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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

Front Cover :

Photomicrograph of polymetallic Sulphide crest

Back Cover :

Photomicrograph of Manganese nodule from Central Indian Ocean basin

This report
has been prepared for the

WORKSHOP ON MARINE INDUSTRIAL TECHNOLOGY FOR THE DEVELOPMENT OF MARINE NON-LIVING RESOURCES

27 - 30 September 1993
Madras, India

Organized by the

United Nations Industrial Development Organization
in cooperation with the Government of India

MARINE INDUSTRIAL TECHNOLOGY PROGRAMME

NEW TECHNOLOGIES UNIT
TECHNOLOGY DEVELOPMENT AND PROMOTION DIVISION
UNIDO, P.O.Box 300, A-1400 Vienna, Austria.
Tel: (43-1)21131-5397/5030, Fax: (43-1)230-7355, Telex: 135612

PREFACE

UNIDO proposes to organise a Workshop on "Marine Industrial Technology for the Development of Marine Non-Living Resources and its Industrial Application" in India at a date to be decided in consultation with the Government of India. As a prelude to the Workshop UNIDO constituted a Mission to bring out a state of art report on Deep Seabed Mining and related technologies and suggest the applicability of technologies so developed to the survey and exploitation of near shore non-living resources. The Mission comprised of:

(1) Shri M.M.K.Sardana, formerly Joint Secretary, Department of Ocean Development, Government of India and presently Advisor (Industry), Government of West Bengal.

(2) Dr. A. Gopalakrishnan, Director, Central Mechanical Engineering Research Institute, Durgapur.

(3) Dr. P.K. Sen, Senior Manager, Engineers India Ltd.

(4) Shri Rahul Sharma, Scientist, National Institute of Oceanography (Goa).

(5) Shri N.N. Prasad, Deputy Secretary, Department of Industrial Development, Ministry of Industry, New Delhi.

(6) Mr. Jan Magne Markussen of the Fridtjof Nansen Institute, Norway accompanied the Mission as representative of UNIDO.

The Mission visited a number of institutions in Germany, Finland, Norway, France, U.S.A. and Japan and held discussions with eminent experts in the field of ocean development with particular reference to deep seabed mining.

The institutions, which were visited in Germany were, THETIS Technologie, Hanover; Institute of Automative Engineering and the Institute of Fluid Mechanics & Computer Application in Civil Engineering, University of Hanover; Geological Survey of Germany; Centre for Marine Climate & Research; and Institute for Hydrobiology, University of Hamburg. The visit to Germany was rounded off with an immensely illuminating discussion with

Professor Thiel on the subject of the Environmental Impact of Deep Seabed Mining.

In Finland, the discussions were held with Rauma Repola Oceanics.

In Norway, the Mission Members held discussions with the representatives of concerns like Simrad Subsea and Simrad Albatross Geoteam, Oceanor, Seatex, Marintek and Sintef Group, Elkem Technology, Klaveness Chartering and Barlindhaug, Frank Mohn R&D Centre, Aker Engineering and Okland and also visited the Nansen Institute.

The discussions in France were with senior officials of IFREMER while in the U.S.A. the Mission Members visited the Marine Minerals Technology Centre, School of Ocean & Earth Science & Technology, Department of Oceanography, Hawaii Natural Energy Institute, Hawaii Under-Sea Research Laboratory and National Energy Laboratory - all-located in Hawaii Islands. Also the Mission Members had invigorating discussions in San Francisco with Mr. Conrad Welling of Ocean Minerals Co.

In Japan, detailed discussions were held with officials of the Ministry of International Trade & Industry. Visits were organised to the Technology Research Associate of Manganese Nodules Mining Systems, Metal Mining Agency of Japan and Sumitomo Heavy Industries.

This report is based on the discussions held with the various institutions and experts on the subject of ocean development, as mentioned above and also on the basis of the published material otherwise available. The Report attempts to provide a detailed insight into the state of art of deep seabed mining programme and related technologies and covers the following major components:

(a) Survey and Exploration;

(b) Deep Sea Bed Mining;

(c) Environmental Impact;

(d) Metallurgy / Processing; and

(e) The Interface of industry with various R&D institutions working in this field.

A reference has also been made on the applicability of the technologies so far developed to areas other than deep seabed mining.

On behalf of the Mission Members, I would like to convey my gratitude to UNIDO for providing the Mission opportunity to prepare this State of Art Report and planning the whole project meticulously. The Mission thanks all the institutions mentioned above for having provided access to the useful information. Our special thanks are to Prof. Thiel and Mr. Conrad Welling, who took special pains in meeting the Mission and providing the Mission insight into their areas of specialisation so generously.

I place on record my appreciation for the keen interest evinced by all the Mission Members in the preparation of this report. I am sure, that their efforts would be well rewarded and the report would be received as a useful document providing uptodate information on the deep seabed mining and its related technologies and would form a basis for the Workshop being contemplated by UNIDO.

The Mission would like to place on record the useful contributions made by Mr. Markussen, as a representative of UNIDO with the Mission, but for whom the Mission would not have been able to accomplish its task. His untiring efforts in arranging the visits to various institutions and facilitating meetings with the experts, have been appreciated by all the Mission Members.

April 20, 1992.

M.M.K. Sardana

LEADER OF THE MISSION.

CONCLUSIONS

The report deals with various issues that emerge for proper development of deep seabed mineral resources and cooperation among entities in developing countries for exploiting larger wealth within their near shore and national jurisdictions.

Much of the present day ***technological research*** *would have to address itself to the following areas:*

(1) *Developing an efficient sea-floor miner or collector with a view to:*

  (a) *reducing transit time and downtime,*

  (b) *increasing its manoeuvrability to avoid obstacles, reducing turning time and selectively mining nodules, areas,*

  (c) *improving methods of nodule harvesting and crust loosening, and*

  (d) *improved dynamic positioning for control of seafloor miner, loading of ore-ships and semi-submersible platform.*

(2) *Use of semi-submersible platforms, rather than standard ships for handling of sub-set mining system, storage and maintenance, transfer and conditions of ore and staff support.*

(3) *Improved efficiency of pyro and hydro-metallurgical processes.*

(4) *Increased mechanisation to reduce personnel costs and improve overall efficiency.*

(5) *Reduction in overall weight and size of mining system.*

Notwithstanding anything as stated above, fundamental changes which ultimately will alter the ***economics*** *of deep sea mining include:*

(1) *Increased economies of scale:*

Proposed mining rates of 1.5 to 3.0 million tonnes per year of dry nodules, is a marginal production rate when compared with on land mines requiring similar capital investment. Improvements in collector efficiency, rate of collector movement and mining of high nodule density areas are all procedures that will require modifications of existing technology. More advanced procedures which would include multiple miners to collect and deliver to a central raise point, which would correspond to multiple faces working in a mine.

(2) *Selective mining of high grade nodules:*

Additional studies would be required to define, in detail, grade / density distribution within the selected area. As with on-land mines, such an approach might significantly alter the initial revenue flow for a project and hence its overall economic viability. It would be advantageous to optimise economic returns of the first "pass" by selectively mining the high grade nodule areas.

(3) *Improve process and reliability:*

Significant changes in deep sea mining would result from improving means of controlling deep sea mining and the reliability of the deep sea collector. For this purpose improved use of micro computer systems which would be low cost, easily "backed up", have low energy requirements and increase functioning capabilities. This would ensure reduction in the risk of malfunction and lost time for repair of the deep sea miner. Closely associated with the use of micro process controllers would be the development of fibre optics capabilities for data transmission need in the mining process.

(4) *In situ processing:*

As processing costs are the largest cost in deep sea mining, considerable attention shall have to be placed on developing alternative processing capabilities. A.G. GRANOVSKY (1989) has indicated possibility for "in situ" processing of manganese nodules and crusts utilising a sulphuric acid leach solution which would produce metal sulphide salts for final processing. If finally method of "at sea" surface processing are developed, *transportation and disposal costs would be substantially reduced.*

(5) *New Lifting concepts and materials:*

New technologies may also improve the lifting devices(Pumps) and the pipe string. New and larger pumps, using ceramic parts to reduce wear, corrosion and breaking, are being developed in Japan and new composite pipe materials of equal or greater strength and 1/10th the weight of conventional pipes, are being developed in the United States, Japan and France. These developments will reduce costs, decrease downtime, decrease overall weight of the mining system and allow for new design concepts for deep sea mining.

(6) *Robotics and artificial intelligence:*

Robotics and artificial intelligence will play a major role in future deep sea mining enterprises. Their application would result in controlling the exploration and mining systems from remote and would allow for continued evaluation and modification, on the sea floor, or mining operations through on site analyses of grade and distribution, density, terrain analysis and recognition and for spatial control of mining. These systems would also give the needed support for mining and transpiration activities to on board surface systems.

Based on information generated on ***environmental aspects****, it can be concluded that at the present insufficient studies have been done on the biota and the impact on biota of deep sea mining. More and more researchers are reconverting to the view that intensive research must be undertaken to define the impact of a surface or near surface plane on the environment. Preliminary studies indicated that, because of the local nature of the plume, and the rapid dispersal of both particulate matter and the nutrient rich cold water, the impact of the surface plume would be minimal. Although perhaps generally valid, more research needs to be undertaken to ascertain the specific impacts which may result even from the dispersal material. This is particularly important with respect to possible crust mining in the central pacific Ocean where impacts on fishing, endangered species, island nations and high bio-productivity are substantial considerations.*

In addition, a major research should be undertaken to establish environmental base lines for areas within and adjacent to possible mining sites. These studies would have to include not only the seafloor but the entire water column to the surface.

A number of ***other potential studies*** *would also include the impact of:*

(1) Transpiration and handling of ores,

(2) Processing of ores, and

(3) Disposal of processed wastes.

All these would add to the cost of R&D activities.

The long term development of the vast potential resources by the countries would have to take into account the infrastructural development in other related sectors, e.g. ship building, offshore structures, iron and steel manufacturing, metallurgy, electronics, and forecasting. Efforts in this regard nationally have to be coordinated taking into consideration the expertise in the related fields so as to optimise the cost of efforts to achieve the commercial goal.

In view of the resource crunch being faced by all the countries and entities aspiring to commercially exploit deep sea minerals, it would be essential that the sub-systems that are developed during the intermediate stages start yielding returns so that further research can be self-sustained with minimum support from the Government and funding agencies. It would be in the interest of all the entities furthering the cause of development of various systems required for successful commercial deep sea mining operations to cooperate among themselves, so that the cost of R&D development can be optimised and shared.

A large number of developing countries have got economic jurisdictions over vast areas under the Convention of the Law of the Sea, which need to be explored and exploited for generating vast reserves of funds and realising the economic wealth that such areas are holding. For this purpose, the technologies which are being developed for the ultimate goal of exploiting deep sea minerals, could be effectively utilised through an appropriate *workshop so that such technologies can effectively generate commercially important activities for the developing countries and appropriate returns for those countries who are developing these technologies.*

This report will be presented in a workshop to be organised by UNIDO and Government of India to develop the action plan to bring about the desired type of cooperation.

CONTENTS

CHAPTER 1

TRENDS AND PROSPECTS FOR DEEP SEA MINING AND DEVELOPMENT OF APPROPRIATE TECHNOLOGIES

1.1 BACKGROUND

Polymetallic nodules occur as small spheroids varying in diameter from 0.5 to 25 cm in some areas of the deep sea-bed of abyssal plains at a depth of 4000 meters to 6000 meters generally beyond the national jurisdictions of EEZs and continental shelfs. These spheroids are oxides of useful metals rich in manganese content as the primary element, followed by copper, nickel, cobalt, zinc, iron, titanium, molybdenum etc. Due to its higher content of manganese, these spheroids are called Manganese Nodules. The Manganese Nodule is more densely spread and richer in metallic contents in the deep sea than in the coastal water.

The existence of these seabed nodules had been known for years. It was not until 1965 when J.L.Mero studied their economic possibilities that a coherent scientific hypothesis of nodule formation began to emerge. Since then, exploration of manganese nodules have been subjected to intensive research and development.

A conservative estimate of weight and grade of manganese nodule in the sea where recovery in commercial scale is anticipated, is summarised as follows from a report by the United Nations and a report presented at the International Symposium on Oceanography in Tokyo, Japan, in 1979:

Metal	Weight Composition (%)	Quantity (mill. ton)
Nickel	1.26	290
Copper	1.00	230
Cobalt	0.25	60
Manganese	27.50	6,330
Total deposit	-	23,000

Adding this estimate to the estimate of ore reserves on the land makes a total ore reserve on the land and in the deep-sea bed. It is estimated that ore reserves on ocean and land in respect of the four important metals are as follows:

Metal	Ocean (%)	Land (%)
Nickel	83.8	16.2
Copper	31.0	69.0
Cobalt	95.2	4.8
Manganese	56.4	43.6

Thus, except for copper, larger ore reserves are in the deep seabed than on land. It was, therefore, quite natural that many companies in the developed countries pooled their resources and expertise to form consortia to develop the entirely new technologies and generate investments needed for their exploration. There was so much optimism in the mid 60s that their exploitation was envisaged to occur within the next few years with profound impact on world economy, trade and metal consumption patterns.

In view of the fact that the nodules richer in metal contents were generally beyond the national jurisdictions of territorial waters, EEZs and continental shelfs, the attention of international lawyers and policy makers was drawn to this. Their situation in the global commons, in turn, called for new legal frameworks for their exploration. These were finally incorporated in the United Nations Convention of the Law of the Sea, and its related resolutions, to which 159 countries are signatories. Protection was granted to countries and entities, in the area of global commons which had made substantial investments in exploration of these important resources with a view to exploiting them subsequently.

The regime, which was finally adopted, has the following salient features:

(i) The country or entity which had invested a minimum of US $ 30 million, and not less than 10 % of which were spent for development of a suitable mine site, would be recognised as "Pioneer Investor"

(ii) Pioneer Investors would subsequently approach an appropriate International Body for obtaining registration of their status, and for doing so, they would be required to present to this Body two mine sites of equal estimated commercial value, one of which would be allocated to the applicant while the other would be reserved by it, for exploration as a common heritage.

(iii) After registration as a Pioneer Investor, the applicant would be called upon to fulfil the following obligations:

(a) continue to invest a minimum agreed amount to develop the site allocated to it, for mining;

(b) train candidates sponsored by the International Authority to provide technical manpower required for exploring and exploiting the site reserved for it;

(c) transfer nodule exploration technologies on reasonable terms to the International Authority;

(d) periodically report the progress of the nodule exploration programme to the International Authority;

(e) carrying out exploration on behalf of the International Authority in the area reserved for it on reasonable commercial terms, whenever required.

(iv) After the Convention comes into force the Pioneer Investor so registered would be expected to approach the International Seabed Authority with a work plan for approval of further exploration and/or exploitation. Grant or authorization would be subject to the condition that it would not adversely affect the interest of land based producers of the metals contained in the nodules.

France, India, Japan and USSR were accorded the status of Pioneer Investors in 1982. Four multi-national consortia dominated by USA, UK, Belgium, Germany, etc. were also granted this status. A provision was also made for developing countries to secure such a status up to the entry into force of the Convention of the Law of the Sea, by fulfilling the minimum criteria.

Subsequently, in 1987, France, India, Japan and USSR were registered as Pioneer Investors. In 1991, China was also registered as Pioneer Investor. The multi-national consort[illegible] ve sought to create their legal rights outside the Conven[illegible] [illegible] getting national enactments, as generally the spo[illegible] Governments have not acceded to the Treaty on the La[illegible] [illegible] Sea. The basic differences betwee those who have not s[illegible] [illegible] Convention are sought to be resolved through negotiatio[illegible] [illegible] political level to work for the universalisation of the Convention of the Law of the Sea.

1.2 TRENDS AND PROSPECTS

While the above development were taking place, to secure the investments made for developing appropriate mine sites with a view to eventual exploitation, various R&D Groups of the International consortia and the national institutions in conjunction with their domestic industry, with or without international cooperation, have been active in developing appropriate technologies in refining the:

(a) survey and exploration techniques,

(b) technology for mining of nodules and their transportation,

(c) environmental impacts of such technologies, and

(d) processing techniques.

According to one estimate, despite the fact that more than US $ 700 million (in constant 1982 dollars) have been expended, there has not been any commercial deep sea mining venture, nor are any commercial deep sea mining planned for the immediate future. Deep sea mining activities, which include exploration, mining, transportation, environmental impact studies and processing, are relatively new fields of research and development for the mining industry. This industry has, as a new activity, since 1985, begun to consider deep sea mineral occurrences other than manganese nodules as possible targets for development in the future.

Thus, cobalt rich manganese crusts are increasingly attracting the attention of scientists, technologists and policy makers, as these crusts are not only rich in cobalt and nickel but are at shallower depths and are available within the national jurisdictions.

The primary reasons for this delay in exploitation can be classified into at least the following areas:

(a) Economic

(b) Technological

(c) Environmental, and

(d) Political

1.2.1 Economic Considerations

From a purely corporate perspective, the use of conservative long-term metal prices in deep sea mining ventures often results in such ventures being evaluated on a "worst case scenario" basis. This scenario is more compounded because of the early experience in evaluating deep sea mining ventures for nodules where unrealistic long term prices for metals were used. Deep sea ventures envisaged today are towards production of varying amounts of manganese, copper, nickel and cobalt from the mining of manganese crusts and copper, lead, zinc, silver and gold from mining of polymetallic massive sulphides. For all these metals, adequate sources of supply presently exist from land resources. For the near term and intermediate (15 to 25 years) term, global reserve of these metals are adequate for world demand. Thus, deep-sea minerals will be developed vigorously in the following circumstances:-

(a) If supply disruptions occur or are likely to occur;

(b) If on land mining costs exceed deep sea mining cost; or

(c) Worldwide or regional demand for metals increases in an unforeseen manner.

All these are factors of uncertainty, with respect to supply and demand. The corporate analysis would still like to make an economic judgement on the basis of "worst case scenario".

Deep sea mining is a new activity for the mining industry in which risks are obviously high because of both economic and technological uncertainty. In such circumstances, higher than normal internal rate of return for a project is required to compensate for the high risk of the project. A.D. Little (1984) has suggested that a nodule mining venture would need to achieve a 30% IRR as invested funds - substantially above the 12-16 % achieved in on land mining ventures. For a workable analysis, an IRR rate of 18-22 % is necessary to convince the prospective investors to evince interest. Nevertheless, a major factor to be assessed in evaluating a deep sea mining venture will be the relative costs of on land production from existing mines and the costs of developing comparable on land deposits. On land mining developments will generally be undertaken, using existing technology and reasonably certain costs. Thus, deep sea mining activity would have to take place on deposits that are either substantially higher grade than on land deposits or deposits which are easier to mine and/or process, resulting in lower operating costs per ton of ore than on land mines.

Coupled with the above scenario, potential investors like the International Consortia, are looking with expectations on the scenario of the United Nations Convention on the Law of the Sea and they would have to take decisions if the investments are finally to be undertaken under the Reciprocating States Agreement or under the United Nations Convention on the Law of the Sea. It is certain that development of crusts and polymetallic sulphide deposits, would, in most cases, take place under the economic regime of nations within whose Economic Zone they occur.

All the factors mentioned above are external economic issues which, however, are of particular importance in that the uncertainty substantially adds to the risk of an already high risk enterprise, further resulting in decision making being made on a "Worst case scenario".

Flipse (1983), A.D. Little (1984), Nyhart et al (1983), Herrouin et al (1989), and United Nations (1989), have analyzed the economic costs relating to deep sea mining of manganese nodules. Manganese crusts have similarly been analyzed by Hawaii Department of Planning and Economic Development (1987), Hakalehto (1989), and Halkyard (1989). No studies of polymetallic sulphide mining economics are presently available.

Capital and operating costs for processing, in both nodule and crust mining, are anticipated to constitute 50 to 65 % of all costs whereas capital and operating costs for mining and transportation ranges from 20 to 30 % and 10 to 25% respectively, of all costs. These studies also show that perhaps deep sea mining ventures require capital expenditures of US $ 750 - 955 million, comparable to the costs associated with the development of a large scale on land mine. However, a similar mine so developed on land would produce approximately 4 to 6 times the quantity of ore for the same investment. Thus, particular attention needs to be paid in achieving the economies of scale in deep-sea mining as are achievable on land. If such economics of scale could be achieved with marginal increase in capital and operating costs, the economic viability of deep-sea mining venture would improve.

Another interesting feature that emerges from the above analysis is that the high risk portion of deep sea mining is associated with 30% or less of the total capital and operating costs (and this would further decrease to 10% or less when only the under sea mining is considered as the only high risk endeavour) whereas 50% or more of the total capital and operating costs are associated with very low risk, proven transportation and metallurgical processes.

The most recent economic analysis of deep sea mining venture has been completed for a manganese nodule mining venture proposed by France (Herrouin et al 1989). The revenues generated by the sale of the produced products have been estimated to be US $ 495 million per year or US $ 440 per tonne of dry nodules. An IRR of 12% has been indicated with a six year pay off period for the project. For additional cases it was found that IRR ranged from 10 - 14%. In this study, although the mining and transportation costs are similar to costs used in other studies, the highly favourable IRR generated is largely attributed to high recovery efficiencies in the processing portion of the mining venture. The IRR projected, however, correspond to the on land mining ventures and given the high risk nature of deep sea mining, the results may at best be considered encouraging.

1.2.2 Technical Factors

Almost all the developments that are taking place in the mining system and transport system are based upon existing marine and offshore petroleum industry concepts and technologies. Significant changes in the economics of deep sea mining could result from technological changes in the mining, transportation and processing aspects of deep sea mining. Such technological changes are discussed in different chapters of this report.

1.2.3 Environmental Issues

Because of increased awareness of environmental issues globally, considerable attention will have to be given to assessing the environmental impacts of a mining venture. More effort will need to be directed toward assessing and mitigating the environmental impact of mining.

The environmental impacts and costs have been in a systematic manner studied by the US National Oceanic and Atmospheric Administration sponsored Deep Ocean Mining Environments Study programme, conducted from 1975 to 1980, for manganese nodule mining and the Manganese Crust Environment Impact Study Project is presently being completed for crust mining in the Hawaiian Archipelago and Johnston Island. The results of both studies are similar in terms of environmental impacts and differ primarily with reference to factors associated with topography and bottom type, i.e. crusts occur on slopes with few sediments whereas nodules occur on abyssal plains carpeted with thick sediments. Consequently, the mining activities differ in their potential for re-suspension of sediments. Three critical areas, according to these studies, need to be studied more closely:

(1) The collector will destroy benthic biota which has both an adverse and unavoidable impact.

(2) A bottom benthic plume will be produced away, from the collector, which may extend over several kilometres.

(3) A surface/near surface plume will be discharged consisting both of sediments and particles, and of nutrient rich cold water.

1.2.4 Political Issues

A quick review of the history of deep sea mining research indicates that in early 1970s, industry interest was very high, specifically for nodules, and industry provided the bulk of the research funds. In the late 1970 and early 1980 industry interest has declined, funding levels have dropped and governments have begun to play a larger role. From the mid 1980s onward only those programmes with substantial government support have continued. With no near-term economic exploitation of deep sea minerals in view, the interest of industry in deep sea mining will continue to be in limbo. Therefore, government support to deep sea mining researches has to be increased if semblance of maintaining the capability and research programmes is to be continued. Because of money considerations, Governments will have to play a greater role in respect of supporting marine environmental research on the impact of deep sea mining. Once mining is round the corner, Government will have a further role in monitoring and enforcing environmental compliance, as economic costs that should not be borne by the mining venture. The Governments will need to carefully assess the economic impact of environmental legislation and policies, under which deep sea mining will take place, and the economic viability of the mining venture. A cut off would have to be developed to ensure that while the environment is protected, deep sea mining does not become too costly because of environmental regulations.

1.2.5 The scope of this study and central issues

UNIDO, in recognition of the need to have international cooperation among the prospectors of seabed minerals and also among such prospectors and the developing countries, commissioned the present study with the twin objective of (a) preparing a status report on technologies for eventual exploitation of deep sea minerals, and (b) to develop a mechanism whereby the already developed technologies can be utilised in the survey, exploration and exploitation of near-shore resources and resources within the national jurisdictions of the developing countries.

Basically, the following fundamental questions arise which ultimately must be addressed and resolved if deep sea mining is to proceed:

(1) Will the emerging economic changes in the world economy overall and the metals industry particularly, provide for a stable economic environment for development?

(2) Will the existing technologies of on land mining and offshore petroleum, provide the basis for economic deep sea mining or will altogether new technologies, mining concepts and mining systems be required?

(3) Whether adequate resources for the modification of existing technologies for developing new concepts would be available through outright grants or through generation of resources, by exploiting the emerging technologies while optimising their use for exploitation of near-shore resources in the country or countries where such developments are taking place or in developing countries which need to exploit their near shore areas to make use of the jurisdictions vested in them under the convention on the Law of the Sea. What type of international cooperation mechanism in the field of development of new technologies and their intermediate uses would emerge to reduce the cost of those who are engaged in developing such technologies?

(4) Will present environmental costs and constraints increase, with increasing global environmental awareness, to a point that deep sea mining is further delayed?

(5) Will deep sea mining be undertaken under the Convention on the Law of the Sea or under the agreements of the Reciprocating States or a combination of both?

In the succeeding chapters, state of technologies in the field of exploration, mining, transportation, environmental effects, processing, have been brought out. As the eventual development would depend on the pace with which the industrial activity is spurred to translate the R&D efforts into actual action, which will depend upon the willingness and zeal of the industry to take new challenges, a chapter on interfacing with the industries has also been added.

CHAPTER 2

STATUS OF EXPLORATION TECHNOLOGIES FOR DEEP SEA MINING

2.1 BOARD OBJECTIVES OF EXPLORATION

The survey and exploration of the seabed minerals in general and of polymetallic nodules in particular needs to be programmed to generate the following information in a given target area:

- Identification of areas covered with nodules
- Abundance of nodules (kg/m^2)
- Grade of nodules (nickel, copper, cobalt, manganese etc.)
- Specific gravity of wet and dry nodules
- Size distribution of the nodules
- Depth of Ocean bottom (bathymetry of the area)

While the above objectives are similar to those of the exploration for onshore mineral resources, the exploration technologies for deep seabed minerals are vastly different (Kunzendorf, 1986).

2.2 A REVIEW OF EXPLORATION TECHNOLOGIES IN USE

2.2.1 Sampling Devices

For recovering physical samples of manganese nodules and the associated sediments from the sea bottom, three types of bottom sampling devices are used: grab samplers, corers and drag dredges. The sampling devices can be lowered to the bottom from the ship and retrieved by pulling the wire up. They can also be dropped from the ship unattached to any wire, called free fall devices. For rapid sampling of nodules, free fall grab is used extensively due to the relative ease of operation. For collection of samples of modules as well as the associated sediments, box corers or spade corers are used which represent wire operated type of sampling devices. For collection of large quantities of nodules, drag dredges are used which represent open mouthed containers (boxes or bags) that are dragged along the ocean floor.

2.2.2 Visual Devices

Visual surveys of manganese nodules on the ocean floor and the surrounding topography are carried out by photographic devices that essentially have to operate close to the sea bottom. Two broad types of surveys are conducted

- Spot visual survey
- Continuous visual survey

The spot survey is carried out by still cameras which are normally placed on free fall devices. The continuous visual survey is achieved by :

- Continuous bottom photography, or
- Underwater television.

2.2.3 Acoustic Devices

Acoustic devices are extensively used in marine survey and exploration since sound waves have a low frequency and can be transmitted easily in the ocean. There are several types of such devices and depending on the frequency and the power of the sound source used, their applications are specified. The devices that find extensive application in deep seabed exploration are briefly discussed below:

(a) Echo-Sounder:

It is a down looking sonar which performs the basic task of determining water depth. The conventional echo-sounding equipment measures the depth of seabed by sending a strong signal that expands in the water inside a large cone of some 30° top angle. The signal is then echoed by the bottom from a large area. The echo sounder is mounted on the keel of the ship which emits a sound pulse. The reflected echo returns to the receiver on the ship and the length of time determines the depth of ocean bottom.

(b) Sub-bottom profiler:

It is used to study the sediment layers and sub-seafloor features. Sub-bottom profilers use a low frequency high energy sound pulse for bouncing acoustic echoes of sediment layers beneath the ocean floor.

(c) Multibeam echosounder:

Recognition of the limitations of conventional single beam echo sounder led to the development of multi-beam echo sounders. There were two major improvements: first was to narrow the cone of emission or reception to 2-3 degrees and second, to integrate several emitters or receivers as an array in such a way that each looks to a specified area of the bottom. With the system developed, a swath width of more than 4 Kilometres for a 5 Km depth range is continuously mapped at a speed of 18 Kms/Hr. The accuracy of mapping is less than 10 meters in altitude. Thus, for bathymetric mapping of the deep seabed, multibeam echo sounding system is both rapid and accurate.

(d) Side Scan Sonar:

The ability to receive a signal from tiny object on ocean floor (resolution) is determined by the frequency of the sound emitted. The higher the frequency, the smaller the size of an object that can be detected. However, higher frequencies result in higher absorption of sound by the water column. Consequently, the distance to the target must be reduced and when the water depth is too great, the equipment must be placed on a fish towed near the bottom.

Side scan sonar for deep sea applications, called short range sonar, is an instrument which uses high frequency emission. In order to achieve a better resolution the sound antenna is built in such a way that it scans the ocean floor by a narrow beam of sound that results in a swath of information perpendicular to the fish track. The continuous recordings of echoes when the fish moves shows black dots where a strong echo has been received and white dots where there is no echo. A kind of negative photography of the sea bottom is produced where obstacles appear as black patches and hollows appear as white shadows. Thus the products of these surveys are similar to aerial photographs or radar imagery and are called sonar imagery. They are useful for the location of relatively small (micro) topographic features as well as for distinguishing major differences in sediment types.

The existing deep towed side scan sonar can cover a swath of seafloor of 1.5 Km width at a speed of less than 2 Km/h when it is towed from the surface ship with a coaxial cable 6-8 Kms long at a distance of 100 meters above the sea-floor. It can identify objects half a metre high such as outcropping layers of indurated sediments as well as vertical cliffs up to 10m high.

(e) Multi-frequency Exploration/Acoustic System:

The multi-frequency Exploration/acoustic system developed by USSR and also by Sumitomo Metal Mining Company of Japan is especially designed to provide information on the distribution density and size of manganese nodules on the seafloor on a real-time and continuous basis when combined with acoustic sounding instruments such as narrow beam sounders and the sub-bottom profiler combined with a precision depth recorder with which ocean research vessels are commonly equipped. In this system, contrast in reflectivity of sound from nodule targets and adjoining sediments is used in mapping the nodules.

2.3 TECHNOLOGY VARIANTS AND THEIR SEQUENCING

2.3.1 Background

As discussed earlier, the objective of deep seabed mineral exploration is to locate, identify and quantify mineral deposits, either for scientific purposes leading to better understanding of their genesis or for potential commercial exploitation. Detailed sampling of promising sites is necessary to prove the commercial value of deposits. Obviously, it would be impractical and too costly to sample the entire seabed areas within the given domain in the detail required to assess the commercial viability of a mineral deposit. Fortunately, this is not necessary as techniques other than direct sampling can provide many indirect clues that help mining prospectors narrow the search area to the most promising area.

Accurate information about seafloor topography is a prerequisite for detailed exploration. Side scan sonar imaging and bathymetric mapping provide indispensable reconnaissance information.

2.3.2 Reconnaissance Technologies

SIDE SCAN SONARS

Side scan sonars are used for obtaining acoustic images of the ocean bottom. Most side scan sonars are ship-towed transducers which transmit sound through the water column to the seafloor. The sound is reflected from the seabed and returned to the transducer. Modern side scan sonars measure both echo-time as well as backscatter intensity. The final product of the sonar is a sonograph or acoustic image of the ocean floor. It is also possible to extract information about the texture of some seabed deposits from the sonar signal. Side scan sonars may be broadly classified into three types, the applications of which go beyond the reconnaissance to detailed mapping technologies:

(a) Long range sonar:

It is capable of mapping swaths 10 to 60 kms wide. GLORIA is a typical long range side scan sonar which was designed by the Institute of Oceanographic Sciences in the U.K. GLORIA images are similar to slant range radar images. It provides an excellent base map which may be used for subsequent planning.

(b) Midrange Sonar:

It is capable of mapping swaths 1 to 10 kms wide. Like GLORIA, midrange systems record the acoustic reflection from the seafloor, however, they are capable of much higher resolution. In addition, whereas GLORIA is used to obtain a general picture of the seafloor, midrange and short range side scan sonars are usually used for more detailed surveys. A seabed miner interested in looking for a specific resource would select and tune the side scan sonar suitable for the job. For example, manganese nodules fields between the Clarion and Clipperton fracture zones in the Pacific Ocean were mapped in 1978 using an imaging system specially designed and built for that purpose.

The Sea MARC 1 developed by International Submarine Technology Ltd. (IST) and Sea MARC II by Lamont - Doherty Geological Observatory and the Hawaii Institute of Geophysics are two of several such systems available. Later developments in this field relate to the interferometric systems. By measuring the angle of arrival of sound echoes from the seafloor in addition to measuring echo amplitude and acoustic travel time, interferometric systems are able to generate multi-beam like bathymetric contours as well as side scanning sonar imagery. Sea MARC II developed jointly by IST and HIG, newer versions of Sea-MARC I and several other systems have this dual function capability.

(c) Short range sonar:

It is capable of mapping swaths of up to 1 km width. Short range side scan sonars are used for acquiring acoustic images of small areas. They are not used for regional reconnaissance work, but they may be used for detailed imaging of seafloor features. Operating frequencies of such sonar are commonly between 100 and 500 KHZ, enabling very high resolutions. Like midrange systems, they are also towed close to the ocean bottom. Deep Tow, developed by Scripps Institute of Oceanography, has been used to study morphology of sediment bedforms and processes of crustal accretion at the Mid-Atlantic Ridge SAR (Systeme Acoustique Remorque) is a similar French system reportedly capable of distinguishing objects as small as 30 by 76 cms. It is towed about 60m off the seafloor and produces a Swath of about 1000 meters.

Sea MARC CL is a short range deep-towed interferometric system which has been configured by Sea Floor Surveys International and the system is available for use on hire.

Shallow water, high resolution side scan sonars developed by EG & G and Klein are used for such activities as harbour clearance, mine sweeping and detailed mapping of oil and gas lease blocks.

BATHYMETRIC SYSTEMS

Until recently, bathymetric mapping mostly used single beam echo-sounding technology. This technology has now been surpassed by narrow, multi-beam technology that enables the collection of larger amounts of more accurate data simultaneously. Improvements in seafloor mapping have resulted from the development of multi-beam bathymetric systems the application of heave roll-pitch sensors to correct for ship motion, the improved accuracy of satellite positioning systems and improved computer and plotter capabilities for processing map data. These improvements make possible

- Much higher resolution for detecting fine scale bottom features.
- A significant decrease in time required for surveys.
- Nearly instantaneous automated contour charts, eliminating the need for conventional cartography, and
- The availability of data in digital format.

These bathymetric systems are of two types: for shallow water applications and for deep water applications. The principal deepwater multi-beam systems currently in use in the USA are Sea Beam and SASS. The sea Beam Technology capable of mapping in depths greater than 5 kms first became available from General Instrument (GI) Corporation in 1977. GI's original multi-beam bathymetric sonar, the Sonar Array Sounding System (or SASS) was developed for the US Navy and is not available for civilian applications. In fact, Sea Beam is a spin off from the original SASS Technology. Sea Beam is a hull mounted system using 16 adjacent beams each beam covering an angular area 2.67 degrees.

Modifications and improvements in Sea Beam have been introduced. One modification relates to the capability to quantify the strength of signal returning from the bottom. With such information, it would be possible to predict certain bottom characteristics. Nodule fields, for example, have been claimed to be quantified using acoustic back-scatter information. Another modification relates to building a towed Sea Beam System which could be moved from ship to ship as required.

Another field of improvements from the Sea Beam Technology is increasing the data intensity by additional number of beams and consequential upgradation in accuracy. The improved systems include:

- KRUPP Atlas Hydrosweep
- HOLLMING Echos XD and
- SIMRAD EM 1000

2.4 SITE-SPECIFIC TECHNOLOGIES

Site-specific exploration technologies are generally those that obtain data from small areas. Some of these technologies are deployed from a stationary ship and are used to acquire detailed information at a specific site. Often, in fact, such techniques-coring, grab sampling and dredging-are used to verify data obtained from reconnaissance methods. Other site specific technologies are used aboard ships moving at slow speeds. Optical imaging and short range side scan sonar towed near the ocean bottom fall under this category.

2.4.1 Optical Imaging

Optical images produced by underwater cameras and video systems are complementary to the images and bathymetry provided by side scan sonars and bathymetric systems. Once interesting features have been identified using long range technique, still cameras and video systems can be used for closing views. Such systems can be used to resolve seafloor features of the order of 10 cm to 1 meter. The swath width of imaging system depends on such factors as the number of cameras used, the water characteristics, and the height of the imaging system above the sea-floor. Swaths as wide as 100 to 200 meters are mappable.

One current limitation appears to be the lack of availability of an adequate transmission cable for the colour television pictures. Colour television transmissions exceed 6 million bits per second and large band width cables capable of carrying this amount of information have not yet been developed for marine applications. Fibre-optic cables are now being designed for this and related marine data transmission needs. However, before fibre-optic cables can be employed in general, problems of handling tensional stress and repeated flexing of the cable must be overcome and research in this field is already active.

The current subject to lens range limit for optical imaging is 30 to 50 metres in clear water. Several improvements are expected in the future that may enable subjects to be imaged as far as 200 meters from the lens under optimal viewing conditions. For instance, efforts have been made to increase the sensitivity of film to low light levels. A 200,000 ASA equivalent speed film was used to take pictures of the Titanic under more than 2 miles of water. Higher film speed ratings, perhaps as high as 2 million ASA equivalent, will enable pictures to be taken with even less light. Improved lighting will also help greatly. The optimal separation between camera and light in the ocean is about 40 meters, which suggests that towed light sources could provide an advantage.

2.4.2 Direct Sampling

Free fall samplers, especially designed for nodules exploration are essentially rapid reconnaissance samplers. For more accurate and comprehensive information, however, coring (box or spade coring) and dredging operations are employed. However, in the case of polymetallic nodules in particular, direct sampling has to be supplemented by the deep seabed photography in assessment of the nodules coverage and hence the nodules resources.

2.5 AREAS OF FUTURE DEVELOPMENTS

The currently available seafloor mapping systems provide variety of data demanded by the exploration objectives. However, the next generation seafloor mapping system is required to produce high resolution data at relatively larger speed with minimum interference. The new areas requiring technical development thus include:

- development of a phased array which can beam-form under the high pressure up to 400 atm.
- to miniaturise multibeam electronics as small as possible.

- development of a telemetry system, including composite optical/electrical cable system.
- to stabilise a towfish when it is towed.
- to develop a positioning system, possibly dual SSBL which can determine a position of a towfish as far as 8000 m.
- to develop high resolution subsea measuring system using laser pointer and acoustic ranger.

It is likely that the next generation system may be a towed interferometric system which combines various information with high resolution.

Developments of above nature are already in hand at various institutions, such as, universities like University of Hawaii, Government organisations like Marine Mineral Technology Centre, Hawaii and Metal Mining Agency of Japan as well as private industries like Simrad A/S, Seatex A/S, Norway, Benthos (USA) and others involved in marine exploration.

2.6 DATA COMPILATION, ANALYSIS AND DISSEMINATION

In addition to acquisition of data on marine minerals as systematic compilation, storage, analysis and dissemination can ensure a reliable identification of potential reserve, in terms of its geographical location, commercial grade and abundance, as well as the various environmental parameters in which it occurs. Various methods for such data management have been used for different types of mineral deposits. For resource estimation of manganese nodules, methods involving nodule coverage, diameter, specific gravity and its recovery in a collector have been suggested and employed by different workers (Anonymous, 1982, Handa and Tsurusaki, 1981; Lenoble, 1980).

Similarly, for compilation of data collected using a wide variety of exploration methods, creation of a data base for efficient storage, analysis and retrieval is most essential. Large quantities of data collected by Ocean Minerals Company, USA, is being catalogued at the Marine Minerals Centre, Hawaii (Morgan and Cruickshank, 1991). A detailed system for interpretation and cataloguing of seabed photography data on nodules (SPHINCS) is being employed at NIO, India (Sharma and Kodagali, 1990).

2.7 SPIN OFF BENEFITS OF R&D IN MARINE EXPLORATION SYSTEMS

Research activities on marine exploration system, can lead to a wide variety of newer subsystems and experiences, which will have still wider applications. For example, development of free fall sampling equipment involves development of its components which can withstand the highly corrosive environment which the sampler would traverse during its two-way journey. This research in suitable material development, can be applied to other submarine applications. Similarly, floatation spheres needed to make such system buoyant, at pressure of 500 bars, is a specialised technological development by itself.

Even in case of developing an active deep-tow photography and sounding system, not only the principles of sound velocity and light propagation are applied, but it also leads to an experience in a variety of applications, such as, handling underwater remotely controlled equipment, knowledge of underwater electronics and sensing systems, long distance data transfer, high-pressure instrumentation etc. This knowledge can be used in applications such as development of deep sea mining system, submersible related technology for military applications, as well as civil engineering purposes like cable and pipeline laying, inspection of underwater equipment, salvaging and rescue of lost equipments.

2.8 NEED FOR INTERNATIONAL COOPERATION

Marine exploration is expensive and time consuming. The commercial benefits are not likely to be immediate. It implies therefore that efforts in technological developments to ensure efficient products must be shared by countries currently engaged or likely to be engaged in near future in exploration of deep seabed minerals. Commercial benefits could be shared in future. In addition to cooperative efforts in technological developments, cooperation among technology users is equally important. This will bring all kinds of problems faced by various users into common focus and the experiences in solving various problems could be gainfully shared. It must be remarked that such international cooperation will be helpful to all the partners of the team.

2.9 INDIAN EFFORTS IN EXPLORATION OF DEEP SEABED

Surveys for manganese nodules in the Indian Ocean were initiated in 1981 at the National Institute of Oceanography and later funded by the Department of Ocean Development. The exploration for nodules covered a very large area initially, and narrowed down to potentially rich areas. Rapid survey techniques like free-fall sampling combined with spot photography and bathymetric mapping using single beam echosounder marked the initial phase of exploration. Occasional use of other samplers (box and spade corers and dredges) supplemented the efforts leading to allocation of 150,000 sq. km. of an area in the Central Indian Basin, by the United Nations (Qasim and Nair).

While the nature of initial efforts continues, India has acquired and installed the multibeam seafloor mapping system (Hydrosweep) on her research vessel Sagar Kanya. Most of the Indian pioneer area has already been mapped using the multibeam technology and detailed contour maps of the seabed have been developed. Development efforts are on hand to use the data on intensity of backscatter to map the nodules fields. Further, optical imaging of the seafloor using deep-tow system with underwater TV has been planned for immediate future. Other technologies like Short range side scan sonar or other improved interferometric systems on the towed vehicle may be employed subsequently.

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CHAPTER 3

STATUS OF DEVELOPMENT OF SEABED MINING TECHNOLOGY

3.1 INTRODUCTION

Sea-bed mining of polymetallic nodules involves collection of potato-shaped concretions embedded in a 100 mm thick layer at the sea bed (approx. 5000 - 6000 m water depth) land and bringing them to the sea surface.

The nodules are of 10-200 mm size (average 25-50 mm), reddish brown (iron-rich) or blue black (manganese-rich) in colour having specific gravity of 2-3 T/M and hardness 1-4 on mho scale. It contains about 30% water by weight.

The sea floor is a biological desert with pronounced topographic variations. The water temperature is few degree above freezing point, the area is completely devoid of light and the sediments of the sea bed have poor cohesion (bearing strength around 0.03 Kgf/cm^2).

3.2 STATE OF ART

Three distinct design concepts have till now been used by different international agencies for developing the mining systems. The concepts vary primarily in the engineering approaches used to lift nodules to the surface. These include:

- Hydraulic Mining System (pump Lift/Air Lift)
- Continuous Line Bucket (CLB) Mining System
- Modular or Shuttle Mining System

The essential features of each mining system are outlined in the following sections:

3.2.1 Hydraulic Mining System

The principle of hydraulics is used for lifting the nodules to the surface ship. A lift pipe attached to the ship extends close to the sea bed and is linked with a collector mechanism. The collector picks up the nodules and feeds them into the lift pipe. The nodules are pumped up through the pipe with pumps installed on the pipe (pump Lift Approach) or are sucked up through the pipe by means of compressed air injected into the pipe from on-board compressor units (Air Lift Approach).

In the **pump lift** approach, submersible motor-driven pumps are mounted in series at depth of 1000 - 2000 m (decided based on cavitation considerations) for lifting the nodules from sea bed. A 2-phase flow (4% nodule, 96% water) with a flow velocity of 3 to 5 m/sec takes place in the lift pipe.

In the **air lift** approach, the principle of expanding air bubbles is used to create the lift required to establish a flow of water from ocean bed to the surface. A 3-phase flow (3% nodules, 12% air and 85% water) takes place in the lift pipe. The velocity of water below air inlet (located at around 2000 m depth) is kept more than the sinking velocity of particles (which is around I m/sec).

The basic elements of the hydraulic mining system are: Collector sub-system, Lift sub-system and Mining Ship sub-system (See Fig. 3.1).

COLLECTOR SUB-SYSTEM

The Collector moves along the sea floor with low drag (it is made buoyant to reduce its weight in view of very low load bearing capacity of sediments). It collects a high percentage of desired size nodules, concentrates them, and feeds them into a vertical lift pipe.

The collector could be self-propelled or towed. A **self-propelled** design collector is manoeuvred by Archimedean screw mechanism or crawler mechanism for movement in all directions while keeping contact with the mining ship (for remote control) by a host of instrumentation placed on the collector. In **towed** design, the collector is equipped with a sledge and is pulled by the lift pipe connected with the mining ship.

LIFT SUB-SYSTEM

It lifts the nodules fed from the collector to the surface ship through a pipe-string. The pipe is sized for optimum transport of slurry based on nodule production rate, carrier fluid velocity, nodule sinking velocity, nodule concentration, and friction between nodule and pipe wall. The design of pipe string has to take care of load due to motion of ship, drag due to towing of pipe through the water column and vibrations excited by vortices shed from the sides of the pipe. Vortices due to hydrodynamic excitations are suppressed through selective use of hinged splitter plates attached to the pipe string.

Dump valves, one located just above the pump and another at the bottom of pipe string, avoid clogging in the pipe when vertical flow of slurry shuts down unexpectedly leading to accumulation of solids at the mouth of the pipe.

The link between pipe string and collector is provided by a properly supported flexible hose or by a pivoted truss supporting a pipe with flexible connections at each end, in order to accommodate variation in sea bed topography and withstanding bending without significant stresses.

The motive force for lifting the nodules is provided by pump lift or air lift. The **pump lift** design consists of several mixed-flow, multistage submersible pumps installed in line into the pipe string. The pump motor is of underwater design, 3 phase, AC motor filled with water for cooling/lubricating the bearings. In **air lift** design pressurised air produced by several on-board compressors is injected into the annular cavity of double-walled, barrel-like construction. Air enters the pipe string through perforations in the wall of the internal cylinder of the barrel and creates the necessary suction effect for lifting the slurry.

MINING SHIP SUB-SYSTEM

A single hull, self-propelled mining ship equipped with the following facilities represents a typical mining ship sub-system:

- A gimbal mounted passive derrick for riser pipe handling.
- Heave compensation by air/oil accumulators located just below gimbal.

- Riser pipe storage racks and overhead gantry crane.

- Deck crane for on-board handling of mining equipment viz. collector, buffer, pumps, hose, cable etc.

- Facilities for washing, separation and crushing of nodules (to -5 mm size), storing of wet nodules on-board and rejecting the waste to sea at minimum 500 m water depth.

- Facilities for transferring nodules to transport ship by re-slurrying in storage tank and pumping thru'hose, along with mooring winch system.

- Control system for positioning of vessel, riser and collector (by dynamic positioning / Hydroaccoustic reference/sonar/ underwater TV System) and for operation and monitoring of mining system.

- Equipment storage and workshop facilities.

- Engine-generator sets for main and emergency power supply.

- Instrumentation, data transmission and general purpose computer.

- Living accommodation for about 100 persons.

3.2.2 Continuous Line Bucket Mining System

A long continuous loop of rope attached with drag bucket is hung from a surface platform in sea such that end of loop touches the sea floor. The loop is caused to rotate so that the buckets during their passage on sea floor excavate nodules and carry them to the surface. Simultaneously, the surface platform is moved in a direction perpendicular to the plane of the loop on a path having width equal to the length of the platform is swept across the sea bed.

The basic elements of this system are: Bucket sub-system, Rope sub-system and Mining ship sub-system.

The bucket clipped to the rope loop at regular intervals collect the nodules and dislodge the sediments from them, as they graze the sea floor. A braided polypropylene rope circulates on the ship thru' umbrella type wheels and is caused to rotate by tracing device on-board the ship. Hydrodynamic separators are provided to avoid tangling of the rope. Buckets are attached to rope at stem deck and filled buckets removed at Bow deck and unloaded on deck storage.

Mining ship sub-system is similar to that described for hydraulic mining system except that the pipe storage and handling facilities and deck crane for handling underwater components are not required. Instead, drive arrangement for rope and its storage and handling facilities are provided.

A two-ship CLB system is preferred to single-ship system as it avoids sub-sea tangling of ropes.

3.2.3 Modular Mining System

The shuttle unit (collector) with ballast material (weight of ballast in water equals weight of nodules to be collected in water) is made weightless in water with the help of buoyancy elements. The shuttle unit launched from the surface platform propels down to sea bed against hydrodynamic resistance alone. The unit moves on sea bed and collects nodules as it simultaneously ejects ballast material of equal weight (in water). When all ballast material is ejected and the weight of unit becomes zero or negative, the unit propels to surface and docks with surface platform, where it is unloaded, serviced and re-ballasted for new mining cycle.

Basic elements of this system are: Collector unit and Surface platform.

The collector unit is provided with on-board energy source and necessary sensors and controls to enable it descend/ascend and lift nodules while being propelled by archimedes screw, as per remote commands or on-board program.

The Surface Platform is provided with:

- Moonpool for launch and docking interface.
- System to command collector unit thru' remote acoustic commands or programs on-board the units.
- Deck space to unload, inspect and maintain recovered unit.
- Facility to store and load ballast material prior to launch of unit.

The modular mining system developed by AFERNOD of France has the following parameters:

(a) Collector:

- 24 m x 12 m x 7.5 m, self weight 550 tons.
- 3 x 250 tons production trips/day.
- Control by acoustic link from surface platform.

(b) Surface platform:

- 100 m x 100 m semi-submersible type.
- 140,000 tons displacement
- 56 m draft.
- Storage of 60,000 ton nodules or ballast material.
- 4 Nos. underwater ports for docking/launching of collector units.
- Accommodation for about 150 persons.

3.2.4 Comparison Between Various Mining Systems

The continuous - line - bucket (CLB) system is simple, flexible in operation, potentially energy efficient and involves lesser cost but has low recovery rates besides the possibilities of tangling of ascending and descending segments (which may result in close down). This system has, therefore, been abandoned.

The remotely controlled shuttle (modular mining) system is yet to be developed and extensively tested in shallow and deep sea waters to establish its reliability. Besides, cost of moving of tailings from a distant onshore processing plant to mine site for use as ballast material may be prohibitive. This system has therefore been temporarily shelved and is considered as a future second generation technology.

The development of hydraulic (pump lift/Air lift) system is based on the technology and experience gained in operating oil risers in deep waters and the know-how built in connection with slurry transportation of minerals at sea and on land. Hydraulic system is currently considered most effective although long-term testing and consequent refinements are necessary to establish its reliability for commercial-stage mining (3 million tonne dry nodules/year capacity). The best judgement for pilot test appears to be a combination of centrifugal pumps and air lift systems.

3.3 INTERNATIONAL SCENARIO

3.3.1 Historical Background

Since their first recovery from the ocean floor in 1870s during the cruises of the HMS Challenger, polymetallic nodules have been found to cover vast portions of the bottoms of the Pacific, Atlantic and Indian Oceans. For more than eighty years thereafter, the nodules were solely of scientific interest. But now, not only ocean engineers and some mining men have become interested in sea bed resources but these resources have become the subject of international organisations like United Nations.

Research and Development of Polymetallic nodule mining technology has been carried out for last two decades. The systems under consideration have been refinements, though, the basic design concepts remain the same. Two of the three basic design concepts of mining systems, viz. continuous line bucket (CLB) system and shuttle system, have been abandoned or shelved temporarily.

3.3.2 Development and Tests by Consortia

The first work on developing ocean mining technology began in the 1970s by the U.S.-based international consortia. These consortia identified commercially interesting nodule deposits in the Clarion Clipperton zone in the Pacific and developed and tested integrated systems for mining.

It is reported that all first-generation systems developed by these consortia are of hydraulic type.

OCEAN MINERALS COMPANY (OMCO)

During 1978-79, OMCO carried out extensive deep sea tests of equipment using converted heavy lift ship "Glomar Explorer". The tests employed air lift technique and floor-based travelling collector using hydraulic concept driven by Archimedean Screws.

The OMCO test site was located about 2400 Km south-west of Los Angeles, California, and Long Beach, California, was used as support base for the operations. The "Glomer Explorer" has since been decommissioned and returned to U.S. Navy's reserve fleet.

OCEAN MANAGEMENT INC. (OMI)

They were the first to carry out successful pilot mining test on polymetallic nodules in 1978 using the converted dynamically positioned drill ship "SEDCO 445" in which 800 tonnes of nodules were recovered from the 4575m deep floor of Pacific ocean.

The OMI test site was located about 1300 Km sough-east of Hawaii, and Honolulu (Hawaii) was used as the support base for the test operations. The mining test rig on the "SEDCO 445" has since been removed and the ship has returned to offshore oil drilling.

The system design has a test mining rate of around 30 T/hr. Two different towed collector concepts viz. hydraulic and mechanical, and two different types of hydraulic lifting systems viz. an air lift system and a pump lift system using multistage mixed below pumps were tested successfully.

OCEAN MINING ASSOCIATES (OMA)

OMA's main partner is Deepsea Ventures, which has been working in marine mining for almost two decades. The OMA's deepsea Miner II tests spanned a two year period 1977-78. The test site was located about 1300 Km southwest of San Diego, California.

The R/V Deep Sea Miner II used by OMA was approximately a 20-30% production scale version of the commercial system (output around 1 million dry T/year). Besides shallow and deep water trials four deep water tests (4575 meters) were conducted. During a 46 day test, 22 hour, continuous successful pumping was achieved. Deepsea Miner II has since been sold as it completed its basic mission and is no longer needed by OMA.

The technology required to proceed into the commercial phase will be an extension of the present developments. The next step is essentially one of system reliability, endurance and long-term production capability.

KENNECOTT CONSORTIUM

The most important member of this group is Kennecott Copper Corporation, which has a broad experience in marine experience in marine exploration and development work since 1962. Prior to the formation of this consortium Kennecott had already completed extensive nodule resource delineation surveys, which prompted the other members to focus their efforts on developing the mining technology.

Much on-land test work has been done with a mining system composed of a single towed collector with an in-line pumping system for a production rate of about 3 million tons dry nodules/year.

3.3.3 Developments by States

JAPAN

Research and development for the manganese nodule mining system, was initiated in Japan in 1970s. In order to develop the mining concept of hydraulic system (Pump Lift or Air Lift) with a towed collector following R&D plan was originally drawn:

- R&D Period Nine years (1981-1989)
- R&D Budget 20 billion Yen (approx. 150 million U.S. $).

However, it is being projected that pilot mining studies in pacific Ocean scheduled for 1989 shall be delayed by a few years (1994) due to certain technical difficulties and budgetary restrictions.

The basic research, including experimentation work and theoretical analysis for the phenomena of collecting and lifting nodules and mining's environmental effects to the ocean, was carried out by the National Research Institute for Pollution and Resources (NRIPR), which is part of Ministry of International Trade and Industry. The Engineering work, including Research and Development of pilot mining system and its at-sea test, was assigned to Technology Research Association of Manganese Nodule Mining System (TRAM), which was formed taking representation from 19 companies (from such industries as non-ferrous metal mining, ship building, machinery manufacture, electronics products and shipping) besides metal Mining Agency of Japan. The program was promoted and directed by Agency of Industrial Science and Technology (AIST), which is a part of Ministry of International Trade and Industry and supported by New Energy and Industrial Technology Development Corporation (NEDO).

The concept design was completed in 1981 which was followed by R&D of elemental technology for the collector, the pipe string, the pump lift, the air lift, the handling systems, and the measurement and control systems. Necessary scale models were manufactured and tested in model basins and in the sea. The simulation calculations to estimate the behaviour of mining ship, collector, pipe string and slurry flow were also carried out.

The basic design of an integrated ocean mining test system was thus established by 1985 at a cost of about 4.6 billion Yen.

The detailed design was initiated in 1986. The manufacturing of necessary equipment such as collector, relief valve pump module, compressor, steel pipes and flexible hose etc. are almost completed. The detail design of handling system for underwater equipment and ship conversion is still under progress. Till 1990, a budget of additional 4.8 billion Yen is further consumed.

The outline of Japanese Pilot mining system are summarised below:

(a) The conceptual design of Manganese Nodule Mining system is shown in Fig 3.2 and the basic parameters for the design of pilot Mining System are given in Table 3.1

(b) The collector system :

A towed design using sleds as travelling mechanism and hydraulic dredging for nodule collection (water jets separate the sediments while picking up only the desired size nodules); employs separator for further separating; sediments and single roll crusher to crush nodules to small size before transferring to lift pipe; buoyancy materials lower bearing load between sleds and the ocean floor.

(c) The Lift System:

Transports slurry (nodules + sea water) from ocean floor to mining ship through the long pipe string using pump lift system or air lift system. In pump lift system, two pump, modules (each comprising two, 4-stage centrifugal pumps driven by a common oil-immersed, submersible motor) are installed on the pipe string at the depth of 1000 m and 2000 m. The design capacity of the system is 50 wet tonnes of nodules per hour when using pump lift.

In air lift system, a 3-stage onboard compressor supplies compressed air through an air pipe (laid along the pipe string) to injection device located at about 1800 m depth. The design capacity of the system using air lift is 36 wet tonnes of nodules per hour.

The lift pipe is made of high tensile steel having 150-230 mm inside diameter and 12 m sections connected by screwed coupling. The flexible rubber hose at the end of lift pipe has 150 mm inside diameter and 12 m section with flanged coupling.

(d) The measurement and control system:

It has two main roles (1) to observe the slurry flow, pipe string and collector's behaviour and ship and weather conditions; and (2) to transmit large quantities of data and power between underwater equipment and the surface ship.

A composite fibre optic and electric power umbilical cable of water-proof design, suitable to withstand 550 kg/cm^2 pressure is used.

FRANCE

Of the state engaged in sea-bed mining, France, an early entrant into the field, initially extended its operations in testing the Continuous Line Bucket concept (1972-76) followed by the programme on Remote-controlled Shuttle concept in 1980. In 1984, the shuttle concept was temporarily shelved since its operational and investment costs far exceeded the cost of other conventional mining concepts. However, the shuttle concept was regarded as the technology of the future, especially because of the flexibility it affords over conventional concepts.

The programme was then re-oriented to the Hydraulic mining concept and was delegated to the newly formed GEMONOD in 1984. France entered into a joint development project with a German Company, PREUSSAG AG, in 1985 on areas covering nodule pick-up device, locomotion of self-propelled collector, and hydraulic lifting of nodules.

A prototype of a freely moving unit PLA 2-6000 was designed, built and tested for travelling on the soft bottom sediments (at 500 m water depth) and to harvest nodules.

The mining system, as envisaged at the end of GEMONOD studies in 1988, for commercial mining operation having annual output of 1.5 million dry tonnes (corresponding to 2.1 million wet tonnes) included the following:

(a) Collector:

A self-propelled dredge, 18 m long x 15 m wide x 5 m high, weighing 330 tonnes (underwater weight about 78 tonnes) sweeping 12 m width at a speed of 0.65 m/sec, collects, conditions (to about 40 mm size) and pumps 600 tonnes per hour nodules through the flexible hose. Installed electric power is 3 MW.

(b) Flexible hose:

600 m long x 382 mm ID connects the dredge to the bottom of the pipe string.

(c) Lift system:

Lift capacity 500 t/hr nodules (slurry has 12% solids by volume). A 4800 m long x 382 mm inside diameter rigid steel pipe string comprising 27 m sections connected by Riser type quick couplings. Either an air-lift with compressed air injection at mid point of the pipe string, or a pump lift using four centrifuge - axial pumps (each 1.1 M OD x 15 m high developing 240 kPa pressure and weighing 27 T) : or a combination of both. 100 Tonnes ballast at the lower end of the pipe. (Crusher, thickener, conditioner etc. for proper ore dressing to give thick pulp with 60% solids, thereby reducing the pipe size are seen as second generation efforts).

(d) Mining Vessel:

A semi-submersible, catamaran type surface platform 100m long x 70m wide x 40m high with an operational draught of 22 m and displacement 41600 tonnes after ballasting. Equipped to manage the pipe string, including fast deployment and retrieval of pipe and collector, heave, roll and pitch compensations, and the possibility to connect/disconnect the pipe in case of hurricane. A few days storage for nodules. Transfer of nodules (crushed to 5 mm size and thickened) to the ore carrier by pumping of thick pulp (60% solids) through a 300 m long flexible hose.

(e) Ore Carrier:

9 Nos ore carriers, 60000 tonnage, equipped with dynamic positioning.

The decision to invest in nodule programme mainly depends on the reliability of mining system. The test of the dredge at 5000 M depth can be done at reduced scale, but not smaller than 1 to 10 without jeopardising the reproducibility of the results. The pilot mining test, requiring a budget in the range of 75 to 150 million US dollars, has to be managed as an international cooperative effort.

With the above in view, France has considered an association with Japanese programme in 1988. Japan's plan to test a pilot mining system in Japanese pioneer area using towed collector with air lift and pump lift could then be further tested using German-French self-propelled collector with Japanese air lift and pump lift system in French Pioneer area. The total cost of this programme has been projected as 900 million US dollars, of which France should be supporting about 25%. However, considering the delay before possible start of commercial operation, France has preferred to defer such huge investment on Research and Development and, in the mean time, to keep alive the acquired knowledge till it is time to start again.

Presently, France, in association with a German Company (Thetis International), plans to test a small dredging crawler from a conventional oceanographic vessel by using fibre optic cable to link the crawler with the surface ship.

3.3.4 Developments by Enterprises

RAUMA - REPOLA, FINLAND

Rauma-Repola, one of the biggest publicly-owned enterprises in Finland operating in ship building, offshore marine technology, paper and pulp industries etc. with a turnover of US $ 1800 million in 1985, have been working in under water technology since 1982.

They claim to have already developed two complete designs for nodule test mining - one for 30 T/hr capacity and another for 10T/hr, and testing and developments are reported to be presently in progress.

Further, they had originally claimed their involvement in a joint development project for a 26 T/hr test mining system with Sudo-import and Ministry of Geology, USSR, but the present status of the said project is not known.

PREUSSAG, WEST GERMANY

PREUSSAG, Marine technology group claim to have gained comprehensive experience in offshore mining during the last decade.

PREUSSAG has performed optimisation study by HYTRANS computer programme for pipe string diameter vis-a-vis different spatial concentration and sizes of nodules. They are also involved in studies on environmental impact of nodule mining carried out jointly by USSR, France and Federal Republic of Germany.

They had some cooperation agreements with Rauma-Repola (Finland) for about 2 years but the same has since ceased.

As a member of OMI (Ocean Management Inc.) they were involved in the first successful pilot mining test carried out in 1978. Since 1985, they are working with France to study in particular the following :

- Nodule pick-up device,
- Locomotion of the self-propelled collector,
- Hydraulic lifting of nodules.

The results of these works have been reported in Offshore Technology Conferences (OTC) 1987 and 1989 (Paper Nos. OTC 5476 and OTC 5998). They had plans to conduct an in situ collector test on the German Research Ship "SONNE" during 1991/1992.

3.3.5 Indian efforts

R&D for development of mining technology was started in 1989-90 with Central Mechanical Engineering Research Institute (CMERI) as the development centre. The current objective is to design & develop a scaled down mining system of 100 TPD capacity with self-propelled collector and bucket-in-pipe lifting system. The system is likely to be tested on land as well as in shallow basin test facilities along with necessary remote controls during early part of 1992. Once the necessary test data are generated, the system for testing at 4000-5000 m water depth will be undertaken. Finally, the development of the mining system on semi-industrial scale and commercial scale will be initiated.

3.4 NEED FOR INTERNATIONAL COOPERATION

The development of mining technology is highly cost intensive and involves enormous multi-discipline efforts in high-tech fields. Moreover, the technology so developed is not likely to find much repetitive use in other industries. It is, therefore, imperative and logical for all the actively participating countries/ agencies to pool their resources and expertise at international level, for their mutual benefit.

Such collaborative arrangements would not only reduce the cost of development by avoiding duplication of efforts but also help to share risk and uncertainties inherent to the high-tech R&D. Only then the pace of progress in this field, which has rather been slowed down during the last few years, could be expected to get a boost.

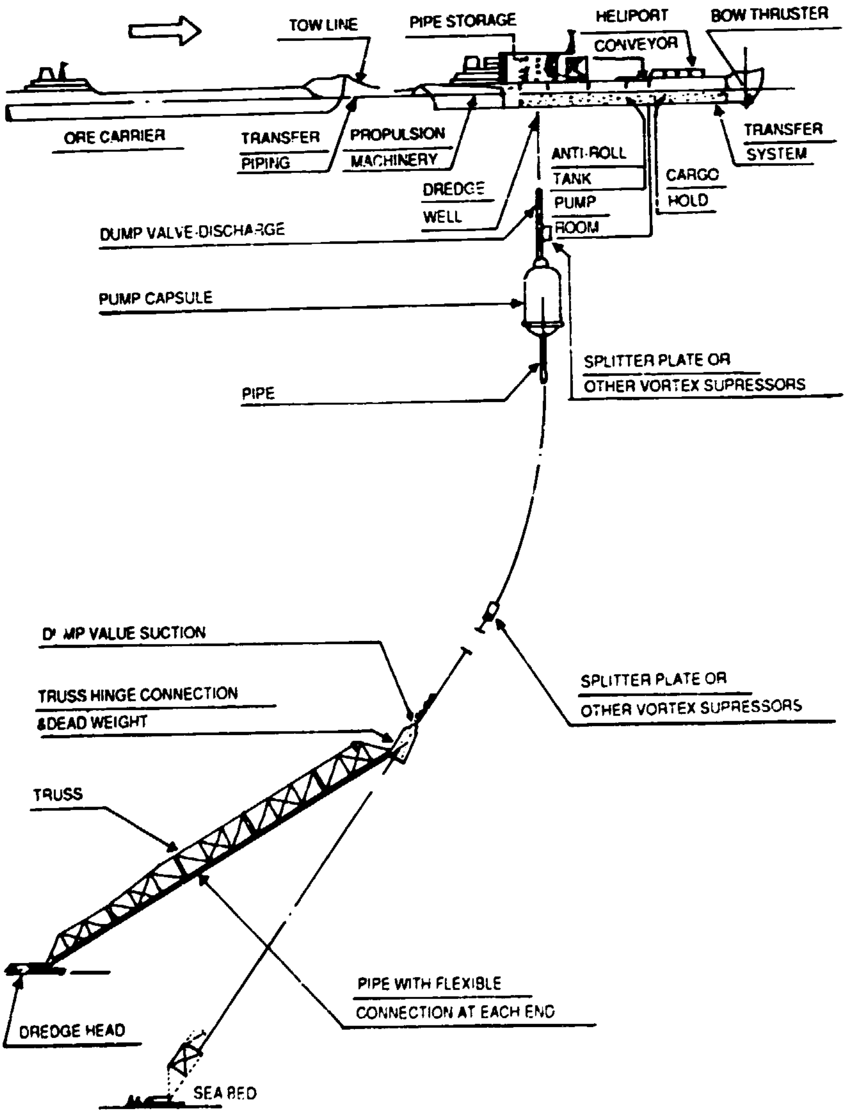

FIGURE 3.1
Basic Elements of Hydraulic Mining System

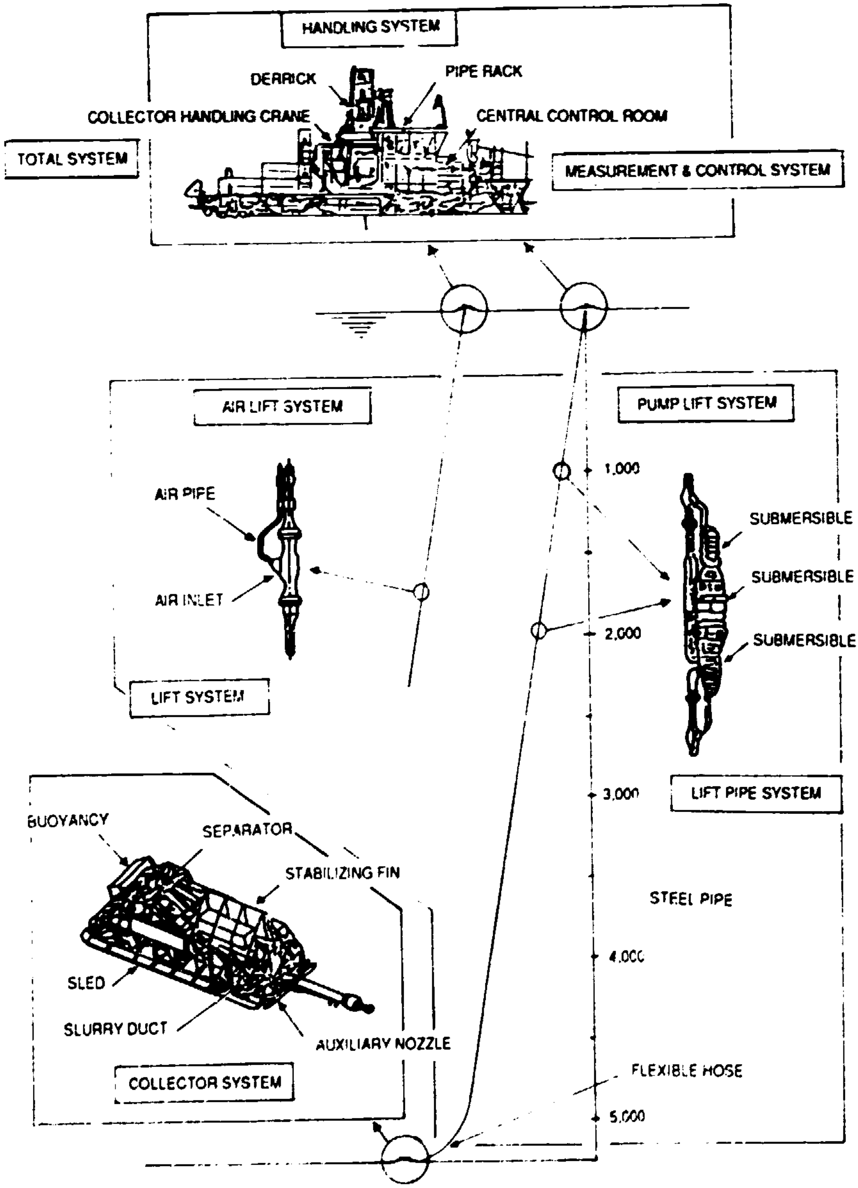

FIGURE 3.2
Concept of Magnese Nodule Mining System
(As developed by Japan)

TABLE 3.1
Basic Design Conditions of Experiment System (Japan)

A. General Conditions

Item	Condition	Remarks
Mining Depth	5,150 m	---
Permitted Depth deivation	± 100 m	Deep sea floor's undulation to be without chaging any pipe string's formations
Lift Pipe Diameter	150 mm Nominal Inner Diameter	Common use for Air Lift and Pump Lift
Mining Speed	abt. 1.2 kt (Pump Lift) abt. 0.8 kt. (Air Lift)	
Navigation Speed	abt. 11 kt	
Limitations of wave heights in operation		These values are significant wave heights
(1) Launching (2) Pipe handling (3) Collector landing (4) Mining	1.8 m 2.5 m 2.5 m 4.0 m	
Power Supply (1) Source (2) Measuring & control Source	(all 60 Hz) 6,600 V, 1-3 ϕ 1,650 V, 1-3 ϕ 660 V, 1-3 ϕ 100 V, 1-3 ϕ	In case of Pump Lift, frequency becomes variable so as to change pumps revolution. Normal frequency is 50 Hz.

B. Collector

Item	Condition	Remarks
Nodule Characteristics		---
(1) Nodule Abundance	Avr. 15.0kgf/m²	
(2) S.G. of nodule	2.00	
(3) S.G. of sediment	2.67	
(4) Bearing force	Abt. 300 kgf/m²	
(5) Mining depth	Abt. 5.250 m	
(6) Collecting capacity	Max. 74 tf/h (wet)	
(7) Collecting Speed	Max. 1.2 kt	
Collected Nodule Size	Avr. 40 mm	As diameter of long axis
	Max. 120 mm	
Nodule Feed Condition (to lifting system)		
(1) Nodule size	Less than 40 mm	As diameter of long axis
	avr. 20 mm	
(2) Feed capacity	Max. 50 tf/h (wet)	
Postural Stability in Water	Min. 0.1 kt.	Collector must b]e towed in the speed of over 0.1 kt.

C. Lifting System

Item	Condition	Remarks
Pump Lift System		
(1) Lift Capacity	Max. 50 tf/h (wet)	
(2) Volume concentration at outlet	8%	In rated operation condition
(3) Slurry capacity	Max. 312 m^3 /h	
(4) Slurry velocity in pipe	abt. 4.0 m/s	
Air Lift System		
(1) Lift Capacity	Max. 36 tf/h (wet)	
(2) Volume concentration of nodules	8%	In two phase flow
(3) Nodule velocity in onboard pipe	abt. 20 m/s	
(4) Air blow rate	abt. 6.1 kgf/s	
(5) Back pressure of air	abt. 6.1 kgf/s	
	(3.0 kgf/s, abs.)	

D. Handling System

Item	Condition	Remarks
Handling Time		---
(1) Pump Lift	abt. 8.0 days	
(2) Air lift	abt. 8.5 days	

E. Measurement and Control System

Item	Condition	Remarks
Ship Positioning System		---
(1) System	G.P.S.	
(2) Precision	less than 100m	
Collector Positioning System		---
(1) System	S.S.B.S	
(2) Precision	less than 100 m	

CHAPTER 4

ENVIRONMENTAL IMPACT OF SEABED MINING TECHNOLOGY

4.1 INTRODUCTION

The study of impact of deep seabed mining on oceanic ecosystem involves three components:

(a) Establishing environmental baselines of the selected parameters likely to be encountered during nodule mining (Environmental Characteristics).

(b) Potential environmental effects of nodule mining and developing prediction capabilities, and

(c) Developing appropriate environmental guidelines.

It may be appreciated that it is not scientifically and economically possible to develop very detailed baseline information on the ecology of all offshore environments in a relatively short period. Accordingly, the consequences of a variety of mining scenarios cannot be precisely predicted. In the very near future, therefore, environmental impact statements will presumably be prepared to identify site specific problems prior to the commencement of mining operations.

4.2 ENVIRONMENTAL BASELINE INFORMATION

The pre-mining environmental characteristics will serve as a data base for measuring environmental consequences associated with mining. Environmental parameters that are specifically relevant to the mining activities and need systematic studies over a period of time and space is summarised in Table 4.1. These parameters represent selected characteristics of the upper water column and the lower column including the seafloor. These are briefly reviewed.

4.2.1 Parameters of Upper Water Column

Characteristics of the surface waters including seasonal variations is important for modelling surface plume dispersion and inference on potential biological impacts.

4.2.2 Nutrients

Certain nutrients (phosphates and nitrates) in the upper water layer affect the marine food chain by controlling the abundance and composition of the phytoplankton. The nutrient levels therefore constitute an important information due to the critical importance of the phytoplankton to the oceanic food chain and the eco-system.

4.2.3 Endangered Species

In view of the possibility of endangered species occurring in the deep sea exploration/mining area or along the ship routes, it is pertient to make observations on identification of the species, location of observation, number of individuals - males, females etc.

4.2.4 Salinity, Temperature and Density

Salinity and temperature values and their spatial and temporal variations are relevant to the location of the thermocline and pycnocline. The change in density due to temperature differences in the pycnocline is important to its effects on the settling rates of discharged particulates.

4.2.5 Currents

The velocity and the variability in the upper layer currents effect the concentration, dispersion and settling of surface plume and are hence relevant.

4.2.6 Lower Water Column and Seafloor

Lower water column and seafloor characteristics are directly relevant to benthic impact. The relevant parameters include the following:

4.2.7 Currents

Like in upper layer, the bottom current measurements are input for the benthic plume model.

4.2.8 Suspended Particulate Matter

The concentration and the variability of SPM concentration in the bottom water is relevant to understanding the dispersion pattern of the benthic plume and in establishing the range of variability of SPM experienced by the benthic organisms.

4.2.9 Benthos

For predicting the consequences of mining on the benthos, it is necessary to know the species, diversity, density, biomass and the relation to topography of the organisms present. Such information obtained from photos, box cores, videotape etc. will constitute the basic information.

4.2.10 Sediment

Size distribution, density, and shape of the sediment are pertinent information since they effect the dispersion pattern and settling rates of the benthic plume.

4.3 POTENTIAL ENVIRONMENTAL EFFECTS AND PREDICTION CAPABILITIES

4.3.1 Deep Sea Environment

In the deep-sea, the abundance of animal life decreases with increasing depth and distance from land. Deep sea animals are predominantly restricted to the surface of the seafloor and upper few inches of bottom. It appears that the species, particularly catalogued at present and the information on their life cycles is inadequate. The density of animals is low but diversity is considered to be high. In these regions, the low total number of animals is thought to reflect the restricted food supply, which comes from either residues raining into the deep sea from above or from in situ production.

4.3.2 Deep Sea Mining Studies

All estimates and inferences regarding environmental impacts of deep sea mining draw heavily on information from the Deep Ocean Mining environmental study (DOMES) funded by NOAA. Till now, this seems to be the only systematic long term research programme conducted in very deep water. Extrapolations from these studies to other ocean sites rest on the assumption that in general, the abyssal ocean is a much more homogeneous environment than shallow water environments.

The mining scenario presumed removal of nodules from the deep seabed by means of collector driven along the seabed at about 2 miles per hour. Animals on the seafloor directly in the mining path or nearby would be disturbed by the collector and the subsequent sediment plume. In addition, when the nodules reached the mining ships, the remaining residue consisting of bottom water, sediments, and nodule fragments would be discharged over the side of the ship, resulting in a surface discharge plume that might also cause adverse impact.

4.3.3 Summary of Possible Impacts

The study carried out under DOMES programme, concluded that while there were 20 to 30 possible negative impact from deep sea mining, only 3 were of sufficient concern to be investigated.

The first of the three important impact occurs at the seabed. First, the collection equipment will probably destroy benthic biota, an impact which appears to be both adverse and unavoidable. The degree of disturbance depends upon the kinds of equipment used and the intensity of mining. Most benthic animals in this region appear to be tiny detritus feeders that live in the upper centimetre of sediment and are fed by organic material that falls from upper waters. In the worst scenario, the benthic biota in a very small part of the mining areas may be killed due to impacts from first generation mining activities. Although recolonisation is likely to occur after mining, the time period required is not known. No effect on the water column food chain is expected.

The second important type of impact identified is due to a benthic plume or "rain of fines" away from the collector which may affect seabed animals outside the actual mining tract through smothering and interference with feeding. Suspended sediment concentrations decrease rapidly, but the plume can extend tens of kilometres from the collector and last several weeks after mining stops. No effect on the food chain in the water column is expected due to the rapid dilution of the plume. However, mining may interfere with the food supply for the bottom-feeding animals and clog the respiratory surface of filter feeders.

The third impact identified as significant is due to the surface plume. Under a possible scenario, a 5,500 TDP mining ship may discharge about 2000 tonnes of solids and about 3 million cubic feet of water per day. The resulting surface discharge plume may extend about 40 to 60 miles with a width of 15-20 miles and will continue to be detectable for 3 to 4 days following discharge. Such plumes may affect the larvae of fish, such as tuna, which spawn in the open ocean. The turbidity in the water column will decrease light available for photo-synthesis but will not severely affect the phytoplankton populations. The effect may be well within the realm of normal light level fluctuations.

The post DOMES research suggests that the problem of surface plume may not be as serious as was considered before due to rapid dilution and dissipation. However, another potential effect has been identified - that of thermal shock to plankton and fish larvae in the immediate vicinity of the cold water discharge, at the surface of cold deep water. However, except for mortality of some tuna and billfish larvae in the immediate vicinity of the cold water discharge, adverse effects appear to be minimal.

4.3.4 Impact Predictions

With the environmental baseline data generated, theoretical models to predict the impact of mining activities will need to be developed which may be refined based on the available experimental data on environmental impact of seabed mining. The most important area of modelling appears to be plume dispersion models covering the surface plumes as well as the benthic plumes. These models should have the capabilities to be used as a basis to assess impacts for site specific situations. The model will be used for predicting the volume of the mixing zone within which certain unavoidable effects may occur; such as, zooplankton mortality from the amount of solids in suspension following discharge to the ocean surface, and to estimate approximately the volume of ocean within which impacts might occur. The model so developed must evolve to incorporate what is learnt in continued data collection programme during exploration as well as test mining operations. In fact the environmental monitoring during even exploration and test mining phases will need to be carried out to provide relevant data for developing effective predictive models. These models, however, will continue to be updated through future research and monitoring especially of full scale mining system tests.

4.4 ENVIRONMENTAL GUIDELINES

It will be required to develop an environmental guidelines document including environment impact statements prior to commencement of mining operations or prior to submission of a work plan. Such a document will be based on detailed environmental baseline information and suitable predictive models for environmental impact.

4.4.1 Reference areas

Before mining commences in the deep sea, it will be required to identify two reference areas which should be maintained for sampling during the operations. One such area will be sufficiently removed from the impact area to serve as a control. This is referred to as the "preservation reference zones" in which no mining shall occur to ensure representative and stable biota of the seabed in order to assess any changes in the flora and fauna of the marine environment. The second area may be adjacent to the mining area called "impact reference zones" which will be used for assessing the effects of mining operations in the area.

4.4.2 Recent German Studies

While systematic studies on long term basis on environmental impact of deep seabed mining were earlier carried out by NOAA under the DOMES programme, some recent studies and programmes of German Companies and institutes supported by the Government are of special interest. THETIS Technologie GmbH supported by German Ministry for Research and Technology have initiated two pronged studies in this regard. The basic approach involves design and development of seabed mining technology in general and of collector subsystem, in particular, incorporating environmental friendly features. Studies are concentrated on controls, pick-up efficiency with minimum cutting depth, optimisation of traction and trafficability and material selection such that the resultant self-propelled, hybrid collector subsystem is environmentally acceptable. In the second set of studies, experimentations have been designed to study on a long term basis the nature and extent of impacts of the operations similar to the deep seabed mining.

4.4.3 Japanese Studies

The studies undertaken by the Japanese agencies involved in seabed mining and related developments include development of simulation models for assessment of the impact of mining activities on the oceanic environment including the benthic eco-system. These agencies have commenced an environmental impact survey to evaluate the simulation models through indoor experiments, field experiments and observations.

TABLE 4.1

Specific Environmental Parameters Relevant to Assessment of Deep Seabed Mining

Affected Environment	Relevant Parameters
Upper Water Column	Endangered species
	Temperature
	Density
	Currents
	Currents & Shear
	Vertical Light
	SPM
	Dispersion
	In-situ Settling Velocity
	Sooplankton & Trace
	Metals
	Fish Larvae Behaviour
Lower Water Column	Currents
	SPM
	Dispersion
	Renthos
	Sediment
	Topography
	In-situ Setting Velocity
	Benthic
	Impact & recovery
	Blanketing
	Mining Efficiency

CHAPTER 5

STATUS OF PROCESSING TECHNOLOGY

5.1 INTRODUCTION

The objective of this chapter is to bring out the state of technological development in the processing sector related to the exploitation of deep seabed nodules. During period of 1970 to 1980, the world-over witnessed large involvement of several research institutions, laboratories and consortia for development of viable process routes. Subsequently the pace of activities had considerably slackened because of various factors like slow growth of nickel market vis-a-vis economic viability, development of mining capabilities, high costs of R&D etc. Till date no one has processed nodules continuously over a long interval of time at pilot plant scale. As against the stage of development related to process development for nodules, metal extraction from commercial processing of land based copper, nickel or cobalt bearing materials have incorporated various process improvements. The last few years have witnessed the introduction of several new reagents for metal processing. Some of the earlier nodules processes developed may have already reached some stage of obsolescence. Since most of the cost of producing metals from nodules are related to the processing sector, constant updating of R&D efforts is required to keep the developed process competitive in the volatile metal markets.

The large scale of operations warranted by nodules processing would need constant attention with regard to scale up aspects of conventional equipments used during processing. The present chapter endeavours to stress that it would be necessary to continue developmental activities with regard to processing with a view to update the existing state of knowledge and also to integrate, wherever possible, experience gained by processing of similar land based resources into the proposed routes for nodules processing. Since profits from seabed mining can only be a matter of future speculation, it is essential to have organised involvement and support for developmental efforts for the nodules processing activity.

There has been debates in the literature about comparative merits and demerits of pyrometallurgical and purely hydrometallurgical options. Various consortia have examined different process routes but the processes studied can be linked to the metals being recovered as also the past experience of the consortia members in similar processing operations. The choice of particular process route depends upon several factors which are time dependent, since commercialisation may take place only in the remote future. As stated previously, none has processed nodules continuously over a sufficiently long period of time for warranting technical choice of a route. At best, extrapolations based on similar processing operations may lead to narrowing down of process alternatives. As the decision variables and objectives change, the chosen processing route may also change. In view of the above, it would be incorrect to conclude at this juncture of time that pyrometallurgical or a completely hydrometallurgical route is the preferred option.

5.2 INFORMATION BASIS

The technological developments reported in this chapter have been based on information collected from patents, open literature and recent visits and discussions with different participating organisations in various countries for assessing the current status of activities on processing.

The information given out by operating companies in different patents constitute in part the approaches pursued by different consortia engaged in nodules research. The companies constituting these consortia have undergone changes. Table 5.1 gives the present constitution of various consortia engaged in nodules research.

The reference reported emphasize the important trends of research activities and no attempt has been made to prepare an extensive account of all research on nodules processing.

5.3 PROGRESSIVE OPTIONS

An initial reaction to processing options is that nodules are contaminated manganese ores. However, presently, the wet impure 30% Mn ore cannot compare economically with dry pure 45 - 50% Mn ore available commercially. A decision to commit substantial capital funds into facilities to produce manganese from nodules may be difficult to justify for certain research organisations/countries. It might be assumed that the porosity of the ore would make direct leaching viable. However, Kinetics of nodules leaching process bring out that it is necessary to use reducing agents to attack tetravalent manganese oxide matrix, thereby releasing the valuable materials.

Both pyrometallurgical and hydrometallurgical processes for nodule treatment have been examined. As a result of the complexity and polymetallic nature of nodules, it is not possible to use purely pyrometallurgical techniques to produce separate metallic products of the contained metal values. However, as a pretreatment step, pyrometallurgy can be used to concentrate the metal values and alter the physical, chemical and mineralogical characteristics to achieve enhanced selectiveness and dissolution rates during subsequent hydrometallurgical processing. Also, the total amount of material sent to leaching can be decreased, thereby affording reduction in processing costs. The various unit operations used for different processing routes are given in Figs 5.1 & 5.2.

Pyrometallurgical processing options examined include reductive roasting, reductive roasting and smelting, chloridizing roast and sulphate based treatment process.

Hydrometallurgical treatment options without a pretreatment step at high temperature includes direct ammonical leaching, hydrochloric acid leaching and sulphuric acid leaching. Reagent recycling may be elegantly conceived in a hydrochloric acid leaching system through the use of suitably designed pyrohydrolysis reactors. Reagent recycle assumes particular importance in cases where reagent consumption/costs are high, for example consumption of HCL for manganese dissolution in the chloride leach route. The energy costs involved in reagent recycle are often substantial and are to be minimised through suitable process design.

Further descriptions for the various process alternatives are given in the following sections. The names of various companies cited may be linked to the concerned consortium by reference to Table 5.1.

5.4 PYROMETALLURGICAL TREATMENT

Pyrometallurgical treatment steps are utilised principally to pretreat the nodules for making them more amenable for a subsequent preferential solubilisation treatment or to produce a concentrated metal containing phase suitable for further hydrometallurgical processing.

Several treatment options exist. These consist of reduction roast, reduction roasting and smelting, chloridising roasting, segregation roasting and sulphation roast. Descriptions of different variants involving reduction roasting option are abundantly available in the literature. The status with regard to the various options are given below.

5.4.1 Reduction Roasting, Solubilisation

REDUCTION ROASTING

In the early seventies, Kennecott Copper Corporation had carried out detailed work at fairly large scale of operation for pre-treatment of nodules by the reduction roasting option. The effects of different roasting variables utilising synthesis gas mixture have been described in detail (1). The basic studies show the relatively lower extraction recoveries for cobalt as compared to copper, nickel and molybdenum. Subsequent patents (2) (3) indicate a preferred embodiment for larger scale of operations involving drying, calcination and reduction steps. The plant feed at Kennecott Copper Corporation consisted of wet nodules introduced into fluid bed dryer/calciner (12",propane/air fired) and then subsequently reduced by synthesis gas in the reducer. Pelletisation of nodules utilising Buynker Coil/coal with/without bentonite (4) (5) produced pellets ranging from 1/2" to 3/8" size which has been conceptually suggested to be reduced in a travelling grate furnace. Several variants of the reduction/roast technology exists; for a version that was followed at Sumitomo

Metal Corporation (6). the reducing agent (coal) was mixed with the pellet and the mixture reduced. Alcohol/aldehyde containing reducing agent has also been described (7). Effect of carbonaceous reducing agents has been explicitly described by Wilder (8). International Nickel Company (9) has also reported selective reduction of nodules under different reducing atmospheres, although the Company emphasis had subsequently shifted to reduction roasting/smelting route. Recent Indian work has been also reported on reduction roasting subsequent to pelletisation (10). Haynes et.al (11) have reported an updated process flow sheet based on bench scale work at USBM on this route and the configuration suggested is substantially the same as reported by Kennecott Copper Corporation.

It may be noted that cobalt recoveries reported by various investigators have scarcely exceeded 70%.

The reduction roasting studies carried out by different research organisations/consortia have largely assumed that a 3 metal recovery route is preferred. Kennecott Copper Corporation reports that the process economics would have to be viable without the manganese recovery option (12). Kennecott Copper Corporation claimed to have finished nodules research in early 1974 (13). During 1973, a 1/2 ton per day pilot plant was successfully run for about 40 days and no process shutdown conditions were reported.

SOLUBILISATION OF REDUCED NODULES

The reduced nodules are solubilised through ammoniacal medium leach. Different leaching media have been used. Typical leach solution composition for an ammoniacal-ammonium carbonate leach is (14) : Cu - 5.7 gpl, Ni - 6.2 gpl.Co - 0.2 gpl, NH^3 - 90.0 gpl and Co_2 - 55.0 gpl. It is to be noted that such compositions would result only when high recycle solution loads are used typical of processing of laterite leach liquors. Detailed solution compositions are scarcely reported: the impurity build up for high solution recirculation loads needs to be closely monitored.

FURTHER COMMENTS

Large scale test work has been reported by Kennecott Copper Corporation and equipment scale up considerations have received attention. It may be noted that out of the various consortia members, only Kennecott Copper has reported large scale work. Presently, no activities are reported by any of the different consortia members.

5.4.2 Reduction Roasting, Smelting, Solubilisation

REDUCTION ROASTING & SMELTING

Sridhar et al have reported (15) the work carried out by International Nickel Company wherein the nodules are dried, dehydrated and electively reduced at 1000° C at a total residence time of about 2 hours in a counter currently heated kiln using substoichiometrically fired fuel oil and then transferred to an electric furnace for smelting the pre-reduced nodules at 1400° C producing a fluid slag and molten alloy. Prior to smelting, pre-reduced nodules were blended with coal for additional reduction as well as maintaining reducing atmosphere during smelting. Alloys with 1.5% Mn were produced for optimising metal recoveries. Some impurities in the nodules were substantially reduced showing that it would be necessary to subject the alloy to further processing.

The further processing steps consisted of oxidation (for manganese removal), sulfidization and converting for elimination of iron. It was not feasible to remove iron completely for ensuring high recovery of cobalt. Typical matte and slag compositions attained were: 25% Cu, 40% Ni, 5% Co, 5% Fe, 20-25% S(matte) and 0.04% Ni, 0.08% Cu, 0.12% P, 2.3% Fe, 34.3% Mn (slag). The slag was further smelted at 1620° C for producing ferromanganese, although stockpiling of the slag is equally possible.

M/s Elkem have also reported (16) studies on an identical process route. However, these were more oriented towards production of the alloy and recovery of Fe-Si-Mn from the slag. Large scale tests are known to have been conducted for the smelting step.

M/s Societe Le Nickel, France (Presently Imetal) have reported (17) pre-reduction smelting studies producing an alloy of 47.3% Ni, 35.1% Cu, 10.2% Fe and 0.47% Mn using anthracite coal as the reductant. Contrary to other approaches, the alloy is directly solubilised.

US Steel as a part of a consortium have carried out smelting tests (18). The USBM have also conducted laboratory scale smelting tests (19), simulating reduction, smelting and alloy oxidation steps. Smelting tests conducted by Minemet Recherche, a subsidiary of Metal Europe have reportedly given excellent recoveries on four metals (45).

SOLUBILISATION

Information on solubilisation of matte from nodules are scantily available. Sridhar et. al (15) cites pressure digestion (110° C, 1.0MPa oxygen pressure, 120 gpl $H_2 SO_4$) which resulted in 99% dissolution of Cu, Ni, Co and Fe. A solution containing 40 gpl Ni, 24 gpl Cu and 5 gpl Co resulted for further treatment (impurity removal, metal recovery). Dissolution of the alloy during aqueous chloride leaching has been described by Societe Le Nickel (17) producing a solution containing large quantities or iron.

Although large scale work on matte leaching has scarcely been reported, it is interesting to note that virtually an identical material is being commercially leached by the Sheritt sulfuric acid pressure leaching process (20, 21, 22) which involves two stage leaching for maximising Cu and Ni recoveries.

FURTHER COMMENTS

The reduction roast smelting route uses conventional equipments the like of which are available in commercial scale at the desired scale of operation. No major equipment scale up considerations are likely to be limiting towards commercialisation of a nodule process. No activities are reported at present on this route.

5.4.3 Segregation Roasting, Solubilisation

SEGREGATION ROASTING

Segregation roasting has been studied by Hoover (23) using $CaCl_2$ and batch retention time of 2 hours at different roasting temperatures. Bell (24) and Sridhar (25) used sulfur/sulfur bearing reagents alongwith a reducing agent at around 1100° C. Sridhar (25) reports a concentrate composition of 15-30 % Cu, Ni and Co. Grigoryeva et.al (26) used coke, $CaCl_2$ and NaCl mixture at 900° C and reported recoveries between 80 - 90 % for Cu, Ni and Co and a concentrated alloy phase. A modified process (27) involving recycling of magnetic separation middlings yielded a concentrate containing as high as 35% Ni, 2% Cu and 3% Co with overall metal recoveries exceeding 80%.

Equipment development and lowering of process energy requirements are constraints to be overcome during the developmental phase. Pilot plant studies have been reported for segregation roasting of laterite ores (28) and scale up considerations have featured.

SOLUBILISATION

No work has been reported on further solubilisation of the nodules concentrate; presumably this would involve a pressure leaching step similar to the treatment of metal concentrate from smelting.

5.4.4 Sulphation Roasting, Solubilisation

SULPHATION ROASTING

Messers Deep Sea Ventures which has an earlier operating agreement with OMA have reported results on sulphalisation roasting utilising iron sulphide (29). Roasting in the presence of H_2SO_4 and a reductant has been described in a patent assigned to UOP (30). Sulphatising roasting for nodules has also been described by Brooks et.al (31) in which batch fluidized bed roasting was conducted using a mixture of 10 - 20% SO_2 and air. Water soluble sulphates for Co and Mn exceeded 90% whereas for Ni and Cu, a maximum of 77% sulfation was reported. Sulfation temperatures were between 400° C to 625° C with variable holding times.

Messrs Deep Sea Ventures have also reported results (32) on SO_2 roasting, preferably in a fluid bed reactor under ambient conditions using pure SO_2 gas and subsequently carrying out differential solubilisation of the sulphated nodules.

SOLUBILISATION

Solubilisation of sulphated metal values have been reported (31) either through use of an acidic aqueous medium pH 2 in single stage or in two stages using aqueous leach at pH 5 and SO_2/

air leach of the leach residue. The objective of the later approach is to solubilise the manganese preferentially during first state of leach. Detailed descriptions of other solubilisation procedures scantily reported.

5.4.5 Chloridisation Roasting, Solubilisation

A typical scheme studied by Messrs Deep Sea Ventures using either HCl or Cl_2 vapours in the presence of carbonaceous material has been described in a patent (33). When chlorine vapours are utilised, the nodules are crushed, blended with carbonaceous material, pelletized and chlorinated in a suitable reactor. Overhead vapours are condensed and mixed with leach solution obtained by further leaching of the residue. Leaching may be conducted by using aqueous HCl having a pH of around 2. A typical pregnant liquor composition (in gpl) reported is Mn - 68, Cu - 405, Ni - 96, Co - 0.565 Bench scale studies conducted at USBM (19) have also reported results obtained by using HCl gas as the chlorinating agent followed by dilute HCl leach.

5.5 HYDROMETALLURGICAL PROCESSES

The hydrometallurgical process options include direct leaching of nodules involving ammonia, chloride or sulphate media. The ammoniacal system consists of processes such as "Cuprion" (Kennecott Copper Corporation) and ammonium sulphur-di-oxide leach. The chloride systems involve direct leaching in hydrochloric acid medium with subsequent variations in the downstream processing of chloride solutions. Sulphate medium investigations include high temperature - high pressure leaching or moderate pressure conditions of acid leaching. Another variant uses of SO_2 as an aqueous phase reductant in the acidic medium. Depending on particular process and its conditions, manganese may be recovered in solution or left back in the failings. Descriptions of various processes are given below.

5.5.1 Acid Leaching

Han et.al (34) and Ulrich et.al (35) have examined acid pressure leaching of nodules. With oxygen partial pressure of 100 psi (total pressure 300 psig) and initial pH of 1.63, reaction time of 60 minutes, substantial nickel and copper recoveries were obtained by Han (34) and still higher recoveries by Ulrich (35) at different leaching conditions. Cobalt recoveries were, however, moderate (35). The Bureau of Mines (19) have published results at higher pressure of leaching (35 atm) at 245° C claiming ≃ 90% recovery of Ni, Cu and Co. With a view to minimise scale formation effects at higher temperatures of leach, Subramanium et.al (36) have studied a two stage acid leaching procedure involving first stage leaching at temperatures of 100° C.

Messers Dusiberger Kupperhutee have reported that 3 hour of dissolution at 200° C and acid concentration of 90 gpl resulted in approximately 90% dissolution of Ni and Cu and 77% dissolution of Co. USBM report (19), however, suggests that cobalt recoveries may be higher when higher temperatures of dissolution and increased residence time are considered, akin go the Moa Bay conditions of leaching laterites. It is not clear from the published data at what temperatures the nodules commenced reacting with the acid : substantial dissolution may also occur at lower temperatures during the start up period of the autoclave if the nodules are exposed to the reactant during this period (38).

Messers OMINCO during 1973 contracted the Colorado School of Mines for undertaking process development on H_2SO_4 based leaching (39). Pilot scale testing was also undertaken but the results of the tests are not known. Acid consumptions for various studies ranged from 3 Kg/Kg to 5 Kg/Kg of nodules, except for the work of Han et.al (34) snowing that high oxygen pressures are required to minimize acid consumption. Work carried out by CEA, France (40) has been reported in a patent in which the nodules are attacked by a sulfur-di-oxide-sulphuric acid mixture. Khallafalla et.al (41) have carried out nodules dissolution in acidic sulphur-di-oxide solution and it was shown that reductive manganese dissolution could be effectively achieved. Messers CEA, France have operated, other than the pilot scale work carried at Coloraqdo School of Mines, a pilot plant in the early 1980s based on reductive leaching in H_2SO_4 medium at a capacity of 5 Kg/hr. of nodules feed based on pressure leaching at moderate temperatures. The ground nodules is partly attacked with a sulphur bearing gas to form Mn ions for catalysing recovery of cobalt. The rest is preleached in counter current leaching unit. The two parts are combined and leached with sulphuric acid at 180° C for 2 hours.

5.5.2 Chloride Leaching

Messers Deep Sea Ventures have concentrated their efforts on direct leaching of manganese nodules in hydrochloric acid (42, 43). The nodules are ground to - 500 m and then contacted counter currently with 11 M HCl at 100° C in a five stage leaching system. Approximately half of the hydrochloric acid is oxidized to chlorine which has to be sold or reconverted to HCl by reaction with H_2. Messers MHO (Metallurgie Hoboken-overpel) of Belgium (44) have suggested that chlorine from the leaching reactors is passed to the end of the process for oxidation of manganous chloride solution with continuous addition of magnesium oxide. Subsequently, $SwCl_2$ is subjected to pyrohydrolysis for recycle of chlorine.

The hydrochloric acid solubilisation process has been tested in a pilot plant of 1 TDP capacity as early as 1968 by Deep Sea Ventures (DSV). The choice of HCl process locked DSV in manganese recovery for recovery of the chloride ion. Further scale up to 40 tpd was considered, but the idea was abandoned because of the high capital costs (46). There were plans to test the MHO process in a pilot plant at Belgium, but this was not eventually conducted. In any case, confidence level in scale up of the process seemed to be high.

5.5.3 Ammoniacal Leaching

The Kennecott Copper Corporation's "Cuprion Process" is perhaps the best studied process in this group (47). The process has been tested on a continuous scale involving cage mill, hydrocyclone, co-current leaching tanks, clarifier and counter current decantation units. Basic metal carbonate recycle has been preferred for monitoring the desired level of cuprous ions in the reactor (48). Process modelling of the leaching step has been undertaken (49). The Department of Ocean Development, India has sponsored research on an ammoniacal-sulfur-di-oxide leach process at Regional Research Laboratory, Bhubaneswar (50) and a pilot plant of 250 Kg/day capacity for testing the process is soon to be commissioned. Reaction mechanisms pertaining to an identical system of leaching have been studied by Okuwaki et.at (51).

5.6 SOLUTION TREATMENT

The pregnant metal bearing solution through the various processing options may be treated through different alternatives. These include ion-exchange, solvent extraction and precipitation schemes used in different combinations. These schemes differ as per the initial solution composition. Various possibilities have been examined for the ammoniacal, chloride and sulphate bearing solutions and are discussed below.

5.6.1 Ammoniacal Solutions

A typical solution composition (in gpl) examined by Kennecott Copper Corporation is (14):Cu - 5.7, Ni - 6.2, Co - 0.2, NH_3 - 90 and Co_2 - 55.0. At the time of process development, LIX 64 N, being marketed by General Mills was used as the preferred solvent. The process consisted of Cu-Ni coextraction, ammonia scrubbing, nickel stripping and copper stripping.

40% LIX 64N was used and extraction and stripping steps were carried out in mixer settlers at a temperature of 40° C. Concentration differentials of 25 gpl and 10 gpl were maintained for the nickel and copper stripping stages. The development and optimisation of the Kennecott flowsheet was aided by the use of a computer model developed (52). Although considerable effort was spent for optimising the extraction flowsheets, the company has completely given up efforts in this direction since 1977/1978. In the meantime, several new solvents have been introduced in the market by Henkel Corporation (earlier General Mills) and it would be necessary to look into the process parameters afresh utilising the newer generation of solvents. Also, Kennecott Cotter Corporation have not explicitly mentioned the cobalt recovery process. However, one patent (53) describes the use of 2.5 HCl solution for selective stripping of cobalt from the solvent. Subsequent patents (54) have examined cobalt stripping by mixtures of concentrated sulphuric acid with glacial acetic acid, methanol or other lower alcohols. USBM (11, 55) have suggested another variant of the Kennecott process in which the LIX raffinate was treated with ammonium hydrosulfide for precipitation of cobalt alongwith residual Cu, Ni and Zn. The sulfide mixture was pressure leached with air for preferentially dissolving Ni and

Co, leaving the copper and zinc sulphides in the residue. After filtering off the residue, hydrogen sulfide was used to 'polish' off residual Zn and Cu impurities and the purified solution was hydrogen reduced to produce nickel powder. The cobalt sulfate solution was purified by the cobaltic pentammine process and about 90% of the cobalt was recovered in the refining process.

The solutions treated in USBM and Kennecott process did not contain manganese. Brooks and Martin (56) have given a scheme or precipitation of manganese from manganese bearing nodule solution ($\simeq$32 gpl) followed by selective copper, iron and mixed nickel - cobalt carbonate precipitation. However, sufficient details on preferred treatment parameters are not available.

A French patent (57) has explored a different route involving precipitation of a metallic concentrate from the ammoniacal leach solution by driving off NH_3, dissolution of the concentrate in hydrochloric acid producing a solution of high metallic tenors (Nickel, 100-120 gpl, Cu, 80-110 gpl, Co 14-21 gpl). This is contacted with TBP and Solvesso (removal of Fe, Zn, Cd, etc.), Tri-iso-octyl-ammine and Alamine 336, Hostarex A324 for a copper-cobalt separation step and electrowinning of nickel from purified $NiCl_2$ solution. The scheme proposed has been covered in sufficient details.

5.6.2 Sulfuric Acid Leach Solution

RELATIVELY DILUTE SOLUTIONS

A typical leach solution composition (58 a) obtained by nodules leach is: Cu - 3.6, Ni - 4.3, Cu - 0.6, Mn - 4.5, Fe - 0.3, SO^4 - 2 - 20.0 (in gpl), pH - 3.5. Such solutions could be treated through different levels of NH_3 additions for selective copper extraction and cobalt-nickel co-extraction (14). When the leach solutions contain relatively high levels of Mn, after copper is extracted (say, by LIX 64N), an ion-exchange step(LKewatit TP 207) removes nickel and cobalt (58 b). Mixed nickel - cobalt chloride solution is obtained by a 5% HCl strip which then is processed for nickel and cobalt separation through differential precipitation. Alternatively, cobalt-nickel separation may be carried out through solvent extraction (59). The ion exchange step used separates the manganese and further concentrates the metal tenors. A French study (40) have suggested a different scheme of treatment of such solutions in which copper is first extracted by a LIX reagent and Fe/Al/Cr is separated from the raffinate by precipitation using CaO. The purified solution is then contacted with 20% D2EHPA - 5% TBP - 75% Solvesso combination (D2EHPA was put in Na form) and the impurities extracted were stripped in different sequences. Cobalt was extracted by a mixture of oxime and carboxylic acid (say LIX 63 and 0.1M versatic acid), nickel was then extracted only by an oxime. The raffinate was treated at pH 8.5 by a basic reagent (MgO) for precipitating $MgSO_4$ and recycling SO_2 by roasting of the $MgSO_4$. Detailed results on any of the above schemes are not available to permit evaluation of the process.

CONCENTRATED METAL SOLUTIONS

Sulfuric acid solutions of concentrated metal tenors would result when precipitated metal sulfide products obtained during various process options are subjected to acid leaching under pressure. Data on solvent extraction separation applied to such acidic concentrated leach liquor solutions are rare. However, procedures developed by Sheritt for mixed nickel-cobalt sulphides (60) may be applied to concentrated leach solution derived from acid pressure leaching of mixed sulphides from nodules. Again, information on actual systems is scanty.

5.6.3 Chloride Leach Solutions

RELATIVELY DILUTE SOLUTIONS

Bulk of the work reported in literature has been carried out by Messers Deep Sea Ventures (51, 62, 63). The basic steps consist of selective extraction of iron with a secondary ammine, selective extraction of copper with LIX 64N, nickel cobalt co-extraction with Kelex 100, stripping of nickel with weakly acidic nickel electrolyte, stripping of cobalt with strong HCl. A modified treatment procedure suggested by Metallurgie-Hoboken-Overpelt (44) removes Fe,Zn,Mo and V with TBP and subsequently re-extracts Mo and V from the strip solution using LIX 63. The other metals (Cu,Ni, Co) are separated as sulphides for further treatment.

CONCENTRATED METAL SOLUTIONS

Treatment of concentrated metal solutions arising out of chloride leaching of alloy/precipitate in various process routes is exemplified by various commercial applications such as Falconbridge process/SLN process. A French patent assigned to CEA (57) also gives a detailed description of the solvent extraction treatment procedure adopted for precipitates dissolved in hydrochloric acid, as described under Section 6.1. During pilot plant trials conducted at CEA pilot plant (45), mixed sulphides precipitated from sulphuric acid solution were attacked by chlorine, the sulfur recovered and the metal chloride subjected to solvent extraction separation as outlined under Section 6.1. Chloride bearing solutions would also result when matte generated during smelting studies (45) is dissolved by controlled oxidation with chlorine. The copper rich residue may be dissolved in cupric chloride and subjected to oxidative solvent extraction. The nickel-cobalt-iron solution is subjected to solvent extraction separation procedure as outlined above.

Problems arising out of materials of construction for the extraction battery have been largely resolved as exemplified by various successful commercial applications.

5.7 TAILINGS CHARACTERISTICS AND PROCESSING

5.7.1 Tailing Characterisation

The various nodules processes operate different kind of tailings. For a 3-metal recovery route, the tailings are to be dumped and subsequently reprocessed at a future date for manganese recovery.

Processing and characterisation of nodule tailings and slags for proposed first generation processes of USBM have been extensively investigated (55, 64). The tailings were generated through bench scale testing and pilot plant tailings were available for characterisation only for one process (Cuprion). The results of leachate testing using the Environmental Protection Agency extraction procedure (EP), toxicity test, the ASTM shake extraction test, the EPA-US Army Corporation of Engineers Sea Water elutriant test showed very low to negligible leaching of metals from the tailings and slags. The reports also include physical property testing, mineralogical analyses, chemical analyses. The key findings of this report are that both pilot plant and laboratory generated tailings could be classified as non-hazardous wastes.

5.7.2 Processing of Tailings

Reports on further processing of the tailings for manganese recovery are scarce. A patent granted to INCO (65) indicates that the ammonium carbonate leach tailings could be further leached with sulfur-di-oxide. Recovery of manganese oxide from the leached solution has been indicated through evaporation/crystallisation of the solution. However, Cuprion process tailings treatment is cited (66 a) to lead to low manganese recovery. Here the manganese is recovered by a simple flotation technique of (66 b). The flotation concentrate would presumably be thickened and filtered to produce a relatively pure manganese carbonate cake which could be calcined and smelted.

The manganese sulphate containing residue from sulphuric acid leaching has been dried, pelletized with coal addition and ignited in a rotary furnace (45). The pellets were then smelted in an electric furnace with anthracite where phosphorous was eliminated. Subsequently, silicc-manganese was produced by smelting further the alloy in a second electric furnace producing 81% Mn, 14% Si, 2.5% Fe and less than 2% C. There are indications that the recovery of manganese via this process route is a difficult proposition and the French Consortia efforts have been redirected towards recovery of manganese from slag.

5.7.3 Recovery of Manganese from Slags

Messers Elkem (16) have conducted large scale studies on recovery of silico-manganese from nodule smelting slags. Laboratory scale smelting trials have been reported by Haynes (19) and Sridhar (15) for production of ferro-manganese. Ferro-manganese slag containing about 42% manganese has been smelted with silicieous flux to yield silico-manganese (45).

5.8 COMMENTS ON STATUS OF PROCESSES, GAP AREAS

5.8.1 Process Status and Alternatives

The above paragraphs have summarised the activities undertaken by different laboratories or Consortia members earlier/at present. Active research on nodules processing is being pursued presently only by some Indian Laboratories and Japanese Firms/ Laboratories.

Earlier work has led to piloting of certain key steps in the processing operation as has been brought out in the text. Pilot operations have been run for limited time periods and there are no references to suggest that there have been sustained and long duration operation of these pilot plants. Only the processes studied by Kennecott Copper Corporation (KCC) and Deep Sea Ventures (DSV) have been tested till the end phase alongwith aspects such as reagent recycle (Table 5.2). No pilot plants have operated during 1980 other than the CEA plant.

It is interesting to note that the various updated flowsheets presented by USBM(11) reflect preferred versions of five processes described therein (Gas reduction/ammoniacal leach, Cuprion, high temperature sulfuric acid leach reduction/hydrochloric acid leach, smelting/sulfuric acid leach) and these need not represent the most optimised version of the various alternatives. For example, subsequent to gas reduction and ammoniacal leaching, the solution may be stripped of ammonia and the concentrates leached in hydrochloric acid medium. Alternatives also exist with regard to mixed sulfide precipitation, pressure leaching and metal separation. Only the front end operations resemble 'Carbon Process' for laterite ore processing. Whereas the sulfuric acid pressure leach operation may be similar to Moa Bay laterite leach operations, variants already exist with regard to lower temperature of leaching under pressure and dissolution of manganese in leach solution (45). Major variations are possible regarding the processing of sulfate solutions involving use of both ion exchange and solvent extraction operations. Smelting may produce an alloy which could be leached in chloride medium similar to commercial SLN operations instead of a matte being produced which is then pressure leached. Flowsheet options of solution treatment after matte leaching include practices being followed by Outokompu Oy, Amax Corporation, Falconbridge, Sumitomo and Nippon Mining Corporations.

In essence, the updated flowsheets presented by USBM is an excellent example for undertaking order of magnitude cost estimates for a preferred process embodiment and starting point of further research/updating efforts on nodules processing. It is interesting to note that some Japanese Companies have recently undertaken further activities on nodules processing based on the starting points presented by the USBM updated process flowsheets (67).

5.8.2 New Reagents for Metal Separation

Various patent literature information makes it abundantly clear that research organisations have been alive to the problem of impurity distributions in solutions and have suggested ways and means to treat the impure nodules leach solutions utilising reagents available then.

A large number of new reagents have been released in the market subsequent to the early 1980s. For example, Henkel Corporation have started marketing LIX 860, LIX 984, LIX 622, LIX 870 ON etc. and many of these reagents are being used commercially in copper plants. Similarly, a number of other reagents (Acorga M5397, M5640, PT 5050, PT 5100, etc). have been marketed and it is indeed necessary to evaluate various reagents for optimising a particular separation process. An example of such an effort is found in work of Nilsen et. al (66) for nickel and copper separation from laterite bearing ammonia liquor. While production of chelating extractants has been the most exciting development in the application of solvent extraction in hydrometallurgy, all the major developments so far had copper recovery as the incentive. With regard to further reagent development, the collective view of reagent manufacturers at a panel discussion at ISEC'80, Liege, in September, 1980 was that new reagents would only be developed if the economics looked favourable. Based on the above factors, and also because of the fact that there has been a recent shift in emphasis towards reducing capital costs (staging requirements) of solvent extraction circuits and compromising on higher operating costs, it is particularly necessary to review whether a chosen solution treatment route through solvent extraction based on some older version of reagent is optimal and worth considering for further scale up for nickel-cobalt-copper separation. It is of some significance to note the various recent developments in reagents for cobalt-nickel separation in sulphate solutions. The Nippon Mining Company uses alkyl phosphoric acid (M2EHPA marketed as PO38A), the Sumitomo Metal Company Versatic-10 and Trialkyl ammine and the Mathey-Rustenburg Refiners phophoric acid (D2EHPA) for achieving cobalt-nickel separation from purified leach liquors. The phosphinic acids may have even larger selectivity of cobalt-nickel separation (Cyanex reagents). The possibilities of using ion-exchange resins such as XFS-4195 (69) for such separations are also under study for synthetic nickel-cobalt bearing solutions containing small quantities of nickel. Keeping in view such commercial scale and other developments, it may be necessary to redesign a nodules solution treatment process.

5.8.3 Equipment & Scale-Up

The front end of various processes have been tested at pilot scale as noted above wherein specific equipment concepts related to the process have been subjected to some sort of scrutiny. However, such pilot plants have not been run for sufficiently long periods to enable testing of equipment performances (for example, if a sulphuric acid pressure leach for nodules is to be tested, the problems of autoclave scaling, shutdown, etc. need attention). Also prototypes of all industrial scale continuous equipments have not been tested in the various pilot campaigns. This may be because of confidence level in equipment performances of the industrial scale version vis-a-vis the scaled down version used during piloting. The equipments to be used for a commercial nodules treatment plant (say 3.0 million tonnes of dry nodules per annum) would perhaps have the maximum capacities conceivable from an engineering point of view because of the large flow rates of process streams. Scale up practices to such large capacitates have to be carefully worked out. Some critical equipments alongwith largest capacities installed for treating raw materials such as laterite ores are described below.

MULTIPLE HEARTH ROASTERS

Largest capacity is around 700 TPD, containing 17 hearths, installed at Greenvale, Australia.

SHAFT FURNACES

Low shaft furnaces of rectangular cross section have been used (10.37m X 5.5m X 8.38m) at Dominican a treating around 600 TPD.

AUTOCLAVE

Single horizontal autoclave volumes are 130 M^3 (Lurgi) and around the same for vertical autoclaves used for the Moa Bay Plant, Cuba.

ELECTRIC FURNACES

Large capacity furnaces (50,000 KVA) capable of treating 2000 TPD of input have been used.

SOLVENT EXTRACTION

Largest single stream throughputs in copper hydrometallurgy plants are about 800 M^3/Hr of aqueous feed.

TAILINGS STRIPPER/RAFFINATE STRIPPER

Diameters of bubble cap columns range between 2.5 - 3.5 metres with a height of about 20 M.

Table 5.3 shows for a proposed capacity of 150,000 TPD of nodules, largest sizes of commercially available equipments would be used. Further scale up of various equipments to an envisaged capacity of 3.0 Million dry tonnes per annum would require considerable efforts as is apparent from scale up strategies adopted for certain equipments (Table 5.4) during processing of laterite ores.

5.9. PROCESS CHOICE FOR THE FUTURE

In view of the various uncertainties in the development of a viable process route and the stage of piloting with regard to different processes, it is extremely difficult to justify one process route for eventual commercialisation. Besides techno-economic viability, the choice of a process route would critically depend on whether manganese is to be recovered.

Various groups have worked out techno-economics for a 3 M TPA nodules commercial production based on the limited information available. These include the reports by Hillman (70), Nyhart et. al (71), a report prepared by A.D. Little, Inc. 1984 for NOAA, US Department of Commerce and Ingham for Australian Bureau of Mineral Resources. These reports are largely based on

Cuprion process with a downstream solvent extraction route for metal recovery, reduction roast ammoniacal leach solvent extraction route and reduction roast-smelting solvent extraction route. These flowsheets with adequate material and energy balances are described by USBM (11) and as brought out previously, there are ample number of alternatives for the downstream section. These studies indicate by and large that future metal prices would have an important effect on the overall economics. For example, rates of return have been computed over ranges of metal prices such as given below:

Cobalt	14,000	-	37,000	\$/ton
Copper	1,300	-	2,500	\$/ton
Ferro-manganese	250	-	570	\$/ton
Nickel	5,700	-	9,300	\$/ton

Ingham has concluded that the nickel prices in particular need to shoot up towards considerably higher values for such a high risk venture to succeed. Also, it is extremely important to maximise recoveries for various metals, especially nickel. It is doubtful whether the present state of art for nodules processing allow a maximum limit to be present for commercial scale processes based on extrapolation of reliable pilot scale data. As such, it is difficult and inappropriate to make a process choice based on preliminary techno-economic indications.

Process comparisons have also been made from the point of view of energy requirements for various processes producing metals from sea nodules (72). Energy consumptions have been calculated for mining and transportation of nodules, processing, waste treatment and disposal and transportation of final products. For various 3-metal recovery route (Cuprion, H_2SO_4 leach), annual energy consumption estimated were virtually identical (30.3 X 10^{12} BTU). However, a 3-metal route based on smelting had a substantially higher energy consumption as compared to other 3-metal routes. Different 4-metal recovery routes (Hydrochlorination, smelting) also showed virtually same energy consumptions (105 X 10^{12} BTU). The various data provided show directions of future work to be conducted for possible energy savings rather than inferences on choice of process.

5.10 TREATMENT OF MANGANESE CRUSTS

It is appropriate to mention as a part of this report that currently various research organisations are engaged in process development effort for this material since the extraction technology is expected to be identical to the sea nodule extraction methods. The mineralogy of the pacific Sea crusts is very similar to the pacific nodules (73). Even with a good selective mining system, benefication will be required to separate crust minerals from the substrate (73). Preliminary flotation tests have recovered around 92 per cent of the cobalt in a crust mineral concentrate. The average composition of these crusts is 1.0% Co, 0.5% Ni and 15-25% Mn.

5.11 CONCLUSIONS

It is suggested that efforts be continued in different countries for continuation of work on process development at least on a scale which is commensurate with updating of various routes developed at the laboratory/bench scale keeping in view the developments achieved on similar land based operations. In view of the global resource crunch affecting nodules research, it is important to draw the land based metal producers for nickel and cobalt into the arena of nodules research; in many instances, modifications of existing land based commercial operations would lead to faster process development for various gap areas cited in this paper. However, it would be necessary to step up international cooperative efforts since purely national initiatives would mean costly development programmes; also, several portions of the technology to be developed can be intelligently linked to a diverse set of land based operations, the technology ownership for which rests with different organisations. It is necessary to recall that comprehensive technological developments have earlier resulted through cooperation of internationally composed industrial groups through various consortia. If the nodule mining companies envisage to earn profits in the near future depending on further developments in metal markets, it is expected that reactivation of some of the industrial groups will occur (74) and there is reason to believe that such groups may be interested in joining a possible collaborative project. Thus, substantial organisational changes could well flow in the course of the next ten years where national initiatives may largely be replaced by international cooperation. In the light of such envisaged changes, government support for development oriented programmes for nodules process research would go a long way in attaining the broad objectives of the overall programme.

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TABLE 5.1

Various Nodules Consortia

Consortia	Comprises of
KENNECOTT CONSORTIUM (KCON)	Kennecott Copper Corporation: 40 %, a US Corporation owned by Sohio/BP, USA. BP Petroleum Development Limited: 12 % (United Kingdom, 1977). RTZ (Rio Tinto Zinc): 12 % Deep Sea Mining Enterprises ltd. (U.K.). Consolidated Gold Fields: 12%, P.L.C. (United Kingdom). Mitsubishi Corporation : 12% (Japan). Noranda Exploration Inc.: 12% (a US Corporation owned by Noranda Mines Ltd., Canada).
OCEAN MINING ASSOCIATES (OMA)	Essex Minerals Company: 25% (USX subsidiary, USA). Sun Ocean Ventures Inc.: 25% (Sun Co. subsidiary, USA). Union Seas Inc.: 25% (a US Corporation owned by Union Miniere, Belgium). Samin Ocean Inc.: 25% (a US Corporation owned by ENI, Italy)
OCEAN MANAGEMENT INC. (OMI)	AMR:25.02% (Arbeitsgemeinschaft Meerestechnisch Gewinnbare Rohstoff, RFA) Metallgesellschaft A.G. Preussag AG Salzgitter AG. Domco: 25.02% (Deep Ocean Mining Col. LTD: 19, Japanese companies).

Consortia	Comprises of
OCEAN MINERALS COMPANY (OMCO)	Lockheed Missiles & Space Co., Inc.: 37.528% (Lockheed Corporation, USA). Lockheed Systems Co., Inc · 12.472% (Lockheed Corporation, USA). Cyprus Minerals Co.: 50% (Cyprus Mining Co., substituting AMOCO Ocean Minerals Company, USA).
DEPARTMENT OF OCEAN DEVELOPMENT (DOD)	Indian organisations working on the nodule program, coordinated by D.O.D.
INTEROCEAN METAL	Organisations from Cuba, Czechoslovakia, Poland, German Democractic Republic, Hungary, USSR and Viet Nam. Based in Shtetin (Szezecin), Poland.
AFERNOD, France	Ifremer: 53% (Institut Francais de Recherche poul'Expolitation de la Mer). CEA: 40% (Commissariat a L' Energie Atomique) Imetal : 4% Normed[1] : 3% (Chantiers du Nord et de la Mediterrance).
DEEP SEA RESOURCES DEVELOPMENT CO (DORD), Japan	MMAJ, Japan and 48 private companies. DORD registered its pioneer area on December 18, 1987 and has been continuing its prospecting activity in this area.
TECHNOLOGY RESEARCH ASSOCIATION OF MANGANESE NODULES MINING SYSTEM (TRAM), Japan	Metal Mining Agency of Japan and 19 private companies together with National Institute of Resources and Environment and AIST, Japan.
DEEP SEA MINERALS ASSOCIATION (DOMA), Japan	Existed from 1980 to 1982. NIRE took research activities from DOMA to develop refining processes from 1983 1986. Since 1989 MMAJ has taken over research work from NIRE

1) withdraw recently (1989)

TABLE 5.2

Status of Piloting Activitites

Company[1]	KCC	DSV	INCO	ELKEM	IFREMER
Pilot Capacity	1/2 TPD (Lexington) 350 kg/day	1 TPD (Virginia)	Unknown	Ten. scale	120 kg/day (Fontenay-aux-roses. CEA)
Whether all steps tested on continuous basis	Yes	Yes	No	No	Yes
Further scale up	No	Planned 40 TPD, did not Materialise	No	No	No
Technological difficulties in piloting	Nil	Nil, but costly operation indicated	-	-	Solvent extraction, subsequently rectified

1) Also Messrs OMINCO, subcontracted research to Colorado School of Mines, details unknown.

TABLE 5.3

Typical Equipment Sizes for a Plant Treating 150,000 TPD of Nodules

Scale up factors	Capacity	Largest commercial capacity	Scale up ratio
1. Reduction Furnace	500 TPD	700 TPD	1.4
2. Autoclave	130 m^3	130 m^3	1.0
3. Solvent Extraction/ Electowinning	75 m^3/hr	800.0 m^3/hr	10.0

Table 5.4

Typical Scle up Stages for Commercialisation

Equipment	Company	Remarks
Shaft Furance	Falconbridge nickel production	Pilot shaft furance 0.68m x 1.37 m x 8 m (1.5 T/hr product).
		Pilot shaft furance 1.37m x 1.37m x 8.2m (5.4 T/hr product)
		Commercial furance 1.32 x 5.49m x 8.38m (20 T/hr product).
Rotary Kiln	INCO	Pilot Kiln 1.5 m x 12.2m
	Guatemala Indonesia.	(≃ 1T/hr prod·ıct)
		Commercial kiln 5.5 m 5.5 m x 100 m (≃100T/hr product) 100T/hr product)
Multiple Hearth Roaster	Sherritt Gordon Mines	Pilot plant 0.9m, 6 hearth (≃ 4 TPD).
		Pilot plant 2.6 m, 12 hearth (≃ 100 TPD).
		Commercial (Surigas) 7.6m, 17 hearth (≃ 5 TPD).
Multiple Hearth Roaster	Freeport Minerals Company	Pilot 1.37m, 8 hearth (≃ 5 TPD).
		Commercial (Yabulu) 7.6m, 17 hearth (≃ 800 TPD).

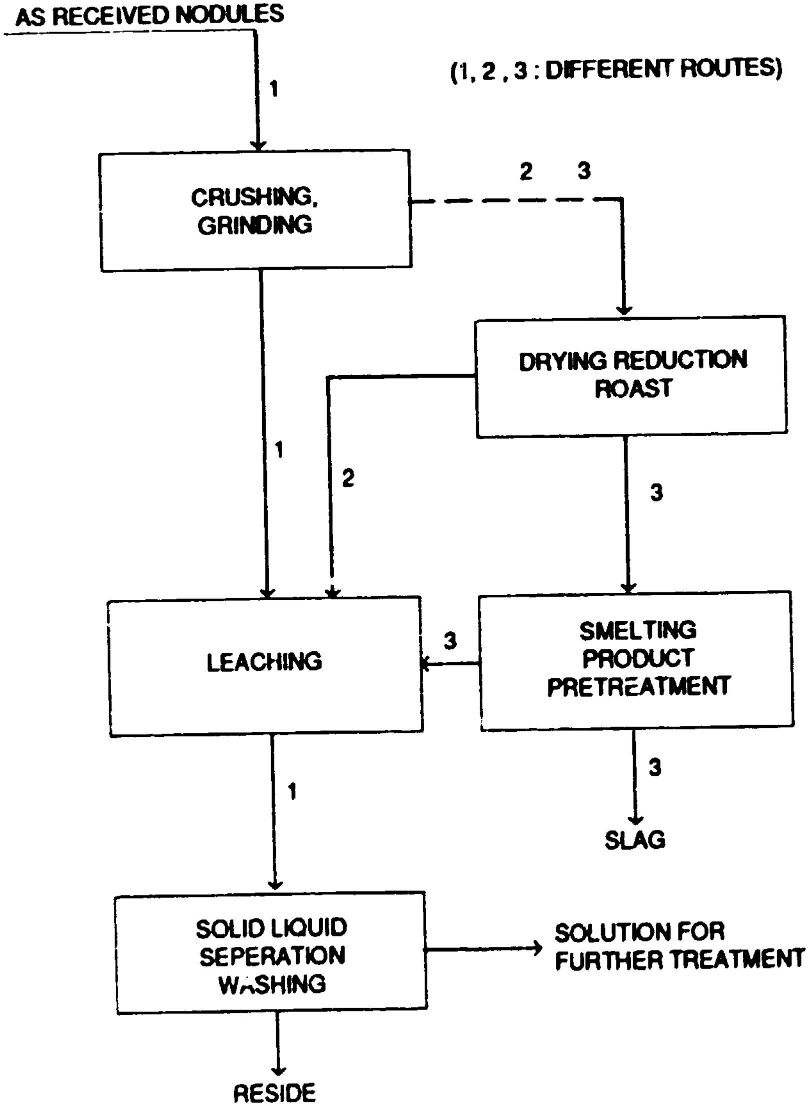

FIG. 5.1

Unit Operations for Solution for Pretreatment & Solubilisation

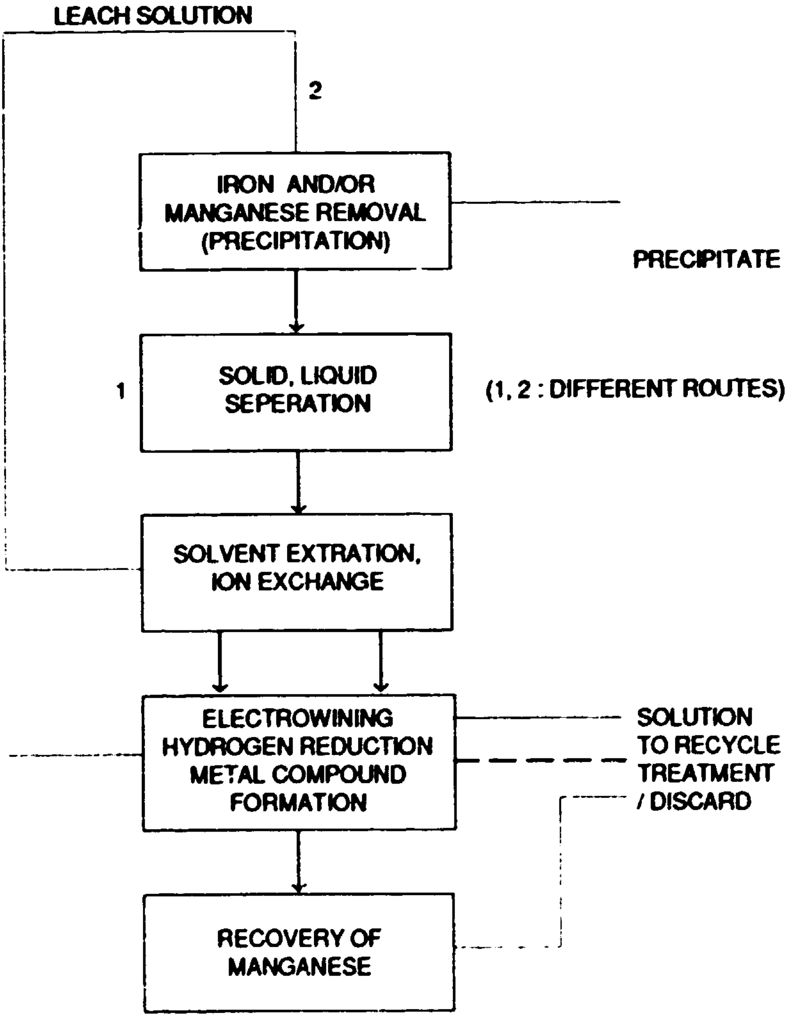

FIG. 5.2

Unit Operations for Solution Treatment

CHAPTER 6

INTERFACE WITH INDUSTRIES

6.1 INTRODUCTION

The previous chapters have outlined the state of technological development in the field of exploration, mining, processing and environmental aspects. Cardinal to meaningful development of new technologies in any area is the need to inter-twine the efforts of R&D institutions, design engineers and the industry within the overall guidance and control of the financing agencies, may it be Government or any other corporate body. A strong feed back mechanism has to be in place to effect corrective measures at different stages during the period when technology for commercial exploitation is being perfected. To ensure that the technology so perfected does not become obsolete because of breakthroughs taking place elsewhere, the basic research institutions which develop initially the technology, have to keep pace with the performance of the systems finally adopted by the industry and monitor on a continuous basis the cost effectiveness of existing technologies and level of performance.

Development of deep seabed mining technologies is also no exception to the above stated principle. It is easier to implement this principle in a technologically advanced environment where it is possible for one of the players to take a lead and to persuade the other players to join to make the end as a common endeavour.

6.2 TRENDS

Initially, the development of deep seabed mining technology took place purely as private initiative in USA, France and Germany, particularly when it was thought that exploitation of deep sea mineral resources was possible in the near time frame. Such organisations in these countries which took interest in the development of these technologies were not very strong commercial entities but were also endowed with very strong R&D Groups in almost all the disciplines which required to contribute to the development of the end technologies. However, when the deep seabed mineral resources receded into the distant possibility as far as commercial exploitation was concerned, these entities, which were generally in the private sector, withdrew from these activities after positioning themselves strategically; yet a substantial part of their findings were passed on to R&D institutions, including Universities, for safe custody of their results under some agreement so that the commercial interests of such entities which took the pioneering interest in the development of these technologies were taken care of.

Wherever substantial Government funding was available for carrying out this programme, e.g. in France and Japan, the development of these technologies have been further continued in a very systematic manner.

To illustrate the inter-relationship between the R&D institutions and the support that these institutions need from the industries and vice versa, it would be interesting to study the practice that has been adopted in Japan.

The Ministry of International Trade and Industry started the research and development projects of manganese nodules mining system in 1981 with a clear objective of developing the hydraulic mining system in which manganese nodules would be collected by a towed vehicle on the ocean floor and transported in a slurry of sea water and nodules through the lift system on to the mining ship.

To achieve the objectives of the project, the Agency of Industrial Science and Technology promoted a Technology Research Association of Manganese Nodules Mining System. This Association was also supported by New Energy and Industrial Technology Development Organisation(NEDO). This Association conducted the R&D programmes effectively by coordinating its members, which are 19 private companies and one agency. Thus, from the conceptual stage itself, the authorities responsible for planning the execution of the project visualised the multidisciplinary nature of the project even at R&D stage and therefore pooled the expertise from amongst the various national resources available within the country, ostensibly not only to avoid the need for duplicating the efforts but also to avail of the expertise and opportunities available.

At the apex, the national R&D programme is coordinated by two organisations, viz., the National Research Institute for pollution and Resources (NRIPR) and the Technology Association of Manganese Nodule Mining System(TRAM). The former is entrusted with the responsibility of performing the basic experimental work and theoretical analysis for the phenomenon of collecting and loading nodules and for determining the environmental effects of mining in the ocean. The latter performs the R&D of the actual Manganese Nodule Mining Pilot System and the pilot scale ocean test in the South Sea North Pacific Ocean.

The R&D stage was completed and the basic design of an integrated ocean mining test system was established at a cost of about 4,600 million yens in 1985.

It may be interesting to note that TRAM, which was the supervisory agency for developing a Manganese Nodule Mining Pilot System, consisted of 19 private companies and one agency. The constitution of TRAM provides that interested parties in the private sector are welcome to join TRAM and even foreign countries are welcome to do so and will be treated like any other Japanese private sector company. It is mandatory for these countries to become members of TRAM and they should assume responsibility for the activities of TRAM just like any other Japanese companies.

Once systematically the basic research was completed to the satisfaction of the peer group, since 1986 the detailed design of the mining test system has been developed and necessary machinery and equipment have been started to be manufactured. While developing the basic test system as above, the facilities that are available in the laboratory where basic design concept was initially thought of, are yet available to the TRAM which again ensures that duplication of efforts are avoided and the experts who were responsible for developing the basic design are still available while the test mining system is being perfected.

The Japanese have also started looking very recently into the processing aspects of nodules. Towards this end also, a somewhat similar strategy has been followed and the giant multinationals engaged in the nickel and cobalt are coordinating the efforts of the Japanese research workers in perfecting the ultimate process that they will choose. Development in France was also on similar lines.

In India, where the development of deep seabed mining system has been taken up very recently, a somewhat similar model to the Japanese model has been contemplated. The Department of Ocean Development, the agency identified by Government of India, as a nodal agency to carry out the programme for development of deep sea mineral resources, have drawn up a list of various subsystems that go into the development of deep seabed mining system i.e. survey and exploration, mining and processing. This list has been made available to the Indian industry to make an in house assessment to conclude as to what type of subsystems they are in a position to develop without further R&D efforts and at the same time to identify the subsystems which the Indian industry can develop on their own by infusing some efforts in R&D. Industry may also come to conclusion about some subsystems, which it thinks it may be capable of producing on its own, immediately or after some efforts but may decide not to produce, on commercial grounds. While the industry is carrying out the exercise on the above lines, a national level Committee involving National Scientific Laboratories having expertise in different disciplines has been constituted to pool in their efforts for refining the techniques in survey and exploration, processing and in the development of mining techniques. Interestingly the Chairman of the Committee and the Chairman of the Committee from industry, which would look into the capacity of the Indian Industry to produce various sub systems, is same so that a mechanism of coordination exists between the industry and the R&D institutions right from the beginning.

Though India does not have as dispersed an industrial base as the developed buyers and potentials abroad, yet some large industrial houses have expressed their readiness to take on the development of various equipments that may be needed at the initial stages of developing the mining system.

6.3. PROBLEMS AND POLICY PERSPECTIVES

In almost all the countries where efforts have been taken or are on to refine existing marine technologies other than the technologies required for exploitation of deep mineral resources, there has been a deep commitment of industry to the R&D and the R&D to industry. Such technologies have generally become self-paying and industry is capable of funding further in R&D.

The basic difficulty that is facing the development of technologies for exploitation of deep sea mineral resources, is lack of interest displayed by big companies because of uncertainty in immediate commercial viabilities of such projects, and the Governments in those countries where this programme was only very recently being started by them have also shown reluctance in infusing further resources at the scales required. Therefore, it becomes all the more imperative that some strategies are devised so that the efforts in developing these technologies become self-sustaining. One obvious strategy that could be is that the industry takes upon itself the task of using the intermediate results in offering their services to those countries where such technologies after some refinements can be utilised for developing the resources within their national jurisdictions, EEZs and continental shelfs. This would give the opportunity to the industry and also R&D institutions to test the performance of their efforts in actual field conditions while the revenue can keep coming for developing in-house technologies. This would also serve the purpose of the developing countries who otherwise are left unaided in exploiting resources which are otherwise available right at their door steps.

Because of shrinking resources and the increasing cost of research, there is a case not only for greater interaction between the industry and R&D institutions within national jurisdictions but also for international cooperation so that expertise gained by the various experts in similar disciplines can be pooled to get maximum return out of the investment that is being made internationally. This would necessarily require a greater opening up of the facilities by those who are already ahead in the race, on the consideration that initially those who joined this international corporate mechanism may ultimately contribute to make the end result more commercially viable. To illustrate this point further, it can be safely concluded that the user of a system like collector capable of operating in deep sea areas would not be many and perhaps it would be much easier for a commercial entity developed out of international cooperation to provide such system to the user at reasonable rates which would not only be beneficial to the users but would go a long way in making the commercial projects viable.