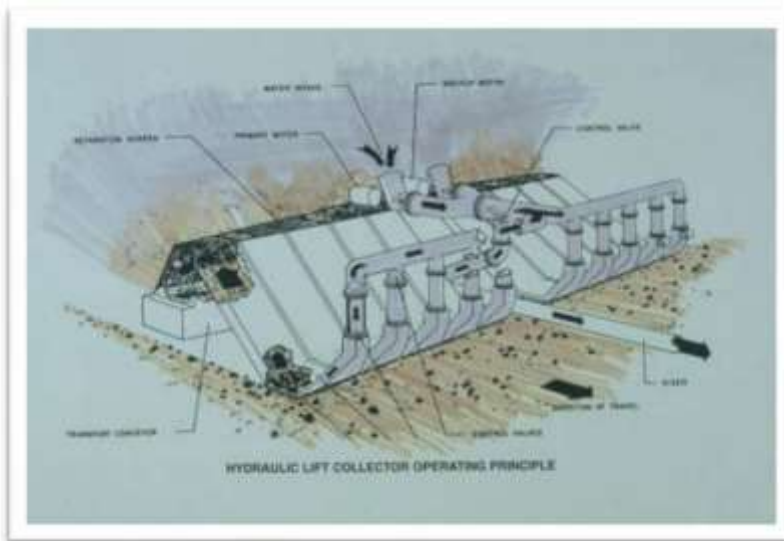


For our cost estimate, we have assumed that the mining ship will have one pump system in operation along with a complete set of spares onboard.

To accommodate the varying depths and slopes of the seafloor at the mine site, a flexible hose is installed at the bottom of the riser lift system. The hose section also protects the end of the riser pipe from pounding into the seafloor as the ship heaves. About 300 m of hose will accommodate seafloor depth changes of up to 150 m. The seafloor interface also includes a series of deadweights to control collector lift off and stabilize the riser pipe during towing, a passive dump valve that allows the riser pipe to dump contained nodules when the pumps are turned off, and a relief valve to relieve vacuum should the collector clog with nodules.

In addition to the seafloor interface, heavy walled sections of riser pipe are required to transition pipe string stresses at the deadweight, pumps housings and hang off point at the derrick floor. Heavy walled instrumentation sections are also required to measure pipe stresses, pump flows, solids concentrations and related data.

For our cost estimates, we have assumed four, 300 m lengths of hose on-board the mining ship. Six deadweights sections, three dump valves and three relief valves are also assumed to be on-board. Duplicate sets of heavy walled pipe sections for stress transitions and instrumentation are also assumed.

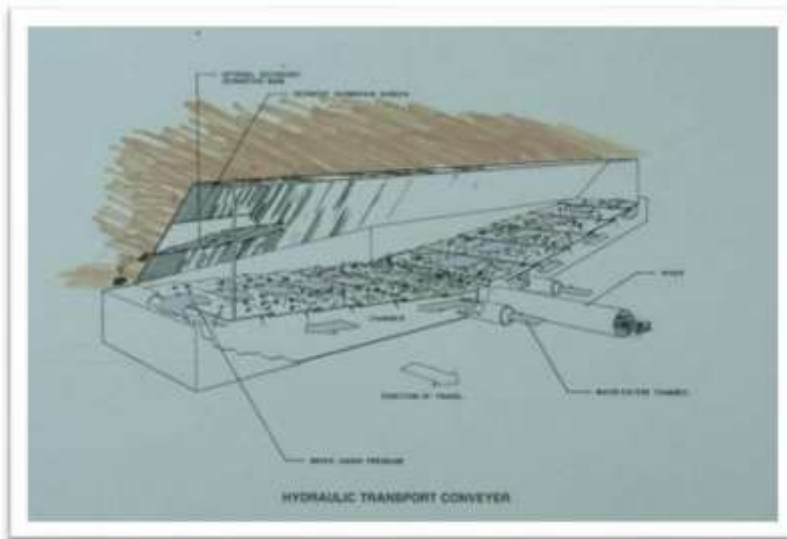


*Figure 19: Commercial hydraulic collector concept*

The commercial scale collector configuration used for this analysis is a passively towed, three runner sled design, that is essentially a scaled-up version of the hydraulic collector used during the PMT. Suspended within the collector's frame and located between the center and outboard sled runners are a series of articulated collection heads as shown.

The collection heads are supplied with jetting water from a branch header that is in turn supplied by a simple propeller style, high-volume, low-pressure submersible pump. As shown in Figure 19, a backup pump is installed on the collector in the event that the primary pump fails. The collection heads are connected to the header using flexible ducts that allow the heads to move up and down independently to accommodate variations in the seafloor surface. A transverse oriented trough is located across the collector at the discharge end of the collection heads. Integral jet sheet nozzles

in the collection heads and the trough are used to perform the basic gathering, lifting transport, and nodule washing functions within the collector.



*Figure 20: Hydraulic nodule transport conveyor*

Figure 20 shows the transverse oriented trough used to transport the nodules across the collector and into the riser entrance located along the center of the trough. Water from the single pump is used to supply the jet sheet nozzles in the collection heads and the trough.

For our cost estimates, we have assumed three collectors onboard the mining ship. Additionally, spares of the critical components of the collector such as motors, sensors, umbilical and complete telemetry and power distribution housings would be kept on-board the mining vessel.

One of the primary objectives of the PMT project was to develop information and data that could be used to engineer and design a mining system for commercial operation. Considerable time and effort was spent to define and design an instrumentation system that would collect as much data as possible as well as provide control of the mining system. Instrumentation was specified and provided to navigate, monitor ship motions and riser / pipe towing speeds and directions, riser pipe loads and stresses, pump / motor flows, power and temperatures, seafloor collector power, flows, speeds, position and behaviour. Underwater television and audio signals were also recorded to provide real time monitoring and control of the system.

A climate controlled van was installed on-board that housed an array of computers and data recording equipment required to monitor and control the system. Several instrumentation cables ranging in length from 300-5,500 m were attached to the riser pipe and connected high pressure instrumentation housings located at the collector, pumps and shipboard nodule handling areas. These cables were connected to the instrumentation van and mining control center.

We have assumed that a similar system would be required to navigate, monitor and control the mining operation. For our cost estimates, we have assumed one instrumentation system on-board the mining ship along with spares that are primarily comprised of subsea components.

### **Capital cost estimate**

Our estimate of capital costs is based on the mining system, major components, and operating scenarios described above. The system was successfully tested at pilot scale and although the requirements have increased for a commercial scale system, the basic equipment functions

remain unchanged. Equipment costs, however, have risen considerably since the late 1970s. We have developed new preliminary estimates and updates of past estimates, and where feasible utilized the cost of similar equipment, published information and personal contact. Table 2 summarizes our capital cost estimate.

*Table 2: Capital cost estimate*

<b>Item</b>	<b>Capital Cost</b> (thousands of USD)
<b>Mining Ship</b>	\$ 400,000
Owner-Furnished Ship Equipment	\$ 50,000
Owner- Furnished Mining Equipment	\$ 50,000
Subtotal –Mining Ship	\$500,000
<b>Mining System</b>	
Riser / Pipe	\$ 16,000
Submersible Pump / Motor	\$ 16,000
Interfaces	\$ 2,000
Seafloor Collectors	\$ 5,000
Instrumentation and Navigation	\$ 12,000
<b>Subtotal – Mining System</b>	\$ 51,000
<b>Total - Capital Cost</b>	\$551,000

### **Operating cost estimate**

The operations scenario for a first-generation mining operation assumes that the mining ship will remain on station for several years and will be mining nodules for 270 days per year. A manning schedule of 30 days on and 45 day off, including travel, has been assumed. The personnel complement is comprised of 72 persons on board and 144 off-duty onshore. Fuel oil consumption is based on earlier estimates, the cost of which has been adjusted to current prices for diesel oil. Maintenance and supplies have been estimated at 1 per cent of capital costs per year. Catering on- board has been estimated at \$25 per day for 75 persons.

As discussed earlier, we have assumed that crew exchanges, re-supply of fuel oil, and some equipment will be accomplished by a combination of ocean going supply boats and by the bulk carriers. We have not included the costs of supply boats, shore-based support, and nodule transfer at sea.

Operating costs for the mining system are primarily the costs of replacing key subsea systems upon wear out or accidental loss. The costs of fuel oil to operate the pumps, pipe handling system, on-board nodule handling and transfer at sea are included in the fuel oil costs for the mining ship. Mining system personnel, on board mining system repairs and transfer of nodules at sea are also assumed as part of mining ship costs. Table 3 summarizes our estimate of typical annual operating costs for the basic mining system described above.

*Table 3: Operating cost estimate*

Item	Operating Cost (thousands of USD)	
	Annual	Daily
<b>Mining Ship</b>		
Amortization (10 yr)	\$ 50,000	\$ 137.0
Insurance (1.5%)	\$ 7,600	\$ 2.8
Personnel & Travel	\$ 11,200	\$ 30.7
Fuel Oil	\$ 11,500	\$ 31.5
Maintenance and Supplies	\$ 5,000	\$ 13.7
Catering / Hotel	\$ 800	\$ 2.2
<b>Subtotal - Mining Ship</b>	<b>\$ 85,300</b>	<b>\$ 235.9</b>
<b>Mining System</b>		
Riser Pipe	\$ 8,000	
Submersible Pump / Motors	\$ 8,100	
Interfaces	\$ 1,000	
Seafloor Collector	\$ 2,000	
Instrumentation	\$ 1,500	
<b>Subtotal - Mining System</b>	<b>\$ 20,600</b>	<b>\$ 5.64</b>
<b>Total - Operating Cost</b>	<b>\$ 105,900</b>	<b>\$ 241.54</b>

**Cost summary**

Our estimates for capital and operating costs are summarized in Table 4 below. As expected, the dominant costs are those for the mining ship. As discussed, the mining ship cost estimate is based on the current construction costs for offshore, deepwater drill ships of similar size and capability. Due to the rising price of oil, the construction costs and day rates have soared in recent years.

*Table 4: Cost summary*

Item	Capital Cost	Operating Cost
		(thousands of USD)
Mining Ship	\$ 500,000	\$ 85,300
Riser Pipe	\$ 16,000	\$ 8,000
Pump Lift	\$ 16,000	\$ 8,100
Interfaces	\$ 2,000	\$ 1,000
Seafloor Collector	\$ 5,000	\$ 2,000
Instrumentation	\$ 12,000	\$ 1,500
<b>Totals</b>	<b>\$ 551,000</b>	<b>\$ 105,900</b>

Our capital and operating cost estimates should be viewed as preliminary estimates that provide a general idea of the magnitude of investment required for the mining portion of an ocean mining project to recover polymetallic nodules. The estimates at this stage typically assume large

contingencies of 20-25 per cent. Early stage estimates are often useful for preliminary comparison of alternatives. With the addition of logistical, transport, processing and indirect costs, an early stage assessment of the overall cost and attractiveness of a project to mine and process nodule resources of the deep ocean can be made.

## **Summary of discussions**

With regard to the hydraulic towed system, one participant asked whether new collector technology should be a self-operated active or a passive device.

Mr. McFarlane responded that it depended on the bottom topography, pointing out that, if one was working in the abyssal plains, nodule distribution was quite even without many outcrops, and so a passive collector could be used on the bottom of the ocean. If, however, one was working in areas with many outcrops, uneven surfaces and various obstructions, the argument was strong for remotely-operated vehicle (ROV)-based technologies, utilizing an advanced robotic system and advanced collection devices, etc., for the efficient collection of nodules. In the latter case, one would have to spend a considerable amount of time undertaking a cost-benefit analysis of utilizing an advanced ROV system. He added that the passive collector system was quite cost-effective, while an advanced robotics system cost a great deal of money and required specialized technicians to operate it. This would result in the maintenance and operation of the system becoming more complex.

With regard to this conclusion, one participant said that cost and the operability would be major considerations, as thousands of seafloor photographs, at least in the Indian Ocean, had shown that nodule distribution was not uniform. Rather, it was patchy and nodules were buried under layers of sediment and there were many outcrops of rocks or crusts which would act as obstructions for the collection device. He suggested that, in order for the collector system to be efficient it would have to be able to sense favourable areas and to avoid those not favourable for mining.

In response, Mr. McFarlane said that it was essential for an operator to know the environment in which it was going to conduct mining operations prior to start-up. The advanced technology currently available, such as autonomous underwater vehicles (AUVs), ROVs, as well as capabilities for seafloor mapping, far exceeded what had been available in 1978. At that time, the OMI developers had towed side-scan sonar around on a wire behind the ship, examined the results and taken a decision as to where the work would be conducted. In contrast, one could now place side-scan sonar and a video camera on an AUV and map an area. The resolution of data obtained by this method was extremely high, comparatively speaking, and would make it easier to target the areas to be mined. Utilization of this technology would make this aspect of the work much more efficient than that undertaken by OMI 30 years earlier. Mr. McFarlane emphasized that the process had to be multidisciplinary; it was not simply a matter of going out, throwing an instrument over the back of the vessel, towing it around, bringing it back and drawing a conclusion as to what resources were available in the area. He reiterated the need to visualize the environment under consideration for mining and, in that regard, suggested the use of a 6,000-m AUV for the gross survey. That would provide an understanding of the scope, the depth and the breadth of the intended target area. Among the advantages of the use of an AUV, Mr. McFarlane noted the fact that the operator could specifically target areas and get high-resolution photography to go along with the bathymetry that would be obtained with the AUV. He said that as a result, one could then target the type of mining equipment and operation that would need to be undertaken in those selected areas. Given the daily cost of operations with a drill ship, the amount of money and time that

went into the front end of actually mapping exploration areas, the rate of return on investment would probably be five or tenfold if such technology were applied before mining commenced.

Mr. McFarlane was asked about the mechanical forces on the vertical risers. In particular, one participant enquired whether damage caused by mechanical forces on the vertical riser when it was moved at 1-knot speed had been assessed. The question was also raised as to whether a comparison had been done between a vertical (rigid) and a flexible riser.

In his response, Mr. McFarlane said that the OMI team had examined the data collected from utilizing a flexible or a fixed riser and had found that the fixed riser coupled with the flexible riser on the bottom gave the team the ability to tow more efficiently because the flexible riser would trail the vessel and allow the collector to stay on the seabed. If one looked at the fleet angle with a flexible pipe, the riser extended outward and the amount of weight needed to bring it back underneath the pipe was much greater. With a rigid pipe, the amount of weight required was not so much and the flexible pipe allowed the collector to lie on the bottom. Mr. McFarlane said there were certainly some extreme forces imparted on the riser that had to be considered. Going too fast would induce strumming on the riser which, in turn, could cause one to go catastrophically faster than desired. One of the ways to mitigate strumming in a riser was by ferrying it. The OMI team had used ferried technologies in a lot of objects going through the water at much greater speeds than those associated with the riser. Therefore, the amount of ferrying required to get the strumming dissipated in the riser sides and at the speeds associated with the riser was quite minimal.

Mr. McFarlane recalled that, in 1978, the OMI watch circle had been 1 or 2 per cent of depth, so the team had thought itself to be in a very large area. He said that progress had been made, noting that better resolution and navigation systems were presently available, but that having the pipe straight under the ship and tied to a differential global positioning system certainly provided an operator with a highly-accurate representation of where the collector was even before considering the acoustic part of the process.

Asked about the maximum slope that the hydraulic tow system could operate on, Mr. McFarlane replied that using an ROV-based system and a bottom crawler allowed for going on more extreme slopes, a capability that he saw as a positive to that sort of system. The passive system was for mining on the abyssal plains, which were relatively level. They had some gradients in them, but it was not extreme terrain. Getting into extreme terrain would require a return to the mission planning stage and having the right tool for the job. He said he would not subscribe to saying that the passive collector may be right when dealing with walls that were over 10 degrees high. One consideration in such a case was that if the pipe were being towed and there was a canyon wall, you wanted to be going along the wall, not up it. If you went up the wall you would spend the time raising the casings up to the surface and taking joints out as the operation took place, whereas if one went along the face of the wall, the collector could certainly orientate itself up to a 10-degree slope quite easily and just be pulled along the side without any problem. However, that related to mission planning and understanding the environment in which one worked. If you did not do a good job of knowing what you were going to do and where you were going before heading out there, the chances of success would be drastically reduced. The required collection rate was 550 wmt per day and the nodule density on the seafloor had to be 2 lbs per square foot.

One participant enquired as to the efficiency of the crawler and another asked about the coverage efficiency of the passive collector, how much of the nodule area could be collected with so

much control coming from the ship only, and whether an active collector wouldn't be more efficient and less strenuous on the ship's controls.

In response to the question about the crawler, Mr. McFarlane said they had laid the nodules and were getting an 80 per cent efficiency rate, but that had been in a man-made environment where the nodule sizes had been hand-picked. With regard to the questions about the passive collector, Mr. McFarlane said that the current state-of-the-art large drill vessels, their horsepower power-to-weight ratios and their control systems were such that whether they were at stations just actively maintaining a single point on the face of the globe or actually transiting an area, the going back and forth would not tax that system very much at all. Those vessels were designed to take beam in 60 to 70-knot winds and maintain position. In big heave sea action, it was important to ensure that the air/sea interface, gimballed riser and heave compensation equipment were sized appropriately to manage the loads being imparted as this occurred. Massive collectors versus what he termed "lifeboat operations", in which the collector was actively driven at the bottom of the ocean, were two different animals with different places for application. There were different technologies that were applicable to the different problems faced on the seafloor. In areas with large ridges, crusts and mantles and other things that had to be navigated, certainly an ROV with a very high control and positioning capability had great desirability. A cost-benefit analysis of which one did the best job needed to be done.

To the question of what the actual numbers had been on the pilot mining test, he replied that there had been no post-survey video excursions done, so it was not possible to go down and look at where the collection swath had been taken and say that one of every five nodules had been collected. Nobody had gone back and mapped it. If one was thinking of spending development dollars in the next phase, as one was taking the collectors out, one would want to map after the fact to see what the collection rates had been.

A participant wanted to know whether the cost estimates mentioned were current or from the 1970s. Mr. McFarlane said they were rough order magnitude, in present-day dollars and referred to the cost of what it would take today to put a system together. Everybody had been watching the price of metal. Fuel costs were rising. He said that the prices that he put up on the screen might hold valid for 30 days, but that he would not say that they would hold much more than that. He was of the opinion that the costs would increase exponentially, and that that was the reason the conversation at hand was so germane, because the value of these materials was such now.

Another question for Mr. McFarlane related to his statement that he had used Honeywell equipment to count the nodules that entered the collector system. The participant asked whether it had been an acoustic-based system and whether the reason for using it had been to measure the efficiency or just to measure the amount of nodules in terms of weight.

Mr. McFarlane replied that that had been in the initial stages, and that no nodules had been collected; the collectors were just being tested on the seafloor and there had to be a way of quantifying how well they were doing and the efficiency of collecting the nodules. It had been an acoustic combination from which could be extrapolated which factor was the most efficient. That technology would not be required today.

A participant asked Mr. McFarlane the total number of days of operations per year, what size seas and wave height the riser system was good for, whether he had mentioned something

about 170 days or 270 days of operation because of bad weather and in the event of bad weather, would he disconnect the riser pipe and drive away from the location.

Mr. McFarlane said that the hope was to do 270 days of operation per year and the remainder would represent allowances for weather or maintenance. As for the last part of the question, the extent of the recovery would depend on how bad things got. For example, if you were in 20 to 30-foot seas and you realized that the amount of flexible riser pipe at the bottom was getting to the point that the collector was starting to come off the bottom, but you knew the storm would pass in two days, you would not spend three days to recover everything to the surface. You would pull three or four joints of riser pipe off the top to make sure that the collector was 300 to 500 feet off the ocean floor. That way, it would not get destroyed, but the riser heave compensation system would allow you to leave it down there. When the sea calmed, you would just lower it back to the bottom of the ocean. The primary concern was what was happening at the touchdown on the seabed mining interface, not what was going on at the top.

The final question for Mr. McFarlane was from the Secretary-General of the International Seabed Authority, who wanted to know whether the system could be used straight away. The author clarified that he was loathe to reinventing the wheel if he could repackage existing technology. Reinventing the wheel was not very cost-effective and with the limited budget and time that people had, he would probably go out and leverage as much existing technology as he could find. Looking at what had been done and what was at hand and what was available at present, he thought that from the moment someone said this had to be done, the longest lead item would probably be procuring the drill ship. Everything else - the instrumentation, control systems - all existed and it was just a packaging effort to make sure that it was tied together in an integrated fashion. Whatever the lead time of procuring a drill ship was, that was what the lead time would be; everything would be fairly easy.



## CHAPTER 2

# Model Mining Units of the Twentieth Century and the Economies (Production Requirements, Area Requirements and Vertical Integration)

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### Summary

Polymetallic nodules on the deep ocean floor have received attention as future resources for cobalt (Co), nickel (Ni), copper (Cu), and manganese (Mn) for the past 40 years. The mining and metallurgical processing technologies studied over this period have been reviewed and re-examined on the basis of current interests, technologies and economic rationale by the author. Preliminary results of an economic evaluation undertaken in the late 1990s, 2004, and 2006 are discussed. To compare with nodule mining ventures, the advantages and disadvantages of cobalt-rich manganese crusts and Kuroko-type polymetallic sulphides are also introduced.

### Introduction

Since the 1970s, researchers have known that polymetallic nodules on the deep floor of the Pacific and Indian Oceans and cobalt-rich manganese crusts (CMC) on the Pacific Ocean seamounts were potential sources for strategic metals such as cobalt (Co), nickel (Ni), copper (Cu), and manganese (Mn), due to their vast distribution and relatively high metal concentration (Mero, 1965; Cronan, 1980). Because similar metals are contained in both, future needs may require that we select between the two.

Several registered pioneer investors have already identified promising sites in the deep-sea regions for polymetallic nodule mining (ISA, 1998), and appropriate mining technologies have been developed during the last 40 years by international consortia and States (Welling, 1981; Kaufman et al., 1985; Bath, 1989; Charles et al., 1990; Yang and Wang, 1997; Yamada and Yamazaki, 1998; Hong and Kim, 1999; Muthunayagam and Das, 1999). The feasibility of mining for polymetallic nodules, including an economic evaluation, has been examined in detail by Andrews et al. (1983), Hillman and Gosling (1985), and Charles et al. (1990).

On the other hand, the only reported information on potential areas for CMC has been scientific in nature (Cronan, 1984; Clark et al., 1984; Misawa et al., 1987; Pichocki and Hoffert, 1987), and only one systematic feasibility study has been published (Hawaii DPED, 1987). The technical and economic advantages and disadvantages of CMC have not yet been evaluated. The reasons for this have been the lack of detailed information about distribution characteristics, mining technologies and ore processing technologies.

The Kuroko-type polymetallic sulphides (SMS) in the western Pacific Ocean have received much attention as sources for the economic recovery of gold (Au), silver (Ag), copper (Cu), zinc (Zn) and lead (Pb). Since the end of the 1980s, the Kuroko-type SMS have been found in the back-arc basins and oceanic island-arc areas. Typical examples are found in the Okinawa Trough and on the Izu-Ogasawara Arc near Japan (Halbach et al., 1989; Kato, et al., 1989; Iizasa et al., 1999), in the Lau Basin and the North Fiji Basin near Fiji (Fouquet et al., 1991; Bendel et al., 1993), and in the East Manus Basin near Papua New Guinea (Kia and Lasark, 1999). They yield a higher concentration of Au and Ag

than the SMS found in ocean ridge areas (Haymon and Kastner, 1981; Malahof, 1981; Hekinian et al., 1983; Rona et al., 1984; Hekinian and Bideau, 1985; Rona, 1985). Similar formation processes with the land-based Kuroko ore deposits in Japan have been expected and outlined by many researchers (Sillitoe, 1982; Scott, 1985; Halbach et al., 1989; Iizasa et al., 1999).

## **Previous research**

### ***Polymetallic nodules***

Many scientific, technical and economic publications are available on polymetallic nodules, mostly because they have been considered a primary commercial target (Mero, 1965; Cronan, 1980). Their geological distribution characteristics have been studied in depth by numerous researchers (Craig and Andrews, 1978; Andrews and Friedrich, 1979; Friedrich et al., 1983; von Stackelberg and Beiersdorf, 1991). However, very little detailed information on the first mining target areas in the Clarion Clipperton Fracture Zone have been available (Morgan et al., 1992; ISA, 1999), even though international consortia have authorized sites through US domestic law (Padan, 1990) and the Pioneer Investors with ISA (1998). Without this type of information, basic factors had to be assumed in some previous feasibility studies of nodule development (Andrews et al., 1983; Hillman and Gosling, 1985; Charles et al., 1990).

In the 20 years following the research and development (R&D) activities of the international consortia in the 1960s and 1970s (Welling, 1981; Kaufman et al., 1985; Bath, 1989), mining technologies have been developed through several national projects (Charles et al., 1990; Yang and Wang, 1997; Yamada and Yamazaki, 1998; Hong and Kim, 1999; Muthunayagam and Das, 1999). Although some of the mining technology results obtained by these consortia have been reported (Clauss, 1978; Burns and Suh, 1979; Grote and Burns, 1981; Chung et al., 1981; Kollwentz, 1990), most of the technically important data remain secret. On the other hand, many publications have been available from the national projects and other studies on seafloor nodule miner design and operation (Li and Zhang, 1997; Yasukawa et al., 1999; Hong et al., 1999; Yamazaki et al., 1999; Deepak et al., 2001), the hydraulic lifting characteristics of nodules in pipelines (Bernard et al., 1987; Saito et al., 1991; Xia et al., 1997; Yoon et al., 2000; Chung et al., 2001), and the hydrodynamics of the pipeline (Aso et al., 1994; Chung et al., 1994; Cheng and Chung, 1997; Ohta and Morikawa, 1997; Handschuh et al., 2001).

Some important results and reviews of metallurgical nodule processing have also been reported (Agarwal et al., 1979; Hubred, 1980; Black, 1982; Kim and Park, 1997; Kojima, 1997; Zhong et al., 1999; Das, 2001). Most of the proposed processing methods and the advantages of the smelting and chlorine leach method have been described by Kojima (1997). Mining feasibility, including an economic evaluation, was examined in detail by Andrews et al. (1983), Hillman and Gosling (1985) and Charles et al. (1990). Feasibility within the Cook Islands EEZ was presented (Soreide et al., 2001). A comparative summary of the studies is shown in Table 1.

*Table 1: Comparison of economic evaluation of polymetallic nodule development*

	<b>Soreide et al. (2001)</b> High-Temperature and High-Pressure Sulfuric Acid Leach Process			<b>Hillman and Gosling (1985)</b> Cuprion Ammoniacal Leach Process			<b>Andrews et al. (1983)</b> Reduction and Hydrochloric Acid Leach Process			<b>Charles et al. (1990)</b> Reduction and Hydrochloric Acid Leach Process		
	<i>Mining (wet)</i>	<i>Trans. (dry)</i>	<i>Process (dry)</i>	<i>Mining (wet)</i>	<i>Trans. (dry)</i>	<i>Process (dry)</i>	<i>Mining (wet)</i>	<i>Trans. (dry)</i>	<i>Process (dry)</i>	<i>Mining (wet)</i>	<i>Trans. (dry)</i>	<i>Process (dry)</i>
<b>Production (t/y)</b>	1.1M	0.7M	0.7M	4.2M 300 d/y	3.0M 300 d/y	3.0M 330 d/y	2.3M 300 d/y	1.5M 300 d/y	1.5M 330 d/y	2.3M 250 d/y	1.5M	1.5M
<b>Capital cost (M\$)</b>	127	93	271	590	310	727	180	176	513	282	188	470
<b>Capital cost ratio (%)</b>	26	19	55	36	19	45	21	20	59	30	20	50
<b>Equity/Loan</b>	30:70			100:0			100:0			50:50		
<b>Operating cost (M\$)</b>	21.8	13.5	22.9	77	37	111	45	25	165	48	36	156
<b>Loan interest (%)</b>	8			0			0					
<b>Survey cost (M\$)</b>	1.9			3			6					
<b>Operating cost ratio (%)</b>	38	23	39	34	16	50	19	11	70	20	15	65
<b>Metal</b>	<b>Price</b>	<b>Recovery</b>	<b>Product</b>	<b>Price</b>	<b>Recovery</b>	<b>Product</b>	<b>Price</b>	<b>Recovery</b>	<b>Product</b>	<b>Price</b>	<b>Recovery</b>	<b>Product</b>
Co	\$20/lb	83%	2,652t/y	\$8.53/lb	65%	5,070t/y	\$5.5/lb	85%	3,375t/y	\$6.8/lb	85%	3,525t/y
Ni	\$3.33/lb	98%	2,548t/y	\$3.62/lb	92%	36,708t/y	\$3.75/lb	95%	18,525t/y	\$3.6/lb	95%	19,730t/y
Cu	\$1/lb	97%	1,890t/y	\$1.17/lb	92%	28,704t/y	\$1.25/lb	95%	15,675t/y	\$0.95/lb	95%	17,810t/y
Mn							\$0.4/lb	93%	404,550t/y	\$0.3/lb	93%	382,500t/y
<b>Taxes (%)</b>	10			29			46					
<b>NPV</b>	-81M											
<b>IRR (%)</b>	9.6			7.4			6.4			12		

### ***Cobalt-rich ferromanganese crusts***

Less information is available for cobalt-rich ferromanganese crusts (CMC), although their resource potential has been of great interest (Halbach, 1982; Manheim, 1986). Only scientific data has been available on potential mining areas (Halbach et al., 1982; Hein et al., 1985a; Hein et al., 1985b; Cronan et al., 1991; Cronan and Hodkinson, 1991 and 1993). Economic evaluations have not sufficed, and only one systematic feasibility study has to date been published (Hawaii DPED, 1987). The reason for this lies in the scarcity of published research on engineering, distribution characteristics (Morgan et al., 1988), mining technology (Halkyard, 1985; Latimer and Kaufman, 1985) and ore processing technology (Haynes et al., 1987; Hirt et al., 1988).

Because information remains insufficient, it is difficult to evaluate the economic potential of CMC with absolute certainty. However, it seems possible to conduct a preliminary economic comparison with polymetallic nodules, thanks to reports on research in key areas, such as geological and engineering distribution characteristics (Yamazaki et al., 1990; Yamazaki et al., 1993; Yamazaki et al., 1994; Yamazaki et al., 1996; Usui and Someya, 1997; Yamazaki and Sharma, 1998; Yamazaki and Sharma, 2000), mining technology (Aso et al., 1992; Yamazaki et al., 1995; Chung, 1996; Chung, 1998) and ore dressing technology (DOMA, 1998). The most important of these is the experimental study of ore dressing methods for cobalt-rich ferromanganese crust samples (DOMA, 1998). Four different methods, including froth flotation, magnetic separation, gravity concentration by vibration table, and colour intensity separation, were tested on the actual samples recovered from seamounts in the study. The effectiveness of all the ore dressing methods, with the exception of colour intensity separation, was partially proved by the study, and some basic data for economic evaluation were collected.

### ***Kuroko-type seafloor massive sulphides***

Much information was gathered during the feasibility study for the development of Red Sea sulphides mud (Amman, 1985; Nawab, 2001). Furthermore, some technical R&D and an in situ mining test were conducted to back up the technical and economic evaluation. In the case of the Kuroko-type polymetallic sulphides (SMS), however, more information for the evaluation became available after 2000.

The higher Au, Ag and Cu content in the Kuroko-type SMS have increased the interest in profitable mining operations in the twenty-first century, which have been under consideration by private companies (Malnic, 2001; Nautilus Minerals HP; Neptune Minerals HP). The important information necessary for resource potential evaluation and commercial mining feasibility is being clarified.

## **Model for analysis**

### ***Outline***

A preliminary economic evaluation model for polymetallic nodules has been created on the basis of previous feasibility reports (Andrews et al., 1983; Hillman and Gosling, 1985). The evaluation models for CMC and Kuroko-type SMS were developed by modifying the model for polymetallic nodules and referring to the one existing CMC feasibility study (Hawaii DPED, 1987). In addition to considering the geological and geophysical differences between polymetallic nodules, CMC, and Kuroko-type SMS, ore dressing subsystems for CMC and Kuroko-type SMS were incorporated in the models. The other

subsystems and components were assumed to be almost alike; for example, the same metallurgical processing method was selected in the two models for polymetallic nodules and CMC. Outlines of the models and the flow chart of mined ore are illustrated in Figure 1 for polymetallic nodules, and in Figure 2 for CMC and the Kuroko-type SMS.

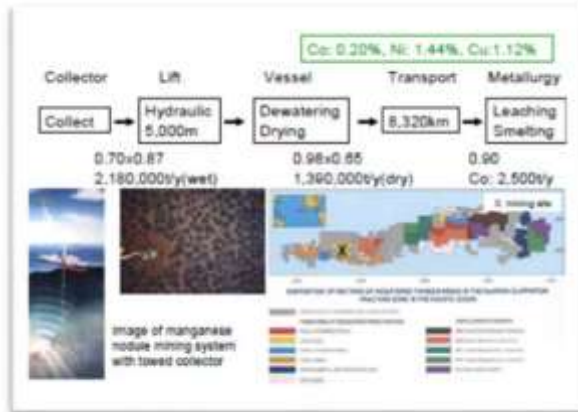


Figure 1: (Left): Evaluation model for manganese nodule mining

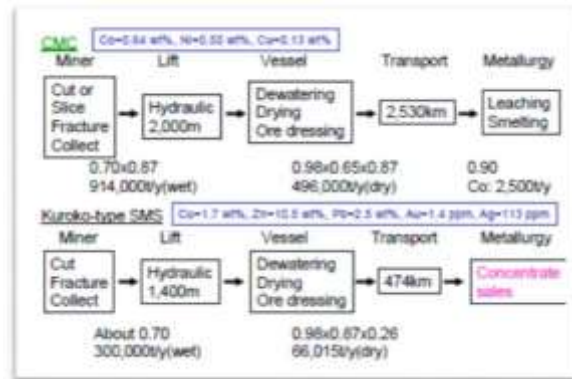


Figure 2: (Right). Evaluation models for CMC and Kuroko-type SMS mining

## System components

### Outline

Basic subsystems and components for the developments have been chosen and identified with reference to Hillman and Gosling (1985) and the technological R&D results introduced in the previous section. Andrews et al. (1983) is sometimes used to make up for gaps in information found in Hillman and Gosling (1985).

### Mining subsystem

The mining subsystem is composed of a seafloor miner, a pipeline with submersible hydraulic pumps for nodule lifting and a mining vessel. The type of miner used is assumed to be a towed collector with the hydraulic nodule pick-up device developed under Japan's national project (Yamada and Yamazaki, 1998). A self-propelled miner with mechanical slicing and crushing, along with hydraulic pick-up devices, are assumed for CMC mining and a similar one is assumed for Kuroko-type SMS mining. The basic components of steel pipe and flexible hose and pumps are similar. Their dimensions, strengths, numbers and capacities differ with depth and production rates. Except for the ore dressing subsystems, facilities on board the mining vessel are similar in all three; these include the handling units for deployment and retrieval of submersible equipment, their support during the mining operation, electric power generators, dewatering units, drying units, ore storage, control units, and general facilities for cruising and mining operations. Ore lifted from the seafloor to the vessel is separated from the water in the dewatering unit. Water in the pore structure of the ore is removed in the drying unit, further reducing weight. The installation of this unit on the mining vessels is a new idea presented in Soreide et al. (2001) and is important in reducing operating costs thereafter.

### ***Ore dressing subsystems***

The ore dressing subsystems for CMC and Kuroko-type SMS are considered to be the most important in the models. The subsystems eliminate the waste rock from mined ore and are necessary for reducing the weight of the ore to be transported and processed. Because the system operation for CRC was examined by DOMA (1998) and that for the Red Sea sulphide mud in the technical R&D (Amman, 1985; Nawab, 2001), these results are referred to and introduced in the models. In both models, the dumping of waste rock into the ambient water column is assumed.

### ***Transportation subsystem***

Transportation by carrier vessel from the mining site to a metallurgical processing plant located near Tokyo in Japan is assumed. Vessel size and number depend on production rates from the mining and ore dressing subsystems.

### ***Metallurgical processing subsystem***

The smelting and chlorine leach method considered in Kojima (1997) is selected for the basic metallurgical processing of polymetallic nodules and CMC. Its advantages are high recovery rates for metals, ease of separating metals from metal-bearing solution, and the repeatable use of sulphur. For Kuroko-type SMS, the sale of the concentrates to existing sulphide customer smelters in Japan after desalting of the mined ore is assumed.

### ***Production scale***

The world consumption of the produced metals was not considered as a factor in deciding the production scales used in the old feasibility studies (Andrews et al., 1983; Hillman and Gosling, 1985; Charles et al., 1990). Soreide et al. (2001), however, chose cobalt as the target production scale metal because the cobalt market is the smallest of the produced metals. They set about 2,500 t/y as the optimal cobalt metal production scale; equal to about 10 per cent of the world's annual consumption in the latter half of the 1990s (Roskill Information Services, (2000)). This assumption seems reasonable as an evaluation criterion, as it keeps quantities comparable with those in the economic evaluation. Therefore, the production scales of the models for polymetallic nodules and CMC in this study are set as equivalent to 2,500 t/y of cobalt metal. The production scales of the models are calculated in reverse from the 2,500 t/y, the recovery efficiencies of each subsystem and unit, and the cobalt content in the ore. The calculation balances for polymetallic nodules are shown in Figure 1 and for CMC in Figure 2. The recovery efficiencies are defined in the following section. The production scale of 300,000 t/y in wet weight is calculated from the duration of the production (about 20 years) and the amount of the Kuroko-type SMS ore body (approximately 9,000,000 metric tons in wet weight, whereas it is assumed that only two-thirds of the ore body will be mined).

## **Geophysical and geological setting**

### ***Polymetallic nodules***

The primary geophysical and geological factors necessary for the technical modeling and economic evaluation of polymetallic nodules are as follows:

Site location: N10°, W147°

Site depth: 5,000 m

Nodule population: 10 kg/m<sup>2</sup> in wet weight

Metal content in nodules: 0.20 % in Co, 1.44 % in Ni, and 1.12 % in Cu in dry weight

Nodule density: 2.0 in wet bulk

Nodule water content: 0.35 in weight

### ***Cobalt-rich ferromanganese crusts***

The factors necessary for modeling and evaluation of CMC are as follows:

Seamount location: N17°, E157°

Seamount depth: 2,000 m

Crust abundance: 100 kg/m<sup>2</sup> in wet weight

Crust thickness: 50 mm

Metal content in crust: 0.64 % in Co, 0.50 % in Ni, and 0.13 % in Cu in dry weight

Crust density: 2.0 in wet bulk

Crust water content: 0.35 in weight

Substrate density: 2.5 in wet bulk

Substrate water content: 0.1 in weight

Substrate weight ratio in excavated wet ore: 0.194

Rock content in substrate: 0.6 in limestone, and 0.4 in basalt

### ***Kuroko-type polymetallic sulphides***

The factors necessary for modeling and evaluation of Kuroko-type SMS are as follows:

Site location: N32°06', E139°52'

Site depth: 1,400 m

Amount of ore body: 9 million tons in wet weight

Assumed metal contents in mined ore: 1.66 %, in Cu, 10.5 % in Zn, 2.45 % in Pb, 1.4 ppm in Au, and 113 ppm in Ag in dry weight

Ore density: 3.2 in wet bulk

Ore water content: 0.128 in weight

Ore compressive strength: 3.1-38 MPa

Ore tensile strength: 0.14-5.2 MPa

### ***Technical setting***

Some technical settings have been introduced in previous sections. The most important point to mention is the recovery efficiency of each subsystem and unit introduced in Figures 1 and 2. The sweep efficiency, defined as the portion of the mining site covered by the seafloor collector or miner, is not included in the recovery efficiencies; while it affects the duration of site mining, it does not affect the total energy consumption, as larger miners consume more energy. The first loss introduced in this study is *excavation efficiency*, defined as the portion of excavated ore actually recovered from the collector or miner track. For safety, the hydraulic nodule pick-up device is sometimes not used while the collector traverses the seafloor. The excavation efficiency is temporarily assumed as 0.7 for the collector and the miner, as suggested in a previous study (Hillman and Gosling, 1985). The second introduced loss is *pick-up efficiency*. Large and small nodules or fragments of crusts are eliminated at the pick-up device and the sediment separator. The third loss is *dewatering efficiency*. A small portion of the lifted ore is lost with the water in the dewatering unit. These two efficiencies are set at 0.87 and 0.98, respectively, on

the basis of Yamazaki et al. (1999 and 1991). *Drying efficiency* is deduced from the water content of the nodule, the crusts, and the substrate defined in the previous section. *Ore dressing efficiencies* for the crust and the substrate differ according to separation techniques, substrate ratio, and rock content in the substrate. Using the limited results from DOMA (1998), they are set as 0.93 for crusts and 0.78 for substrate.

The *leaching efficiencies* in metallurgical processing, namely 0.90 for Co, 0.97 for Ni, and 0.94 for Cu, are borrowed from Kojima (1997). In the case of Kuroko-type SMS, the total *excavation efficiency* and *pick-up efficiency* is roughly assumed to be 0.7. *Drying efficiency* is deduced from the water content of the Kuroko-type SMS samples defined in the previous section. The *ore dressing efficiencies* are the same as 90 per cent of metal yield for Cu, Zn and Pb concentrates of the Kuroko ore data in Iijima (1967), because seawater froth flotation is assumed in the ore dressing process. The last important point in the models is the operation time of each subsystem. These are set at 300 days per year for all the subsystems in polymetallic nodules and CMC models at sea and 330 days per year for the processing subsystems, as in previous studies (Andrews et al., 1983; Hillman and Gosling, 1985). In the case of Kuroko-type SMS, they are set at 250 days per year for all the subsystems at sea, because the Kuroshio Current (with a speed of 3-5 knots) is close to the site, and it is expected to be difficult to keep the mining system at an exact position against this strong current in some cases. For land-based subsystems, 360 days per year are set, as the operational days of the custom smelters.

## Economic modeling

### Outline

The whole development period is 25 years for polymetallic nodules and CMC, and 23 years for Kuroko-type SMS. No inflationary factors for capital and operational costs or metal prices are considered for this period. The operating costs are recalculated taking into account the economic factors in the three evaluation timings, but not the capital costs for the mining system, ore dressing, transportation, or metallurgical processing. Only the continuing expenses and working capital are recalculated in the initial investment costs. The total investment is covered by 30 per cent equity and 70 per cent loan. The calculation included the following cost elements: (a)variable; (b)depreciation; (c)repair; (d)insurance; (e)labour; (f)interest; (g)general and administrative costs; (h)miscellaneous expenses; and (i)taxes (property, excise, corporate and local). Differences in metal prices and economic factors at the three evaluation timings (the late 1990s, 2004 and 2006) used in the analyses are summarized in Tables 2 and 3.<sup>1</sup>

*Table 2: Differences in metal prices used in analyses*

Metal	1995-1999 (US\$)	2004 (US\$)	2006 (US\$)
Cobalt	15/lb; 20/lb; 25/lb; 30/lb	26.8/lb	16/lb
Nickel	3.3/lb	6.28/lb	10/lb

<sup>1</sup> <http://www.lme.co.uk>; [http://www.jogmec.go.jp/data/data\\_2\\_3.html](http://www.jogmec.go.jp/data/data_2_3.html) and (in Japanese); <http://gold.tanaka.co.jp/commodity/souba/index.php> (in Japanese); *Note*: US\$ 1/lb = US\$ 2.2/kg and US\$ 1/oz = US\$ 32.154/kg  
[http://www.boj.or.jp/type/stat/dlong/fin\\_stat/rate/prime.htm](http://www.boj.or.jp/type/stat/dlong/fin_stat/rate/prime.htm) (in Japanese)  
<http://www.federalreserve.gov/releases/H10/hist>  
[http://www.geocities.jp/tetchan\\_99\\_99/](http://www.geocities.jp/tetchan_99_99/) (in Japanese)  
<http://www.meti.go.jp/statistics/index.html> (in Japanese)  
[http://www1.kyuden.co.jp/agreement\\_adj\\_index](http://www1.kyuden.co.jp/agreement_adj_index) (in Japanese)



<b>Metal</b>	<b>1995-1999 (US\$)</b>	<b>2004 (US\$)</b>	<b>2006 (US\$)</b>
Copper	1/lb	1.26/lb	3/lb
Lead	0.45/lb	0.37/lb	0.6/lb
Zinc	0.55/lb	0.47/lb	1.5/lb
Gold	336.4/oz	407.5/oz	600/oz
Silver	5.2/oz	6.76/oz	11/oz

*Table 3: Differences in economic factors used in analyses*

<b>Items</b>	<b>1999 (US\$)</b>	<b>2004 (US\$)</b>	<b>2006 (US\$)</b>
Heavy oil (US\$/kl)	113	238	415
Coal (US\$/t)	30	35.9	50
Electricity (US/kWh)	0.086	0.11	0.14
Calcined lime (US\$/t)	66.6	85.5	110
Materials	1	1.25	1.5
Currency	1 US\$ = 121 Yen	1 US\$ = 112 Yen	1 US\$ = 115 Yen
Labour (US\$/mon)	2,350	2,327	2,400
Interest (%)	8	3	5

### **Scale factor**

In order to calculate the capital costs required for the production scales selected in this study, the following formula was used:

$$P1 = P2 (L1 / L2)n$$

where  $P1$  = unknown cost of component, or unit selected in this study

$P2$  = known cost of component, or unit

$L1$  = capacity of component, or unit selected in this study

$L2$  = known capacity of component, or unit

$n$  = constant coefficient ranging from 0.6 to 0.7

This formula is generally used in cost estimates to scale-up plants (JATEC, 1993). For known cost and capacity, the estimates of previous studies (Andrews et al., 1983; Hillman and Gosling, 1985; Hawaii DPED, 1987) are introduced. The selected capacities in this study, such as the production scales and the recovery efficiencies, are also introduced to the formula. The constant coefficient is given as 0.6 in this study.

### **Calculated results**

The initial investment costs for the three mining ventures are summarized in Tables 4 to 6. Because the construction and test production periods (i.e. of 4-6 years) are covered by the working capital, the values in Tables 4 to 6 are relatively high. All cost increases are mainly due to the increase in the price of the heavy oil. However, other economic factors have also become expensive. The recalculated operating costs are summarized in Tables 7 to 9.

*Table 4: Comparison of initial investments in nodule mining*

Subsystem	Manganese nodules production scale 2.2 million t/y		
	Capital costs (in millions of US\$)		
Mining system	202.6		
Mineral proc.	-		
Transportation	142.7		
Metallurgical proc.	417		
<b>Sub-total</b>	<b>762.3 M\$</b>		
	1999 factors	2004 factors	2006 factors
Continuing expenses	177.1	133.2	198.6
	219.8	275.5	355.6
<b>Total investment</b>	<b>1,159 M\$</b>	<b>1,171 M\$</b>	<b>1,316.5 M\$</b>

*Table 5: Comparison of initial investments in CMC mining*

Subsystem	Cobalt-rich manganese crusts production scale 910,000 t/y		
	Capital costs (in millions of US\$)		
Mining system	107.3		
Mineral proc.	28.5		
Transportation	45.7		
Metallurgical proc.	224		
<b>Sub-total</b>	<b>405.5 M\$</b>		
	1999 factors	2004 factors	2006 factors
Continuing expenses	127.3	114.6	165.3
	86.9	119.4	152.8
<b>Total investment</b>	<b>619.7 M\$</b>	<b>639.9 M\$</b>	<b>723.6 M\$</b>

*Table 6: Comparison of initial investments in SMS mining*

Subsystem	Kuroko-type seafloor massive sulphides		
	Capital costs (in millions of US\$)		
Mining system	55		
Mineral proc.	19.5		
Transportation	9.6		
Metallurgical proc.	-		
<b>Sub-total</b>	<b>84.1 M\$</b>		
	1999 factors	2004 factors	2006 factors
Continuing expenses	18.9	20	28.9
	9.1	13.4	17.7
<b>Total investment</b>	<b>112.1 M\$</b>	<b>117.5 M\$</b>	<b>130.1 M\$</b>

*Table 7: Comparison of operating costs in nodule mining (in millions of US\$)*

Subsystem	Manganese nodules production scale 2.2 million t/y		
	1999 factors	2004 factors	2006 factors
Mining system	45.4	56.3	71.5
Mineral proc.	-	-	-
Transportation	27.1	39.5	57.5
Metallurgical proc.	53.5	61.6	74.2
<b>Total (M\$)</b>	<b>126</b>	<b>157.4</b>	<b>203.2</b>

*Table 8: Comparison of operating costs in CMC (in millions of US\$)*

Subsystem	Cobalt-rich manganese crusts production scale 910,000 t/y		
	1999 factors	2004 factors	2006 factors
Mining system	16.9	24.3	31.2
Mineral proc.	4.3	6.7	10.2
Transportation	9.2	11.9	16
Metallurgical proc.	19.3	25.4	30
<b>Total (M\$)</b>	<b>49.7</b>	<b>68.3</b>	<b>87.4</b>

*Table 9: Comparison of operating costs in SMS mining (in millions of US\$)*

Subsystem	Kuroko-type seafloor massive sulphides production scale 300,000 t/y		
	1999 factors	2004 factors	2006 factors
Mining system	6.6	11	14
Mineral proc.	2.2	3	4.3
Transportation	3.4	4	5.3
Metallurgical proc.	-	-	-
<b>Total (M\$)</b>	<b>12.2</b>	<b>18</b>	<b>23.6</b>

*Table 10: Evaluation results of nodule mining*

Case	Manganese nodules production scale 2.2 million t/y		
	Payback period (year)	NPV (M\$)	IRR (%)
Metal prices 1995-1999 and economic factors in 1999 (Co : US\$ 15/lb)	16.9	-156	4
Metal prices 1995-1999 and economic factors in 1999 (Co : US\$ 25/lb)	11.7	77	10
Metal prices and economic factors 2004	6.6	584	19
Metal prices and economic factors 2006	5.7	902	23

*Table 11: Evaluation results of CMC mining*

Case	Cobalt-rich manganese crusts production scale 910,000 t/y		
	Payback period (year)	NPV (M\$)	IRR (%)
Metal prices 1995-1999 and economic factors in 1999 (Co : US\$ 15/lb)	NA	NA	NA
Metal prices 1995-1999 and economic factors in 1999 (Co : US\$ 25/lb)	11.1	62	11
Metal prices and economic factors 2004	9.7	105	12
Metal prices and economic factors 2006	NA	NA	NA

*Table 12: Evaluation results of SMS mining*

Case	Kuroko-type seafloor massive sulphides production scale 300,000 t/y		
	Payback period (year)	NPV (M\$)	IRR (%)
Metal prices 1995-1999 and economic factors in 1999	9.4	23	13
Metal prices and economic factors 2004	12.9	-1	8
Metal prices and economic factors 2006	3.1	209	61

Positive effects in metal prices and negative effects in economic factors drastically affect the economic validation results as summarized in Tables 10 to 12. The economic return on CMC mining has become very low because of the cobalt price decrease between 2004 and 2006 and the lower copper and nickel content. On the other hand, Kuroko-type SMS mining became amazingly profitable between 2004 and 2006. All metal prices for Kuroko-type SMS, especially zinc and copper, strongly affect the results. The copper and nickel prices and their higher content in polymetallic nodules are the reasons for the economic improvement between 2004 and 2006.

Against a background of record-breaking metal prices, a Kuroko-type SMS mining venture is active in the territorial waters of Papua New Guinea (Nautilus Minerals HP). The project collected substantial financial support from mining companies and capital markets in 2006 and 2007. The evaluation results of Kuroko-type SMS mining, introduced in Table 12, may suggest the economic attractiveness of the venture.

Metal prices themselves are the most sensitive factors in the economic analyses. Quick and drastic changes affect economies, as demonstrated by CMC and Kuroko-type SMS. The capital costs of the mining system, ore dressing, transportation and metallurgical processing, which are assumed to be the same as the old validation analyses (Yamazaki et al., 2002 and 2003), have become more expensive in 2006. The negative economic effects need to be clarified in the next detailed studies.

## Concluding remarks

According to economic validation analyses using metal prices and economic factors from 2006, the mining ventures' economic effects are clarified. Given Japan's current economic situation, the most attractive and profitable mining ventures are Kuroko-type SMS and polymetallic nodules in the three deep-sea mineral resources.

There are many uncertain factors in the economic validation analyses. For example, three-metal recovery (such as that of copper, nickel, and cobalt), or four-metal recovery (which includes those three metals plus manganese), have been major discussion topics in the feasibility studies of polymetallic nodule mining ventures over the past 30 years (for example, Kojima, 1996). Polymetallic nodule and CMC mining ventures compete with each other in metal production.

When one venture enters actual mining operation, the other one may lose the chance for development. According to the present analyses, the CMC mining venture appears to have no chance of profitable development. However, because large amounts of CMC are widely distributed inside Japan's EEZ (Usui and Someya, 1997), and some additional rare metals and rare earth elements are concentrated in them (J.R. Hein, personal communication), continuous R&D efforts in CMC development are also necessary for Japan.

The investment cost of Kuroko-type SMS mining for Japan is quite small, because no new metallurgical plant is required and the production rate is relatively low. Among the three deep-sea mineral resources, excavation of the ore body on the seafloor is the easiest. The largest problem associated with development is the environmental impact assessment of the marine ecosystem. No quantitative data on the background ecosystem are available, and nothing has been clarified about mining's impacts upon it. We need to concentrate great effort in these fields.

Although this study uses only Japan's cases as examples, some other metal-importing countries, such as the Republic of Korea and some members of the European Union, are in the same situation as Japan. We had better re-evaluate the important potential of deep-sea mineral resources in the world metal markets.

## Acknowledgments

This study was mainly supported by the Japan Oil, Gas and Metals National Corporation (JOGMEC), Japan. The author would like to express appreciation to everyone concerned with the studies introduced in this paper.

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## Summary of discussion

The first question for Mr. Yamazaki related to the derrick, the Workshop had been informed, had a hanging capacity of 1,250 tons. The participant asked whether that was for both the *Chikyu* drilling vessel and then the mining vessel that he had priced separately and whether it was the same tonnage. The author replied that he had mentioned only the mining vessel. In his model, because of the 8,300-km distance, he had assumed two or three carrier vessels for the transportation of nodules to Japan.

Another participant wanted to know whether the cost of the drilling vessel was driven primarily by the tonnage requirement to hold the riser system and whether a reduction in the weight of the riser could result in a reduction in the cost for the vessel. Mr. Yamazaki replied in the affirmative and said that, for example, for the heave compensation system, reduction in the size of the ship was an important factor. All the technological factors affected the economics.

Another participant asked the author, having reviewed all the technology today, which mining technology would he recommend in terms of efficiency for nodule collection. Mr. Yamazaki said that the passive-type towed collector by pipe string and the hydraulic system was better for nodule pick-up. There was no interaction between the sediment and the pick-up device. Japan had studied the hydraulic device. The pick-up efficiency of the hydraulic device was 0.87.

On a question about three or four-metal recovery, Mr. Yamazaki replied that the three metal recovery could be used as the metal recovery method, but that the four metal recovery would be problematic. He pointed out that the four metal recovery would result in too much manganese in the markets. In his opinion a second venture for metal recovery was not recommended. An important point was also that high construction costs were necessary for manganese recovery. So, the first one was quite okay, but the second was quite risky and not a beneficial investment.

A participant asked about Mr. Yamazaki's rate of return. He said the internal rate of return was in the order of 23 per cent; that was good enough and, in spite of that, mining had not reached the level required if it really was 23 per cent. The participant asked Mr. Yamazaki why, in his opinion, was this so. Mr. Yamazaki replied that it was because of the nickel and copper prices in 2006 and because the construction cost of the mining system was that of the late 1990s and that some reduction would occur if he improved his mining model. Still, it was a very attractive internal rate of return. An important point was that the environmental protection cost was not known and it was not known how strict the environmental regulations would be. That was a negative factor for the nodule mining venture and the current economic situation.

The final question was why the parameter for sensitivity analysis had been based on the price of cobalt and not on nickel and copper, as cobalt had been quoted as .2 per cent in the presentation and in the case of the Indian Ocean nodules, it was less than 0.2 per cent. The participant asked why it had been so critical to choose that parameter instead of the other metals. Mr. Yamazaki's reply was from an economic viewpoint. He said that the cobalt market size was quite small compared with the copper and nickel markets and that everyone knew the historical price differences. Fundamentally, it was necessary to recover the mining cost from nickel and copper. Cobalt and other rare metals should be by-products.

## **CHAPTER 3 Seabed Mining Economics: Lessons to be Learned from Old and Dusty Models**

Caitlyn Antrim, Executive Director, Rule of Law Committee for Oceans, Arlington, Virginia, USA

Dr. Caitlyn Antrim, one of the authors of the Massachusetts Institute of Technology (MIT) model, presented a paper on cost models developed during the 1980s for deep seabed polymetallic nodule mining. She began her presentation on the general components of a deep seabed polymetallic nodule mining venture, and reviewed some of the models developed during that period. She pointed out that all of the models: addressed the recovery and processing of polymetallic nodules; assumed that a ship-based slurry lift system would be utilized in mining; assessed economics in terms of the IRR of the project; and had three phases (pre-investment, construction and operation).

Pointing out major differences in the models, she said some assumed that three metals (copper, nickel and cobalt) would be recovered from nodules, while others assumed that a fourth metal (manganese) would also be recovered. Ms. Antrim said that in some models the mine life was taken to be 20 years, while others assumed a 25-year mine life. She said that the models also showed differences in factors such as debt and taxation regulation.

Dr. Antrim explained the MIT model in greater detail and spoke about its preparation, construction and operation. She described the model as a tool for understanding metal markets, and for helping public education about marine mining ventures. She said that in 1982 the National Oceanic and Atmospheric Administration of the United States Department of Commerce of the United States (NOAA) commissioned Texas A & M University (TAMU) to improve technical and economic models of deep seabed polymetallic nodule mining to support the NOAA regulatory mission, and provided details of TAMU models 1 and 2. She said that in 1985, the US Bureau of Mines developed another model, and also presented the Australian Bureau of Mines and MIT Pioneer models. The MIT pioneer model envisaged a capital investment of US\$ 1162 million, annual operating costs of US\$ 217 million and annual returns of US\$ 415.6 million in a 3 million short ton polymetallic nodule mining operation that would last for 20-25 years. She concluded by saying that it is time to update the models to reflect the advances in technology and likely development schedules.

During discussion, Dr. Antrim explained trends in metal prices over the previous 5-6 years and the influence of markets like those of the Russian Federation, China and India.

As the paper on 'Seabed Mining Economics: Lessons to be Learned from Old and Dusty Models' was not available, Dr. Antrim's powerpoint slides are reproduced in the following pages, followed by a summary of her presentation.

## NOAA's Public Models of Deep Seabed Mining

- NOAA's Objectives
  - Prepare for regulatory role
  - Support Stakeholders
- MIT Models
  - The original "MIT Model" of 1978
  - The "Pioneer Model"
- Texas A&M/Jack Flipse

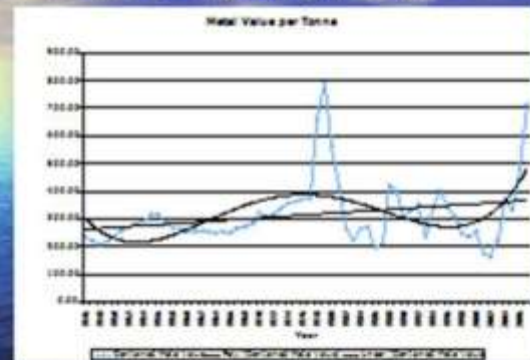
## Seabed Mining Economics

Lessons to be learned from  
Old and Dusty Models

## Goals for this Presentation

- The Most Important Point
- Review What Has Been Done
- Generalize Components of Seabed Mining Economics
- Review Selected Models
- Discuss Implications of Differences
- Look to the Future

## The Most Important Point:



## Principal Modeling Efforts

- Sorenson and Mead
- Proprietary Industry Models
- Ocean Mining Administration
- National Oceanic and Atmospheric Administration
- Bureau of Mines/Bureau of Mineral Resources

## The Beginning

- Sorenson and Mead
- Gale Hubred
- OMA1: Arthur D. Little
- OMA2: Kildow & Bever/MIT
- OMA3: Summary Report

## Key Elements of Economic Models

- They have an objective that shapes the model
- They provide a metric of economic feasibility
- They represent technology and markets of their time
- They vary in depth of complexity

## Common Points of the Models

- Address the recovery and processing of polymetallic nodules
- Model production of Three Metals
- Utilize a ship based slurry lift system
- Assess the economics in terms of Internal Rate of Return
- Have phases of pre-investment, construction, and operation

## Important Differences

- Manganese or No Manganese; One or more mineships
- Year of Cost and Price Estimates
- Duration (20 to 25 years of production)
- Modeling by Analogy versus Detailed Analysis
- Debt, Taxation, Regulation and other Factors

## The "MIT Model" as a Guide

- Begun in 1975, published in 1978
- Cost Model developed by identifying major components and costing analogs from other industries
- Economic Analysis applied discounted cash flow, US Taxation, Debt Financing and other US specific concerns
- Objective: To provide a public model to illustrate private and public interests in Seabed Mining

## Structure of the MIT Model

- Phases: Preparation, Construction, Operation
- Major Cost Sections: Exploration, Mining, Transportation, Processing
- Financial Section: Scheduled costs and revenues over project, calculated taxes and debt payments and performed cash flow calculation

## Basic MIT Assumptions (1)

- Single Mineship (baseline)
  - Capital \$493 million
  - Operating \$100.5 million
- Two Mineship System
  - Capital \$542.9 million
  - Operating \$107.6 million

## Basic MIT Assumptions (2)

	Ni	Cu	Co
Ore Content	1.5%	1.3%	0.25%
Processing Recovery	95%	95%	60%
Price	\$2	\$0.71	\$4
Recovered value/year	\$258 million		

## Examples of MIT Model Results

- Base model with 50% debt financing, US corporate taxation, 25 year production life, single mine ship, foreign vessel construction and flag  
– IROR: 18.14%
- No Debt Financing  
– IROR: 15.41%
- US Ships and Crews:  
– IROR: 16.26%

## More Results

- 25% Drop in Metal Prices  
– IROR: 9.51%
- 25% Increase of Capital Costs  
– IROR: 15.01%
- Two mineship system  
– Increased capital cost by 10%  
– Increased operating costs 7 to 17%

## Uses of the MIT Model

- Target Areas for Improvement  
– Understanding metal markets  
– Improve model of mining system  
– Increase expert review and critique
- Public Policy Support  
– Public Education  
– LOS Financial Negotiations

## TAMU/Flipse - 1982

- NOAA contracted with Jack Flipse and TAMU to improve technical and economic models to support NOAA's regulatory mission
- Coordinated with MIT Team and shared information

## The TAMU Model

- Costs based on 1960 estimates and measurements in short tons
- Greatly enhanced Mining and Marine Transportation sectors
- Recommended Two Ship system for Mining



## TAMU Model (2)

- Incorporated New Processing Technology Description
- Increased Working Capital Requirements
- Added Explicit Marine Support and Waste Disposal Sectors

## TAMU: Revenues

	Ni	Cu	Co
Ore Content	1.3%	1.1%	0.2%
Processing Recovery	95%	95%	70%
Price	\$3	\$1.25	\$5.50
Recovered value/year	\$423 million		

## TAMU Baseline Results

- Annual Revenue: 422.5 million
- Capital Cost: \$1022.2 million
- Operating Cost: \$228.6 million
- Working Capital: \$175 million
- IROR Results:
  - Before US Tax: 8.5%
  - After US Tax: 7.05%

## TAMU Variations

- Single ship/1.5 million tons/year
  - IROR before tax: 4.65%
  - IROR After Tax: 4.5%
- Foreign Ship Construction & Manning
  - IROR Before Tax: 10.65%
  - IROR After Tax: 8.95%

## TAMU: 1985 Model

- New Model incorporating:
  - 50% Increase in Throughput
  - Second 4-Metal Design
- Costs in 1982 dollars
- Explores Benefits of Economies of Scale

## TAMU 1985: Assumptions

- Metal Prices: amount unchanged but now in 1982 dollars (net reduction in value)
- Gross Revenue increase by 50% over TAMU 1982 to \$634 million

## TAMU 1985: Results

- Significant IROR increase due to economies of scale at 4.5 Million tons/year
- Major IROR Benefit (about 5%) results from 75% debt financing
- High throughput, debt financed system with partial manganese recovery estimated at about 25% IROR (in contrast to original base case of 7.05% IROR)

## TAMU 1985: Results

- Base Case:
  - NH<sub>3</sub>, 4.5M/yr, three metal recovery, 5% inflation, 75% debt Finance: IROR=25%
  - As above with partial or full Mn recovery: IROR=25% and 27%
  - Smelting with partial or full Mn recovery: IROR= 22% or 28%
- Loan and inflation have major positive effect; deflation would be harmful
- Tax treatment of depletion allowance can reduce IROR by as much as 5%

## TAMU 1985: Recommendations

- Investigate Effect of Improved Exploration Technology
- Research new (post-1985) processing technologies
- Consider economic effects of foreign processing

## US Bureau of Mines

Hillman and Gosling, 1985

- 3 M tonne/year
- 20 Year Project Life
- No Debt Financing
- US Flag Construction and Manning
- Examined 3 and 4 Metal Systems (manganese as ferromanganese)
- Standard BuMines Economic Analysis

## BuMines 1985 Cost Data

- Capital: 1.628 Million (3 metal); 1.843 Million (4 metal)
- Operating: \$224.1 million (3 metal); 440.7 (4 metal)
- Capital includes working capital at about double the Flipse level

## BuMines 1985: Mineral Data

	N	Cu	Co	Mn
Ore Content	1.33%	1.04%	0.26%	26.8%
Recovery Rate	92%	92%	65%	44%
Price (\$/lb)	3.62	1.17	8.53	0.25
Annual Revenue	\$462.2 million (from 3 million metric tons)			

### MIT "Pioneer Model": Revenue

	Ni	Cu	Co
Ore Content	1.29%	1.09%	0.25%
Processing Recovery	95%	95%	60%
Price	\$3.75	\$1.25	\$5.63
Recovered value/year	\$415.6 million		

### Comparison

	MIT	TAMU 1	USBM	MIT 2
Capital	493	1021.2	1628	1121
Operating	100.5	228.6	224.1	217
Annual Revenue	253	423	462	416
After Tax IROR	18.14%	7.05%	7.38%	9.21%
PPI	62.1	85.8	102.8	85.8
Notes	1, D, F	2, US	2, US	2, D, US

- ### Recommendations
- Create simple standard financial analysis tool to compare and contrast costs, revenues and IROR
  - Update models to reflect advances in technology and likely development schedules
  - Use the models when necessary to simulate effects of technical, environmental and financial regulations or to have a focus for discussions of potential development plans

## Summary of presentation

Dr. Antrim said that it was with some degree of envy that she had listened to Mr. McFarlane's presentation earlier because at the time he had been working with the INCO consortium, she was in academics trying to get her hands on any information such as he was presenting and having to make do with things that she could find in slips of the tongue from engineers, reports that they published in obscure journals, to try to put together a public model of ocean mining economics.

She said that the charge of the participants at the workshop was to identify opportunities and barriers to commercialization of deep ocean mining. She observed that many of the presentations were made by people who specialized in areas of technology, management and operation in seabed mining. She said she would be trying to show ways to pull that information together to learn some lessons from the modelling of the cost and economics of seabed mining.

According to Dr. Antrim, there had been a trend line over the past 60 years on a representative nodule in terms of metal content of copper, nickel and cobalt and the prices of each year brought to constant dollars in 2007. Showing a graph, she said the blue line connected the actual data points of what those values were in each year. There were a few points that were off the line, particularly around 1979, when there had been a shortage of cobalt due to disruption in the Katanga province. In general, one would see a wave that had a slow trend upwards. That wave represented a period from around 1945 up to 1980 when there had been heavy development in the industrialized world. After the Second World War, Europe was rebuilding, Japan was developing its economy and the United States of America

was still growing in terms of manufacturing and heavy industry. During that period, economies had been growing and the intensity of the usage of the metals had been increasing.

By about 1980, the necessary rebuilding of damaged economies had been complete. The major countries had been moving into service economies and giving up some of their rush to heavier industrialization. So the result had been a period of another 20 to 25 years of decline in metal prices in real terms, only to see that changed again with China's increased industrialization and prospects for Brazil and India, and for more rapid industrialization of the Russian Federation. The United States Bureau of Mines anticipated that China's increase in intensity of use of the metals would continue for at least another 35 years. Ms. Antrim said it would be nice to see her graduate work finally brought to fruition by someone or some firm.

### ***Early modelling efforts***

The author said that Sorenson and Mead had written an article in 1968 in the *Journal of Agricultural Economics* that had started people looking at ocean mining as a potential economic investment. All the mining consortia had had their own proprietary models that nobody had been able to get a look at. The Ocean Mining Administration which had been formed in the United States Department of Interior had actually funded research. However, that information was not widely available in the public domain. It had been mainly used and controlled by the Ocean Mining Administration in support of its positions at the Law of the Sea Conference.

The change had come with the National Oceanic and Atmospheric Administration (NOAA) in the United States Government. NOAA had a different philosophy. Its idea was that it was there to serve the public through developing regulations as necessary, but it tried to do that by building consensus among stakeholders. What it wanted to do was gather information, not only to sequester to itself, but to make available to the public. It did this through a number of contracts, particularly through the Massachusetts Institute of Technology (MIT), Texas A&M University, as well as support contracts with Arthur D. Little and several other companies.

Finally, Dr. Antrim said that she would present two models prepared by the United States Bureau of Mines and the Bureau of Mineral Resources in Australia. The objectives of NOAA in its funding were to prepare for the regulatory role and support stakeholders. The two MIT models had been produced in 1978 and in 1984, Texas A&M University had begun its work when Jack Flipse retired from Deep Sea Ventures and became a professor at Texas A&M University taking with him first-hand experience with the seabed mining technology of deep-sea ventures.

Dr. Antrim said that, in looking over the models, a number of things would be found. They all had an objective in mind, these objectives were not the same. Some models had been developed to help to decide whether to invest in a business. Some had been designed for sensitivity analysis to decide where to put development money; what was the worst that could go wrong; what was the best that could go right; and to make relative decisions, rather than absolute ones.

All the models represented the technology of their time. The period being looked at was between 1975 and 1985. It was a period when ocean mining had risen and had begun to fall. In all the cases they had used internal rates of return, and in some cases, some additional metrics. They varied a great deal in the level of complexity of the model. All the models addressed the three-metal production -nickel, copper and cobalt. Some of them addressed manganese in addition to that. They all used a ship-

based slurry lift system. In many cases, they were not specific as to whether it was airlift or hydraulic pumps. They all had phases of pre-investment, construction and operation.

### ***The important differences***

Dr. Antrim said that some of the models had included manganese, but most did not. It was very confusing trying to compare them, because each of the models seemed to have been done in a base year, which meant that \$1 million in 1980 would not be the same in 1984. If one wanted to compare them, one would have to normalize across years. In some cases the analyses had been done for 20 years of production and in others, for 25 years, which had caused a small difference in economic return.

One of the points that Dr. Antrim was most familiar with was the difference in modelling techniques. She said that in the early models, particularly the first MIT model, it was necessary to really model by analogy. They had broken the model down into components that could be compared to activities in other industries and then priced those, scaled them appropriately and brought them into the model in different segments of the structure.

As the models were better developed, more consultants were brought in, it had been possible to move to a more traditional itemized list and work out costs specific to that model.

Factors that could make models incomparable included: whether there was debt financing or not - that was a very significant point; taxation - whether the model was done including taxation, and if so, for what country; business format – that could account for several points of internal rates of return and if one was looking at something to see whether one process was better than the other and one was comparing different models, if one had debt and the other one did not, that would totally invalidate the other; regulation - the United States had something that was called the Jones Act, whereby in certain cases, ships had to be United States-built and United States-crewed, that could also account for several per cent of internal rates of return difference. In fact, in some of these cases in which the models looked quite different, some of the factors were because of the different selections that were not technical issues, but policy issues and the modeller had to decide whether to incorporate them; whether to model the system that followed one regulation or another.

### ***The MIT model***

Dr. Antrim said that work had begun in 1975 and had been published in 1978. That was the one that had been defined by identifying major components and then pricing them according to similar equipment in other areas. It had applied discounted cash flow accounting, used United States taxation, had 50 per cent debt financing and it followed other specific United States concerns in terms of transportation distance, cost of power and waste disposal.

She explained that the purpose of that model was to educate people. In 1978, not that much had been known outside of the companies involved in ocean mining. The effort was to try to give people not just a sense of the economics, but of the structure - what the industry really was and the interrelation between components. The major components were: exploration, mining, transportation and processing. The financial section was scheduled costs and revenues over the life of the project, then calculated taxes and debt payments and performed cash flow analysis.

Dr. Antrim said that two examples of that - and it had been calculated in 1976 United States dollars - was that its capital cost may have gone up by a factor of two and one-half times since that time. If one normalized this to 2007 United States dollars, the capital in the entire project would be in the order of \$1.2 billion; operating costs were increasing in a similar fashion. At that time, she said, it had seemed that a single mining ship could produce 3 million tons of nodules per year, so that was the base case. They had taken the opportunity to model a system that used two ships of half that capacity and had seen about a 10 per cent increase in capital costs and a little less than that in operating costs.

With another graph, Dr. Antrim said that, compared to other analyses, the model being shown was rather high grade. It was taking a large enough area that it could go through and skim the cream of the crop for 20 to 25 years. As in most operations, it had shown a recovery of cobalt of 60 per cent. It had used the metal prices that were prevalent at that time - \$2 for nickel; \$4 for cobalt; 71 cents for copper and had gross revenues in that year which had been extended through the entire project life of \$258 million per year.

The result with the base model at 50 per cent debt financing, United States corporate taxation, 25-year production life, single mine ship, foreign construction of the ship and the transport gave an internal rate of return (IRR) of 18.14 per cent: did not use debt financing, the IRR dropped by about 3 per cent - a significant amount; if United States ships and crews had to be used, the IRR dropped from per cent to 16.26 per cent. She observed that there were a number of factors that a model such as the one being shown would be useful for.

According to Dr. Antrim, a large part of the analysis had been sensitivity analysis; a 25 per cent drop in metal prices had cut the internal rate of return in half.

She said there were two main uses for the model. One was to figure how to do it better - that was the first step - to try to at least begin to understand what the metal markets were. It certainly identified that more models were needed in the mining system and it needed more input from people with the experience, and should not be kept as an ivory tower exercise.

### ***Public policy support***

Dr. Antrim said that the model had been used widely in the United States Government to explain what ocean mining was to the legislators who were preparing legislation for United States mining and for hearings on the law of the sea. Its most prominent use was in the Law of the Sea negotiations where it had first been used in a seminar for delegates to give a common basis for debate about seabed mining and its cost and structure. It had provided a tool for developing the financial arrangements, in effect the taxation system, for seabed mining. It had done so not by presenting a single number, but a range of six possible outcomes: what persons believed the inflation of metal prices would be; and whether they thought that the model overestimated or underestimated cost. The goal was not to tell people what would happen, but to say, "if you believed this, then when you take this action, something in particular was likely to happen".

Dr. Antrim told participants that, in 1982, Jack Flipse had done a report at Texas A&M University. NOAA had contracted him and he had worked with the MIT team so that they had been a division of effort; they had benefited from each other. His costs had been based on 1980 numbers. Measurements had been in short tons. All non-United States persons knew that the persons from the United States were sometimes slow to adopt world standards and they were in this period of being very

slow to adopt metric tons as a common measure. That had had an effect because there were economies of scale on a model and, all other things being equal, a 3 million short ton per year operation would be perhaps six tenths of a per cent less economic than a 3 million mt per year operation.

According to Dr. Antrim, Flipse's model incorporated some new work on reduction ammonia leaching that had come from the Dames and Moore contract report. He had added explicit marine support and waste disposal services, both of which had been underestimated in the original MIT model. This being four years after the original MIT model with lower ore grade, processing recovery was almost the same, except that Flipse had used a slightly higher cobalt recovery. Prices were about 50 per cent higher than they had been in the MIT model and revenues had totalled \$423 million in 1980 dollars.

Dr. Antrim said that Flipse's capital costs had been just over \$1 billion and his operating cost \$228 million per year; his working capital had gone up to \$175 million. This had given much lower estimates of return; after tax, down to about 7 per cent, before tax, 8.5 per cent. He had done some variations; he had looked at a single ship producing 1.5 million tons per year. As there were economies of scale, there were diseconomies of going the other direction. That dropped the internal rate of return after tax, down to 4.5 per cent. The original model had used United States construction and crews. By moving to foreign construction and crews he had been able to increase the internal rate of return by about 2 per cent.

In 1985, they had come out with a new model. Dr. Antrim said she thought that Jack Flipse had been discouraged by those numbers. He had wanted to bracket the situation from another direction. She showed another model and said it had looked at economies of scale moving from 3 million tons per year to 4.5 million tons per year - a 50-per-cent increase. He had held the metal prices unchanged, but had used 1982 dollars, which in effect, had been a reduction of value. However, gross revenues had increased by 50 cent because it was proportional to metal recovered.

Flipse had gotten significant return benefits on this basis. About 5 per cent of the benefit had come from using 75 per cent debt financing. Dr. Antrim said that she assumed that some of the miners in the audience would say good luck at that, but that had been the result of the calculations. By using high throughput, 50 per cent of the capacity, and by moving to debt financing to a high degree with a partial manganese recovery, Flipse had been able to achieve a 25 per cent internal rate of return, up from that 7.05 per cent that he had had only a few years earlier, but a lower throughput and with no debt financing. He had made some recommendations that were still valid at present: to investigate the effect of improved exploration technology; to conduct research into the newer processing technologies.

Dr. Antrim said that at the time of all those models, the ammonia leach system had been the new thing. Since then there had been a lot of work on processing nickel laterites using pressure acid leach which have apparently given a significantly higher recovery of cobalt. That would be well worth modelling in this to see whether there were offsetting costs that countered that benefit of increased return. By modelling one segment and putting it into a model like this, one could get a sense of how important that particular change was and whether it was worth pursuing.

Dr. Antrim also noted that there could be benefits from siting a processing plant outside the United States and said that, until she was preparing for the meeting she had forgotten to take note of how chauvinistic those models were. Almost all the models developed in seabed mining in the period from 1975 to 1985 had been developed in the United States by United States citizens for consideration of United States operations. The Jones Act was simply one of a number of biases built into those

models. People who looked at the numbers and just skimmed the reports would never have seen that they were there and would not have considered that finding a port close to land that could be bought for a processing facility, which in turn was close to a place where the tailings of an operation could be disposed of was a very expensive proposition in the United States and would very well be something that another country would find much more economical to do than in the United States.

Two other models had been prepared and Dr. Antrim found them interesting, because part of the difference came from a bureaucratic attitude. NOAA was aiming to get information out to the public, was seeking input from the public and was trying to make a tool that could build consensus.

Dr. Antrim said that, in 1985, the United States Bureau of Mines had prepared an analysis of seabed mining. It had drawn on Flipse's work and had used a standard modelling package that it had for consideration of all types of mines. This had been the first model that used metric tons. It kept a 20-year project life, had not used debt financing and had used the United States flag in mining and construction. If there was a choice on a variable to go high cost or low cost, it had tended to go high cost.

Its capital requirements had been \$1.6 billion, four metal plants had added another \$220 million to it and its operating cost had been \$224 million, which was very similar to the preceding two models. The difference here on the capital, in part, rested because, instead of including the working capital at the six-month level, which Flipse had done, these authors had included 15 months' operating cost as working capital on the mining, 12 months on the transport and a lower amount on the processing. There had been a significant increase in cash that had been set aside that affected the cash-flow calculations.

Dr. Antrim said that the numbers that she had spoken about were actually very similar to the Flipse numbers, coming out at \$462 million total annual revenue. The internal rate of return on the three-metal system came out with an IRR of 7.38 per cent, which was just three tenths of a per cent above Flipse's numbers, the four-metal system was somewhat less. She said that she had seen models in which manganese production did increase, but it was very dependent on whether one was producing manganese oxide, ferromanganese or manganese metal. If producing manganese metal, one would probably want to have a contract with the consumer because it was not that big a market.

The Bureau of Mineral Resources of Australia, in preparing a report for the Preparatory Commission on the Enterprise, had taken the United States Bureau of Mines model and made some adaptations to it. They had used two mine ships – 3 million tons per year, had not used United States construction and manning and pricing was in 1985 dollars. Their capital operating costs had been simply indexed, not recalculated from the United States Bureau of Mines. It had retained the high working capital percentages from the United States Bureau of Mines and had roughly the same metal prices, except that it was lower in copper. The cost had been inflated by over two years, but metal prices had declined in total by about 6 per cent over that period, and therefore, economic analysis would come down on that. However, the report had been given in statistics rather than a baseline case.

Dr. Antrim told participants that a lot of sensitivity analysis had been done, but that it had been the standard United States Bureau of Mines package. There were a lot of things to look for in a seabed mining operation that one would not look at, for example, siting of port facilities, the Jones Act or other things related to waste disposal that would be significantly different for seabed mining.



The final model presented by Dr. Antrim was the MIT Pioneer Model. This had been printed in 1984 and incorporated most of Flipse's findings from his 1982 study. It had greatly increased the level of detail and had moved away from reasoning by analogy to reasoning by analysis. One of the things that had been added had been incorporated from an interim report that had provided a detailed schedule of investments and costs, and of the sequence of activities.

In the preparatory cost of \$30 million in capital expenses, \$142 million had been expended. Those amounts had gone both for research and development, prospecting and initial exploration of the site. Capital costs had been \$1,121 million and operating costs, \$217 million. She said that this last group of models were seen hovering around the same place; they used United States taxes, 50 per cent debt financing and United States crews and construction. Again, the ore content was a little different, but it still stayed above \$400 million per year revenue.

Dr. Antrim provided the following quick comparisons:

The first MIT model was much lower in numbers, but one had to consider that it had been priced about four years earlier, during a period of very high inflation – during the second energy spike. Capital cost – the producer price index had risen about 40 per cent during that period. Those numbers were not as widely separated as one may think. The MIT model had all the things that tended to make a highly profitable operation and had been done at a period before the cost had become inflated.

Looking at the models, the first thing that had struck Dr. Antrim was that they could not be compared. The differences in years and the non-technical parts, whether in tax systems or domestic regulations, had clouded what the true differences were among them. In fact, for systems in which one was looking at the effect of variations of change, or sensitivity, one could get by with a much simpler system. One could use a system that did not even incorporate the national taxation to get a first cut of sensitivity once the basic technical model was in place. A very simple spread sheet model could be a first cut to do an analysis on the impact on regulation, or for a company, the first opportunity to see where best to place research and development funds.

All the models that were available needed to be updated in technology. She had not seen a model of this depth of study that incorporated new processing technology for oxide ores or certainly not ones that incorporated the potential of remote vehicles for exploration.

Finally, Dr. Antrim said that the models could be used to stimulate responses when changes were made; whether they were changes that they wished to consider or changes that were imposed from the outside.

### **Summary of discussions**

One participant recalled that Dr. Antrim had said clearly that she could not compare their models and asked how all those models stood today and whether they were valid or not. The participant wanted to know how those models had improved, taking into account the improvement in metal prices and the negative factors derived from oil and the evolution of technology.

Dr. Antrim replied that the basic structures of those models were similar and that, by using the information in the models and appropriately scaling it to bring it up using price indexes and accounting for inflation, a new baseline could be obtained, at least until better information came in. She suggested

going through and looking at the effects of, for instance, increased consumption by China, asking if that forced the prices up, what that would mean. She said one could look at things such as, whether there was metal price inflation, which was actually a good thing for a seabed mining operation. If metal prices went up faster than capital, it had increased the rate of return. In effect one could take the world as one thought it might be and apply it to the estimates that one had for the past, add in improvements that had been made over the past 15 years, and even improvements that may have occurred that very week. Dr. Antrim said that, in fact, she believed that a simple model could be taken and the rest of the workshop used as the participants saw fit to look at the recommendations that people may make in that group.

A participant said that he was with the Kennecott consortium and that they were always challenged to compare ocean mining with competing sources of metals. He wondered whether in the models presented by Dr. Antrim, economics had been run against the Greenfield laterite mine or other potential sources for those metals that would be the option for investors. He said it had always seemed to him that the issue with whether nodules were competitive was whether they were competitive against an alternative source of the metals and not so much pure internal rates of return. His question was whether the modellers had carried out their models against not just sensitivities in ocean mining but against other sources of metals in the world.

Dr. Antrim replied that the United States Bureau of Mines, particularly in relation to nickel, did have a chart that showed when new deposits would come on at new price levels they competitively opened. They did it through their own sources. She said she did not know how they got that; at present, she believed that a new laterite mine had to have a nickel content of 1.5 per cent to be considered attractive, given the fact that there were no other detriments to it, such as being too far away from the shipping, etc.

She added that there were no other deposits of that size that fell into the “next one to open” category and that one of the biggest effects on the nickel market - the Nuris deposit in the Russian Federation - in its core production had nickel as a by-product. The Bureau had reported that there was some consideration of moving their production to metals that had copper as a by-product. With the Russian Federation being the largest producer of nickel in the world, a decision to change its production would have a major effect on the nickel price that would push it upward. Nickel was more likely to go up rather than down.

## CHAPTER 4      **Economic and Technical Considerations Underpinning the Pioneer Regime and the Regulation on Prospecting and Exploration for Polymetallic Nodules in the Area**

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### **Introduction**

Polymetallic nodules, also referred to as manganese nodules, are rock concretions on the sea bottom formed of concentric layers of iron and manganese hydroxides around a core or nucleus. Nodules are found on seabed sediment, often partly or totally buried. Polymetallic nodules are found in all oceans and even in lakes.

Manganese nodules were first discovered in 1873 in the Kara Sea (former Soviet Union), in the Arctic Ocean of Siberia. They were collected by many scientific cruises throughout the first half of the twentieth century.

During the scientific expeditions of the H.M.S. *Challenger* between 1872 and 1876, many polymetallic nodules rich in nickel, copper, cobalt and manganese were collected from the deep sea. In 1900, an American, Alexander Agassiz, collected polymetallic nodules from all parts of the Pacific Ocean. More polymetallic nodules were collected from all oceans of the world using core devices or dredges.

It was only around 1957 that the American, John Mero, succeeded in convincing some industrialists about the economic interest that might be drawn from the exploitation of polymetallic nodules and the possibility of exploiting the central Pacific Ocean.

In the 1960s, as mineral resources were becoming increasingly difficult to extract on land, polymetallic nodules began to be considered as a possible source of nickel, copper and manganese. Recent research in the deep sea has identified rich ore deposits; polymetallic nodules that may be economically extractable through the development of a deep-sea mining industry within the next decade (Fujita 2001).

Moreover, the increase in the commercial use of copper, nickel and cobalt in the early 1960s caused a significant rise in metal prices, focusing attention on mining the deep sea for polymetallic nodules; as polymetallic nodules are mostly found in international waters, four multinational mining companies were started and the governments of the Soviet Union, India and China sponsored deep-sea mining enterprises (Yamazaki 2005).

The first company interested in polymetallic nodules was the Kennecott and Newport Shipbuilding Company (1962), which started a programme of sampling when some academics started geochemical studies of polymetallic nodules and their metallurgical processing.

The economic significance of polymetallic nodules as a new source of ore for manganese, nickel, and cobalt and copper generated immense interest worldwide in the mining industry.

It was widely felt that to promote or develop and rationalize deep seabed prospecting, exploration or exploitation, there was a need to elaborate a legal framework (Mining Code) within which those activities could be performed.

At that precise moment, the Third United Nations Conference on the Law of the Sea took the initiative to consider who exactly owned the mineral deposits on the ocean floor in international waters. This initiative followed the adoption of the 1952 High Seas Convention which was followed in 1982 by the United Nations Convention on the Law of the Sea, refined by the 1994 Agreement relating to the Implementation of Part XI (seabed provisions) of the Convention, and the ultimate establishment of the International Seabed Authority in 1994, with responsibility for controlling all deep-sea mining in international areas.

Part XI of the United Nations Convention on the Law of the Sea deals specifically with the resources in the Area.

A major Principle of this Convention remains the affirmation of the existence of an international area free of State Sovereignty, which cannot be subject to appropriation, by any means, by States or private persons. This area constitutes the common heritage of mankind and its resources must be exploited for the benefit of mankind as a whole and, in particular, for developing countries.

### **Pioneer regime**

With the growing interest in polymetallic nodules as a source of nickel, copper, cobalt and manganese, a lot of work has been carried out to determine the existence of reserves or mine sites for economic operations.

As polymetallic nodules are mostly found in international waters, four multinational mining companies were started and the governments of the Soviet Union, India and China sponsored deep-sea mining enterprises (Yamazaki 2005). Close to US\$0.5 billion went into developing the technology and processes required for the retrieval of deep-sea polymetallic nodules.

Our present knowledge of polymetallic nodules is mainly due to the work of the Pioneer Investors. These consortia and companies did a tremendous amount of work, which was recognised by the Third United Nations Conference on the Law of the Sea and during the work of the Preparatory Commission.

The special regime for Pioneer Investors was created by the Conference so that countries and enterprises that were part of the venture and technologically capable of carrying out mining activity on the seabed would have reason to continue their pioneering work. By adopting Resolution II of the Final Act, the Conference established a special regime to protect the preparatory investment made by such countries and enterprises, which were to be referred to as 'Pioneer investors'. Registration with the Commission as a Pioneer Investor would entitle a State or entity to explore – but not exploit – a selected area of the international seabed, and give it priority over others when applying to the Authority for commercial production later.

Interest in the potential exploitation of polymetallic nodules generated a great deal of activity among prospective mining consortia in the 1960s and 1970s. Almost US\$0.5 billion dollars were invested in identifying potential deposits and in research and development of technology for mining and

processing nodules. These initial undertakings were carried out primarily by four multinational consortia composed of companies from the Belgium, Canada, the Federal Republic of Germany, Italy, Japan, the Netherlands, the United Kingdom of Great Britain and Northern Ireland and the United States of America and two groups of private companies and agencies from France and Japan. There were also three publicly sponsored entities from the Soviet Union, India and China.

The first legislative achievement of the International Seabed Authority (ISA), which entered into force on 16 November 1994 through the Preparatory Commission, was the adoption of regulations for prospecting and exploration for polymetallic nodules (2002), with special provisions to protect the marine environment from any adverse effects. The Authority followed this up between 2001 and 2002 by signing 15-year contracts with seven private and public entities, giving them exclusive rights to explore for nodules in specified tracts of the seabed, each 75,000 square kilometres in size.

The United States of America, whose companies were among the key actors in the earlier period of exploration, remains outside, as a non-party to the United Nations Convention on the Law of the Sea.

During the Preparatory Commission the following entities or consortia were registered as 'pioneer investors':

- The Government of India registered on 17 August 1987.
- Institut français de recherche 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.
- Deep Ocean Resources Development Company (DORD) of Japan registered on 17 December 1987.
- State Enterprise Yuzhmorgeologiya of the Russian Federation registered on 17 December 1987.
- China Ocean Mineral Resources Research and Development Association (COMRA) of China registered on 5 March 1991.
- Interoceanmetal Joint Organization (IOM), a consortium formed by Bulgaria, Cuba, the Czech Republic, Poland, the Russian Federation and Slovakia, registered on 21 August 1991.
- The Government of the Republic of Korea registered on 2 August 1994.

During the pioneer regime, many technological, geological and economic challenges needed to be overcome.

### **Considerations underpinning the Pioneer Regime**

During the Pioneer Regime the main impeding factor was *the lack of knowledge and scientific information*. One of the laws of nature is that "everything obeys the unavoidable law of evolution", and in this respect, activities developed over the years and more information was acquired. Consequently, more light was shed on the evolution of activities for the Pioneer Regime.

With this enlightenment, many factors underpinning the Pioneer Regime surfaced. At this time, the mining industry worked on assumptions because there was only *rare and sparse information*

available on geology, topography, mineralisation, distribution, abundance, metal content, recovery and exploitation, transportation, processing, and commercialization. Each of those parameters included a technological factor as well as an economic factor.

## **Size**

Size is a physical parameter. Obviously, it is better to begin with a very large exploration area, which can be reduced with more work to individual areas with very good concentrations for recovery.

These factors depend very much on the topography, and specifically with the micro-topography (mountain chains, seamounts, hills with slope). During the pioneer regime, the issue was not to obtain detailed maps to individualize micro-topographic features (isolated volcanoes, rocks, out-crops faults, etc. All those elements reduce the area for future exploitation or may not allow any device to collect nodules.

The size also depends on the quantity of recoverable nodules, and the recoverable nodules depend on:

- Nodule presence.
- Nodule abundance.
- Nodule grade and metal content.

To predetermine an optimum size, there must be agreement on an accepted figure for the quantity of nodules to be recovered in an economically viable operation. The proposed quantity for recoverable nodules evolved over time from 60 to 120 million.

The figures generally accepted from the literature are 3 million dry metric tons per year for at least a 20-year period. This could produce for processing 60 to 120 million dry metric tons.

During the Pioneer Regime, everybody in the mining industry was looking for the biggest areas to explore.

## **Duration**

A period of 40 years was suggested for the estimated duration of a single economical mine site. This period relates to the guarantee. This figure varied from 40 to 25 and 20 years.

A duration of 20 years was generally accepted, taking into account the requirements of financing institutions and the maximum practical rate of return for a project.

## **Recovery**

The recovery rate was an important parameter. Some actors in the mining industry favoured the recovery of only three metals: nickel, copper and cobalt. At that time, only Deep-sea Ventures envisaged the recovery of manganese in addition to the three other metals. Recovering additional metals in this way will improve the overall economy of any mining operation project.

In 1983, Glasby came to the conclusion that the previously accepted 3 million tons per year operation was not viable, and the idea of using two mining ships to enable a production of 3 million tons a year over a period of 20 years were accepted as working values.

All of these parameters are also dependent on others factors that influence their efficiency, including topography, the mining system, and nodule distribution and abundance.

### **Technical and economic considerations on regulations during the pioneer regime**

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.

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 part 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 that need to be 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.

In the field of extractive metallurgy, metal extraction has been achieved by hydro-metallurgy as well as by pyrometallurgy. A large number of processing routes have been developed for recovery of three of 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 available results are not adequate for upscaling and use in feasibility study estimates.

The capital and operating costs of deep seabed mining have sometimes been considered too high to allow the 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 that of a land-based lateritic nickel operation.

### **Technological factors**

During the pioneer regime it was not easy to elaborate regulations accepted by all parties due to a lack of precise knowledge and exact information on the Area, because the main activities were related only to prospecting and exploration. Even to undertake prospecting or exploration in the Area requires a set of regulations that will define the condition of the undertaking of any activities or any investment.

‘Prospecting’ means the search for deposits of polymetallic nodules in the Area, including estimation of the composition, size and distribution of polymetallic nodules and their economic values, without exclusive rights.

'Exploration' means searching for deposits of polymetallic nodules in the Area with exclusive rights, the analysis of such deposits, the testing of collecting systems and equipment, processing facilities and transportation systems, and the carrying out of studies of the environmental, technical, economic, commercial and other appropriate factors that must be taken into account in exploitation.

'Exploitation' means the recovery for commercial purposes of polymetallic nodules in the Area and the extraction of minerals there from, including the construction and operation of mining, processing and transportation systems, for the production and marketing of metals.

## **Conclusions**

During the pioneer regime, activities relating to polymetallic nodule prospecting or exploration were at a very early stage. This period was characterized by a lack of precise data on the genesis, distribution and controlling geological factors related to polymetallic nodules, as well as on the economic parameters determining a viable mining operation. At the same time, prospecting and exploration activities at a global level were not very widespread. This situation naturally resulted in the absence of sufficient data from which to undertake comparative studies. Another consequence was that many parameters lacked precision, especially because nodule mining was a new topic that had not yet been mastered by researchers.

During this period, communication and exchange among the various operators were completely lacking. Each jealously kept their technological, methodological findings and discoveries to themselves.

As a result of this lack of precise knowledge and the difficulty of grasping all aspects of the pioneer regime, all the currently known parameters were also still vague. The imprecision of the major parameters is also reflected in the formulation of rules and regulations meant to serve as a Mining Code to govern activities in the zone relating to the prospecting and exploration of polymetallic nodules. With the expected intensification of activities, all the parameters have to become more clear-cut.

## **Summary of discussions**

The first question to arise during the discussions was about pressure and low temperature environment and whether it was what was happening at the seafloor; whether there was a value for the external pressure from the water column; and what the temperature at the seafloor was. In reply, one of the participants said that, at about 5 km of water depth there were pressures of about 500 bars, and that around those depths, the temperatures were about 2 to 3 degrees centigrade and sometimes even 1 degree centigrade. Those were the kinds of temperature and pressure conditions that existed. The gradient of temperature/pressure was not uniform but rather, it was an exponential reduction in temperatures and pressures, where the temperature decreased and the pressure increased on a scale that needed to be worked out for designing any kind of mining system.

The participant added that, in fact, as they were looking at the economic, legal and technical considerations for developing a nodule mining system, as rightly pointed out, those were the environmental parameters that could help to design mining systems to work at those depths. If one looked at the environment and at how it would help in designing a mining system that would start at the surface platform to the subsurface components to the one that was going to work at the seafloor. One had to look at the atmospheric and surface conditions. Atmospheric conditions included the rain, wind and cyclone conditions throughout the year and how those conditions would affect mining, because



there were weather windows, especially in the open sea. There were weather windows wherein one could operate safely and those in which one could not operate safely, because those were seasons. Cyclones and rainfall would definitely influence one's design. There were currents moving in different directions at different levels in the water column. So, once again, all the pipes or risers that would bring the nodules from the seafloor would be subjected to all the environmental conditions in the water column – all 5 km of the water depth. The most important were the seafloor conditions. The seafloor was not flat, and even with a micro topographical undulation, it could topple. If one could manoeuvre a slope of 3 degrees, for example, but the undulation was more than 5 metres, it would just topple upside down. So there were environmental conditions that would go very deep into the designing of a mining system.

Finally, the speaker said, one had to consider the distribution characteristics of the mineral itself, which did not lie like a carpet, as one would expect. The distribution of the minerals or nodules was extremely heterogeneous, not homogenous. There were patches of high concentrations of minerals and of very low concentrations. If one looked at the underwater pictures, one would see one patch with just 10 per cent of the seafloor covered with nodules, and then an adjacent patch - about 20 metres away - with up to 90 per cent of the seafloor covered by the mineral. He asked how a nodule collector could be designed on that basis, noting that it was not only nodules that were there, but also rock outcrops. Those were undulations covered with millions of years of sediments that had settled on the seafloor. Those sediments occupied the basins or deeper portions, but not the peaks or the highs.

A participant asked the presenter who the current members of the pioneer group were. Mr. Diène replied that, from the pioneer groups comprised of France, the Russian Federation – Yuzhmoregeologiya, India, Japan, China, and KORDI from the Republic of Korea. The United States was not part of it, but the work done by its researchers was known. Germany had also registered.

The Secretary-General wanted to make a clarification on the pioneer issue. He said that, as Mr. Diène had noted, there were seven pioneers that had registered. The pioneer period was from the time during the negotiations of the Convention to the time it had entered into force. It had continued for another two years until it had been possible to adopt the regulations for polymetallic nodules for exploration. Once that had been done, the Authority had issued them contracts, for which they had had to apply. Once the contracts went into force, effectively the pioneer regime was over; it no longer existed. They were called pioneers only to identify them as the early registrants so that they could continue to undertake their research work until they got their contracts from the Authority. Of course, the United States-based consortia were entitled to be registered, but as was well known, the United States had not become a party. The Secretary-General said he did not know how close the United States was in becoming a party, but that it was as close as it had ever been to becoming a party, so it was no longer considered a pioneer.

# PART TWO The current status of technology development by contractors for polymetallic nodule exploration with the Authority

## CHAPTER 5

### The Status of India's Mining Programme

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## CHAPTER 6

### Sea Nodule Processing Status Review for Commercialization

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## CHAPTER 7

### An Overview of the Interoceanmetal Deep-sea Technology Development (Mining and Processing) Programme

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## CHAPTER 8

### KORDI: A Way to Accomplish the Mining Technology for Polymetallic Nodules

*Sup Hong, Principal Researcher, Maritime & Ocean Engineering Research Institute, KORDI, Republic of Korea*

## CHAPTER 9

### Status of Exploration for Polymetallic Nodules in the German Licence Area

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## CHAPTER 10

### COMRA: Research and Development of Polymetallic Nodule Mining Technology in China

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## CHAPTER 11

### The Concept of Engineering and Technological Support for Mining and Processing of Polymetallic Nodules from the Russian Exploration Area

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## CHAPTER 5

## The Status of India's Mining Programme

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### Introduction

India, with its strong science and technology base, is carrying out exploration and technology development for the exploitation of polymetallic nodules under the Polymetallic Nodule Programme (PMN) of the Government's Ministry of Earth Sciences (MoES). This is one of the ministry's major research and development (R&D) efforts towards the development and use of ocean science and technology for the exploration for marine non-living resources for the socio-economic benefit of the society. This multi disciplinary programme utilises multi-institutional participation. On 26 January 1981, the Indian Oceanographic Research Vessel Gaveshani collected the first sample of polymetallic nodules from the Indian Ocean. Continued Indian efforts succeeded in identifying a prospective site with polymetallic nodules in the Indian Ocean, and India was recognised as a pioneer investor in 1982. Subsequently, India became one of the first Registered Pioneer Investor in August 1987 along with Japan, France and the Soviet Union (now the Russian Federation). India's allocated mine site is in the Central Indian Ocean Basin.

As a pioneer investor of the International Seabed Authority (ISA), India has made substantial progress in efforts to develop technology for polymetallic nodule mining. MoES, under the PMN, allocated the different aspects of the nodule mining, such as surveying and exploration, mining technology, extractive metallurgy, and environmental impact analysis, to various institutes in the country. The National Institute of Ocean Technology (NIOT) is actively involved in developing technology for the mining of nodules on the deep seabed.

This paper details the efforts made by NIOT in the development of mining technology in the last decade with a focus on the task of commercialization of nodule mining during the next decade. The initial work conducted at other National laboratories is also briefly covered. The developmental work done on three major projects for mining is presented, without details of the infrastructure being developed for the testing and qualification of systems inland. The areas where mutual collaboration can operate between the different organisations involved in the field are also indicated.

### Initial development work

The work on estimating the mineral content of the nodules gathered by grab sampling was done by the National Institute of Oceanography (NIO), Goa, from the 1980s. The work on Environmental Impact Assessment (EIA) has also been done in greater detail by NIO. NIO has conducted an extensive survey in the area allocated to India, and has provided the necessary data for relinquishing the area allocated by the ISA.

The design and development of a remotely operated underwater mining system, with a collector module, lifting system and instrumentation and control systems, was initiated in 1990 at the Central Mechanical Engineering Research Institute (CMERI), Durgapur. Initial efforts were designed to test the concepts to generate basic data, and to acquire an understanding of the functional and operational needs of the system and its sub-systems. The underwater mining system, which had a capacity of 100 tonnes/day, had a remotely operated crawler based collector module, a bucket-in-pipe based lifting system, and a control system with the necessary instrumentation. The performance of the

sub-systems was evaluated on land and subsequently in an on-shore shallow test basin. Subsequently, the development of a remotely operated vehicle (ROV) for inspection and maintenance of the underwater systems up to a depth of 200m was also undertaken by CMERI. The performance of the ROV was evaluated, and it is currently being upgraded with enhanced features.

### **Development of an underwater mining system for long-term operations**

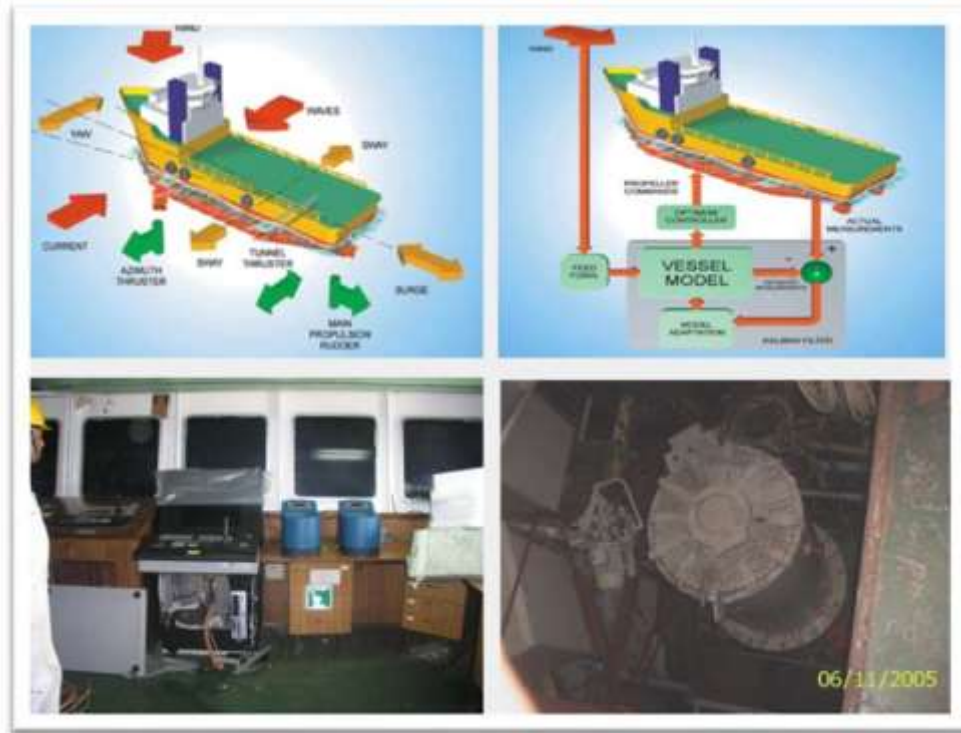
The work on technology development for nodule mining began in 1997 at NIOT. NIOT has been working on a concept involving a crawler-based mining machine and a flexible riser system for developmental work. In variance to the concepts proposed earlier, the concept of a flexible riser would result in considerable cost savings as this constitutes a major element in the overall cost of the mining system. The Institut für Konstruktion (IKS) at the University of Siegen, Germany, developed an underwater crawler as part of its research work. NIOT teamed up with the University of Siegen to refurbish the crawler with a manipulator, cutter, slurry pump, flexible riser, electrical instrumentation, telemetry and control systems.

The mining machine (underwater crawler) uses an electro-hydraulically operated system with transducers for the measurement of velocity, drum speed, heading and sand concentration. The machine has a closed loop control for speed, heading and slip. An electro-mechanical umbilical cable with copper conductors and optical fibres facilitates power and data transmission, respectively, to the machine. The flexible hose is also launched from the ship and attached to the cable, to pump the slurry. The cable-hose combination is considered to be the flexible riser. During launching, floats are attached at appropriate locations to enable the flexible riser to obtain an S-shaped profile at the bottom.

The mining trials were conducted using the MoES research vessel ORV Sagar Kanya and the underwater crawler was successfully tested during 2000 off the Tuticorin coast at 410 m depth for a short period. During the first phase of this trial, the mining system pumped 10-45 m<sup>3</sup>/h of sea floor material with a maximum density of 1,170 kg/m<sup>3</sup>. This initial success gave the necessary confidence to proceed further with the development of a mining system for long-term operations. For such operations, close coordination of the position of the mother ship in relation to the underwater mining system is essential. Further, to facilitate docked launch and retrieval of the mining system, a 'launch and retrieval system' (LARS) was required. Therefore, the ORV *Sagar Kanya* was equipped with a 'dynamic positioning system' (DP) for effective station keeping, with operating accuracy of 15 m radius, and a heading accuracy of  $\pm 10^\circ$ , for operations in sea state 3, and a LARS with a safe working load of 12 tonnes to facilitate safe launching and retrieval, during a major retrofit and dry docking period from July 2005 to January 2006. These major modifications were cost-intensive, as they involved changing the generators and engines of the ship, apart from new thrusters, resulting in an extended time frame for qualification work.

The experience gained from the short duration sea trials was effective for modification and refurbishment of the underwater crawler with a new pressure-compensated hydraulic system, fins for system temperature stabilization during underwater operations, and a new data acquisition and telemetry system. The modified underwater crawler was tested during sea trials from the ORV *Sagar Kanya* to evaluate the performance of the underwater mining system for long-term operations, and to evaluate the manoeuvrability of the crawler and the position keeping of the vessel during mining operations. In order to qualify the LARS and the dynamic positioning system, a sea trial was conducted initially with a simulated dummy weight of approximately 3m<sup>3</sup>, to represent the underwater crawler.

*Figure 1: Dynamic Position (DP) System schematic and actual system on ship*



*Figure 2: Launch and Retrieval System (LARS) and DP Systems being tested using a dummy load similar to the underwater mining machine*



During testing, it was observed that position keeping could be attained with less than 2m accuracy. After testing the DP system, the dummy weight was launched using the LARS.

To summarize, the dummy weight was launched successfully to a depth of 357m (Lat.13,18.00N, Long.80,39.5E ) using the new LARS, and an additional length of 120 metres of cable and hose was reeled out to obtain an S-shaped profile. The vessel was maintained at an operational radius of 2m using DP and the performance of the Field Installable Termination Assembly (FITA), altimeter, ambient pressure transducer and other instruments was satisfactory.

### Sea tests of the developed system

After the completion of dummy trials and the satisfactory performance of the LARS and DP system, sea trials were conducted near Angria Bank off the Goa coast, to evaluate the performance of the underwater mining system for long term operations by evaluating the following:

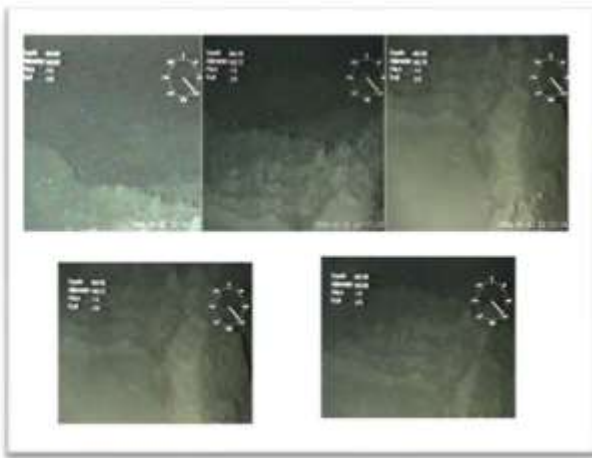
- Performance of pressure-compensated hydraulic system
- The system's temperature rise and stabilization underwater
- Performance of new data acquisition and telemetry system
- Performance of high voltage system, FITA and slip ring assembly
- Trafficability of crawler and position keeping of vessel during mining Operations
- Mining and slurry pumping operations

The mining system was launched to reach the ocean floor at a depth of 451m. The vessel was moved up to a distance of 30m in steps of 2m, towards the starboard side. The cable-hose combination was also released out about 120m to form an S-shaped profile. The system was underwater for a total of three days. Manoeuvrability tests were conducted in co-ordination with the DP system. Slurry pumping was conducted for set flow rates of 10-30m<sup>3</sup>/h. Effective co-ordination between the underwater mining system and the vessel was achieved. Station keeping was achieved within 2m radius under a sea state of 2.

Figure 3: Underwater crawler entering the splash zone at sea



Figure 4: Footprints of the crawler track viewed through an underwater camera



*Figure 5: Mining and pumping of slurry viewed through an underwater*

camera



*Figure 6: Initial pumping of clear water and collection of slurry*



During the tests, coordination between the underwater mining system and mother vessel was achieved during manoeuvring, thereby avoiding crawler dragging and associated problems faced earlier. Station keeping of the mother vessel with respect to the crawler position was achieved within 2m radius under a sea state of 2. No oscillations of the crawler were observed during the launching and retrieval operations due to the presence of LARS and DP.

Many indigenous systems, such as the ambient pressure transducer and the data acquisition and control system with its enclosure were proven, and the S-shaped profile of the cable-hose combination was obtained almost as per the theoretical analysis.

Subsequently, the underwater mining system was augmented with a larger oil filled pressure compensated sub-sea power pack and tested at a depth of 515 m off the Chennai Coast during July 2006. The new power pack can also be used for future mining systems at 6,000 m depth.



*Figure 7: Underwater crawler with new sub-sea power pack being launched*

### **Development of underwater collection and crushing system for polymetallic nodule mining**

The second phase was the development of collection and crushing systems for polymetallic nodule mining. The scope of this stage included: the development of pick up devices, underwater cleated belt conveyors and underwater crushers, the assembly intergration of

developed subsystems with an underwater mining machine; and qualification in a test pond, and finally qualification in-site created using artificial nodules at 500 m depth. The system was designed for a mining rate of a 8 tonnes/hour of wet nodules with nodule abundance of 5 to10 kg/m<sup>2</sup> at the sea floor. The manipulator in the sand mining crawler will be removed and replaced with a collector and crusher.

Artificial nodules were developed using clay and saw dust to achieve a density, hardness and texture close to that of manganese nodules.

The preliminary design of the crusher was completed and a scaled down model was constructed for experiments using charcoal and polymetallic nodules.

The collector and crusher system was evaluated for performance and qualified in-site created using artificial nodules at 500 m depth. For this, an artificial nodule laying arrangement on the ocean floor was developed with a sub-sea hopper propelled by thrusters and tested at a depth of 520m. Nodules were laid artificially with a remotely controlled nodule laying system, and a nodule field was created at the test site.



*Figure 8: Artificial nodule laying system being launched*

### **Development of soil tester for in-situ measurements of soil properties in the Central Indian Ocean Basin**

In-situ soil strength values are very useful inputs for the design of an underwater crawler for mining nodules from the soft sea floor. A tester capable of operation at 6,000m depth has been developed jointly with Sevmorgeo (Russian Federation) to measure the in-situ soil properties in the Central Indian

Ocean Basin. The soil tester system consists mainly of sub-sea systems mounted on a mechanical structure, and ship-mounted systems that are interconnected through an electro-optical umbilical cable.



The cone and vane tester provided for the measurement of bearing and shear strength of the soil. The soil tester module was successfully pressure tested and calibrated at 600bar pressure. A new winch with drum and pedestal was fabricated to handle a 7,000m long umbilical cable. The winch was qualified by a load test for 15 tonnes.

As a part of the development of the in-situ soil tester for 6,000m water depth, sea trials were conducted between 18 October and 16 November 2006. The objective of the sea trial was to deploy and test the assembly of the soil tester developed jointly with Sevmorgeo to measure and validate in-situ soil properties at different depths in the Central Indian Ocean Basin.

Experiments were conducted at different locations and depths. The cone and vane operations were performed using the application software that had been developed using LabVIEW. The sea trials were conducted in two phases: one at around 1,000m depth for the initial qualification of the system; and another at full ocean depth for final qualification of the system.

The first test was conducted off the Mangalore coast (Latitude -12° 35'.99N, Longitude-73° 56'.00E) on 25 October 2006 at a depth of 1,272m to qualify the soil tester system for its operation. Two experiments were conducted at this position by shifting the soil tester and landing it in other locations.

*Figure 9: Soil tester entering splash zone*



*Figure 10: Views of deck operations during launching*



*Figure 11: Control panel for in-situ soil tester*

A gravity coring test at 1,230m at the same two locations yielded results that were found to be comparable with the in-situ soil tester results.

The second test of the soil tester was conducted in the Central Indian Ocean Basin (Latitude  $-10^{\circ} 05'.85S$ , Longitude  $-75^{\circ} 15'.59E$ ) at 5,200m depth on 10 November 2006.

Post-test analysis and overhauling of the whole system is in progress. Because of the handling, launching and retrieval experiences in the recently concluded trials, an attempt is also being made to convert the in-situ soil tester equipment to make it more compact and light.

### **Infrastructure development for deep sea work**

Various pieces of infrastructure for the deep sea mining work are already in place. Two of the major pieces are the new technology demonstration vessel, *ORV Sagar Nidhi* and the high-pressure testing facility.

#### ***ORV Sagar Nidhi***

TDV Sagar Nidhi has been added to the fleet at NIOT. The details of the vessel are presented below.

LOA	: 104.20 m
Breadth (MLD)	: 18 m
Draft	: 4.8m
Speed	: 13.5 knots
Endurance	: 45 days

The vessel has been built to cater to the various operations connected with deep sea mining. The vessel has an A-frame with a capacity of 60 tonnes. It is a DP class 2 vessel and demonstrates accurate position keeping during trials. Its free board is used to facilitate ease of launching and retrieval.



*Figure 12: Research vessel Sagar Nidhi*

### **Hyperbaric test facility**

NIOT has established a high pressure test facility to qualify the components and sub-systems used for deep sea work. The facility has been designed to test up to a maximum pressure of 90 MPa (900 bar), which is approximately equal to 9,000m water depth. It consists of a steel cylinder with lids at the top and bottom.



*Figure 13: Hyperbaric chamber Test components can be placed inside the vessel and pressurized using a high pressure pump. A programmable logic controller is used to set parameters including set pressure and dwell time.*

The hyperbaric chamber is the first of its kind in the country. The facility can save a lot of time and money for testing underwater components before venturing into sea.

### **Remotely Operated Vehicle for 6,000 m**

Work on the development of a work class ROV has been taken up by MoES through the National Institute of Ocean Technology. The ROV is powered by thrusters for locomotion and has two manipulators for operations. It is designed for a depth of 6,000m. This would help in the

emergency maintenance assistance of the mining system. The work is in the final stages of completion, with preliminary sea trials at shallow water completed successfully.



*Figure 14: ROV being launched*

### **Other developmental activities**

Other related areas are also being developed in order to compliment the various activities of the deep sea mining work. These include analysis of the flexible riser system, and the development of sub-systems including the underwater motor, transformer and connector.

### **Cost minimization**

While many options for the development of mining sub-systems are considered, the major concern is to reduce the infrastructure cost of the systems. The cost of a flexible riser is estimated to be considerably less than that of a conventional rigid riser. However, after testing the prototype mining system at 6,000m, the cost analysis will be re-examined.

Another aspect of cost minimization is to use components that are already proven, especially in the oil and gas industries, such as subsea cables, platforms and launching systems. This would reduce the development cost and hence the overall cost of the system.

Using a hyperbaric chamber means that many of the systems can be tested and qualified before sea trials, drastically reducing costs and the waste of valuable ship time.

The main problems likely during development relate to the high cost of procuring systems as single, custom made products. The identification of partners to work in this area with common goals would be beneficial.

### **Scope for collaboration**

It is beneficial to have collaboration in order to avoid duplication of work among countries working in this area. Moreover, many of the technologies used result from research and product development aimed at the oil and gas industry. It is in the interest of all, therefore, to conduct some of the developmental work jointly. Some areas where collaboration can be explored are:

- Crawler design and testing, and seabed-crawler interaction
- Nodule collection systems
- Slurry pumping system

- Cable, hose, buoyancy system for riser
- Acoustic imaging for nodules
- Crawler navigation underwater

## **Conclusion**

This paper presents a summary of the work done in the area of technology development in the area of nodule mining. The infrastructure developed to cater to this development is also described. Various areas for possible collaboration are listed, which can be discussed during deliberations and fine-tuned.

Against this background, the Deep Sea Technology and Ocean Mining group at NIOT is continuing its journey towards the development of systems for polymetallic nodule mining in the Central Indian Ocean within the next five years.

## **Summary of discussions**

The discussion started with one participant asking Mr. Atmanand about the power lines and the hose, remarking that they must be managed very carefully and that, if one had to use multiple 14 units of such a miner, the fleet of the miner would be problematic. The partitioning of each miner would be under threat and the operation of the individual units would cause different technological problems. The participant wanted to know what the authors thought about such a complex operational concept of a multiple miner fleet for mining on a commercial scale, not for testing.

Mr. Atmanand replied that the point was that the system existed because the current in the depths was almost nil and therefore the effect of current on it would be less. Nevertheless, at the top layers, at a few hundred metres, due to the motion of the crawlers, there would definitely be some forces when the analysis was being done. On the next part of the question of having this multiple machine concept, the multiple machines would not be operating in exactly one area; one could see that if one put them on one mother station there would be various multiple stations at different areas under its control. He said that when they had started 11 years ago, some of the systems were not as sophisticated as what they had now. Later on, there would be much more sophisticated systems to locate the flexible risers, etc., so entanglement could be prevented and each would be able to work independently. It was known that all these developments were taken from the oil and gas industry because they were driven by the actual commercial requirements compared to that mining system. One got more sophisticated position control systems, and riser control systems of the order of even few centimetres' accuracy was available nowadays.

A participant with a background in the oil industry said that when there were so many flexible risers they may come into contact with each other. He made the following two points: with a flexible pipe, the construction was a series of polymer layers through the cross section. So generally speaking, when the contact was because of current load to where they were going to flow together and they would make initial contact, there would not be this banging effect because it was due to current and not wave. Generally speaking, that was acceptable for the flexible pipe. One would not want to have clashing between steel pipes, for example, but for flexible it could be tolerated because of the construction having polymer layers. The other point was that if it was going to be in a severe environment where there was clashing, such as in the North Sea, for example, a reference gas project

for you would be the “Troll” project. On that system, there were 40 flexible risers coming out; it was a buoyed system. The bottom looked like what Mr. Atmanand was demonstrating, but instead of distributed buoyancy per flexible pipe, there was a tank to which the flexible pipe was clamped, so as to keep the pipe moving together with fixed spacing between each pipe.

Mr. Atmanand clarified that the reason for choosing the flexible riser system was that the crawler was already working and it was easily done. It was easily multiplied without increasing in size. The mother ship requirements were much less compared to what the riser required. The investment on the mother ship was much less and so were the risks. With the increase in the cost of material, even less than a million tons per year would be viable. In his opinion, the time taken to realize the system would be less, with less investment and less risk.

A participant asked how many crawlers were going to be put on a vessel, whether the number was about 40 crawlers deployed or 5 crawlers per vessel, and what the density was going to be. The participant also said that with the amount of material that was being recovered, the vessel size and crawler management systems were starting to get fairly large. He said it was difficult to reduce the size of the ship if the numbers were what was being claimed. Mr. Atmanand clarified that not all the crawlers would be launched simultaneously. They would be added one by one. It was expected that, with the increase of the capacity of the crawler, something like 20 crawlers may be needed. All may not be launched simultaneously; the risks were less.

A participant wanted clarification on the things bundled together with the flexible riser. He wanted to know whether the recovery system was tied together with the hose itself. Mr. Atmanand replied in the affirmative, saying that at present, cable and hose were being done independently. It was difficult connecting them and that was why a 6,000-metre hose, such as that used in the oil and gas industry, was being considered. That would be put together as one entity. At that stage, all would be in one bundle.

Another participant asked if, when using the flexible hose, the flexible riser became twisted due to the manoeuvring of the miner on the seafloor or turning behaviour; and how the problem could be solved. Mr. Atmanand replied that the flexible riser must be wound on the drum; with the current system, it was wound on a drum and launched. It could get twisted, but when the pump was working, the twists got normalized because it was flexible; it became untwisted and then the slurry got pumped. It was something that had to be looked at and that was why a test had been set up for the hydraulic transport facility. He provided further clarification saying that their test was being done with sand slurry. Mr. Atmanand also clarified that the profile of the flexible hose was S-shaped and that the distribution of weights was regulated so that when the crawler was moving, only the vertical portion of the hose that was attached to the crawler would move. The main hose would not really move. He added that there was a separate group of his colleagues that working to find the actual trajectory of the flexible hose under water in the deep sea.

A participant wanted clarification with regard to the size of the crushed nodules. Mr. Atmanand said it would be a maximum of 15 mm.

A participant noted that the continuous transportation of the nodules without any intermediate storage station would be problematic because the mining rate was not constant; it fluctuated. The concentration variation in the pipeline might cause pipe clogging and the reduction of pumping efficiency. This might be a serious transportation problem without any intermediate control unit such as a buffer system. The author agreed and said that experiments were being conducted to determine

whether a buffer was necessary.

The final question was about the expected efficiency and life expectancy of the equipment. Mr. Atmanand replied that that part had not yet been worked out and that a mining prototype would first have to be developed before those details could be worked out.

### **Acknowledgements**

The authors acknowledge the work done by all the members of the project team, especially the senior members, C. R. Deepak, Muthukrishna Babu and N. R. Ramesh.

Owing to the absence of the audio portion of this presentation, no summary is available for this presentation.

## CHAPTER 6

### Sea Nodule Processing Status Review for Commercialization

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#### Introduction

Polymetallic nodules represent the largest metal-bearing seabed deposits. The exploitation of nodules has assumed importance because of the potential for metal production. Economic evaluation of projects related to multi-metal extraction of copper, nickel, cobalt and manganese from deep sea nodules, however, has often failed to provide enough incentive to prospective industrial investors for pre-investment planning because of several issues, such as the high direct costs of metal extraction from sea resources in which mining and transportation costs feature predominantly, compared with the cost of terrestrial mining and transportation of ores. Extracting resources from the sea requires the mobilization of substantial capital, which does not yield returns commensurate with the risks involved. From the investor's side, a polymetallic nodules processing project needs to be evaluated not only from an absolute standpoint, but also from the standpoint of environmental acceptability and sustainability. In other words, the various processing options need to be technologically acceptable from the point of view of current perspectives on strategies of metal production from terrestrial resources.

On the other hand, high prevailing metal process (specifically for nickel) require a re-evaluation of potential returns and a careful comparison with the prevailing options of exploiting similar terrestrial deposits, such as laterites. Moreover, the specific characteristic of nodule deposits that maintain a constant metal concentration (unlike terrestrial resources, which require further evaluation as the ores are exploited and the deposit gets depleted) would be an important factor in the potential commercialization of seafloor deposits.

The Indian work programme on technology development for metal extraction from seafloor deposits has operated since the early 1990s, with the active support of the Indian Ministry of Earth Sciences. The present technology development programme is driven by the goal of reaching a technology level suitable for commercialization and it has reached the stage of pilot demonstration. The current status of this work is summarized below.

#### Processing options and development thrust

The Indian efforts have been driven by the necessity of generating large scale data to enable the engineering goal of process scale-up and flow sheet design for implementation. The papers by Agarwal (1976) and Shridhar (1976) were two of the first attempts to provide a basis for the technical evaluation of projects related to large scale multi-metal extraction of copper, nickel, cobalt and manganese from deep sea polymetallic nodules based on generated data. The focus was clearly on flow sheet development for technology evaluation. The present Indian programme has attained a level from which engineering flow sheet development work can commence.

Current global efforts, however, are not directed towards flow sheet development and subsequent testing for commercial viability. A review of the relevant literature indicates that the present thrust is more towards finding alternative reagents that could enhance the performance of conventional reagents. This includes the study of potentially novel reagents for polymetallic nodules such as those



reviewed by Mukherjee et al. (2004). Zhang et al. (2001) have described the use of specific aromatic reductants in sulphuric acid mediums during laboratory scale studies. Whereas such studies were directed at improving the performance of sulphuric acid leaching, the results have scarcely been analysed from the point of view of flow sheet development. In contrast with current approaches, earlier consortia studies were directed primarily towards developing flow sheets; a number of sponsored research programmes considering sulphuric acid leaching system development under high pressure were undertaken by universities (Han, 1975; Ulrich, 1973; Hubred, 1973) to aid flow sheet development.

It is not possible to use purely pyrometallurgical techniques to produce separate metallic products from metal content. Pyrometallurgical processes have been used either as a pretreatment step to enhance the solubilization of metallic values, or as a first step in reducing the quantity of material to be solubilized during the subsequent step. Metal solubilization without pretreatment of the nodules may also constitute the first step of metal recovery. Subsequently, the solution is processed further to yield the metals/alloys at the desired specifications. Pyrometallurgical processing steps have been considered to be energy-intensive. Totally hydrometallurgical process options, however, need to be reviewed with respect to reagent and environmental burden costs, since such processes are typically reagent-intensive and generate effluent that must be treated. Alternatively, reagents can be recycled, which would increase energy costs that could then be comparable to those associated with pyrometallurgical processes.

Under the Indian programme, three process development approaches have been extensively tested: (a) a direct leaching process in an ammoniacal medium with dissolved sulphur-dioxide as aqueous reducing agent; (b) a combined pyrometallurgical process of reduction roasting and ammoniacal leaching; and (c) high temperature reductive acid leaching. The technology development status of each of these processes is briefly described below.

## **Status of technology development**

### ***Hydrometallurgical processing: ammoniacal route***

The hydrometallurgical process option is based on reductive leaching of nodules using sulphur dioxide as a reducing agent in the presence of ammonia and ammonium sulphate. Copper was first separated by solvent extraction from leach solution and copper metal was electrowon. Subsequently, a cobalt-nickel bulk sulphide was precipitated from the solution after recovery of copper. This bulk sulphate cake could be readily leached in an aqueous acidic medium under moderate oxygen pressure to generate a concentrated cobalt-nickel bearing solution. Subsequently, a solvent extraction scheme was developed for separation of cobalt and nickel, followed by further recovery of individual metals by standard steps such as electrowinning.

Under the aegis of the Indian Ministry of Earth Sciences, a pilot plant capable of treating 500 kg per day of polymetallic nodules was designed to test the hydrometallurgical option. An Indian engineering company conducted the scale up, basic engineering design and implementation of the pilot plant, based on the developed laboratory process. An industrial metal production unit was the nodal agency for the operation of the plant. Process route developers and the engineering contractors were to jointly provide technical support for data collection and analysis during the pilot operation.

The broad objectives for the operation of the pilot plant were:

- Carry out process demonstration campaigns at 500 kg per day of nodules to revalidate the laboratory scale process package.
- Enhance the process technology through further laboratory scale experiments and modification of the pilot circuit configuration, if required.

The data generated were categorized under various 'Process Demonstration Campaigns', which were regularly analyzed. Several campaigns were undertaken with the participation of all of the process developers and the engineering consultants between 2002 and 2006.

Initially, wide variation was observed between solid-based leaching efficiency. Re-dissolution of nickel after sulphide precipitation and substantial loss of fine sulphide particles during nickel-cobalt bulk sulphide filtration were identified as key problem areas. Data analysis also revealed that second stage leaching contributed very little towards improvement in overall leaching efficiency. Modifications were made in the flow sheet to carry out leaching in a single stage instead of two stages. Accordingly, modifications were carried out at the pilot plant to bypass gravity settler and second stage leaching.

Plant modifications resulted in simplified operation and reduced batch operating time without the loss seen in metal recovery. Some of the technological improvements and parameter changes were:

- Leach reaction time enhanced from 2 to 2.5 hours.
- Two-stage washing introduced for leach residue.
- Fresh water replaced by hot raffinate for leach residue washing.
- Demanganization reaction pressure increased from 3.5 to 4.5 kg/cm<sup>2</sup>(g) to reduce reaction time.
- Copper solvent extraction circuit water dilution discontinued, and
- Existing bulk sulphide filter cloth replaced to arrest losses of fine particles.

Metal recovery in the leach solution reached: 86 per cent for copper; 92 per cent for nickel; and 80 per cent for cobalt. These rates exceeded the design values.

Leaching of nodules at higher pulp density (15 per cent against 10 per cent in earlier campaigns) was conducted at the pilot plant using a different set of jointly developed process parameters. Several batches at 390 kg nodule batch were processed as per an adopted modified flow sheet.

The following process improvements were noted during the pilot campaigns:

- Increased throughput of nodules during leaching without loss in the leaching efficiency of copper, nickel and cobalt.
- Leach solution containing 1.5 gpl of copper could be used directly for solvent extraction without dilution with water after making necessary parameter changes, and
- Flocculant (proprietary) was added to the slurry for faster settling of solids after bulk sulphide precipitation reaction. This reduced the filtration time and loss of solids during filtration.

It was noted that the design recovery values were also attained at the higher pulp density of leaching. Regarding chemical consumption, the design values were closely reproduced for all chemicals except for  $\text{NH}_3$ ; it was felt that at the scale of operation of the pilot plant, complete recovery of  $\text{NH}_3$  was not possible. Losses identified pertain to autoclave vents, filtration systems and vapour losses at various stages of handling the rich ammonia solution. Only the recovered  $\text{NH}_3$  is being re-circulated and hence the fresh ammonia additions were relatively higher.

### ***Pyrometallurgical pretreatment and leaching***

Pyrometallurgical processing options have been examined as a requisite pretreatment step for the nodules. Reduction roasting using LD oil followed by ammoniacal ammonium carbonate leaching and solvent extraction had earlier yielded high nickel and copper recovery, but low cobalt recovery during the leaching step. It was observed from kinetic studies that cobalt was cemented out when copper dissolution commenced. The practice of two-stage leaching was adopted. The first stage (Leach-I) led to dissolution of, principally, cobalt. The second stage (Leach-II), which was of longer duration, was used to dissolve mainly copper and nickel. It was observed that in the leaching of higher grade nodules containing more copper, cobalt recovery decreased in the specified leaching time (1 hour). Therefore, merely fixing a certain time at the Leach-I stage did not work with the various grades of nodule. To overcome this problem, the concept of 'Redox Potential' monitoring was applied to the Leach-I stage. The leaching was terminated at a certain redox potential (-266 mV) rather than at a specific time. This resulted in higher cobalt recovery irrespective of nodule grade. Later on, a microprocessor-based redox potential monitoring system was introduced during Leach-I to automatically control the leaching.

In spite of introducing the microprocessor-based redox potential monitoring system at the Leach-I stage, cobalt recovery could not be improved beyond 60 per cent. In order to find the reason for low cobalt extraction, the interaction between cobalt and other metals present in the roast-reduced nodules (copper, nickel, iron and manganese) during leaching was examined. Leaching of pure metal powders individually and in combination was carried out for this purpose. Results suggested that iron and manganese had the most detrimental effects on cobalt recovery, as cobalt was adsorbed on the iron and manganese precipitates during leaching. The problem was overcome using a low cost additive at the leaching step, and cobalt recovery increased to 80 per cent. The role of the additive was its preferential adsorption on iron and manganese precipitates, sparing cobalt for the same. Currently, validation of the results at higher scale of operation (500 kg/day) is being planned.

### ***Reductive acid leaching***

Besides carrying out the operation of the pilot plant as mandated by the Ministry, the industry participant also developed a laboratory process based on reductive acid leaching. Large scale studies pertaining to demonstration of this process route were planned with partial use of the downstream facilities of the pilot plant.

Around 16 metric tonnes of nodules were subjected to a two-stage reductive sulphuric acid leaching route. The typical operating parameters were:

Parameters	20 % Nodule
Reaction time (hr)	Up to 4
Reaction temperature (°C)	92 - 95
H <sub>2</sub> SO <sub>4</sub> (gpl) (2 <sup>nd</sup> stage)	Maximum 150
Reductant (g/g)	Variable
Amm Sulphate (g/g)	Up to 0.15
Acid concs. (g/g)	0.72

Liquid basis recoveries were:

Nodule (Wt%)	Liquid basis (%)			
	<i>Copper</i>	<i>Nickel</i>	<i>Cobalt</i>	<i>Manganese</i>
20	95.6	98.9	96.8	96.67

A copper-nickel-cobalt bulk sulphide cake was precipitated from the leach solution and dissolved at 110°C in an autoclave at a system pressure of 8 kg/cm<sup>2</sup> using oxygen gas. A typical analysis of recoverable metal values in this solution is: 10.2 gpl for copper; 12.0 gpl for nickel; and 1.5 gpl for cobalt. The solution was subjected to solvent extraction separation. The process route developed and tested provides an alternative approach to metal recovery, including of manganese.

### ***Residue treatment***

Large scale trials were conducted to formulate a suitable residue treatment process for the recovery of manganese from the generated leach residue at the pilot plant after ammoniacal leaching of the nodules. This activity required generation of sufficient quantities of residue at the pilot plant to enable the development of a residue treatment process. The pilot plant, therefore, also served as a residue generation unit.

The residue after ammoniacal leaching contains mainly manganese (22 per cent), iron (9 per cent) and silicon (8 per cent). It was envisaged that an electro-thermal smelting route to recover manganese in the form of an iron-silicon-manganese alloy could be obtained. However, the manganese/iron ratio required in the raw material for the production of standard grade iron-silicon-manganese is at least 3:1, whereas in the leach residue, it is around 2.4:1. One option was to blend the residue with high grade manganese ore or iron-manganese slag, which were not easily available and involved extra cost. To overcome this problem, a two-stage smelting process without any external ore/slag blending was developed. In the first stage of smelting, the leach residue was mixed with a small amount of coke for selective reduction of iron only and quartz (flux) for the formation of a manganese-rich slag. Subsequently, an iron-rich alloy was tapped out and a manganese-rich slag, now with a favourable manganese/iron ratio, was subjected to reduction. To this hot, manganese-rich slag, extra coke was added with lime as flux in a second stage smelting step to produce standard grade iron-silicon-manganese. The iron-rich alloy obtained after the first stage, which contained a small amount of manganese was found to have properties of improved cast iron, which might be used for specialized applications. Large scale (300 kg dry residue) smelting trials were conducted using untreated residue, which showed that manganese recovery up to 75 per cent could be obtained in the silicomanganese alloy. A modified smelting process has now demonstrated that manganese recovery up to 80 per cent is attainable with smaller scale smelting; larger scale trials have been planned to validate the results obtained.

### ***Solution treatment***

A major part of the Indian technological development efforts on solution treatment concerned the development of an effective scheme to separate cobalt from nickel from the pregnant leach solution generated after acid leaching of bulk cobalt-nickel sulphides. Because of the control difficulties experienced in the multistage extraction operation involving several scrubbing stages, a 3-4 per cent loss of nickel values was noted during solution separation, which at times would go up. An improved process flow sheet for separation of cobalt from cobalt-nickel sulphate solution has been developed on similar lines in the existing Indian demonstration plant. The flow sheet has recently been tested in a continuous scale pilot plant run conducted during August 2006. The cobalt is upgraded and separated from nickel by extraction with CYANEX 272 using a modified solvent extraction process. Cobalt recovery in excess of 99 per cent is achieved at the pilot plant and a concentrated cobalt electrolyte suitable for the electro-winning of high purity cathode has been produced. The initial bench scale work was conducted with small apparatus (a shake flask). Following the successful completion of these tests, when the best conditions for the system were established, small scale continuous operations were also conducted in mini mixer-settlers. Finally the data was validated and optimized in a continuous operation in large mixer-settlers available in the pilot plant. Mixer-settler units, each with a mixer volume of 10 litres and a settler volume of 40 litres, were operated in a counter current configuration. A solvent extraction circuit was operated continuously for about 80 hours and treated approximately 3,000 litres of cobalt-nickel sulphate solution. The diluent of choice for cobalt-nickel solvent extraction plants is either 100 per cent aliphatic or slightly aromatic (less than 20 per cent). The reason for this choice is because aliphatic or slightly aromatic diluents are much more resistant to diluents oxidation than are 100 aromatic diluents. The extractant concentration required to extract a metal at a phase ration will depend essentially on the metal concentration in the aqueous feed solution. A typical composition of the feed solution to the cobalt circuit is:

pH 6.0, Cu – 35.7 ppm; Ni – 11.0 gpl; Co – 1.2 gpl; Mn – 81.9 ppm; Fe – 2.0 ppm; Zn – 27.4 ppm; SO<sub>4</sub> - 38.95 (total) gpl.

Typical process performance with extraction, scrubbing and stripping stages is given below. A series parallel system of stripping was used to minimize extractant loss.

<b>Process performance (%)</b>		
	<b>Cobalt</b>	<b>Nickel</b>
Extraction	99.43	0.09
Scrubbing	0.10	55.3
Stripping	99.75	77.6

### ***Observations on solution treatment***

The solution treatment portion of the flow sheet constitutes a major factor in the establishment of the technical viability of nodule processing. Unfortunately, present efforts in nodule processing seem to concentrate on upstream processes rather than looking into the aspects of final metal recovery establishment. The various larger scale studies taken up during the mid-1970s and early 1980s have all placed due weight on the solution recovery aspect, as is evident from the types of patents assigned to the companies concerned. It is necessary to update the flow sheets specifically for solution treatment since there is no clear cut analogy with land-based operations.

### **Comments on pilot activities**

The costing studies become more realistic when engineering flow diagrams are prepared. The various options that have been tested at larger scale form the basis of engineering flow diagrams along with preliminary equipment specifications. Examples have been detailed in USBM reports (Haynes, 1982 and 1985). The updated flow sheets presented by USBM are excellent examples of the starting point from which to undertake order of magnitude cost estimates based on flow sheets established after large scale testing.

It is interesting to note that various updated flow sheets presented by USBM reflect preferred versions of five processes as perceived by the authors (gas reduction/ammoniacal leach; Cuprion; high temperature sulphuric acid leach; reduction/hydrochloric acid leach; smelting/sulphuric acid leach). These versions, however, may not represent the optimal flow sheet alternatives based on present technological advances. For example, subsequent to gas reduction and ammoniacal leaching, the solution may be stripped of ammonia and then the concentrate leached in hydrochloric acid medium to effect metal separation through solvent extraction. Separation of metal chlorides using solvent extraction has been implemented in a number of commercial plants. Only the front-end operations resemble the 'Caron Process' for laterite ore processing. Whereas sulphuric acid pressure leach operation with nodules may be similar to Moa Bay laterite leach operation, variants already exist with regard to the lower temperature of leaching under pressure and dissolution of manganese in leach solution. Major variations are possible regarding the processing of sulphate solutions similar to matte leaching solution processing. It is worth referring to industrial practices being followed by Outokumpu-OY, Sumitomo and Nippon Mining Corporation.

Large scale data to inform preferred flow sheet versions for the preparation of engineering flow diagrams have scarcely been reported. Earlier work by various consortia partners and companies led to the piloting of certain key steps in the processing operation. Pilot operations have been run for limited periods and there are no references to suggest that these have been sustained. Only the processes studied by Kennecott Copper Corporation (KCC) and Deep Sea Ventures (DSV) were carried out to the end phase, along with aspects such as reagent recycling (Table 1). No pilot plant activities were reported during 1980 other than at the CEA plant (AFERNOD). Active research on nodule processing is presently being pursued in some Indian, Chinese, Japanese and Korean firms and laboratories. However, large scale testing information has scarcely been reported.

*Table 1: Status of pilot activities (reported)*

<b>Company name</b>	<b>KCC</b>	<b>D</b>	<b>INCO</b>	<b>Elkem</b>	<b>IFREMER</b>
Pilot capacity	½ TDP (Lexington) 350 kg/day	1 TDP (Virginia)	Unknown	Tensedé	120 kg/day (Fontenay-aux-roses, CEA)
All steps continuously tested	Yes	Yes	No	No	Yes
Further scale up	No	Planned 40 TPD, did not	No	No	No
Technological difficulties in pilot	No	No, but costly operation			Solvent extractions subsequently rectified

## Economic Evaluation of Sea Nodule Extraction Processes

### *Indicative cost of sea nodule processing*

Efforts have been initiated in India to assess the indicative costs of nodule processing.

Several studies have been reported globally in the past on the techno-economics of exploitation of seabed nodule resources. The average contents of recoverable metal for techno-economic studies have reported area-specific values and show substantial variation with respect to manganese and cobalt nodule content. At the higher end, typical composition of recoverable metal has been reported as 6 per cent (iron); 30 per cent (manganese); 1.37 per cent (nickel); 1.25 per cent (copper); and 0.25 per cent (cobalt) for computing the techno-economics.

The capital and operating costs of mining, transportation and processing have been reported in the literature for different process routes and different dry nodule processing capacities. The earliest compilation was by Nyhart (1983). Subsequently, different authors have provided estimates of internal rates of return pertaining to different processes. The process routes followed after mining include: ammoniacal leaching; reduction and hydrochloric acid leaching; smelting followed by leaching; and high temperature sulphuric acid leaching. Estimates of total adjusted capital cost/ton (2004 US\$ values) are reported in Table 2.

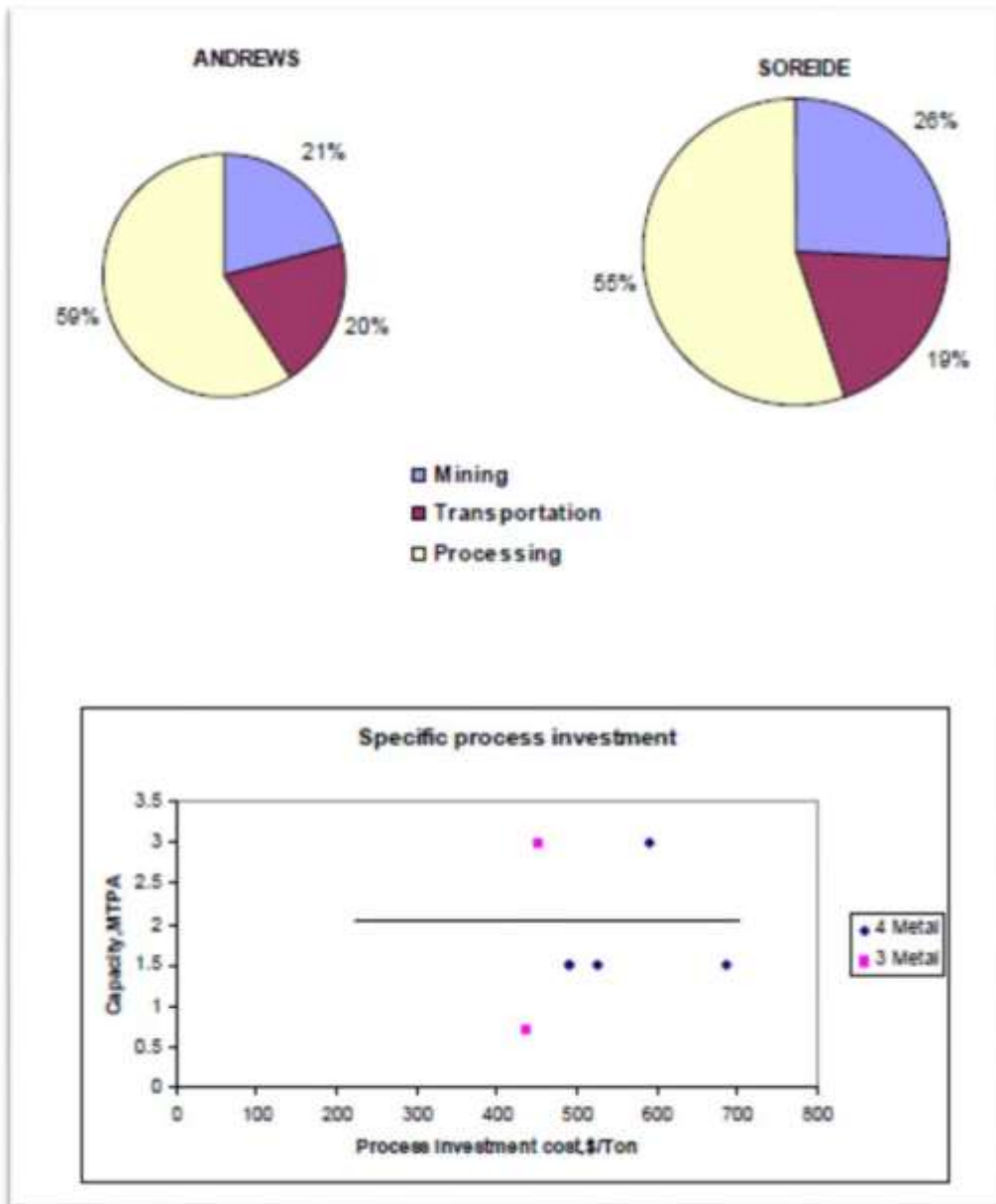
*Table 2: Adjusted capital cost (US\$ 2004 per ton)*

Reference	Year	Adjusted mining cost	Adjusted transportation cost	Adjusted processing cost	Adjusted project cost	No. of metals, capacity MTPA
Andrews	1983	241.20	235.17	687.42	1163.79	4 metal, 1.5
Lenoble	1990	276.32	211.95	489.84	978.11	Do
Lenoble	1990	276.32	211.95	525.95	1014.22	Do
Charles	1990	295.16	196.25	491.41	982.82	Do
Ham	1994	130.95	91.80	591.30	814.05	4 metal, 3.0
Hillman	1985	368.39	192.61	452.54	1013.54	3 metal, 3.0
Soreide*	2001	204.53	150.29	437.31	792.13	3 metal, 0.7

\* The study by Soreide (2001) is for manganese nodule-like material rich in cobalt.

Figure 1 demonstrates the importance of process investment costs based on data provided (Lenoble, 1990; Soreide et al, 2001; Ham, 1997; Andrews, 1983; Hillman, 1985). The figure also shows escalated specific processing sector investment costs in dollars/annual ton for three metal and four metal recovery processes, which show scale dependence. Corresponding specific investment for the total project (dollars/annual ton, escalated) can be read from Table 2. For 1.5 million tons per annum (MTPA), a range of specific investment for processing is exhibited for the same capacity of processing for recovery of four metals. Limited data is available for 3 MTPA of processing and recovery of four metals. Specific investment for recovery of three metals shows some variation with respect to capacity. The lower specific cost for the data provided by Soreide et al (2001) is in part due to the different raw material (cobalt-bearing crust). Insufficient data is available to group the specific investments per technology and capacity ranges.

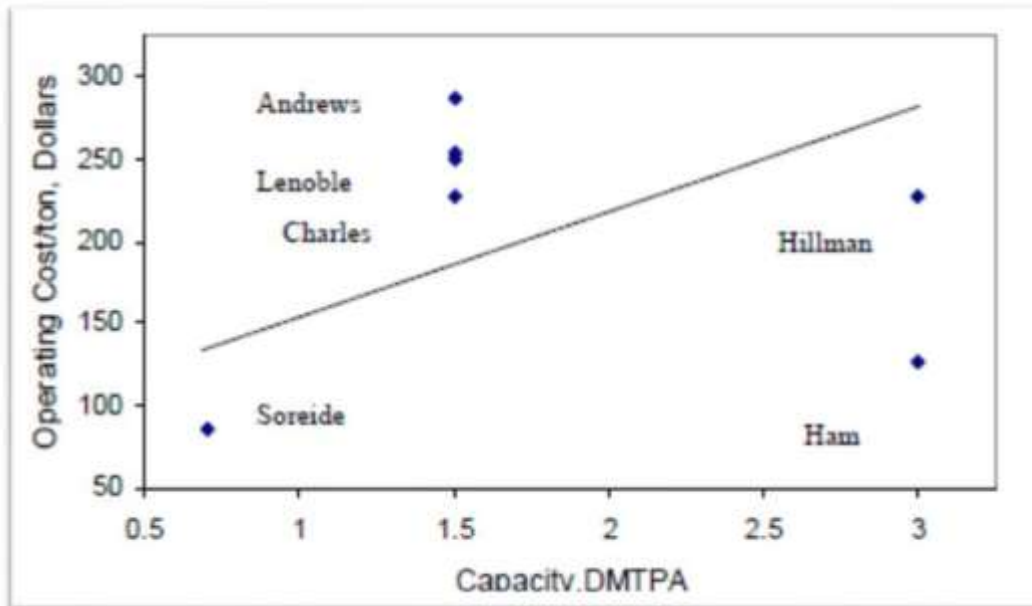
Figure 1: Process investment costs and their importance in overall investment cost



Available data (Lenoble, 1990; Soreide et al, 2001; Ham, 1997; Andrews, 1983; Hillman, 1985) on specific operating costs (escalated with CPI 2004) is plotted as a function of plant capacity in Figure 2. The lower data points represent specific costs for three metal plants. The relative dependence of specific costs on plant capacity is complex since diverse process technologies have been used to extract the metals. The operating costs reported by Ham appear to be on the low side (Ham, 1997). Considering that specific operating costs for diverse technologies at identical processing capacities fall within a range, it does appear that technology choices need to be made with respect to lowest specific operating costs.



*Figure 2: Specific operating costs*



### ***Comparison with laterite processing***

To bring an economic focus to technology development efforts, Indian development partners have felt the need to compare indicative capital and operating costs with land-based laterite ore processing, because of the similarities in the processing approaches being followed. The focus of earlier global techno-economic studies had also been to draw up comparative estimates of metal processing from nodules vis-à-vis terrestrial laterite resources. Earlier indications (for example, Kleppe et al. 1976) concluded that the cost of processing terrestrial ores is similar.

It is useful to review such conclusions in view of the high capital cost of metal extraction from sea resources in which mining and transportation costs feature predominantly, compared to the cost of terrestrial mining and transportation of ores for a given scale of operation. Comparing the specific investments for laterite ore and seafloor nodules enables us to understand the barriers to the mobilization of substantial capital, preventing returns commensurate with the risk involved etc. Typical specific laterite processing costs (in terms of US\$ per kg nickel produced) and nodule processing are given below. The laterite data were reported by Dalvi et al (2004). For nodules, two types of generic processes may be considered: a roast reduction ammoniacal leach process adapted for nodules is one of the earliest endeavors and is similar to the Caron Process for laterites (Nyhart, 1983); and direct hydrometallurgical treatment of nodules such as that reported by Lenoble (1990). In the case of nodules, it is appropriate to report capital expenditure in units of nickel equivalent; the recovered tonnage of nickel, cobalt, copper (for a three metal recovery process) and manganese (for a four metal recovery process) are multiplied by the price ratio of the recovered metal and nickel to obtain the nickel equivalents.

The capital costs reported for nodule processing include mining and transportation. The metal production capacity corresponds to 3.0/1.5 DMTPA per annum of nodule mining with specific grade and recovery values cited in the references. The costs were updated to 2004 US dollars using CPI values. The capacity chosen approximates that of annual nickel production capacity as reported by Dalvi (2004).

For nickel production from laterites, the costs reported include the surface mining of laterite deposits. The estimated specific costs are reported below.

Laterites		Nodules	
Grade, % nickel	CAPEX charges \$/annual kg nickel	Grade	CAPEX charges \$/annual kg of nickel equivalent
2.5	20-24	Ni-1.29, Cu-1.09, Co-0.25, 3 metal	40.6
2.0	24-28	-	
1.7 or lower	30	Ni-1.33, Cu-1.03, Co-0.26, Mn-26.8, 4 metal	28.6

It is immediately apparent from the table above that a three metal recovery nodule processing venture is unlikely to compare with a land-based laterite processing option unless the grades are markedly high or there is a more favourable metal price ratio with respect to nickel. On the other hand, the manganese recovery option provides a better basis of comparison with laterites.

Following a similar procedure, an estimation of specific operating costs for a nodule processing venture shows higher specific operating cost (\$8/kg of nickel equivalent without considering capital charges, based on Ingham (1985) and Nyhart (1983), compared to land-based laterite plant operation (\$4-\$5/kg of nickel equivalent). The data provided by Lenoble (1990) yields approximately \$6/kg of nickel equivalent because of a good manganese recovery rate. Once the capital charges are taken into account, it appears that a higher nickel price can justify a nodule venture in comparison with laterite processing.

### ***Cost simulation model***

A simplified cost simulation model was constructed to assess the techno-economics of the Indian processes. The resulting predictions were compared with published models, principally to assess the applicability of the proposed model for preliminary assessment. Mining costs have been assumed to be identical to reported values. Improvements in mining technology leading to a different cost structure have not been considered in this paper.

The cost simulation model proposed in this paper treats nodule processing as a primary nickel producing operation with by-product recovery of copper, cobalt and manganese. The major advantage of this is to draw a direct comparison with land-based nickel laterite operations and to highlight the importance of recovering other revenue-bearing products.

For a given payout period (POP) for the entire operation of exploitation of the resources, including mining and transportation, the estimated nickel price ( $E_{Ni}$ , \$/kg, before tax), profit after tax (PAT) and net present value (NPV) are expressed as:

$$E_{Ni} = C_{opmin.} + C_{opmetal} - \sum_{i=1}^{i=N} P_i * R_i + C_{capexmin} / POP + C_{capexmetal} / POP$$

$$PAT = (E_{Ni} + \sum_{i=1}^{i=N} P_i * R_i - C_{opmin.} - C_{opmetal}) * Ni(kg / yr) * (1 - Trate)$$

$$NPV = PAT * \frac{(1+i)^N - 1}{i(1+i)^N} - INV$$

Where:

$C_{opmin}$ ,  $C_{opmetal}$  and  $C_{apex}$  = the operating costs for mining and metallurgical processing in \$/kg nickel.  $C_{capex}$  = the capital cost of mining and transportation (converted to \$/annual kg nickel based on POP).  $C_{capexmetal}$  = the capital costs of processing (converted to \$/annual kg nickel based on POP).

Trate = the prevailing tax rate. I = the required interest rate.

N = the lifetime of the investment. INV = the total capital investment.

Using the above model and data available in the references cited in the table, the internal rates of return (IRR) were computed for NPV=0, and the computed values were compared with the literature values provided below.

Reference	Hillman (1985)	Andrews (1983)	Charles (1990)	Lenoble (1990)	Lenoble (1990)	Ham (1996)	Soreide (2010)
IRR (%)	7.4	6.4	12.0	15.4	15.7	11.93	9.6
Capacity (DMTPA)	3.0, three metal	1.5, four metal	1.5, four metal	1.5, four metal	1.5, four metal	3.0, four metal	0.7, three metal
Process route	Cuprion	Reduction smelting and Cuprion processes	Reduction HCl leach	Sulphuric acid leach	Smelt reduction	Reduction roast ammon. leach	Sulphuric acid Pr. leach

The predicted values of IRR (pre-tax/post-tax as reported) show good agreement with reported values (Figure 3). This is true over the entire capacity range of processing and for a variety of process routes.

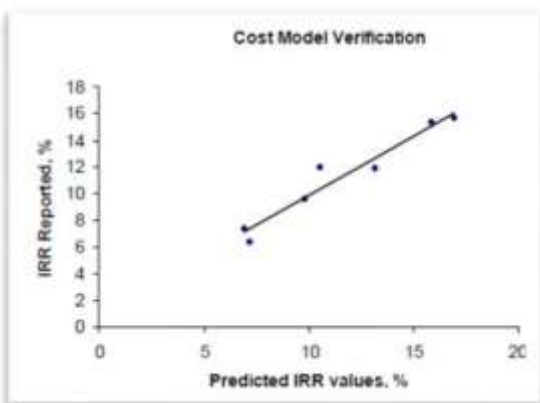


Figure 3: Predicted vs. reported IRR values

#### Indicative costs for Indian process

Preliminary cost estimates (capital and operating) have been initiated by the Indian development team based on the large scale data collected. The order of magnitude of capital costs are of the same order as the enhanced index Lenoble (1990) base case; using higher metal prices (Ni- \$12/kg; Co- \$30/kg; Cu- \$6/kg; Mn- \$0.98/kg), the ROI is 11.88 per cent. However, the revenues are grade sensitive.

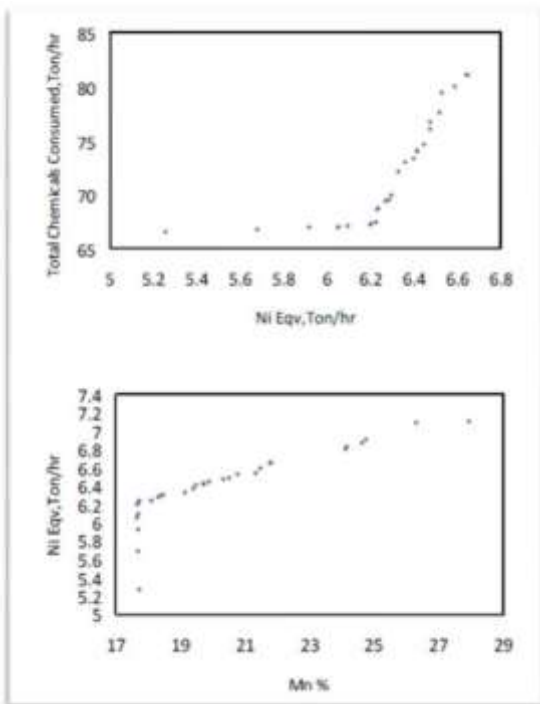
A drop in manganese grade to 24 per cent (compared to the Lenoble base case of 30 per cent) at the range recovery rates reported reduces the ROI to 10.12 per cent, with a corresponding IRR of 8.9 per cent. Clearly, this scenario would attract less potential investment.

It appears that: (a) a reduction in operating cost at the process plant is necessary through the adoption of improvement measures or different process technology. This may also be possible if the number of value added products can be increased to bring about a favourable impact on nickel equivalent; and (b) a reduction in capital cost for the nodule venture needs to be explored. This may be possible if a lower throughput is chosen while maintaining acceptable returns on investment. It is necessary to work out specific research themes, which would reduce the operation/investment costs.

The directional changes to the profitability of a nodule venture were predicted using our simplified cost model; the impact of changes using base data leads to quantification of the results. The cost estimates used in Lenoble’s paper (in 1988 \$) have been chosen for this paper as data for our base case.

**Process recovery and nodule grade**

A sensitivity analysis of the Lenoble case for H<sub>2</sub>SO<sub>4</sub> leaching was carried out to ascertain the effect of change in recovery values from the base case values shown in parentheses. The values chosen for simulation are: Ni- 90 per cent (96); Co- 85 per cent (94); Cu- 90 per cent (95); and Mn- 80 per cent (85). The ROI values dropped to 16.97 per cent, as against 18.95 per cent in the enhanced base case with higher metal prices. The Indian case return is more sensitive to a drop in recovery rates, presumably because of the lower grade of nodules used for this estimate; the return drops to 10 per cent when the process recovery rates for nickel, copper, cobalt and manganese are 90 per cent, 86 per cent, 82 per cent and 75 per cent, respectively.



*Figure 4: Effect of nodule manganese grade on Pareto-optimal solution*

The effect of nodule grade vis-à-vis the nickel equivalent was taken up for optimization analysis leading to Pareto-optimal solutions. Typical data are reported in Figure 4 (Biswas et al, 2008). The data pertains to the ammoniacal SO<sub>2</sub> reduction route. Optimization was carried out to minimize chemical consumption and maximize nickel equivalent over a wide range of possible grade variations. The effect of manganese grade is also shown in Figure 4, which suggests that restricting chemical consumption and maximizing nickel equivalent requires the restriction of manganese grade to around 18 per cent.

## **Metal prices**

In the case of nickel, the lack of new sizeable sulphide ores, and the need to move to greater use of nickel laterite ores (where processing is more difficult and expensive, and currently problematic in some cases), may tend to increase the cost of nickel because of the shift in resource base. For other metals, the prospect that major new developments will be in remote areas and require significant new infrastructure investment is also seen as likely to increase costs. The commencement and sustainability of major new developments may require higher prices than the average over the 1990-2004 period to be in place. This may lead to more profitable nodule ventures in future.

It is supposed that the rising trend in metal prices, which is expected to continue to some extent (although it may not be as pronounced as recent data indicates), would make it worthwhile to re-examine the commercial potential of a nodule extraction plant. The effect of nodule grade is likely to be pronounced, helping the delineation of a first generation mine site. Thus the case for a commercial polymetallic nodule venture would have to be viewed as an alternative resource exploitation venture, which may be rendered feasible by metal prices relating to future and selected mining areas.

The estimated return for the Indian case (with enhanced prices of Co- \$40/kg, Cu- \$4/kg, Ni- \$12/kg and Mn- \$1/kg) is 14.69 per cent.

## **Energy costs and operating expenditure variation**

The metallurgical plant direct operating expenses compromise energy and consumables costs. Because of the similarity with the processing of land-based nickel laterite ore, the process operating costs are dominated by fuel costs. The fuel serves as both metal ore reductant and process energy supplier. The high temperature reduction process can be substituted by sulphuric acid leaching as in laterite processing, but fuel cost still dominates total operating costs.

Although ammoniacal leaching subsequent to high temperature reduction consumes less energy compared to the sulphuric acid leaching step, recycling ammonia also consumes energy. The issue of energy requirements for recycling (involving separation of the reagent) can be understood by considering the ammonia recovery steps for ammoniacal leaching of reduced nodules. Considering a base estimate of 7 tons of steam requirements for recovering 1 ton of NH<sub>3</sub> from aqueous solution, the following table provides estimates of energy for steam production for different leach S/L ratios for nodules containing 1.3 per cent nickel, and leach solution containing 50 kg/m<sup>3</sup> ammonia.

S/L ratio	1.0	2.0	3.0
Ni recovery (%)	80.0	85.0	90.0
Energy for NH <sub>3</sub> recovery (MJ/kg Ni)	109.0	205.3	387.7
Other energy requirements (MJ/kg Ni)	528.9	497.0	470.0

*MJ/kg: megajoules per kilogram*

Energy values are reported per kg of nickel produced with a view to making a comparison with laterite energy costs. The table above shows that the energy cost of recovering NH<sub>3</sub> is critically dependent on the pulp density of leaching. The energy figures related to other requirements are associated with factors including drying and nodule reduction. The total energy cost is similar to that for processing laterite ore. In the case of using a non-recyclable reagent such as H<sub>2</sub>SO<sub>4</sub> for leaching at 250 C using an S/L ratio of 3.0, the steam energy requirement is estimated at 375.2 MJ/kg nickel, which is not

very different from NH<sub>3</sub> recovery energy requirements at an identical S/L ratio. The steam requirement based on 40 per cent recovery is estimated at 0.81 ton steam/ton of nodules. Referring to Lenoble (1990), the estimated operating cost of the upstream operations prior to manganese recovery is \$3.9/kg of nickel (40 per cent of the total operating costs). At the prevailing crude price of \$20/bbl during the period cited, and 13 T of steam generation/ton of fuel oil burned, the steam costs can be estimated at \$0.8, which amounts to about 20 per cent of the total operating costs for a non-recyclable reagent such as sulphuric acid. For the case of high temperature reduction/ammoniacal leaching involving reagent recycling, the energy costs would be around 40 per cent, which includes drying and high temperature reduction requirements.

It is apparent that savings in energy (or reduction in energy costs) would have an impact on operating costs. The steam requirements may be halved if H<sub>2</sub>SO<sub>4</sub> is manufactured at an auxiliary site and the excess steam is used for the acid leach step. For example, the Cuban nickel laterite sulphuric acid leaching operation used to obtain 50 per cent of its steam requirements from waste heat boilers at an auxiliary plant. Friedman (1982) has made an excellent analysis of sulphuric acid plants, and points out that the steam generated in such plants may exceed 1.3 T per ton of acid produced. This could halve the steam requirement, leading to a steam cost of \$0.4/kg nickel in relation to the case discussed above. Technology aimed at replacing refinery fuel with other fossil fuels (for example, coal) may lead to another 10 per cent reduction in direct operating costs.

The IRR is likely to be enhanced markedly by these measures. For realistic estimates of operating cost reduction, Lenoble's post-tax IRR could be enhanced to 14.3 per cent for a 10 per cent reduction in operating cost, rendering the process more economically viable.

Work has been initiated by the Indian developers to assess the impact of operating cost reduction through the energy saving measures indicated above.

## **New technology**

### ***Multiple production for cost reduction***

Nodule processing operations have been traditionally limited to the four metal production option in order to estimate the profitability of the processing operation in relation to the recovery techniques. Another approach is to recover further value from the core processing technology, permitting profitable operation at lower capacity.

It is possible to produce metal-bearing alloys, slag and enriched H<sub>2</sub> containing syngas simultaneously using a thermo-neutral process, with a hydrocarbon (for example, CH<sub>4</sub>) reductant and oxygen.<sup>1</sup> This has been proved experimentally for metallic oxides like ZnO (Halman et al, 2002). The process is non-catalytic, although catalysts may enhance the reaction rate. The approach is different to the one proposed by Vranka et al (2003), who suggested integrating the polymetallic nodule processing industry with another chemical industry. In the present case, it is suggested that the number of products

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<sup>1</sup> Syngas is the abbreviation for synthetic gas. This is a gas mixture that comprises carbon monoxide, carbon dioxide and oxygen

originating from the process reductant be increased. The extent of capacity reduction was estimated by assuming Lenoble's base smelting cost data at 1.5 million TPA capacity, and reducing the capital and operating costs with 0.6 exponent. This case may be further optimized with respect to capacity reduction. The approach is under further theoretical analysis.

### ***Novel reagents***

Various novel reducing agents have been proposed for aqueous reduction and tested in Indian laboratories. Some of the reducing agents, such as coal and pyrite, are only useful in special cases. The reducing agents are typically not recycled. The potential reducing agents can be analysed techno-economically only after large scale data collection. The route developed by USBM based on  $H_2O_2$  leaching (Allen et al, 1991) deserves special analysis, since the leaching rate is very fast, the reagent consumption very low and above all, the oxidation products of hydrogen peroxide are water and oxygen, so the reducing agent does not produce environmental pollution. The direct reagent cost is, however, high, at around \$1.5/kg, which is comparable to  $H_2$  cost (DOE target cost). Since reduction of capital expenditure would occur because of high leaching rates, the techno-economics of such a process needs to be assessed in relation to the sulphuric acid leaching process. A post-tax IRR of 15.7 per cent may be estimated, assuming base costs for a new hydrometallurgical plant for  $H_2O_2$  leaching with a 10 per cent reduction of both capital and operating expenditure compared to the Lenoble case for  $H_2SO_4$  leaching (because of low consumption norm and energy requirement). However, no detailed analysis was done.

### ***Other measures: on-site reagent and plant energy integration***

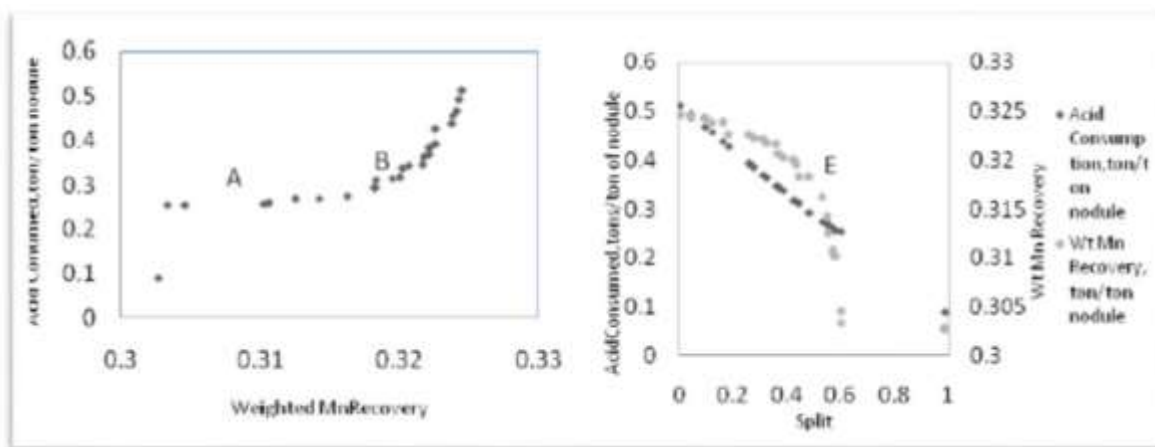
Analysis of the Indian processes has revealed that chemical and utility costs can be reduced by adopting on-site reagent generation. Estimates of reagent utilization patterns for a proposed 1.5 million dry ton nodule treatment plant reveals more interesting features of the Indian process. For an ammoniacal leaching process based on chemical reductant, ammonia and reductant consumption has been reported at around 1,000 tpd and 1,500 tpd, respectively. These are large consumption figures and are likely to make infrastructure limitation probable, unless such reagents are manufactured at an auxiliary site from a primary source that is available in large quantities at a comparatively low cost, for example,  $NH_3$  from natural gas or  $SO_2/H_2SO_4$  from elemental sulphur. Such auxiliary units need to be integrated with the principal metal production facility following established approaches, such as evolving minimum utility targets followed by heat pinch targeting maximum energy recovery network objectives. Mayze (1999) reports that the Murrin laterite plant draws 50 MW power from an acid plant through steam turbines. Whereas conceptual flow sheets for integration of ammonia and sulphur dioxide plant generation with the ammoniacal SO leach process have been finalized, detailed cost economic studies are yet to be conducted.

### **The specific role of manganese recovery in processing**

It was earlier emphasized that a high manganese recovery rate is crucial to obtaining appropriate nickel equivalents for nodules, and to make the nodule extraction process competitive with that of laterite-bearing ores from the point of view of specific operating and investment costs. The manganese recovery step, which is energy-intensive, is likely to be critical for processes utilizing the silico-manganese production route. In view of the higher grade of manganese in terrestrial resources, it may be necessary to rethink strategies for manganese recovery from leaner manganese-bearing resources such as nodules and processed nodule residues. One strategy could be production of another

value-added product such as electrolyte manganese dioxide (EMD) in addition to silico-manganese. Acid consumption for a lower temperature reductive acid leaching route for manganese recovery could be critical compared to lower consumption of acid in a pressure leach process without reductant. A feed split between the two processing routes to minimize acid consumption and maximize recovery leads to pareto-solutions (Figure 5) (Biswas et al, 2008).

*Figure 5: Circuit feed split for production of EMD and silico-manganese in parallel processing of sea nodules*



### Role of international cooperation

In view of the global resource crunch, it is important to draw the land-based metal producers for nickel and cobalt into the arena of nodule research. In many instances, modification of existing land-based commercial operations would lead to faster process development for the gap areas cited in this paper. Several portions of the technology to be developed can be intelligently linked to a diverse set of land-based operations, the technology ownership of which rests with different organisations. It would also be necessary to step up international cooperative efforts, since purely national initiatives would mean costly development programmes. International cooperative efforts would mitigate costly national development programmes. It is also necessary to recall that comprehensive technological developments have earlier resulted through cooperation between internationally composed industrial groups. In the light of such envisaged changes, government support for development-oriented programmes for nodules and other seabed minerals would go a long way towards attaining the broad objectives of the overall programme.

### Conclusion

The status of technology development work carried out in Indian laboratories has been reviewed. This includes various upstream operations such as leaching, residue treatment and solution treatment. The efforts were directed towards attaining a scale of process development commensurate with the requirement of generating engineering data for large scale operations. The basis for comparison between nodule processing and land-based operations was examined. A simplified cost model was developed, and formed the basis for the prediction of directional changes of technology for the commercialization of nodule processing ventures. The importance of energy cost reduction has also been examined. The adoption of energy integration measures, the use of novel reagents, and the



conceptualization of multi-product options for cost reduction have been discussed. Some of these measures are likely to decrease plant investment costs. International collaboration involving land-based international producers of nickel from laterite is expected to lead to faster commercialization of nodule ventures.

## Acknowledgements

Data reported in this paper were generated under the Ministry of Earth Science (MOES)-sponsored polymetallic nodule programme. The role of laboratories in generating the voluminous amount of data under these programmes is highly appreciated.

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## **Summary of discussions**

A participant said that he was trying to get a feel for economics and that it may vary from country to country and from investor to investor. He asked what would be the required minimum return on investment to make this a viable business. Mr. Sen recalled that if one was asking about a three or four-metal minimum, which is required, he had shown a slide on that specific investment. That kind of specific investment fluctuated somewhat, because the technology was different. When one tried to draw that graph, it was not that he had worked on sulphur dioxide; someone would have worked on something else. But they fell within the range, so he had drawn a simple straight line to say that that range would be followed.

Another participant, also with an economics-related question, said that different people had shown what the return on investment would be under different assumptions. He asked if one broke even, whether that was a viable business. Mr. Sen replied that, in calculating all those returns, typically 25 years had been taken as the period. Whether one spoke about the early adventures, or whoever was doing the capital cost analysis, talked about 20 or 25 years because of the coming royalty payment and other things. When one spoke about breaking even, detailed internal rate of return, one would see that

it would take eight to ten years before one would see any profit.

Another query for Mr. Sen related to the \$8 per kg of nodules and whether that was for the nodules or the metals recovery. Mr. Sen replied that that was the value picked up through communication from the laterite people and that that was what he got from the best possible estimates. Contrary to the laterite producers, one had to add mining and transportation costs. That was the difference.

Another participant wanted to know how it compared to land-based nickel. Dr. Sen said that the comparison was about \$6 at current (2004) dollar-per-kilogram prices for the annual nickel equivalent, according to Ifremer. He said he considered that to be the most remarkable. With regard to land-based laterites, when one spoke about 1 per cent nickel, that would equal about \$5 per annum.

## **CHAPTER 7      An Overview of the Interoceanmetal Deep-Sea Technology Development (Mining and Processing) Programme**

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### **Abstract**

In order to prepare a sound basis for mining technology, IOM analysed existing practices and the development of a conceptual design for a mining system applicable to the IOM exploration area. A comparison of alternative variants to enable assessment of the technical requirements for the basic components of mining technology was also carried out.

The development of a system of mining complex control involved, among others, mathematical modeling of mining complex systems and control process computer simulations, which included an assessment of the effects on the marine environment of the mining complex movement of the mining vessel and nodule miner, and the effects of movement on the transport riser pipe length, and riser pipe deformation. Laboratory tests were carried out to estimate slip velocity and experimental verification of nodule vertical flow on a selected lifting sub-system.

Based on existing facilities in IOM member countries, research on nodule processing technology included the reassessment of technological schemes for hydrometallurgical, pyro-hydrometallurgical, and acid and ammonia leaching routes. In addition, prefeasibility studies based on previously selected and partly optimized technologies were accomplished, and research was expanded on non-traditional routes for nodule treatment.

This paper outlines a brief overview of strategy and some results of the IOM programme for development of mining and processing technologies.

### **Introduction**

The Interoceanmetal Joint Organization (IOM), an intergovernmental consortium created by the Governments of Bulgaria, Cuba, the Czech Republic, Poland, the Russian Federation and Slovakia, signed a contract on 29 March 2001 with the International Seabed Authority (ISA) to explore for of polymetallic nodule deposits in an area of 75,000 km<sup>2</sup> in the eastern part of the Clarion-Clipperton Zone (CCZ) in the north-eastern Pacific.

In implementing the 15-year plan of work for exploration, IOM is carrying out comprehensive research and development studies in geology, the marine environment, as well as in the mining and processing technologies of polymetallic nodules.

The main objective of IOM for activities during the first and the second 5-year periods (to 2010) has been the delineation of nodule fields and the identification of nodule deposits and reserves in prime areas for possible future mining. IOM has made considerable progress in geological exploration using a multi-beam echo-sounder system, deep-towed photography surveying (digital format) and bottom

sampling, and has conducted a huge amount of analysis of physical, mechanical and chemical properties of sediments and nodules.

Environmental studies have focused on the collection of environmental baseline data specifically on the physical, chemical, geological and biological components of the marine environment in the exploration area. Research on the development of mining technology included an analysis and assessment of existing nodule technology, and the development of a conceptual design for a future mining system.

Work on nodule processing involved the optimization of existing technological schemes for extracting valuable components from polymetallic nodules, and the development of the basic technological schemes for polymetallic nodule processing. However, in accordance with IOM's 15-year plan of work, exploration and investment in research on the development of mining and processing technologies would only be launched towards the end of Phase 2 (2010-2012) of exploration.

### **Advances in mining technology: An integrated model for a nodule mining system**

The IOM strategy includes the following research and development activities for nodule mining technology:

- Prefeasibility studies on existing mining technologies.
- Development of a site-specific conceptual design.
- Modeling and testing of the most important sub-systems and components.
- Development and in-situ testing of an engineering design for a pilot integrated mining complex.

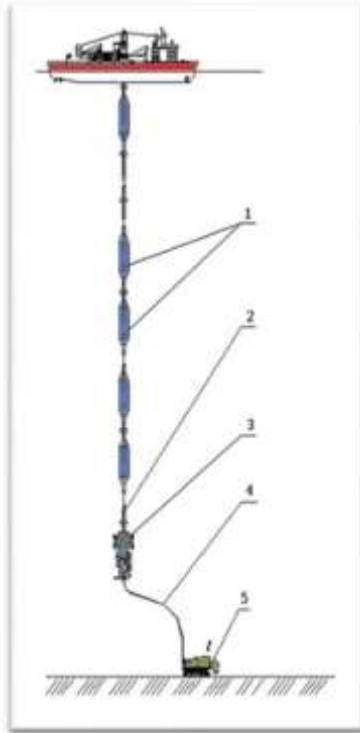
It is assumed that the most essential requirements in the development of a deep seabed mining system are the technical and technological adaptations of equipment to the geological, geotechnical and environmental conditions of the IOM exploration area. The relationship between mining system parameters and the particular conditions of nodule deposits are taken into account, as are the relationships between the components of deep-sea exploration, exploitation, transportation, nodule processing and environmental impact. The IOM strategy to develop deep-sea nodule mining systems takes into account the following elements and their interrelationship:

- Existing information on ore exploitability conditions and state-of-the-art equipment;
- Existing and proposed state of technical and technological development;
- Competitiveness and patent protection; and
- Requirements for environmental protection.

Conceptual design incorporates the basic principles of mining functionality and consists of complex units, sub-systems and components based on worldwide practices and IOM country experience (Figure 1), and includes a:

- Mining vessel or floating platform;
- Seabed collecting miner (nodule mining collector);
- Buffer, platform temporary storage in front of vertical transport;

- Control and management system; and
- Energy subsystem.



*Figure 1: Concept of a nodule mining system*

**Legend:** Mining vessel; 1 - Buoyant elements; 2 - Lifting pipe; 3 - Buffer; 4 - Flexible hose; 5 - Self-propelled collector.

The development of advances in mining technology included mathematical modelling of mining complex production systems, ship and ocean transportation, and computer simulations of the integrated control process.

Computer simulations of the control process included the assessment of the effects of the marine environment on the mining complex, the movement of the mining vessel and nodule miner and the effects of the movement on the transport riser pipe length paid out, and riser pipe deformation (Figure 2).

Preliminary simulation results showed that stress in the collection system riser pipes did not exceed acceptable levels; riser pipe shape deformation depends mainly on mining vessel movement speed and can be reduced or controlled by horizontal forces applied at low speeds.



*Figure 2: Main principles of designing mining systems with mining paths*

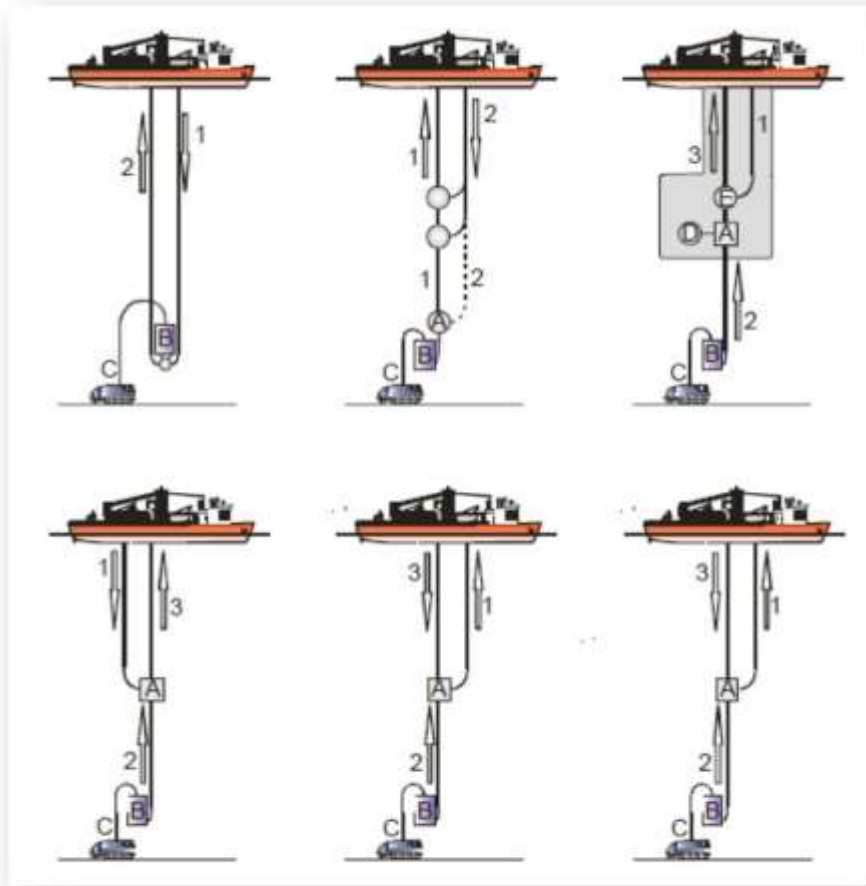
### **Nodule lifting sub-systems**

The nodule lifting sub-system is designed to realize the following basic functions:

- (a) Continuous vertical transport of nodules from sea floor to mining vessel;
- (b) Maintaining the position of the mining collector; and
- (c) The framework for power and communications channels lining bottom and surface.

Six hydraulic lifting options were theoretically evaluated and suitable varieties were selected on the basis of the chosen criteria (Figure 3).

*Figure 3: Components of hydraulic lifting mining sub-systems*



**Legend:** A – crusher; B – buffer; C – collector; 1, 2 and 3 – progress mixture direction.

Investigations to establish nodule and water velocity measurements during upward flow were conducted on a made-to-measure experimental stand located in the hydraulics laboratory in the Department of Water Engineering and Hydrotransport of the Agricultural University of Wrocław, Poland.

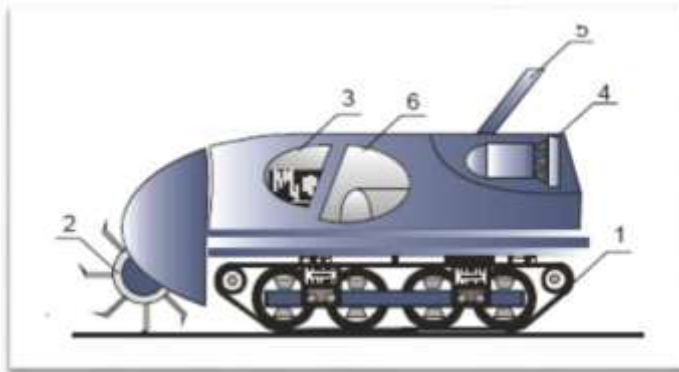
The mixture phase velocity measurements were carried out with the application of radio-isotopes using both natural and modelled nodules. The slip velocity values measured for 10-, 30- and 50 mm diameter nodules at a volume concentration of 10 per cent. The investigations were carried out in a 150 mm diameter pipeline, which could probably be applied in ocean conditions.

A comparison of measured and calculated values confirmed that the different densities of nodules examined may be the reason for the isotope differences of 50-, 30-, and 10-mm diameters found during the isotope examinations. The different shape of natural and modelled nodules is also a reason for the differences. Modelled nodules are almost regular in shape, while all nodules are irregular. Therefore, the resistance coefficient for these different shapes may differ significantly, which in turn is expressed by different values for both natural and modelled nodules.

## Nodule collector subsystems

The choice of the nodule mining collector was based on a miner construction scheme that responds to pilot test operations, and provides minimal changes to ensure semi-pilot exploitation in real mining conditions. In addition, manufacturing, operating and technological parameters are to place priority on the comparison of the miscellaneous characteristics of alternative nodule collector versions.

The nodule mining collector is composed of three main module parts (Figure 4), namely an undercarriage; a collecting device and a control unit.



*Figure 4. Nodule mining collector*

**Legend:** 1. Caterpillar belts; 2. Collecting devices; 3. Operations and control equipment; 4. Power units; 5. Riser system; 6. Buoyancy elements.

The development of the collector must take into account distribution characteristics associated with seabed features, bottom topography (such as the relationship of nodules with topography), seafloor morphology, nodule size and the type of mine site that influences the method of exploitation and the environmental impacts on the seafloor and water column.

Harmful environmental effects also need to be taken in design considerations to reduce the mass of sediment disturbed in the bottom near-water layer and to minimize sediment penetration and transportation.

Multiple investigations with the different types of working devices is made possible under the approach used in nodule collector construction. The main operating mode must be automatic mode with minimal intervention to remotely programme-controlled stirring. Flat nodule distribution demands constant contact between the nodule collector and seabed and the ability to orientate itself in the workspace.

Collector properties, such as manoeuvrability, controllability, stability and the ability to surmount hurdles, must respond to deposit conditions and enable the adjustment of the collector to variable exploitation requests. Another function of the nodule mining collector is to carry buoyancy elements and operating equipment for eventual unloading, washing, sorting, crushing, grinding and nodule displacement to the buffer. The collectors will affect in non-bearing floors, the carriage's main function will ensure mobility and nodule collection in large measure of variant interrelationships collector – seabed. Redistribution loading on carriage by different extracted nodule quantity and dynamic environs effects will specify the range of these variations.



## Future plan

Work is currently underway to develop a nodule mining system that addresses ongoing geological and environmental research in the exploration area. IOM is presently planning to focus on the:

- Development of the basic subsystems and components of the integrated mining system;
- Acquisition of in-situ geotechnical and environmental data and information for the nodule collector development;
- Development of a preliminary prospective mining system project which should take into account geotechnical features of delineated nodule deposits within the exploration area;
- Development of experimental models of the basic subsystems and components of the mining integrated complex, and their modeling and testing in a simulated seabed environment in a laboratory or under offshore conditions.

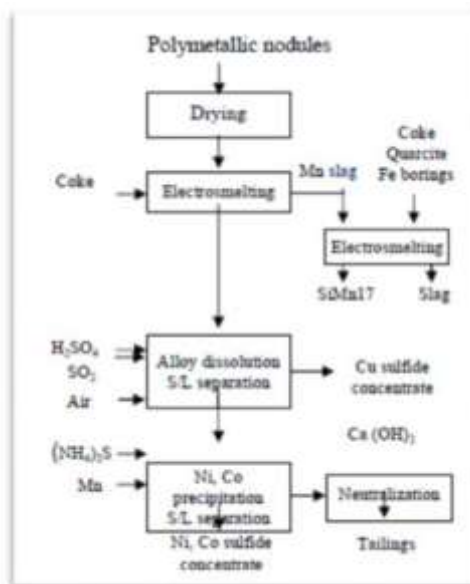
IOM is interested in collaborating with other contractors in order to share the cost of innovative solutions and the time-consuming nature of mining technology development.

## Polymetallic nodule processing

The following projects were identified for evaluation, based on existing facilities in IOM member countries: pyro-hydrometallurgical, hydrometallurgical, acid and ammonia leaching technologies.

### Pyro/hydrometallurgical processing

This type of polymetallic nodule processing (Figure 5) has been studied at the University of Chemical Technology and Metallurgy, Sofia, Bulgaria, and at the Hutni Project, Bratislava, Slovakia.



*Figure 5: A preliminary scheme for the pyro-hydrometallurgical processing of polymetallic nodules*

The 'mixed' process scheme consists of two main parts:

1. A pyro/metallurgical process with the selective reduction of non-ferrous metals to a complex Cu-Ni-Co alloy, and transition of the manganese and ferrous oxides to the slag phase with its subsequent processing to obtain silico- manganese alloys. The high-manganese slag subject to processing contains 47 per cent Mn, 1.07 per cent Fe and 0.04 per cent P; the complex alloy - 1.30 per cent Cu, 15.2 per cent Ni and 1.30 per cent Co (with extraction rates for the main elements of Cu, Ni and Co of 92, 93 and 89 per cent, respectively).

2. Hydrometallurgical processing of the complex alloy in two stages:

- Selective dissolution in a solution of sulphuric and sulphurous acid. Ni (nickel), Co (cobalt) (partly Mn [manganese] and Fe [iron]) pass into the solution while Cu (copper) remains as a soluble residue of CuS (53 per cent Cu).
- Sulphidic precipitation of the Ni-Co concentrate (in the presence of oxygen and after neutralization).

The mixed pyro/hydrometallurgical scheme is characterized by simple organization, affordable, non-expensive equipment and moderate investment costs. However, it is energy-intensive to a certain extent, as can be gathered from the relative power consumption per ton of high-manganese slag of 700 kWh/ton. At the process optimization phase, solutions will be sought to reduce this consumption using suitable reducers and process heat utilization.

A preliminary technical/economic assessment was made of the pyro/hydrometallurgical scheme (Tables 1, 2 and 3). Tables 2 and 3 present the estimated cost of product output in the case of processing of 1.5 million tons of polymetallic nodules per year. Items including materials, electric power and fuel are priced at 2001 level. The cost of the mined polymetallic nodules is assumed a priori to be a constant. Therefore, of all cost components, those of electric power and fuel have the highest variable weight – 33 per cent. Reducing this cost through improving process scheme efficiency will have the most significant impact on the final product costs.

*Table 1: Annual commercial production and extraction of metals*

Product	Silico-manganese	Cu concentrate	Ni-Co concentrate
Output, t/year	432,000.0	28,200	50,600
Mn Content, t	301,800.0	136	296
Mn Extraction, %	72.8	-	-
Cu Content, t	216.0	14,970	104
Cu Extraction, %	-	90	-
Ni Content, t	104.0	840	14,800
Ni Extraction, %	-	-	84
Co Content, t	80.0	96	1,890
Co Extraction, %	-	-	79

*Table 2: Raw material, feedstock, and energy consumption*

Description	Quantity (t/year)	Price (US\$/year)	Amount (US\$/year)	%
Raw polymetallic nodules	1,500,000	97.4	146,100	37
Other feedstock			94,693	24
Energy, including:			158,319	39
• Power, MWh/year	2,644,500	42 US\$/MWh	111,069	
• Natural gas, m <sup>3</sup>	270,000,000	175 US\$/1,000 m <sup>3</sup>	47,250	
TOTAL			399,052,000	100

*Table 3: Operating costs for processing 1 500 000 tonnes nodules/year*

No.	Description, items	Cost (US\$)	%
1	Raw materials and feedstock	240,793,000	58
2	Power and fuel	158 319 000	33
3	Administrative costs	4,100,000	1
4	Salaries	4,290,000	1
5	Depreciation costs	23,800,000	6
6	Other costs	2,700,000	1
7	TOTAL	414,002,000	100

### **Hydrometallurgical processing**

The hydrometallurgical nodule processing schemes were mainly developed at CNIGRI-Moscow, Russian Federation. Polymetallic nodule processing using sulphuric acid (Figure 6) is based on manganese oxide reduction by means of sulphuric anhydride and formation of soluble manganese sulphate. A specific feature of the process developed is selective dissolution of the non-ferrous metals and manganese. The process takes place at 70-80°C temperature and atmospheric pressure. The gases released during the burning of sulphur or roasting of pyrite concentrates can also be used to extract useful components from nodules (SO<sub>2</sub> 10-16 percent).

The product solutions containing non-ferrous metals, manganese and smaller quantities of other impurities are subjected to copper sulphate precipitation through the introduction of activated sulphur powder and the feeding of sulphuric anhydride into the reactor. Under these circumstances, a high degree of copper sulphide precipitation is achieved and, after its separation from the solution, Ni-Co concentrate is precipitated by the introduction of powdered sulphur and metallic manganese.

The manganese contained in the Ni-Co concentrate is dissolved through its re-pulping in sulphuric acid solution. Thus, all of the metallic manganese passes into the solution with subsequent regeneration.

Nodule processing using the sulphuric-acid method results in commercial products with the following chemical composition: copper concentrate with copper content - 40 per cent; Ni-Co concentrate – 20.8 per cent Ni and 2.7 per cent Co; and Mn-concentrate with 62 per cent Mn. Recovery rates of metal from the concentrates are: Cu – 92 per cent; Ni – 96 per cent; Co – 92 per cent; and Mn – 96 per cent.

The hydrometallurgical process that was developed incorporates operations such as extraction, dissolution and production of the concentrates, at atmospheric pressure and low temperatures, without the need for preliminary drying of the feedstock, which improves their energy efficiency.

Based on the enlarged Russian laboratory results, the Slovak engineering company performed a prefeasibility study based on a scheme shown in Figure 6.

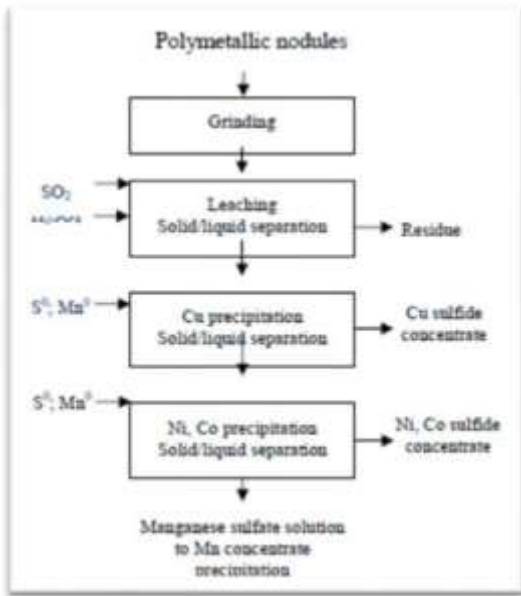


Figure 6: A simplified scheme of leaching using  $SO_2$  as a reductant

The study's main boundary conditions were: 1.5 million tons of nodules processed; battery limit restriction; the following metal recovery in the concentrates: 92 per cent Cu (40 per cent Cu in the concentrate), 96 per cent Ni (20.8 per cent Ni in the concentrate); 92.6 per cent Co in Ni-Co sulphide concentrate (2.7 per cent Co in the concentrate); 94.4 per cent Mn (59.5 per cent Mn in the concentrate); concentrate metal prices: US\$1,030 /ton Cu in Cu sulphide concentrate; US\$3,325 /ton Ni in Ni-Co sulphide concentrate; US\$18,000 /ton Co in Ni-Co sulphide concentrate; US\$250/ton Mn in Mn

oxide concentrate; and US\$75 /ton ammonium sulphate as a by-product; depreciation included; the assumed cost of 1 t dry polymetallic nodules equal to US\$97 at processing site; the profit estimate is about US\$7 million per year. Any further refinements to the project will probably lower the profit estimate.

### Acid and ammonia nodule processing technologies

Based on the research work carried out by the Nickel research center in Moa, Cuba, we have on hand two technological schemes; the first for application at the Moa plant, the second for application at the Nicaro plant, both containing preliminary economic estimates for the process. However, both processes suffer from bad pulp settling characteristics. The simplified schemes are shown in Figures 7 and 8.

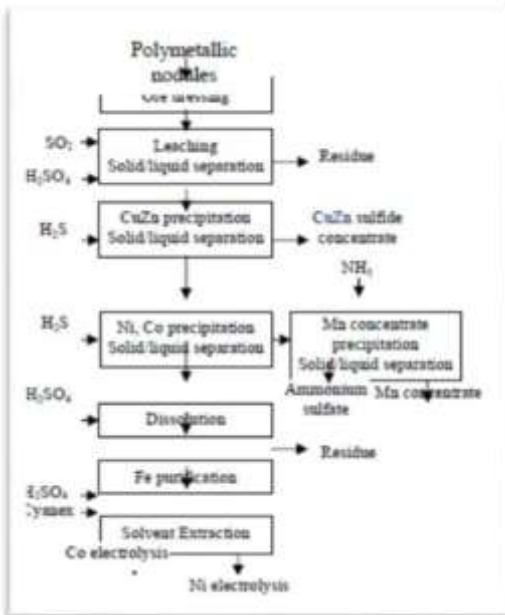
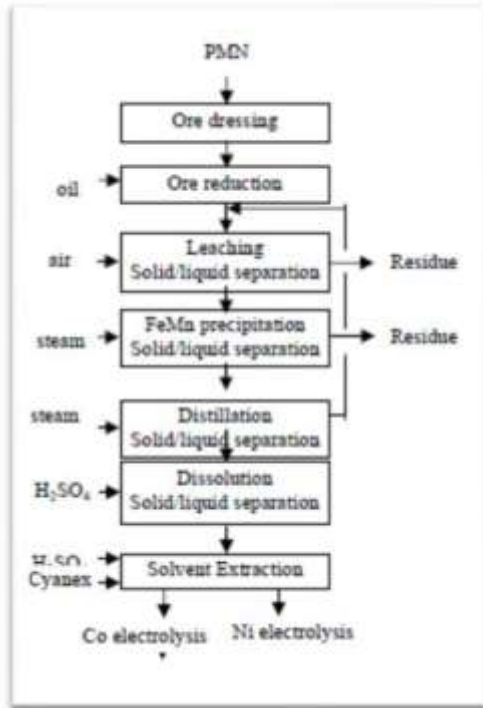


Figure 7: Sulphuric acid and  $SO_2$  leaching of polymetallic nodules

Metal recovery for acid leaching is Ni 91.2 per cent as electrolytic Ni; Cu 98.7 per cent in sulphide concentrate; Zn (zinc) 97.4 per cent as a sulphide concentrate; Co 85.6 per cent as electrolytic Co; Mn 92.1 per cent as a Mn concentrate; for ammonia scheme is Ni 91.5 per cent as electrolytic Ni; Co 41.4 per cent as Eco; Cu 74.9 per cent as electrolytic Cu; Zn 79.6 per cent as electrolytic Zn; Mo 75.3 per cent as a  $CaMoO_4$ .

One variant of the sulphuric acid process of metal extraction from polymetallic nodules is that it is conducted at high temperatures (over  $100^\circ C$ ) and high pressures (autoclave methods). It was developed on the basis of technologies currently used for nickel ore processing in Cuba (Punta-Gordo).

The ammonia carbonate process schemes, as an alternative to the sulphuric acid process, were dropped from planned IOM activities due to the high energy consumption required for evaporation of the adsorbed and chemically fixed water in the nodules during their reduction at a temperature of 600°C.



*Figure 8: Ammonia ammonium carbonate leaching (adapted Caron process)*

Along with the studies of the nodule processing technology schemes and their comparative technical/economic assessment, IOM also began research on the potential regions with suitable nodule processing plants and infrastructures. The research investigated production capacities (mainly pyro- and hydrometallurgical technologies), infrastructure (ocean and river ports), and other factors in South-East Europe.

### Perspectives

IOM research in nodule processing technology is one of the four main directions of activity during the second five-year programme (2006-2010) approved by the ISA. In accordance with the IOM long-term programme, the main part of IOM research is directed at pyro- hydrometallurgical and hydrometallurgical processing methods but will also include:

- Improvement of hydrometallurgical polymetallic nodule processing.
- Improvement of pyro/hydrometallurgical polymetallic nodule processing.
- Preparation of the input data and the technology selection for pilot plant experimentation.
- Analysis of existing plant capacities and estimation of their capability for industrial nodule processing.
- Assessment of environment impacts arising from nodule processing and development of technologies using polymetallic nodule processing for the solution of environmental protection problems.
- Development of new polymetallic nodule applications to improve the processing efficiency and/or extraction of valuable components.

IOM believes that greater levels of cooperation are needed among contractors and other stakeholders in the development of nodule processing technology. Opportunities exist in the methodological aspects of building a valuable metal market database, providing a methodological background for the procedures of developing and evaluating the economic rationale of projects, and developing new application areas.

## Acknowledgements

The studies described were supported by the IOM sponsoring States of Bulgaria, Cuba, the Czech Republic, Poland, the Russian Federation and Slovakia.

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Kotlinski, R. and M. Zadornov (2002), 'Peculiarities of nodule ore potential of the eastern part of the Clarion-Clipperton field (prospecting area of Interoceanmetal)', Proc. Intern. Conf. Minerals of the Ocean, Ministry of Natural Resources, Russian Academy of Sciences, St. Petersburg, Russia, pp. 21-24.

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Vranka, F. and R. Kotlinski (2005), 'Polymetallic nodules processing in Interoceanmetal: The present and the future', Proc 15th ISOPE Conference, Seoul, Korea, pp. 392-397.

Yamazaki, T., S.H. Park, S. Shimada and T. Yamamoto (2002), 'Development of technical and economical examination method for cobalt-rich manganese crusts', Proc Twelfth (2002) ISOPE Conference, Kitakyushu, Japan, pp. 454-461.

## Summary of discussions

A participant, initiating the discussion, said that he had two comments to offer. First, he said he was happy to see the environmental considerations in the design of the mining system, something that had been discussed briefly the previous day. Those environmental considerations included the IOM distribution characteristics, as was mentioned, which he considered to be very important, and also the association of those nodules with the substrates; that is, the sediments and rocks, etc. The second comment was that he was aware that the moment the subject of environment was discussed, the engineers tried to take a back seat, thinking that the environment lobby opposed technological development, but in fact it was the opposite, in that the experiments that had been done for environmental impact assessment of deep seabed mining thus far did not show a serious impact on the benthic environment or that there was any impact. But then, he continued, none of the experiments had shown that there was 100 per cent recovery of the condition of the environment back to where it was before the experiment. The speaker said that the point he was trying to make was that engineers did not have to be extremely wary of the environment lobby because environmental data only added to

the design that they were making.

There were several questions regarding the processing of the nodules. One participant said that, during the presentation it had been mentioned that the ammonium carbonate scheme had been dropped because of high energy consumption. The participant was curious to know what the specific energy consumption per ton of alloy produced in the first scheme that IOM pursued was. He had also seen that IOM was producing concentrates for which it had done some sort of economic evaluation. He asked why IOM had not taken it to the metal stage when the values showed that they would have fetched a lesser price and what the barrier was in converting concentrate to the metal and then doing a basic cost analysis. Dr. Stoyanova said that it had been dropped from the activities of the IOM owing to the high energy consumption required for evaporation of the absorbent and chemically-fixed water in the nodules during their reduction at a temperature of 600 degrees.

Another participant wanted to know why IOM had dropped the pyro-metallurgical scheme which worked at a higher temperature and asked whether IOM was getting values in the order of 2,000 to 3,000 kwh. Dr. Stoyanova replied that, in that scheme, the temperature was 600 degrees and that she did not know why exactly.

A third participant asked whether in the scheme for sulphide precipitation, that is nickel and cobalt sulphide, the sulphur powder was used, adding that usually in the industrial process the preference is for sodium sulphide, ammonium sulphide or even hydrogen sulphide gas, which can be used at room temperature. But if sulphur powder was being used, it was necessary to use very high temperatures. The author replied that it was over 100 degrees, because sulphur was stable at that temperature and because it could not precipitate as a sulphide.

The final question was on cooperation amongst contractors. One participant wanted to know whether IOM was thinking of a new organization of seabed miners association or something like that in order to safeguard the market. He also asked whether IOM visualized the new area for exploration that it had suggested to be in the reserved area in cooperation with developing countries or some other area outside the current reserved areas. Dr. Stoyanova replied that cooperation, especially in processing technology and metal prices, should be like collaboration in other areas, for example, environmental areas. In the opinion of IOM, it should be under the administration of the International Seabed Authority. It was like a database that had been developed for mineral resources and initial data should be included about the metal prices and the technology of the processing of those metals which are in nodules. Regarding the second question, she said that IOM activities, as a contractor with the Authority, were exploration activities only in the exploration area. Within that exploration area, based on its geological research in accordance with the 15-year workplan for exploration, the prime areas for the more detailed research would be conducted there, including estimation of nodule reserves, development of mining technologies. Based on its estimated reserves, IOM should find an optimum processing scheme for nodules that could be mined in the future.

## CHAPTER 8

### **KORDI: A Way to Accomplish the Mining Technology for Polymetallic Nodules**

Sup Hong, Principal Researcher, Maritime & Ocean Engineering Research Institute, Republic of Korea

Dr. Sup Hong presented a paper prepared with colleagues from KORDI and the Korean Institute of Geosciences and Mineral Resources.

Dr. Sup Hong said that Phase I of the Government of the Republic of Korea's work was limited to feasibility studies and some fundamental research, and that in Phase II of the work, technology development and at-sea tests would be undertaken. He said that the Government of the Republic of Korea, like the Government of India, is also pursuing a flexible riser system. He said that at-sea tests at 100 m water depth are planned for Phase II, and presented a comparison between the test system and the proposed commercial system. In relation to research and development, Dr Sup Hong said that the Government had built a ROV, an underwater launcher and a new support vessel.<sup>1</sup> He also said that the Government was working on underwater telemetry and developing high pressure hyperbaric chambers. With regard to technology development, Dr Sup Hong said that the Government was using both model and simulation techniques.

Dr. Sup Hong said that design methods have been established through systematic fundamental research like the dynamic simulation method for analysis of the mechanical feasibility of the total system; experiments on collecting operation devices such as pick-up, seafloor driving and slurry transport; Multidisciplinary Design Optimization (MDO) for developing a self-propelled miner; and two- and three-phase slurry pipe flow analyses. He described the Government's large scale test facilities, namely its Deep-Sea Mining Laboratory and Lifting Test Laboratory; in addition, he informed the workshop that a self-propelled test miner at 1/20 scale of commercial production capacity has been developed. Finally, Dr. Sup Hong said that the test miner and the flexible nodule transport system would be subjected to a sea-test in near-shore waters in 2009.

The discussions following the presentation centred on buffer storage in the flexible riser and the weight of the buffer. Dr. Sup Hong said that at present, no buffer storage is provided for but that should it be utilized, it might weigh up to 200 tons. He said that the mining operation envisaged would be a one-riser and one-crawler system for a 1.5 million tons/year operation.

Dr. Sup Hong did not provide a paper on "A way to accomplish the mining technology for polymetallic nodules". He, however, used slides to make his presentation. Dr. Sup Hong's powerpoint slides are reproduced in the following pages, followed by a summary of his presentation.

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<sup>1</sup>. Remotely operated underwater vehicles (ROVs) are unoccupied, highly maneuverable underwater robots operated from aboard a surface vessel. They are linked to the ship by a group of cables that carry electrical signals back and forth between the operator and the vehicle.



# A Way to Accomplish the Mining Technology for Polymetallic Nodules

Sup Hong, Kyung-Hyun Kim, Jong-In Choi,  
Seo-Eungh Woo, Seung-Jae Park  
BOEFT/KORDI  
Guk-Ho Won, Won-Ho Kim, Jong-Hyung Park,  
Yong-Chan Park, Seok-Ho Kim, Jung-Seok Yang  
KORDI

## Contents

- ◆ Overview
- ◆ Purposes of R&D
- ◆ R&D approaches & achievements
- ◆ Tests
- ◆ Concluding remarks



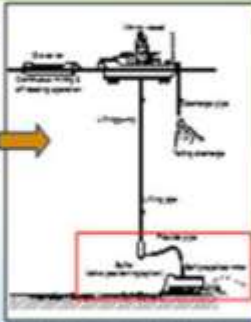
# Overview

## Polymetallic Nodule Mining

◆ Continuous recovery seems to be most feasible for polymetallic nodules.

◆ The total system is based on self-propelled collector, flexible link, cutter and vertical lifting system, which has been proposed by many investigators, e.g.

- Shim & Chung (1993), OTC400
- Park et al. (1995), OTC207
- Antonucci et al. (1995), OTC090
- Chung (1996), SDFC
- Wang & Kim (1996), ISA Workshop
- Lee & Yang (1996), ISA Workshop
- Chou et al. (2001), OCS-2001
- etc.



## R&D Investments

◆ National Project Phase I by MOST

- > Period: FY1993 - FY2000
- > Objectives
  - Feasibility Study
  - Fundamental Research

◆ National Project Phase II by MOST

- > Period: FY2001 - FY2010
- > Objectives
  - Achievement of Technology Base for Practical Application
  - Sea Tests



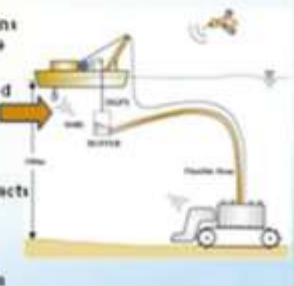
## Sea Tests

◆ Objectives

- > Performance evaluations of collector and flexible conduit transport
- > Evaluation of integrated performance

◆ Scale and scope

- > Minimizing of scale effects
- > Capacity: 1/10 ~ 1/20 scale for commercial system
- > Water depth: abt. 100m



# Purposes of R&D

- ## Target & Goal
- ◆ Achievement of Commercial Mining System for Polymetallic Nodules
    - > Self-propelled continuous mining
  - ◆ Development of Core Technologies
    - > Design Technology
    - > Operation Technology
  - ◆ Accumulation of Operational Know-How
    - > Near-shore Sea Test
    - > Deep Water Test (optional for Int. collaboration)
    - > Pilot Mining Test (=)

- ## Main Interests
- ◆ Self-propelled Continuous Mining Technology
  - ◆ Core Technologies
    - > TBD (To be Determined) Based Design
      - Modeling and Simulation, Coupled Dynamics of Total System
    - > MDO (Multi-disciplinary Design Optimization) for Miner
      - MDO: Meta-modeling (e.g., ROM, FEM/NANO/S)
        - Optimization Tool: ModelCenter
    - > 2-Phase (Solid-Liquid) Slurry Transport
      - Vertical Mining
      - Reliable conduit transport
  - ◆ Total Integrated Operation
    - > Integrated Control of Coupled Dynamics
    - > Integrated Control of Mining Operation
    - > Sea Tests

## Commercial Mining vs Test Mining

◆ Mining Capacity = 2 system × 1.11 million ton / year (wet)  
= 2.22 million ton / year (wet)

System	Name	Unit	Commercial capacity	Sea test capacity (2007-2008)
SP	Self-propelled Continuous Miner	ton/year (wet)	1.11 × 10 <sup>6</sup>	300,000
MC	Mobile Crane	kg/MT	5	5
SC	Slurry Collector	MT	5	5
ST	Slurry Transport	MT	5	5
PL	Pressure Loss	%	90%	90%
FL	Flow Loss	%	90%	90%
LC	Leakage Loss	%	90%	90%
HL	Head Loss	%	90%	90%
T	Total System	ton/year (wet)	2.22 × 10 <sup>6</sup>	1.11 × 10 <sup>6</sup>

# Related Researches

# Development of Deep-sea ROV MOERI/KORDI (2001~2006)

**Underwater Launcher HENUVY**



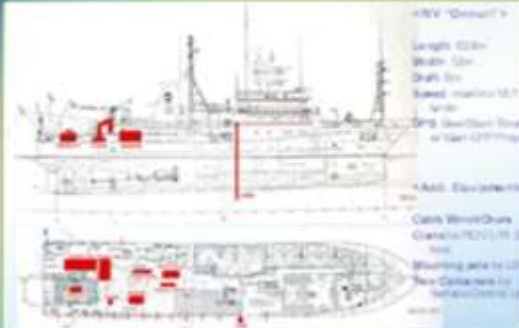
Max. Depth	Autonomy
Operation (Labell)	3.5h x 1.5h x 1.5h
Weight	1.500kg
Pressure	1 MP a2
Equipment	2 Cameras (RGB), 2 Hydrostatic Light, Altimeter, 2000 images/sec, 2000 fps max, Pressure lockable storage
Autonomy (range)	3.5 hours
Control mode	Handing control with low Pressure Receiver

**ROV HEMIRE**



Max. Depth	Autonomy
Operation (Labell)	3.5h x 1.5h x 1.5h
Weight	1.500kg
Pressure	200kg
Pressure	1 MP a2
Max. speed	100cm/sec 33.33 FT/1.32 min
Control (Labell)	20. 30' 100'
Equipment	1000' 20' 30000' 1000' 1000' 20' 30000' 1000' 1000' 20' 30000' 1000'

**Support Vessel : R/V Onnuri**



-R/V "Onnuri"  
 Length: 62m  
 Width: 12m  
 Draft: 5m  
 Speed: max 10.0 kt  
 GPS, Starlink, Starlink  
 of Starlink (GPS)

-Add. Equipments  
 Cable Winch/Drum  
 Crane (1000L/1000  
 lbs)  
 Working area to 1000'  
 New Capabilities for  
 (Starlink)

**Sea-trials**



Top Left: 1000' 20' 30000' 1000'  
 Top Right: 1000' 20' 30000' 1000'  
 Bottom Left: 1000' 20' 30000' 1000'  
 Bottom Right: 1000' 20' 30000' 1000'

**Other Related Researches**

- ◆ Underwater Acoustic Telemetry: National Research Lab.
  - > Data transmission
  - > Image transfer
- ◆ Hyperbatic Chambers
  - > 600bar
  - > 1,000bar (designed and under construction)

**R&D Approaches**

KORDI  
Thanks To

- VWS / TU Berlin
- U Karlsruhe
- THETIS
- BIS / TU Siegen
- IPREM
- AIST
- CRMM
- CIMR
- CSU
- SOI
- ISE
- SCOPE
- ISA
- etc.

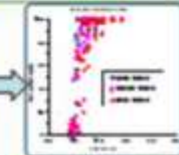
## Test & Experiment

3. Methodology

### Hybrid Nodule Pick-Up



Hydraulic Lifting-up of Nodules  
• Mechanical Transportation



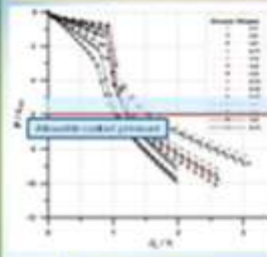
Laboratory Test of Performance  
in 1996



3. Methodology

### Cohesive Soil Test(1)

Over stress more cohesion test in cohesive soil

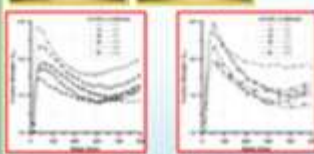
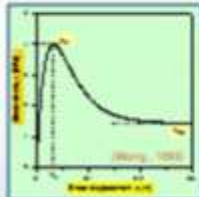


→ Ring and Shear, CMS-2001



3. Methodology

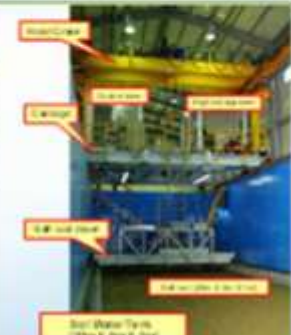
### Cohesive Soil Test(2)



Ring and Shear

3. Methodology

### Deep-Sea Mining Laboratory



# Modeling-and-Simulation Techniques

**Simulation Techniques<sup>(1/5)</sup>**

**Simulation Techniques<sup>(2/5)</sup>**

### Lifting Pipe Simulation

- Kryts v Beam Theory
- Lumped-Parameter Model
- Euler Angle

- Kim, 3D Analytical Behavior of Mining Pipe of Deep Seated Mineral Resources, IATOME, 1999
- Kim, 3D Dynamic Analysis of Lifting Pipe Systems in Deep Seated Mining, IATOME, 1997

**Simulation Techniques<sup>(3/5)</sup>**

### Flexible Pipe Simulation

- Euler Angle = Euler Parameters
- Hong, A New Method Using Euler Parameters for 3D Solution of Analysis of Mining Pipe, IP OMS, 2002
- Hong, Effects of Internal Flow on Dynamics of Underwater Flexible Pipe, IP OMS, 2002

**Simulation Techniques<sup>(4/5)</sup>**

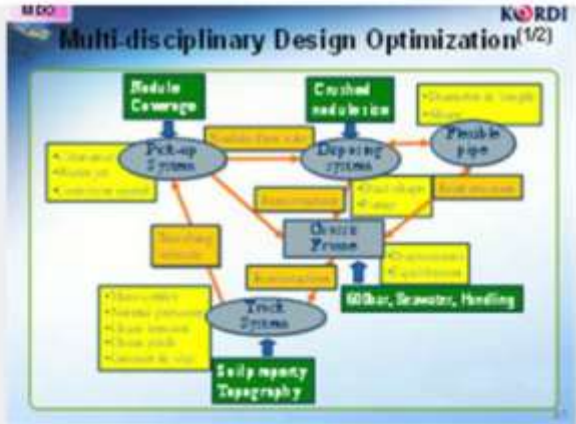
### Tracked vehicle Simulation

**Simulation Techniques<sup>(5/5)</sup>**

### Coupled Dynamic Simulation

- Kim, 3D Dynamic Analysis of Lifting Pipe Systems in Deep Seated Mining, IATOME, 1997
- Kim, 3D Dynamic Analysis of Lifting Pipe Systems in Deep Seated Mining, IATOME, 1997

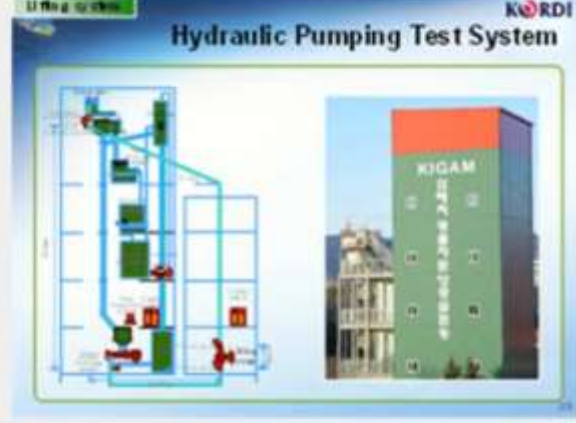
# Multi-disciplinary Design Optimization



# Tests

KORDI

## Lifting System Test



KORDI

### Hydraulic Pumping Test System

The diagram shows a vertical hydraulic system with a pump at the bottom, a reservoir, and various valves and pipes. It is surrounded by four inset photographs showing physical components of the system.

KORDI

### Coastal Experiment of Lifting System

25 April, 2007

The top image shows a yellow lifting platform suspended in the water next to a boat. The bottom image shows a diver in a black suit working on a structure in the water.

KORDI

### Coastal Experiment of Lifting System

전해 양광시스템 해양 실험

A group of about ten people wearing red safety vests and hard hats are standing on a pier or boat deck, looking towards the water.

KORDI

### Test Miner

A large, empty white rectangular area, possibly representing a test environment or a placeholder for an image.

Te cMiner

KORDI

### Test Miner: Digital Mock-up

Labels in the diagram include: Reservoir, Compressor, Hydraulic Motor, Control, Suspensy module, Signal J.B., Valve pack #2, and Valve pack #1.

400014 30x114 30x18  
Weight : 10.8 ton  
Undercarriage : 4.2 ton

$F_{max} = 1.17 \text{ MPa}$

Te cMiner

KORDI

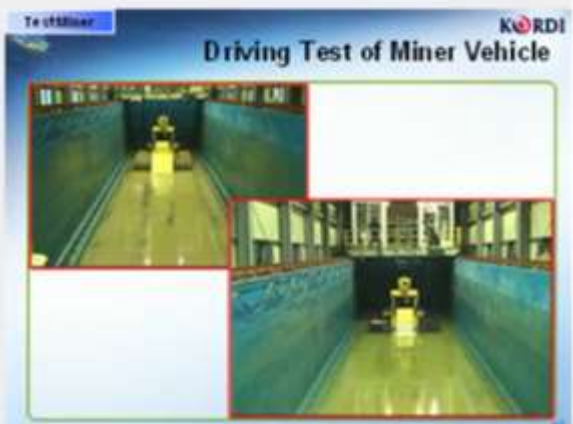
### Test Miner

The photograph shows the interior of the Test Miner, featuring two operator seats with orange backs, a control panel, and various mechanical components.



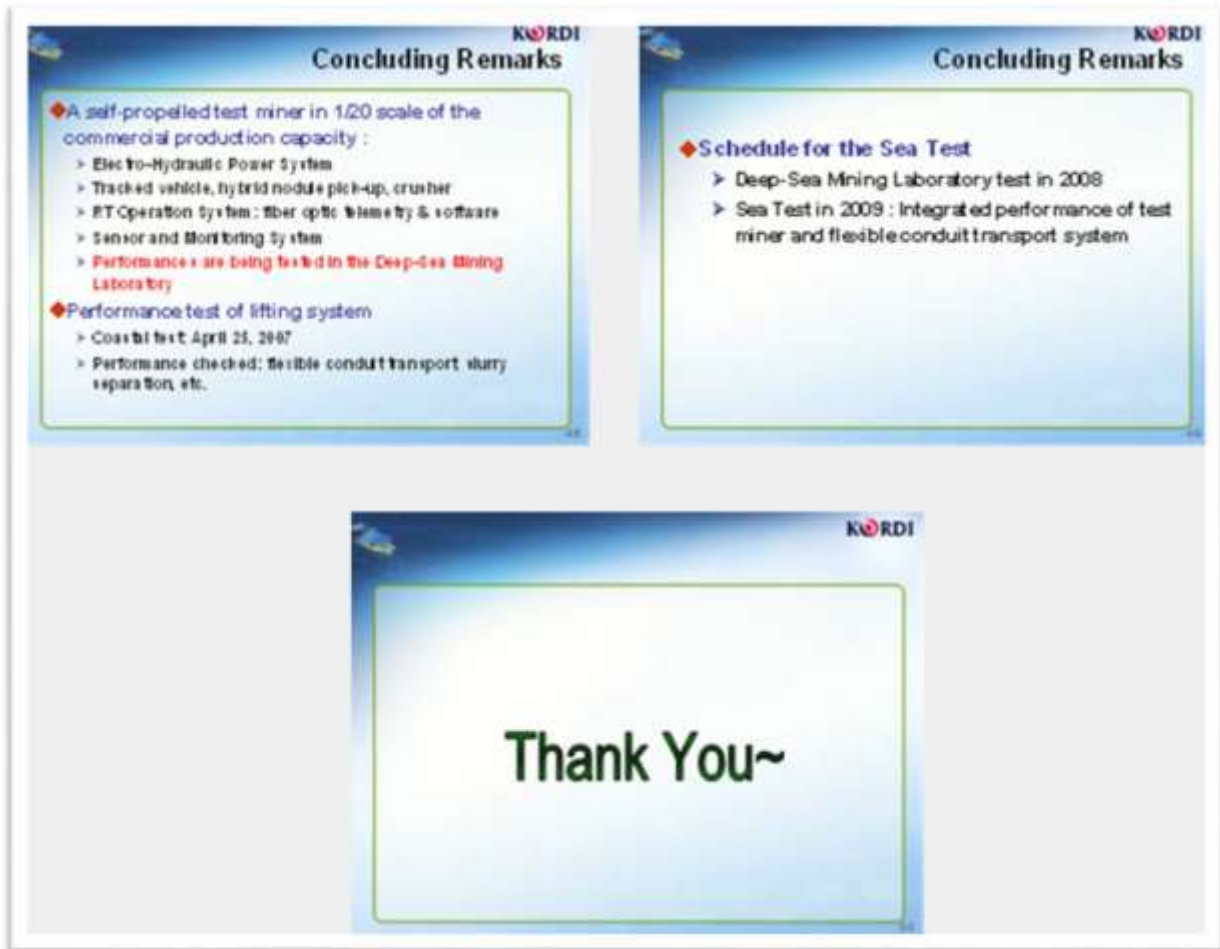
**Monitoring/Operation System**

- **Hardware**
  - ▶ Embedded computer (PI 2010)
  - ▶ Control and monitoring boards
- **Software and GUI (Deep-Miner Software)**
  - ▶ Developing tool: NI Inc. LABVIEW™
  - ▶ Operating program and monitoring program



- Concluding Remarks**
- ◆ Design methods have been established through systematic fundamental researches
    - > **Dynamic vibration method** to analysis of mechanical feasibility of total system
    - > **Experiments** of collecting operation devices: pick-up, seat-floor driving, slurry transport etc.
    - > **RDO**(Multidisciplinary Design Optimization) for development of self-propelled miner
    - > 2-phase and 3-phase **slurry pipe flow** analysis: experiment and numerical
    - > **ETOC**: electric-electronic unit and monitoring system developed
    - > **Large Scale Test Facilities**: Deep-Sea Mining Lab., Lifting Test Lab.





### Summary of presentation

Dr. Hong said that in the Republic of Korea they were mostly involved in mining research and not in processing. His presentation would therefore cover only mining technology. He said that the title of his presentation was “A way to accomplish the mining technology for polymetallic nodules” but frankly speaking, the Korean Ocean Research and Development Institute (KORDI) was the latest starter in the deep seabed mining area. The Republic of Korea was still on the learning curve; the learning process was not yet finished, so he wanted to emphasize the technological difficulties which had confronted KORDI and the technological efforts that it had put into overcoming them.

He pointed out that KORDI was not the only company to have taken part in the research and development; the Korean Institute of Geoscience and Mineral Resources (KIGAM) had also taken part in developing lifting technologies.

### *Overview of polymetallic nodules mining*

Dr. Hong said the continuous recovery concept seemed to be most feasible for polymetallic nodule mining. Continuous mining meant that the nodules on the sediment floor should be transported

up to the surface continuously without any stopping or intermediate stations. To reach a continuous mining operation concept, there might be two different options. The first was towed-type mining and the second was self-propelled mining. For the self-propelled continuous mining the total system consisted of the self-propelled miner on the seafloor linked with the flexible conduit to the buffer system. That buffer was the intermediate storage tank from the buffer up to the surface 5-kilometre-long lifting pipe and on the surface mining vessel. That kind of concept had been investigated a lot by researchers and academics since the beginning of the 1980s.

In the self-propelled continuous mining concept the self-propelled miner and the buffer played an important role. First the buffer played a role of a pendulum weight on the long pipe. Due to that weight, the total lifting pipe configuration could be kept in a straight formation and the flexible conduit between buffer and miner was of particular importance in the operational sense. In order to maintain the driving performance of the self-propelled miner vehicle, the flexible conduit should be able to give some freedom so as not to prevent the motion of the vehicle.

In order to provide freedom, the flexible pipe should be long enough, but if long pipes were chosen, the energy consumption rates would be very high. Therefore a compromise solution was needed in the design of some of the parts.

Mr. Hong said that the Republic of Korea had started the national project during the period 1993-2000. That had been the first phase supported by the Ministry of Mining and Technology. During that phase a feasibility study and fundamental research had been carried out. During the years from 2001 to 2010, the second phase was supported by the Ministry of Maritime Affairs and Fishery. The objectives of that phase would be the achievement of a technology base for practical application. That technological achievement must be evaluated by sea tests.

Dr. Hong said that because of budget limitations, the sea tests had to be restricted in scope. Its objectives were: performance evaluation of the collector and flexible conduit transport system, and evaluation of the integrated performance. In order to minimize scale effect the capacity of the test collector chosen had been 1/10-1/20 for the commercial system and the water depth about 100 m near the shore of the Korean peninsula.

He also said that research and development investments had several targets and goals. The first target was the achievement of commercial mining technology for polymetallic nodules by means of self-propelled continuous mining. On the way to achieving that technology the Republic of Korea wanted to develop and accomplish core technologies, which were design and operation technologies. Finally, through a series of sea tests, the Republic of Korea wanted to accumulate operational know-how.

Dr. Hong explained that, in the development of core technologies, their main interests were self-propelled continuous mining technologies. In that regard, the core technologies were: simulation-based design technology, which could reduce investment costs and also the technological risks and development hardware; the second technology was the multidisciplinary design optimization for miner development. He pointed out that the self-propelled miner had to be able to crawl on the seafloor and effectively separate the nodules from the sediments, and energy minimizing transportation through a flexible conduit to the buffer. He further pointed out that the two operations had to be linked to each other in such a way as to minimize the total energy consumption rate. Dr. Hong said that the third technology was the two-phase (solid-liquid) or three-phase (solid, liquid and gas) slurry transportation. The final goal was the effective transportation of nodules from the seafloor to the surface. That meant

that this energy-minimizing slurry transportation technology was one of the key technologies.

He said that, for the realization of continuous mining, two different kinds of lifting processes were necessary: the vertical lifting through 5-km-long channel and the flexible conduit transportation between miner and buffer.

Finally he said that the total integrated operation comprising the coupled dynamic control and the mining operation has to be established and evaluated through sea tests. In the case of research and development, the Republic of Korea had selected test mining scores against commercial mining. Dr. Hong showed a table with the simple calculation results and said that, if they had 1.5 million dry tons per year as commercial mining, he calculated that the 2 mining systems used, would produce 2.2 million wet tons of nodules per year.

Dr. Hong said that mining production was determined by eight parameters which were: nodule coverage; speed of the collector; pick-up efficiency; width of collector, time efficiency; lifting efficiency, handling efficiency and time. He said that with 2 collectors, each unit would produce 1.1 million wet tons per year. As a result, the test collector would have a 65,000-tons-per-year capacity. He informed participants that calculation assumed the coverage of nodules to be 6 kilograms per square meter. In the case of the commercial system, the collector was 10 metres and in the case of the test collector, it was 1 metre.

Dr. Hong said that in the commercial system, the target speed of the collector was 1 m/s, but in the test collector it was 0.5 m/s. He pointed out that time efficiency was assumed to be 75 per cent. That meant 270 days of production per year. Dr. Hong stated that 75 per cent time efficiency would be difficult to attain in the first phase of commercial mining.

Separate and apart from the deep seabed mining technology project, Dr. Hong said that KORDI had conducted several research and development projects. The first one was the development of a deep-sea ROV with a 36-metre diving capacity during 2001-2006. The ROV, called *Hemire*, consisted of two parts. The launcher named *Henuvy* had played a similar role as the tether management system of the ROV system developed by India's National Institute of Ocean Technology (NIOT). The weight was about 1 ton and two thrusters were used for petitioning the launcher. That launcher had two cameras, two underwater lights, an altimeter, an ultra-short baseline responder, a side-scan sonar and a forward-looking sonar. The umbilical cable was connected to the surface; and the whole length of the cable was 8,500 m.

The main part of the launcher was its total weight which was 3.6 tons in air; and in water neutrally buoyant. Its length was 3 m and its height was 2 m. With the ROV and launcher its tethers were selected from 35 m, 50 m and 100 m. That meant that the launcher had no tether management system.

Dr. Hong displayed pictures of the research vessel, *Onnuri*, which was being used for exploration of the Clarion-Clipperton Fracture Zone area, and also of the ROV *Hemire* and the launcher. The *Henuvy* launcher system was deployed through a frame and the ROV was launched by side ports using a crane.

Dr. Hong said that to date the Republic of Korea had conducted several sea trials. In 2007 in the East Sea near the Philippines at a depth of 6,000 m, diving had been successfully carried out. Besides that ROV development project, he said that there were other related research projects. One was the

underwater acoustic telemetry system. That research topic had been initiated by the National Research Laboratory, and concerned data transmission and image transfer, using ultrasonic acoustic telemetry technologies.

According to Dr. Hong, Korea had a 600-bar capacity hyperbaric chamber from the *Institut für Konstruktion* at the University of Siegen in Germany and planned to construct a 1,000-bar hyperbaric chamber. The design was finished and it was under construction. Before talking about research and development approaches Dr. Hong expressed his appreciation to various research institutes, friends and colleagues for having shared their research and development and approaches.

In the first phase of fundamental research, Dr. Hong said that the Republic of Korea had carried out systematic and serial experiments on hybrid pick-up devices. Nodules were lifted from the sediment layer by means of a pair of water jets and then through specially-shaped plates. They were transported to a certain height, from which the mechanical transportation would convey the lifted nodules into the miner.

Dr. Hong was of the view that mining nodules was a hard struggle against cohesive and soft soil on the seafloor and the need to keep the miner vehicle floating on the seafloor. Dr. Hong showed a graph to demonstrate that if the contact pressure increased to a certain level, sinking would occur. That phenomenon was considered a design parameter for the choice of allowable contact pressure of the vehicle. If the contact vehicle was more than six times the residual shear strength of the soil, then sudden excessive sinking occurred. That meant that the contact pressure of the vehicle should be below the limit.

Dr. Hong showed a slide depicting the traction performance of cohesive soil, explaining that it imitated deep-sea soil by water mixture. By changing the water content, the target shear strength could be obtained. In variation of the grouser shape and the track, one could obtain different types of traction forces. There was certainly some optimal design of the track from that kind of experimental data, some mathematical model of cohesive soil could be obtained; shear strength in relation to the shear displacement of the soil.

Dr. Hong said that, based on this fundamental experimental research, Korea had constructed a large-scale deep-sea mining laboratory which was more than 40 m in length. A special feature of the lab was the soil/water tank, the bottom of which was filled with artificial soil. The softer soil was made of bentonite and water, the length was 29 m, width was 5 m and the soil depth was 1 m. The whole amount of the artificial soil is made by using an automated soil mixer. On the top of the tank there were rails and a carriage which was able to move precisely and controlled. On the carriage was an electric power supply system with .3 kv with a 250-kw capacity.

In order to reduce the research and development budget and reduce the technical risks, Korea had focused on the development of a simulation model of the whole system. The whole mining system can be divided into three parts: the lifting pipe, the flexible pipe and the tracked vehicle.

Dr. Hong said that, step by step, the dynamic simulation technologies for the sub-items had been developed. Finally, he said that the dynamic performance of the miner vehicle could be investigated by two kinds of computer simulation models. One was the single-bodied dynamics and the second was the multi-bodied dynamics. With that computer simulation model, the performance of the vehicle, as well as the turning or steering process or the driving performance, could be predicted.

By combining several of the simulation software, the Republic of Korea had been able to develop the total couple dynamic analysis software. By using this computer simulation model it had been possible to predict the structural behaviour of the flexible and lifting pipes, the buffer and miner vehicle in the kriging and retrieval process and also in the operational procedure. Dr. Hong reiterated that the self-propelled miner consisted of various kinds of sub-operations. First it must be able to move on the seafloor and at the same time it should separate the nodules from the sediment and, through the flexible pipe, dispose the picked-up nodules directly to the buffer system. Each subunit was related mechanically and operationally. If one wanted to design such a complex system one had to get a good system design optimization tool.

Dr. Hong said that a multidisciplinary design optimization technique for the development of the self-propelled miner had been developed. In that design optimization process, they had considered pick-up efficiency by using a hybrid pick-up device and two-phase slurry transportation through a flexible hose, and tracked vehicle performance and the frame structure. The four kinds of design domains should be optimized in order to minimize the energy consumption rate. Energy consumption comprised the operational cost.

Based on these research achievements, Dr. Hong said that the Republic of Korea had recently conducted a lifting systems performance test. He showed participants a photo that had been taken at KIGAM, where a 30-metre high-lifting test facility had been constructed and several experiments constructed.<sup>1</sup> By using artificial nodules, slurry efficiency had been studied. On 25 April 2007, coastal experiments had been carried out. An artificial nodule tank had been deployed under water, in which the nodules were stored and a pump had lifted the artificial nodules.

Stating that Korea was preparing to test the miner, Dr. Hong showed participants a slide of the original mock-up of the test miner. It weighed about 9 tons in the air and 4.2 tons under water. The contact pressure beneath the track was 5.7 kPa, which he said was quite low.<sup>2</sup> The test miner was driven by means of an electric hydraulic power unit with a total capacity of 135 kw. The Republic of Korea had developed an electronic system for the control of hydraulic units and sensor systems, and communication through fibre-optic telemetries in-house. The monitoring and operation systems were achieved through hardware and software.

Dr. Hong showed a video that demonstrated the controls for driving the miner vehicle. He pointed out that the driving path could not be kept straight. On the other hand, on the right hand side, by means of feedback control, the driving path could be controlled and kept straight.

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<sup>1</sup> KIGAM – Korea Institute of Geoscience and Mineral Resources

<sup>2</sup> kPa – Kilopascal is a unit of pressure. 1kPa is approximately the pressure exerted by a 10 gram mass resting on a one square centimetre area

In closing his presentation, Dr. Hong remarked that, during the past ten years of research and development activities, the following design methods had been established:

- Dynamic simulation methods had been systematically developed to analyse the mechanical feasibility of the total system;
- A series of experiments had been conducted to determine the design parameters for the pick-up device and seafloor driving mechanism and slurry transportation etc.;
- A multidisciplinary design optimization technique had been successfully achieved for the development of the self-propelled miner;
- Slurry pipe flow analyses were conducted experimentally and numerically;
- A real time operating system of the self-propelled miner had been developed in electric-electronic unit;
- Two types of large-scale test facilities had been constructed - for collecting technology and a lifting test laboratory, and
- A self-propelled test miner had been designed and constructed on the scale of 1/20 of the commercial production capacity.

In 2008, the integrated performance of the collector and the flexible hose transportations would be tested in the deep-sea mining laboratory. In 2009, the sea test would be conducted for evaluation of the integrated performance of the test miner and the flexible conduit transportation systems.

### **Summary of discussion**

The discussion following the presentation was initiated by a participant asking about underwater acoustic telemetry and wanting to know what sort of transmission rates were being obtained. Dr. Hong answered that the recent test had shown the band rate to be about 9,600. That performance was quite good; the range was over 8 km.<sup>3</sup>

A participant said that the Republic of Korea had talked about having a buffer between the flexible component and the riser pipe and asked what the weight of the buffer was. Dr. Hong said that, in the sea test planned for 2009, that buffer did not have the function of an intermediate storage function. Only at the buffer station would the suction pump be installed. In the case of the commercial system, the performance and size of the buffer were very critical for decision-making. If the buffer weight was large enough, then the positioning of the vertical lifting was more effective, but at the top of the pipe the tensile stress would be very high. A compromise had to be found. That buffer had another different, important role. He reiterated that the buffer was an intermediate storage tank into the vertical pipe. The transported nodules should be fed into the pipe at a constant rate in order to minimize the operational cost of the lifting. If one wanted to transport the nodules from the sediment surface to the sea surface directly, then the pump should be very powerful; that meant the operational cost would be increased. If the buffer can control the feeding ratio into the vertical pipe, then the pumping energy could be minimized. Dr. Hong could not provide the weight, but he believed it was within 200 tons.

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<sup>3</sup>. Band rate roughly means the speed that data is transmitted, and it is a derived value based on the number symbols transmitted per second.

A participant wanted to know whether any flow analyses had been done. Dr. Hong replied that the slurry flow analysis was a very difficult topic. The experimental approach was inevitable. In the case of vertical lifting, there was an empirical relationship, but in the case of the flexible riser having complex configuration, there was no mathematical formulation about the flow characteristics. It depended on the transportation concentration of the solids, the pipe size and the relative size of the solid particles. To date, the optimum diameter of the vertical lifting pipe was about 200 mm. because a larger pipe would mean larger drag forces. It was almost impossible to pull the whole system. The maximum was about 240 mm inner diameter. In the case of the flexible pipe, it was different. The particle size must be smaller than the vertical pipe. So in the case of the sea test to be held in 2009 the inner diameter of the flexible hose was 10 cm. and the maximum size of the solid was 20m.

Another participant, in relation to the sea test to be carried out, asked what size the nodules were and how they were fed to the pump because one wanted to have a continuous flow. Dr. Hong said that the sea test would be carried out in a depth less than 100 m. It was not easy to find a proper site for such a test. First the seafloor characteristic must be similar to deep sea conditions. In the vicinity of the Korean peninsula there were very limited choices from which to select a proper site. Korea was considering two possibilities, namely, using natural and artificial nodules. If natural nodules were used, the crusher would be tested together, but if the artificial nodules were used, the crushing unit would be eliminated by passing through a pipe conduit to the flexible hose. Dr. Hong said that they were talking about using natural nodules; some people said that using natural nodules would cause environmental problems for the fishermen and the fishery area. It had not been decided whether the nodules would be natural or unnatural. If the nodules were natural, they would be laid on the seafloor. The average size would be 5 to 6 cm in diameter. If artificial nodules were used, then the maximum size would be around 20 mm.

The question from another participant was whether the types of distribution obtained followed the Gates and Schuman distribution. Dr. Hong said that he had not considered that in depth.

A participant, referring to the 130 kw for the hydraulic power unit and to the fact that for every buffer there was a submersible pump, asked how the Korean team managed the power and how it coped with the drop in voltage. Dr. Hong replied that, in using the electric hydraulic system of the seafloor miner, the energy transmission through the cable was very important. In the case of the test miner, the water depth would be less than 100 m and therefore the voltage drop through the cable was not a significant problem. However, in the case of commercial mining the cable performance capability should be considered first of all to operate seafloor machinery. In the sea test the Korean team would have no such problems because it was a shallow water test.

Another participant asked whether the Republic of Korea had a buffer and a miner in its current commercial mining configuration, and whether it would like to have a multiple system or a one-set system. Dr. Hong replied that each miner had one riser. Referring to the table that he had showed, he said that it had been assumed that two units of the mining system were used for the production of 1.5 million dry tons of nodules per year. However, at the time the assumption was that nodule coverage was 6 km per m<sup>2</sup>. He said that if the coverage were doubled then the production capacity would be also doubled. The base calculation assumption was that nodule coverage was 6 km per m<sup>2</sup> and the final production target was 1.5 million dry tons of nodules per year with one mining collector.

The participant wanted to know whether the Korean team proposed to have an increased

concentration when it pumped from the buffer to the ship. Dr. Hong said that the lifting process was not his field. However, the volumetric concentration in the lifting pipe could not exceed 15 per cent. The more critical region was the flexible hose because the shape was complex (almost an S-shaped configuration) and that meant in the vertical pipe the specific weight of the solid particles did not cause too many problems, but in the case of the curved pipe the heavy solids would sink down to the bottom of the pipe so a great deal of power would be required from the pump to transport the nodules through the flexible hose. In that case, the best concentration would be much lower.

A participant, observing that sea tests were important because one got closer to the environment of work, asked if the test was successful, what would be the next step. The author replied that Korea had plans for the national project until 2010. After that, it was planning for pilot mining, including environmental impact tests in the deep sea. The experimental results obtained with the sea tests in 2009 would be used to design the pilot mining system for deep-water testing.

A participant asked how long it would take to design the pilot mining test and how long pilot mining would last. Dr. Hong said that the question was beyond his scope. He could not decide on the budget, but he believed that the construction of the mining system would require a huge budget. During that phase, he believed that international collaboration would be helpful in undertaking the results of pilot mining, including its large-scale environmental impact. The Korean Government had a contract with the Authority until 2015, so it was now planning what the scope of the national project would be. It would also consider the possibility of international cooperation during the five-year period from 2011 to 2015. Nothing was final.



## CHAPTER 9      **Status of Exploration for Polymetallic Nodules in the German Licence Area**

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### **Abstract**

In July 2006, the *Bundesanstalt für Geowissenschaften und Rohstoffe* (Federal Institute for Geosciences and Natural Resources, hereafter referred to as BGR) signed a contract with the International Seabed Authority on the exploration for polymetallic nodules in the so-called 'Pacific nodule belt'. German exploration activities in this area reached back to the late 1970s and early 1980s when an international consortium of enterprises, including the Preussag Company, considered mining nodules from the deep sea. However, the subsequent fall in commodity prices prevented the launch of commercial extraction, and after the retreat of German industry from deep-sea ventures, BGR inherited the archived exploration data. Currently, BGR is preparing an exploration cruise to the licence area with a focus on detailed bathymetric mapping and a survey of the geographical distribution and regional abundance of the nodules. Moreover, the Federal Ministry of Economics commissioned BGR to plan a series of pilot projects including: (a) a feasibility study of nodule mining from recovery and extraction to smelting, including consideration of future market trends; (b) state-of-the-art exploration technology (e.g. using acoustic sources for polymetallic nodules); (c) technological concepts for the extraction and lifting of nodules from the deep sea; and (d) the development of a specific metallurgical processing technology for polymetallic nodules. Current associated research projects at BGR concentrate on trace element geochemistry and quality assurance in the analysis of ferro-manganese nodules.

### **German activities in polymetallic nodule exploration (1958 – 2000)**

The BGR in Hannover acts as Germany's federal geological survey and is accountable to the Federal Ministry of Economics and Technology (BMWi). It advises federal ministries and German industry on issues of (marine) natural resources and in this capacity carries out marine research and exploration campaigns related to deep-sea mineral resources.

As early as 1958, German scientific institutions and industry were evaluating the potential of the seabed as a source for economic minerals through scientific research and prospecting. These activities aimed to secure access for German industry to such 'unconventional' resources, particularly if land-based supply were to falter (e.g. due to political reasons or unexpectedly rising demand). Germany's predominant dependence on imports of various commodities was considered a reason for special safeguards to ensure continuity of supply. In 1968, a comprehensive study was undertaken by BGR, which laid the foundation for a major government programme that started in 1969. It aimed at assessing the economic potential of the seabed. Within this programme, research on deep-sea polymetallic nodules has played a major role since 1970, including 44 cruises with the research vessel *Valdivia* and 30 cruises with the R/V *Sonne*. Exploration concentrated on two regions; the Clarion-Clipperton Fracture Zone (CCFZ) area and the Peru Basin. These areas were selected because of the high abundance of nodules (up to 28 kg/m<sup>2</sup>) and their relatively high metal concentrations (around 0.2 per cent cobalt, 1.2 per cent copper and 1.5 per cent nickel).

Scientific campaigns by academic institutions and BGR focused on the genesis of nodules and related sedimentary processes. These efforts resulted in a great number of fundamental findings on the distribution and formation of nodules. The main objectives of the industrial exploration campaigns, led by the 'Arbeitsgemeinschaft meerestechnisch gewinnbare Rohstoffe' (AMR), including Preussag AG, were data collection related to abundance and grade of nodules and the development and testing of special exploration techniques. Detailed studies of seafloor relief and physical properties of sediments were also undertaken. Sufficient data were gathered to enable AMR to join Ocean Management Incorporated (OMI), an international consortium of companies planning to seek an exploration licence under US and German laws. A successful pilot mining test followed in 1978 during which several hundred tons of nodules were recovered. However, the subsequent price decline of commodities prevented the start of commercial extraction.

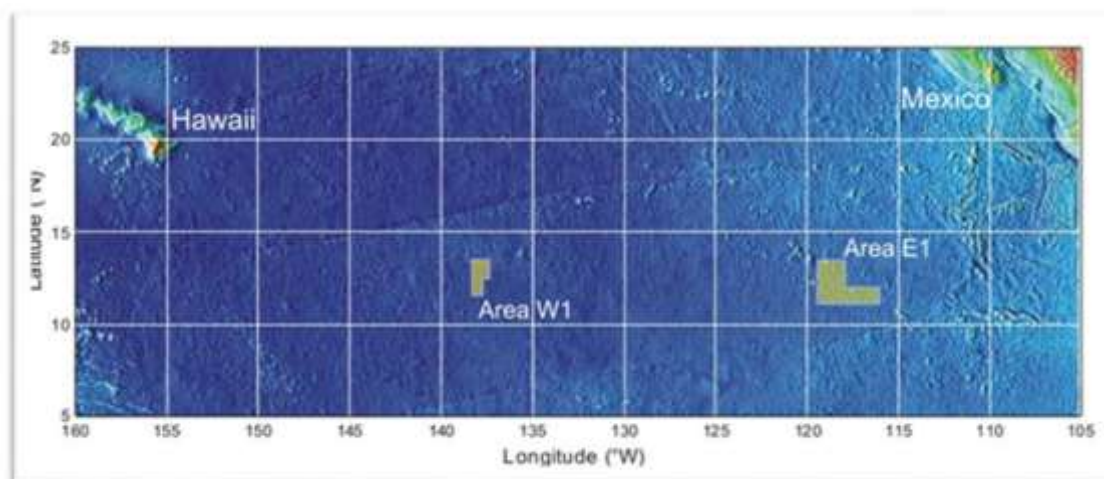
As a result of ongoing political changes (for example, the breakup of the former Soviet Union, which is associated with a declining mineral demand by its weakened economy) and new land-based discoveries, prices on the international metal market decreased significantly, and consequently the interest of German companies in deep-water prospecting and exploration of mineral resources dropped. The frontier research undertaken by BGR was deemed sufficient to build up and maintain relevant knowledge on marine resources in Germany. Governmental research programmes now focused on the assessment of the potential environmental impact of future deep-sea mining (e.g. the Tiefsee-Umwelt-Schutz [TUSCH] Deep-Sea Environmental Protection programme carried out between 1989 and 1996). Due to the prevailing unfavourable conditions on the metal markets, OMI was eventually dissolved in the 1990s. After the concurrent retreat of German industry from marine mineral resource issues, BGR inherited the archived exploration data from the Preussag Company. The marine archive comprises about 3,000 files with details on the expeditions, scientific data on the Pacific nodule belt including the German licence area, maps, numerous films and video tapes, and about 5,000 photographs of the seafloor.

## **Current German activities in polymetallic nodule exploration**

### ***Application for an exploration licence***

As a consequence of the recent economic growth (e.g. in China and India, and the recovery of the economies of the states of the former Soviet Union), metal prices have increased again since 2002. The unpredicted surge of commodity prices triggered new government interest in marine mineral resources: the German ministry (BMWi) commissioned BGR in 2005 to apply for an exploration licence for polymetallic nodules. Consequently, BGR submitted an application largely based on data from the former Preussag archive to the International Seabed Authority, and in July 2006 signed a contract for a licence area in the so-called 'Pacific nodule belt'. The area of interest covers 75,000 km<sup>2</sup> and is separated into two parts, W1 and E1 (Figure 1, Table 1).

**Figure 1:** German licence areas W1 and E1 for the exploration of polymetallic nodules, covering a total of 75,000 km<sup>2</sup>



Currently, BGR is preparing the first cruise (scheduled for October-November 2008) for a detailed exploration of the licence area using the research vessel *KILO MOANA* (University of Hawaii, Honolulu). The center of activities will be in Area E1 (Figure 1). Exploration work will concentrate on high-resolution bathymetric mapping using a state-of-the-art multibeam echo sounding system, and a survey of the geographical distribution and regional abundance of polymetallic nodules. In addition, chemical composition, including trace metals, will be determined using state-of-the-art equipment and methods with optimal detection limits. Furthermore, representative sampling using the giant box corer developed at BGR, as well as the recovery of deep-sea sediments using a gravity corer will be conducted. Polymetallic nodule mass samples will be retrieved by dredging.

**Table 1:** Basic parameters for licence areas W and E based on samples acquired during the 1970s and 1980s

Area	W1	E1
Area size (km <sup>2</sup> )	17,000	58,000
Water depth, average (m)	4,838	4215
Nodule coverage (kg/m <sup>2</sup> )	7.8	13.5
Nodule resources (10 <sup>6</sup> mt)	130	780
Average metal contents:		
Mn (%)	26.1	29.8
Fe (%)	6.4	7.1
Ni (%)	1.3	1.3
Cu (%)	1.0	1.1
Co (%)	0.23	0.15
Area	W1	E1
Ni + Cu + Co (10 <sup>6</sup> mt)	3.4	40
Number of sampling sites	124	195

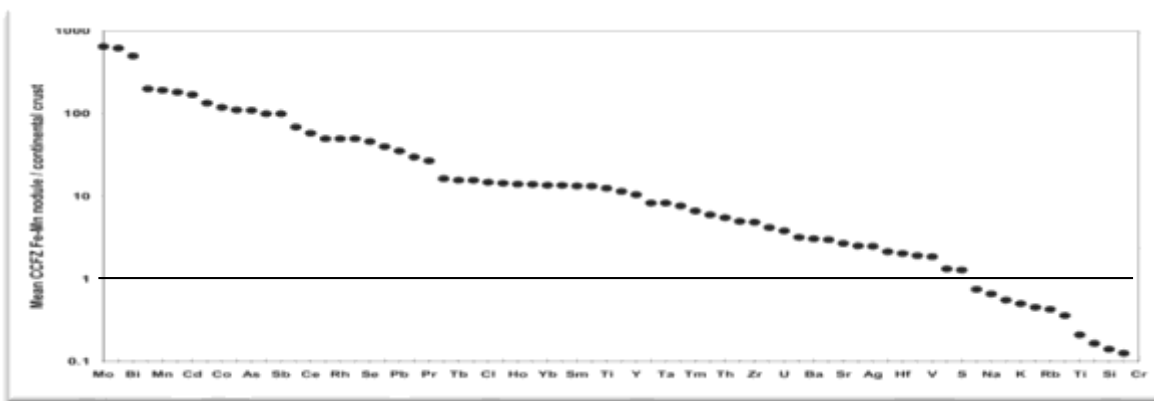
Furthermore, BMWi commissioned BGR to plan a series of projects regarding the technological and economic development of deep-sea mining and the processing of polymetallic nodules. The overall assignment addresses several aspects of polymetallic nodule mining, including: (a) an economic analysis of ore recovery from mining to smelting with consideration of future market trends; (b) exploration technology (acoustic detection system) for polymetallic nodules; (c) concepts for the extraction of nodules; and (d) the development of a specific metallurgical processing technology for polymetallic nodules. Although technological solutions were already available 25 years ago, all the above mentioned points require a complete reevaluation considering the substantial technological advances that have taken place in recent decades.

The results of several research projects on polymetallic nodules carried out during the past two years at BGR or Jacobs University in Bremen are presented below, as are details of the projects planned for 2009 and 2010.

### ***Trace element geochemistry of polymetallic nodules***

Polymetallic nodules recovered in the 1970s and 1980s have usually been analysed for Mn, Fe, Co, Cu and Ni only. More recent analyses indicate, however, that numerous so-called ‘electronic metals’ such as Te, Mo, and Pt, which are essential in high technology applications (solar panels, flat screens, mobile phones, optoelectronics), are also enriched in nodules (Figure 2) and should be included in their economic evaluation. Increased industrial demand for these elements during recent years has led to a shortage and a considerable increase in prices.<sup>1</sup> In contrast to the major elements, the concentration of trace elements in polymetallic nodules has been poorly studied, due to analytical problems and lack of economic interest in the past.

**Figure 2:** *Mean concentration of elements in CCFZ polymetallic nodules compared to the average composition of the continental crust.*



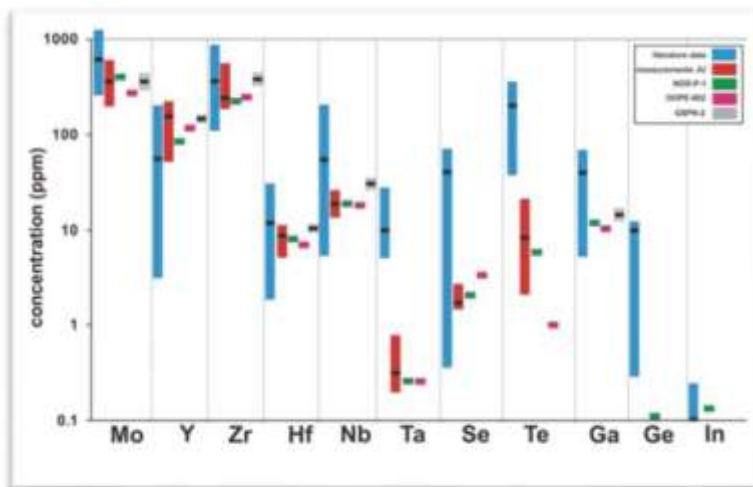
**Source:** Marbler et al., 2007 . Note. Element data from continental crust derived from various authors, compiled in the GERM Reservoir database: <http://earthref.org/GERM/>

<sup>1</sup> Te (tellurium – a Group 6 chemical element with an atomic number of 52), Mo (molybdenum – a Group 6 chemical element with an atomic number of 42), Pt (platinum – a Group 10 chemical element with an atomic number of 78).

To obtain an overview of current knowledge, BGR funded a research study in 2007 focusing on the elements Molybdenum (Mo), Niobium (Nb), Terbium (Tb), Zirconium (Zr), Hafnium (Hf), rare earth elements (REE), Yttrium (Y), Selenium (Se), Tellurium (Te), Gallium (Ga), Germanium (Ge), Gold (Au) and Silver (Ag), as well as the platinum group elements (PGE). Results from new measurements of nodules recovered from the CCFZ, which were carried out at the Jacobs University Bremen, and information on metal concentrations available from international reference samples were used for a critical comparison with published data. Relatively extensive data exists for REE but there are still discrepancies and gaps in the literature for La, Ce and Nd, and particularly for the elements Tb, Ho, Er and Tm<sup>2</sup>. Several publications from past decades also exist for Mo, Nb and Zr. The range of metal concentrations indicated in these papers, however, is very large and the mean values are too high compared to recent analytical results (Figure 3). For the elements Ta, Hf, Se, Te, Ga and Ge, only few data were found in the literature. Most of the concentrations given for these elements largely exceed modern state-of-the-art measurements, due to insufficient analytical methods and deficient sample treatment in the past.

Most problematic within the range of elements investigated in this study is the database for PGEs, which are highly important for economic purposes. Here, the values reported in the literature show very large ranges with diverse mean values from various analytical methods compared to recent measurements. This inconsistency might be an effect of inadequate sample preparation of the PGEs (digestion and element separation), as well as the application of inappropriate analytical methods. The development of new digestion, separation and analytical methods, especially for the elements Se, Te, Zr, Hf, Nb and Ta in polymetallic nodules, are in progress at Jacobs University in order to improve the accuracy and precision of measurement of element concentration in polymetallic nodules.

*Figure 3: Comparison of element concentrations of Pacific polymetallic nodules from literature data, recent measurements at Jacobs University (JU) and three reference standards, which derived from the CCFZ: NOD-P-1, OPOE602 and GSPN-2*



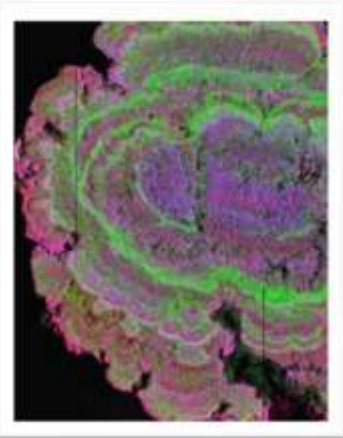
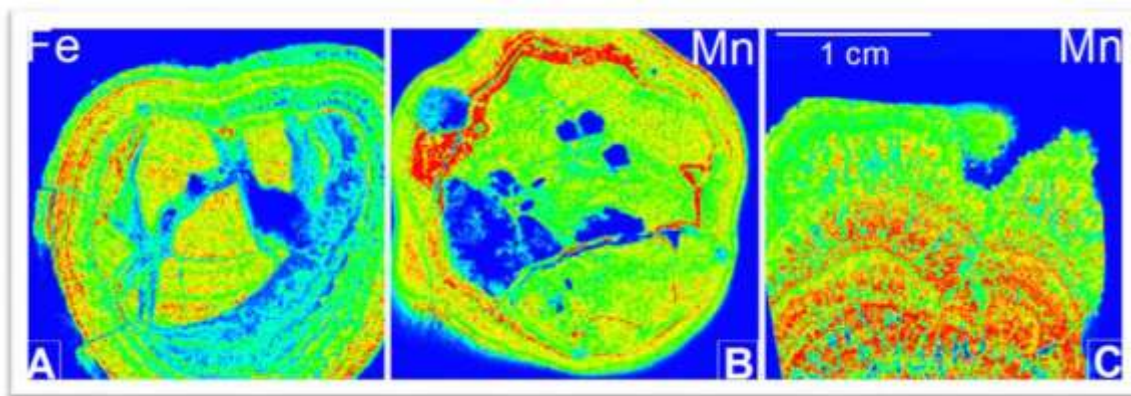
*Source: Marbler et al., 2007.*

<sup>2</sup> La (lanthanum - a Group 3 chemical element with an atomic number of 57); Ce (cerium - a Group 3 chemical element with a atomic number of 58); Nd (neodymium - a Group 6 chemical element with an atomic number of 60); Tb (terbium - a Group 11 chemical element with an atomic number of 65); Ho (holmium - a Group 13 chemical element with an atomic number of 67); Er (erbium - a Group 14 chemical element with an atomic number of 68), and Tm (thulium - a Group 15 chemical element with an atomic number of 69).

### ***Element distributions in polymetallic nodules using in situ $\mu$ -EDXRF***

The knowledge of the distribution of economically interesting elements in polymetallic nodules is important (e.g. in the metallurgical processing of nodules where suitable grain sizes are needed for the separation of the metal-bearing nodule fragments). In 2007 BGR initiated a study of the microchemistry of polymetallic nodules recovered from various locations within the Pacific nodule belt and the Peru Basin (Graupner and Wittenberg, 2007). For this study we: (a) adapted an existing energy-dispersive X-Ray fluorescence spectrometry technique ( $\mu$ -EDXRF) for routine measurement of nodules in order to visualize the major and trace element distributions; and (b) compared the spatially resolved element distribution data with high-quality, multi-element bulk analysis (these analyses are currently performed at BGR). The analytical work performed during this project has shown that the applied techniques are capable of providing a good range of geochemical information for a large sample suite of polymetallic nodules within a short time. The data from in-situ  $\mu$ -EDXRF provide a detailed characterization of the distribution of the major, and also some trace, elements in individual nodules at meso-scale (Figures 4 and 5). This characterization forms the basis of area selection for  $\mu$ -EDXRF investigation with extended counting times or using methods with higher spatial resolution (e.g. ESEM-EDAX techniques). Compiled micro-structural and geochemical information derived from in-situ  $\mu$ -EDXRF allows excellent area selection for extended scientific studies with high-resolution micro-structural and isotopic methods (e.g. Sr, O isotopes) or micro-scale quantitative chemical analysis.

*Figure 4: Element distribution patterns for iron and manganese obtained with in situ  $\mu$ -EDXRF on polymetallic nodules from the CCFZ (red = high concentration, green = low concentration).*



*Figure 5: Element distribution patterns for copper (red), cobalt (green), and nickel (blue) obtained with in situ  $\mu$ -EDXRF on a polymetallic nodule from the CCFZ.*

### ***Quality assurance in geochemical analysis of polymetallic nodules***

A fundamental part of any economic evaluation of deep sea mineral deposits is a reliable assessment of analytical data quality, not only for the major metals Mn, Fe, Cu, Ni and Co, but also for modern high technology metals such as Te, Indium (In),

Se, Ge, Ga, Thallium (Tl) and Rubidium (Rb).<sup>3</sup> For these trace metals, as well as for PGE and REE, analytical protocols are not well established and inter-laboratory results may cover a wide range. Furthermore, the available reference materials for polymetallic nodules frequently lack data for many key trace elements. In order to fill this gap the BGR has prepared a reference sample for which 50 kg of polymetallic nodules from the CCFZ and the Peru Basin have been ground and homogenized. This powder will form the basis of a proficiency test in an international inter-laboratory comparison study with a main focus on high technology metals. After evaluating the quality of analytical protocols and data, a certification process for a new batch of a polymetallic nodule material will begin.

### **Construction of a giant dredge**

Our planning of the exploration cruise scheduled for 2008 suggests the extraction of a few bulk samples of nodules of 1-2 metric tonnes. For this purpose we have constructed a chain-bag dredge to ensure sliding of the instrument atop the soft sediment in order to enable accumulation of the surface coverage of nodules (Figure 6).



*Figure 6: Chain-sack dredge adapted for use during the upcoming exploration cruise to the German licence area. The dredge has been fitted into a frame which is thought to prevent the sampling instrument from sinking into soft sediments and enabling sliding at the nodule-covered surface.*

### **Perspectives**

BGR further plans to initiate a series of pilot projects aimed at promoting small and medium-sized German enterprises to take an active part in innovative developments in marine technology. It is expected that the solutions and technical concepts suggested within the scope of these projects will be continued and realized through subsequent government funding. The pilot projects shall include:

1. An economic analysis of the industrial development of marine minerals. This project will consider the basic economic conditions for the future commercial use of marine mineral resources regarding major and trace elements. In particular, the enrichment of the electronic metals considerably exceeds those of land-based deposits in part and requires re-evaluation of the marine resources. An economic analysis will evaluate the worldwide commercial potential of polymetallic nodules. Questions to be considered are: (a) the worldwide demand for metals until 2030; (b) the recovery costs for polymetallic nodules including exploration, mining technology, vessel operation, transportation and nodule processing; (c) an environmental assessment for potential mining operations; and (d) a comparison of costs with those of terrestrial mining.

<sup>3</sup>. In (indium - a Group 13 chemical element with an atomic number of 49); Se (selenium - a Group 16 chemical element with an atomic number of 34); Ge (germanium a Group 14 chemical element with an atomic number of 32); Ga (gallium) - a Group 13 chemical element with an atomic number of 31), and Rb (rubidium - a Group 1 chemical element with an atomic number of 37).

2. The objective of a second project will be the development of a high-resolution hydro-acoustic system, including the software for the remote detection of nodule distribution and coverage. An efficient recording of these indicators is a prerequisite for the estimation of the profitability of deposits and the detailed construction of specific mining tools. Such a detection system may be based on the acoustic reflectivity signal, which has to be designed according to the frequency and signal characteristics of the nodules. In this respect, two potential approaches have to be tested: the application on board a vessel and on a deep-towed ROV or autonomous vehicle.
3. A conceptual study shall address the design of an innovative industrial-scale nodule mining system. Such a system should make use of the substantial technological advances over the past decades in the fields of automation, sensor technology and materials science. The study shall involve a mining vessel, lifting pipe, buffer, flexible hose and self-propelled collector.
4. Finally, BGR plans to assign a project that addresses the design of a processing method for nodules with special regard to electronic metals. The mass samples necessary for experiments will be recovered during the forthcoming cruise in 2008. The project shall deliver a detailed material flow analysis for optimized recovery of the major and trace metals. The result shall be a feasibility study and the concept for a pilot plant.

## Acknowledgements

The *in situ*-EDXRF measurements were performed and analyzed by Torsten Graupner and Antje Wittenberg, BGR.

## References

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- Marbler, H., A. Koschinsky and M. Bau (2007), Manganese Nodules: A Review, *Berichte zur Lagerstätten- und Rohstoffforschung*, vol. 50, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, pp. 58.

## Summary of discussion

With regard to the pressure-tolerant electronics, a participant asked whether Germany had got them working thus far and whether it had noticed any specific failures in the components that it had been using. Mr. Ruhlemann said that they had been developed by the Enitech company and had been tested up to 2,000 m. Another participant spoke of his experience with pressure-tolerant electronics, and said it had failed at 4,000 m. He asked whether Germany had experienced anything like that. The author said he would check and inform the participant.

A third participant said that any recovery scheme for getting at the electronic metals would critically depend on what kind of distribution one had after processing and asked whether Germany had



a specific scheme in mind. Mr. Ruhlemann replied that there was a proposal from the University of Aachen metallurgy department suggesting combined pyro and hydrometallurgical processing and that the expectation was for those electronic metals to be concentrated.

Another participant wanted to know more about the project on trace and rare elements and asked whether Germany had developed technology for their recovery and whether it had any estimates on the potential expenditures. Mr. Ruhlemann said that was one of the conceptual projects. He said that if the participant was interested in participating in the analytic portion of the project, he could get a few of the samples for free from BGR and take part in the interlaboratory comparison. Development of analytics would be done together with the universities in Germany, for example, Bremen University and Jacobs University.

To a question on how big BGR was, Mr. Ruhlemann replied that there were 700 employees in all. His unit had 17 employees, 2 of whom worked part-time on the project.

With regard to acoustics for the visualization of the polymetallic nodules, a participant asked how much progress the Institute had made with that work, in view of the fact that visualizing polymetallic nodules lying on the seabed was quite tricky. Mr. Ruhlemann replied that, at the moment, BGR had no experience with that; it was a future project.

Finally, a participant said he thought someone might have worked on the isolation of the microbes from the polymetallic nodules and asked whether they were bacteria, fungus, etc. The author replied that it was a project carried out by the BGR microbiology group and thus far there had been no ideas. It was something they wanted to check out.

## **CHAPTER 10      COMRA: Research and Development of Polymetallic Nodule Mining Technology in China**

Yang Ning, Changsha Research Institute of Mining & Metallurgy, Lushan Nanlu, Changsha, Hunan, China

Professor Yang Ning made a presentation on the development of polymetallic nodule mining technology by the China Ocean Mineral Resources Research and Development Association (COMRA). He said that COMRA had worked on a tracked miner and an Archimedean screw miner. He said that COMRA had also worked on hydraulic and mechanical collectors, and air and hydraulic lifting. Professor Yang also said that COMRA is working on a rigid riser system with a self-propelled miner. He presented details of the technical components of the pickup device, the miner and the riser. He informed participants that COMRA had carried out a successful trial of the system in a lake environment, and declared that the required modifications have been made to carry out tests in the 1,000 meter water depth range, and that the necessary model and simulation tests have been completed.

Professor Yang informed participants that COMRA's studies indicate that deep seabed polymetallic nodule mining is technologically feasible. He said that this was especially the case if polymetallic nodule mining was compared to cobalt-rich ferromanganese crust and polymetallic sulphide mining. He noted that with the help of technology from the offshore oil industry, deep sea mining should be economically feasible.

With regard to cooperation in technology development among contractors, Professor Yang suggested sharing data and participation in tests, joint environmental investigation and exploration, exchange of data and comparison of results.

During discussions, Professor Yang clarified that the depth of the lake where COMRA's test trial was conducted ranged between 5 and 8 meters. On the processing routes proposed by COMRA, the workshop was informed that COMRA had recovered molybdenum from nodules in addition to nickel, copper, cobalt and manganese. Participants wanted to know how COMRA proposed to obtain carbon monoxide in large quantities. There was also a discussion of the mining system proposed by COMRA, in particular the number of pumps it would use. Professor Yang informed participants that two pumps would be used.

Professor Yang did not prepare a written report for his presentation. He however presented slides. These slides are reproduced in the following pages followed by a summary of his presentation.



## RESEARCH AND DEVELOPMENT OF POLYMETALLIC NODULE MINING TECHNOLOGY IN CHINA



Chennai India  
19 February 2008

1.

## COMRA's Progress in the Development of Polymetallic Nodule Mining Technology



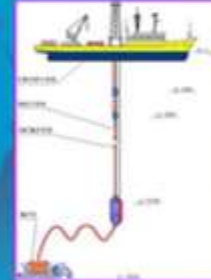
### 1.1 Prototypes of Poly-metallic Nodule System Mining developed by COMRA

Supported by the national project, COMRA has built some laboratories which can carry out collecting and lifting tests of the nodules. Some methods and new ideas about the nodules mining technology were tested, such as the tracked miner and Archimedes screw miner, hydraulic collectors and mechanical collectors, the air lifting and hydraulic lifting, etc.



### Model Poly-metallic Nodule System Mining

Based on the preliminary research, a design proposal of the mining system for pre-pilot mining test has been finally determined, which consists of the surface vessel, the rigid lifting pipe, a buffer, the flexible hose and the self-propelled miner.



### Model Poly-metallic Nodule System Mining

#### Hybrid pickup device:



Hybrid Pickup Device

The pick-up device developed here consists of an upper baffleplate and a lower baffleplate, front jets and rear jets. The upstream, which was produced by two rows of the jets working together. The water from the nozzle mounted at proper position supplied power. Nodules from double jets system were caught and transported to certain height.

It is simple in structure which consists of two pumps, pipes and jets, reliable in working, only single power supply, high pick up rate, and low sediment content.



### Model Poly-metallic Nodule System Mining

#### Miner:

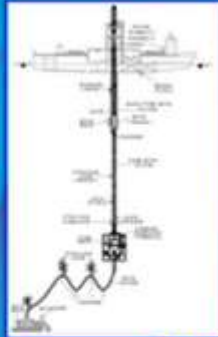
A self propelled miner was designed and tested. It is composed of a caterpillar tread, the driving wheels, the guide wheels, the loading wheels, the supporting wheels, a frame, and the hydraulic system. The miner can move forward and backward, turn around, and brake freely on extremely soft soil.



### Metall Poly-metallic Nodule System Mining

#### Hydraulic lifting system:

A hydraulic lifting system was proposed, which includes the vertical rigid steel pipes, slurry pumps, the buffer and the flexible hose. In this system, the flexible hose connects the buffer and miner, and some buoyancy balls are attached at two points of hose so that the flexible hose form a saddle shape near the seafloor.



### 1.2 The Trial of Partial Mining System in the Lake

COMRA carried out a trial of port mining system in a lake in 2001. Major tasks in the lake trial include:

- ▶ Maneuverability test of miner
- ▶ Lifting trial of transportation subsystem of flexible hose
- ▶ Integrated trial of collecting and lifting
- ▶ Operation and controllability of the whole system



### The Trial of Partial Mining System in the Lake

In the trial, partially simulating deep-sea condition, the artificial nodules lying on the floor of lake was collected by the collector and transported up to the surface vessel by flexible hose.



### The Trial of Partial Mining System in the Lake

#### Environmental condition

Water depth	120~140m
Wave and winds	≤ grade 4
Abundance of artificial nodules	5~10kg/cm <sup>2</sup>
Diameter of artificial nodules	3~5cm
Area paved	300×100m
Shear strength of the sediments	≤3KPa
Inclination of the lake bottom	≤5°



### The Trial of Partial Mining System in the Lake

The trial system in the lake consists of three parts: miner, transportation system of flexible hose and surface vessel. The miner used in the lake test can work 1000 meters underwater. There are no the steel pipes and buffer due to 140 meters water depth only. The lifting pump is a centrifugal slurry pump of 8/6EG. The surface ships used in the lake test are not mining ship as future.



### The Trial of Partial Mining System in the Lake

The trial in the lake started from June, finished in September. The results show that the devices of the trial system run properly. The whole mining operation process of collecting artificial nodules from the floor of lake and transporting up to the surface vessel is realized.



The environment investigation has been conducted after the mining trial; the results indicate that trial in lake has tiny influence on the floor of lake and water column.





### L3 Preparation of the 1000m sea trial

Taking the differences of lake and sea into account, COMRA plans to test the developed nodules mining system in shallow sea about 1000m depth. Preparation of the sea trial has been done in two aspects:

- Modification and upgrade of the mining system
- Virtual reality research of the operation of the 1000m sea trial system



#### Modification and upgrade of the mining system

##### Modification of Miner

Based on the results of the lake tests, some parts and structure of the miner are improved, such as control of total weight and distribution of buoyancy, renovation of the power supply, and design of trajectory control.



#### Modification and upgrade of the mining system

According to the requirements of 1000 meters sea trial, technical specification for the lifting pump used in steel pipelining is proposed. Structure of the pump is defined after simulating tests of the passage. A proposal for four stages pump is worked out. As a prototype, a pump of two stages is manufactured, then tested with fresh water and the artificial nodules. Design of the power supply for the lifting system is fulfilled at same time.



#### Modification and upgrade of the mining system



Two stages pump



#### Virtual reality research of the operation of the sea trial system

The dynamic analysis of COMRA's polymetallic Nodule mining system has been carried out taking into account the ocean environment facts of 1000-m depth. The dynamic models and the virtual prototypes of the subsystem in the mining system have been built and form the whole mining system. The kinematic and dynamic characters of the whole system and the cooperating maneuver among the subsystems have been calculated and evaluated.



### Virtual reality research of the operation of the sea trial system

#### Dynamic Analysis of Mining Pipeline:

The 3-D dynamic models of the 1000-m pipeline subsystem have been built and simulated by using the finite element method and discrete element method. The pipeline motions performance under the different operation conditions are discussed and forecasted. Some effective suggestions for the operation of the mining system during the mining are given. Also the experiments which verify the accuracy of the simulation results of the pipeline dynamic models in towing tank were carried out.



COMRA

### Virtual reality research of the operation of the sea trial system

#### Evaluation on the Maneuverability of Miner:



The dynamic models and virtual prototype of the pilot miner were built and simulated. The dynamic characters of pilot miner were investigated. Moreover, the simulation model and results of the pilot miner have been verified successfully using the measured data of the pilot-miner in lake trial.

COMRA

### Virtual reality research of the operation of the sea trial system

#### Dynamic Analysis of the Launching Process:

The launching process of the pipeline subsystem has been simulated. The behaviors of the flexible hose during the launching have been investigated and evaluated. Some significant results have been obtained. For example, to avoid entanglement and form the saddle shape of the flexible hose, it is necessary to have the suited speed between pipe launching and the miner during the launching.



COMRA

#### 1.4 Construction of research centers of deep sea mining technology

To strengthen the research of key technologies for the deep sea mining system, COMRA enhances the construction of research facilities.

COMRA

### Research centers of deep sea mining technology

#### Miner test laboratory :



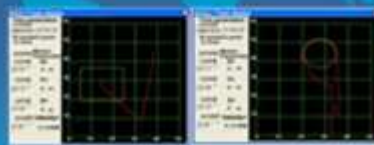
A new laboratory for the miner test and a new installation for the lifting test were built up in 2006. The laboratory consists of a basin(50\*50\*5m), a workshop, position system and data collecting system.

COMRA

### Research centers of deep sea mining technology

#### Miner test laboratory :

Artificial sediments are paved on the bottom of the basin to test the traction and manipulation of the miner. If artificial nodules are paved on the bottom, collecting tests can be carried out.



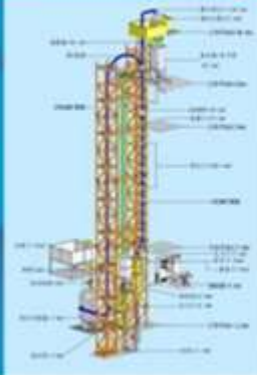
the track of the miner travelled in the basin

COMRA

Research centers of deep sea mining technology

Lifting test laboratory :

Newly built lifting test installation includes two towers of pipestrings, five working platforms and instrumentations. The height of two towers is 30 meters. Inner diameter of lifting pipe is 204mm. One way and circular lifting tests can be run in this laboratory.



Research centers of deep sea mining technology

Lifting test laboratory :

Circular lifting test, the nodules in the storage bin can fall back to the storage bin after passing the feeder, the pump and the pipe. To simulate sea level during the tests, the storage bin and water tank is acted on water head of 30 meters to make back flow close to mining operation as much as possible. With such set of lifting, pump can be tested under low revolution, and simulation of discharge for the pipestrings can be done when accidental stop is encountered.



Research centers of deep sea mining technology

Lifting test laboratory :

One way transporting tests: The nodules transport directly to a separator with pressure regulation via the feeder, the pump and pipe. Nodules no longer return to the storage bin. Maximum pressure can reach 2.5MPa by adjustment of the opening of the valve. With such set of lifting test, the pump performance with nodules can be obtained.



2.

Prospects For Mining Deep Sea Poly-metallic Nodules



2.1 Increasing demands for the deep sea minerals due to development of economy



2.2 Feasibility of deep sea mining



Last century, pilot mining test by OMI, OMA and OMCO verified the feasibility of the principle and method of the deep sea mining. Although there is no breakthrough in deep sea mining technology in 21st century, offshore oil industry achieves gratifying successes.



### Feasibility of deep sea mining

Global production of offshore oil reaches 20% of total oil production. Water depth for oil production offshore is over 2000 meters, furthermore exploration area ranges up to 2500 meters water depth or even deeper.



### Feasibility of deep sea mining

Underwater power supply, instrumentation and materials technologies from the offshore oil and supplementary operation will support the development of pipeline transportation, seabed vehicles and surface ship in Poly-metallic nodules mining system.



### Feasibility of deep sea mining

Deep sea mining is feasible on the view point of technology. Especially comparing with cobalt-rich crust and massive sulfide, poly-metallic nodules are easy to be mined. With the help of technologies from offshore oil industry, deep sea mining should be economically favorable.



### 2.3 Acceptable in environmental impacts caused by deep sea mining

#### Is environmental impacts caused by deep sea mining acceptable?

Some researchers propose that the impacts by deep sea mining can be curbed to acceptable level, whereas some researchers suggest that the impacts by deep sea mining will be less than that by land mining.



Excavations of land mining



Acid Drainage of land mining



### Acceptable in environmental impacts



- Results from dredging industry for waterway show that quality of water and ecosystem can recover in a short time.
- A monitor research shows that the seawater quality and plankton status recovered basically in a month after the disposal activity of 500000 m<sup>3</sup> dredging tailing.
- The similar results was obtained in our lake test.



## 3.

### Proposal for The Cooperation on The Development of Deep Sea Mining System





### 3.1 Exchange of data and comparison of results for vertical lifting and flexible hose transporting

Last century pipeline transporting in deep sea mining system was used to conduct successful mining tests, such as OMI. Right now, COMRA and KORDI develop the mining system based on pipeline transporting, NIOT proposed soft mining system at same time. There are some diversity but more or less similarity on those system.



COMR

### 3.1 Exchange of data and comparison of results for vertical lifting and flexible hose transporting

It is necessary for ISA coordinating a cooperative project to exchange data and achievements in the development of vertical lifting and flexible hose transporting. Thus costs, performance and environmental impacts can be analysed under same condition.

COMR

### 3.2 Participating tests and sharing facilities

Deep sea mining system is a complicate large scale equipment and custom made. Vast investment is needed during research and development. Facilities and requirements are high. The contractors have set up several facilities themselves separately, and prepare large scale tests. These facilities and tests possess similarity or complementarities possibly. To reduce costs of research and development and increase efficiency of research and development, cooperative scheme should be set up by ISA to enable participation of large scale tests and share of facilities.

COMR

### 3.3 Jointly participating survey of environmental investigation

Understanding environmental parameters of deep sea, especially the Area, is basic requirements for the development of deep sea mining system. At same time this is a bottleneck for the engineers working in deep sea mining due to lack of sufficient information. The cruises of investigation for manganese nodules arrange in a large scale, data collecting during those cruises cannot serve as design basis. It is strongly suggested that contractors arrange special cruises of environmental investigation objected to the design of deep sea mining system. Researchers from different country can participate jointly in such cruises.

COMR

### 3.4 Jointly organizing large scale sea trial

After 80's last century, no test in deep water is carried out with deep sea mining system. Pilot mining test is one of necessary procedure before we start commercial mining of deep sea minerals based on recent technical development. Twenty years past, it is necessary and sufficient to mine manganese nodules with a new deep sea mining system equipped by modern technologies. In fact, NIOT, COMRA and KORDI conduct or prepare various sea trials; Therefore a large scale sea trial is expecting that coordinated and organized by ISA to exploit our advantage to the full, to increase efficiency, and to improve quality.

COMR

Thank you for your attention!

COMR

## **Summary of presentation**

Professor Yang said that the presentation from COMRA would be in two parts. He would introduce COMRA's mining system development and Mr. Jiang would introduce the mineral processing and economic analysis. He began with brief statement on COMRA activities.

### ***Prototypes of nodule mining system developed by COMRA***

He said that in China, a national project had been initiated led by COMRA in which a number of laboratories had been built to carry out collecting and lifting tests of nodules. He said that some old methods and new ideas about nodule mining technology were tested, such as the tracked miner, Archimedes screw miner, hydraulic and mechanical collectors and air and hydraulic lifting.

Professor Yang said that COMRA had developed a hybrid pick-up device. It had two rows of jets (front and rear) to wash the nodules and push them up to a certain height from which they fell into the crusher after the nodules collected had been crushed into small sizes for transportation. Professor Yang said that the device had been chosen because it had a relatively simple structure without moving parts. A hydraulic lifting system, which included vertical rigid steel pipes, slurry pumps, the buffer and the flexible hose had been proposed. In that system, the flexible hose connected the buffer and miner and some buoyancy balls were attached at two points of the hose to form a saddle shape near the seafloor.

Professor Yang reported that COMRA had a partial mining system which had been tested in a lake. COMRA had carried out a trial of a port mining system in a lake in 2001. He said that the major tasks in that trial had included:

- Manoeuvrability test of the miner
- Lifting trial of transportation subsystem of flexible hose
- Integrated trial of collecting and lifting
- Operation and controllability of the whole system

Professor Yang said that artificial nodules had been prepared and placed on the lake bottom. He showed a photo that had been taken by an AUV after paving the bottom of the lake with the artificial nodules. The water depth of the lake was between 120 and 140 m; wave and winds were less than grade 4; abundance of artificial nodules was 5 to 10 kg per m<sup>2</sup>; diameter of the artificial nodules were from 3 to 5 cm; the area paved was 300 x 100 m; shear strength of the sediments was less than 3 kPa; the inclination of the lake bottom was less than 5 degrees. Because the partial system was only about 1,000 m, a flexible hose had been used. A pump had been put in the middle of the pipe and two buoyancy balls had been attached at two points to the hose to form a saddle shape and then the miner could move forwards and backwards. Researchers had spent three months on the lake, had done an AUV test and also an environmental investigation and a mining test together.

### ***Preparation of the 1,000 meter sea trial***

Professor Yang said that, taking the differences of lake and sea into account, COMRA planned to test the developed nodules mining system in shallow seas at a depth of about 1,000 m. Preparation for the sea trial had been done in two parts: first the modification and upgrade of the mining system and second, the virtual reality research of the operation of the 1,000m sea trial system. COMRA was trying to reduce the weight of the miner and renovate the power supply and the trajectory control.

According to the requirements of the 1,000-metre sea trial, Professor Yang said that technical specifications for a lifting pump used in steel pipe string was proposed. After the simulation test COMRA defined the structure of the pump and proposed a four-stage 1 cm pump. COMRA also decided that before designing and manufacturing the four-stage pump, it would build a prototype two-stage pump and test it with fresh water and artificial nodules. The design of the power supply for lifting nodules would be fulfilled at the same time.

Professor Yang showed a picture of the pump that would be built in China. He indicated the curve with fresh water in which to put the nodules with concentration of 5 and 8 per cent. Secondly Mr. Yang used virtual reality research to imitate the operation of the sea trial. He said that COMRA had put the whole system in operation to see how it would react and how to control such a system. The launching process had also been simulated. He also said that when the system was being launched, it was necessary to know the manner in which it contacted the bottom and moved forward.

After working for several years preparing for the 1000 meter test, Professor Yang said that COMRA had found that researchers had financial problems; the money from the Government had been reduced. The team had therefore shifted its research back to the laboratories. In 2005, COMRA had started to support the construction of a deep-sea mining research centre with the aim of strengthening the research of the key technologies for the deep sea mining system.

The team had built a miner testing laboratory within a basin that was 605 metres deep. It also had a lifting test laboratory. The team also built new instrumentation. With the circular lifting test, the nodules in the storage bin were fed into the pump system. When they fell back, parameters could be obtained for the lifting at different concentrations.

### ***Prospects for mining deep-sea polymetallic nodules***

Professor Yang said that Mr. Jiang would talk more about prices, which had increased dramatically. Over the past century, pilot mining tests by Ocean Mining Associates (OMA), the Ocean Managed Inc (OMI) and the Ocean Minerals Company (OMCO) had verified the feasibility of the principle and method of deep-sea mining. Although there had been no breakthrough in deep-sea mining technology in the twenty-first century, the offshore oil industry had achieved gratifying success.

Global production of offshore oil had reached 20 per cent of total oil production. Water depth for oil production was over 2,000 m; furthermore, the exploration area ranged up to 2,500 m deep, or even deeper. Underwater power supply, instrumentation and materials technologies from the offshore oil and supplementary operation would support the development of pipeline transportation, seabed vehicles and surface ship in the polymetallic nodules mining system.

Deep-sea mining was feasible from the viewpoint of technology. Especially compared with cobalt-rich crusts and massive sulphide, polymetallic nodules were easily mined. With the help of technologies from the offshore oils industry, deep-sea mining should be economically favourable.

### ***Acceptable environmental impacts caused by deep-sea mining***

Professor Yang said that the results from the dredging industry for waterways showed that the quality of water and the ecosystem could recover in a short time. China had done monitoring research at the University of Zhongshan. The research showed that the seawater's quality and plankton status

recovered basically in a month after the disposal activity of 500,000 m<sup>3</sup> dredging tailings. Similar results had been obtained in the lake test. Mr. Yang made a proposal for cooperation in the development of deep-sea mining, as follows:

### ***Proposal for cooperation in the development of a deep-sea mining system***

#### ***1. Exchange of data and comparison of results for vertical lifting and flexible hose transporting***

During the past century, pipeline transporting in the deep-sea mining system had been used to conduct successful mining tests, such as OMI, COMRA and KORDI are now developing the mining system based on pipeline transporting. The Republic of Korea and China have almost the same system. NIOT proposed a soft mining system with the flexible hose at the same time. There was some diversity, but more or less there was similarity in those systems.

The International Seabed Authority should coordinate a cooperative project for the exchange of data and achievements in the development of vertical lifting and flexible hose transporting with a view to reducing the costs.

#### ***2. Participating in tests and sharing facilities***

A deep-sea mining system is a complicated, large-scale equipment and custom made. Vast investment was needed during the research and development phase. Facilities and requirements were costly. The contractors had set up several facilities themselves separately and had prepared large-scale tests. The facilities and tests possessed similarities and possibly complemented each other. To reduce the costs of research and development and increase efficiency of research and development, a cooperative scheme should be set up by the Authority to enable participation by contractors in large-scale tests and sharing facilities.

#### ***3. Joint survey of environmental investigation***

Understanding the environmental parameters of deep sea, especially the area, was a basic requirement for the development of a deep-sea mining system. At the same time, that was a bottleneck for the engineers working in deep-sea mining, due to a lack of sufficient information. The investigative cruises for polymetallic nodules arranged for large-scale data collecting during those cruises and so could not serve as a design basis. It is strongly suggested that contractors arrange special environmental investigation cruises geared towards the design of a deep-sea mining system. Researchers from different countries could participate jointly in such cruises.

#### ***4. Jointly organizing a large-scale sea trial***

Since the 1980s, no deep-water test had been carried out with a deep-sea mining system. A pilot mining test was one of the necessary procedures before we start commercial mining of deep sea minerals based on recent technical development. Twenty years earlier, it had been necessary and sufficient to mine polymetallic nodules with a deep-sea mining system equipped with modern technologies. In fact, NIOT, COMRA and KORDI had conducted or prepared various sea trials. Therefore a large-scale sea trial was expected to be coordinated and organized by the Authority to exploit the COMRA advantage to the fullest, to increase efficiency and to improve quality.

## Summary of discussion

Professor Yang was asked what the water pressure of the jets that were used on the collector was and also what the flow rate was. He replied that the pressure was very low - 5 to 6m – and that the flow rate was 12mm per minute.

When asked whether COMRA had an auto-leveling rate, the presenter said that they had to adjust and that they actively adjusted by hydraulically raising and lowering.

A participant asked how COMRA hoped to generate carbon monoxide in the larger version of the process and whether it was using carbon monoxide. Professor Yang said they had not reached that point in research.

Turning to processing, one of the participants said that, when it came to smelting Professor Yang had said that 92 to 95 per cent of the metals, namely, nickel, cobalt, copper and iron, were recovered in the alloy. The question was how much manganese went in there. The reply was 7 to 9 per cent.

Another participant asked whether, in view of the closeness of the two lines on the Ellingham diagram for manganese and copper reduction, he had observed co-relation between manganese and copper recovery. The author said he was not aware of the actual work and hence, did not know.

One participant wanted to know, given the fact that Chinese nodules were close to 3 per cent total metals, what the cobalt content was. Professor Yang replied that cobalt was 0.16 per cent; the quality was less than that of the Indian nodules.

Another participant asked what the size of the pump was and how many would be required in the riser system for the 5,000 m water depth. The reply was that it was about 600 mm in diameter and 4 m in length; the power was 200 kw and the flow rate was 3.

Another participant asked what was being pumped for 5,000 m, how many of those pumps were needed in the line of the riser. Professor Yang replied that two pumps were needed; one placed at 800 metres below the sea and the other at 2,000 m.

The Deputy to the Secretary-General said that Professor Yang Ying had indicated several routes for processing and that he was suggesting that, at present, there were no estimates of operating costs and capital costs for processing. The author replied that that was also his question; he could not answer.

With regard to the suction pump installed in the buffer, a participant asked about its flow rate and power consumption. Professor Yang said that he did not have many details but that it depended on the flexible hose: 150 mm and about 300 m<sup>3</sup> per hour. Pressure was about 80 m for 200 m of flexible hose.

A participant was curious about the use of nodules for nano tubes and about some research that COMRA had initiated in collaboration with universities and laboratories. The author invited him to see the university website for more details.

A participant observed that in the miner, the interconnectable flexible system had a double-S shape; it was not one that fit normally. He wanted to know whether there was any specific reason or

advantage to that. Professor Yang said that when the self-propelled miner had been chosen, if there had been just one peak, then the force on the miner would have been higher and they would not have been able to control the miner. With assimilation, there were two at the side and thus they had freedom in the bottom.

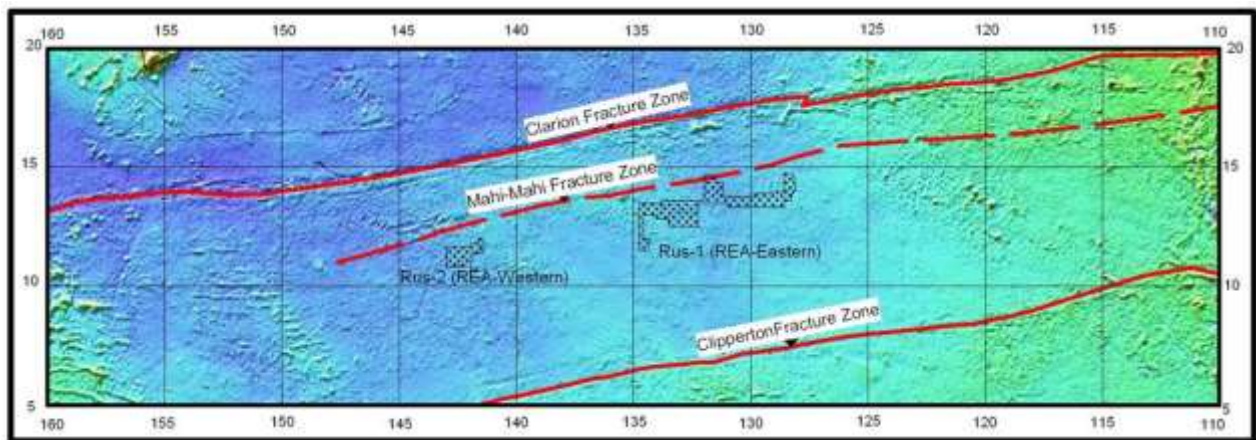
A participant with ROV background said he had done that to a lot of ROV systems and what it did was increase the numbers watch circle, the area in which one could work; it afforded some more compliance and removed the heave compensation portion of the ship going up and down. If there were only one and there were two smaller watch circles, as the ship heaved, the system would be pulled off the bottom.

## CHAPTER 11 The Concept of Engineering and Technological Support for Mining and Processing Polymetallic Nodules from the Russian Exploration Area

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The Russian Exploration Area (REA), which covers 75,000 km<sup>2</sup>, incorporates two territories (Figure 1); an Eastern territory (61,600 km<sup>2</sup>) and a Western territory (13,400 km<sup>2</sup>). The cumulative resources of the polymetallic nodules within the REA (as dry mass) are assessed at 448 million tonnes. The average percentage concentrations of commercially valuable components in the nodule ore of the REA add up to: nickel – 1.39 per cent; copper – 1.1 per cent; cobalt – 0.23 per cent; manganese 29.3 per cent.

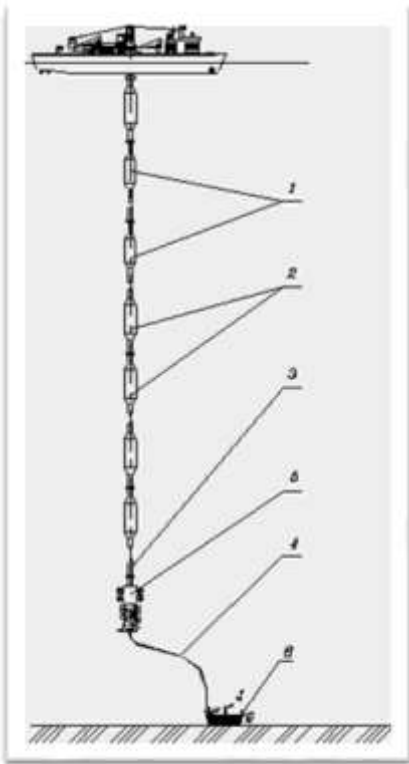
*Figure 1: Location of the Russian Exploration Area (REA) within the Clarion-Clipperton Zone*



The basic conceptual decisions for the commercial exploitation of polymetallic nodules in the REA were taken in our country in the early 1980s. The decisions were aimed at the creation of a future mining enterprise, with production at the maximum level permitted by the United Nations Convention on the Law of the Sea, and based on paragraph b of article 151 of that Convention. As is known, this article limits the maximum annual nickel production from polymetallic nodules to 46,500 metric tonnes. Considering the aforementioned average concentrations of this metal in nodules from the REA, the estimated output of a future mining enterprise will be about 3 million tonnes of dry nodules per year.

The conceptual basis for the exploitation of polymetallic nodules from the REA implies mining operations involving three mining complexes, each with an annual production of 1 million tonnes of dry nodules, with subsequent transportation and processing of the recovered ore mass in one of the metallurgical plants in the Russian Federation. The technological solutions that were developed as a result of the engineering design imply that each mining complex consists of three elements: a mining vessel; a self-propelled collecting device; and an air-lift system. The basic diagram of the mining complex is given in Figure 2.

Although the possibility of mining polymetallic nodules from a depth up to 6,000 meters was experimentally demonstrated by an international consortia (OMCO, OMI, OMA, KCON) in the early 1970s, many aspects of conducting commercial mining operations still remain unclear.



**Figure 2:** *Structural scheme of the mining complex*

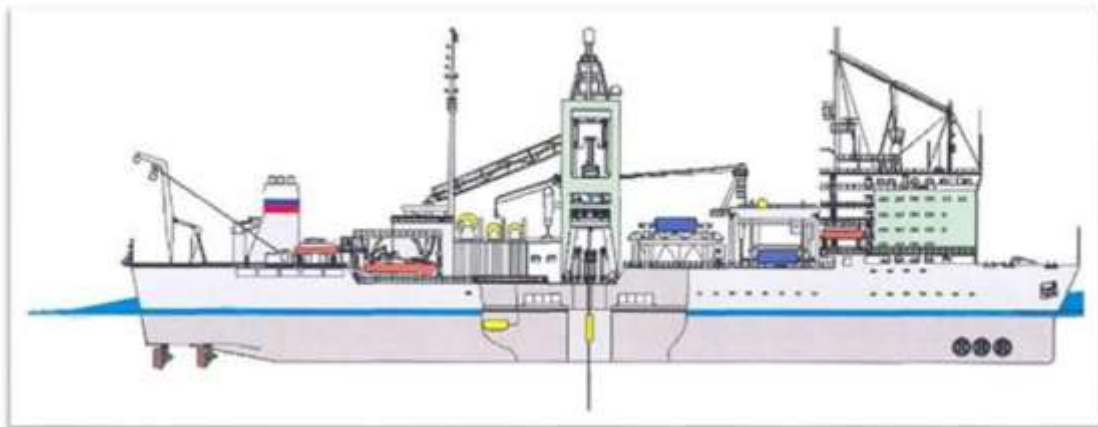
**Legend:** 1.Pumping pipe sections; 2. Pipe sections with buoyancy blocks; 3.Ordinary pipe sections; 4. Flexible manifold; 5. Platform; 6. Collecting unit

In this context, continuing research and development (R&D) of technological aspects of nodule mining is fully justified. The first priority of such research and development should be the creation of a pilot mining complex. The results of full-scale experimental tests at this complex, including the pilot mining of about 10,000 tonnes of nodules, will make it possible to make final decisions about the engineering and technical support for the pilot mining of polymetallic nodules. In accordance with the contractual obligations of Yuzhmorgeologiya, the creation of such a complex was planned for the period after the completion of three stages of exploration activity. The specifications of the basic elements of the mining complexes for the pilot and commercial development of the polymetallic nodules deposits are given below.

### **Mining vessel**

According to Russian experts and many other international specialists, the type, displacement, power requirements and equipment of the mining vessel require specialized and sophisticated hardware and equipment, in particular, a system of dynamic positioning, which should be similar to that of the famous specialized vessel *Glomar Explorer*. An approximate view of the mining vessel is given in Figure 3.

**Figure 3:** *Mining vessel configuration*





*Table 1: Specifications for pilot and commercial mining of polymetallic nodules*

Specification	Vessel designation	
	Commercial mining	Pilot mining
<b>Main dimensions, m:</b>		
- overall length	230	173
- midship breadth	32	27
- hull height	18.3	14.2
Draft, m	10	8
Tonnage, t	70,000	25,000
Hull capacity, t	30,000	2,000
Power-plant capacity, M Wt	37.8	24
Crew number	180	180

Due to the currently unpredictable development of the world economy, it is difficult to evaluate the capital investment for the construction of mining vessels. Nevertheless, we calculated that the construction cost for the pilot mining vessel will not exceed US\$200 million, and that an average vessel for commercial mining would cost \$300 million.

### Mining unit

As was mentioned above, the Russian concept for the engineering and technical support for mining operations gives preference to a mining unit, which consists of a hydraulic pumping system and a self-propelled device for collection. The functional design of the collection device requires excavation of the ore mass and its preparation for transportation to the mining vessel. The design of the collecting device was developed by our specialists on the basis of a modular structure (Figure 4).

Presently, the technical requirements for the collectors for both pilot and commercial mining (Table 2) have been set, the design documentation prepared, and the prototypes of the basic units of the collector for pilot mining have been constructed. Various approaches to the module arrangement were studied for their optimum configuration (Figure 5).

*Table 2: Technical requirements for collectors for both pilot and commercial mining*

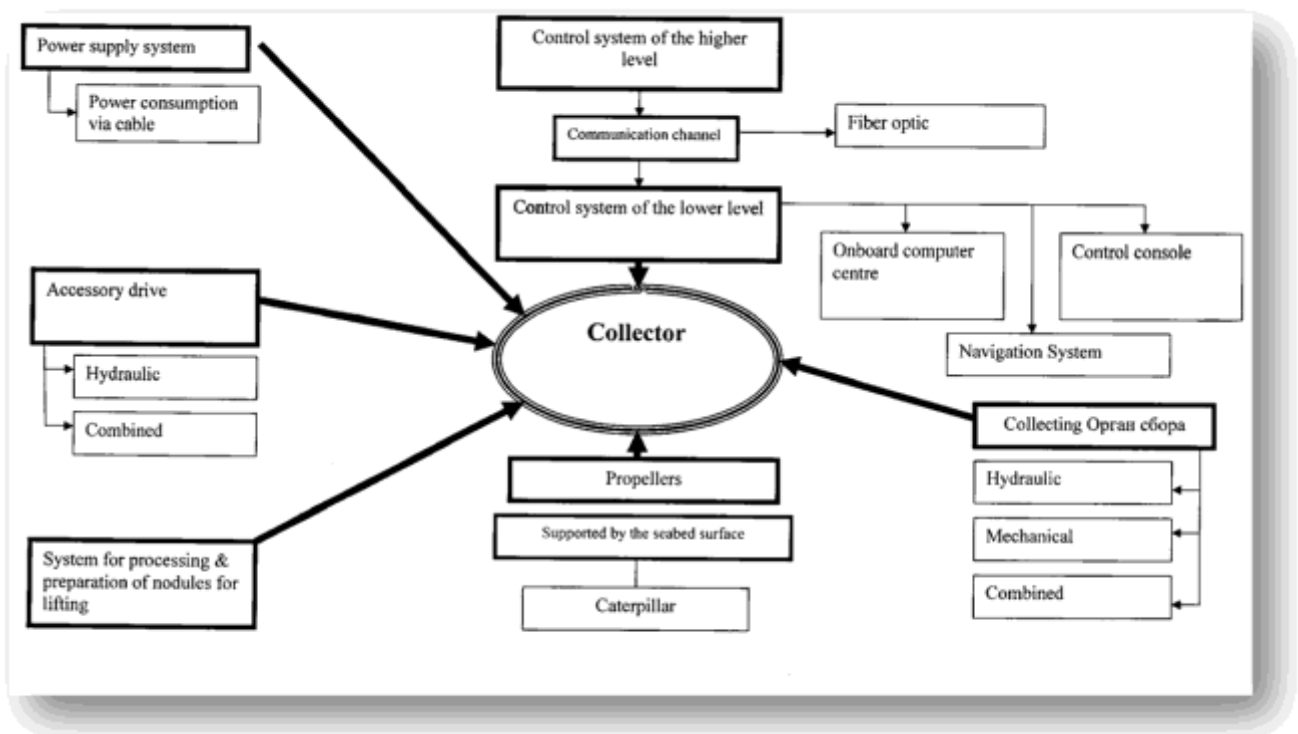
Specification	Collector designation	
	Commercial mining	Pilot mining
Capacity tonnes/hour	to 300	30
Collector speed, m/s:		
- when mining	0.5	0.5
- when maneuvering	0.5÷1	0.5÷0.8
Height of the obstacles to be overcome (without changing the collector track), m:		
- in automatic mode (without operator), m	0.3	0.3
- in manual mode (with operator)	>0.3	>0.3
Acceptable change of seabed relief (without reassembly of the pipe column), m	70 (200*)	70 (200*)
Swath of the collector, m	~ 20	3-5
Swath acceptable for maneuverability of the collector without changing the vessel track, m:		

- with simultaneous vessel and collector tracks	100	100
- with lateral slicing	170	170
Consumed power in the mining mode, kWt	?	1,990
Mass, t	?	30

The following considerations control the basic policy of Russian specialists working on the problem of the creation of the commercial variant of a self-propelled collecting device:

- From the technical and the environmental points of view, the best way of obtaining thrust for the collecting device is by using a caterpillar movement. This is able to provide substantial load capacity and drag force on the very soft and friable seabed. Slip can be regulated. The caterpillar tracks destroy the sea bed to a lesser extent than, for example, an Archimedean screw
- All types of movement (acceleration, stops, bends and slip) have to be regulated and checked in situ with the help of microprocessors in order to minimize the amount of data transmitted via cables in both directions
- For automatic control, sensors controlling the position and speed of the caterpillar tracks, and also the altitude above the sea bed, should be constructed

*Figure 4: Flow Chart of the collector*



- An important requirement of the design is the separation of nodules from sediment, both after collection and before their transportation through the pipe column. This is important in view of the need to maximize the amount of sediment left behind on the seabed left , together with the benthos and microfauna that will preserve seabed life

- The disturbed sediments have to precipitate on the seabed under the collector and after it whilst avoiding a large turbid cloud
- A high efficiency of nodule collection (90 per cent or more within the collection swath) will be the most important technical and environmental requirement under the design philosophy. Furthermore, the width of the collector should be at least the same as that of the crawler
- The reliability, operational and standby safety, maintenance and repair of the crawler must be of a high standard. The energy consumption of the collector should be minimal. As for the mechanical aspects, the collector must be simple, rugged and flexible, but still very lightweight. Most important is that the collector should not be a source of environment pollution, such as that which can be caused by leakage of oil from the hydraulic system



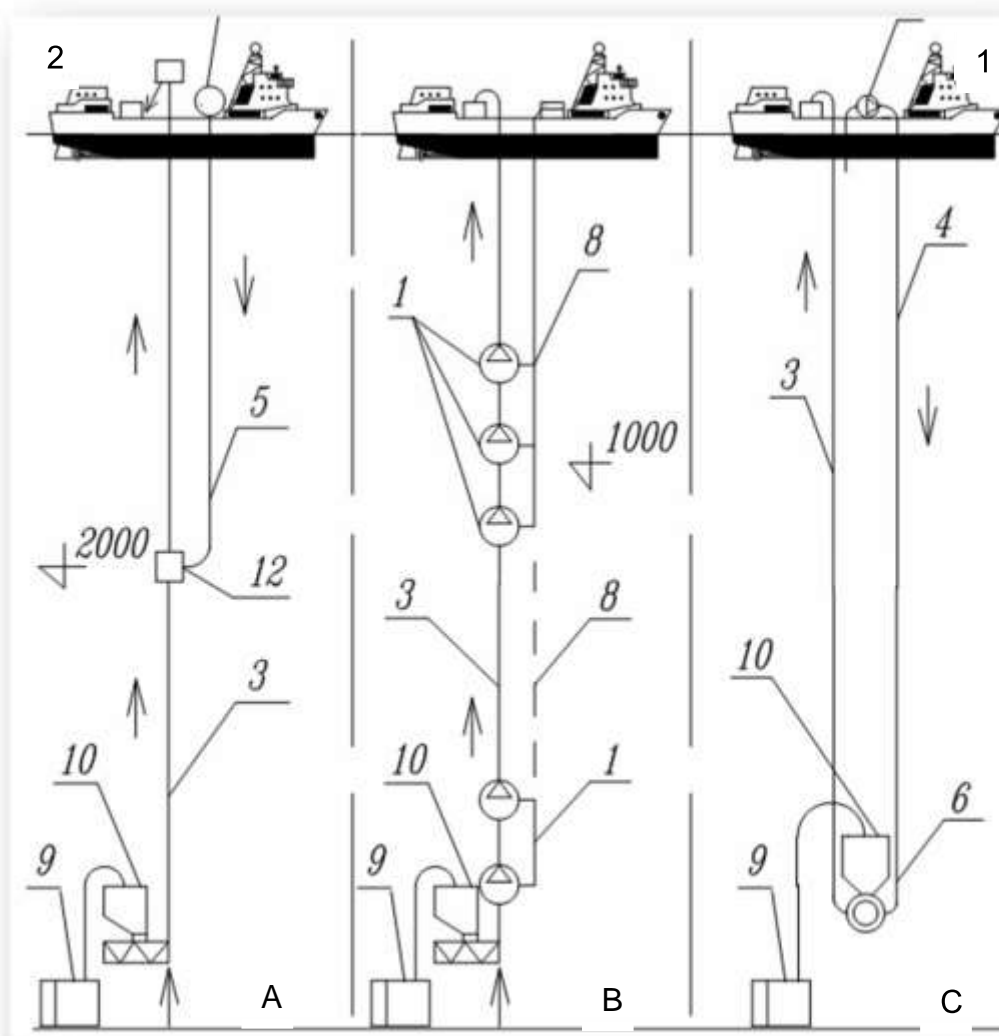
*Figure 5: Model of self-propelled collector*

The transportation of the collected ore mass aboard the vessel is probably one of the major components of the technological process of mining. Two factors are important: lifting a significant amount of nodules from the bottom of the ocean to a vessel requires maximum power

from the entire shipboard complex; and the manner of lifting the nodules determines the entire type of the mining system and its hardware.

According to Russian scientists, the most advanced and technically implementable method currently available is a mining complex based on hydraulic systems. There are three options for such a system (Figure 6).

*Figure 6: Hardware configuration for various types of hydraulic system for nodule lifting*



**Legend:** 1. Electric pumping unit; 2.Compressor; 3. Transportation pipeline; 4. Pipeline for supply of power fluid; 5. Air conduct; 6. High-pressure feeder; 8. Power cable; 9. Collecting device; 10. Low-pressure hopper; 12.Mixer.

All three options for the airlift system possess one common element – the transportation pipeline – whilst the fundamental difference between them lies in the manner of energy transfer to the flow of slurry in the pipeline. In the first option (Figure 6, A) the energy to the slurry flow can be transferred due to the decrease of the average density of liquid in the upper sections of the pipeline. For this purpose an airlift method is used with compressed air supplied to the conveyer pipeline at a certain depth (5 in Figure 6A).

In the second type (Figure 6B) this problem is solved by means of electric-pumps mounted on the pipeline (1 in Figure 6B), making the system viable at great depths and the transportation of slurry containing solid material. Finally, in the third type (Figure 6C) the energy is transferred to the slurry by

pumping sea water into the pipeline through the use of pumps located on the vessel (1 in Figure 6C). In this case one additional pipeline (4 in Figure 6C) for supplying power fluid into the mixer - converter is required.

One of the most acute problems connected with the creation of the pipeline system for the transportation of the recovered ore mass lies in the fact that providing for commercial production using the mining complex will require substantial enlargement of the dimensions of the lifting system if the content of solids in pulp is usual (up to 10 per cent). Calculations indicate that the diameter of the pipeline in this case would be about 1 m, with a wall thickness of about 0.4 m, thus increasing the overall mass of the pipeline to hundreds, possibly even to thousands, of tonnes.

It is obvious that in this field it is necessary to continue to search for ways to reduce the total mass of the pipe column to an appropriate size, particularly since the tendency is for the development of a hydro-transportation technology involving a higher concentration of solid components in the pulp, and based on new materials obtained through the latest achievements in nanotechnology for manufacturing pipe columns.

Although the task of determining the expense of creating a mining complex has many imponderables, Russian specialists have managed to calculate their approximate cost as about US\$250 million. Thus, the creation of three mining complexes will cost about US\$750 million. Therefore, the cumulative capital investments for the polymetallic nodule mining complex that will include a vessel and a mining module for pilot mining and three mining modules for commercial mining will be approximately US\$1.5 billion.

According to the estimates of Russian experts the operating costs for mining will be about US\$300 million. This sum includes the costs of the offshore stage of the transportation of the produced ore mass to a Russian port. Transportation of the ore mass will be assured by 5-6 bulk-carrier vessels at a cost of no more than US\$100 million.

### **The development of technologies for the metallurgical processing of polymetallic nodules**

Because of the complex composition of polymetallic nodules, it is impossible to use mechanical methods of enrichment (e.g. gravitation, flotation, magnetic separation) of the primary raw material. Therefore, the whole mass of the primary ore has to undergo metallurgical processing. The technological schemes developed for this can be divided into three main groups: (a) pyrometallurgical; (b) hydrometallurgical methods with recovery of non-ferrous metals and manganese; and (c) hydrometallurgical techniques with selective recovery of only non-ferrous metals.

The pyrometallurgical methods of polymetallic nodule processing are based on selective reduction and separation of iron, nickel, cobalt and copper from inert rock (Figure 7). Primary ore enters a pelletization process, which is achieved by means of a reducing agent (coke fines), and then undergoes reduction firing at a temperature of 800-900°C. After firing, the material enters reduction smelting in the electric furnace.

In the process of reduction electro-smelting, 98 per cent of non-ferrous metals and up to 90 per cent of iron pass into the alloy and manganese is concentrated in the slag. For example, the output of alloys in processing polymetallic nodules of the CCZ is 6-8.5 per cent, with the content of valuable components occurring in the following percentages: nickel 12.6-21.0; copper 8.5-11.5; cobalt 2-3; iron

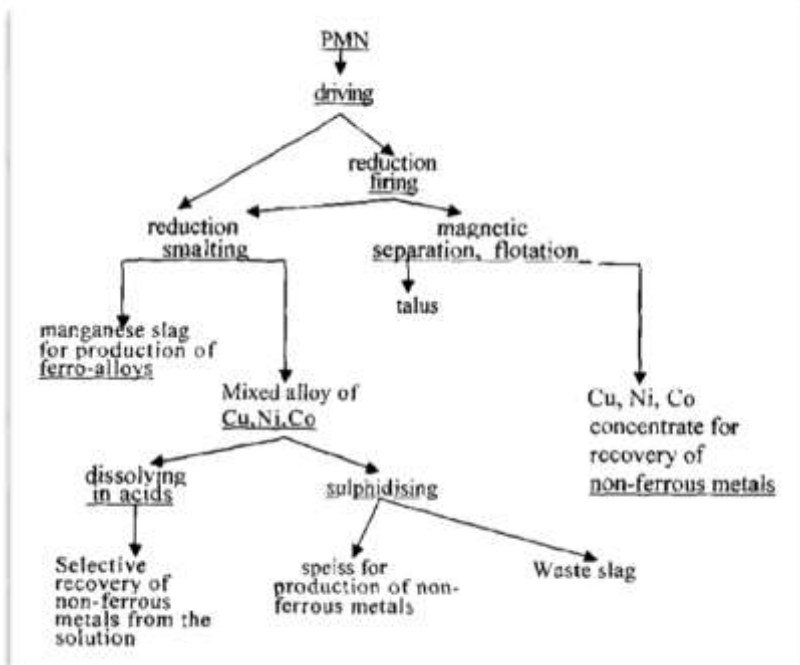
60-70; manganese 0.3-6.0. The output is 72-80 per cent of the primary ore mass with the percentage concentrations of manganese occurring as follows: 39-44; nickel 0.01-0.03, cobalt 0,01, copper 0,02, silicon dioxide 12-30; the calcium oxide 4-10; aluminum oxide 5-15; and phosphorus oxide 0.02-0.03.

The quality of converted slag can be determined mainly by the content of manganese (min 40 per cent) and phosphorus (max 0.1 per cent). In the process of smelting the majority of phosphorus is reduced and passes into the complex alloy, helping to obtain low-phosphorus slags during the smelting of polymetallic nodules. Polymetallic nodule smelting to the complex alloy of non-ferrous metals and converted manganese slag is the basic pyrometallurgical technology used to process these types of deep water raw material. The elements of the technology have been tested and patented in many countries, including in the Russian Federation.

Besides the basic version, sulphidization of the complex alloy to obtain a cupro-nickel matte, and its processing with the use of the standard technology was developed. The techniques of magnetic separation or flotation of polymetallic nodules after reduction were proposed, but these lead to reduced amounts of metal being recovered from the nodules and they were not developed further.

An obvious advantage of the pyrometallurgical technology used for polymetallic nodule processing is that the processes of electrosmelting of various types of ores have been well developed by industry. Therefore, the potential for the implementation of the technology is very high.

The process has a number of disadvantages, e.g. it requires high energy consumption in connection with the necessity for drying and aggregating the entire mass of primary material, and also the low content of manganese in the converted slag.



*Figure 7: Conceptual scheme of the pyrometallurgical techniques for polymetallic nodule processing*

The hydrometallurgical technologies for the extraction of valuable components from polymetallic nodules are distinguished by the means of the preliminary preparation of primary ores, the type of the solvent used, technology of the leaching processes and separation of metals from the solutions and other parameters.

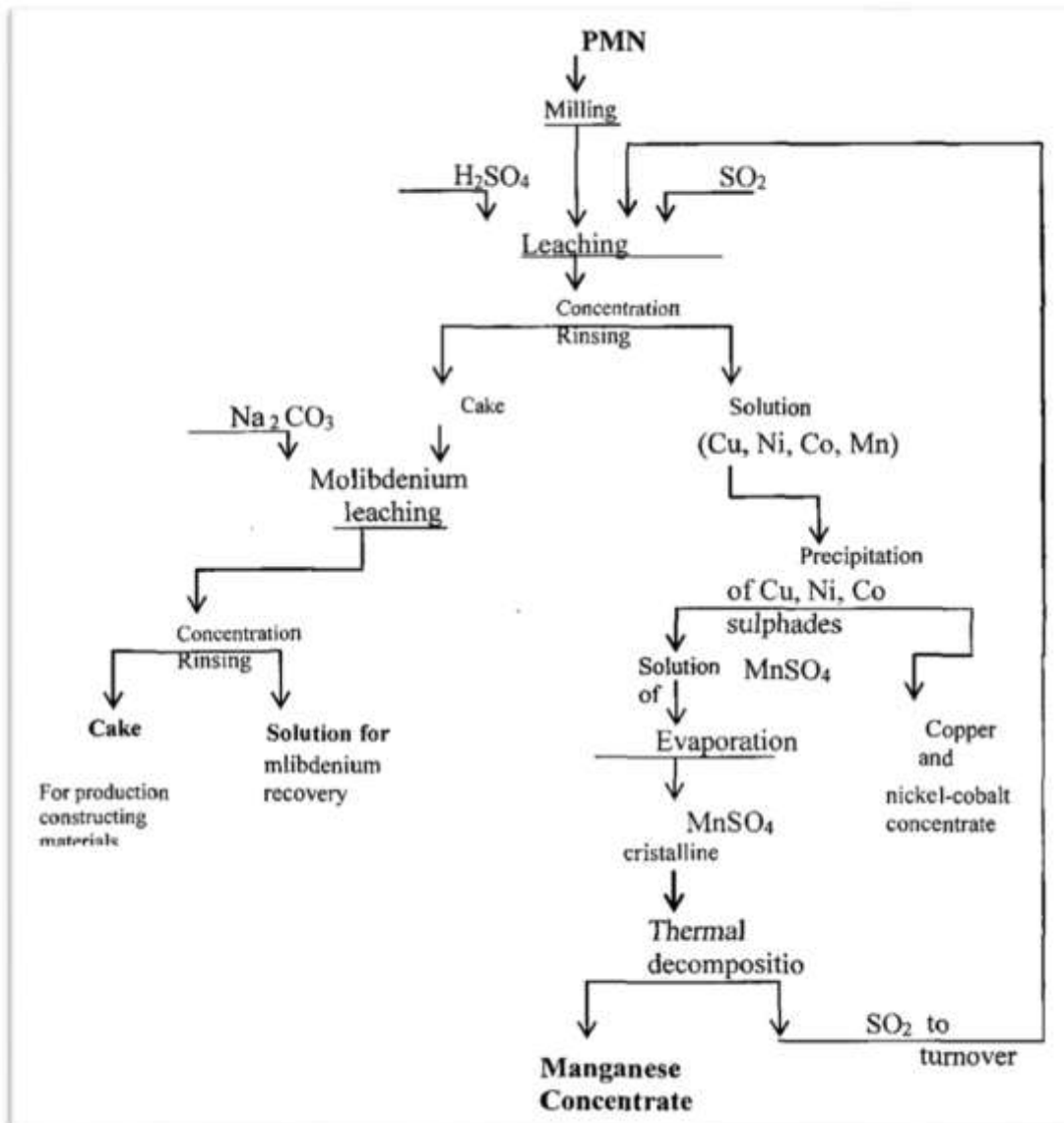
A few dozen versions of the hydrometallurgical techniques of processing are known.

The key hydrometallurgical operation of the complex processing of polymetallic nodules is their leaching by a solution of acids in the presence of reducing agents ( $\text{SO}_2$ ,  $\text{Fe}^{2+}$  and others).

In the process of leaching,  $\text{Mn}^{4+}$  is reduced to  $\text{Mn}^{2+}$  and goes into solution. Simultaneously, non-ferrous metals are dissolved and partially iron and the elements of waste ore. At the stage of leaching it is important to fully separate valuable components from iron and other elements, since their presence in the solution complicates the technology for further processing.

The conceptual scheme of hydrometallurgical processing of polymetallic nodules using sulphurous anhydride is shown in Figure 8. The technology of leaching by sulphurous anhydride is interpreted by experts from different countries as one of the advanced techniques for the processing of primary raw manganese material.

*Figure 8: Technological scheme of hydrometallurgical processing of polymetallic nodules*



Leaching is carried out by waste gas from the combustion of sulphur or the firing of the pyritic concentrates containing 8-12 per cent of sulphurous anhydride. To avoid the formation of dithionates (hyposulphates), sulphuric acid is added to the pulp.

In the process of leaching, 95-98 per cent of the manganese, copper, nickel and cobalt form sulphates that go into solution from which they are extracted by the sequential precipitation of copper sulphides and nickel/cobalt. The copper and nickel/cobalt concentrates can be processed using traditional pyrometallurgical or hydrometallurgical methods.

The solution of manganese sulphate undergoes evaporation and concentration. Some of the sulphates in the form a 20 per cent solution or crystalline salt go to the production of mineral fertilizers, siccatives, and catalysts etc. The remaining sulphates go for thermo-chemical breakdown to obtain chemical manganese concentrates, and for the regeneration of sulphurous anhydride.

In the process of polymetallic nodule leaching and during the processing of solutions, the phosphorus and other contaminating impurities are removed; thus the manganese concentrate is phosphorous-free and has a high content of the basic metal (more than 55 per cent). In the insoluble residue resulting from polymetallic nodule leaching, molybdenum is concentrated, which can be extracted by a solution of soda.

The advantages of the technology of polymetallic nodule leaching by sulphurous anhydride are low energy consumption, accessibility of the required reagents, the possibility of carrying out leaching at low temperatures and pressure, and the efficient processing of the deep water ores of different chemical composition, including cobalt-bearing crusts with a high phosphorus content. The main disadvantage of the technology is the absence of a tested technological prototype.

Thus the Russian concept for metallurgical processing of raw ore material allows for the realization of one of two possible technologies: pyrometallurgical and hydrometallurgical. The development of both technologies has passed the stages of R&D and laboratory testing. The results of laboratory tests demonstrated the following possibilities for the recovery of metals into commodity products: 1) using the pyro-metallurgical technology (percentages): Ni 90; Cu 88; Co 86; Mn 74, 2) using the hydrometallurgical technology (percentages): Ni 94.6; Cu 83.6; Co 92.1; Mn 82.3.

The estimated value of capital investment and the annual operating costs for the processing of raw ore material are US\$1,000 million and US\$400 million, respectively, proving that the most expensive proportion of the total cost of the project for the production of polymetallic nodules of the REA is related to the metallurgical processing of the ore mass. In this respect it is obvious that a reduction of the expenditures for ore processing is the key element in the reduction of the total cost of the project. Collaboration with other contractors in this sphere is vital. Another important sphere of collaboration is connected to the provision of environmental safety during mining.

### **Predictive assessment of the economic activities for the development of the polymetallic nodules of the REA**

An economic assessment was made of the pyrometallurgical method of nodule processing (Figure 7) with the following annual outputs of commodity production (in thousands of tonnes) and the cost of 1 tonne (in brackets - in US dollars at 2006 prices):



Nickel powder - 34 (22,600)  
 Copper powder - 26 (6,400)  
 Cobalt powder - 5.4 (34,800)  
 Manganese in the ferromanganese - 584 (1,750)

Besides the expenses mentioned in the text, the estimates include other expenditure connected with support operations (processing, cargo and passenger transportation), environmental protection, unforeseen expenses and payments to the International Seabed Authority. The results of the estimates are provided in Table 3. For comparison, the economic indices evaluated in 1986 [1] within the so-called 'Australian project' are also provided.

As the table clearly shows, the total expenditure required for the implementation of a future project for production of the polymetallic nodules from the REA is great. In spite of this, the final results of the assessment are optimistic, since the payback period can cover about 10 years and the total profit for the 20-year period of project implementation could reach US\$20 billion. This will only be possible if prices of commodity products and production costs provided in this assessment are balanced.

In this respect the results of the correlation of the economic activities we have provided and those mentioned in Ingham, P.D. (1986) are very interesting. At first sight the results are entirely different. However, such correlation can be correct only in the case of the Gross Domestic Product (GDP)-deflator, considering the modern cost of the USA GDP of recent years, being applied to the values. The deflator has been used many times for the cost estimation of mineral resources, including the polymetallic nodules of the world's oceans. Its value can be defined online at: <http://measuringworth.com/calculators/uscompare/#>.

*Table 3: Estimate of Expenditure for deepsea mining venture*

Expenses	Assessment of the authors		According to Ingham, P.D. (1986)	
	Capital investment	Operational costs	Capital investment	Operational costs
<b>Geologic exploration</b>		17		21
Mining (including pilot)	1500	300	312.2	89.4
<b>Sea transport</b>	500	100	85.5	25.5
<b>Metallurgical conversion</b> (considering railway transportation and environmental protection)	1,650	400	860.4	353.7
<b>Environmental protection</b>	170	20		
<b>Unaccounted expenses</b>	250	50	491.5	
<b>Deductions to the Seabed Authority</b>	8	40	7.9	98.7
<b>Total</b>	4,078	927	1,757.5 (2882*)	588.3 (965*)
<b>Total per 1 t of nodules</b> (in US dollars\$)	1,359.3	309	585.8 (960.7*)	196.1 (321.7*)
<b>Cost of annual commodity output</b> (in 2006 prices of, millions of US dollars)	44.7			
<b>Recoverable value of 1 t of nodules</b> (in in US dollars)	714.9			
<b>Payback of investment</b>	~ 10			
<b>Total profit for the twenty-year period</b> (millions of US dollars)	20,276			

In our case the value of the deflator was 1.64. The values of capital investment and operational costs for the Australian project calculated with the deflator are provided in Table 3 in brackets (in bold type with asterisks). They are obviously close to our values and for the operational costs they are practically the same. That leads us to hope that the practical implementation of future projects will be profitable.

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## Summary of discussion

The discussion started with one participant asking whether the cost estimates were based on pure metals. He wanted to know whether one could achieve the kind of purity required for those kinds of metals and whether the cost estimate took into account the purification aspect with regard to the combustion hydrometallurgical process or just based on the concentrates that were being produced. Mr. Yubko's reply was that cobalt, nickel and copper were as pure metals and that manganese was as ferromanganese.

To a question on the price of nickel and why the Russian Federation had taken \$22.6 per kg, Mr. Yubko said it was metal in powder, so it was the final product of the metallurgical process.

The participant repeated the question about the prices of those commodities, saying he could understand that powder was being produced, but was it at the price which had been considered. Mr. Yubko repeated the response, that nickel, cobalt and copper were in powder, then added that probably they were misunderstanding each other.

The question was repeated a third time. The participant wanted to know whether the prices reported were for metals or powder. This time around, Mr. Yubko said that the technology that would be used implied the use of the powder. However, volumes of that powder were provided in the price of metal.

Another question was on the disparity in the manganese price, which was \$0.80 per kg whereas Mr. Yubko had said \$1.75 per kilogram. Mr. Yubko said that the data in his presentation was two years old and had been done deliberately because the Russian team had had the target of making comparisons with the Australian project. That assessment had been done 20 years earlier. They knew that the period of exploitation of polymetallic nodules would be limited to 20 years. Therefore, they had been interested to see if they applied that deflator what changes would take place during that 20-year period with the ratio of expenses and the revenue would be reserved for after the 20-year period.

Another participant wanted to know what the molybdenum content of the Russian area's nodules was, observing that in the flow sheet, an attempt was being made to recover molybdenum as a by-product. Mr. Yubko replied that it was from 0.1 to 0.8 per cent.

The final question was from a participant who wanted to know whether the Russian project was a joint project with IOM. Mr. Yubko replied that Yuzhmorgeologiya and IOM were collaborating with the same Russian experts. Hence, there were some similarities between the data reported by IOM and Russian data.

## PART THREE

# Possible Application of Technology Developed for Other Marine Resources to Deep Seabed Mining

### CHAPTER 12

#### From Space Robotics to Underwater Mining

*Piotr Jasiobedzki and Roy Jakola, MDA Space Missions, Ontario, Canada*

### CHAPTER 13

#### Status of Lift Systems for Polymetallic Nodule Mining

*John Halkyard, John Halkyard & Associates, Houston, Texas 77079 USA*

### CHAPTER 14

#### The Direct Nickel Process for Treating Seafloor Ferromanganese Deposits

*Julian Malnic, CEO, Direct Nickel Pty Ltd, Sydney, Australia*

### CHAPTER 15

#### Nautilus Minerals Inc: Technology Development for Polymetallic Sulphides Mining

*Mr. Michael Johnston, Vice President, Nautilus Minerals, Australia*

### CHAPTER 16

#### Applicability of Flexible Pipe Riser Technology to Ultra Deepwater Mining: Case Study

*Tricia Hill, Yanqiu Zhang, Thomas Kolanski; Wellstream International  
Limited, Houston, Texas, USA*

## CHAPTER 12

## From Space Robotics to Underwater Mining

Piotr Jasiobedzki and Roy Jakola, MDA Space Missions Ontario, Canada

### Abstract

Exploration for mineral resources on the ocean floor calls for unmanned systems and machines controlled from the surface. Removing operators from the vicinity of worksites introduces many technical challenges; low situational awareness in unknown environments; complexity of operated machines; and the need for high bandwidth real-time communication. Precise maps of the worksites underwater do not exist and accurate localization of remote machines at the end of several kilometer-long tethers is not straightforward. Additionally, the cost of teleoperation is high, requiring highly skilled operators to avoid committing errors. These factors make it difficult to exploit the underwater resources economically and with minimum environmental damage.

The challenges of operating underwater mining machinery are similar to those of robotic systems in orbit or during planetary exploration. For space systems, a combination of two approaches is used to address the difficulty of teleoperation: (a) presenting virtual models of worksites and controlled hardware to operators; and (b) increasing the remote systems' autonomy. Immersing the operators in virtual environments increases their situational awareness. Autonomy enables the remote systems to perform some of their tasks using on-board sensors and intelligence, control certain degrees of freedom and operate safely with minimum operator involvement. Planning space missions and developing the necessary technologies includes various structured processes, for example, phased development, assessment of the maturity and difficulty of required technologies, and analysis and management of project risks. Technologies and expertise gained in developing systems for space may be useful for autonomous seabed mining systems.

### Underwater mining operations

Deep sea mining poses a very significant challenge, as it is not possible to have mining staff on site at such depths. Thus, all operations need to be performed by automated or semi-automated craft and robotic equipment specially designed to withstand pressure and capable of performing their tasks. These systems must either be controlled remotely via teleoperation or endowed with a certain degree of autonomy.

Removing operators from the equipment or even from the vicinity of the worksite restricts their situational awareness as they have to rely on camera views, real time telemetry, estimated locations and prior maps of the worksites [Whitcomb, 2000]. Autonomy requires real-time perception that enables the underwater craft to position themselves with respect to local features and in a global sense, allowing them to perform the mining tasks. The challenges of underwater mining using remote mining equipment include:

- Low situational awareness of the operators due to restricted camera views, unnatural light conditions, lack of 3D perception and non-visual sensory perception.
- Potentially poor visibility underwater, especially when close to active mining areas.
- The need for real-time and wide-bandwidth communication links to the surface transmitting images and telemetry.

- Complexity of the teleoperation tasks that need to be performed, for example, navigation of a ROV, which is performed in all six degrees of freedom, and operation of mining tools during precise mining.
- The presence of long tethers connecting to the surface (directly or indirectly).
- The lack of accurate, detailed and current maps of the seabed at the mining worksite.
- The need to maintain a positioning system infrastructure enabling accurate localization.
- The need for underwater infrastructure in support of the mining operations and craft.
- The cost of retrieving craft due to failure, operator error or for maintenance.

Similar challenges exist in tele-operating robotic systems in space: in orbit and in systems deployed on the moon or planets. Expertise gained from space missions will be invaluable to underwater mining systems.

### **Space exploration and underwater mining**

Similar challenges to the underwater teleoperation of complex equipment in partially known environments and with restricted situational awareness are faced by the space community in space exploration, and spacecraft and robotics operations in orbit. Limited camera views, harsh lighting conditions, limited communication bandwidth and latency, and the significant cost of operator errors mean that highly skilled and trained tele-operators are required. Indeed, in outer space some operations cannot be performed using teleoperation at all, due to the communication latency, windows and low bandwidth available. For space systems, solutions are sought by increasing the remote systems' autonomy in such a way that they can perform some of their tasks autonomously using onboard sensors and intelligence, and work safely without operator involvement.

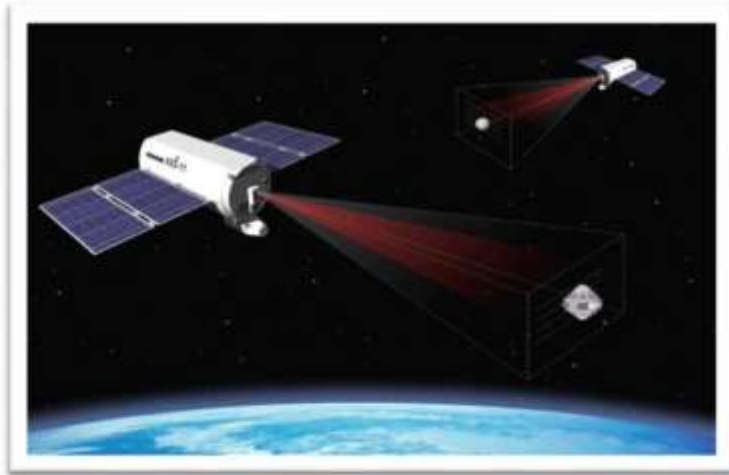
MDA Space Mission is actively involved in the development of novel robotic technologies for space exploration, servicing and operations. These technologies include: P the robotic hardware (manipulators, planetary rovers, tools, control systems); sensors and vision systems (image analysis); vision-guided operations (visual, navigation, localization and mapping); operations planning; and autonomous monitoring of robotic operations.

Selected technologies are currently being adapted for underground mining in order to reduce the workload of teleoperation, and increase the productivity and safety of ore transfer underground. The creation of virtual models of underground mines and integration with mine management software allows monitoring of mine advancement without the need for highly trained staff to visit the active mine faces. Developing such mining tools requires technical solutions in a range of technologies including autonomous navigation, modelling and monitoring, and sensor-guided operations, as described below.

### **Sensing and autonomous navigation**

Sensor-guided autonomous navigation is an enabling technology that has been used to great success in outer space. The MDA Spaceborne Scanning Lidar System (SSLS) [Nimelman, 2005], deployed on board the AFRL XSS-11 satellite and launched in 2005, was used to detect and track the position of a target spacecraft, and to guide the servicer from distances of between several kilometres to 10 m

(Figure 1). SSLS could also create high resolution 3D models for spacecraft inspection, 3D modelling and measurement.



*Figure 1: XSS-11 spacecraft equipped with the MDA SSLS*

Sensor-based vehicle navigation systems developed by MDA Space Mission enable shared control, ‘auto- trammig’, of Load Haul and Dump (LHD) vehicles transporting ore underground. The operator on the surface tele-operates the vehicle during loading only and the vehicle operates fully autonomously during traverses and dumping into ore passes. The guidance systems do not require

Any infrastructure to be installed in the mine and use on-board light detection and ranging (LIDAR) and sensors to localize the vehicle and follow paths “learned” by the vehicles during a training phase (Figure 2).

*Figure 2: Underground LHD vehicle driving autonomously with no infrastructure*

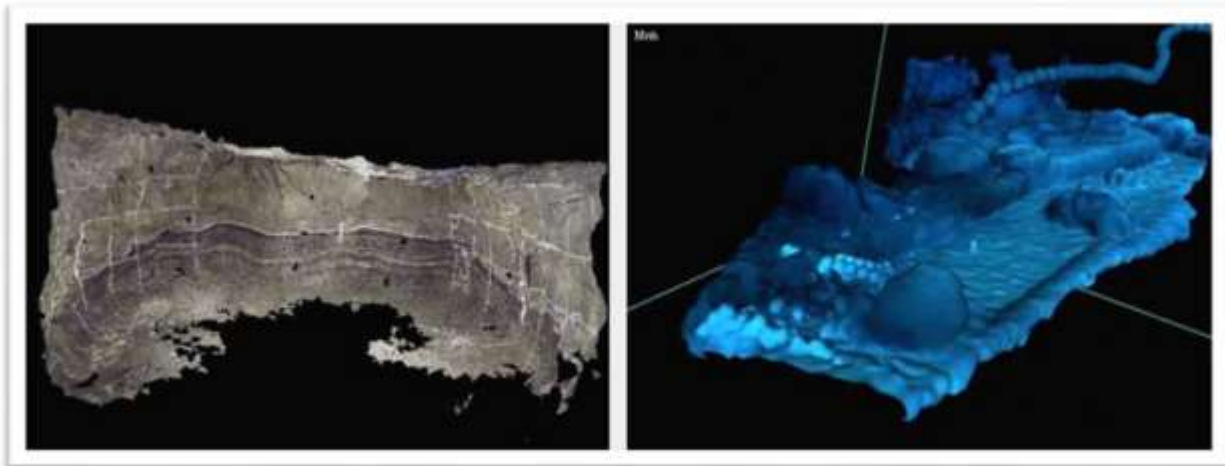


### **3D modeling and monitoring**

3D photorealistic models created using devices such as the MDA Space Mission’s instant Scene Modeller (iSM) [Se and Jasiobedzki, 2007] and the AQUA Sensor [Dudek et al., 2007] bring the remote environment to the operator’s workstation, enabling virtual presence (Figure 3). The iSM system, initially developed for planetary exploration, is currently used in underground mining to assess ore distribution in 3D on active faces and to monitor mine advancement. iSM creates 3D models from sequences of stereo camera images. The models are annotated by a technician operating the system underground to indicate ore concentration; samples are taken and their location and concentration are recorded within the model. As the models are registered in the mine coordinate system the data is entered into the mine management system and combined with other mine information (borehole samples, geo-seismic models) to approximate ore distribution in 3D, and to plan and monitor mining operations. A similar 3D modelling system has been developed by York University and has already been deployed on the aquatic robot AQUA [Dudek et al., 2007]. The AQUA sensor records sequences of stereo

images and automatically estimates the relative motion and creates 3D models of the seabed, coral reefs and submerged vessels. The system is equipped with inertial sensors, which help in estimating motion in the aquatic environment. The on-going research focuses on monitoring the growth of coral reefs using automatic change detection in 3D and by analysing 2D images.

*Figure 3: Examples of 3D models created using the MDA Space Mission's iSM underground (left) and the York University AQUA sensor underwater (right)*



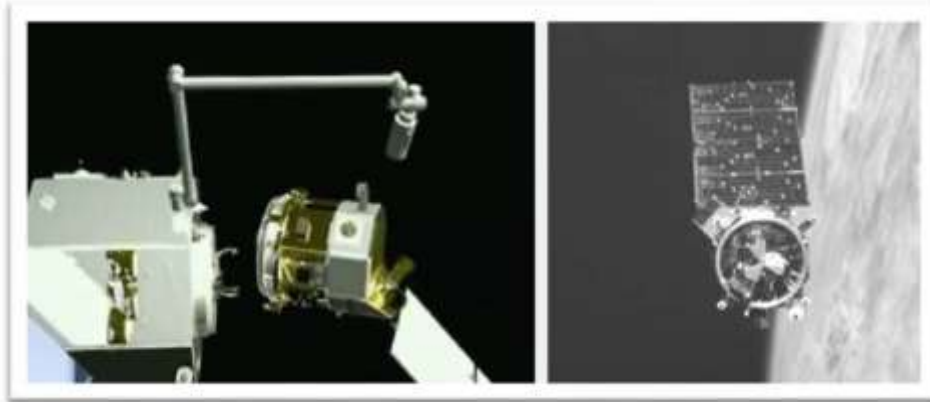
### **Sensor guided precision operations**

Access to accurate real world data in real time enables sophisticated robotic operations to be performed autonomously. For example, the Orbital Express Demonstration Mission uses an MDA Space Mission system consisting of a robotic arm guided by a vision system to capture autonomously a free-floating satellite. The vision system detects the location of a robotic interface on the target and commands the robotic end-effector to close in on the interface [Ogilvie, 2008], see Figure 4. The same arm and vision system are used for inspection and for servicing of the target spacecraft.

Performing unplanned precision tasks, especially on satellites not designed for robotic servicing, still requires a human operator with perception skills, dexterity and an understanding of the task. Vision systems sensing the environment in 3D endow the operator with virtual presence by displaying the worksite models in synthetic (immersive) environments. Such environments include photorealistic models created from images or range data, models of known structures, and kinematic models of robots and tools. The operator uses these models to plan and rehearse the operations in virtual environments, before the operation sequence is transmitted to the remote site for autonomous execution. On-board sensors and processing systems are used to sense the real environment, providing feedback (on position, force, movement) to remote robots and tools, ensuring correct and safe operation.



*Figure 4: Autonomous robotic capture in orbit (left) and an image from space (right)*



### **Autonomous underwater mining**

Given the ability to sense and reason based on these complex sensor representations, autonomous systems can be built to support autonomous mining at depth. Although developed for outer space, if suitably modified, these technologies can be used to enable deep sea mining. MDA Space Mission is currently exploring such technologies and focusing on the following tasks:

- Modelling and monitoring of underwater environments.
- Shared control of underwater craft and machinery for precision operations and mining.

### ***Modeling and monitoring of underwater environments***

Recent years have seen the rise of a number of light-based sensing technologies for ROVs and unmanned underwater vehicles (UUVs). Laser-based ranging systems (for example, Moore et al., 2000) adapt surface-based laser systems to the underwater domain, leading to the need to address critical issues related to backscatter of the laser beam due to suspended particulate matter and absorption of the laser energy by the water column. The effects of absorption can be reduced via an appropriate choice of laser wavelength (ideally in the blue-green range). Once the details of the unique aquatic environment have been addressed, traditional terrestrial- and space-based laser technologies find direct applications in the aquatic domain.

An alternative to laser-based technologies is the use of multiple camera (in stereo configuration) sensing technologies to obtain 3D surface structure representations that can later be used for localization tasks. Devices such as iSM and AQUA sensor, discussed earlier, can be used to obtain 3D representations of the environment for navigation, obstacle detection and vehicle localization. Recent advances in 3D imaging sonar will offer a similar 3D sensing and modeling capabilities that will operate reliably underwater; albeit currently at lower resolutions than camera-based systems [CodaOctopus, Zimmerman].

Near real-time access to 3D models will significantly increase situational awareness of operators of the remote craft or underwater mining machines by effectively immersing them in the environment.

This will provide them with virtual views of the scene in 3D and optimum viewing angles and distances for precision operations.

Scanning the same environment multiple times and registering the 3D models will enable detection over time. This will allow monitoring of the mining operations and assessment of environmental impact by directly comparing the same locations in photorealistic 3D using data collected over extended periods.

### ***Shared control of underwater craft and machinery for precision operations and mining***

Shared control of underwater craft and mining machinery will alleviate some of the limitations of teleoperation by autonomous execution of mundane operations (e.g. traversals between sites), thereby retaining operators' involvement in tasks requiring skill and reducing fatigue. Reducing the operators' load per craft will allow them to control multiple systems reducing thus the cost.

The need to navigate around subsea features, minimize environmental impact and maximize the value of the ore which is extracted will underpin efforts to develop precision mining capabilities. Assigning some of the control functions to the autonomous controller will allow the operator to concentrate on tasks that require high-level skills. For example, precise automatic control of the ROV with respect to the mooring ensures the ROV hovers automatically with respect to the mooring and the pilot is free to focus only on the manipulation tasks [Plotnik, 2005]. Similarly, tasks such as visual homing to a target designed by the operator, maintaining safe distance and obstacle avoidance can be performed autonomously.

### ***Technical management of space projects***

Space systems, e.g. the network of satellites of the Global Positioning System (GPS), the International Space Station (ISS) or missions to Mars, are necessarily complex systems. This complexity is created by many factors: the number of subsystems and components, their interactions and dependencies, and required extremely high reliability. Testing of the complete systems on the ground is often impossible, and very limited capabilities to perform repairs after the launch exist. Space programmes typically take 7-15 years and involve large multi-disciplinary teams working in different geographic locations. At the start of a project many of the required technologies may not exist at all, or only exist as laboratory prototypes, or require re-engineering to operate in the space environment. Mission planners are faced with alternative solutions offering different performance and at different maturity level. It has been necessary to develop structured processes for phased development, assessment of maturity of proposed technologies and difficulty of developing new technologies, and analysis and management of risks, uncertainty and cost.

### ***Lifecycle of space projects***

The NASA lifecycle of formulation and implementation of space projects is divided into incremental phases that allow assessing management and technical progress [NPR 7120.5D]. Major reviews are carried out between the phases and their outcome determines if the project is continued in the next phase. Projects typically start from concept studies (Pre-Phase A) and are followed by project formulation, which consists of: Phase A (concept and technology development) and Phase B (preliminary design). Project implementation consists of Phases C-F, which involve: final design (C), integration and test (D), operations (E), and closeout (F). The objectives and scope of the major reviews between the

phases, as well as, reviews during each phase are clearly defined and include progress to date against the approved baseline, the implementation plans for current and upcoming work, budget, schedule, and all risks and their mitigation plans. Reviews during Phases A and B focus on the readiness of the programme to proceed into implementation: proposed programme's objectives and the concept for meeting those objectives are assessed, and key technologies and other risks are identified. During the implementation phases the reviews focus on readiness for the fabrication, integration and testing of components, readiness of the overall system for testing, development of operational procedures and readiness for launch.

This project lifecycle is used for all of the projects; however, only a minority of the projects considered in pre-Phase A concept studies are launched and operated in space. This happens for a variety of reasons but mostly because of inadequate performance of technologies and change of priorities. Some of the technologies required for the mission may carry high risks due to their technical immaturity or require a significant and costly development that exceeds the project budget or schedule. Change of priorities relates to modification of the scientific objectives of the proposed mission or redirection of the funding. Selecting technologies for a mission requires measures that can be used to assess maturity of existing technologies and difficulty of advancing them to a level when it becomes suitable for the mission. The same measures should allow comparison of alternative technologies. Two such metrics have been used: Technology readiness level (TRL) and Research and develop degree of difficulty (R&D3), and they are described below.

### ***Technology Readiness Level***

Technology Readiness Level (TRL) [Mankins, 1995], had been originally developed by NASA for space programmes, and is currently used in military and civilian industries, and measures maturity of technologies on a scale from TRL 1 to 9. The following definitions are used:

TRL-1 - Basic principles observed and reported.

TRL-2 - Technology concept and/or application formulated.

TRL-3 - Analytical and experimental critical function and/or characteristic proof-of concept. TRL-4 - Component and/or breadboard validation in laboratory environment.

TRL-5 - Component and/or breadboard validation in relevant environment.

TRL-6 - System/subsystem model or prototype demonstration in a relevant environment (ground or space).

TRL-7 - System prototype demonstration in a space environment.

TRL-8 - Actual system completed and “flight qualified” through test and demonstration (ground or space).

TRL-9 - Actual system “flight proven” through successful mission operations.

For example, if a novel 3D imaging system assembled on a laboratory bench produces first 3D images at low rates, it will be rated as TRL-3. If it is launched and operates successfully under space conditions it will be rated as TRL-7. It will reach TRL-9 when it is used as a guidance system during space rendezvous.

### ***Research and Development Degree of Difficulty***

TRL is a measure allowing to assess maturity of a specific technology and to compare alternatives; however, it does not provide any information about technical difficulty and cost of maturing the technology to the next level. Research and Development Degree of Difficulty (R&D3) provides such a measure [Mankins, 98]:

R&D3 - I        A very low degree of difficulty is anticipated in achieving research and development objectives for this technology. Probability of Success in “Normal” R&D Effort 99%

R&D3 - II       A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology. Probability of Success in “Normal” R&D Effort 90%

R&D3 - III      A high degree of difficulty anticipated in achieving R&D objectives for this technology. Probability of Success in “Normal” R&D Effort 80%

R&D3 - IV      A very high degree of difficulty anticipated in achieving R&D objectives for this technology. Probability of Success in “Normal” R&D Effort 50%

R&D3 - V        The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required. Probability of Success in “Normal” R&D Effort 20%

Continuing with the previous example of the 3D imaging system for space rendezvous - advancing it from a proof-of-concept system (TRL-3) to a prototype suitable for laboratory testing (TRL-4) may require increasing the processing speed tenfold. The difficulty of this task may be rated only as R&D3-I, if it involves porting the software from a prototyping language to C, and if such an improvement was achieved before in a similar project. However, if this change requires developing a new high performance computing platform and such an improvement has never been achieved before, it might be even rated as R&D3 – IV. In order to achieve the success, multiple approaches (e.g., using general purpose computing platforms or dedicated hardware processors) may have to be investigated.

### ***Risk management***

Space and other projects relying on novel technologies carry significant risks. These risks may involve unplanned development costs and schedule delay, or failures during operation and considerable losses. It is therefore essential to identify and manage the development and operational risks. NASA and their contractors use the Continuous Risk Management (CRM) process [SP-610S]. CRM is an iterative and adaptive process used during the full life cycle of a project to help with its successful execution. CRM includes the following iterative steps (see Figure 5):



*Figure 5: NASA Continuous Risk Management process [SP-610S]*

**Identify** – Identify programme risk by identifying scenarios with adverse consequences

**Analyse** – Estimate the probability and consequence of identified risks

**Plan** – Plan the Track and Control actions. Decide what will be tracked, define decision thresholds for corrective actions, and proposed risk control actions

**Track** – Track programme performance as compared to its plan

**Control** – Given an emerging risk issue, execute the appropriate control action, and verify its effectiveness.

**Communicate and Document** – These are elements of each of the previous steps. Focus on understanding and communicating all risk information throughout each programme phase.

## Concluding remarks

Deep sea mining is the next frontier of mineral development. Operating underwater craft and machinery remotely from the surface to depths of several thousand meters can be as much of a challenge as working in Earth orbit or on the surface of Mars. A range of robotic and sensing technologies recently developed for space and other difficult terrestrial applications can be adopted for underwater mining. Specifically, developed technologies can be applicable for tasks such as: mapping and monitoring of underwater deposits, increasing situational awareness of tele-operators and reducing their workload by providing shared autonomy, and allowing for precision mining with minimum environmental impact.

Development of unmanned semi-autonomous underwater mining systems that will operate reliably and efficiently is a technically complex endeavor. Additionally, this must be achieved at an acceptable cost and schedule to ensure commercial success. Some of the systems engineering processes and project management methodologies developed for space programs may help to achieve these objectives.

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## CHAPTER 13

## Status of Lift Systems for Polymetallic Nodule Mining

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### Abstract

There has been a lot of development in the offshore industry related to risers and subsea technology since the early nodule mining research in the 1970s. Related technology includes deepwater top tensioned and steel catenary risers operating in large currents, subsea electrical pumps operating at power ranges required for the lifting of nodules, and a plethora of new technology, such as high performance marine connectors and pipe, subsea mud pumping, controls and umbilicals, all of which are enabling the development of reliable deep-sea mining systems. This paper presents a review of the most important of these technologies and how they might be used for nodule recovery.

### Oil and gas progression to deep water

There has been a rapid development of deepwater technology for deep and ultra-deep water. This began with the Auger project, which came on stream in 1994. Auger well productivity turned out to be much greater than expected, which was prophetic for future exploration in the deepwater Gulf of Mexico. Figure 1 shows the well productivity figures for projects in the Gulf of Mexico. While the productivity of shallow water wells is typically 3-5,000 barrels per day (BPD), the labeled projects, primarily in deep water, have wells producing at 30,000 or more BPD. Wells of this magnitude generate a lot more interest and investment.

Deepwater records are continuously being broken. The current depth records are: Drilling –

3,050 m

Floating Production – 2,450 m

Subsea Completion – 2,400 m

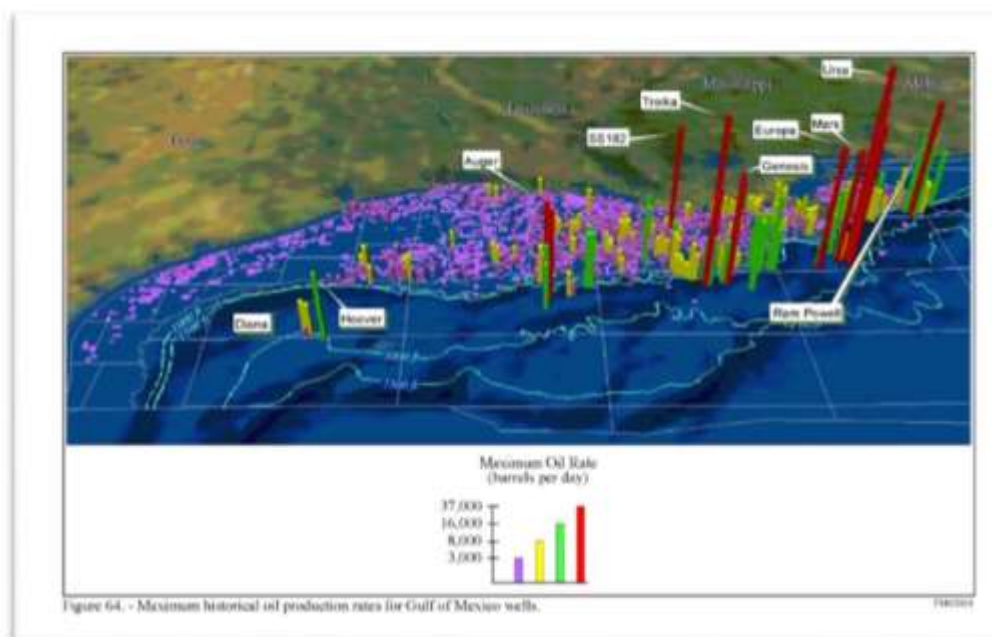
Historically, exploration (drilling) has set new depth records far in advance of production. For example, the first well was drilled in 7,000 feet in 1983, but floating production did not reach this depth until 2006. From the mid-1990s, however, the gap between a drilling and a production record has shrunk to around five years. This might be attributed to the large incentive for bringing high-yielding wells into production. On the other hand, many marginal fields in deep water are being fast tracked too. This might be attributed to the rapid development of technology to achieve affordable production in deepwater that goes along with the development of the more prolific fields. The following are examples of the progression of technology:

1. Low heave floaters with dry trees (spars, mini-TLPs). These platforms have allowed direct well access in fields of questionable properties. This has allowed operators the flexibility to defer drilling expenses until some production history has been established (Glanville and Vandeman, 1999).<sup>1</sup>

<sup>1</sup>. R.S. Glanville and R.D. Vardeman, 1999; Offshore Technology Conference paper 111073.

2. Subsea components: innovations and improvements (in, for example, umbilicals, flowlines, risers, subsea electrical connectors, subsea metering and manifolding) have enabled subsea production to progress reliably to ever deeper waters (Rijkens, Frederik and Hassold, 2003).<sup>2</sup> The reliability of subsea electrical components may have a direct impact on ocean mining.
3. Downhole, 'smart wells': instrumentation and drilling techniques have led to the ability to perform multiple completions from a single well bore (Johnson, Turner, Walker, Harris and McDaniel (2002)).<sup>3</sup> Side tracks are commonly used now to exploit different parts of a reservoir. The 'smart well' concept means that the flow from each part of the reservoir can be monitored and controlled automatically and remotely. Instrumentation has proven rugged and reliable in very harsh conditions.

*Figure 1: Productivity of deepwater wells in the Gulf of Mexico (Minerals Management Service)*



## Deep water riser systems

Ocean mining may benefit directly from the successful development of deepwater risers in the past decade. Risers fall into one of following classes and all have one thing in common: they must act as a conduit under dynamic conditions:

- Drilling
- Top Tensioned Production (or export)
- Steel Catenary

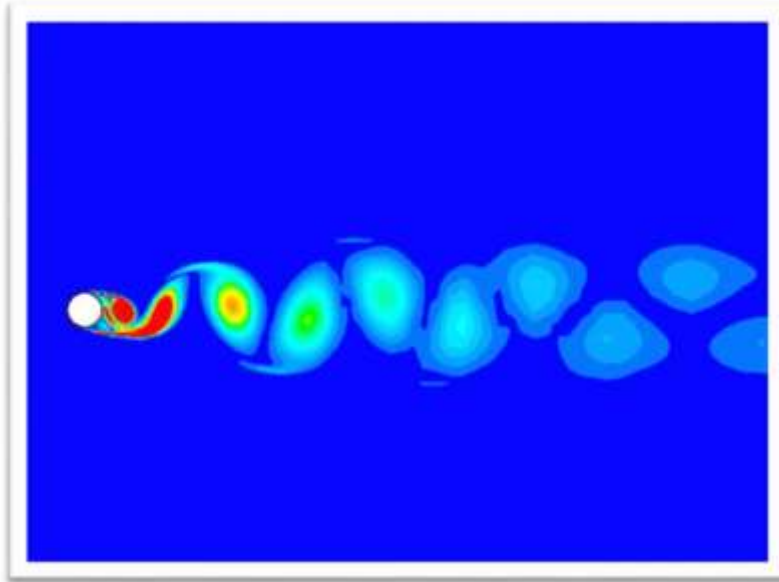
<sup>2</sup>. Rijkens, Frederik and Thomas Hassold (2003), 'Overview of the Canyon Express project, business challenges and industry firsts', Offshore Technology Conference, paper 015093.

<sup>3</sup>. Johnson, D.E., D.M. Turner, D.J. Walker, D. Harris and D. McDaniel (2002), 'Reliable and Completely Interventionless Intelligent Well Completion Technology: Application and Field Study', Offshore technology Conference, paper 014252.



- Flexible

The distinction between risers and conductors used on fixed platforms is dynamic loading. The vessels that support these risers move with the wind, waves and currents. The risers themselves are unguided and can move to the effects of current and waves. Currents induce Vortex Induced Vibrations (VIV), which may be a big concern for many of these risers, for example.



*Figure 2: Vortices being shed from a fixed cylinder*

VIV is a result of vortices being generated in the wake of a cylinder (Figure 2). These vortices produce an alternating transverse force on the cylinder at the Strouhal shedding frequency defined by:

$$f_s = S \frac{U}{D}$$

Where:  $f_s$  = Stouhal frequency, Hz.  $S$  = Strouhal number (non-dimensional);  $U$  = Fluid velocity;  $D$  = Cylinder diameter

$S$  depends on Reynold's number. For risers, it may typically be taken as about 0.2. When the Strouhal frequency is close to a resonant frequency for an elastically mounted cylinder, or especially in this case for a riser with flexure modes of vibration, the cylinder will oscillate with an amplitude dependent on damping and the ratio of the mass of the cylinder to the mass of the displaced water. The theory of VIV may be further explored in Blevins', Flow Induced Vibrations.

Since long risers have many modes of vibration, an appreciable current is bound to excite one of its modes. The consequences of this include:

1. Accelerated decline in the fatigue life of the riser
2. Added drag forces

VIV was identified in early polymetallic nodule projects as a key issue for mining riser systems. This was not only due to currents, but due to the fact that the mining risers had to be towed at fairly high speeds (1-2 m/sec) to allow the collection of nodules.

As oil exploration and production has extended into deep water and higher current regimes in recent years, VIV has also been a major concern in the offshore industry. Many references on the subject may be found in conference proceedings and Journals in recent years.<sup>4</sup> All of the research and gains in VIV suppression and associated riser design may be directly applicable to nodule mining. Two methods of VIV suppression are commonly used offshore today:

- Fairing
- Helical strakes

*Table 1: Pros and cons of fairings and strakes*

Fairings	Strakes
<u>Pros</u> Eliminates VIV Low drag ( $C_d = 0.8$ )	<u>Pros</u> Eliminates VIV Storing and Installation
<u>Cons</u> Storing and Installation	<u>Cons</u> Higher drag ( $C_d = 1.3 - 1.5$ )

While either strakes or fairings may be used to mitigate VIV, they each have their own advantages and disadvantages (Table 1). Fairings result in low drag, but storing fairings takes a large amount of deck space. Especially when applied to the 5,000 m of riser required in the case of mining, this is a major consideration in layout of the deck. Of course the higher power required to tow a lift pipe with strakes as opposed to fairing could be an overriding issue.

Fairings are unidirectional and need to be able to swivel around the pipe. Figure 3 shows fairings designed for Kennecott’s airlift system in the 1970s.<sup>5</sup> The aspect ratio (length divided by width) is about 3.5:1. Shell Global Solutions has developed a short fairing with an aspect ratio of 1.3:1 (Figure 4), which make storage and deployment much easier.



*Figure 3: Fairings proposed for airlift system in early mining development (Kennecott)*

<sup>4</sup> A starting point for literature on this and other aspects of riser design is: American Petroleum Institute, Recommended Practice RP-2RD, 1998 “*Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs)*”, First Edition. See also papers in the Offshore Technology Conference and the annual International Conference on Offshore Mechanics and Arctic Engineering ([www.oma.org](http://www.oma.org)), an organization of ASME.

<sup>5</sup> Kennecott Exploration, Inc., (1978), ‘Lift Pump Assessment and Comparison’, Report TAC-S-157, Jan. 18

*Figure 4 (Left): Short fairings (Shell Global Solutions)*

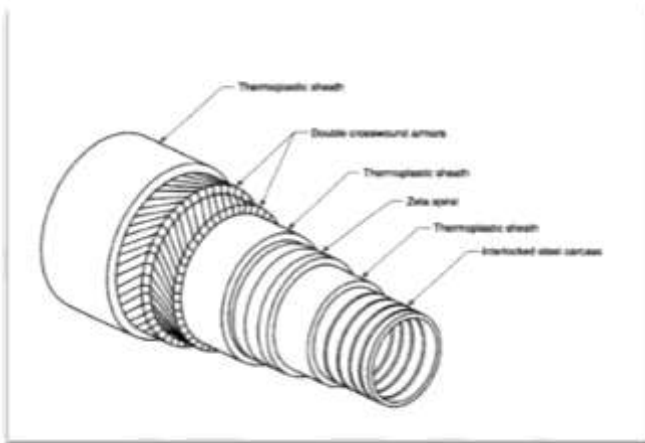
*Figure 5 (Right): Shows helical strakes on a production riser.*



The strakes may be preinstalled on the risers and the risers may be stacked closely together.

### **Flexible risers**

Flexible risers have been developed which are much more robust than steel risers, and which allow operation from vessels with considerably more motion than required for steel risers. These risers are also greatly immune to fatigue damage from VIV; hence they do not require strakes or fairings to mitigate fatigue. There is still an issue of drag, however, since VIV itself increase the effective drag coefficient of risers by a factor of up to 2.0.<sup>6</sup>



*Figure 6: Flexible riser construction*

Flexible risers consist of a number of layers (Figure 6), beginning with a series of interlocking rings (carcass) which provide hoop strength and flexibility, then alternating thermoplastic liners and additional strength layers of either interlinked rings or cross wound armor. The flexible pipe may be custom designed for a particular application. An advantage of flexible pipe is its ease of installation. It may be stored and deployed from reels in long lengths.

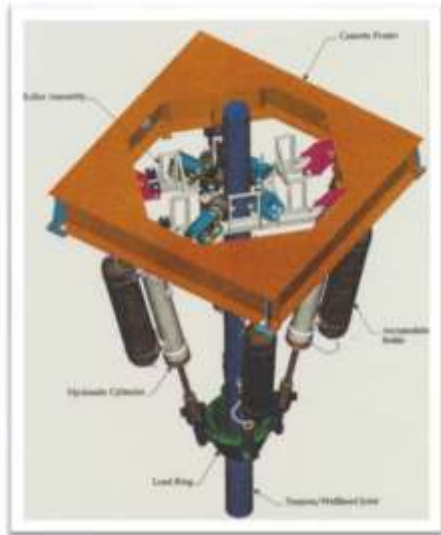
A drawback of flexible pipe is its much higher cost and its limited size capability compared to steel pipe. At present the upper bound on flexible pipe diameter (I.D.) in ultra deep water is about 6"

<sup>6</sup> See Blevins, R. D. (1977), Flow Induced Vibrations, Van Nostrand Reinhold, NY.

(356 mm).<sup>7</sup> Developments by manufacturers of flexible pipe might lead to larger diameters in the very near future.

### Tensioners for steel risers

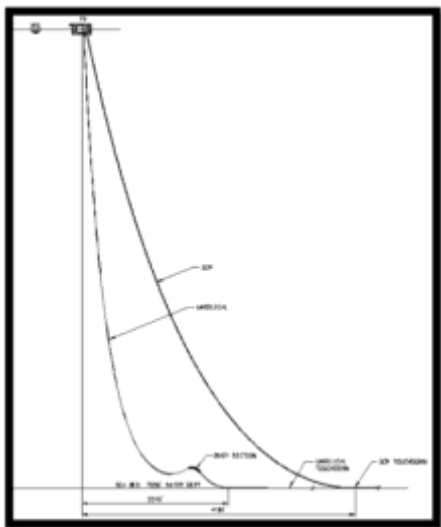
The support of steel risers on a dynamic vessel requires a means for accommodating heave and pitch motions. Vertical risers are fixed at the seabed and special tensioners employing hydraulics are required to maintain a more or less constant tension while the vessel heaves up and down (Figure 7). Tensioning of this kind is not necessarily required of a mining riser since it will not be vertically connected to the sea bed. Instead, it will form a modified catenary shape and will be able to accommodate the vertical motions of the vessel by changing its shape.



*Figure 7: Hydraulic tensioner for top tensioned steel riser*

The closest analogy to the towed mining lift pipe is the steel catenary riser (SCR). An example is illustrated in Figure 8.

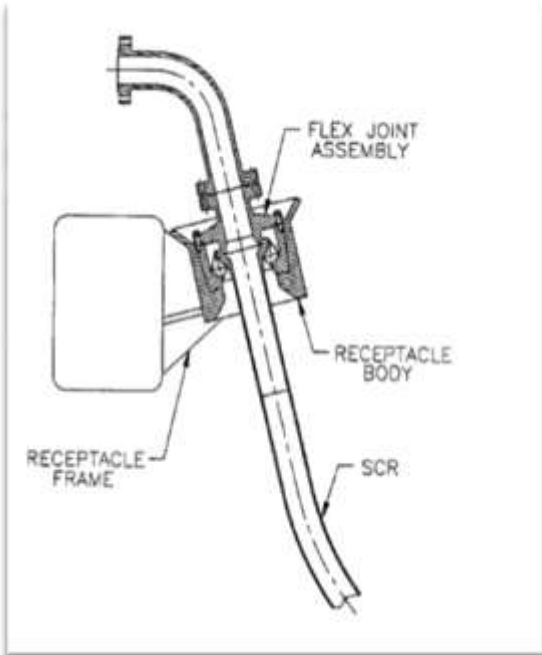
SCRs are typically a continuous extension of a pipeline (for export) or flowline (for import). The angle from the vertical, or 'hang-off angle', at the surface vessel is selected to minimize the bending stresses at the point of tangency at the sea floor when the vessel offsets or heaves. No vertical compensation is required, but angular compensation is required to prevent overstressing the pipe where it connects to the vessel. Two methods are typically employed for this: Flex joint and Stress joint.



*Figure 8: Example of steel catenary riser and umbilical*

The flex joint (Figure 9) consists of a ball joint allowing the riser to articulate. The inner ball is fixed to a spool piece hard pipe to the vessel.

<sup>7</sup> Luo, Y. and W. Ye (2005), 'Mooring and Riser Design for GOM FPSOs in 10,000 ft Water Depth', Offshore Technology Conference, paper 17620.



*Figure 9: Flex joint assembly*

The outer ball is supported on an elastomeric sandwich material that carries the high axial loads, but allows the pipe to pivot. The whole assembly mounts on the side of the vessel. The assembly seals the pipe so that the ball bearing doesn't have to hold pressure.

A stress joint is a tapered section of pipe that makes up the riser immediately outboard of a connection to the vessel, or a tapered pipe that shrouds the riser in this area. The riser pipe is continuous, but the tapered section distributes the angular bend over a long enough length to maintain acceptable stress levels.

Both of these methods could be employed in a towed mining pipe. The complication in mining is that the length of pipe may need to be changed frequently to accommodate changes in depth. This will require adaptation of the SCR technology.

## Steel riser pipe

Steel top tensioned risers for drilling have been used in 3000 m of water. The largest ultra-deep water SCR is the 20" Independence Trail SCR is 2,500 m water depth in the Gulf of Mexico<sup>8</sup>. The design of deep risers, both SCRs and top tensioned, is limited by issues of strength and fatigue. The selection of material grade and strength is dependent on whether the riser is welded or not. Welded risers are typically limited to steel grades of about 65 ksi or less (450 MPa). At this stress level the allowable stresses are consumed entirely by hanging weight at about 4,300 m (14,000 ft). There are a few options to get around this limitation:

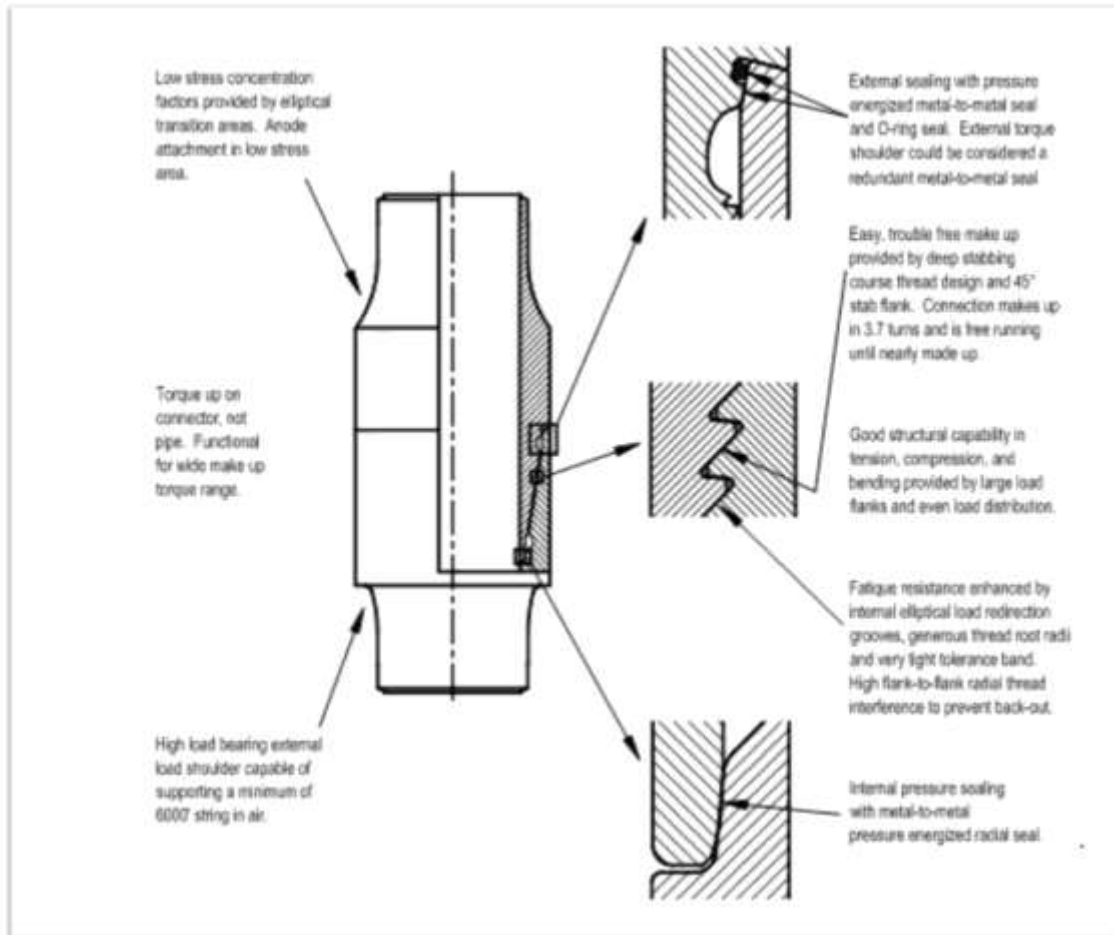
- Adding buoyancy to the riser. This reduces the tensions at the top but introduces a larger diameter profile, which in turn increases drag on the pipe. This might make this an unattractive option for mining, but one that should be considered in any event.
- Higher strength steels may be used, but they exhibit brittle behavior when welded. This can be mitigated by using post weld heat treatment (this was the proposed solution in earlier ocean mining designs). This has been utilized for certain classes of steel, for example, HY-80.
- Steel forged pipe may be made with thicker sections at the weld (upset ends) to reduce the nominal stresses in this region. The upset ends may be welded to each other or to mechanical connectors; the more likely solution in ocean mining.

<sup>8</sup>. Galvin, Conor and Rick Hill, Rick (2007), 'Independence Trail – Steel Catenary Riser Design and Materials', Offshore Technology Conference, paper 19057.

## Connectors

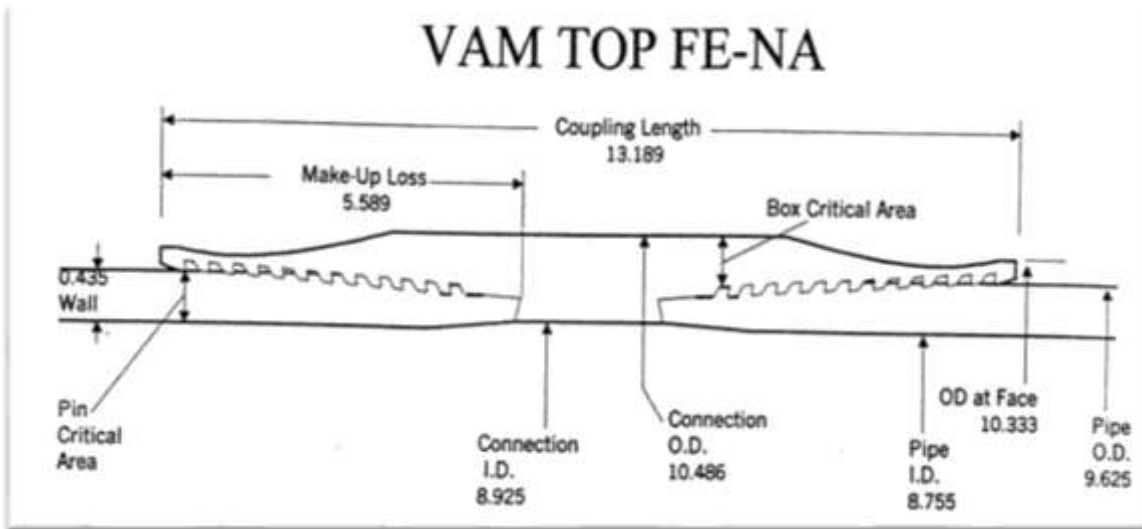
Figure 10 shows a typical weld-on type pin and box connector. Note that the connector itself in this case has an upset and can achieve both the strength and fatigue resistance of the bare pipe.

*Figure 10: Pin and box type weld-on connector*

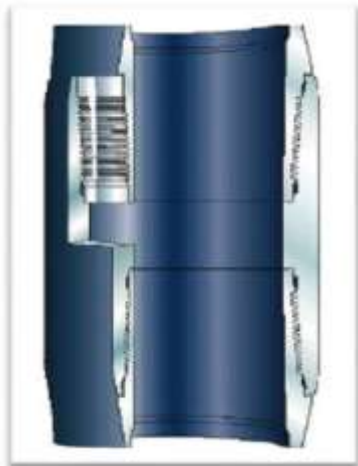


Casing pipe typically has connectors that are not welded, and hence much higher strength steel may be used, up to 110 ksi (750 MPa). Connectors in this case consist of threads machined into the end of the pipe and a separate coupling that goes between the pipe sections. These are referred to as 'threaded and coupled' joints (T&C).

*Figure 11: Fatigue resistant threaded and coupled joint*



Most T&C joints used in casing have extremely high stress concentration factors (SCF) over 5.0, which make them inappropriate for risers that are subject to dynamic loadings. The VAM joint shown in Figure 12 uses an improved thread design, and has an SCF of less than 2.5.



*Figure 12: Upset pipe with threaded and coupled joint*

Even better performance may be achieved with a T&C joint on an upset pipe. In this case the capability of the higher strength may be fully utilized, and the fatigue performance is excellent.

Finally, there is another class of connectors that do not use threaded joints. An example, the Merlin Connector, is shown in Figure

13. This does not require rotation to be made up, and exhibits very good strength and fatigue resistance. They have been used in casing, tension leg platform tendons, pipelines and risers.

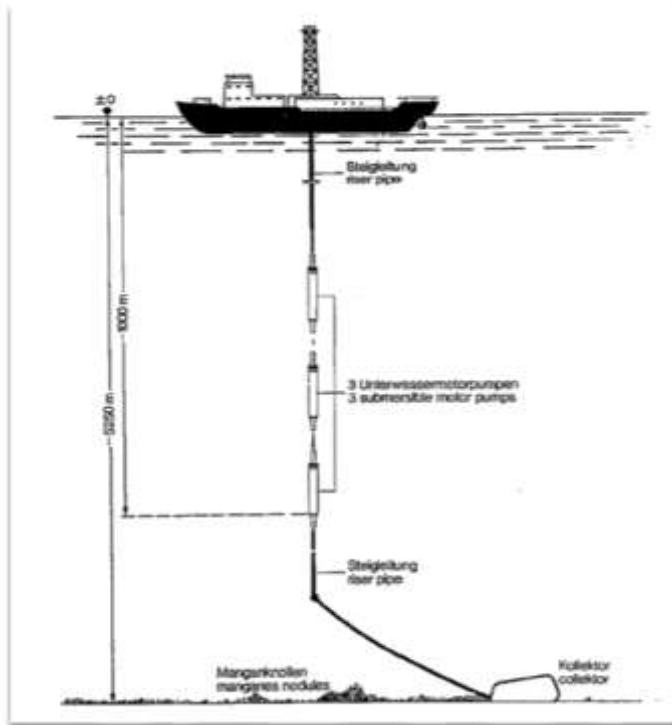


*Figure 13: A non-threaded mechanical Merlin Connector (Oil States)*

## Pumping systems

Early pilot mining tests successfully proved both airlift and submerged pumps as candidates for lifting polymetallic nodules.<sup>9,10</sup> The Ocean Management Inc. (OMI) consortium tested both systems using the *SEDCO 445* as a mining ship in 1978. They collected almost 1,000 tons of nodules. The OMA Consortium was able to produce at rates up to 70 tons/hr using a 6 – 9” lift pipe and airlift. Figure 14 shows the submersible pump arrangement used by OMI. It used a mixed flow scheme.

It would appear that either pumping system would work and could be scaled up to a commercial system.



*Figure 14: Submersible pump configuration used in the OMI pilot mining tests*

Source: Kuntz (1979)

While the author was working for Kennecott Exploration Inc. (KEI) in the late 1970s, we conducted a two-year investigation to compare airlift with submersible centrifugal pumps for ocean mining. There were complicated trade-offs. The centrifugal pumps are relatively efficient, but the reliability of high power subsea connections and motors was not proven at that time. Also, handling large pump modules and power cables is a difficult task on the mining ship. The airlift is simple and involves no machinery below the surface.

However, an airlift system was much less efficient than a pumping system. We performed a reliability/availability analysis and determined that an airlift system could be expected to allow 20-30 more operating days per year than a system with submersible pumps.

The KEI research led to the conclusion that airlift and submersible pumps were about equal in total life cycle costs, provided the airlift system was designed to operate in an efficient ‘froth-flow’ flow regime, where losses due to solid slippage and air flux through the mixture are kept to a minimum.<sup>11</sup> This comparison also rested on an adjustment to the design throughput based on the number of days

<sup>9.</sup> Kaufman et al (1985), ‘The Design and Operation of a Pacific Ocean Deep-Ocean Mining test Ship: R/V Deepsea Miner II’, Offshore Technology Conference, Paper 4901.

<sup>10.</sup> Kuntz, G. (1979), ‘The Technical Advantages of Submersible Motor Pumps in Deep Sea Technology and the Delivery of Manganese Nodules’, Offshore Technology Conference, paper 3367.

<sup>11.</sup> Doyle, R. L. and J. Halkyard (2007), ‘Large Scale Airlift Experiments for Application to Deep Ocean Mining’, Proceedings of the 26<sup>th</sup> International Conference on Offshore Mechanics and Arctic Engineering, OMAE 2007, San Diego.



expected to operate per year, i.e. the production rate per hour of the centrifugal pumping system was adjusted upward to achieve the same annual throughput.

Advances in subsea technology since the 1970s have been remarkable, suggesting that our earlier conclusions about the reliability of subsea cables, connectors and motors should be revisited. Particularly relevant is the success of subsea booster pumps and compressors.<sup>12</sup> King multiphase pumps are now operating in 1,680 m (5,500 ft) of water. This is close to the depths at which pump for ocean mining would be required to work.

Figure 15 shows an example of a large subsea multiphase pump. The powers are comparable to those required for deep sea mining. The packaging of submersible pump modules is still a challenge. Figure 16 shows the arrangement proposed by KEI. Two pumps are fixed to either end of an electrical motor with the shaft extending from both ends. Flow bypass is provided in case of a motor failure or pump blockage, or in case of a system shutdown for the slurry to back flush. These issues complicate the design and need to be dealt with. Some development and testing is required.

Another pumping system developed for the oil and gas industry is a candidate for ocean mining. This is the 'Subsea Mud Pump' (SMP) developed by Hydril as part of a joint industry project (JIP) in the late 1990s.<sup>13</sup>



*Figure 15: Large subsea multiphase pump*

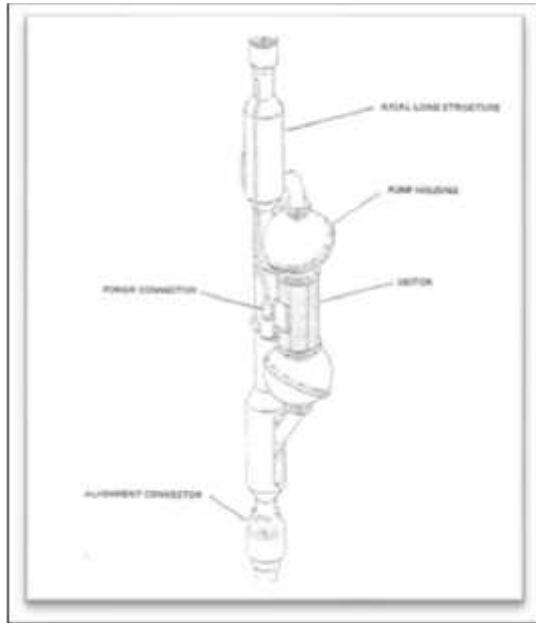
Participants in this JIP included BP, Chevron, Conoco, Diamond Offshore, Global Marine, Hydril, Schlumberger and Texaco

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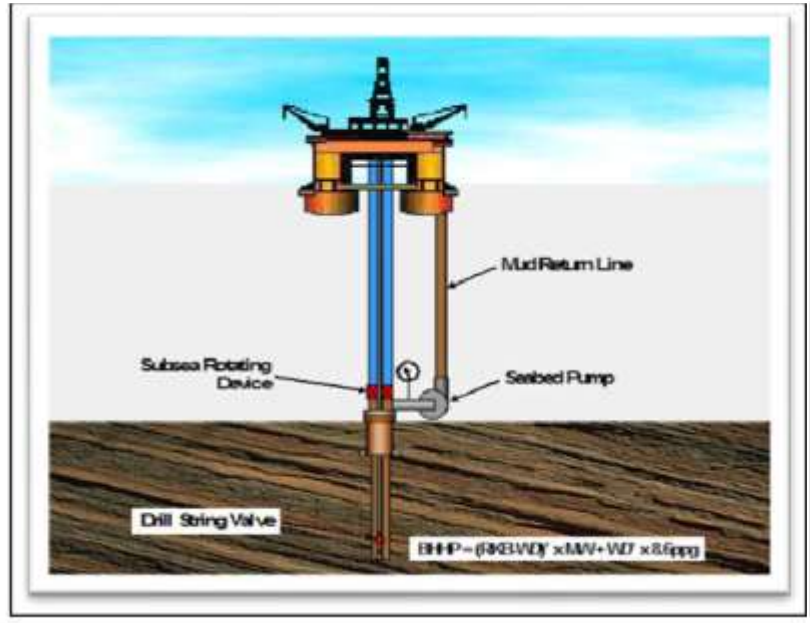
<sup>12.</sup> Kelly, C. (2008), 'World Records in Water Depth and Tie-Back Distance – The BP King Project', Proceedings, the 2<sup>nd</sup> Evolving Multiphase Boosting Technology Conference, EMBT, Hannover, Germany.

<sup>13.</sup> Smith, K. L., A.D. Gault, D.E. Witt and C.E. Weddle (2001), 'Subsea Mudlift Drilling Joint Industry Project: Delivering Dual Gradient Drilling Technology to Industry', SPE Annual Technical Conference and Exhibition, paper SPE 71357, New Orleans, Sept. 30 – Oct. 2.

*Figure 16 (Left): Centrifugal pump arrangement for deep-sea mining (KEI)*



*Figure 17 (Right): Schematic of dual gradient drilling using a submersible mud pump*



The SMP is designed to remove mud and cuttings from the well bore at the sea floor and pump them to the surface through a mud return line that is separate from the riser (Figure 17).

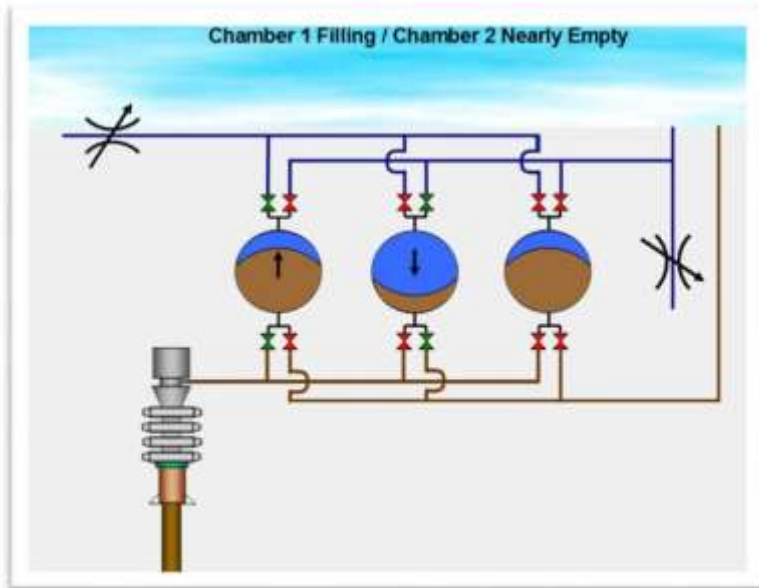
This eliminates the pressure on the well that results from the heavy drilling mud occupying the riser. This greatly simplifies the design of the well in deep and ultra-deep water.



*Figure 18: Subsea mud pump (Hydril)*

The pump itself is illustrated in Figure 18. It is essentially a series of pulsation dampers configured to pressurize a slurry. The chambers are alternately filled at low ambient pressure (from the well, or in the mining case from the collector), pressurized then discharged into the lift pipe under high pressure. ‘Low ambient pressure’ means low differential pressure between the slurry and the surrounding sea water. Figure 19 shows one phase of this operation. Here, chamber 1 is filling with mud from the wellhead. Chamber 2 is discharging at high pressure to the mud return line and chamber 3 is full and waiting to be pressurized. The pressurization comes from high pressure seawater

that is pumped from the surface. There are no underwater motors or pumps. The chambers have a flexible membrane that keeps the high pressure seawater segregated from the slurry.



*Figure 19: One phase of the SMP operation (Hydril)*

When a chamber is being filled (chamber 1 in Figure 19), the seawater side of the chamber is open to the sea through a throttle valve. Water displaced in the chamber is simply ejected into the sea. When a chamber is filled, the valve to the sea is closed. Subsequently, the valve to the high pressure seawater source is open, pressure in the chamber increases to the injection pressure for the lift pipe, and the valve to the lift pipe is opened causing the slurry to go up the lift pipe

(or mud return line).

This is like a positive displacement pump on the sea floor, but it doesn't require subsea motors to drive it. Multiple chambers allow the flow to the lift system to be steady without pulsations.

A prototype unit was built and tested offshore for the JIP. Over USD US\$50 million was spent on this development, which included several months of testing offshore. Table 2 shows the performance during these tests. For comparison, a large scale nodule lift system will pump about 2,200 m<sup>3</sup>/h with a total head of about 1,000 m of sea water. This would require 10 to 12 centrifugal pumps, for example.

*Table 2: Performance of SMP in offshore tests*

<i>Maximum pump rate with unweighted mud</i>	<i>1800 gpm (396 m<sup>3</sup>/h)</i>
<i>Maximum pump rate with 18.5 ppg mud (2216.3 kg/m<sup>3</sup>) and 400 m seawater head</i>	<i>800 gpm (182 m<sup>3</sup>/h)</i>

While the mud slurry consists of finer particles than a nodule slurry, the SMP has proven capable of passing large particles (Figure 20).



*Figure 20: Solids pumped through the SMP*

Another subsea mud pump that has been tested in a dual gradient drilling operation is the Discflo™ pump.<sup>14</sup> This is an impactless centrifugal pump. Instead of using impellers, the Discflo™ pump uses parallel discs. The flow between the discs is laminar and head is generated by the friction between the fluid and the discs. The advantage of this is lower wear on the impeller/discs. It also is amenable to passing larger particles, but not any better than a dredge pump with the opening in the impellers increased in order to pass solids. The pump still requires submersible motors. The efficiency of the Discflo™ pump is about 50 per cent, compared to a centrifugal dredge pump of around 67 per cent.

## **Conclusions and recommendations**

The oil and gas industry is operating in water depths approaching those of the polymetallic nodules in the Clarion-Clipperton pelagic zone. The nodule mining venture has a rich source of commercial technology on which to draw to develop a successful project. In essence there are no barriers to the construction and operation of a successful nodule project other than the functional design itself (for example, can the nodules be extracted from the sea floor?). Much of the work to develop functional designs in the 1970s is still valid today, provided it can be analysed and documented. What is required is a suitable functional design basis that can be turned over to an offshore contractor. A Front-End Engineering Design study would then yield a true picture of what a commercial venture would cost.

## **Summary of discussion**

The presentation evoked a large-scale discussion among the participants. One began by asking whether when air was being induced into the airlift system, that came in at a single point of entry or whether it had to be diffused around the pipe. Mr. Halkyard said that in all of his company's testing they had had a chamber with small angular radial holes. He was not sure whether it was necessary.

The next question came from a participant who, observing that there were many more floating production, storage and offloading units than the other types of platforms (semi-sub, spars and tension leg platforms), asked the presenter the reason for this. Mr. Halkyard said it was because the vast majority of floating production, storage and offloading units were converted tankers that were very cheap. Mr. Halkyard pointed out that the fastest and cheapest way of putting an oil field on line was with a converted ship. Most of them were done in remote areas where there was no infrastructure. In such areas as South-east Asia or Africa, where there were no markets and no pipelines, the oil had to be stored and transhipped. So those platforms were natural solutions for that.

The author was pointedly asked whether, in his opinion, the floating production, storage and offloading unit could be a natural solution for seabed mining. Mr. Halkyard said that it was the preferred solution. He added that, if one looked at it again, the issue was storage of the ore. To optimize transportation you needed to have two to three days of ore storage on the vessel. You needed a lot of dead weight displacement. The ship was the best way of doing that. In so doing you gave up some of the availability, because, as opposed to drilling, in storms and high seas, you had to maintain the course. In drilling the ship could be pointed into the weather, and so could be operated always with head seas. When mining, you had to follow a track dictated by the seabed; you were going in all heading. That placed a burden on the roll motions of the ship and maybe when you got into the details of the mine planning you might find that it was going to cost you. There might be days on which you could not do a turn because the sea was coming from the wrong direction, which might lead you to favouring semi-submersibles or spars. That was an open issue at the moment, but the ship was the best case, based on its storage capabilities.

When asked about solid concentrates, Mr. Halkyard clarified that it was 25 per cent, adding that it was a volumetric concentrate.

A participant wanted to know the maximum particle size it could handle and what slurry concentration it could handle if it was used for crushed nodule slurry pumping. Mr. Halkyard replied that that was still an open question. The development done in the early millennia was based on drilling mud which had fragments that might be 15 mm in diameter. The mud pump had a lot of bends and elbows and you were moving the slurry in a chamber and when it came to rest, then you got it out. He believed that there were many questions about slurry handling and that it would require testing.

Another participant remarked that it seemed as though there had been enough changes in the technology and enquired what the lifetime of an assembled pipe string was if it were supported buoyantly to, for instance, a couple of hundred feet below the surface. The participant also asked if it had enough flexibility at the bottom to handle as much terrain difference as 100 metres, whether it could be left there for five years using towing, rather than having it assembled on a ship with its own gimbal and all the other equipment that was so difficult and expensive. Mr. Halkyard replied that present-day production risers were designed to have a 20 to 30-year lifespan. Thus far, none had been out there for 20 years, but some had been out there for 15 years.

A participant said that if you could avoid excessive stresses induced by having this by moving through the water, then that would take it beyond design specifications per station when you might be able to, in effect, build the pipe string once and not need to assemble new parts of it, but to drop it down. He said that, when he was looking at it, the ship with its derrick for assembling the pipe was by far the most expensive component of the system. It seemed as though it might be possible to eliminate some of that cost now. Mr. Halkyard said that it was something worth investigating. He also said that he believed the collector would be the thing you would have to be pulling up all the time. It would make sense to have a separate deployment/retrieval system for the collector. Unless you had a centrifugal pump, a motor failure or something similar, the riser pipe could be down for 20 years. The deployment systems were not as complicated as the drilling systems because you did not have to rotate anything. You needed a derrick and a pipe-handling system. Those were not too expensive. You did not need a mud system.

## CHAPTER 14      **The Direct Nickel Process for Treating Seafloor Ferromanganese Deposits**

Julian Malnic,\* CEO Direct Nickel Pty Ltd, Sydney, Australia

### **Abstract**

Direct Nickel (DNi) is currently preparing to demonstrate its new proprietary process for the low-cost tank leach of terrestrial nickel laterites. The future of commercial extraction of metals from seafloor ferromanganese-hosted mineralisation depends on low-cost mining and low-cost metallurgical extraction. With experience as the founder and developer of Nautilus Minerals Inc, the author is satisfied that the physical mining of all types of seafloor ores increasingly promises to reach a low-cost stage compared with terrestrial mining for the same metals. With respect to their processing, the economic picture is less clear. As with the processing of the metallurgically-analogous terrestrial nickel laterite ores, existing technologies (pressure acid leach PAL, ferro-nickel smelting, and the Caron process) are at a crossroads commercially, placing upward pressure on nickel prices.

Using the DNi process, DNi has successfully recovered high levels of nickel, cobalt and manganese from seafloor ferromanganese mineralization. The patented process operates at low temperatures and pressures, uses commercially available equipment and largely recycles its reagent. Detailed studies have shown the DNi process is significantly lower in opex and capex. DNi's current programme will demonstrate the process for application to terrestrial nickel laterites.

### **Introduction**

This paper is the result of thoughts before and discussions during the ISA-NIOT Workshop in Chennai. It is not a scientific paper per se, but rather presents perspectives given from an industry viewpoint about the potential of the DNi process and the broader significance of new processing technologies to deep sea ferromanganese crusts and nodules.

### **The Direct Nickel (DNi) process**

Developed over the last 15 years through development research in the chemical engineering sector, the Direct Nickel (DNi) process will be piloted for nickel laterite processing over the coming 12 months. The process is a low pressure, low temperature leach and metal recovery process using a new reagent package. It has the following features:

- Processes limonite and saprolite with one flowsheet.
- No exotic materials, no major off-gases.
- Magnesia and other valuable co-products.
- Nickel and cobalt recoveries similar to HPAL.<sup>1</sup>

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\* Julian Malnic (BSc Hons) is also founder and developer of Nautilus Minerals Inc. and CEO of Sydney-based nickel company Direct Nickel Pty Ltd.

<sup>1</sup>. HPAL – High Pressure Acid Leaching

- Reagent is recycled.
- Faster development cycle, ramp-up, more availability.
- Lower energy use and greenhouse effect than other methods.
- Waste reduced, benign tailings.

A prefeasibility study completed for DNi in May 2007 by Aker Kvaerner of Toronto (Canada) gave estimates of plus or minus 30 per cent for operations at two hypothetical and possible project sites in Australia where inputs could be accurately costed:

1. The Queensland port of Gladstone, where there are high quality infrastructure and laterite ore import facilities.
2. The eastern goldfields of Western Australia (Kalgoorlie district) where limonitic laterite deposits are plentiful although widespread, and infrastructure is good. (Saline water supplies necessitated the costing of a reverse osmosis plant).

The prefeasibility study found that 5,000tpa Ni plants, a scale well below the current economic thresholds of the established technologies such as HPAL, would have a capital cost range of US\$150-175 million, the variation depending primarily on the need for raw water treatment by reverse osmosis.

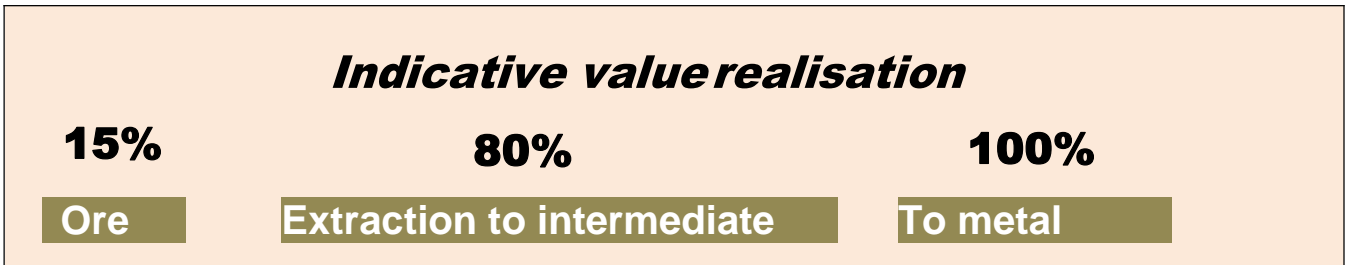
### **Commercial setting**

The hydrometallurgical DNi process represents a promising new breakthrough for potential application to deep seafloor refractory ferromanganese ores from seafloor nodule and crust deposits. The arrival of the DNi process, or any similar process, raises two key questions for the would-be seafloor ferromanganese miner:

- Can a new metallurgical process create a sufficient reduction in processing costs to make seafloor mining economic? The probable answer is 'yes'.
- If an efficient plant with low unit capital cost is constructed to treat ferromanganese ores using the DNi process, will currently-available alternative nickel ores - notably terrestrial nickel laterite ores - become an inevitable substitute for the higher mining cost seafloor ferromanganese ores? The view here is also 'yes'.

The various interests pursuing the mining of seafloor ferromanganese appear to be driven at least partly by the geopolitical aspirations of players, rather than the profit motive that drives the global mining industry.

For example, China is a relatively weak supplier of nickel to its own market from Chinese sources and is buying into nickel laterite deposits and supplies in Papua New Guinea, the Philippines, Australia and New Caledonia to satisfy its ballooning demand. Such open market approaches to metal supply are increasingly being practiced and highlight the open access to oxide nickel ores of terrestrial provenance. The following diagram represents the three basic steps of value realization in the current laterite nickel market. Ore comes increasingly from distant sources and processing is increasingly to a 'mixed hydroxide product' (MHP) of nickel and cobalt.



### Capabilities of the DNi process

The reagent package used in the Direct Nickel process is commercial-in-confidence and not disclosed. However the key characteristics of the Process have been independently studied and verified by engineering firm Aker Kvaerner of Toronto, and clear statements have been made as to its performance characteristics. Estimates of its capex and opex have been derived using actual scenarios at the two Australian sites outlined above at the Queensland port of Gladstone where ore can be received by ship, and at a site in the Eastern Goldfields of Western Australia where a variety of local nickel laterite ores are available. Actual input costs are well known for each of these sites and were used in the estimates.

*Table 1: Estimated capital and operating costs of the DNi process*

<i>Plant Scale tpa Ni</i>	<i>Gladstone Queensland Capital Cost US\$M</i>	<i>Opex US\$/lb</i>	<i>Western Australia Capital Cost US\$M</i>	<i>Opex US\$/lb</i>
5,000	145	2.00	184	2.12
20,000	334	1.30	422	1.42
25,000	382	1.25	483	1.38
30,000	427	1.22	539	1.35

*Table 2: Comparison of the DNi process to alternatives*

<b>Parameter</b>	<b>Units</b>	<b>DNi</b>	<b>HPAL</b>	<b>Heap Leach</b>	<b>Caron</b>	<b>Fe/Ni</b>
<b>Reaction Temperature</b>	° C	<115	250-280	Ambient	750	750-1370
<b>Reaction Pressure</b>	kPa	<500	4,500	Ambient	-	-
<b>Reaction Time</b>	Hr/days	2-4h	2h	90-350d	+12h	-
<b>Ni Recovery</b>	%	+90%	+90%	70	70-85	80-+90
<b>Co Recovery</b>	%	+90%	+90%	70	20-50	zero



*Table 3: Successful leach trial of a ferromanganese crust using the DNi process*

<b>Pure metal</b>	<b>Indicative Grade</b>	<b>Recovery</b>
<b>Nickel</b>	<b>0.43%</b>	<b>98.9%</b>
<b>Cobalt</b>	<b>0.41%</b>	<b>92.2%</b>
<b>Copper</b>	<b>0.09%</b>	<b>99.6%</b>
<b>Iron</b>	<b>16.5%</b>	<b>90.8%</b>
<b>Manganese</b>	<b>18.5%</b>	<b>84.1%</b>
<i>Aluminium</i>	<i>0.32%</i>	<i>98.1%</i>
<i>Zinc</i>	<i>0.05%</i>	<i>99.2%</i>
<i>Magnesium</i>	<i>0.9%</i>	<i>99.4%</i>

*Samples tested at the DNi Laboratory.*

During 2007 and 2008, over 90 laterite samples from Australasian and global sources were leached using the DNi process . All results were in the range of 85-99 per cent for nickel and 80-95 per cent for cobalt. The tabled results from the leaching of the ferromanganese crusts fell at the upper end of these ranges. For now, the main observation is that high iron and high manganese content do not impede the DNi process recovery of the commercial metals copper, nickel and cobalt. The test indicates that the DNi process recovers metals from seafloor ferromanganese mineralisation at least as well as it does from nickel laterites.

### **Strategic value of DNi process**

The implication of the DNi process recovering equally well from both terrestrial and marine oxide nickel-cobalt mineralisation is that the DNi process will not give an exclusive advantage to seafloor ores. Its advantage will be shared by would-be marine producers with the growing number of terrestrial nickel laterite producers.

Inco's Dalvi <sup>2</sup> says that the world inventory of global laterites contains 161 million tonnes of nickel in measured resources. This represents around a 100- year supply at the current global rate of nickel consumption. With knowledge of this abundance widely appreciated in the nickel sector, corporate news in the nickel laterite sector is scant regarding exploration news, major drilling programmes and share-price-lifting announcements of 'discovery'. When compared with other terrestrial commodities and ores, nickel-cobalt laterite deposits are unique in that they lack 'discovery constraint'. This can be said of the marine deposits too. Both ore types represent effectively 'bottomless' sources for centuries to come.

Ophiolitic sequences of high iron-magnesium rocks contain high levels of olivine within which iron and nickel substitute. Weathering and deep leaching have the effect of concentrating nickel to commercial concentrations over the wide areas in which such sequences are typically exposed. Terrestrial nickel laterites are essentially widespread weathering phenomena. This contrasts with the infrequent and relatively unique ore bodies of the major nickel sulphides deposits (like Sudbury and the

<sup>2</sup> Dr. Ashok D. Dalvi; Dr. W. Gordon Bacon; Mr. Robert C. Osborne. *The Past and the Future of Nickel Laterites*. Inco Limited, 2060 Flavelle Boulevard, Sheridan Park, Mississauga, Ontario, L5K 1Z9 Canada. PDAC 2004 International Convention, Trade Show & Investors Exchange March 7-10, 2004.

Bushveld) and most other base metals that are the result of the rare confluence of many critical geological factors that contribute to each genesis.

Laterite and seafloor ferromanganese deposits are both globally widespread sources of oxide nickel. From a strategic viewpoint, the seafloor deposits lie on the abyssal plains in the Area.

### **Market segments and profitability**

Over the last decade, there has been an escalating sophistication emerging in the nickel laterite market. Crudely processed ores are being direct shipped from Palawan, Zambales and the Eastern Samar Islands in the Philippines and several ports in New Caledonia. Potential suppliers include parts of Indonesia and the Solomon Islands.

One typical upcoming project supplying to China and Australia's BHP plant at Yabulu is Toledo Mining Corporation PLC/Atlas Consolidated Mining and Development Corporation Limited's Berong Project on Palawan, which ships 500,000 tonnes a year of 1.5 per cent nickel and 0.1 per cent cobalt. The initial project facility was constructed for approximately US\$5.0 million with the entire exploration/proving programme costing a similar amount. Many similar projects are at various stages of development in the Philippines.

The price formula used at Berong and elsewhere is that 1.4 per cent Ni pays 14 per cent LME of contained nickel; 1.5 per cent Ni pays 15 per cent LME; 1.6 per cent Ni pays 16 per cent, etc. With nickel currently enjoying firm support around US\$28,000 a long tonne (US\$12.50/lb), 1.5 per cent nickel ore is currently trading at US\$420 a dry tonne.

Increasing competition from the many budding direct shipping laterite producers is expected to increase competition and lower this price. Terrestrial nickel miners are arranging funding for new projects based on five-year nickel prices of US\$5.70 to US\$8.00. Increased competition and lower prices could see 1.5 per cent nickel trading at US\$300/tonne in five years' time. A price calculated along these lines is a useful benchmark for price expectation for any plans to substitute available nickel laterite ore for seafloor ferro-manganese ore.

If one accepts that the DNi leach performance experiment is indicative of how other marine ferromanganese mineralisation will perform, there is a basis for estimating the market value of mined marine ferromanganese ores using the same formula. By valuing the cobalt, copper and nickel grades of metal in marine nodule and crust deposits, and assuming that the processor will have equal success recovering similar levels of metal, the pricing formula can be used to benchmark the value of a specific mined ferromanganese ore of specific water content.

The marine mining of ferromanganese ores must be achieved sufficiently within this cost to provide strong profits, or nickel laterite ores will be supplied from the highly profitable direct shipping operations of Australasia as a substitute for them. Pursuing unprofitable marine mining 'in the national interest' will be unsustainable. Marine ferromanganese ores do have a grade advantage over terrestrial laterites with respect to cobalt and copper. Direct Nickel does not have a vested interest in either source and from early indications can treat both with similar efficiency.

The relative global abundance of both nickel laterites and seafloor ores and their similar amenability to many processes, including the DNi process, would bring them into direct price competition if they were simultaneously available.

The preference for building processing facilities in chosen locations with more stable sovereignties is increasingly a driver in promoting the seaborne trade of nickel laterites. It can similarly be expected that if seafloor nickel ores were to be mined, economic pressure would dictate them supplying various processing facilities around the globe rather than a dedicated facility. In any case, such marine nickel ores would fall into direct competition with the nickel laterites supplied from terrestrial sources equally amenable to processing by the processes of the day.

## Summary of discussion

The discussion following Mr. Malnic's presentation started with a question on application of the technologies for the commercial processing of nodules and whether the existing facilities, for example, Direct Nickel's plants, required a lot of conversion and substantial financial resources. Mr. Malnic said he would need to know the specifications of the existing plant. Direct Nickel's reaction vessels were low-cost vessels so any non-corroding vessel could be used.

Mr. Malnic was asked about the \$150 million for capital expenditures which he had indicated was for 5,000 tons of nickel, which worked out roughly to about \$30 per annual kg. The participant pointed out that the graph showed by Mr. Malnic for the capital expenditure in terms of annual kilograms indicated \$3 to \$6. Mr. Malnic replied that that was as the scale went up and that the same thing applied to the \$13 figure as well; that was for 10,000 tons.

A metallurgist observed that the laterite price capital expenditure was so high with the value of \$3 million, it came to around \$75 per annual kg. He said that the papers that they had seen in open literature referred to around \$35 to \$40. He said he was talking about the capital expenditure; if it was \$3b + high pressure acid leaching (HPAL). If one took, for instance, 40,000 to 50,000 tons per annum of nickel. He presumed that Mr. Malnic was talking about the capacity, and it worked out to about \$60 to \$70. Maybe a larger capacity was envisaged. Mr. Malnic said they were finding that they could not control the cost when they built the power plants. That made it hard to raise the money because there was a wild-card risk involved, so people could not raise the money from banks and their companies could not go to any outside participation; therefore only big companies were involved.

Another participant commented that the process shown by Mr. Malic was similar to what had been done in his native India. The recoveries were just as high, except that manganese was still higher. In the Indian process, almost all the manganese was gotten in solution. And in nickel they got almost 98 to 99 per cent. He asked what the selling point was and whether the capital expenditure included manganese recovery. Mr. Malnic said they had not used by-products in their calculations.

A participant recalled that in his flow sheet for nickel laterites Mr. Malnic had shown that they were precipitating the oxides. He noted that Mr. Malnic had said that they were recycling reagents. The participant noted that with the pH adjustment there was going to be consumption since it would not be recycled. Mr. Malnic said that there was an 8 per cent loss.

Another participant said that for each case, if pH precipitation was to be used, every hydroxide would be contaminated. He also asked about the purification scheme. Mr. Malnic replied that it could indeed be a bit misleading. He said that Direct Nickel did have a study of the penalties.

## **CHAPTER 15**

### **Nautilus Minerals Inc.: Technology Development for Seafloor Polymetallic Sulphides Mining**

Michael Johnston, Vice President, Nautilus Minerals, P.O. Box 1213, Milton Qld 4064, Australia

Mr. Michael Johnston made a presentation on the technology development process of Nautilus Minerals Inc. for the commercial mining of seafloor polymetallic sulphides. Mr. Johnston informed participants that Nautilus has been a spectacular success story, raising over US\$349 million in 18 months, with three major resource groups as shareholders, and plans to start commercial operations by 2010 in the waters of Papua New Guinea. He informed the workshop of the major advantages of seafloor mining over land-mining ventures. He said that Nautilus had pioneered new drilling and aeromagnetic survey techniques. He presented a short video of rock cutting carried out at a depth of 1,600 m, and showed the preliminary results of drilling and other geophysical surveys recently carried out by the company.

Mr. Johnston elaborated on Nautilus' proposed mining system and metallurgical test work to determine if valuable metals and products could be won from the recovered sulphide ore. He also informed the workshop that environmental impact assessment tests were underway and were likely to be completed by the end of 2008.

Most participants expressed keen interest in the rapid strides made by Nautilus in commercializing the ocean mining of polymetallic sulphides. Asked how much the mining system would weigh, Mr. Johnston said it would be around 300 tons. He said that the 16- to 18-meter long cores collected were all vertical cores and that no horizontal coring was done. He also said that Nautilus planned to crush ore at the seafloor and to bring up material of constant size.

Mr. Johnson made a power point presentation. As the paper on 'Nautilus Minerals Inc.: Technology Development for Seafloor Polymetallic Sulphides Mining' was not available, Mr. Johnson's powerpoint slides are reproduced in the following pages, followed by a summary of his presentation.

# NAUTILUS MINERALS INC.

Technology development for seafloor massive sulphide mining.

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TECHNOLOGY    MINERALS

## FORWARD LOOKING STATEMENTS

This presentation includes certain "forward-looking statements."

All statements, other than statements of historical fact, are forward-looking statements that involve various risks and uncertainties. There can be no assurance that such statements will prove accurate and actual results and future events could differ materially from those anticipated in such statements.

Such information contained herein represents management's best judgment as of the date hereof based on information currently available. The company does not assume the obligation to update any forward-looking statement.

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## Talk Outline

- NUS history and current status
- Developing a business model
- Developing a mine plan and tools.

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## CORPORATE – TICKER : NUS

- Toronto TSX & London AIM : NUS
- Listed May '06 - in 18 months we have:
  - Raised US\$349 million - 146 million shares
  - US\$310 million in bank\*
  - Three major resource groups as shareholders
  - Staked an area size of UK on seafloor
  - Mine start-up planned to commence 2010\*\*

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## WORLD CLASS PARTNERS AND INVESTORS

Epion	22.4%	US\$109 MM	IRON ORE
ANGLIO AMERICAN	5.7%	US\$25 MM	OFFSHORE DIAMONDS
teck.cominco	7.2%	US\$25 MM	ZINC
	+	US\$12 MM	option payment right to JV
	+	US\$15 MM	warrant exercise

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## Developing a business model

What you need for a viable business model

- A "brand" – what makes you different
- Good land package – with resources
- Technology that will do it – exploration, mining, processing
- Viable economics – price & extraction metrics
- Good people – who have done it before

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## The Nautilus "brand"

- First mover advantage
- Large company interest
- Results – more equipment, quality resources
- Well financed – access to capital
- Support – govt. land & permits, shareholder support, industry support



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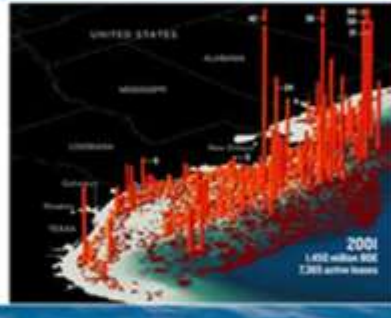
## Developing the Business Case



- Offshore Oil & Gas
- If you can't find what you're looking for, you can't find it.
- Offshore Mining is next.

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## DEVELOPMENT OF OFFSHORE MINING VS THE OIL & GAS INDUSTRY



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## Developing the Brand



Nautilus is the first company to commercially explore the seafloor for copper, gold, zinc & silver deposits

Emerging producer – start up planned 2010

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## NAUTILUS FIRST MOVER ADVANTAGE



- Western Pacific focus.
- Approx. 300,000 sq km
- PNG
- Cookos
- Fiji
- Tonga
- New Zealand

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### SIX ADVANTAGES TO SEAFLOOR MINING

- Minimal mining infrastructure
- Less green house gas emissions
- Limited to total disturbance
- Minimal environmental or shipping
- Minimal mining waste
- Increased worker safety

From 2007 Annual Report

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### Developing New Technologies


New ROV/drills - gave improved ore recovery, NI 43 101 resource.



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### SUBSEA ELECTROMAGNETIC GEOPHYSICS TOOL - WORLD FIRST




- Great response from ore body
- Developed with Tech Controls (a supplier partner).

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### SOLWARA 1 RESOURCE MAP

NI 43 101 compliant - first ever.  
Resource open to the west and at depth  
More work planned in 2008 exploration program



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### Developing the Mining tools

2005/6 "P proof of Concept".

- Engineering studies
- Lab testing
- Scale model tests.



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### 2007 - more GEOTECHNICAL TESTWORK



- 350 000 tests: 3 MPa to 35 MPa at 10 MPa
- Compressive strength: tensile strength ratio of 0.9
- Over 600 dry bulk density measurements
- Average dry bulk density 2.3 t/m<sup>3</sup>



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### The Proposed Mining Model



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### 1. SEAFLOOR MINING TOOL CONTRACT


#### Scale of Existing Subsea ROVs




- Deep Sea Tracking Machine with up to 1,000 hp to engage seafloor
- Same hp of D11 dozer!
- 250 tonnes at sea diameter
- Core at generation over 300 bases!!

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### The mining system



- Competitive tender process to arrive at SMD.
- Q4 2009 integration with mining platform.

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### 1. SEAFLOOR MINING TOOL CONTRACT

#### Awarded contract to Colli Machine Dynamics (UK) Dec 2007

- £35.5M contract for 2 machines (100% submersible)
- Avg. production 100 tonnes and peak production 6,000 t/d
- Includes comprehensive test program and vessel integration

#### Q4 2009 integration with mining support vessel

CDM is a world leader in design and manufacture of complex marine excavation systems for the Energy, Telecom and Mining industries.



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## 2. RISER AND LIFTING SYSTEM (RALS) CONTRACT

Expect award design and build contract by Q2 2008

Competitive, post-Feasibility engineering design program underway

- Pump selection key design element
- Riser handling equipment is off the shelf



## 3. MINING SERVICES CONTRACT

Competitive, post-Feasibility design study underway to:

- Identify the required logistics of GMIT and RALS with the proposed vessel
- Demonstrate proposed optimal vessel configurations

Scope of contract includes:

- Provision of the mining support vessel
- Manage the daily production operations as a performance based fixed fee

Expect contract award in Q2 2008

Target capital expenditure and operating costs following award

## ORE TRANSPORT TO ON-SHORE STORAGE



- 6,000 tonnes of ore to treatment facility
- Self-propelled, self-unloading barges Off
  - "Dumb" tugged barges

## SITE SELECTION FOR PORT AND CONCENTRATOR ON TRACK



- Exact metallogenic work is difficult
- Feasibility study ongoing studies of best process
- Site investigations in PNG to finalise site selection and prephase site

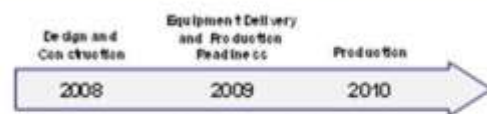
## METALLURGICAL TEST WORK

- Copper Concentrate
- Preliminary flotation test work results on our best material
- Recovery > 50%
- Produced saleable grade Concentrate



- Major test work program
- METECC (Perth Australia) applied for major program based on Okara 1 drill core

## FOCUSED ON PRODUCTION BY 2010



- Exploration work in PNG, Surua and other projects by EAC
- Generate accurate picture of ore reserves
- Continue increasing known reserves
- Complete remaining system equipment
- Main production work in PNG, Surua and other projects
- Continue increasing known reserves
- Obtain all necessary permits, licenses and mining leases
- Complete construction
- Further develop projects in partnership with other projects
- Begin commissioning of additional production facilities
- Bring Surua 1 into full production

**ENVIRONMENTAL IMPACT ASSESSMENT UNDERWAY – EXPECTED Q2 2008**

ENVIRONMENTAL IMPACT ASSESSMENT UNDERWAY – EXPECTED Q2 2008

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**NAUTILUS Business Model - how it works**

- Major mining companies: Teck Cominco, Anglo & Epiion
- US\$310 million in cash to move project forward
- First mover advantage
- Exploration tenements size of United Kingdom
- Large mineral belts – aggregation of deposits
- High grade copper, gold and zinc
- Target production Q3, 2010 (subject to timely permitting)
- Compressed development time line – no pre strip or shaft

NAUTILUS Business Model - how it works

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## Summary of presentation

Mr. Johnston said that the project that he would speak about was seafloor polymetallic sulphides, but that it would be the first commercial deep-water mining project in the world once the company got it up and running in 2010. He said you could do a lot of research and planning, but that ultimately there came a point at which you had to bite the bullet, spend the money and have the first generation mine occur. That was what Nautilus was trying to do.

He said the company started in 2006. He said that when it had decided on a strategy for Solwara 1 it became very clear going forward that they had to grapple with what they wanted out of the notion of trial mining for a commercial company. He said they felt that they couldn't just go out in a 30 metre ship in the middle of the Pacific Ocean looking for nodules. He said that they would have to go out there in a large vessel, big enough to handle the conditions. He said they then started to ask themselves about the mining unit. He said they could build a small vessel and try to demonstrate it, but that they needed to go through all the risk elements and decide what the potentially critical risks needed to be demonstrated. He said that once risk had been demonstrated, shareholders would have enough confidence to make the decision to go and mine.

Mr. Johnston said that because Nautilus was a publicly listed company it had to put up all the disclaimers about forward-looking statements, etc. Mr. Johnston spoke about the history and current status of Nautilus and then talked about a business model, develop mine plans and the tools they needed. He said their focus was on risks to their company, a small company.

Mr. Johnston informed participants that Nautilus had been a private company until May 2008. It had been listed in 2006 and in 18 months had raised almost \$350 million. Currently, Nautilus had \$310 million in the bank. It had three major resource groups as shareholders and a lot of applications or grounded title in the South-West Pacific. That ground was focused on seafloor polymetallic sulphides. He said that they were planning to be in production by the end of 2010. That is subject to permitting by the government of Papua New Guinea (PNG) which had been very supportive of the project. He said that PNG had a long history of mining, but they also recognize that like most countries, on land their resource base is depleting, their mines are getting old; their copper and gold mines are very large but most of those are scheduled to close within the next ten years. The country's mining industry is going through a transition of mining smaller deposits and also seafloor resources.

Nautilus had three major companies as shareholders: (a) Epion, owned by a Russian billionaire, who owned nearly 25 per cent of the company; (b) Anglo America, which was London-based but had its roots coming out of South Africa. It was the fourth largest mining company in the world; and (c) Teck Cominco, which was Canada's largest mining company. All three companies had the same issue, namely, how do they continue to grow. All of them knew that they had to be finding new mines and new discoveries. It was hard to do that on land.

Mr. Johnston asked: in developing a business case, what did you need for a viable business model? He gave the following answer:

- (a) One of the things that you had to have was a brand – something that nobody else had.
- (b) In the mining business you needed to have a good land package with good resources. Usually the higher the grade the better the right metallurgy.
- (c) You needed the right technology. Sometimes those technologies were not available directly today, but the concepts behind them were available. But if you were prepared to spend the money and put the right people onto the problem they would solve it for you.
- (d) You also had to have viable economics. At the end of the day, many projects were about making money. You would not be allowed to stay out there in the ocean mining if you were constantly losing money. Different countries and different companies had different views about what the investment thresholds were. Private companies required, for new projects, a very high threshold; government companies with whom he had had contact with over his 25 years of mining, had a different view on the return on investment. Sometimes it was not about making money, but the strategic importance of the minerals. At the end of the day though, the operation had to be cash-flow positive.
- (e) Another thing you had to have was good people, generally people who had done it before. Many studies done over the years had showed that if you backed people who had been successful previously, the chances of them being successful again were extremely high.

Mr. Johnston said that Nautilus had “the first mover advantage”. It had a very large land holding in the South Pacific Ocean, which was focused on polymetallic sulphides. It had also developed with some of its partners, new equipment which it had used to evaluate its deposits. It also had access to a lot of cash and the support of government, landowners and shareholders. In the deep ocean in the area, with the International Seabed Authority, it had a balanced organization which was prepared to trade off some impacts for the benefits that could be returned from the activities.

One of the things that Nautilus had done in developing the business case was to go back to the petroleum industry. In 1961, there had been 415 leases in the Gulf of Mexico. The company’s focus had been in the South-West Pacific Ocean because it was chasing polymetallic sulphides; it was chasing those tectonic boundaries and plate boundaries, which is where those deposits occurred. The polymetallic nodules were out in the more passive deep ocean, but they had a known distribution.

One of the areas of concerns for investors was the notion of security of title. In the South-West Pacific Ocean where Nautilus had its applications and had been granted title, Mr. Johnston said there was legislation which allowed the company to physically own title to the minerals. With the Authority being established, there was a regime to allow title ownership in the deep ocean as well.

Mr. Johnston said that with seafloor mining there were six main advantages that he wanted to talk about. One that was important to him was the limited social disturbance; the laterite projects that Mr. Malnic had talked about were generally sited in somebody’s backyard etc. When mining on land, nine times out of ten, you had to end up moving people. That did not occur in the deep ocean. Another was increased worker safety; everything that the company did was robotic and it had been going now for nearly two years and was yet to have what it called lost time due to injury. In the land mining business that was unheard of. The most the company had had was a band aid. A third advantage was that there were less greenhouse gases; if one was dealing with high grade ores, one was going to produce less greenhouse gases. The remaining three advantages were minimum mining waste, minimal overburden or stripping, and minimal mining infrastructure.

Over the past couple of years, Mr. Johnston said that Nautilus had developed some new technologies with some of its partners. Perry Slimsby had designed and built an ROV drill which was used on Nautilus’ deposit in 2007. This had allowed Nautilus to recover all samples down to a depth of 18 m for the first time. It then allowed them to quote a resource to National Instrument 43 101, which was a Canadian standard for the disclosure of mineral projects within Canada which investors and the stock market had to see if you wanted to try to raise money.

He said that another thing that Nautilus had developed with a couple of its partners - Teck Cominco and Erick Jackson and some of the people from Vancouver, Frontier Geophysics - was a new electromagnetic survey tool which mapped the concentration of copper on the seafloor. Because the copper was conductive, the conductivity increased and you could map out the distribution of the copper-rich metal on the seafloor. Nautilus had been able to develop that system in about six months and deploy it, and was looking forward to using it extensively over the coming year in Tonga and Papua New Guinea.

Mr. Johnston informed participants that for risk assessments one of the key things that people saw with Nautilus’ project was a potential show stopper from day one was the need to continuously mine that material without explosives. He noted that if the deposit could not be mined, the project

would become moribund. He said that back in 2005 Nautilus had recognized that this possibility was a major issue for it, so it needed to prove to investors that it could physically mine the deposit. As a result, he said that the mining tool had been built and taken down to the bottom of the sea in the Manus Basin and that over a three-day period, the company had mined about 15 tons of material to its vessel. They had not had a riser system, but had just mined it into a series of drums.

Mr. Johnston stated that prior to designing that equipment, Nautilus had done some test work on samples obtained from an earlier programme and they had indicated that we were looking at about 30 megapascals. The unit was designed to handle materials of about 18 megapascals.<sup>1</sup> It had been tested on concrete in Vancouver and then taken down to the bottom of the Manus Basin and tested again and it had worked fairly well.

The next step for the Nautilus team had been to do further evaluation of the deposit, a lot more geotechnical test work, because the next stage of the way forward had been to tender the design and construction of the actual units which were going to mine the deposit. They had had a full geotechnical laboratory on the ship. He reminded participants that a lot of technologies were already out there already mining at the bottom of the ocean.

Mr. Johnston said that was the mining system as planned at the moment. The company had let the contract for the design and building of the mining unit in December 2007 after a competitive tender process. The job had been split into the mining unit, the riser and the lifter unit and then the ship and related services. Tender documents had then been put out to interested parties to tender on the design and building of those various bits of equipment. Once expressions of interest were received, the tender list would be narrowed down to three or four tender parties.

Nautilus was going to build two mining units at a cost of 33 million pounds. They had an average production unit of 100m<sup>3</sup>/hour with peak production rates of 6,000 t/day. The design and building would include a testing programme and vessel integration. The people who were going to build them would not get paid if it did not work. There was a high incentive for them to ensure that the hydraulics and everything worked. It would get sea trials in 2009 and then Nautilus would start mining with them in Papua New Guinea in 2010.

The unit had the capacity to have a crawler or legs. It could move forward and could swivel. The terrain where the team would be working was rugged so it had to be fairly flexible initially and then as it mined it would create level surfaces and then could be converted to a caterpillar traction system. Nautilus had two units; one would be down on the deposit mining, while the other was at the back of the ship so as to have 100 per cent redundancy.

Mr. Johnston identified the next stage of bringing the first mine into production as being the riser and lifting systems. He said that he contract to design and build that system would be let towards the end of 2008. Nautilus also had the mining services contract which was all the activities on the surface: the ships and barges, etc. The company expected to award that in 2008 as well. That contract could not be awarded until they knew the approximate configuration of the riser system.

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<sup>1</sup> Megapascals - A unit of measure to determine the amount of stress on a piece of material. The United States uses a different unit of measure: PSI or pounds per square inch.

The deposit was situated in the Bismark Sea. It was about 50 km from the port of Rabaul, which was a natural harbour and surrounded by volcanoes, one of which was mildly active. The plant would be located in Lassul Bay, which was 50 to 60 km from the deposit. Nautilus would mine the ore, put it on barges and then take it back to a plant in Lassul Bay.

Mr. Johnston said that Nautilus had already completed geotechnical drilling in the Bay, testing the foundations for the port facilities that had to be put in. The company was looking at various options for the processing plant; one of them was a floating mobile plant. It had a lot of advantages, in that it could be moved very quickly to another country or nearer to another deposit.

Nautilus would also be doing detailed metallurgical test work. Preliminary results of that showed that there was more than 90 per cent copper and the company was producing saleable copper grade concentrates that were quite high.

In 2008 the company would conduct more exploration work. It would start construction of the mining system. 2009 would be about the delivery of the mining systems, testing towards the end of the year and then in 2010 putting the whole thing together in Papua New Guinea and commencing production.

As part of the permit process in Papua New Guinea, one had to submit an environmental impact assessment statement which had to be publicly reviewed. Nautilus had collected all the data for that and had been working with experts from Australia, Canada and the United States.

In summary, Mr. Johnston said that three major mining companies who were big supporters and Nautilus had a lot of cash to move forward. The model was to aggregate deposits: to identify high-grade deposits on the seafloor and try to mine them, and produce high-grade copper, gold and zinc concentrates. One of the advantages with offshore mining is that, once the decision is made to go ahead, the timelines are compressed, unlike land mining, where, if you were going underground, you had to sink a shaft to get down to 1,500 m.

### **Summary of discussion**

The discussion started with participants asking, respectively, the weight of the mining units and whether they had to be anchored when moving forward. To the first question, Mr. Johnston replied that they weighed around 300 tons. To the second question, he replied that they were not dealing with abyssal plains and it was therefore pretty rocky and the seafloor was basically high-grade copper, so it had a level of strength that you would not have on the abyssal plains that the nodules were on.

Another question was on the diameter of the 18-metre cores and how long it took for them to be drilled. Mr. Johnston replied that that was conventional drilling, so the diameter was HQ<sup>2</sup> which was about 60 mm and because it was conventional coring, you had to drill a 2-metre rod length, pull the bow and then add another rod length, drill that for 2 metres, pull the rods and then the bow.

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<sup>2</sup> HQ - outside diameter 96 mm. Inside diameter 63.5 mm.

He said the first run would take about 15 minutes, but as you had to pull more and more rods to recover each 2-metre run, the runs started to lengthen and then the last one would take about an hour to recover. To do 18 metres you had about nine runs. From ship to ship it was the best part of the day for a haul; any time between 16 and 20 hours.

To a query on whether the coring was both horizontal and vertical, Mr. Johnston clarified that just vertical coring was done.

One participant asked Mr. Johnston about the escalator and how confident Nautilus was about the particle size coming out of that, and whether Direct Nickel had an idea about buffing or crushing. The reply was that there would be a crushing facility on the mining unit. They were doing an extensive testing programme on the pick designs over the first couple of months of the design and build. Nautilus had sent the designers a lot more samples and geotechnical material for the designers to decide on the pick designs, but back on the mining unit itself, there would be a crushing unit to keep the sizing as constant as possible.

The next question pertained to the economics of the venture and another participant asked what return Nautilus was looking at and over what period of time would its initial investment be paid at that rate. The participant also asked whether, whatever the required duration of mining, Nautilus felt that its concentration of deposits was there for it to mine at that same rate. The reply was that, in the business model being contemplated, one of the keys to the rate of return was what the metal price was going to be when you were in production. The Nautilus business model was to get into production as soon as possible, because at present the copper price was about \$3 per pound. Long-term metal prices that the banks tended to use at the moment were between \$1.30 and \$1.60 per pound. That made a big difference to your economics and your projected rate of return. If you used the forward curve (take the current day's metal price and the long-term metal price and then project a curve to connect those which decayed going forward) in 2010, you could talk about anything from \$2.20 to \$2.60 per pound. At those metal prices, the Nautilus project might be very profitable.

In continuation a participant asked whether Nautilus had a number in mind as to when it recovered its capital expenditures or when it would like to recover its capital expenditures, and how much time it would take. The answer was that mining rates were around one and one-half million tons. Once in production, the company would try to push the rates as hard as it could. It had a lot of redundancy and that was part of the philosophy of making sure that it could maximize production.

## CHAPTER 16

# Applicability of Flexible Pipe Riser Technology to Ultra Deepwater Mining: Case Study

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### Abstract

Currently, flexible pipe risers are a field-proven technology operating all over the world, with the deepest water depth being off Brazil at 6,500 ft. Free-hanging pipe weight in water depths greater than 6,500 ft creates a challenge for any riser system. The flexible riser configuration presented here is a continuance of the concept(s) presented by T. Hill, Y. Zhang, B. Chen, T. Kolanski (2006).

Discussed herein are the challenges and benefits associated with using a 10-inch internal diameter x 5,000 m water depth flexible riser pipe as applicable to the offshore mining industry. The key technical challenges include:

- Collapse load;
- Top tension load;
- Active mobility; and
- Upward flow (pumping).

The purpose of this paper is to demonstrate the technical feasibility of unbonded flexible pipe for ultra deepwater seabed mining via a unique riser configuration. In addition to the operability of the risers, unbonded flexible pipe offers numerous benefits including:

- Erosion resistant inner liner;
- 25-year service life;
- Re-usability;
- Pipe is fully tested before delivery - Factory Acceptance Testing;
- Wet storage on the seabed;
- Flexibility of installation methods, e.g. carousel or reel and towing from shore.

Future work to confirm the flexible pipe riser system as suitable to field operation includes:

- Optimize riser solution for intended operating conditions;
- Optimize buoyancy requirement;
- Detail method of attaching/integrating buoyancy in the riser system;
- Detail method of integrating pumps in line with the flexible riser pipe.

### Introduction

Unbonded flexible pipe has been used in the oil and gas industry for more than 25 years. Current flexible pipe structures are derivatives of WWII rapid pipe-laying technology. The technology is a natural enabler where:



- Topside vessel dynamic motions are high;
- Flexibility at the seabed touchdown point (TDP) is required; and Vortex-induced vibration loads are prevalent.

To meet the needs of ultra deepwater mining via hydraulic mining systems, advances in unbonded flexible pipe riser solutions are required. This paper confirms the feasibility of unbonded flexible pipe to meet the ultra deepwater needs of the seabed mining industry. The key challenges for the riser lift pipe in ultra deepwater are:

- Collapse load;
- Top tension load; and
- Bending.

The case study presented herein will quantify each of the key technical challenges and set forth methods for meeting each challenge. Pipe design and riser configuration system optimizations are summarized and technical feasibility confirmed.

### Flexible pipe riser design

The flexible pipe riser is designed using proprietary design tools calibrated with test data. The design tools are certified by Lloyds Register. The flexible riser is designed for the parameters listed in Table 1.

*Table 1: Design parameters*

<b>Internal Diameter (in)</b>	<b>10</b>
<b>Internal Design Pressure (MPa)</b>	15
<b>Temperature (c)</b>	50
<b>Water Depth (m)</b>	5,000
<b>Service</b>	Sweet slurry
<b>Host</b>	Ship shape, DP

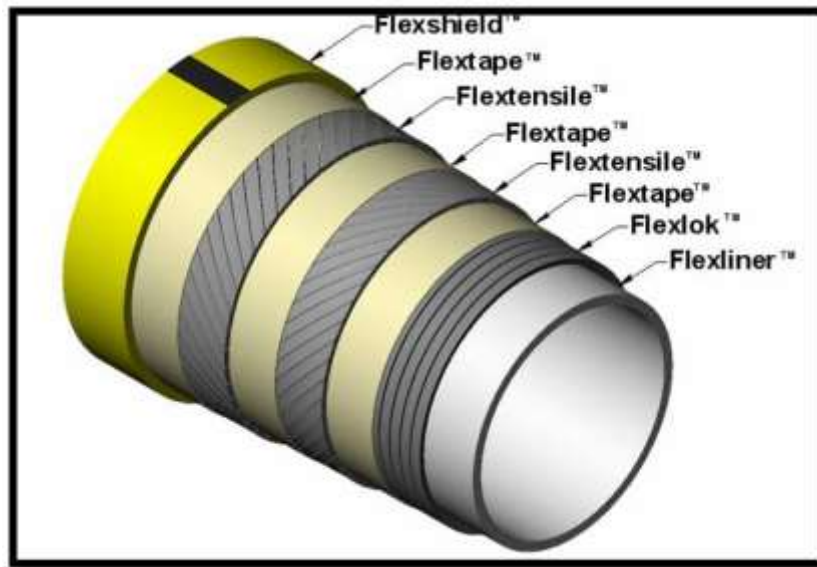
Key assumptions in the basis of design are:

- A stepped riser configuration (as depicted in Figures 3 and 4);
- Minimum specific gravity at all times during installation and operation:  $SG > 1.0$ ; and
- Maximum specific gravity of lift slurry at any time during operation:  $SG < 1.7$ .

API 17J Specification for Flexible Pipe Design provides the design load cases and corresponding utilization factors based on application in the oil and gas industry. These same utilization factors are assumed for designing the flexible riser pipe for subsea mining.

The flexible pipe riser cross-section design is illustrated in Figure 1. The corresponding flexible pipe riser properties are listed in Table 2.

*Figure 1: Flexible pipe riser cross section*



*Table 2: Flexible pipe riser properties*

<b>Internal diameter (mm)</b>	<b>254</b>
<b>External diameter (mm)</b>	330.8
<b>Weight empty in air (kg/m)</b>	117.3
<b>Air filled in seawater (kg/m)</b>	29.15
<b>Nominal bend stiffness (kN/m<sup>2</sup>)</b>	70.628
<b>Axial Stiffness (kN)</b>	642.063
<b>Minimum bend radius, MBR (m)</b>	3.2
<b>Failure tension (kN)</b>	5.375

#### ***Factory acceptance hydrostatic pressure test***

The factory acceptance hydrostatic pressure test (FAT) is performed in the factory for a hold period of 24 hours. This test serves to prove the pressure integrity of the product before it leaves the factory and to condition the flexible pipe. Currently, API 17J specifies the FAT pressure for a flexible riser to be tested to 1.5 times design pressure. The primary support for internal pressure is the Flexlok hoop layer. The utilization ratios are given in Table 3. The burst to design ratio is 3.4. The proposed riser structure meets the API 17J requirements with margin to ensure a robust design.

The FAT is a prominent benefit of the flexible pipe technology because any material or manufacturing defect will be identified before the pipe leaves the controlled environment of the factory. If a defect is recognized it can be most efficiently addressed onshore. Once the problem is rectified the pipe will undergo another FAT before it leaves the factory.

*Table 3: FAT pressure test load results*

FAT Pressure (MPa)	Hoop utilization	Hoop utilization, allowable	actual / allowable
15	0.67	0.91	0.74

### **Required analysis**

To evaluate the feasibility of flexible pipe for deep water high pressure service, the following three main load criteria need to be considered:

- Collapse load;
- Top tension load; and
- Bending load.

The flexible pipe must have sufficient collapse resistance to withstand the hydrostatic pressure exerted by the water column. This can be accomplished in two ways. First, internal collapse-resistant layers can be implemented into the pipe structure. Second, the system can be designed to assure that the pipe remains filled with an incompressible fluid. For the current application the pipe will remain fluid filled.

The Flextensile wires provide axial strength for the flexible pipe. The function of the wires is to support the top tension load of the pipe. The section of wires under the highest load is in the top hang-off section. As the flexible pipe reaches into deeper and deeper water depths the uppermost armour wires must support the ever increasing weight of the pipe. In order to sustain increased top tensions, thicker armour wires can be used, or the riser can be configured with buoyancy to decrease weight. Below is an evaluation of the stepped riser system which implements buoyancy to reduce top tension. Dynamic analysis shows that the structure of the flexible pipe remains within the allowable utilization limits.

The bending range of flexible pipe is governed by a minimum bend radius (MBR). Every flexible pipe structure has a unique MBR that is calculated using proprietary software. All riser configurations need to be checked to assure that the pipe never exceeds its MBR. The following analysis shows that in the stepped riser configuration the flexible pipe will never approach its minimum bend radius.

### **Collapse analysis**

The basis of design for collapse is that the bore of the pipe is filled at all times such that there is not a negative pressure differential across the barrier. Thus, collapse of the pipe is not possible.

### **Tensile utilization**

The Flextensile layer provides the tensile strength of the flexible riser. The stress in the Flextensile layer is determined with proprietary design tools. The stress of the Flextensile layer is heavily dictated by the maximum top tension load. The maximum tension load is determined in the global dynamic analysis and then fed back into the design tools. The load cases include an additional load to the Flextensile layer created by end load effects of the internal pressure. The Flextensile layer supports the axial load of the pipe and works in conjunction with the Flexlok layer to provide hoop strength. Design tools output the maximum utilization ratios. These ratios must comply with the

allowable limits specified by API 17J. The utilization ratios are provided in Table 4.

*Table 4: Extreme operating tensile utilization*

Max Top Tension	Internal Pressure	Flextensile Stress Utilization	Allowable Stress Utilization	Actual /Allowable
2430 kN	15 MPa	0.67	0.85	0.79

**Riser configuration analysis**

In order to assess the top tension load the riser configuration must be defined. The simplest riser configuration is the free-hanging riser. If top tension is high, a shaped riser system with buoyancy may be used to mitigate high tension loads. Two riser configurations are considered and compared: a vertical stepped riser, and a traditional free-hanging riser. The free-hanging riser is illustrated in Figure 2. The shaped riser with buoyancy, referred to here as the stepped riser, is illustrated in Figure 3.

The free-hanging riser does not have any buoyancy. Therefore, the top section of the flexible will experience the full load of a 5,000 m long free-hanging pipe. The stepped riser system has four groups of buoyancy, which decrease the top tension load. The uplift provided by the four groups of buoyancy is shown in Table 5. Figure 4 shows the location of the buoyancy along the flexible riser.

*Figure 2 (Left): Free-hanging riser (not buoyed, free-hanging weight)*

*Figure 3 (Right): Stepped riser (buoyed)*

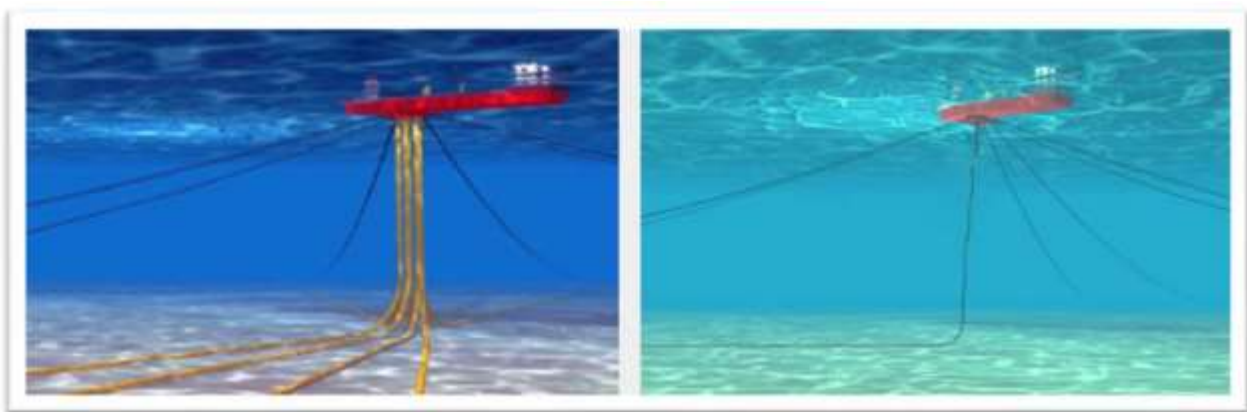
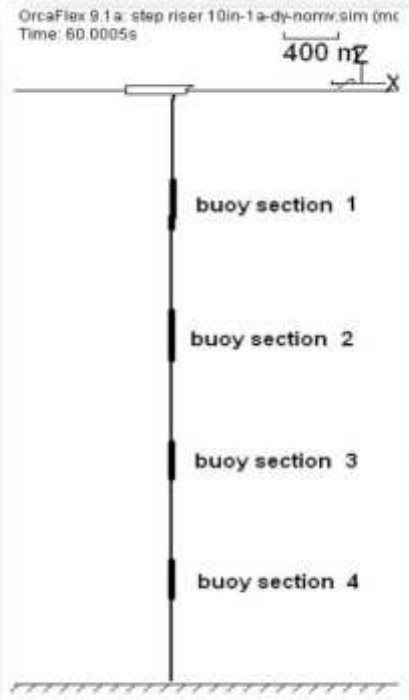


Table 5 summarizes the total net buoyancy, corresponding maximum water depth of the buoyancy, and the maximum effective tension in the mean static loading condition for the stepped riser.

*Table 5: Net buoyancy load summary*

Buoy Section #	Arc Length at Start Point of Section (m)	Section Length (m)	Net Buoyancy (kN)
1	750	400	942
2	1,850	400	942
3	2,950	300	707
4	3,950	300	707
	Total:	1,400	3,300

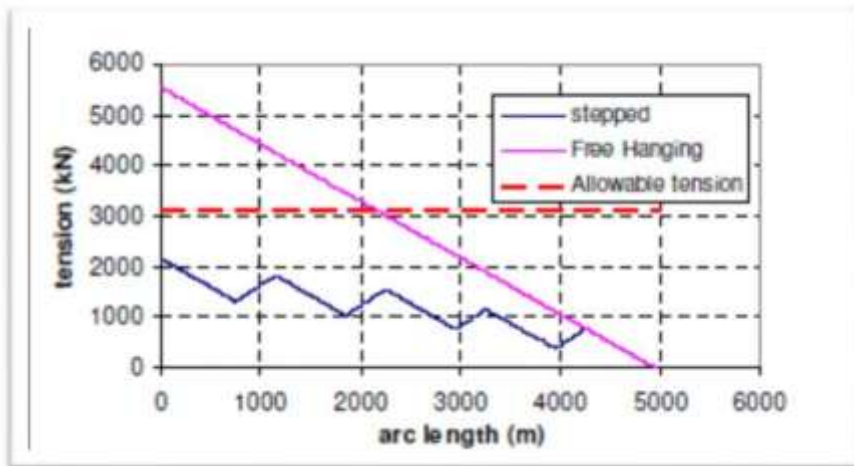


*Figure 4: Vertical stepped riser*

The dynamic analysis method used in this study is a time domain finite element analysis performed with a commercial software package.

In a static condition, with no wave or vessel motion and no current, the maximum tension at the top of the stepped riser is approximately 2,150 kN. The maximum top tension of the static free-hanging riser is 5,540 kN. For comparison, the free-hanging riser results are plotted with the stepped riser results in Figure 5.

The maximum allowable tension is 3,090kN according to the allowable stress utilization, 0.85, specified by API 17J. Figure 5 shows that the uppermost section of the free-hanging riser is over utilized from approximately 2,000 m and above. Conversely, the maximum tension experienced by the stepped riser system is within acceptable API limits, at 2,430 kN.



*Figure 5: Buoyed catenary riser vs. free-hanging catenary riser tension load distribution*

### **Dynamic analysis**

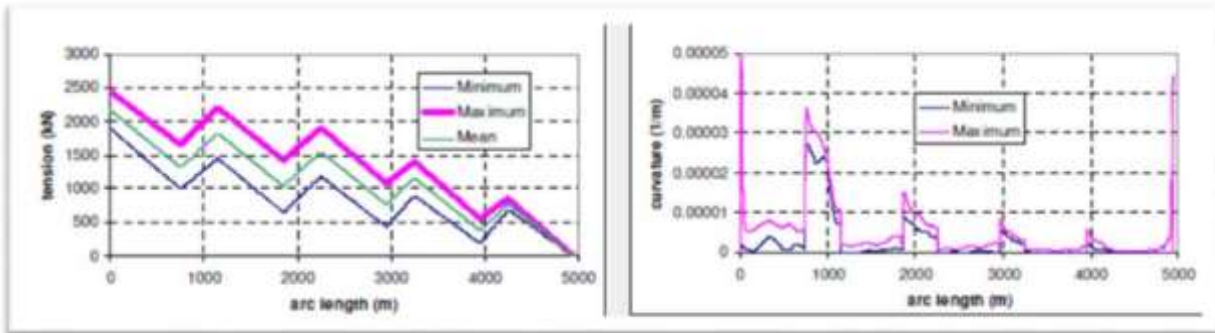
The dynamic analysis is based on the following environment and surface vessel RAOs:

- Maximum wave height: 5 m.
- Wave period: 9 seconds.
- Surface current: 0.3 m/s.
- Vessel RAO: deepwater FPSO.

The maximum top tension of the stepped riser under dynamic loading is 2,430 kN. Figure 6 illustrates the dynamic tension response of the stepped riser system. Figure 7 demonstrates the curvature response of the system.

*Figure 6 (Left): Stepped riser tension load distribution*

*Figure 7 (Right): Stepped riser curvature distribution*



The tension range reduces as the length approaches the TDP. In the stepped riser configuration, the tension range and the curvature range become negligible at the TDP, simulating a static riser system in the touchdown region.

Moreover, the stepped riser system never exceeds its MBR. The calculated dynamic MBR of the current design is 3.2 m. Under dynamic loading the smallest bend radius the pipe will experience is 20,000 m. This analysis shows that the stepped riser will move through an acceptable bending range and will never be damaged by over bending.

### ***Dynamic analysis discussion***

Based on the comparison of tension load distribution plotted in Figure 5, one can conclude that the top tension load is naturally reduced in the buoyed stepped riser compared to the free-hanging riser. It is important to maintain a positive tension at the bottom of the riser; the buoyancy in the bottom section is sized accordingly.

From the tension load distribution curves, one can conclude that the top tension load in the stepped riser is significantly less than the top tension load in the traditional, non-buoyed free-hanging riser configuration. It is also noted that the delta between the minimum and maximum tension load is significantly smaller in the bottom sections of the stepped riser compared to the top sections. As expected, this demonstrates that the distributed buoyancy decouples the dynamic top motion of the surface vessel from the weight of the riser system. The decoupling effect reduces the dynamic response in the riser system which lends itself to significant benefits over a traditional free-hanging riser system. These benefits include:

- Lower payload requirement for the surface vessel; and
- Longer riser fatigue life.

The advantages at the touchdown region are:

- A positive tension is maintained;
- The riser is static; and
- The interaction between riser and seabed mining unit is independent of the riser response to the dynamic motion of the surface vessel.

### **Active mobility**

The flexible riser pipe enables active mobility of the overall mining system by means of the following benefits:

- Inherent flexibility of the pipe; and
- Natural damping of the flexible pipe to minimize the effect of vortex induced vibration (VIV).

Furthermore, the buoyancy in the system decouples the top dynamic motion from the seabed mining unit connection offering further advantages to the system:

- Relaxed constraint on vessel offset with respect to the bottom riser position and vice versa; and
- The design of the bottom riser interface with the seabed mining unit can be optimized without a heavy burden of dependency on the top riser section(s) response to the surface vessel.

The rate of mobility, however, is critical to the system. If the lag between the top vessel and the seabed mining unit movement is too large and/or not counter reacted with a gravity weight at the bottom; the seabed mining unit could lift off the seafloor. Results of a sensitivity study are presented in Figures 8, 9 and 10 to quantify the effect of drag on the riser system. These studies assume that the seabed mining unit is not independently mobile, but pulled behind the surface vessel.

*Figure 8 (Left): Horizontal displacement distribution with a 60 ton bottom weight*

*Figure 9 (Right): Vertical displacement distribution with a 60 ton bottom weight*

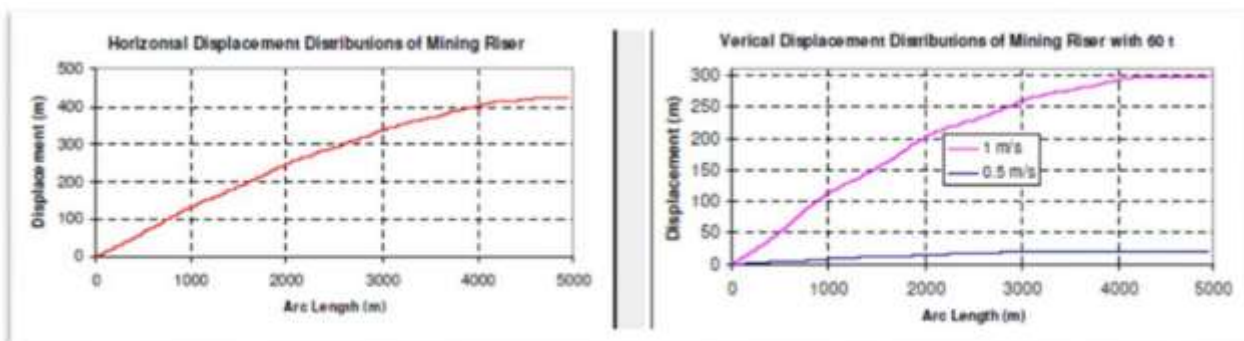
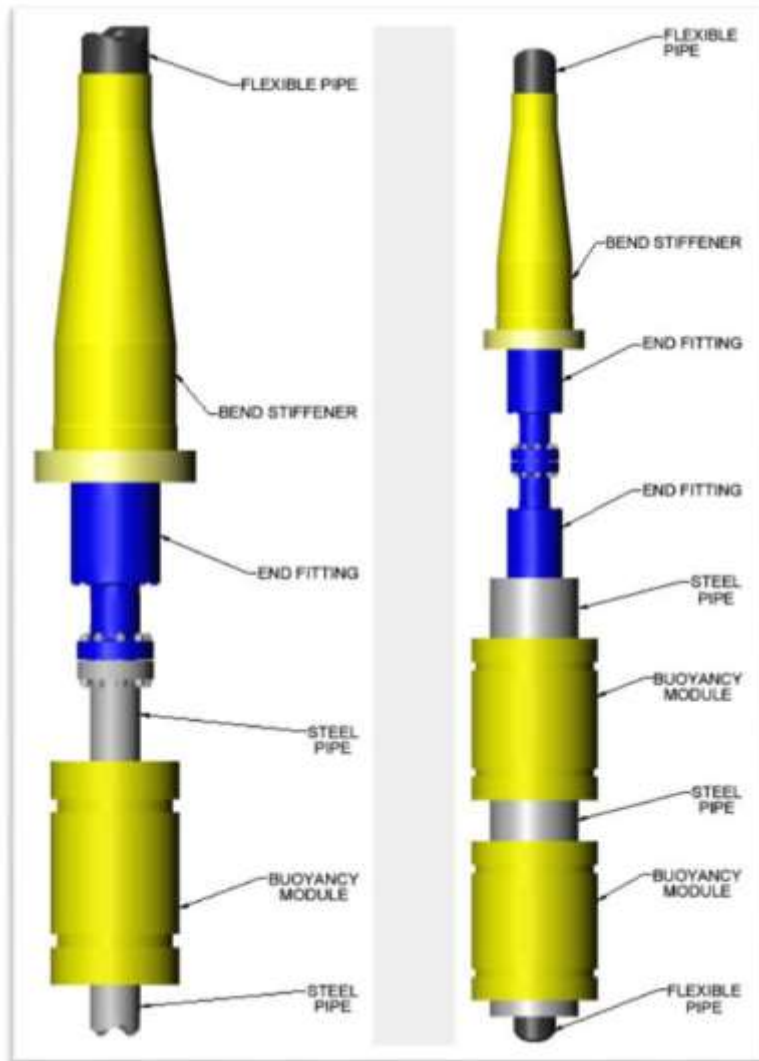






Figure 12 (Left): Steel spool piece buoyancy clamp arrangement      Figure 13 (Right): Steel sleeve buoyancy clamp arrangement



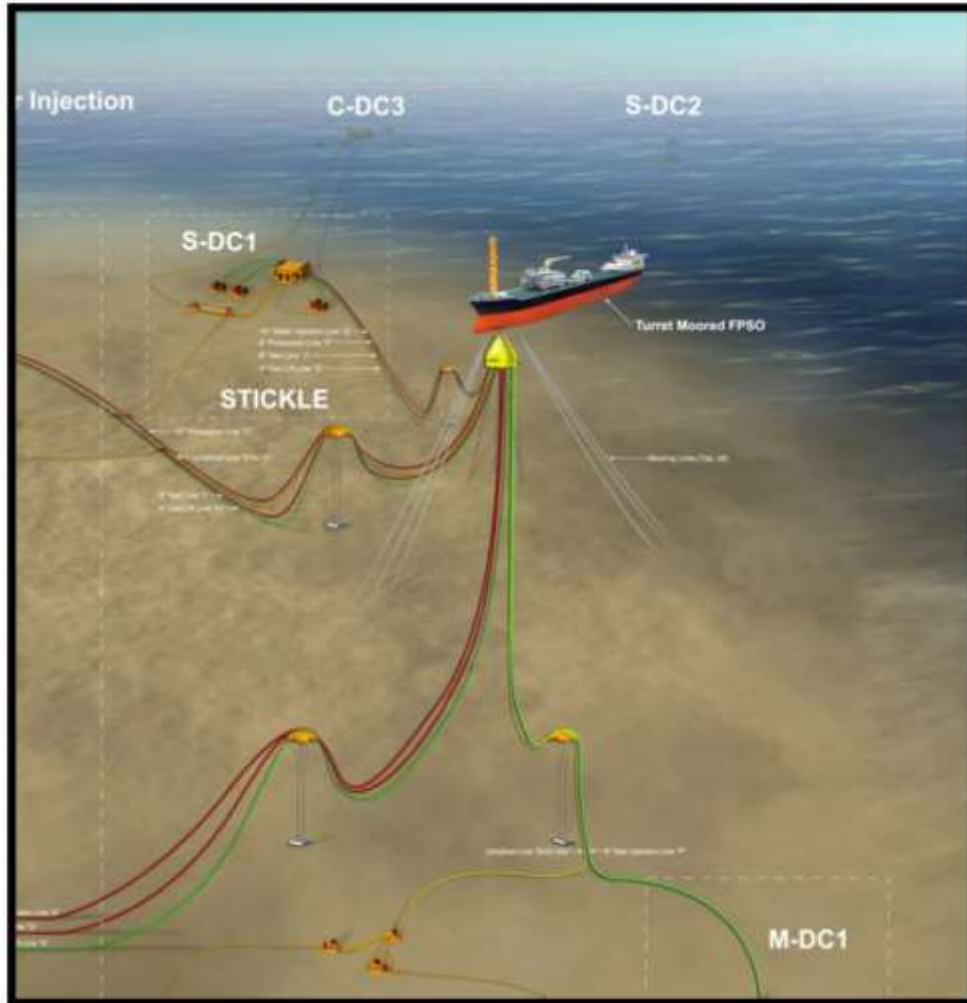
***Production vessels used in the oil and gas industry***

Ship-shape production facilities are among the highest dynamic response vessels used in the oil and gas industry.

Flexible pipe is a natural enabler to this type of vessel, commonly referred to as a Floating Production Storage and Offloading (FPSO) vessel, because of its compliance with high dynamic loads. These production facilities and riser systems are designed for continuous service for a design life of over 25 years. In extreme weather regions, like the North Sea and the Gulf of Mexico, FPSOs are designed with a disconnectable turret whereby the risers are connected to the vessel via a turret with a disconnect/reconnect system. The disconnectable turret is designed with enough buoyancy to hold the weight of the riser system at some level below the wave action of severe seas (for example, 100m below

sea level). Figure 14 depicts the field development for the BHP Billiton Pyrenees Oil and Gas Production Project.

*Figure 14: Oil and gas development: BHP Billiton Pyrenees Project*



Disconnecting the risers via a disconnectable turret in severe seas allows the surface vessel to move out of the line of weather, then come back on site, reconnect and re-start production. Shut down to start up is estimated at 10 days in the oil and gas industry. This type of system is expected to improve economic results by maximizing production time.

## **Conclusion**

Unbonded flexible pipe has been an enabler for deepwater (2,000m) oil and gas development for over 10 years and it is also applicable to the seabed mining industry. For application in ultra deepwater mining (5,000m), non-traditional riser configurations will be required to alleviate top tension loads for the surface vessel and for the riser itself.

This case study enables the following conclusions:

- Collapse is mitigated by maintaining the pipe in a constantly fluid filled state.
- Top tension load is sufficiently alleviated via distributed buoyancy.
- The surface vessel heave motion is decoupled from the free-hanging weight of the riser.
- The drag load from active mobility can be counteracted by a bottom gravity weight.
- Disconnectable turret technology may allow increased production time and improve the rate of return on investment in the economic models.

The results of this case study confirm the technical feasibility of unbonded flexible pipe risers for ultra deep water seabed mining.

Future work to confirm the flexible pipe riser system as suitable to seabed mining field operations includes:

- Optimize riser solution for intended operating conditions.
- Optimize buoyancy requirement.
- Detailed method of attaching/integrating buoyancy in the riser system.
- Detailed method of integrating staged pumps.

## References

*Analysis of exploration and mining technology for manganese nodules*. Seabed Minerals Vol-2, Chapter 5. Published by Ocean Economics and Tech Division, United Nations (1984).

T. Hill, Y. Zhang, B. Chen, T. Kolanski (2006), 'The Future for Flexible Pipe Riser Technology' in *Deepwater: A Case Study*, 17768, Offshore Technology Conference, May 2006.

## Summary of discussion

Asked what material was being used for the flotation on the riser, Ms. Hill said it was syntactic foam.

A participant asked whether different densities of foam would be required for the deeper sections and whether additional size requirement had been taken into consideration. Ms. Hill said that, technically, the answer was yes. All that foam was qualified, just as one would have on an RV.

An interesting point raised by another participant was that the use of flexible risers for deep-sea mining had advantages and disadvantages. To date, the lifting system had been based on the steel riser because in the mining scenario, the periodic inspection and maintenance of the underwater machineries were included once or twice per year. Then for this kind of work the whole system had to be retrieved periodically, which meant that, by using a derrick tower, the steel riser unit could be decoupled and examined. In the case of the flexible riser, such inspection would be different from the conventional way. Therefore, the use of a flexible riser was structurally safer, but in an operational sense, there were some limitations, causing longer down time. The participant noted that in the first few days of the workshop, OMI had calculated 270 days per year as working days. To maintain that goal, the participant noted that the down time must be minimized. But by using flexible risers one had to consider different

ways of inspection, maintenance, retrieval, etc.

Ms. Hill said that she appreciated the comment. With regard to the installation spread required for the flexible pipe, she said she did not know that it would be any more expensive than the large derrick that was used for the steel pipe, adding that she was also surprised to see that the operation time was 270 out of 365 days. In the oil and gas industry that would not be acceptable. She said that if the nodules were available and the concentration was there to produce continuously, she would work on that part of the equation. She pointed out that flexible pipes had been used in the oil and gas business for over 20 years without it being pulled up for inspection.

To this, the participant said that that was the difference between the oil and gas industry and deep seabed mining. For the production of offshore oil with the pipeline system, both ends were plugged into the well and the surface unit and therefore, no additional decoupling or monitoring was necessary. In the case of deep seabed mining, the submersible pumps must be inspected regularly, along with the miner on the seabed. The whole system must be pulled up. By using the steel riser, the axial vibration was a critical design parameter. The fundamental frequency of the actual vibration of the steel riser was 5 to 6 seconds. It was very near to the spectrum of the energy-rich wave frequency zone and therefore very sophisticated heave compensation machinery must be installed on the surface unit and additional damping mechanism had been investigated by a number of researchers or academicians. He wanted to know from Ms. Hill whether she had checked the vibration period of flexible risers. Ms. Hill said she had not and asked whether that axial vibration was due to vortex-induced vibration.

The participant continued that the vortex was lateral vibration - the vertical riser vibrated axially. When Ms. Hill asked what caused the axial vibration, the participant said it was the surface vessel's motion in the waves. Ms. Hill said that it was because the deep seabed miners were not hanging the steel riser off the vessel. Rather, they were holding on to it and allowing it to heave up and down.

ANNEX I

Background Document

## Introduction

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.<sup>2</sup> 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), the annual periodic reports submitted by the six pioneer investors<sup>3</sup> and publicly available information on the state of land-based mining, world's metal markets and their future prospects, and the relative role in the future world metal market of the two sources of supply.

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 5km-long vertical riser pipe utilizing a centrifugal pump or an air lift. Collector systems designed to be operational in a high pressure and low-temperature environment while operating on soil of poor strength demand special equipment components and materials that need to be 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.
- 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 and 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.

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<sup>2</sup> 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.

<sup>3</sup> The Government of India – registered on 17 August 1987. The contract was signed on 25 March 2002; Institut français de recherche 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 Yuzhmorgeologiya 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.

- iv. Capital and operating costs of deep seabed mining have sometimes been considered too high to allow the 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 that cost of a land-based lateritic nickel operation.

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.”

With regard to 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.”

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.”

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, the 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, and the third was the conclusion of exploration contracts between the pioneer investors and the International Seabed Authority of 15-year duration.<sup>4</sup> Fourth was the contract for polymetallic nodules exploration between the Federal Institute for Geosciences and Natural Resources of Germany and the

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<sup>4</sup> Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, ISBA/6/A/18, dated 13 July 2000.

International seabed Authority signed on 19 July 2006.<sup>5</sup>

With regard to structural developments, first was the discovery of the Voisey's Bay nickel deposits in Labrador, Canada<sup>6</sup>, and the second was the break-up of the Union of Soviet Socialist Republics and the introduction of mineral resources/metals from this geographic area to the world's metal markets.<sup>7</sup>

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 and growing economy of China. 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.

The new demand has driven commodity prices up. Market prices for copper have more than tripled since 2002, risen six-fold since 2001 for nickel and cobalt, and more than doubled for manganese. Technological developments in the offshore oil and gas industries, in particular as they relate to deep water oil and gas and in relation to risers (the pipes which connect the drilling platforms to the well), which now go to water depths of over 10,000 feet, have rekindled interest in polymetallic nodules as reserves of nickel, copper, cobalt and manganese.<sup>8</sup>

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**

Polymetallic nodule deposits of commercial interest are very deep (4,500-5,500 m), and miles 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).

It is to be recalled that the metals of primary interest in polymetallic nodules are nickel, copper,

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<sup>5</sup> 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.

<sup>6</sup> One of the richest nickel-copper-cobalt finds in the world, the Voisey's Bay Deposits are located approximately 35 km 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. 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.

<sup>7</sup> Russia's MMC Norilsk Nickel Company has been the world's leading producer of nickel in the world. In 2005, it produced 19 per cent of world mine production.

<sup>8</sup> Reserves of a mineral resource are those under the existing legal, technical, economic and social conditions that can be mined at a profit.



cobalt and manganese. The fortunes of any polymetallic nodule mining venture in the Area will be closely linked to the prices of these metals and to the costs associated with collecting nodules from the seabed, transporting them thousands of miles to refineries on land for their conversion to the metals of commercial interest, and payments made to the Authority in keeping with the concept of the common heritage of mankind.

For instance, in the case of nickel, although demand for nickel grew continuously in developed countries between 1985 and 1991, the London Metal Exchange (LME) price peaked in 1988 and declined each year afterward until 1994. The reasons for this paradoxical trend were threefold: the former Soviet Union gradually began to increase nickel shipments to the West; scrap availability increased worldwide; and world production of primary nickel increased.

The breakup of the former Soviet Union in December 1991 produced massive changes in the Russian economy, one of which was the partial privatization of the largest nickel producer in the country, RAO Norilsk Nickel. At the same time, nickel consumption within Russia plummeted due to the downsizing of several industries. In 1997, Russia consumed only 20,000 metric tonnes of primary nickel, compared with 180,000 tonnes in 1989 (International Nickel Study Group, 1998). Russian consumption weakened even more in 1998, slipping to less than 18,000 tonnes. These changes led to a surge of primary nickel from Russia, putting downward pressure on world prices for primary nickel and nickel-bearing scrap. Russian exports of stainless steel scrap and high-nickel scrap to the European Union (EU) also sharply increased, further depressing world nickel prices.

The Russian Federation continues to maintain its position as the largest nickel producer in the world. More than 90 per cent of its current output (1998) comes from mines operated in the Arctic by Norilsk Nickel. Because of internal demands within the Russian Federation for hard currency and the depressed state of the Russian stainless steel industry, Norilsk Nickel is expected to continue exporting the bulk of its production.

In summary, the price of nickel has been volatile over the last 20 years. In the first half of the 1990s the economic collapse of the former Union of Soviet Socialist Republics resulted in a surge of nickel exports that drove nickel prices lower than the cash costs of production, resulting in reduced nickel production. Until 2003 the nickel cash price remained below US\$10,000 per tonne. The price reached \$14,000 per tonne in 2005 and then escalated dramatically through 2006 before peaking at \$52,179 per tonne in May 2007. World nickel usage in 2006 stood 16 per cent above the level recorded during the price trough of 2001 and climbed further in the first half of 2007 due mainly to buoyant demand from the China.

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

## Mining technology development

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.<sup>9</sup> Three publicly sponsored entities from the USSR, India and China also undertook some work.

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 economically viable, no less than 3 million metric tons of dry nodules need to be mined annually for up to 20 years. Three basic design concepts for the 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 the bucket up 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).

The hydraulic mining system has drawn most of the attention of the technology developers. This system uses the principles of hydraulics in lifting the nodules to the surface ship. The system envisaged and developed in part 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, and the lifting of nodules through the pipe utilizing hydraulic pumps fixed to the pipe, or sucking up the nodules through the pipe by means of compressed air injected into the pipe (air lift).

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 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 mining system was studied in which it was envisaged that free unmanned submersibles would gather nodules from the seabed and lift them to the surface. However

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<sup>9</sup> 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 Océans (CNEXO), Commissariat à l'Énergie Atomique (CEA), Société Métallurgique Le Nickel (SLN), and Chantiers de France-Dunkerque, and Deep Ocean Resources Development Company Ltd (DORD) 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.

this system had inherent difficulties. Later (1984-89) the programme was reoriented to a hydraulic lifting system with a motorized collector able to be manoeuvred on the seafloor from the 5,000 m pipe string. A vehicle, *PLA-2 6000*, was designed and built to test the use of Archimedean screws for travelling on the soft bottom sediment and a collector device to harvest nodules.

However, all the tests pointed to some engineering problems in each system that needed to be solved. Improvements or changes in design were needed to achieve better system performance. Additionally, 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.

Until now, an integrated mining system (even at pilot scale) has not been demonstrated. Development of an integrated mining system to operate in a deep seabed environment on a sustained basis is demanding both in terms of time and effort and requires substantial financial input and technological advancement.

## **Mining technology developments since the Group of Experts' report**

IKS Germany worked independently and later in collaboration with India until 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 system with a mining unit consisting of a crawler, collector, crusher, slurry pump, floating hose and flexible cable.

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 the sledges. The test was carried out on a terrace like feature on a seamount at 2200 m depth and achieved around 87 per cent efficiency.

COMRA (China) has been working on developing a special mining system for collecting and lifting nodules in its exploration area, since 1990. 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 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 frame. The caterpillar tread is composed of rubber with a high involutes grouser. The crawler is hydraulically driven and can move forwards, backwards, turn and brake easily. COMRA carried out tests of the hydraulic system using a concentrated jet pump and a circular jet pump.

KORDI (Republic of Korea) has been engaged in R & D activities for nodule mining since 1993. The first phase 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 sub-systems. The performance and efficiency of the deep seabed collector has been determined by the Republic of Korea to be the primary factor for successfully producing nodules at commercial scale. It 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 the 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.

The Department of Ocean Development (India (became Ministry of Earth Sciences in 2006)) 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-type 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 less. 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**

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 hydro-metallurgical processing.

Metal extraction from 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) that it is not possible to employ physical separation methods. Nodules also have very high porosity, which results in higher costs for processes involving nodule drying. Nodules are also fragile and require more energy in crushing and grinding. Since valuable metals are present in nodules as integral part, of iron-manganese oxides, they have to be released by disintegrating the matrix of Fe-Mn lattice in order to achieve high recovery rates. This can be done by subjecting the nodules to reducing conditions. In pyro-metallurgy, such reduction is done by roasting with gaseous, solid or liquid reductants, while in hydro-metallurgy, this is done by leaching with reducing agents.

A number of pyro-metallurgical processes such as chlorination, sulphation and smelting have been tried to extract metals from nodules.

Hydrometallurgical processes 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 gives good recovery. To enhance the kinetics of leaching, pressure leaching at higher temperature has been adopted.

## Work of the consortia

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

*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. Valuable 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.

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.

The Cuprion process has a number of factors to recommend it: all the steps in the process take place at ambient temperature and pressure; energy consumption is relatively low; most of the reagents used in the process are relatively inexpensive or recyclable; and there is only limited use of corrosive and highly toxic reagents.<sup>10</sup>

*The Ocean Mining Associates Process.* Deep sea Ventures used the chloride- and sulphate-based routes. Direct leaching of nodules in hydrochloric acid has been described in the literature.<sup>11</sup> The acid is sufficiently reductive in nature to reduce manganese to soluble divalent state, thereby releasing the Cu, Ni and Co from its lattice. The liquor is enriched with CO, Ni, Cu, Fe and Mn. The sulphate-based process manganese is selectively converted to  $MnSO_4$  by reacting nodules with  $SO_2$  in the absence of oxygen in a fluidized bed reactor. The reacted ore is counter-currently leached in water to produce manganese sulphate solution from which Mn can be electrowon. Residue containing Cu, Ni and Co is leached in water in the presence of air and  $O_2$  mixture to produce sulphate solutions of metal.<sup>12</sup>

*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

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<sup>10</sup> United Nations, Ocean Economics and Technology Branch. Analysis of processing technology for manganese nodules.- (Seabed Mineral Series vol3) 1986.

<sup>11</sup> Kane and Cardwell 1974.

<sup>12</sup> Patent Cardwell and Kane, 1975

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.

*The International Nickel Company (INCO) Process* initially separates manganese and iron initially from other metals by smelting. Nodules are reduced at 1,000°C in a rotary kiln to convert almost all Ni, Cu, Co and part of Fe to metal. This is followed by smelting at 1,400°C in an electric furnace under reducing atmosphere to produce Mn-rich slag and an alloy containing almost all of the Cu, Ni and Co.

## **Exploration contractors with the Authority**

The International Seabed Authority has signed exploration contracts with eight seabed entities. Seven of the contractors have completed the first (five-year) phase of their contract periods. Among these contractors, COMRA, KORDI, IOM, India and to some extent Yuhzorgeologia are actively engaged in R & D on nodule processing technologies. Of the remaining two, IFREMER has not been actively working on nodule processing while DORD had an active programme in the 1980s and 1990s but presently is assessing the route to follow. The status of contractors' work on development of mining and processing systems is described below.

## **Interoceanmetal joint Organization (IOM)**

### ***Mining technology***

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

- Analysis and assessment of existing and potential designs for nodule development technology.
- Collection of data for preparation of technological fundamentals for basic components of a nodule mining system.
- Development of a conceptual design for a future mining system.
- Design and laboratory modelling and testing of a lifting sub-system.

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 sites and the oceanographic, meteorological and other factors of the sea environment also have been analyzed.

To select a conceptual design for a nodule mining system, including the design of the collector and the transport system, IOM decided that work on the power supply system mining control and management systems had to be initiated first. With regard to the nodule collector, IOM reports that a scientific and technical scheme of collectors with neutral buoyancy and a design for a collector-tracked carrier have been prepared. It also reports that a hydraulic system has been selected involving suction of water-sediment-nodule mix, with sediment collection intensified by employing hydraulic hydro-magnetic devices that ensure vertical integration of sediment and nodules. 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 riser pipes did not exceed acceptable levels. It also reported that laboratory work has been conducted to estimate slip velocity and experimental verification of nodule vertical flow on selected lifting sub-systems.

### ***Nodule processing***

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

- Optimization of existing technological schemes for extraction.
- Development of basic technological scheme for polymetallic nodule processing.

IOM reassessed the variants of technological schemes for polymetallic nodule processing by both hydro-metallurgical 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 to 98.7 per cent for Ni, 90.1 to 92.6 per cent for Co and 98.2 to 99.4 per cent for Mn .

It also reported that options for precipitating Cu, Ni, Co and Mn concentrates using solid precipitation reagents had been 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 per cent purity grade at 55 per cent efficiency.

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 the processing of Mn-containing slags into silico-manganese.

With regard to hydro-metallurgical smelting methods, IOM reported that their method employed results in selective concentration of more than 50 per cent copper in non-soluble residue. 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 per cent. It also reported that it had 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.

IOM has informed the Authority that it will continue working on both hydro-metallurgical and pyro-metallurgical processes during the next five 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***

During phase I of its contract, COMRA finalized a mining system for a pre-pilot deep sea mining

test based on technological and economical 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.

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. The environmental studies conducted on the trial site also indicated that lake test had only a very small influence on the floor and water layer in the area.

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 a virtual reality test of the mining system has also been performed. The R & D programme on deep sea mining was revised and adjusted during 2005. Laboratory tests of its collector and lifting system have been performed.

### ***Extractive metallurgy technology***

COMRA reports that during the first five years of its contract it undertook 14 research projects on extractive metallurgy involving around 60 scientists in seven institutes. Two processing units of 100- 500 kg/day were set up and pilot tests were 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 reached. The effect of additives was tested to improve cobalt extraction from ammonia leaching. 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 two months in 2004. Healthy extraction rates of 90 per cent cobalt and 98 per cent each for Copper and Nickel were achieved. Additionally, 84 per cent of zinc and 96 per cent of Mo were leached from nodules.

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 reached during the tests, and that metal recovery from this process was 91.94 per cent, 94.28 per cent, 89.29 per cent, 82.39 per cent, and 91.45 per cent for Ni, Cu, Co, Mn and Fe, respectively.

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

In the ensuing years, COMRA's programme has included:

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



## **Yuhzmergeologiya- Russian Federation**

### ***Mining technology***

As part of the research activities under its contract, Yuhzmergeologiya modernized 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 sediment in nodule fields was developed. The sea trials of the seabed probe station UGI were carried out at Yuhzmergeologiya's exploration site at 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).

Yuhzmergeologiya 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***

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 *Sagar-kanya*. The crawler was tested in 2000 at a depth 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 system was tested underwater for three days in the Angria bank region on the west coast of India during 2006. 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.

The Collector and crusher system will be tested at a depth 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 a depth of 5,000 m. India also reports that it is developing a Remotely Operated Submersible, to be operated at depths of up to 6,000 m, and in this regard, it reports that the conceptual design of the system has been completed. It also reports that a Tether Management System (a suspended subsea station) is being developed, and has been tested at an acoustic test facility. India further reported on different sub-systems 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.

During the next five years, India reports that the tasks it intends to undertake are:

- Design and development of a new crawler capable of operation at 6,000 m depth.
- Development of small semi-submersible floating station.
- Testing of its Remotely Operated Submersible.
- Conducting in-situ soil testing and micro-level demarcation of its mine site to isolate sites of very low soil bearing strength.
- Undertaking studies on material behaviour in hyperbaric and low temperature conditions for long-term operations.

### ***Processing technology***

India undertook trials of 15 metallurgical processing routes at different institutes. Of these, three 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 methodology. Metal recoveries were found to be 90 per cent for Cu and Ni and 60 per cent 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-stage 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 the 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-electrowinning.

India has set up a demonstration plant (500kg/day capacity) for processing nodules. It 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 second stage leaching. This helped to reduce the time and money required without sacrificing recovery efficiency. The recovery percentages of nickel and cobalt exceeded the design values. Average recovery efficiency during Phase I was 92%, 96% and 82% for Cu, Ni and Co, respectively. Validation of processes developed by the different laboratories was taken up from 2004 in three further campaigns. Testing of the flow sheets that were developed was conducted in a separate campaign. Due to problems in recovery, a new flow sheet had to be developed for the recovery of Ni and Co. 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 two laboratories. Over the next five years, India proposes to: develop a process for extracting metals from nodules through the smelting route and 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 polymetallic nodule processing; and to test and develop a process for the production of metal powder through hydrogen reduction.

India reports that it will try to optimize its pilot plant to further enhance the leach pulp density from 15 per cent to 18 per cent. 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, R & D activities continue at the two laboratories to improve cobalt extraction in ammonical solution and the recovery of metals from leach liquor by the bulk sulphide precipitation-chloride leaching route

## **KORDI (Korea)**

### ***Mining technology***

KORDI has developed an integrated computer simulation programme that 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. Experiments and results from previous efforts have enabled it to modify the impeller and guidevane.

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 until 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 five years, KORDI proposes to take the nodule processing technology programme to the engineering conceptual design and experimental level.

ISBN-13: 978-176-4043-08-5



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