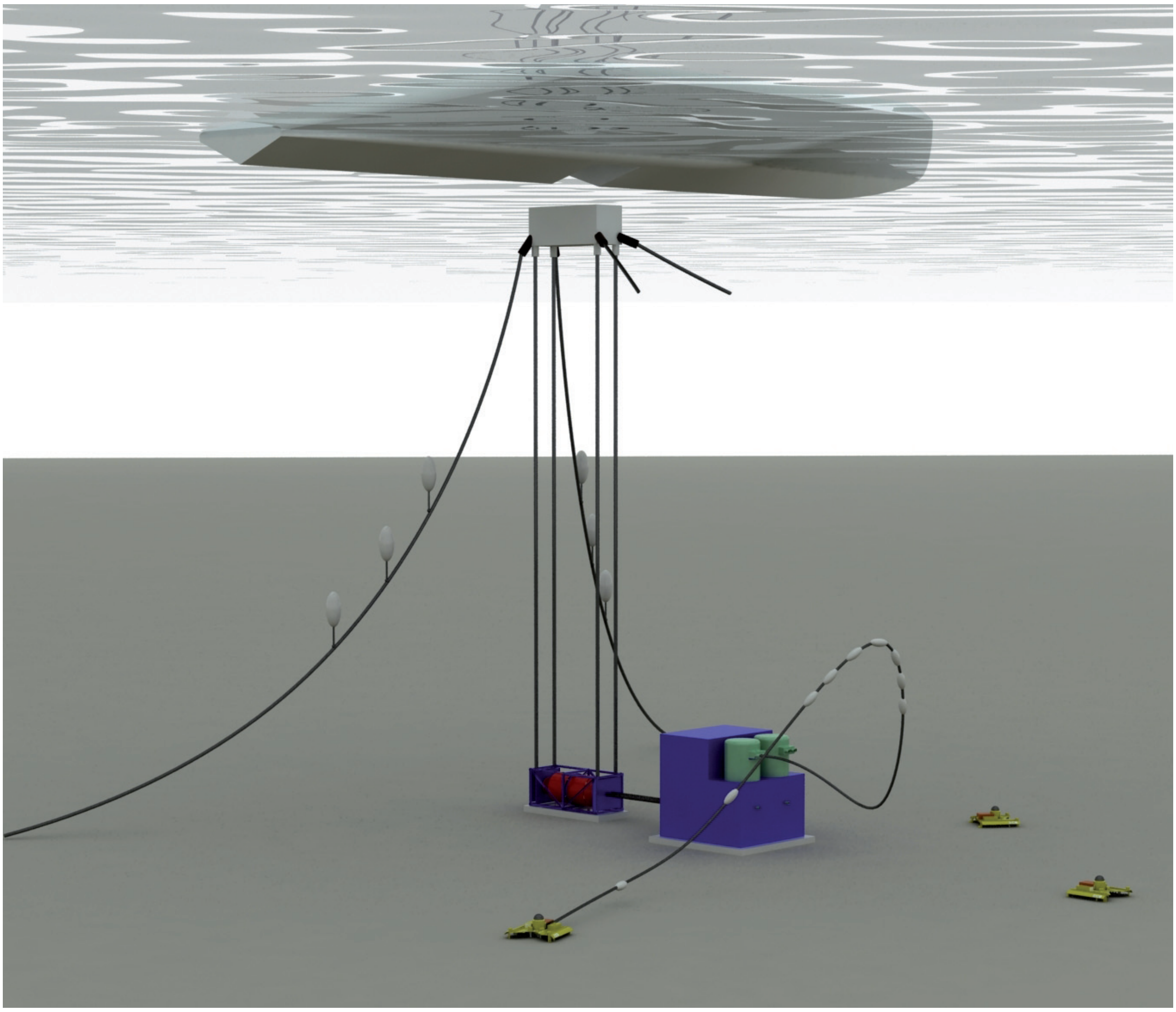
Seabed Exploitation

The LRET Collegium 2012 Series, Volume 5

Polymetallic nodule mining: Innovative concepts for commercialisation



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Lloyd's Register Educational Trust

UNIVERSITY OF Southampton

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- Research – adding value to society by funding research programmes which address fundamental challenges that affect us all."

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Warren Flentje Sang Eui Lee Anastasia Virnovskaia Shiping Wang Suraiya Zabeen

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Foreword

The Lloyd's Register Educational Trust (The LRET) in collaboration with the University of Southampton instituted a research collegium in Advanced Ship and Maritime Systems Design in Southampton between 16 July and 7 September 2012.

This year's collegium has focused on The LRET's research-led education agenda. Successful ship and maritime systems design depends on the collaborative application of a broad range of engineering competences as the drive for improved efficiency and environmental performance places greater demand on the design community. This aspect needs to be reflected in the education of naval architects, marine engineers and others who are the active contributors to the ship design processes.

The aim of the research collegium has been to provide an environment where young people in their formative post-graduate years can learn and work in a small, mixed discipline group drawn from the maritime community to develop their skills whilst completing a project in advanced maritime systems design. The project brief that initiates each project set challenging user requirements to encourage each team to develop an imaginative solution, using individual knowledge and experience, together with learning derived from teaching to form a common element of the early part of the programme.

The collegium format provided adequate time for the participants to enhance their knowledge through a structured programme of taught modules which focussed on the design process, advanced technologies, emerging technologies and novel marine solutions, regulatory and commercial issues, design challenges (such as environmental performance and climate change mitigation and adaptation) and engineering systems integration. Lecturers were drawn from academic research and industry communities to provide a mind-broadening opportunity for participants, whatever their original specialisation.

The subject of the 2012 collegium has been systems underpinning seabed exploitation. The 25 scholars attending the 2012 collegium were teamed into five groups. The project brief included: (a) quantification of the environmental challenge; (b) understanding of the geo-political legal-social context; (c) possible techniques for harvesting or recovering resources from the seabed; (d) one engineering system to achieve seabed exploitation; (e) economics and logistics challenges. While all the groups addressed the items (a) to (c), each team focused on just one engineering system in dealing with items (d) and (e). This volume presents the findings of one of the five groups.

R A Shenoi, P A Wilson, S S Bennett
Southampton
2 September 2012

Preface and acknowledgements

The seabed contains a wide variety of important resources, which are increasingly the target of exploitation. The LRET research collegium 2012 has focussed on future concepts for exploitation of seabed resources. Group E (the Group) has focused on polymetallic nodule mining.

Polymetallic nodules are a rich source of important metals. They have been the subject of many research projects over the last 40 years but excessive investment risk is preventing their commercial exploitation.

Group E of the LRET Research Collegium 2012 have proposed a number of technological and business strategy concepts to reduce investment risk in polymetallic nodule mining. This volume will introduce these concepts, discuss the preliminary validation performed, distil and describe the underlying principles and make recommendations based on our preliminary work.

The LRET research collegium 2012 took place at the University of Southampton in the period 14 July to 8 September 2012. This volume is one of the outputs produced by the Group during this Collegium.

The Collegium was funded by Lloyd's Register Educational Trust.

Group E would like to express sincere gratitude to the following individuals:

- Prof. Ajit Shenoi, Prof. Philip Wilson and Dr Sally Bennett for the skillfull guidance thoughout the Collegium.
- Ms Aparna Subaiah-Varma for her great organising skills and for always being there when we needed her help.
- Ms Mirjam Fürth for being friendly and helpful and for taking care of us on our trips.
- Mr Kwon Young-Gon for 3D imaging of our front cover.
- Our fellow-scholars for making this collegium such an enjoyable experience.
- Our family and friends for letting us spend these 8 wonderful weeks here in Southampton.

Guide to readers

This report is produced in three parts; Part 1 contains a review of the field and background information required for a full understanding of the marine mining industry. Part 2 is a review of polymetallic nodule mining and introduces the current major issues and challenges preventing commercialisation. Part 3 consists of a number of novel concepts proposed by Group E (the Group) to directly address these challenges.

The barriers to commercial seabed mining of polymetallic nodules are explored in the context of investment risk. Part 2 of this report introduces the risk landscape facing polymetallic nodule miners, Part 3 contains concepts designed to reduce this risk and Part 1 provides some background information to provide context for this risk. Consequently these parts can be read in isolation depending on the readers interest.

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List of abbreviations

ADCP	Acoustic Doppler Current Profiler
AFERNOD	Association Française Pour L'Etude Et La Recherche Des Nodules
BOD	Biological Oxygen Demand
CAD	Computer Aided Design
CAPM	Capital Asset Pricing Model
CCZ	Clarion Clipperton (Fracture) Zone
CJCE	Canadian Journal of Civil Engineering
COMRA	China Ocean Mineral Resources R&D Association
CTD	Conductivity, Temperature, and Depth
DORD	Deep Ocean Resources Development Co. Ltd.
EEZ	Economic Exclusive Zone
EMD	Electrolytic Manganese Dioxide
HAZID	Hazard Identification
IFREMER	Institut Française De Recherche Pour L'Exploitation De La Mer
INCO	International Nickel Company
IOM	Interoceanmetal Joint Organization
IRR	Internal Rate of Return
ISA	International Seabed Authority
ISOPE	International Society of Offshore and Polar Engineers
KCON	Kennecott Consortium
LRET	Lloyd's Register Educational Trust
MHO	Metallurgie Hoboken Overpelt
NML	National Metallurgical Laboratory
OMA	Ocean Mining Associates
OMCO	Ocean Minerals Company
OMI	Inter Ocean Metals
OTC	Offshore Technology Conference

PMN	Polymetallic Nodules
R&D	Research and Development
REE	Rare Earth Elements
ROV	Remote Operated Vehicle
RRL	Regional Research Laboratory
SMS	Seafloor Massive Sulphides
SONAR	Sound Navigation And Ranging
TOM	Tonga Offshore Mining
UNCLOS	United Nations Convention on the Law of the Sea

Executive summary

Seabed resources of value to the modern economy include oil and gas reserves, placer deposits including diamonds and gold, and minerals found in the form of Seafloor Massive Sulfides, Sediments, Crusts and Polymetallic (Manganese) Nodules.

A review of the published literature from previous research studies and field trials indicates that polymetallic nodules (PMN) are one of the most attractive marine mineral resources for commercial exploitation. Despite this the review clearly demonstrates a significant gap between the profitability of a PMN mining venture and that necessary to attract commercial investment. The level of investment risk for current polymetallic nodule mining warrants a return on investment (IRR) of 30-35%. The most optimistic projections for returns at current prices and using current technology are in the range 15-20%. Under these circumstances polymetallic nodule mining will not be commercially viable until risks are reduced or metal prices rise substantially.

In light of this finding a review of the technical, environmental, financial and legal-social aspects of marine mining was carried out with a view to identifying opportunities to reduce the level of investment risk.

Based on this analysis recommendations are made for technical and strategic decisions that may reduce the investment risk and remove the barrier to commercial seabed mining. Among these recommendations is a new concept for a PMN collector designed for greater efficiency and reduced downtime and a processing system that combines marine nodule feedstock with land-based laterites.

In addition to these two primary concepts a number of other technology-related areas are identified for reducing risk. Principles designed to increase the reliability of a marine mining system are illustrated in the form of ancillary concepts.

Finally the underlying principles behind these concepts are summarised and discussed in detail to provide recommendations for potential technology proponents on the various methods to reduce the investment risk confronting marine mining.

1 Seabed exploitation – an overview

In the following sections we have defined the terms "Seabed", "Exploitation" and "Exploration", followed by our interpretation of the term "Seabed Exploitation" in light of the objective of the Collegium. Further, it gives an overview of the resources available on the seabed and uses of some of the metals which can be derived from subsea minerals. Further, this chapter presents a brief rationale for the need of marine minerals, followed by a resource assessment of the marine resource which is the main focus of this volume – polymetallic nodules. This section presents also a brief review of seabed exploration and exploitation techniques, a well as marine environment.

1.1 Definitions

1.1.1 Seabed

Seabed can be defined as the floor of the sea or ocean, from the inshore areas to the greatest depths of the ocean. According to (Cronan, 1980b), (Webber and Thurman, 1991) and (Anand, 1976) the seabed can be divided into:

- Continental shelf
- Continental slope
- Continental rise
- Abyssal plain
- Mid-ocean ridge.

Continents are usually surrounded by continental shelf; the submerged portion of the continental land mass. Its depth rarely exceeds 200 m. This is a relatively flat area of the seabed, with the slope usually varying between 0.1 and 3 degrees. The width of the continental shelf usually ranges from less than 1 km to more than 1,300 km. Seawards of the continental shelf occurs the continental slope, where the angle of inclination may range from 3 to over 45 degrees. The continental slope usually extends down to depths of around 1,200 to 3,500 m. Around most of the Pacific Ocean the slope extends down into deep ocean trenches. Where no trenches have developed the continental slope is bounded on its seaward edge by the continental rise. The continental rise represents the margin of the continental land mass. The water depths of the rise usually range from 1,500 to 5,000 m, the width up to 10,000 km. Together continental shelf, slope and rise constitute the continental margin which covers around 20% of the seabed.

Seawards of the continental slope and rise is the deep ocean floor, the main features of which are the abyssal plains and mid-ocean ridges. The abyssal plain is an extensive, generally flat area of the deep ocean floor at about 3,300 to 6,500 m below the surface of the sea. Mid-ocean ridges are broad volcanic mountain chains rising from the abyssal plains. Mid-ocean ridges extend across some 65,000 km of the deep ocean floor and cover over 30% of the seabed. The main features of the seabed are outlined in Figure 1.1 below.

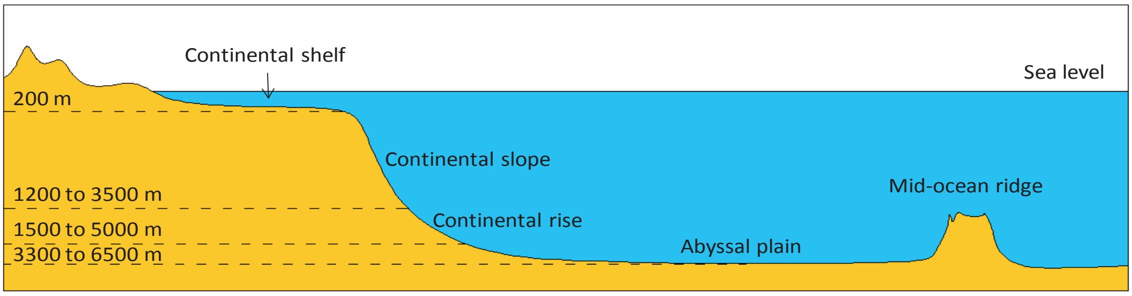


Figure 1.1: Sketch of the main features of the seabed

Although the seabed may encompass both the seafloor area and the area beneath the seafloor, for the purposes of the Collegium we have narrowed the definition of the seabed to apply to the area of the seafloor only. This issue is further elaborated in the section "Seabed Exploitation in light of the objective of the Collegium".

1.1.2 Seabed exploitation and exploration

The terms "Seabed exploitation" and "Seabed exploration" can be defined according to the definitions provided by the International Seabed Authority (ISA) for seabed mining.

Seabed exploitation means the recovery for commercial purposes of a deposit such as an ore, from the seabed and the extraction of minerals therefrom, including the construction and operation of mining, processing and transportation systems for the production and marketing of metals.

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

1.1.3 Seabed exploitation in light of the objective of the Collegium

As stated above, the term "Seabed" has in light of the objective of the Collegium been refined to apply to the area of the seafloor only. The rationale for this definition comes from the description in the Collegium Handbook *"…reserves of minerals and metals on the ocean bed…"*. By using the term 'on the ocean bed' the Group interpreted the convenors meaning as referring to material located on top of, or near the top of the ocean bed sediment, thus excluding resources located at some depth below the seabed such as oil and gas, as well as resources located in the water column above the seabed, such as mineral and biological resources in the sea water. This means that for the purpose of this study seabed resources are restricted to mineral and biological resources located directly on or near the surface of the seafloor. These resources are further described in the following sections, however taking into account the objective of the collegium, in our understanding the following constraints apply to the topic to be studied further:

- The collegium is generally aimed at emerging technologies related to the marine environment and does not tend to focus on existing technologies.
- We are to consider topics and technology applicable in the near future, i.e. some 5-20 years ahead.
- The Group considers it important that the resources we consider will benefit the society at large, in line with the objective of the Lloyd's Register Educational Trust.

The considerations above exclude placer deposits such as sand and gravel from the scope of the collegium as the technologies for their extraction fall more into the category of existing technologies while activity like diamond trenching may also be excluded on the basis of not producing a resource which would be of benefit to society at large. Finally, considering the professional background of the group members, the group has decided to focus on the mineral resources.

1.2 Resources available on the Seabed

Oceans cover vast areas, around 80% of the earth's surface. In the past few decades the knowledge of deep seabed resources has increased significantly, and some believe that deep sea will become a 21st century strategic development base for a variety of natural resources which may include a deep-sea mining industry, deep-sea biotechnology industry, deep-sea technology and equipment manufacturing and other industrial categories.

Seabed mineral resources include:

1. Seabed oil and conventional gas which has been widely exploited with the reduction of inland oil and gas resources.
2. Gas hydrates, ice-like solids that contain a gas molecule within a lattice of water molecules stabilized by hydrogen bonds, which can be found both on seabed and on land (Borowski, 2004).
3. The seabed placers, which usually have been supplied from the adjacent land mass.
4. The metalliferous sediments which are chemical precipitates of a variety of elements formed as a result of volcanic activity in underwater volcanic areas (Cronan, 1980a).
5. Seafloor Massive Sulphides (SMS), which form in the areas of volcanic activity, such as mid-ocean ridges and fracture zones.
6. The cobalt-rich crusts, which can often be found on seamount surface.
7. Polymetallic (manganese) nodules rich in copper, nickel, cobalt, manganese and other minerals. Polymetallic nodules are usually distributed on the seabed at depths of 4,000 to 6,000 meters (Anirudhan, 2005).

These resources are described further in the following sections.

1.2.1 Oil and conventional gas

The first seabed oilfield was explored near California in 1887 and since then offshore oil and gas fields have been found in many different places all around the world. The most famous offshore oil producing regions include Persian Gulf, Venezuela, the North Sea in Europe, and the Gulf of Mexico in South America. The subsea oil and gas reserves are formed from organic matter in conditions of increased temperature and pressure by long term complex physical and chemical processes. With the shortage of land-based oil resources the seabed is playing an ever more important role in the development of modern world.

1.2.2 Gas hydrates

Gas hydrates are found both on land and the seabed.Seabed gas hydrates were first found on the seabed of east America in 1970 and are therefore considered a new mineral resource. Gas hydrates are a solid material of gas and water under high pressure and low temperature similar in appearance to snow and ice or solid alcohol. Along with the seabed gas hydrates are widely distributed in nature. They can be found in continental permafrost, continental margins, the polar continental shelf as well as the deep water environment of oceans and lakes.

1.2.3 Minerals

While ocean gas and oil reserves have been intensively studied and exploited over the past 50 years, development of solid minerals on the seabed has been much slower. Seabed mineral exploitation was limited for a long time to the most valuable minerals – gold and diamonds, but there are a number of other important ores available from the world's oceans. These are briefly described below.

1.2.4 Placer deposits

In geology a placer deposit is an accumulation of valuable minerals formed by gravity separation during sedimentary processes. Placer materials must be both dense and resistant to weathering processes. To accumulate in placers mineral particles must be significantly denser than quartz as quartz is usually the largest component of sand or gravel. Placer environments typically contain black sand, a conspicuous shiny black mixture of iron oxides, mostly magnetite with variable amounts of limonite and hematite. The substances commercially mined from placer deposits include gold, platinum, tin, diamonds, thorium, titanium and uranium.

1.2.5 SMS deposits

Seafloor Massive Sulphide (SMS) deposits were found at the crest of the East Pacific Rise at 21^{o} N in 1979 in water depths up to 3,700m. The first evidence was a chimney-like black rock on the top of sulphide mount. Hydrothermal seawater fluid (up to 400^{o}C) discharges from the black smoker chimneys. When these hydrothermal fluids mix with the surrounding cold seawater the metal Sulfides in the water will deposit on the chimney and nearby seabed. These seabed sulphides can reach a considerable size (up to 100 million tons) and often carry high concentrations of copper, zinc, and lead in addition to gold and silver (ISA, 2010, Hein, 2012a). Due to the high concentration of important and precious metals seafloor massive sulphide deposits have recently attracted the interest of the international mining industry.

1.2.6 Sediments

Metalliferous sediments include deposits rich in iron, manganese and several other elements found in association with submarine volcanic activity throughout the world's ocean. It has been proposed that the Mid-Ocean Ridge system is formed by these deposits (Cronan, 1980a). Metalliferous sediments also occur in association with submarine volcanism in some island arcs. Similar to Seafloor Massive Sulphides, sediments are rich in minerals and are derived from the activity of hydrothermal vents where minerals are solubilized by supercritical water rising from the volcanic activity beneath. The minerals contained within the rising water precipitate out to form chimneys through which the plume of black smokey water emanates, and also precipitate out of the cloud as it cools. The chimneys formed in the region of the vent are the basis for SMS deposits while the precipitated minerals derived from the cloud form mineral-rich sediment dispersed farther afield. The deposits there are rich in iron, copper, zinc, silver, gold, manganese and other metals (Cronan, 1980a).

1.2.7 Crusts

The cobalt-rich crust deposits occur across all the world's oceans. Crusts are mainly concentrated at seamounts, ridges, slopes and plateaus where currents have kept the rocks swept clean of sediments for millions of years. There are about 50,000 seamounts all around the world (Hein, 2012a, ISA, 2010). Cobalt-rich crusts are mainly found at a depth of 400-4,000 m. The thickness of the crust can reach up to 250 mm. Due to the grade of ore and oceanographic conditions the central-equatorial Pacific offers the best potential for crust mining, particularly the Johnston and Hawaii Island (USA), Marshall Islands, Federated States of Micronesia economic zones and the international seabed area of the central pacific ocean. In addition the proportion of the mineral content of the shallow areas of crust is higher, an important factor in exploitation.

1.2.8 Polymetallic (Manganese) nodules

HMS Challenger found polymetallic nodules (also known as manganese nodules) on 18 February 1873, 160 miles south west of Ferro in the canary island group. After WWII a comprehensive investigation of the ocean began and new data was obtained on the wide distribution of polymetallic nodules leading scientists to consider nodules as one of the major resources of the deep oceanic zone. Since the 1960's polymetallic nodules have been recognized as a potential ore source, investigation of which is stimulated by the progressive depletion of land-based mineral resources. Polymetallic nodules are mainly distributed on the seabed at a depth of 4,000-6,000 meters (ISA, 2010).

While concentrated minerals from hydrothermal ‘black smokers’ precipitate quickly in the surrounding region, the more dilute metal constituents of seawater precipitate very slowly via chemical and biogenic processes onto rocky substrate to form crusts, and onto a source of nucleation on the soft seafloor sediment to form polymetallic nodules.

Still today the total amount of polymetallic nodules remains unknown. But it is established that there are more than 500 billion tons of polymetallic nodules distributed on the seabed, although not all of them are suitable for exploitation. A mine site is defined as a seabed area where continuing commercial operation for 20~25 years may yield an annual output of 1.5~4 million tons of high-quality polymetallic nodules. According to this definition there are around 225 potential mine sites in the world with total exploitable polymetallic nodules amount up to 13.5 billion tons.

The elements found in polymetallic nodules can be divided into 5 categories, and their average composition in the Pacific Ocean nodules is shown in Table 1.1:

1. Major and Minor elements of potential economic interest (Mn, Fe, Ni, Cu, CO, Zn, V, Mo, Sr, Ti, Zr)
2. Rare Earth Elements (La, Ce, Nd, Tb, Dy, Ho, Tm, Yb, Lu, Hf)
3. Precious metals and radioactive elements (Au, Pt, Ra, U)
4. Elements of environmental interest (As, Ba, Cd, Pb, Hg, Se)

Table 1.1: An average composition of pacific Polymetallic nodule (Mero, 1965)

Constituent	Weight, percent[a]
MnO_2	31.7
Fe_2O_3	24.3
$CaCO_3$	4.1
Al_2O_3	3.8
SiO_2	19.2
Ni Oxide	1.6
Cu Oxide	1
Co Oxide	0.5
Mo Oxide	0.006
H_2O	13
Total	99.2

[a] On an air-dried basis

1.3 Usage of different kinds of minerals

In this section examples of the usage of some metals which can be derived from seabed minerals are presented.

Manganese (Mn) is essential to iron and steel production by virtue of its sulfur-fixing, deoxidizing, and alloying properties. Steelmaking, including its ironmaking component, accounts for most globalmanganese demand, around 90% of the total. Manganese ferroalloys, consisting of various grades of ferromanganese and silicomanganese, are used to provide most of this key ingredient to steelmaking. Products for construction, machinery, and transportation are leading end uses of manganese. Manganese also is a key component of certain widely used aluminum alloys and, in oxide form, dry cell batteries. As ore, additional quantities of manganese are used for such nonmetallurgical purposes as plant fertilizers, animal feed, and colorants for brick.

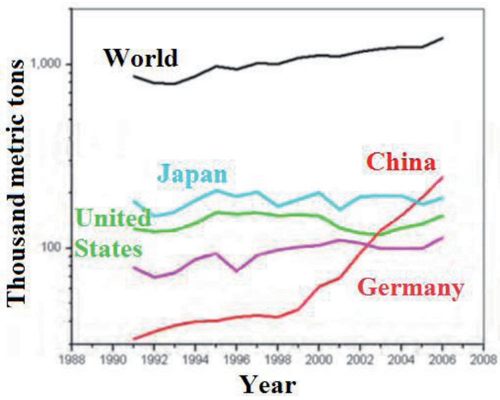
Cobalt (Co) is a metal used in numerous diverse commercial, industrial, and military applications, many of which are strategic and critical. On a global basis, the leading use of cobalt is in rechargeable battery electrodes. Superalloys, which are used to make parts for gas turbine engines, are another major use for cobalt. Cobalt is also used to make airbags in automobiles; catalysts for the petroleum and chemical industries; cemented carbides (also called hardmetals) and diamond tools; corrosion- and wear-resistant alloys; drying agents for paints, varnishes, and inks; dyes and pigments; ground coats for porcelain enamels; high-speed steels; magnetic recording media; magnets; and steel-belted radial tires.

Copper (Co) is one of the oldest metals ever used and has been one of the important materials in the development of civilization. Because of its properties, singularly or in combination, of high ductility, malleability, and thermal and electrical conductivity, and its resistance to corrosion, copper has become a major industrial metal, ranking third after iron and aluminum in terms of quantities consumed. Electrical uses of copper, including power transmission and generation, building wiring, telecommunication, and electrical and electronic products, account for about three quarters of total copper use. Building construction is the single largest market, followed by electronics and electronic products, transportation, industrial machinery, and consumer and general products.

Nickel (Ni) is used in many specific and recognizable industrial and consumer products, including stainless steel, alnico magnets, coinage, rechargeable batteries, electric guitar strings, microphone capsules, and special alloys. It is also used for plating and as a green tint in glass. Nickel is preeminently an alloy metal, and its chief use is in the nickel steels and nickel cast irons, of which there are many varieties. It is also widely used in many other alloys, such as nickel brasses and bronzes, and alloys with copper, chromium, aluminium, lead, cobalt, silver, and gold.

1.4 Need for marine minerals

World nickel and copper consumption has been increasing as has that of China and Germany, among the leading consumers, shown together in Figure 1.2 on a logarithmic graph to accommodate the wide range of values on a compact scale. Compared with other leading consumers, China moved from the least amount of consumption to the greatest amount during this time period because the rapid increase of Chinese economy.



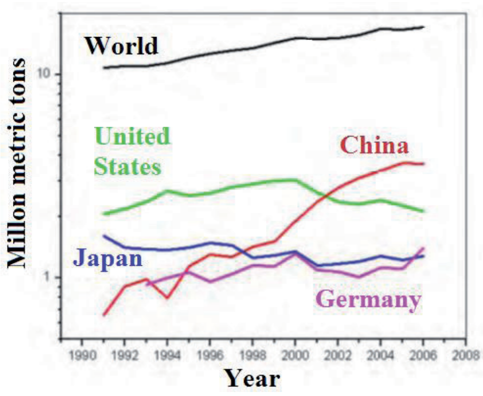


Figure 1.2: World and leading national nickel (left) and copper (right) consumption. (Papp et al., 2007)

Nowadays, despite the recent worldwide economic recession, metal prices are now well above levels that existed before the recession began. Generally, the number of mines has decreased over the past decade, while the consumption of the metals has steadily increased, due to the on-going rapid development in Asia.

As shown in Figure 1.3, the number of new mines starting production peak in the middle of the Twentieth Century and has been decreasing dramatically since the 1960's. Part of this trend can be explained by the fact that newer mines are generally larger than older mines, but the implications of this graphic are unmistakable; we are running out of minerals on land.

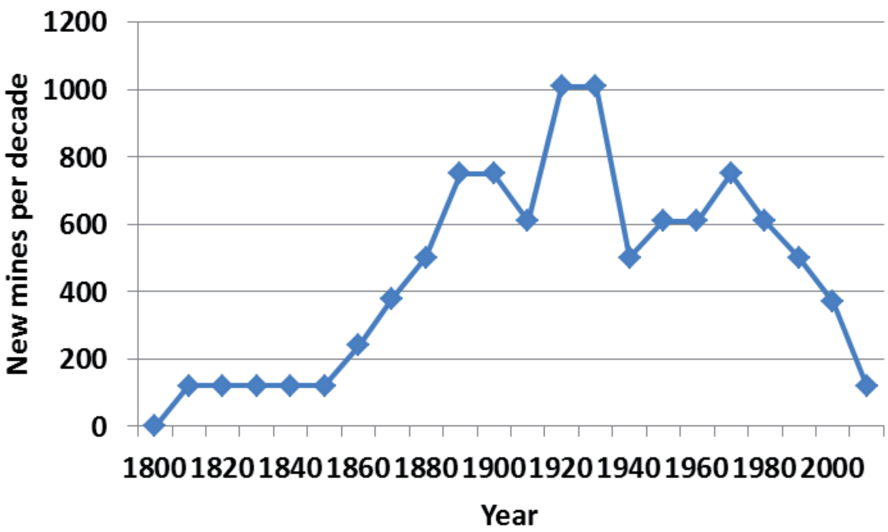


Figure 1.3: Number of new mines per decade. (Morgan, 2010)

1.5 Resource assessment

The resource assessment presented in this section focuses on polymetallic nodules. The most economically viable resources of polymetallic nodules are found in Clarion-Clipperton Fracture Zone (CCZ) (ISA, 2008b). In this section a brief resource assessment for this area is shown.

CCZ is located in the eastern central Pacific, to the southeast of the Hawaiian Islands; the geographical limits are between 110°-160° west longitude and 0° -20° north latitude, as shown in Figure 1.4. The CCZ with a total area of 4.5 million square kilometers is much larger than any land-based mine. This zone is considered to be the richest, containing high grade and high abundance nodules. The seafloor of the CCZ lies mostly between 4,000 and 6,000 meters water depth. The seafloor is characterized by a number of seamounts. Some of the seamounts reach depths of less than 3,000 meters. CCZ provides a large number of flat floored valleys, separated by irregular, often discontinuous ridges a few hundred meters high. The area explored is divided into an east area and a west area. Water depth in the east area is between 3,901 m and 5,590 m and the west area between 2,969 m and 5,986 m.

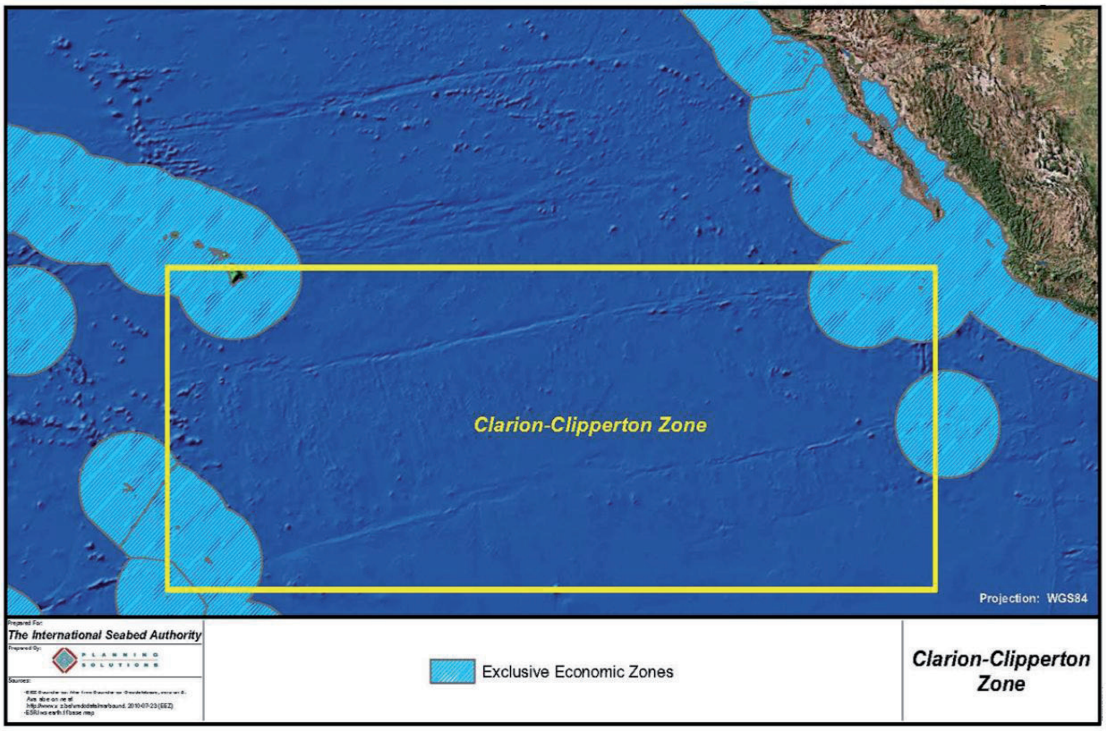


Figure 1.4: The Clarion-Clipperton Fracture Zone (CCZ)

Resources of polymetallic nodules in CCZ can be estimated from the geological model of the area currently under development by International Seabed Authority (ISA), based on the datasets of polymetallic nodule abundance and metal content supplied by exploration contractors. According to the data sets, the nodule abundance is plotted with different interpolation method, and the total amount is inferred. It is shown in Figure 1.5. The area pointed by the arrow contains the highest abundance of manganese nodules. The average abundance can reach 15 kg/m^2.

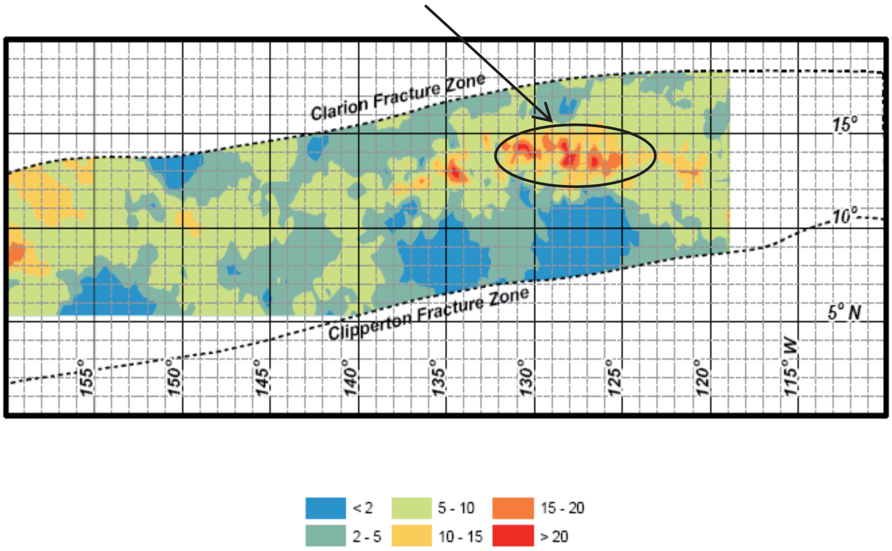


Figure 1.5: Abundance of Polymetallic Nodules

According to the abundance of the Polymetallic nodules, the total resources are inferred up to 21.1 billion metric tons. According to the mean estimation of the elementary statistics, Mn accounts for 28.2%, Co 0.22%, Ni 1.28% and Cu 1.11%. According to the elementary statistics, the abundance of Mn, Co, Ni, and Cu can then be estimated, and is shown in Table 1.2.

Table 1.2: The inferred resources of CCZ

Source	Included Area (km^2 × 10^6)	Estimated Tons (metric tons × 10^6)				
		Nodules	Mn	Co	Ni	Cu
Reduced area	3.83	21,100	5,950	46.4	270	234

If we divide the total abundance by the annual production of 2010, the manganese, cobalt, nickel and copper can be exploited for 425, 280, 170 and 18 years, respectively. Valued by dollar of 1998, they are valued 8.9, 1.3, 4.2 and 1.6 trillion dollars, as shown in Table 1.3. This demonstrates the great value of the CCZ area, estimated to be in excess of 16 trillion 1998$ (ISA, 2003, ISA, 2010).

Table 1.3: Resources assessment summary

	Abundance ton	Production on land ton/year	Year	Value trillion(98$*)
Manganese	5,950,000,000	14,000,000	425	8.93
Cobalt	46,400,000	165,900	280	1.33
Nickel	270,000,000	1,590,000	170	4.24
Copper	290,000,000	16,100,000	18	1.61

1.6 Exploration and exploitation techniques

Exploration involves the ability to look around, measure, record, and retrieve samples. A broad range of equipment and techniques have been developed to investigate the seabed, useful both for finding resources and for studying the environment in which they lie. Here we introduce the main exploration techniques and give a brief overview of the exploitation methods.

1.6.1 Gravity techniques

Sounding weight

One of the first instruments used for the seabed exploration is the sounding weight. It was designed as a tube on the bottom which forced the seabed in when it reach. british explorer Sir James Clark Ross employed it to reach a depth of 3,700 metres in 1840. The British researchers used wire-line soundings to investigate sea depths and collected hundreds of biological samples from all the oceans.

Gravity corer

A more advanced version of the sounding weight is the gravity corer. The gravity corer allows researchers to sample and study sediment layers at the bottom of oceans. The corer consists of an open-ended tube with a lead weight and a trigger mechanism that releases the corer from its suspension cable when the corer is lowered over the seabed and a small weight touches the ground. Cores capture a time capsule that, in some cases, can span the past hundreds of thousands and even millions of years.

1.6.2 SONAR (SOund Navigation And Ranging)

Sonar is a technique that uses sound propagation to navigate or detect objects on or under the water.

The main features of sonar are:

- Sonar operation is affected by variations in sound speed in the vertical plane.
- Sound travels more slowly in fresh water than in sea water, though the difference is small.
- The speed is determined by the water's bulk modulus and mass density. The bulk modulus is affected by temperature and pressure. The density effect is small.

The speed of sound can be calculated using the empirically derived approximation equation shown below. It is reasonably accurate for normal temperatures, concentrations of salinity and the range of most ocean depths.

$$V = 4388 + (11.25 \times T) + (0.0182 \times D) + S$$

V: The speed of sound

T: Temperature in °F

D: Depth in feet

S: Salinity in parts per thousand

The main applications of sonar include maritime archaeology, fisheries research, dredging operations, military applications and environmental studies.

Side scan sonar

A sonar device, which may be towed from a surface vessel or submarine, or mounted on the ship's hull that emits conical or fan-shaped pulses down toward the seafloor across a wide angle perpendicular to the path of the sensor through the water. The intensity of the acoustic reflections from the seafloor is recorded in a series of slices. When stitched together along the direction of motion, these slices form an image of the sea bottom.

The main features of the side scan sonar are:

- Create an image of large areas of the sea floor
- Provide an understanding of the differences in material and texture type of the seabed
- Detect debris items and other obstructions on the seafloor such as pipelines and cables
- The sound frequencies range from 100 to 500 kHz

Development of the side scan sonar technique can be summarised in the following steps:

- A single conical-beam transducer
- Two transducers to cover both sides
- The transducers were either contained in one hull-mounted package or with two packages on either side of the vessel
- The transducers evolved to fan-shaped beams to produce a better "sonogram" or sonar image.
- In order to get closer to the bottom in deep water the side-scan transducers were placed in a "towfish" and pulled by a "tow cable".

Historical Records:

- One of the inventors of side-scan sonar was German scientist, Dr. Julius Hagemann. His work is documented in US Patent 4,197,591 which was first disclosed in Aug 1958, but remained classified by the US Navy until it was finally issued in 1980.
- Experimental side-scan sonar systems were made during the 1950s in laboratories including Scripps Institution of Oceanography and Hudson Laboratories and by Dr. Harold Edgerton at MIT.
- The first commercial side-scan system was the Kelvin-Hughes "Transit Sonar", a converted echo-sounder with a single-channel, pole-mounted, fan-beam transducer introduced around 1960.
- Martin Klein at Edgerton, Germeshausen & Grier (later E.G. & G., Inc.) developed the first successful towed, dual-channel commercial side-scan sonar system from 1963 to 1966.
- In 1968 Klein founded Klein Associates, Inc. continued to work on improvements including the first commercial high frequency (500 kHz) systems and the first dual-frequency side-scan sonars, and the first combined side-scan and sub-bottom profiling sonar.

Sonic depth recorder (Echo sounding)

Sonic depth recorder is the technique of using sound pulses to find the depth of water. A sound pulse is transmitted vertically downward by a piezoelectric or magnetostriction transducer mounted on the hull of the ship. Echo sounding is a more rapid method of measuring depth than the previous technique of lowering a sounding line until it touched bottom. Echo sounding is effectively a special purpose application of sonar used to locate the bottom.

The main features of a sonic depth recorder are:

- The majority is dual frequency, meaning that a low frequency pulse can be transmitted at the same time as a high frequency pulse.
- Advantages of dual frequency echosounding include ability to identify a vegetation layer or a layer of soft mud on top of a layer of rock.
- Most hydrographic operations use a 200 kHz transducer, which is suitable for inshore work up to 100 metres in depth.
- Deeper water requires a lower frequency transducer range from 24 kHz to 33 kHz as the acoustic signal of lower frequencies is less susceptible to attenuation in the water column

Historical Records:

- Developed in the 1970s by the US Navy to assist the underwater navigation of its submarine force.
- The first commercial multibeam is now known as the SeaBeam Classic produced up to 16 beams across a 45-degree swath and was put in service in May 1977 on the Australian survey vessel HMAS Cook.
- In the 1980s and 1990s, higher-frequency systems suitable for high-resolution mapping in shallow water were developed.
- Since the 1990s for offshore oil and gas exploration and seafloor cable routing, they are also commonly used for geological and oceanographic research, and.
- In 1989, Atlas Electronics installed a 2nd-generation multibeam called Hydrosweep DS produced up to 59 beams across a 90-degree swath.
- The Teledyne Odom ES3 incorporates a motion sensor at the face of the acoustic transducer.

1.6.3 Existing ocean instruments

Acoustic Doppler current profiler (ADCP)

ADCP is to measure how fast water is moving across an entire water column and water currents with sound, using a principle of the Doppler Effect. It measures small scale currents and a water column up to 1000 m long.

Floats

Floats are drifting instruments that measure ocean temperature and salinity. After they are deployed, they navigate along the ocean currents and can travel in deep distances on their own without any propulsion systems. Floats are programmed to come to the surface regularly to transmit ocean mass.

The floats have the ability to change their own buoyancy. When they are deployed, they sink to a pre-specified depth. To control the buoyancy of the float, a small amount of oil is contained within the float. When the float is submerged, all of the oil is kept entirely within the hull. When it is time to rise to the surface, the oil is pumped into an external rubber bladder that expands. Since the weight of the float does not change but its volume increases when the bladder expands, the float becomes more buoyant and floats to the surface. Similarly, when the float is on the surface and it is time to submerge, the oil is withdrawn from the bladder into the hull of the float and the buoyancy decreases.

Magnetometer

A magnetometer is a scientific instrument used to measure magnetic field strength. Under the sea, marine geophysicists, ocean engineers and nautical archeologists use marine magnetometers to detect variations in the total magnetic field of the underlying seafloor. Marine magnetometers are generally “fish-type” instruments. They are towed at least two and a half ship-lengths behind the ship, so that the ship’s magnetic field does not interfere with magnetic measurements.

Moored profiler

A moored profiler makes repeated measurements of ocean currents and water properties up and down through almost the entire water column, even in very deep water. The basic instruments it carries are a CTD (Conductivity, Temperature, and Depth) for temperature and salinity and an acousting current meter to measure currents.

The moored profiler is attached to a subsurface mooring cable that can run from a depth of 50 metres down to the sea floor at 5,000 metres or more.

Ocean-bottom seismometer

Seismometers measure movement in the Earth's crust. About 90 percent of all natural earthquakes occur underwater, where great pressure and cold make measurements difficult.

Seismometers work using the principle of inertia. The seismometer body rests securely on the sea floor. Inside, a heavy mass hangs on a spring between two magnets. When the earth moves, so does the seismometer and its magnets, but the mass briefly stays where it is. As the mass oscillates through the magnetic field it produces an electrical current which the instrument measures.

Ocean-bottom seismometers are hard to install with pinpoint accuracy. That soft layer can dampen the very tremors the instrument is trying to measure. Short-period seismometers have short battery lives, so large numbers of them must be set out repeatedly during 30-day cruises.

Piston corer

The piston corer is a long, heavy tube plunged into the seafloor to extract samples of mud sediment. A piston inside the tube allows scientists to capture the longest possible samples, up to 27metres in length.

Simply making a gravity corer longer does not insure the recovery of a longer sample. The addition of the internal piston allows the soft sediment to be captured without significant compression or disturbance. This allows researchers to capture the best possible sediment sample.

They are heavy, long, and sometimes difficult to handle. Because of the operations involved and equipment needed, piston corers cannot be executed from every research vessel. Special handling equipment is required to safely launch and recover a deep sea piston coring system.

Cores extracted from the sea are especially useful because, unlike land sediments, they are largely undisturbed; no people have dug around them, or walked on top of them. By minimizing disturbance, scientists are able to see the clearest picture of specific time periods on Earth.

Autonomous underwater vehicles

AUVs are robotic submarines resembling torpedoes that navigate without a human crew on-board and without cables connecting them to research vessels at the sea surface. The vehicles are designed for coastal monitoring as well as survey operations at various depths in the ocean. They are used widely for both scientific and military operations. Oceanographers use them as a vehicle to carry a wide variety of ocean instruments for data collection. Computers on the vehicle are used for system control, such as navigation and propulsion, as well as for data collection.

Digital camera system

Digital camera system that photographs the seafloor as it is towed above the ocean bottom behind an oceanographic research vessel. A regular underwater camera would not work in such an extreme environment, where it must take pictures in total blackness, crushing pressure, and freezing temperatures. The camera system is towed 100 to 300 metres behind the ship at speeds of 1/4 to 1/2 knot, the equivalent of walking at a leisurely pace.

1.6.4 Mining techniques

Land-based mining techniques have been developing for over 1000 years. Marine mining is in its infancy and presents many more complicated technical challenges when compared with land-based mining. The methods for finding, accessing and exploiting valuable minerals on the seafloor have been adapted from land technology and marine oil & gas. Placer deposits on the continental shelf such as gold and diamonds are commercially mined but no hard minerals on the deep sea floor have been the subject of commercial mining ventures. Two of these targets have been of particular interest in recent years; SMS deposits and polymetallic nodules. Research and development of mining techniques for these two resources has advanced to field tests/pilot scale. Following is short introduction to the existing mining concepts. A detailed overview of the proposed mining techniques developed so far and current research in the field is shown in Chapter 3.

SMS and sediments

Active and extinct hydrothermal vents are rich sources of SMS minerals. While little progress has been made towards mining sediments, SMS minerals are the target of a number of mining processes. The most advanced of these is the Nautilus Minerals' Solwara 1 mine off the coast of Papua New Guinea.

Nautilus plans to use technology adapted from land-based mining processes to excavate the material at Solwara 1, risers adapted from the oil and gas industry to transport it to surface, and a land-based refinery to process the ore.

Crusts and nodules

Many different concepts have been designed and tested but all include three key components: a collector to cross the seafloor and retrieve the nodules, a transportation system to convey the collected nodules to the sea surface, and a ship and processing system to bring the nodules into the supply chain and process them into saleable product.

1.7 Marine life

This section will give an overview of the marine life in the areas relevant to seabed mining.

1.7.1 Ecological divisions of Ocean

In order to better understand the environmental impact deep seabed mining might have on sea life this section begins with a short introduction of what goes on in the different zones of the water column and the seabed. Figure 1.6 shows the basic ecological divisions in the ocean (Lalli and Parsons, 1997). The most basic division separates the water column environment (pelagic) from that of the seafloor (benthic). The species that live on or within the seabed are called the benthos. The species that inhabit the pelagic environment are divided into plankton and nekton. Further divisions of the pelagic and benthic environments which divide them into distinctive ecological zones based on depth and topography can be made. These are shown in Figure 1.6. The pelagic zones (biozones) are further described below (Markussen, 1994).

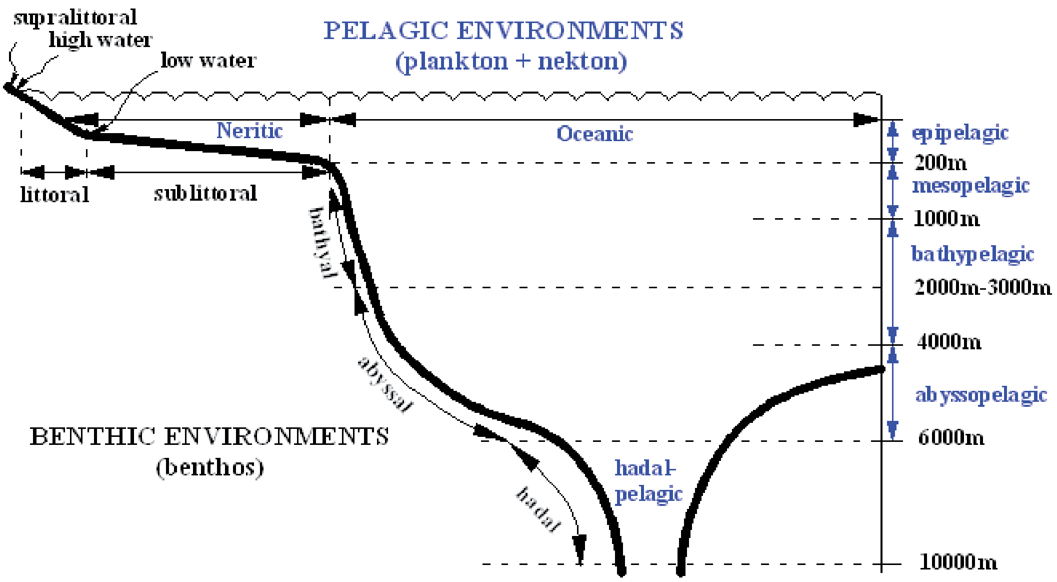


Figure 1.6: The basic ecological divisions of the ocean, from (Lalli and Parsons, 1997). The neritic pelagic zone is separated from the oceanic pelagic zone by the edge of the continental shelf. Benthic habitats are in bold type, pelagic divisions are in blue.

Zone 1 (epipelagic zone): This zone extends from the surface down to approximately 200m depth. An important part of the zone is the portion through which sufficient light penetrates to enable photosynthesis to take place. This layer - the photic zone -is defined as the region from the surface down to the depth where light intensity is reduced by 99 per cent. The lower limit of the layer will necessarily vary according to geographical co-ordinates and the time of year. Typical examples from the Pacific and the Atlantic have the 1 per cent limit at about 50 metres, although in tropical waters this limit lies at about 90 metres. The epipelagic zone is by far the most productive part of the water column. Estimates indicate that around 80 per cent of the total biomass in the oceans is found here. The biomass in this zone comprises phytoplankton and zooplankton, fish, and fish spawn. It is here that almost all the world's fishery resources are to be found.

Zone 2 (mesopelagic zone): The mesopelagic zone extends from around 200 metres to around 1,000 metres. In this intermediate zone important chemical and physical parameters reach their maxima. For instance the mesopelagic zone includes minimum values for the content of oxygen in solution and maximum values of plant nutrient phosphate (PO_4). In this layer certain species of pelagic fish stocks and deep-sea shrimp are found, rendering the mesopelagic zone of some importance for commercial fisheries.

Zone 3 (bathypelagic zone): As a lower intermediate zone, the bathypelagic extends from about 1,000 metres down to about 4,000 metres below the surface. The biomass in this zone is relatively sparse due to minimal energy in the form of sunlight penetrating to such depths and a poor supply of nutrients. For the few animals living in this area conservation of energy is a cardinal principle.

Zone 4 (abyssopelagic zone): In the high seas this zone extends from about 4,000 metres below the surface down to the seabed and is characterized by a high degree of stability. Temperatures are low, ranging between 1 and 4 degrees Celsius and very stable. Stability characterizes the abyssopelagic zone in other contexts as well: low rate of sedimentation, extremely low light penetration, and limited supply of nutrients. The low supply of elements necessary to living organisms means that the few biological resources existing here are to be found on the sea floor and in the upper few centimetres of the seabed sediments. Although many species are found at the deep seabed their density is very low.

1.7.2 The deep sea environment

In the following section seabed fauna will be addressed in more detail as these are most likely to be affected by seabed mining. The emphasis will be on the deep sea environment. The information presented below is mainly based on (Lalli and Parsons, 1997) and (Webber and Thurman, 1991). In general, relative to intertidal regions comparatively little is known about life in the benthic, abyssal, and hadal zones. This is due to their relative inaccessibility. In the following, a few general considerations will be given. As for the organisms of the water column, vertical gradients of temperature, light and salinity are important in establishing distinctly different living regimes for benthic organisms depending on depth and topography. This means that each of the benthic habitats shown in Figure 1.6 presents distinctly different living conditions. The animals that inhabit different zones will generally be of different species, adapted to the particular environment in which it is found. These benthic habitats are coupled in a dynamic fashion with the overlying pelagic environment. The majority of benthic communities are located in the part of the ocean where the sunlight is absent, and most are entirely dependent on organic matter that is photosynthetically produced in the upper zone. The only exceptions are certain communities in which the food chain begins with chemosynthetic production by the bacteria (see below). Part of the organic matter that sinks or is transported from the surface waters is the food source that supplies deep-water benthic communities. Sinking organic and inorganic particles also form the sediments in which the benthos live. Decomposition processes tend to take place in deep water or on the seafloor, and the nutrients that are released are eventually returned to the surface where they are used by the phytoplankton.

The deep sea environment beginning at a depth of 1,000m, is generally regarded as stable and homogeneous. There is no sunlight, water temperatures are generally low (from -1 ^{o}C to 4 ^{o}C), salinity and oxygen content are constant and hydrostatic pressure high. Soft bottom sediments originating from land and/or from the sinking of dead planktonic organisms cover most of the deep sea floor. Hard substrates are largely limited to mid-ocean ridges and seamounts. Relative to the surface currents, bottom currents in the deep ocean basins are slow (generally < 5 cm/s). Some areas experience abyssal storms during which the currents increase in speed and may reverse direction.

An example of the types of animals that may be found in the deep sea is shown in Figure 1.7 along with relative abundances of the different seafloor animal groups at different depths in the Kurile-Kamchatka trench. In general the distribution of the deep-sea species does not overlap that of shallow water. Certain deep-sea species can be used to measure the boundaries of the deep-sea environment in specific locations. Despite the uniform environmental conditions throughout the deep sea, individual species have distinct patterns of distribution. Some deep-sea residents have a cosmopolitan distribution and are found in all major oceans, other species are restricted to relatively small areas. In general species become more limited in geographic range as water depth increases. Only about 20% of the species present below 2,000 m in Atlantic Ocean are also found in the Pacific or Indian oceans.

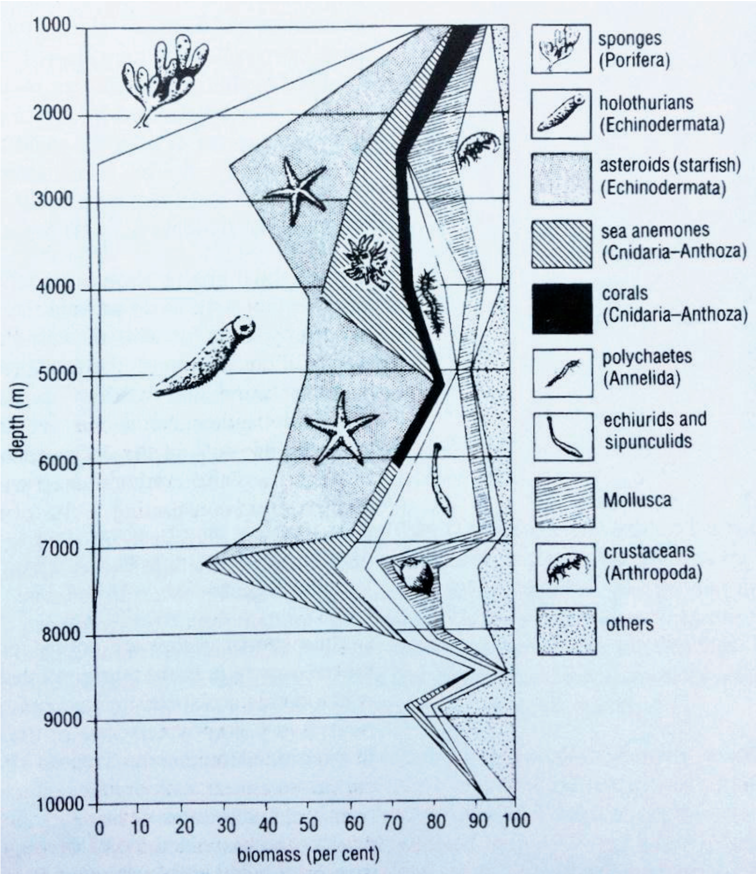


Figure 1.7 The percentages of different animal groups in the biomass of macrobenthos at different depths in the Kurile-Kamchatka trench, from (Lalli and Parsons, 1997).

Deposit-feeding animals are dominant in the soft, organically rich sediments of the deep sea, usually comprising 80% or more of the fauna by numbers. Because bottom currents are usually slow and do not disturb compacted sediments the topographic features produced by these animals persist for long periods. Animals that feed on suspended particles are also found in the deep sea but they are much less abundant and are usually restricted to particular locations. This is because most such epifaunal animals require relatively firm substrates for attachment as well as high concentrations of suspended food particles. Food supply is the limiting factor for the benthic biomass and is the reason why there is so little life in the deep sea (with the exception of the vent communities). Biomass is defined as the number of individual organisms (in some area or volume or region) multiplied by the average weight of the individuals.

It is now established that there is high species diversity in the deep sea, especially among the small infaunal deposit feeders. Although the number of species is high in the deep sea, communities occupying the typical soft-sediment seafloor are characterised by low population densities and low biomass. Numbers of benthic individuals per unit area tend to decrease roughly exponentially with increasing depth as can be seen in Table 1.4. The dominant infaunal species tend to be small as well as sparse. On most of the deep ocean floor the animal population has a density similar to that found in the inhospitable deserts of land.

Table 1.4 Average biomass values of benthic animals at different depth (Lalli and Parsons, 1997)

Depth range (m)	Mean biomass (g wet weight m^{-2})
Intertidal	3×10^3
< 200	200
500-1000	< 40
1000-1500	< 25
1500-2500	< 20
2500-4000	< 5
4000-5000	< 2
5000-7000	< 0.3
7000-9000	< 0.03
> 9000	< 0.01

Accumulating evidence suggests that various biological processes in deep-sea animals such as metabolism, growth, maturation and population increase are slow in comparison to such processes in shallow-water environments. Many deep-sea species have a low rate of reproduction. The number of eggs produced per individual is generally much lower in the deep-sea residents when compared to their shallow-water relatives. Low reproduction and therefore low dispersal suggest low rates of recolonisation in the deep sea, and this has been confirmed by experimental studies. In one experimental study boxes of sterilized sediment were placed at depth of 10 m and 1,760 m, and examined after 2 month and after 26 month. After 2 month the shallow boxes contained 47 species and 704 individuals (35,714 individuals m^{-2}) while the deep-sea boxes yielded only 14 species and 43 individuals (160 individuals m^{-2}). After 26 months the deep-sea boxes still contained 10 times fewer individuals and species than the surrounding sediment at the same depth (Lalli and Parsons, 1997).

1.7.3 Hydrothermal vents and cold seeps

Hydrothermal vents and cold seeps support unique communities that are independent of solar energy and photosynthesis. Instead, the food chain in these environments is based on the presence of hydrogen sulphide that is utilized by chemosynthetic bacteria to form organic compounds from carbon dioxide. The bacteria are the primary producers in these communities, and they are either consumed directly by animals or they are found in symbiotic relationship with animals. Deep-sea vents and seeps support extremely dense concentrations of large animals, and biomass may be as much as 30 kg/m^2. Approximately 95% of the animals discovered in hydrothermal vents have been previously unknown species, many very different from related known species. Metabolic and growth rates of the large vent animals are similar to those of shallow-water relatives, and are orders of magnitude higher than those of related animals in other parts of the deep sea. As more hydrothermal vents are discovered and sampled the list of new species of animals grows rapidly. Hydrothermal vents and cold seeps are unique concentrations of life in depths that usually are characterised by low density and low productivity.

Hydrothermal vent communities are quite small, usually only about 25-60 m in diameter. Both hydrothermal vent and cold seep communities may be separated from other similar communities by as much as hundreds to thousands of kilometres. Each vent has its unique suite of species as well as species similar to other vent communities. Although these environments have plentiful food and in the case of vents, temperatures that are higher than usual in deep water, relatively few animals have developed the ability to live in high concentrations of H_2S and species diversity is low.

1.7.4 Environment in the polymetallic nodules region of the Pacific Ocean

Substantial amount of research has been carried out to characterise the biological environment in the areas of potential polymetallic nodules mining in the Pacific Ocean. (Tilot, 2006) studied distribution of the megafauna at the NIXO 45 site, which lies within Western French mining claim area in CCZ at 4,950 m depth. The megafauna is defined as organisms >1-4 cm that are visible in photographs of the ocean floor, and constitutes 17-50% of benthic abyssal biomass. The total desity of the megafauna was estimated to 498 ind/ha. The author reports also that in several other studies the total density of the megafauna in several areas in CCZ is estimated to line in the range from 300 ind/ha and up to 4000 ind/ha, depending on the location, measurement method and primary production of the water column above the zone. In the NIXO 45 site suspension feeders are more abundant than detritus feeders, carnivores and scavengers. Figure 1.8 shows the most abundant types of megafauna in the NIXO 45 site, and shows that the megafauna in this site is dominated by cnidarians, echinonoderms and sponges. Cnidaria consist principally of actinids and octocoralliarids while echinoderms are represented mostly by holothurians and crinoids. The macrobentos types shown in Figure 1.8 are also representative for the CCZ area as a whole.

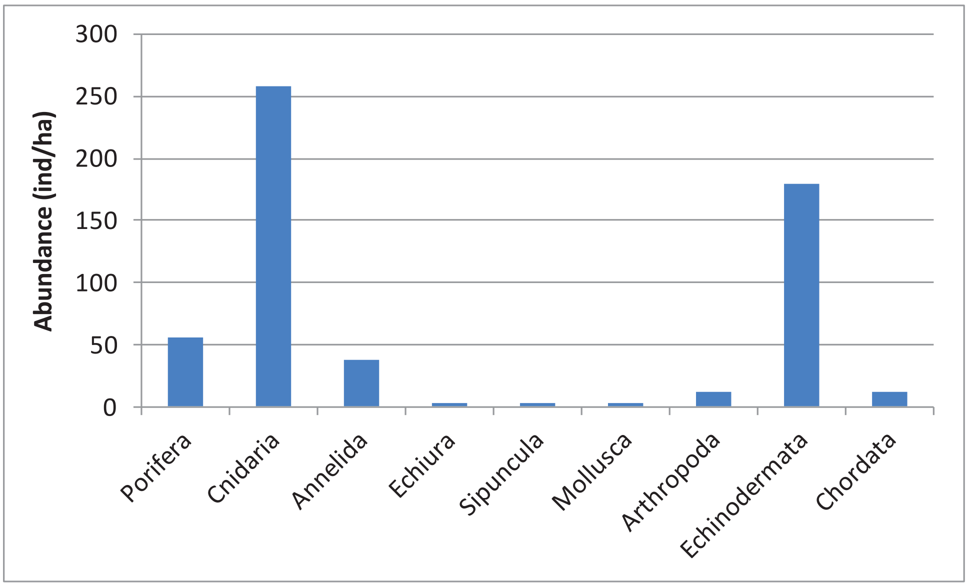


Figure 1.8: Abundance within each phylum at the NIXO 45 site within Western French mining claim area in CCZ (Tilot, 2006)

(Tilot, 2006) report also that abundance and composition of megafauna varied with different nodule-facies existing on the site. The greatest abundance of fauna was found on the facies with large scattered nodules (10 % area nodule coverage, close to 1200 ind/ha).

In the ISA Technical Study No. 3 (ISA, 2008a) the authors focused on polychaets, nematodes and foraminifera to study biodiversity, species ranges and gene flow in the abyssal Pacific Nodule Province. The reasons of focusing on these three animal types were:

- Polychaete worms dominate the abyssal macrofauna (animals between 0.3 to 30 mm in smallest dimension), constituting 60-75% of mactrofaunal abundance and species richness.

- The nematode worms make up the bulk of the meiofauna (animals between 0.03 to 0.3 mm in smallest dimension) and may be the most abundant and species-rich, multi-cellular animals in deep-sea sediments.
- Foraminifera (amoeboid animals ranging in size from ~0.03 mm to 10s of centimetres) are the most abundant protozoans in deep-sea sediments, and substantially influence seafloor habitat structure and energy flow in the Pacific nodule province.

The main findings of the above study indicate that unexpectedly high and still poorly sampled levels of species diversity for all three sediment-dwelling animal types. Further, the result indicated that the abyss harbours a specially adapted fauna, distinct from the fauna of the continental margins. Also, the results provided significant evidence that community structure of the foraminifera and polychaetes differ substantially on scales of 1,000 to 3,000 across CCZ.

2 Polymetallic nodule mining – status and risk

This report seeks to understand some of the major barriers to the commercialisation of deep seabed mining and the technical developments necessary to achieve it. Part 1 of this volume has provided a general overview of seabed resources and their environment. Part 2 (this part) will introduce the field of deep seabed mining for polymetallic nodules (PMN) particularly from the view of commercial risk and provide some analysis to understand the major barriers to its commercialisation. Following this Part 3 will describe some new engineering concepts to address these barriers.

2.1 Risk

Detailed financial analyses of marine mining ventures have estimated that in order to attract investment the required Internal Rate of Return (IRR) for a mining venture must be over 30% (Little, 1979, Agarwal and Goodrich, 2003, Andrews et al., 1983). This is due to the high investment risk inherent in marine mining. The term 'risk' in this context specifically refers to unpredictability in corporate outcome variables or 'uncertainty' (Miller, 1992). This uncertainty impacts on corporate performance and is an important factor in strategic management and organization theory (Miles et al., 1978, Pfeffer and Salancik, 1978).

Risk management and the Capital Asset Pricing Model were developed to incorporate the concept of risk into corporate decision making. CAPM was first designed by (Traynor, 1961, Sharpe, 1964, Mossin, 1966, Lintner, 1965b, Lintner, 1965a).

CAPM is now widely used to calculate the required rate of return from an investment according to its total risk. It is particularly relevant for investments in new fields that employ new technology as the outcome uncertainty is commonly much greater than in established fields using a variety of proven technologies.

To manage risk experts have attempted to categorise the full range of uncertainties facing a firm. Table 2.1 to Table 2.3 below illustrate some of the categories risk can fall into.

Table 2.1: Industry Uncertainties

Input market uncertainties	
	Quality uncertainty
	Shifts in market supply
	Changes in the quantity used by other buyers
Product market uncertainties	
	Changes in consumer tastes
	Availability of substitute goods
	Scarcity of complementary goods
Competitive uncertainties	
	Rivalry among existing competitors
	New entrants
	Technological uncertainty
	Product innovations
	Process innovations

Table 2.2: Firm Uncertainties

Operating uncertainties	
	Labor uncertainties
	Labor unrest
	Employee safety
	Input supply uncertainties
	Raw materials shortages
	Quality changes
	Spare parts restrictions
	Production uncertainties
	Machine failure
	Other random production factors
Liability uncertainties	
	Product liability
	Emission of pollutants
R&D uncertainty	
	Uncertain results from research and development activities
Credit uncertainty	
	Problems with collectibles
Behavioral uncertainty	
	Managerial or employee self-interested behavior

Table 2.3: Organizational Responses to Uncertainties

Financial risk management
Forward or futures contracts
Insurance
Strategic management
Avoidance
Divestment
Delay new market entry
Low uncertainty niches
Control
Political activities
Gain market power
Exchange of threats
Vertical integration
Horizontal mergers and acquisitions
Cooperation
Long-term contractual agreements with suppliers or buyers
Voluntary restraint of competition
Alliances or joint ventures
Franchising agreement
Licensing and subcontracting arrangement
Participation in consortia
Interlocking directorates
Interfirm personnel flows
Imitation
Imitation of product and process technologies
Follow other firms in moving into new markets
Flexibility
Diversification
Product diversification
Geographic diversification
Operational flexibility
Flexible input sourcing
Flexible work force size
Flexible work force skills
Flexible plants and equipment
Multinational product

Risk management procedures attempt to comprehensively cover the full range of uncertainties facing operations. With regards to the nascent field of deep sea mining both industry uncertainties (technological uncertainty) and firm uncertainties (R&D uncertainty) have their origins in the technical developments required for marine mining.

Miller goes on to list some of the organizational responses to uncertainty (see Table 2.3). Organisational responses are formalized in the risk management field to provide good governance standards for stakeholders.

Technology risk

Among the various sources of risk the impact of new technology as described above has become an important consideration often referred to as 'technology risk' (Mankins, 2009). Technology risk and operational risk are particularly high for seabed mining ventures that depend on new technologies operating in poorly-described hostile environments. Among the many different sources of risk for a marine mining venture this report will address technology risk directly by proposing new concepts based on a review of field test data and distilling them down to underlying principles to inform the design stage of a seabed exploitation venture. This approach is well articulated by the Lloyds Register Risk Management consultancy services;

'A risk-based approach helps you assess the ability of your ships and marine engineering systems to reach the required levels of performance…

..Risk assessment methods can be particularly effective during the design stage, when changes can be more easily accommodated and alternative design solutions explored.'

- From http://www.lr.org/sectors/marine/Services/Consultancy/Riskmanagement/Riskmanagement.aspx

Research and development of new technologies is key to increasing the effectiveness of an operational system. If R&D is executed poorly the resultant technology can lead to reduced effectiveness and increased risk (Mankins, 2009). Early research and development in deep sea nodule mining technology resulted in lower than expected yields. The high cost and poor reliability of field-tested technology has contributed directly to an inflated required IRR assessment (over 30%). One of the major routes by which technology R&D has effected increased risk in mining ventures is through poor reliability and increased downtime. Research on the nodule collector subsystem was critical to downtime and as a consequence directly impacted the commercial risk environment.

The following sections will discuss the mining systems and some of the key technologies and major non-technological issues that contribute to this high risk assessment.

2.2 Review of previous mining ventures

Polymetallic nodules were first identified during the scientific voyage by HMS Challenger in 1868. The commercial exploitation of these resources was first seriously proposed by John Mero in 1959 (Mero, 1959). Since this time there have been a number of academic and commercial projects conducted to assess the feasibility of harvesting nodules for their metals.

The mining of polymetallic manganese nodules received considerable attention in the 1970's and 1980's due to the spike in copper and cobalt prices (Martino and Parson, 2012, Yamazaki, 2008). During this time many processes for extracting and processing nodules were developed and they remain the only proven methods for nodule mining today.

Due to the United Nations Convention on the Law of the Sea (UNCLOS) and the establishment of the International Seabed Authority (ISA), exploration licenses are restricted to groups representing participating countries that agree to the ISA's terms and apply for a license. The groups that have carried out nodule mining to date are listed in Table 2.4 below. Typically these groups are organised as a consortium with part or full funding from the government involved. Table 2.4 also lists the volume of nodules recovered as part of these projects. To date only exploration licenses have been issued, therefore the number of nodules recovered is restricted to evaluation purposes only.

Table 2.4: Previous nodule mining ventures and yield

Organization/Consortium name	Members	Year	Sampling Yield
India	NIOT (India) DOD (India)		
De Beers Marine			
Kennecott Consortium (KCON)	Sohio (USA) Rio Tinto Zinc Corporation (UK) British Petroleum (UK) Noranda Mines (Canada) Mitsubishi Group (Japan)	1974	
Ocean Mining Associates (OMA)	US Steel (USA) Union Miniere (Belgium) Sun Company (USA) Ente Nazionale Idrocarburi (Italy)	1974	500 tons
AFERNOD	CNEXO (FRA) Commissariat a I' Energie Atomique (FRA) Societe Metallurgique le Nickel (FRA) Chantiers de France-Dunkerque (FRA)	1974	
Deep Ocean Resources Development	Japan (C. Itoh and Co.) Japan (Marubeni Corporation) Japan (Mitsubishi Corporation) Japan (Mitsui and Co.) Japan (Nichimen Co.) Japan (Nissho Iwai Co.) Japan (Sumitomo Corporation) Japan (Mitsubishi Metal Corporation) Japan (Sumitomo Metal Mining Co.) National Institute for Resources and Environment (Japan) Deep Ocean Minerals Association (Japan) Technology Research Association of Ocean Mineral Resources Mining System (Japan)	1974	7.25 tons
Ocean Management Incorporated (OMI)	INCO (Canada) Metallgesellschaft AG (Germany) Preussag AG (Germany) Salzgitter AG (Germany) SEDCO (USA) Deep Ocean Mining Company (Japan)	1975	1000 tons
Ocean Minerals Company (OMCO)	Amoco Ocean Minerals Co. (USA) Lockheed Systems Co. (USA) Ocean Minerals Inc (USA) Billiton BV (NED) BKW Ocean Minerals BV (NED)	1977	
ISA Enterprise			
Yuzhmorgeologiya	Russia		

Organization/Consortium name	Members	Year	Sampling Yield
Inter Ocean Metals (IOM)	Bulgaria Cuba Czech Republic Poland Russian Federation Slovakia		
COMRA	China		
CRIMM	China		
KORDI	Korea		
KIGAM	Korea		
NOR	Nauru		
Tonga Offshore Mining (TOM)	Nautilus Minerals (Tonga)		
KSB	Germany		
OceanflORE	IHC Merwede (NED) DEME (Belgium)	2011	

Each of these PMN mining systems employ a similar design – 3 major components; the nodule collector, the lifting (riser) system and a processing system.

Risk – Technology and investment

As illustrated in Table 2.4 there have been a number of research programmes conducted by consortia around the world. It is estimated that over one billion US dollars has been spent on nodule mining technology development over the past forty years (ISA, 1999). Despite this expenditure no successful marine mining venture has developed.

Polymetallic nodule mining investments have been assessed to represent very high risk for investors. This was originally established by Arther D. Little (Little, 1979) and reinforced by numerous financial analyses as above. Much of this risk is due to the novelty of marine mining ventures. The technology for PMN mining has not developed beyond experimental units and is prone to regular breakdown, high wear, high cost and reduced effectiveness.

This technology risk is manifest in investment risk for financiers of PMN mining ventures. As is the case for most industrial investments, banks will not finance first-of-a-kind plants even after successful pilot scale tests. Operation in the deep sea environment is even more fraught with risk due to the complications of mining combined with maritime risks.

Researchers such as Hoagland and Johnson (Hoagland, 1993, Johnson and Otto, 1986) have emphasized the contribution of technology development to the risk profile for PMN mining. Below is a brief introduction to the various technology components of a PMN mining venture, as well as an introduction to some other key areas of investment risk.

2.3 Collector systems

Published ISA resources include a large number of granted international patents covering nodule collector designs. Ted Brockett and Wilhelm Schwarz presented a useful summary of collector design at ISA's 1999 workshop on Proposed Technologies for Mining Deep-Seabed Polymetallic Nodules (ISA, 1999), and Charles Morgan (Underwater Mining Institute) published an updated review in late 2011 (Morgan, 2011). The following overview of nodule collector technology is drawn largely from these three resources.

The variety of nodule collectors tested to date can be categorized as active or passive, self-propelled or dragged, hydraulic or mechanical (Figure 2.1).

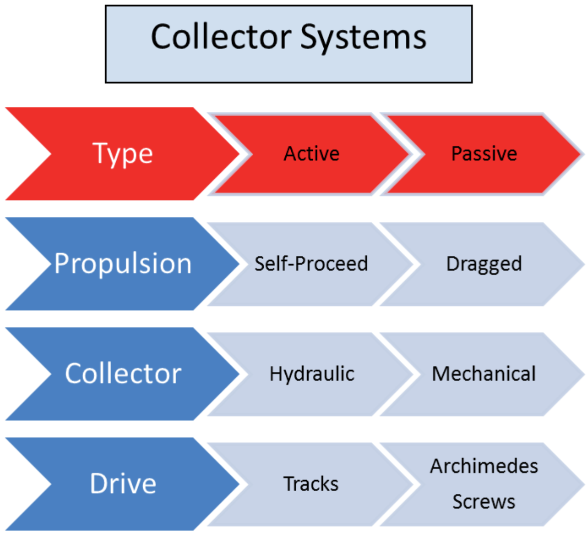


Figure 2.1: Nodule collector designs

Passive collectors have been largely abandoned due to reduced effectiveness from fouling with sediments and the massive bow waves they produce.

Active self-propelled collectors are preferred and current designs include both hydraulic and mechanical mechanisms. Hydraulic mechanisms pick nodules from the seafloor using water jets to create pressure differences according to the Coanda Effect which move nodules from the sediment onto a conveyor as the apparatus passes over them. Mechanical mechanisms perform this function by physical interaction with the sediment. Hydraulic systems have the advantage of less wear, less sediment disturbance and those tested demonstrate lower energy use, however they are far more complex and prone to breakdown. Downtime is generally recognised as a major factor affecting the high cost of nodule mining and simplicity of design is a key requirement for nodule collectors, therefore mechanical concepts have been favoured in recent times.

Many different designs for propulsion of the collector machine have been trialled. The most successful have been Archimedes screws and tracks. Two recent examples provided by Morgan are included in Figure 2.2 below; the Lockheed Bottom Crawler and the Kennecott Bottom Trawler.

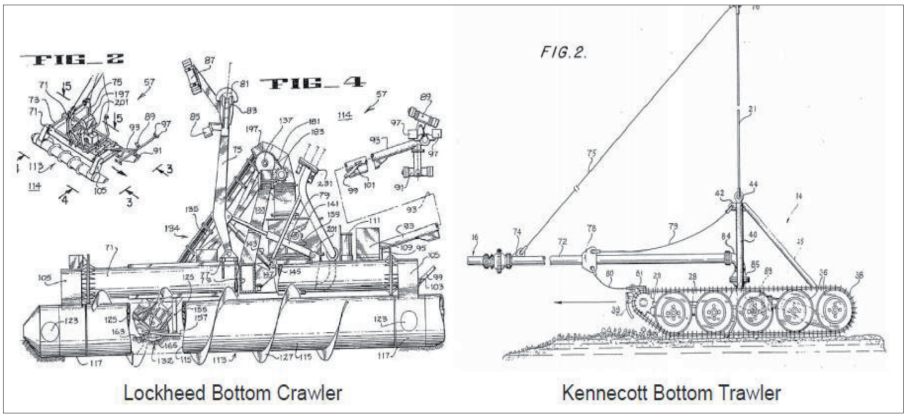


Figure 2.2 Two different designs for nodule collectors as presented by Morgan. The Lockheed bottom Crawler is a self-propelled screw-based design (patented in 2011) whereas the Kennecott Bottom Trawler is a dragged track-based design.

Collector designs are the core technology of PMN mining systems. While risers, ancillary components and processing are adapted from other marine industries the collector is unique to PMN mining and the primary focus of research for marine mining ventures. Due to this the nodule collector contributes significantly to the technology risk and consequently the investment risk for PMN mining ventures.

2.4 Riser systems

To convey collected nodules from the seafloor collector to the surface requires transportation over the 4-6 km distance of vertical water. Many concepts have been proposed for this purpose including line-bucket dredges, shuttle conveyors and riser systems. In-situ leaching has also been suggested. All of the concepts to have been field-tested (Table 2.4) have used riser systems adapted from the oil and gas industry.

Risers may consist of solid pipes (rigid risers), bendable tubes (flexible risers) or a combination of both. The riser runs from a source at the seafloor to a terminal at or near the sea surface. Risers in the oil and gas industry have been limited to around 1,500 m depth, so polymetalic nodule mining requires a significant extension of riser technology.

2.4.1 Pump-based risers

The use of pumps to drive material through a riser system is most commonly found in the oil and gas industry where fluids are required to be conducted to the surface in large volumes. Pumps have also been developed for the dredging industry where solid sediment and aggregate is mixed with seawater to form a slurry.

In the case of polymetallic nodule mining pumps have been tested by the Deep Ocean Resources and OMI consortia. These trials found pumps distributed along a hybrid flexible and rigid riser string to be an effective and efficient means of transporting material, but the weight and energy required is extreme as is the rate of wear on the working surfaces, see Schwarz in (ISA, 1999).

2.4.2 Air-lift risers

Another alternative for riser systems is the air-lift design in which high-pressure air is pumped into the riser to reduce the density of the riser contents and thereby create an upward mass flow. This design is advantageous for nodule applications as the slurry does not come into contact with rotating pump components so wear is significantly reduced. However air-lift systems have proven to be difficult at such extreme depths because the riser contents continue to reduce in density as they rise, creating a ‘run-away’ effect in which the rate of flow is difficult to control. In addition air-lift systems at such extreme depths operate at reduced efficiency due to the very high pressure required to pump air into deep sections of the riser string.

2.5 Processing methods

The extraction of valuable metals from PMN dates back to the 19th century when they were first discovered. Since the nodules are a concretion of many metals the extraction process is complex. In the last decade many different methods of nodule processing have been reported. Processing of PMN for their respective metal values can be divided into two broad categories: (a) Pyrometallurgical Processing and (b) Hydrometallurgical Processing (Fuerstenau and Han, 1983). Some researchers advocate a hydrometallurgical route for economic extraction of metal values. Other studies have argued that hydrometallurgical processing of nodules with a pre-pyrometallurgical treatment is more economical (Senanayake, 2011, Sridhar et al., 1977, Sen, 2010).

In order to gain a detailed understanding of the reaction between metal oxides in the nodule with the active elements/solvent, the physicochemical property of the nodules needs to be ascertained.

PMN are mainly composed of metal oxides including Manganese, Iron, Cobalt, Nickel, Copper and rare earth elements (REE). Typical nodule compositions from various sources are presented in Table 1.1.

The type of processing technique to be used depends largely on the following factors:

a. The composition of the ore grade
b. The cost involved for the power and chemical consumption
c. Process optimization for maximum metal throughput at a minimum cost
d. Possible options for the by-product recovery and their prices
e. Processing waste management

2.5.1 Pyrometallurgical treatment

Pyrometallurgical treatment refers to high temperature smelting or hydrochlorination processes.

Smelting

In this process the nodules are usually dried and subjected to calcination in a rotary kiln, selectively reduced at high temperature (~1400°C) in a submerged electric arc furnace to recover copper (Cu), nickel (Ni) and cobalt (Co) and some Fe while the majority of iron (Fe) and manganese (Mn) components are discarded as slag (Beck and Messner, 1970).

Chlorination process

In this process nodules are chlorinated with excess hydrochloric acid (HCl) gas to convert the oxides of Mn, Ni, Cu, and Co to their corresponding chlorides (Cardwell, 1973). One of the major advantages of this process is that chlorine can be recovered as a by-product and reused, reducing the overall cost. However, hydrochloric acid is highly corrosive; therefore measures should be taken to protect the reaction vessels pipelines etc.

Segregation roasting

In this process polymetallic nodules are treated in the presence of a reducing agent (coke) and a chlorinating agent (generally solid chloride) at temperatures of 700°C to 1000°C. The metal reacts with chloride to form metal chloride, subsequently recovered by screening, leaching, and flotation techniques (Hoover et al., 1975).

Table 2.5: The chemical composition of polymetallic nodules from various source as reviewed by Senanayake (2011)

Origin	Chemical Composition (mass%)						References
	Mn	Fe	Ni	Co	Cu	Zn[a]	
Pacific Ocean	16.8[b]	12.5	0.6	0.2	0.4	-	Heimendahl et al.(1976)
	24.5[c]	11.5	0.7	1.15	0.25	-	Heimendahl et al.(1976)
	23.5	15.1	0.8	0.2	0.5	-	Han and Fuerstenau (1975,1976a,b)[d]
	31.3	5.62	1.61	0.14	1.75	-	Hsiaohong et al.(1992), Hsiaohong (1996)
	13.1	15.8	0.59	0.38	0.11	-	Ninae et al.(1996)
	27.1	4.12	1.23	0.13	1.21	0.12	Vu et al. (2005)
South-West Pacific Basin	16.6	22.8	0.35	0.44	0.21	-	Sen (2010)
Samoan Basin	17.3	19.6	0.23	0.23	0.17	-	Sen (2010)
Peru Basin	33.1	7.1	1.4	0.09	0.69	-	Sen (2010)
Indian Ocean	10	11.4	0.26	0.14	0.23	-	Kanungo and Jena (1988a,b),Kanungo and Das(1988),Kanungo (1999a,b)
	18.3	7.4	0.9	0.13	0.7	0.08	Jana (1993)
	20.1	6.29	0.99	0.1	0.1	0.13	Acharya et al.(1999)
	24	10	1.1	0.14	1.2	-	Kumari and Natarajan (2002a,b)
South Sea	27.7	8.92	1.62	0.02	0.1	0.08	Shen et al. (2007)

[a] Zinc content was not reported by some authors.

[b] Depth 4.9km

[c] Depth 1.27km

[d] Also contains molybdenum

2.5.2 Hydrometallurgical treatment

Hydrometallurgical processing of polymetallic nodules generally refers to low temperature aqueous processes where nodules are leached with hydrochloric acid (HCl), sulphuric acid (H_2SO_4), or ammonia (NH_3) in the presence of suitable reducing agents (Lenoble, 2000). In some cases hydrometallurgical treatment is combined with a pyrometallurgical pretreatment to optimize recovery from the nodules.

Acid leaching process

Polymetallic nodules can be leached in acid media such as HCl and H_2SO_4 at ambient temperature and pressure. This process selectively leaches out Cu, Ni and Co (leachate solution) leaving a residue of Mn and Fe (solid product). Many research projects have optimized the acid leaching process with respect to high temperature and pressure to increase the reaction rate and resultant yield (Fuerstenau and Han, 1983, Glasby, 1972, Senanayake, 2011).

Ammonia leaching process

Metals may be leached from nodules using ammonia in place of acid. The nodules are crushed and ground to a specific mesh size and a pre-reduction is carried out to disrupt the nodule crystal structure. In this step metal (Mn, Fe, Cu, Ni and Co) oxides are reduced and dissolved in the leachate. Among the many variations of this process are ammonium carbonate and ammonium sulphate leaching (Fuerstenau and Han, 1983, Han et al., 1974, Redman, 1973, Skarbo, 1973) discussed in detail in section 3. Another variation of this process is the use of excess cuprous ion to reduce and leach concurrently in ammonia solution. This process, namely Cuprion Ammoniacal Leach (Szabo, 1976) excludes the high temperature pre-reduction process thereby making the process more cost-effective. This process is further elaborated in section 3.

Extraction of Metals from leaching liquors

The separation of metal values from the leach primarily depends on the condition of the system. As described in the previous sections the leach liquor can be either acidic or alkaline in nature. Copper, Nickel and Cobalt can be separated from the acidic leach liquor by contacting with H_2S and precipitating as metal sulphide ‘matt’. The metal values can be separated from ammoniacal leach liquor is described in (Brooks et al., 1970)

2.6 Geo-political context

The most influential driver for deep sea mineral exploitation to date has been security of supply. Of the 7 registered Pioneer Investors in the International Seabed Authority all are governments or state-funded consortia[1].

These are;

- The Government of India
- Institut Française De Recherche Pour L'Exploitation De La Mer (IFREMER)/ Association Française Pour L'Etude Et La Recherche Des Nodules (AFERNOD) (France)
- Deep Ocean Resources Development Co. Ltd. (DORD) (Japan)
- Yuzhmorgeologiya (Russian Federation)
- China Ocean Mineral Resources R&D Association (COMRA) (China)
- Interoceanmetal Joint Organization (IOM) (Bulgaria, Czech Republic, Poland, Russian Federation and Slovakia)
- The Government of Korea

The interest of state enterprises in PMN mining is driven by the critical role such metals play in national economies, including defence. Copper, cobalt, iron and manganese are important components of a wide variety of metal alloys and Rare Earth Elements are becoming an ever more vital component of consumer electronics, clean energy technology and defence applications.

Currently China dominates the REE market and has demonstrated a propensity to control the trade of rare earths through embargoes, taxes and export restrictions. This market intervention poses a threat to the free running of national economies, notably those of Japan Germany and the USA.

Rare Earth Elements are actually found in mineable concentrations in many regions around the world, including in the U.S. and Australia, but they are almost invariably found in association with radioactive thorium (Hensel, 2011). The production of radioactive waste water at mines in developed countries and the need to remediate such waste has led to increased cost. At the same time relatively cheaper labour costs

[1] (DORD is partly owned by the Japan Oil, Gas and Metals National Corporation, previously Metal Mining Agency of Japan – see http://www.jogmec.go.jp/ Yuzhmorgeologiya is one of the leading Russian scientific organizations – see http://en.ymg.ru/w/Business_Card IOM is an intergovernmental organization – see http://www.iom.gov.pl/welcome.htm

in China and more relaxed environmental requirements has allowed Chinese producers to outcompete those in the developed countries and as a consequence over 90% of the world's rare earth market is supplied from China.

Under these conditions other states see a strategic value for PMN resources beyond their extrinsic market value. An active PMN mining industry, even at small scale provides an important check to intervention by extra-commercial forces. This condition has been the primary driver for PMN mining development and the few important research efforts to have studied the field to date have only done so due to the geo-political context.

2.6.1 Legal/regulatory environment

The development of marine resources falls under the jurisdiction of two separate regulatory regimes depending on the location of the resource. The overarching legislation that defines these boundaries is the United Nations Convention on the Law of the Sea (UNCLOS). If located on a continental shelf (up to 350 nautical miles offshore) a resource is fully within the jurisdiction of the government claiming that region. This is analogous to the similar situation with marine fisheries which exist within a nation's Economic Exclusive Zone (EEZ). Beyond 200 nautical miles offshore (or 350 nautical miles offshore if specified) the resource is considered to lie on the Deep Seabed (The Area), analogous to the 'high seas' or 'international waters'. Resources located on the Deep Seabed are within the jurisdiction of the International Seabed Authority (ISA), created to administer the Law of the Sea.

Currently UNCLOS is structured to support the principle of 'the common heritage of mankind' according to which international resources such as those found on the Deep Seabed belong to humanity as a whole and the benefits of their exploitation should be distributed fairly among all countries. In pursuit of this principle the International Seabed Authority is empowered under the Enterprise clause within UNCLOS (section XI) to a share of benefits of a marine mining venture within The Area for distribution to developing countries through approved humanitarian channels.

As a consequence the legal environment in which contractors operate is complex and constantly evolving. No exploitation licenses have yet been granted, and there have been numerous changes to UNCLOS and the ISA charter since its inception. The USA still refuses to ratify the convention and negotiations continue. At present the ISA has the power to charge fees, enforce compliance with environmental protection and maintain ownership of license areas at the cost of contractors. The ultimate structure of an exploitation license is not clear today and is a significant source of uncertainty for commercial interests seeking to invest in PMN mining in the Area.

2.7 The marine environment

2.7.1 Environmental impact of deep seabed mining

In this section environmental issues associated with different activities of deep seabed mining are introduced and classified according to the location of the impact.

Figure 2.3 shows seabed mining activities with potential environmental impact. These activities are:

1. Disaggregation and/or gathering ore on the seafloor.
2. Lifting of the ore to surface, usually with seawater.
3. Separate ore and seawater on board the vessel. Seawater is then filtered and returned to the sea at an appropriate location, which can be
    a. Sea surface
    b. Deep water, just above the seafloor or at some level above.
4. Possible further processing of the ore on board the vessel.
5. Transporting of the ore to shore for metallurgical processing.
6. Metallurgical processing.

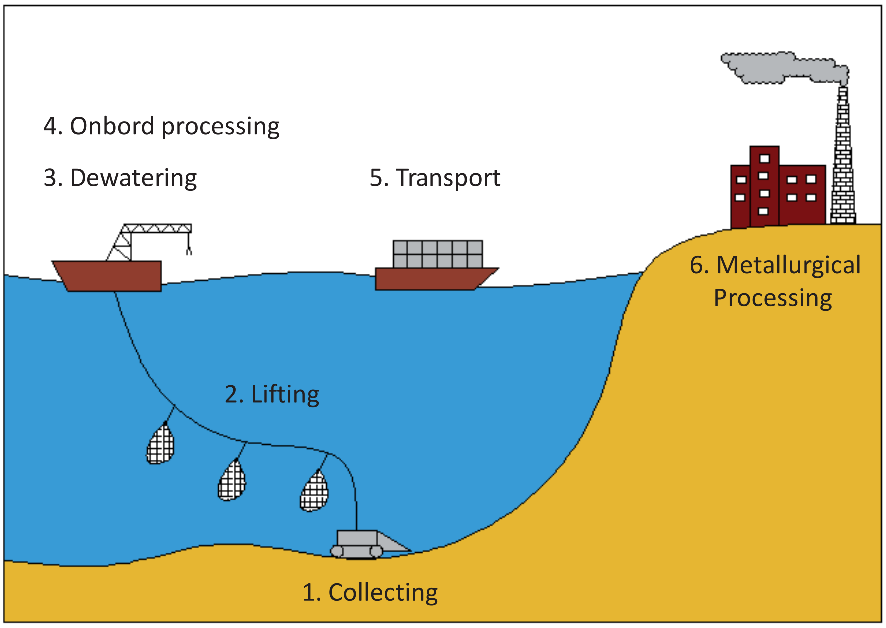


Figure 2.3: Seabed mining activities with potential environmental impact

The environmental impact from deep sea mining can be divided into three main environmental problem areas (Markussen, 1994, Halfar and Fujita, 2007, http://www.nautilusminerals.com/):

1. **Impact on the seabed**: As the cutter and/or collector unit gathers ore it will destroy the top layer of the seabed causing major disturbance and disruption to the flora and fauna in the mining tracks. In addition, a particle plume will be created by the cutter head or the propulsion system of the collector unit which will stir up sediments. As a result in sediment rich areas organisms in and around the tracks will be partially or entirely buried. In the areas where sediment coverage is low (such as recently created ocean floor around active hydrothermal vent systems, where mining for seabed hydrothermal sulphides may potentially become important) there is a likely potential of smothering, clogging and contamination of vent communities by drifting particles. For organisms found in the mining tracks a mortality rate of 95-100% may be expected.
2. **Discharge of waste water from the mining ship**: The ore collected and crushed on the seabed will be brought to the surface as slurry containing both crushed ore and water. When the slurry reaches the surface there will be a partial discharge of waste water containing particles and trace metals. Depending on the discharge location of the waste water the discharge may interfere with light penetration and reduce photosynthesis in the surface layers. Furthermore, the waste water may be considerably colder then surface water.
3. **Onshore processing**: Onshore processing produces waste water, tailings and slag. Here roughly the same problems will be encountered as in land-based mining operations, although the ore composition and resultant waste from seabed mining may differ from that of land-based mines.

There are other types of environmental impact from deep sea mining, such as the possibility of accidental discharge of oil or ore during transport, noise/vibrations on the seafloor and aerosols at the surface. These impacts are usually not identified among the major environmental problem areas of deep sea mining in the literature reviewed (Markussen, 1994, Halfar and Fujita, 2007, ISA, 2008b, ISA, 2011). In the following sections environmental impact issues specific to mining of polymetallic nodules in the Pacific Ocean will be addressed in more detail.

2.7.2 Mining of polymetallic nodules in the Pacific Ocean

Over the last decade a number of studies were carried out to investigate the biological environment of potential mining areas of polymetallic nodules in CCZ and the impact mining activities would have on the environment of this area (ISA, 2011), (ISA, 2008b) and references therein). Based on the performed studies ISA summarizes the environmental impact of polymetallic nodule mining in CCZ as follows (ISA, 2008b):

- Abyssal nodule mining will affect large areas of the sea floor owing to direct mining disturbance (estimated scales of 300-600 km^2 per year) and redeposition from sediment plumes (over scales of 10-100 km from the mining site). The redeposition range of 10-100 km mainly is due to near-bottom plumes created by tailings from the mining head during nodule extraction from the sea floor. Plumes in the water column derived from sediments attached to nodules during lifting from the seabed will contain orders of magnitude less sediment mass than near-bottom plumes, but may drift for years and disperse for several hundred to over 1000 km, depending on release depth. However, based on the estimated mass flux of lifted sediments and the estimated space scales over which these particles will be deposited after dispersing more than 100 km, resultant deposition rates will be much less than ambient net sediment accumulation rates in the region. Thus the benthic ecological impacts of a water column plume after dispersing more than 100 km are expected to be negligible.
- Each mining claim area consists of 75,000 km^2 of sea floor. Over the 15-year timescale of an individual mining operation it could be mined virtually anywhere within the claim area, so for conservation management the entire claim area must be considered to be potentially directly impacted.
- Benthic ecosystem recovery from mining impacts will be very slow, requiring decades or more for the soft sediment fauna and thousands to millions years for the biota specialising on Polymetallic nodules.
- Over the timescales of benthic ecosystems recovery (millennia), all current mining claim areas will potentially be exploited. The slow ecosystem recovery rates at the abyssal sea floor will cause the environmental impacts of mining to be widespread and simultaneous across CCZ.

To ensure protection for the marine environment from harmful effects of mining operations in CCZ, ISA has established several rules and regulations (ISA, 2000), (ISA, 2002) and (ISA, 2011). Some of the main aspects of the regulations for protection and preservation of the marine environment during exploration and exploitation of polymetallic nodules in the CCZ that may affect Contractor activities in the area are summarized below.

Site specific environmental baseline studies

Every exploration contract for polymetallic nodules shall require the Contractor to gather environmental baseline data and to establish environmental baselines against which to assess the likely effects of its programme of activities. When applying for approval of a plan of work for exploration a description of a programme for oceanographic and environmental baseline studies must be provided. Contractors will provide their environmental data from the CCZ on an annual basis to the ISA. The guidelines for the required environmental baseline studies are provided (ISA, 2002).

Site specific impact reference zones and preservation of reference zones

According to the governing regulations (ISA, 2000) and (ISA, 2011) if the Contractor applies for exploitation rights it shall propose areas to be set aside and used exclusively as impact reference zones and preservation reference zones. "Impact reference zones" means areas to be used for assessing the effect of each contractor's activities in the Area on the marine environment and which are representative of the environmental characteristics of the Area. "Preservation reference zones" means areas 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. Impact reference zones should be designated to be within the seabed claim area actually mined. Preservation reference zones should be designated to include some occurrence of polymetallic nodules in order to be as ecologically similar as possible to the impact zone and to be removed from potential mining impact.

Environmental impact assessment

When applying for approval a plan of work for exploration must be provided together with a description of a programme for oceanographic and environmental baseline studies and a preliminary assessment of the possible impact of the proposed exploration activities on the marine environment. The guidelines for the required preliminary environmental assessment are provided (ISA, 2002) and activities requiring environmental impact assessment as well as an environmental monitoring programme to be carried out during and after the specific activity are:

- Dredging to collect nodules for on-land studies for mining and/or processing;

- Use of special equipment to study the reaction of the sediment to disturbances made by collecting devices or running gear;
- Testing of collection systems and equipment.

The baseline, monitoring and impact assessment studies are likely to be the primary inputs to the environmental impact assessment for commercial mining.

The environmental management plan for the Clarion-Clipperton Zone

On the 26th of July 2012 the Council of the International Seabed Authority adopted a decision to establish an environmental management plan for the Clarion-Clipperton Zone. The environmental management plan for the Clarion-Clipperton Zone establishes nine areas of environmental interest to protect the biodiversity and ecosystem structure and functioning of the zone from the impact of mining of polymetallic nodules in the area, as shown in Figure 2.4. The nine areas of environmental interest span 400 × 400 km each. The placement of areas of particular environmental interest avoided overlap with licence areas, as well as reserved areas where possible. By establishing the nine areas of environmental interest the environmental management plan aims at protecting 30 to 50% of the total CCZ management area. The environmental management is implemented for an initial three-year period which includes the designation of a network of areas of particular interest. The plan will be applied in a flexible manner to allow improvement as more scientific technical and environmental baseline data are available. The decision states also that for a period of five years from the date of the decision or until further review by the Legal and Technical Commission or the Council no application for approval of a plan of work for exploration or exploitation should be granted in the areas of particular environmental interest.

The plan was formulated based on results from extensive scientific studies on biodiversity in the polymetallic nodule ecosystem in the Pacific Nodule Province (ISA, 2008a, Tilot, 2006) and data and assumptions from workshops held in 2007 and 2010. Faunal communities vary across CCZ, with north-south and east-west gradients in productivity, depth and other environmental variables. In order to protect the full range of habitats and biodiversity across the CCZ, destructive seafloor activities must be excluded in particular areas distributed across those gradients. The areas of particular environmental interest were chosen so that they contain large areas with self-sustaining populations and a broad range of habitat variability. Moreover, those areas should not be affected directly by physical activity or indirectly by mining effects such as plumes, although the degree of impacts raised by potential deep sea mining is still unknown. Based on a consideration of environmental and impact data briefly summarized above it was determined that a section of each area of particular environmental interest should be protected. Each section should be at least 200 km in length and width, i.e. large enough to maintain minimum viable population sizes for species potentially restricted to a subregion of the CCZ and to capture the full range of habitat variability and biodiversity within each subregion. In addition each section of particular environmental interest should be surrounded by a buffer zone 100 km in width to ensure that it is not affected by mining plumes from any activities immediately adjacent to an area of particular environmental interest. Thus the dimensions of each full area of particular environmental interest, including the 200 × 200 km section surrounded by 100 km buffer zone, should be 400 × 400 km, as shown in Figure 2.4.

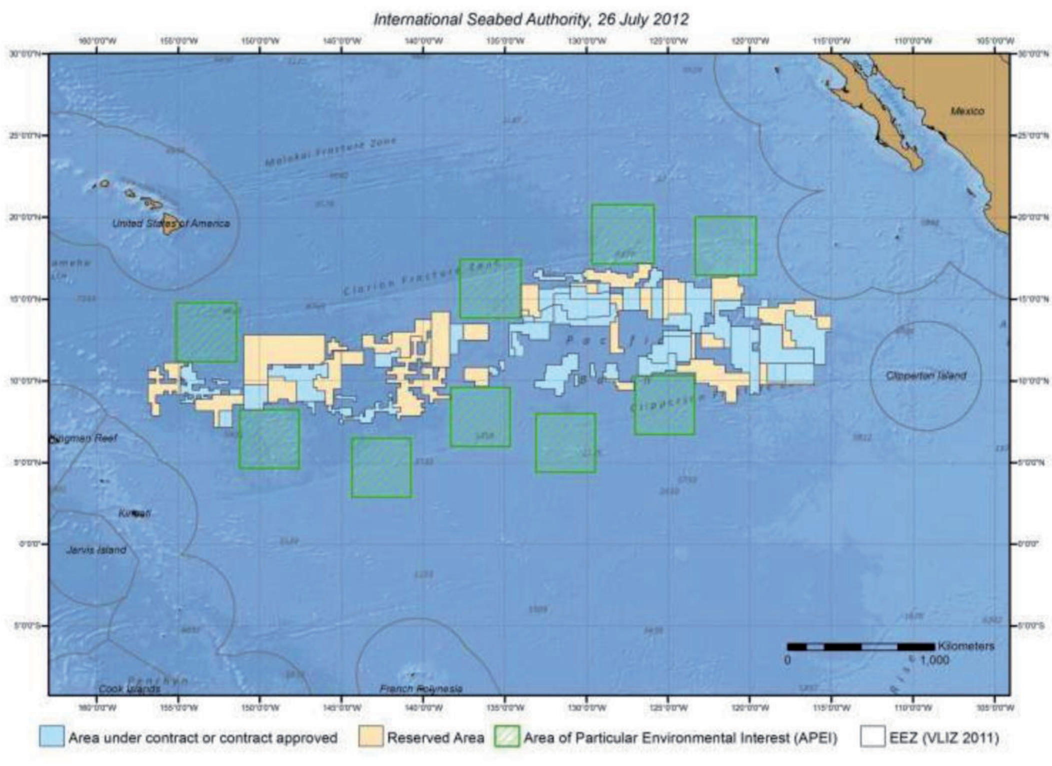


Figure 2.4: Exploration areas, areas reserved for the authority and areas of particular environmental interest in the Clarion-Clipperton Fracture Zone. Abbreviations: APEI – area of particular environmental interest, EEZ – Exclusive Economic Zone, VLIZ – Flounders Marine Institute, WGS 84, World Geodetic System 1984.

2.8 Summary - The marine environment

As described above, PMN mining is expected to pose three primary threats to the environment – disruption of the seabed directly and indirectly at the collector and discharge of waste water from the mother ship during on-board pre-processing and from the land-based processing operations.

The marine environment in regions rich in polymetallic nodules is generally less prone to damage than areas around hydrothermal vents. This is because nodules exist at great depths well beyond the photic zone. The absence of light energy and any other means of harvesting energy mean primary producers exist at very low population densities (biomass). The low biomass at these sites cannot sustain a large population of higher species, so the deep seabed is characterised by an absence of life. This is in stark contrast to hydrothermal vent regions where the abundance of chemical energy in the form of gases such as hydrogen sulphide support a rich diversity of primary producers using chemosynthesis to in turn support a large population of higher species.

On the deep seabed there are however a variety of unique microbial species which are impacted by the disturbance and sedimentation produced by nodule collection operations.

The potential for greater impact is found at sea level where waste water produced by the dewatering of slurry and pre-processing. This waste water poses a threat to the environment through three major constituents; heavy metals, nutrients and fine sediment.

Heavy metals have the potential to poison living systems at dangerous concentrations. Deep sea nutrients also pose a threat to living systems through eutrophication. Details of these contaminants and methods for bioremediation marine mining waste water are discussed in Part 3.

2.9 Current status of seabed exploration and exploitation

Currently PMN mining is not a commercial activity despite over 40 years of research and development and favourable economics. Commercial development has not occurred mostly due to the high level of investment risk (Hoagland, 1993, Little, 1979, Johnson and Otto, 1986, Andrews et al., 1983, Hillman and Gosling, 1985).

It is widely regarded that further technology development will reduce the assessed investment risk through increased efficiency and reduced cost (Sen and Singh, 1999, Handschuh et al., 2001, Lenoble, 2000, Soreide et al., 2001, Yamada et al., 2009).

However technologies for PMN mining have not changed much since the research efforts of the 1970's and 1980's. Today's technologies are still based on oil & gas and ROV systems originally developed for shallow water and specialized small-scale work.

The equipment failures, high rate of wear, downtime and reduced yield from the few successful field tests of PMN mining systems contribute to the assessed investment risk. In addition the potential environmental impact, geo-political context and legal/regulatory environment are not conducive to industrial development.

2.10 Summary – Status and risks

Despite the slow progress in technical development over the past 20 years and the drop in core metal values since the 1980's the Group considers that the biggest single barrier to industrial deep sea mineral exploitation is the commercial risk environment. In particular the regulatory, technical, foreign investment, operational and market risks are clearly excessive for traditional corporate governance standards. What development has occurred in deep sea mining has been driven by state investment on the grounds of supply security and/or conducted in near-shore waters within the Economic Exclusive Zones (EEZ) where the regulatory and foreign investment risks are reduced.

In this section we have provided a brief review of some of the major technological and non-technological issues and barriers to commercial polymetallic nodule mining. With this cursory introduction of the commercial barriers the subsequent section (Part 3) will propose concepts for overcoming some of these barriers and make recommendations for future work based on the experience gained in the process of concept proposal.

3 Concept development

Part 1 of this report has reviewed some of the key technologies applied to deep sea resource exploitation. In Part 2 we detailed the major technical issues confronting polymetallic nodule (PMN) mining in particular. From these two analyses the Group has identified some key components of the deep sea mining system that must be further developed if the field is to be commercialized. This section will detail the conceptual designs proposed by the Group to address these barriers.

The main barrier to commercialisation of PMN mining is the issue of investment risk. As detailed in Part 2, the required internal rate of return (IRR) for a deep sea mining venture is prohibitive. Most authors agree that developments in technology should reduce the required IRR but little progress has been made in PMN mining in the past 20 years. After a review of the industry the Group assessed that the major barrier to commercialization of PMN mining remains high risk related to lack of technology development, inadequate regulatory regime, concerns over environmental impacts and the market for minerals. In the context of the LRET Collegium 2012 convened as a part of systems engineering the Group has proposed a number of specific technical concepts designed to reduce the risk of a mining venture.

Specific concepts have been proposed and some preliminary validation has been performed. Part 3 will detail these concepts and make general recommendations based on the resultant learning from the conceptual development process.

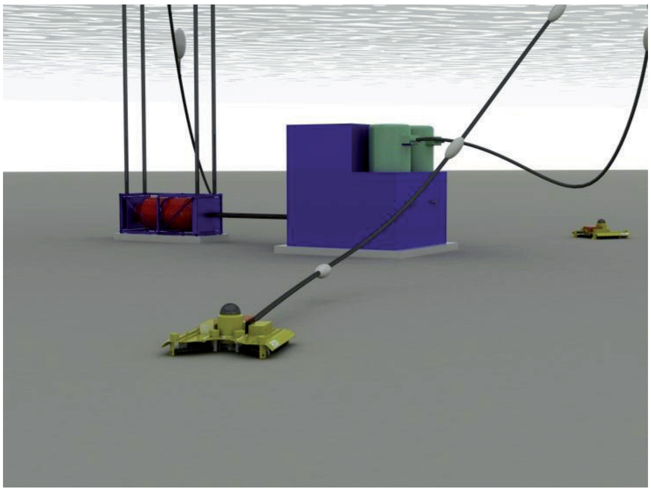
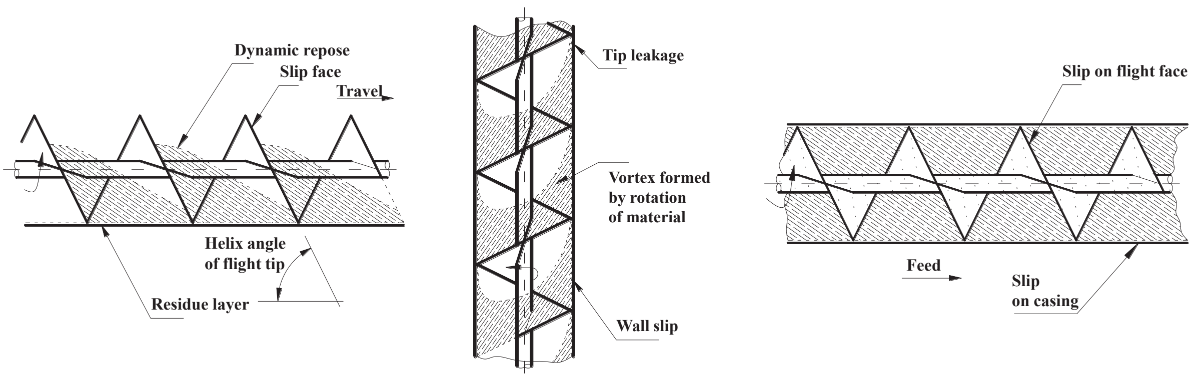


Figure 3.1: Conceptual design of nodule mining

Conceptualization

After a review of the published literature and investigation of the previous nodule collector designs, the Group determined that to reduce complexity and decrease downtime the core mechanisms of a collector system should be based on principles proven to be effective in this environment. Archimedes screws were chosen as a core method for moving material as these have been established to work successfully with the deep seabed material by the OMI collector system (Spickermann, 2012). Archimedes screws have the advantage of being a simple design with continuously moving working surfaces, allowing for the mass flow of material that effectively scours any accumulating bulk. There are three types of screw types as shown in Figure 3.2. Further advantages of the Archimedes screw are presented in Figure 3.2.



(a) gravity mode (b) dynamic mode (c) flood mode

Figure 3.2: Classifications of the conventional screw system.

Table 3.1: Classifications of screw and characteristics.

Screw type	Mode	Description
Conveyors	Gravity	Where the material slides down the face of the screw as an inclined plane
Elevators	Dynamic	Where the material transit is rotated to form a continuous annular vortex, one restrained by boundary friction on the casing.
Feeders	Flooded	Where material occupies the full cross-section of the screw and is promoted to move by the rotating face of the screw blade acting as a moving inclined wedge.

Table 3.2: General characteristics of the Archimedes screw design

Advantages	Disadvantages
Robust construction and reliable performance.	Interaction between the screw and the media handled introduces a behaviour relationship, which must be satisfied for effective operation.
Require relatively imprecise fabrication limits.	
Simplicity of design, construction, and operations with few moving parts.	Screw equipment is not entirely self-cleaning of the product conveyed, because there is an essential operational clearance between the screw flight and the wall of the casing in which it rotates.
Allow for compact cross-section of the machine.	
Enclosure can provide for safety, weather protection and washing down, and the containment of dust, gases, vapours, internal or external pressures, and even explosion containment if required.	Flight tip clearance is also a potential hazard for trapping and fracturing granules that wedge in this clearance space.
The equipment can be designed to stop and restart under load.	Mechanical efficiency of transport is low in comparison to belt conveyors.
The equipment can be made in a wide range of sizes, from about 10 mm diameter to in excess of 2m diameter	Whereas screw conveying can be reliably sized and assessed for power requirements simply, many types of equipment require specialized knowledge and tests in order to prove their performance.
Operating speeds are effective from below 1 to over 500 rpm.	
Designs allow for multiple screws, variable geometry and inclination from horizontal to vertical.	Designers have limited knowledge of material flow properties, hence some screw equipment remain the domain of specialists.

Preliminary design

The primary systems of collector can be divided into three components, the propulsion system, collection guide system (horizontal screws) and the collection system (a vertical screw). These three systems are mainly based on the Archimedes screw.

The primary drivers of the collector's productivity are the sweep area of the collection component and the forward moving speed.

When calculating the productivity of the collector, the density of polymetallic nodules on the seafloor is assumed to be 15.0 kg/m^2. Annual operation time is assumed to be

300 days per year (20 hours per day, 25 days per month). The angle of friction is taken as 44 degrees of “Gravel with some sand”. The summary of the screw, the frame and the assembly designs have been presented on Table 3.3 and Table 3.4.
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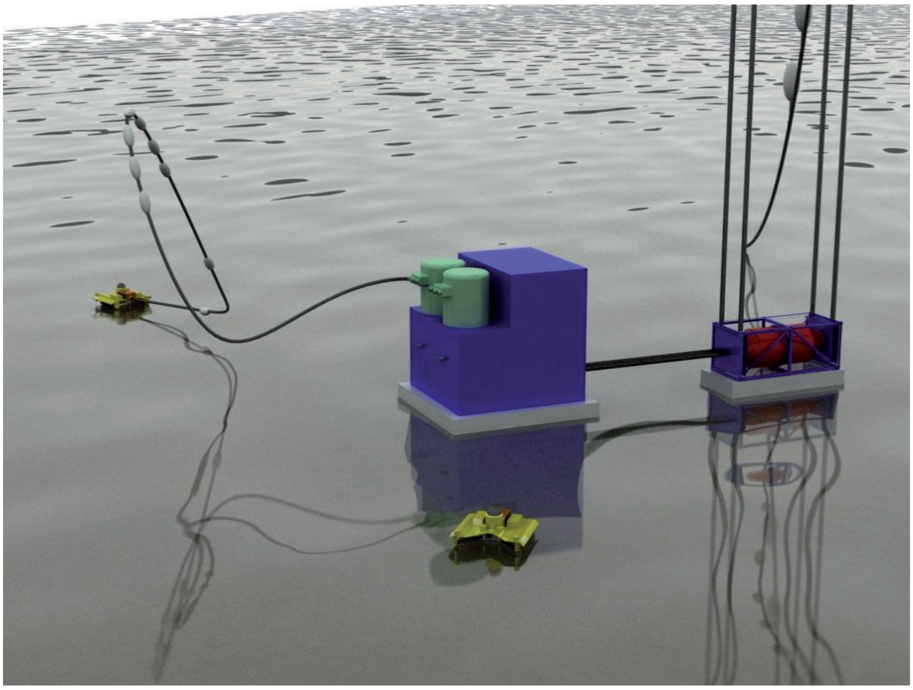
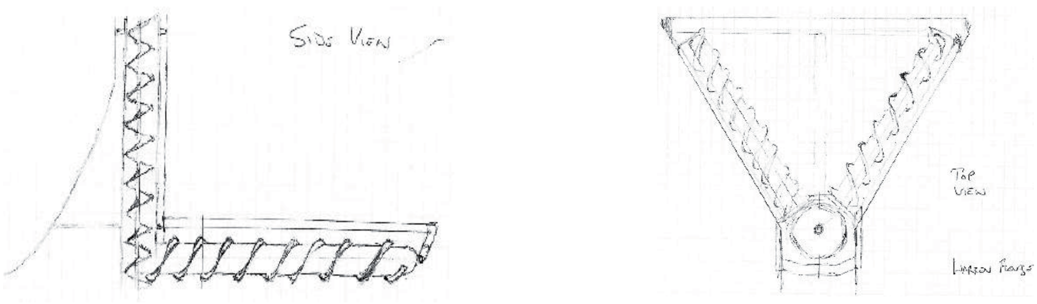


Figure 3.3: The overall concept of the seabed mining.



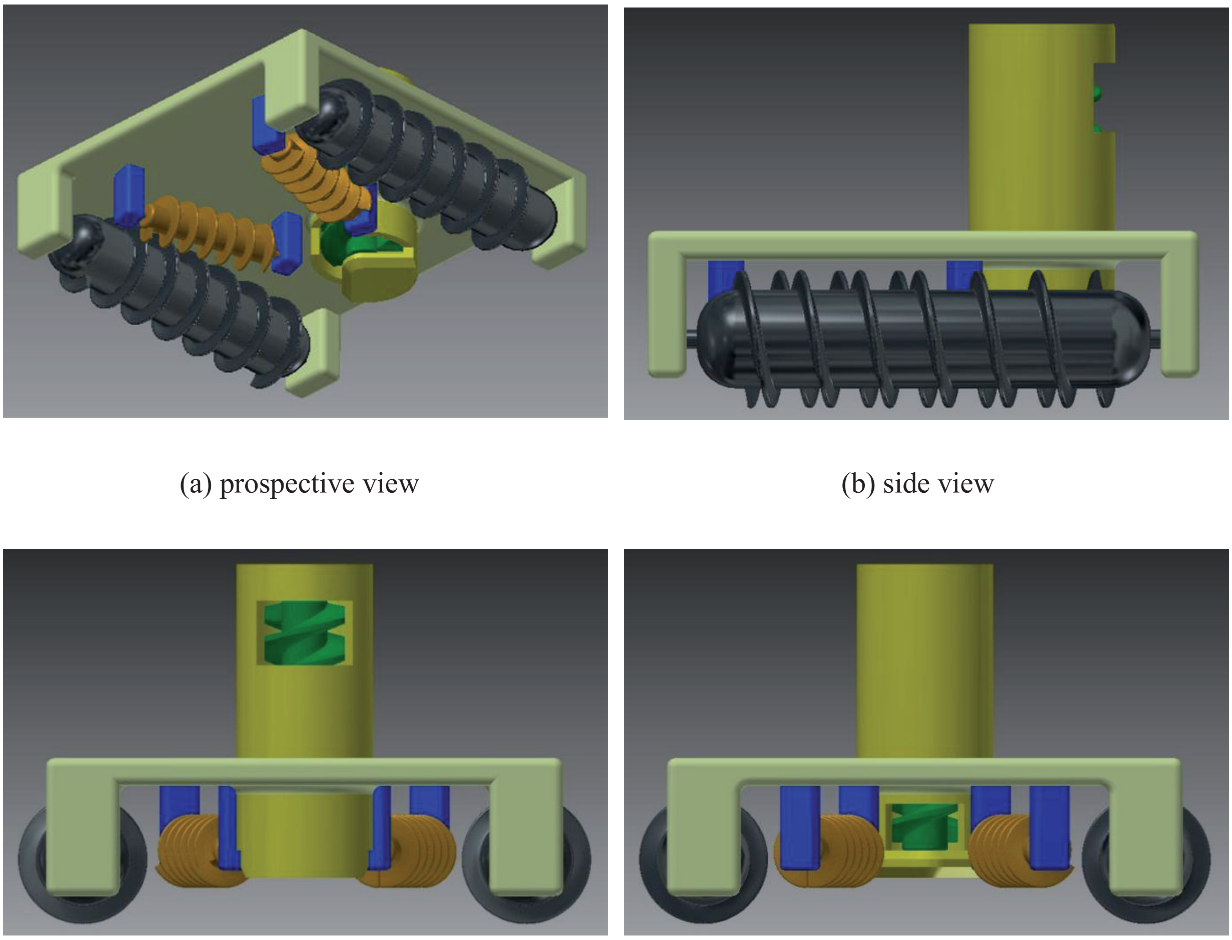
(a) side view (b) top view

Figure 3.4: Hand-drawn sketch of the collector design.

Design Phase I

The main objective of Design Phase I is the realization of the hand-drawn sketch shown in Figure 3.4, to the 3D drawing by the commercial software INVENTOR illustrated in Figure 3.5.

Based on the sketch design of the main collector screws, the preliminary design has been developed. Further, through 3D modelling of the collector the interferences between mechanical components and the layout of the design have been reviewed and their results are applied directly to the next design phase. For example, in the design phase I, assembly 1 has too narrow the sweep area between horizontal screws, so there are two options to increase the productivity of the collector. One is expanding frame width but this would inevitably increase the weight of the collector. The other is shortening the length of the main propulsion screw and moving the collection component forward at the same time. Hence, the sweep area of the collector system will increase without any weight increase.



(a) prospective view (b) side view

(c) back view (d) front view

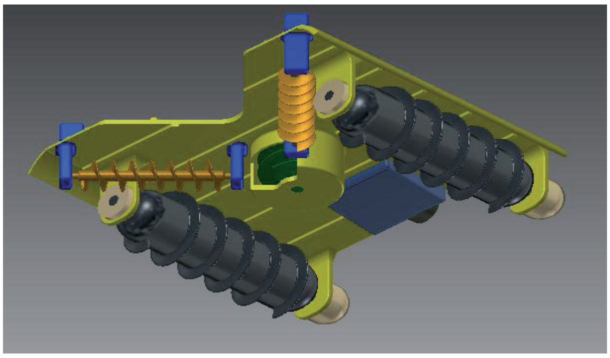
Figure 3.5: Conceptual design of the collector in Design Phase I.

Design Phase II

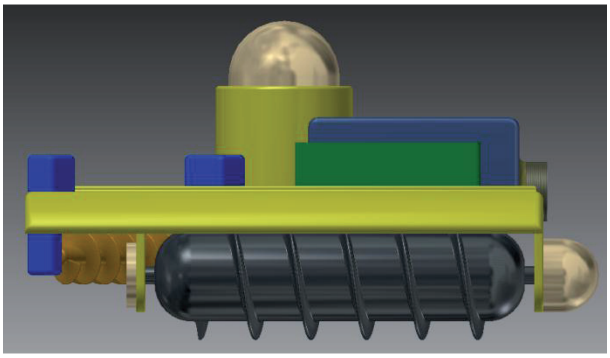
The design goal of design phase II is to decrease the overall weight and increase the productivity of the collector model at the same time. In order to operate the collector on the seabed, the shear strength of the seabed soil must be taken into account for the design stage.

In phase II, the main frame has been designed by stiffeners supported structure and the length of the main propulsion screws have been shortened to reduce the overall weight of the collector system. Further, to increase the sweep area, the position of the collection component moves 600 mm forward, so the angle between horizontal screws is changed from 30 degrees to 90 degrees.

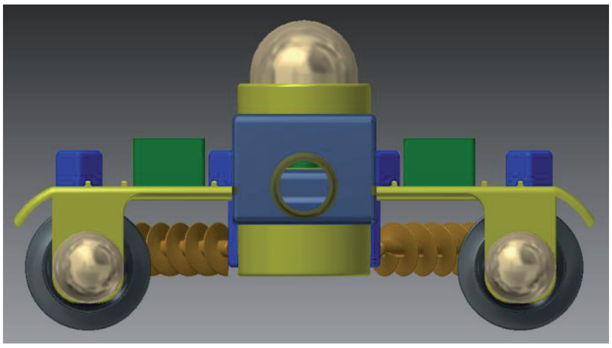
In phase III, the limitation of the screw dimension will be reviewed and taken into account. There are the diameter, the length and the flight dimensional limitations.



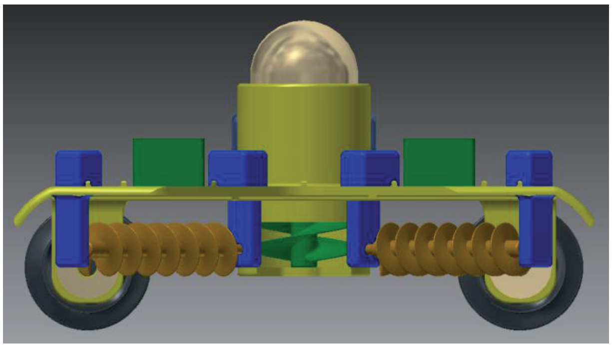
(a) prospective view



(b) side view



(c) back view



(d) front view

Figure 3.6: Conceptual design of the collector in design phase II.

Design Phase III

In phase III, some dimensional limitations have been taken into account for developing practical design of the screw collection components. There are some limitations for the diameter, the length and the flight dimensions. Further, in order to decrease the overall weight of the collector model and avoid the interference between screws, the main propulsion screws and the main frame plate have been re-designed. The results of the design phase III are presented in Figure 3.7 and Figure 3.8.

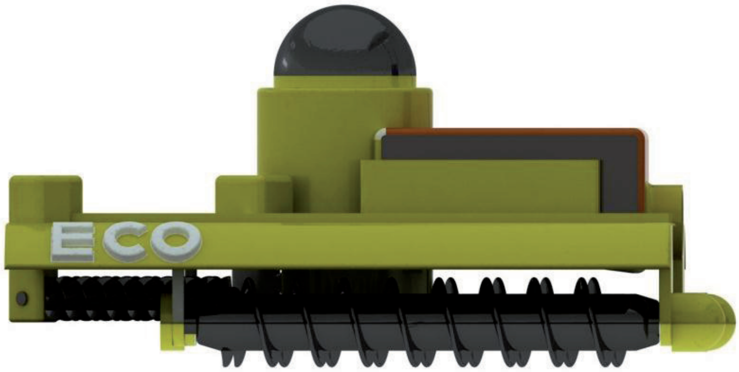
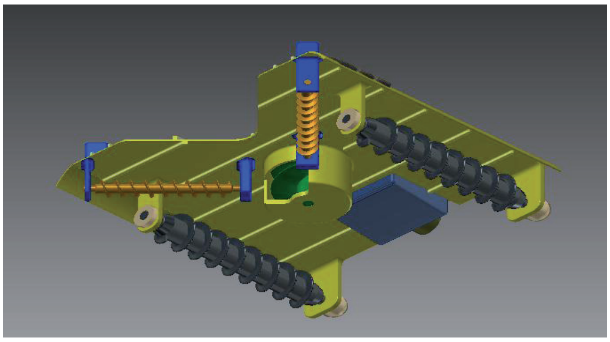
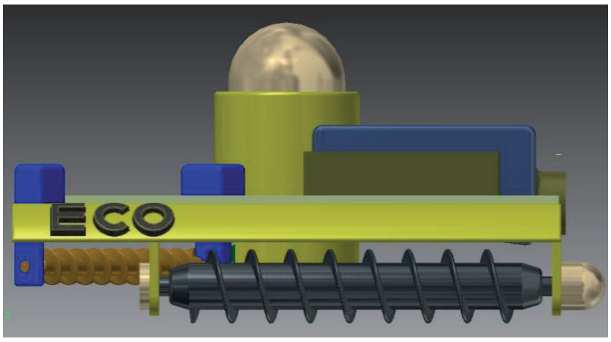


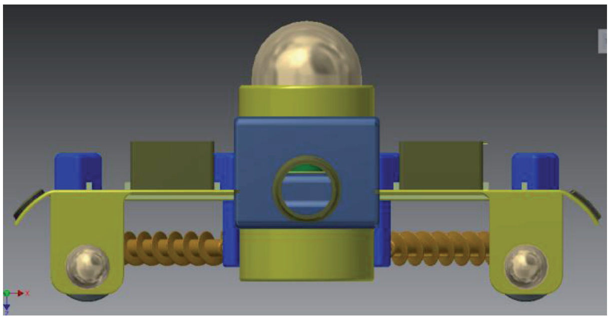
Figure 3.7: Final Conceptual design of the collector.



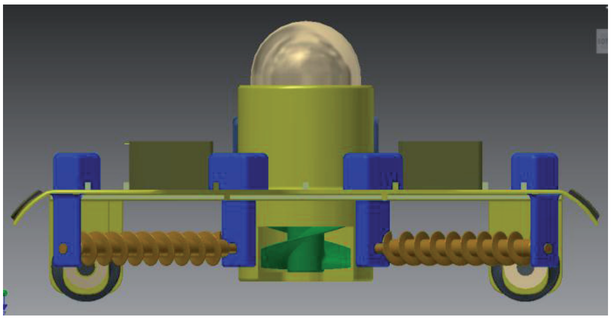
(a) prospective view



(b) side view



(c) back view



(d) front view

Figure 3.8: Conceptual design of the collector in design phase III.

3.1 Component Design

In this part, the detailed dimensions of the collector components including 3 screw systems and frame will be presented in terms of the Design Phase I, II and III.

The overall dimensions, the required power and the weights of the screws are listed on Table 3.3. In order to review the screw designs by the dimensional limitations, the ratio of the diameter and the pitch to the flight depth have been calculated. To estimate the required power for each screw design, the axial load and the turning force have been assessed. The required power of screw designs are 300kW, 3kW and 11 kW for the main propulsion screw, the horizontal screw and the vertical screw respectively. The total weights are about 0.5 t, 0.06, and 0.3 t for the main propulsion screw, the horizontal screw and the vertical screw respectively if the material is used as titanium.

Screw design

The main propulsion screw, the horizontal collection guide screw and the vertical collection screw have been designed and presented in Figure 3.10 to Figure 3.12 below.

Here are some backgrounds for the screw design. Screw boundary shear forces increase with area exposed and the distance at which these forces operate increase with the radius. As a consequence the torque required to start and run a screw increases at least as the square of the screw diameter.

Large screws serve large and long openings, so overpressure also tends to be higher to further raise these torque values. As a result, screws larger than 400mm tend to require very heavy drives, much larger screws than this are generally impracticable. Higher capacities and larger openings for flow are better served by the use of multiple screws than large-diameter units.

In case of cantilever-mounted screws, overall length from around 200 mm to 1000 mm for shaft-less screws, 500 mm to 2000 mm long for screws with centre shafts. The span of screws supported at both ends ranges from around 2000 mm for 100 mm diameter screws, to over 6000 mm long for 400 mm diameter screws.

The maximum ratio of the centre diameter to depth of the flight is about 3 to 1. The flight pitch-to-depth ratio also has practical limits, to avoid clogging by material revolving with the screw, or excessive compacting pressures. The flight pitch-to-depth ratio is in a range from 0.5 to 3.

A feature that causes most difficulty in assessing the theoretical output of a screw is that the helix angle of the flight face varies over the radius from the outside rim, where the angle is $tan^{-1}(\pi D/P)$ to $\pi d/P$ adjacent to the centre shaft, where D= screw outer diameter, d=center shaft diameter, P= screw pitch. A mean effective diameter may be used to secure an approximate average value for the helix.

$$D_m = \sqrt{\frac{D^2 + d^2}{2}}$$

The optimum pitch for maximum forward is when the pitch helix angle, $\theta = 45^o - \varphi_f/2$, where φ_f= angle of surface friction between the screw flight, and the product. This lead to an optimum theoretical output per revolution for a feed screw when the pitch= $\pi D_m \tan(45^o - \varphi_f/2)$.

Material carried within the normal feeder speed range from 15-100 rpm tends to relatively dense at low speeds but more dilated at the faster speed.

The power required to drive a screw is related to speed and torque taken by the screw shaft. The two conditions of start-up and running torque have to be separately assessed. When considering start conditions, in the inlet region, the torque has to overcome the shear strength of the interface area and the resistance to frictional force on the face of the screw face. The axial load, A, and require turning force per pitch length, T, to be

$$\mathrm{A} = \pi D^2 PF \cos(\varphi_f + \theta_{min})$$

$$\mathrm{T} = \pi D^2 PF \sin(\varphi_f + \theta_{max})$$

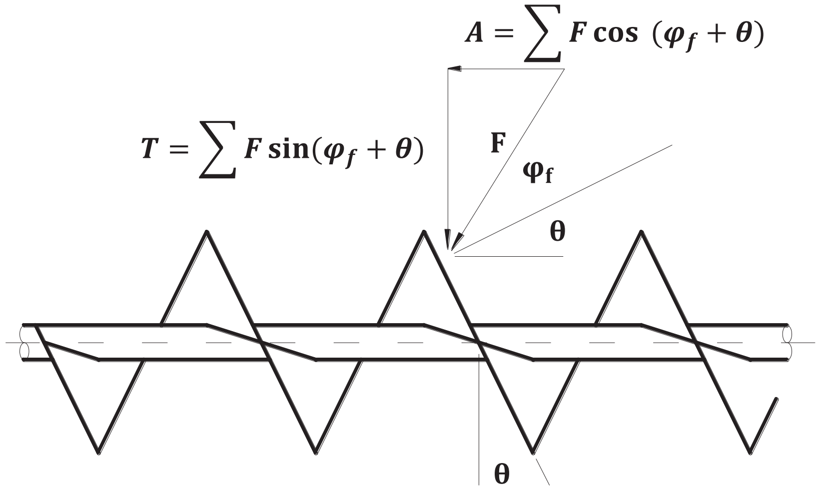


Figure 3.9: Force acting on the flight face

Where, P= screw pitch(m), F= boundary shear strength(kg/m^2), θ= screw helix angle(tan^{-1}(P/πD)), φ_f= angle of friction of the material on the face of the screw flight. The power required per pitch in kW

$$P_p = T(Newton\ metres) \times \frac{rpm}{9550}$$

The total power requirement of the screw design in kW is below.

$$\text{Total power (kW)} = \frac{T \times number\ of\ flight\ pitches \times rpm}{9550}$$

The effective geometry, dimensions, and flight face frictional value are unchanged as the screw continues to perform. The key variable is the shear strength of the interface material, which drops markedly as soon as flow commences. The reason for this fall is that material significantly dilates and shears much more easily, usually to a small fraction of its static value. The force required to shear a high flow rate stream becomes almost an insignificant factor of power requirements. It is normal to find that the running torque is less than half the torque required of first initiate movement.

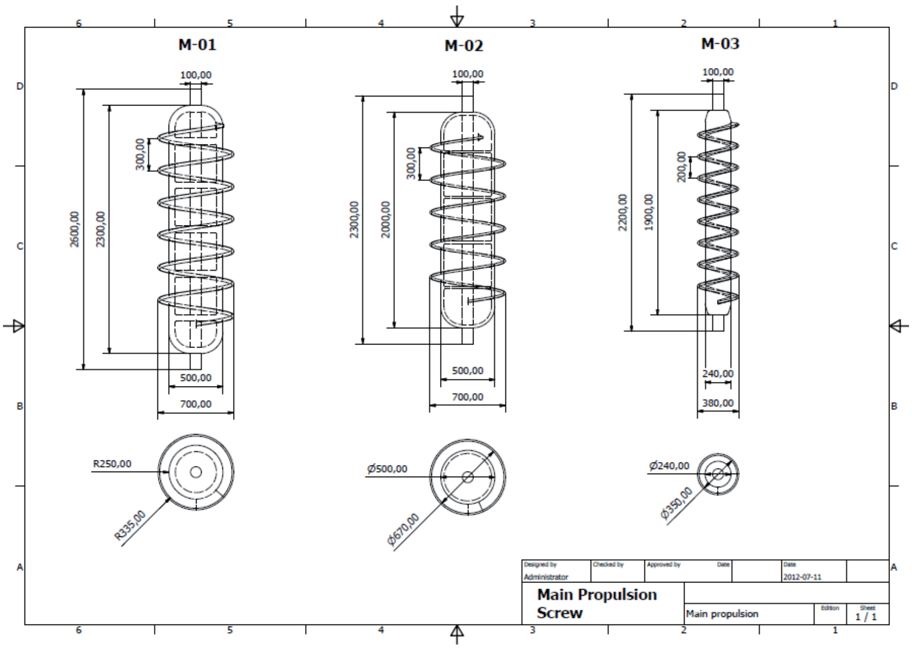


Figure 3.10: Designs of the main propulsion screw in terms of design phase I.

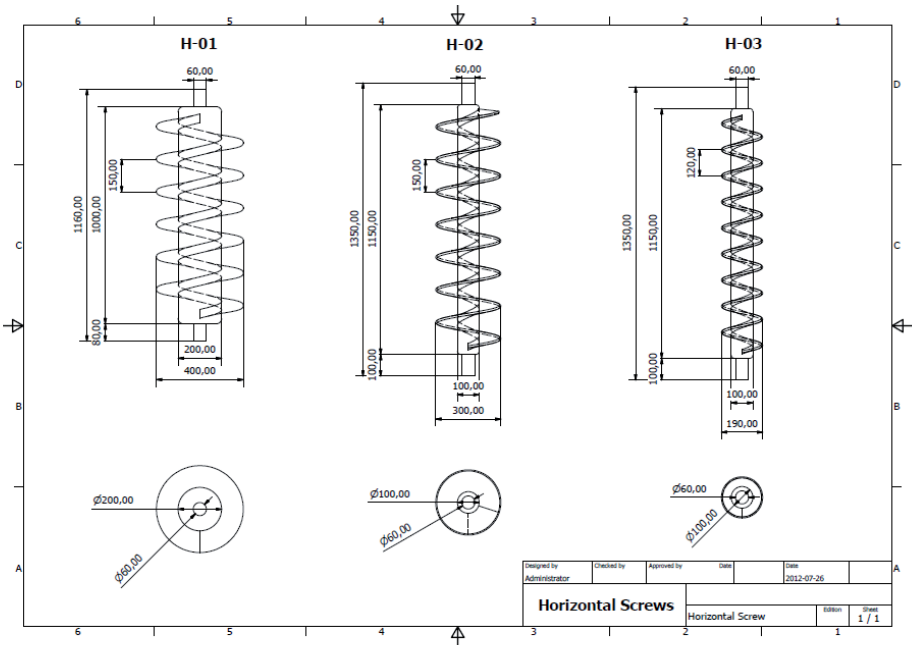


Figure 3.11: Designs of the horizontal screw in terms of Design Phase II.

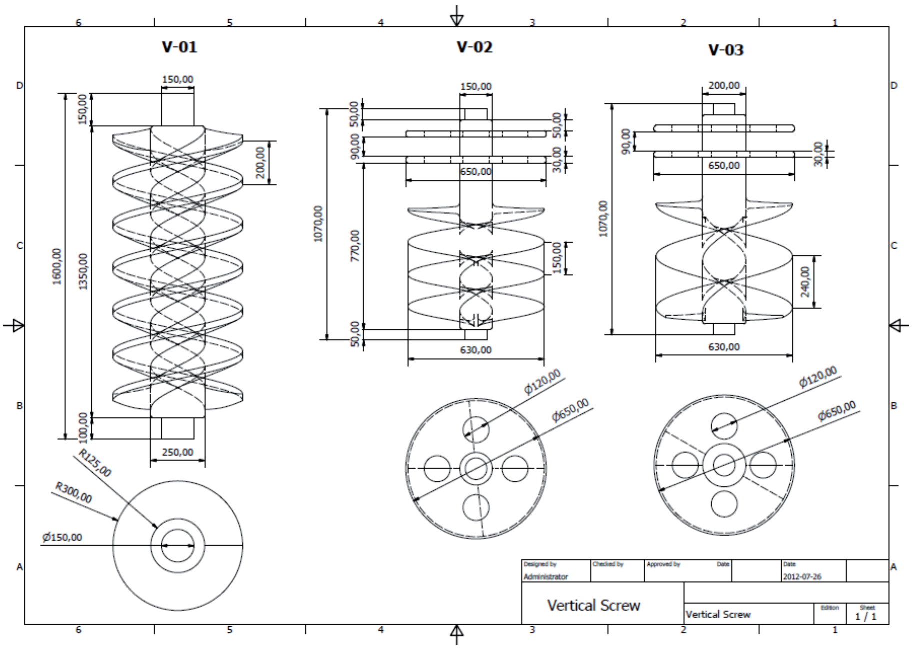


Figure 3.12: Designs of the vertical screw in terms of Design Phase III.

Table 3.3: Design components of screw systems in terms of the Design Phase I, II, and III.

Components		Main Propulsion System			Horizontal Screw			Vertical Screw		
		Phase I	Phase II	Phase III	Phase I	Phase II	Phase III	Phase I	Phase II	Phase III
		M-01	M-02	M-03	H-01	H-02	H-03	V-01	V-02	V-03
Length (mm)		2400.0	2100.0	2100.0	1160.0	1350.0	1350.0	1600.0	1070.0	1070.0
Outer Diameter (mm)		700.0	700.0	380.0	400.0	300.0	190.0	600.0	630.0	630.0
Center Shaft Diameter (mm)		500.0	500.0	300.0	200.0	100.0	100.0	150.0	150.0	200.0
Mean Effective Diameter (mm)		608.3	608.3	342.3	316.2	223.6	151.8	437.3	457.9	467.4
Optimum Pitch (mm)		811.2	811.2	456.5	421.7	298.2	202.5	583.2	610.7	623.3
Flight (mm)	Pitch	300.0	300.0	300.0	150.0	150.0	120.0	400.0	300.0	480.0
	Height	1840.0	1520.0	1520.0	900.0	1080.0	1080.0	1200.0	520.0	520.0
	Lower Span	60.0	50.0	50.0	40.0	30.0	20.0	100.0	35.0	35.0
	Upper Span	30.0	20.0	20.0	20.0	10.0	-	40.0	10.0	10.0
	Depth	100.0	100.0	100.0	100.0	100.0	45.0	175.0	240.0	215.0
Ratio, Diameter/Depth (<<3)		7.0	7.0	3.8	4.0	3.0	4.2	3.4	2.6	2.9
Ratio, Pitch/Depth (0.5-3)		3.0	3.0	3.0	1.5	1.5	2.7	2.3	1.3	2.2
Axial Load (N)		2714.5	2714.5	799.9	443.2	249.3	80.0	2659.1	2198.7	3518.0
Turning Force per Pitch Angle (Nm)		38286.1	38286.1	11282.7	625.1	351.6	112.8	3750.5	3101.2	4961.9
Total Required Power (kW)		1229.4	1015.6	299.3	7.9	5.3	2.1	21.2	10.1	10.1
Weight (ton)	Titanum	1.298	0.665	0.448	0.216	0.080	0.055	0.728	0.236	0.264

Frame Design

In the Design Phase I, the frame had been designed for simple realization of our concept shown in Figure 3.13. Without any considerations for soil bearing capacity, the weight was too heavy. So in Phases II and III the stiffener supported structure has been selected as a solution to reduce the weight depicted in Figure 3.14 and Figure 3.15.

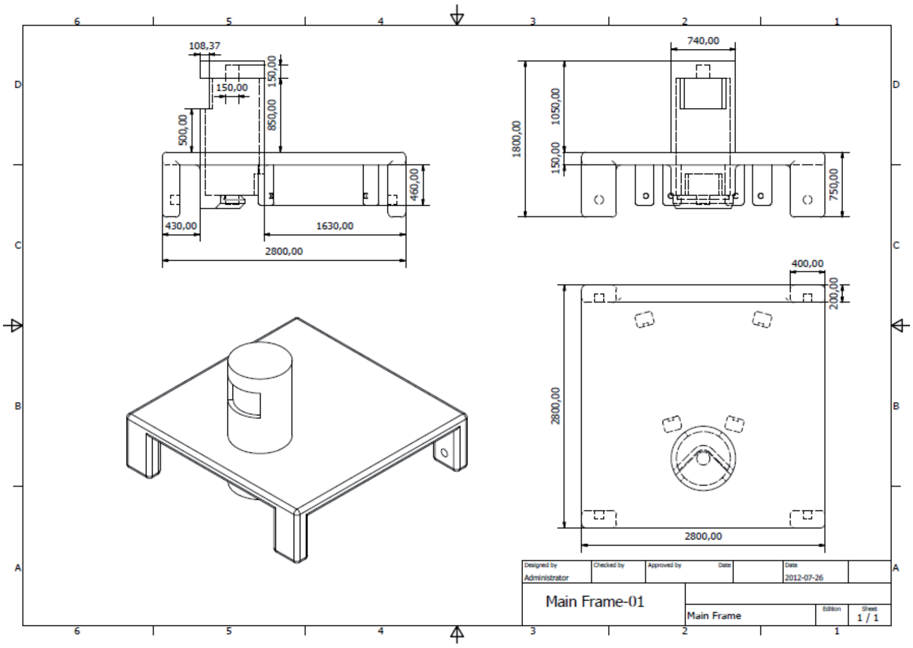


Figure 3.13: Design of main frame of the collector in terms of Design Phase I.

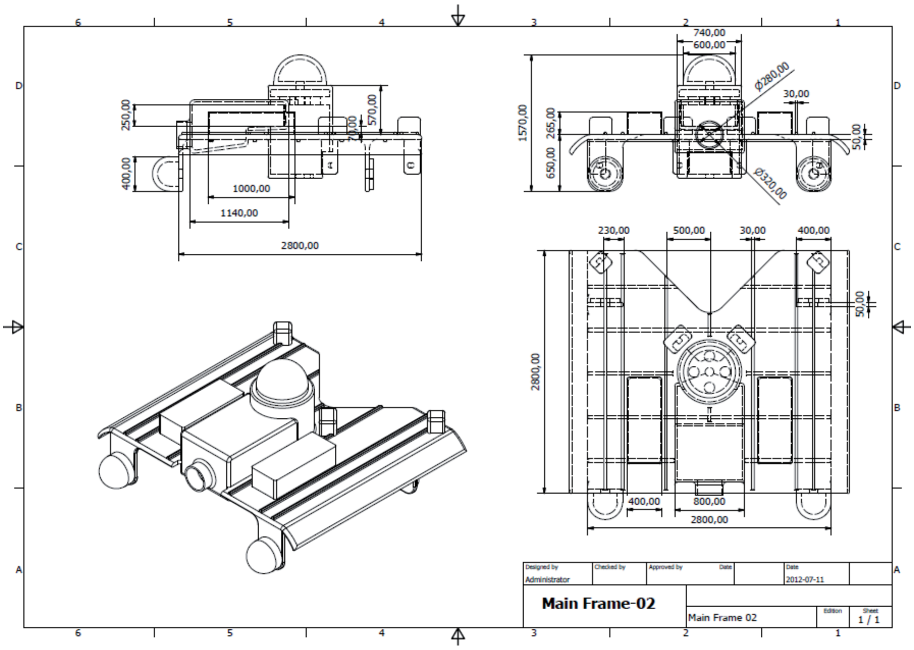


Figure 3.14: Design of main frame of the collector in terms of Design Phase II.

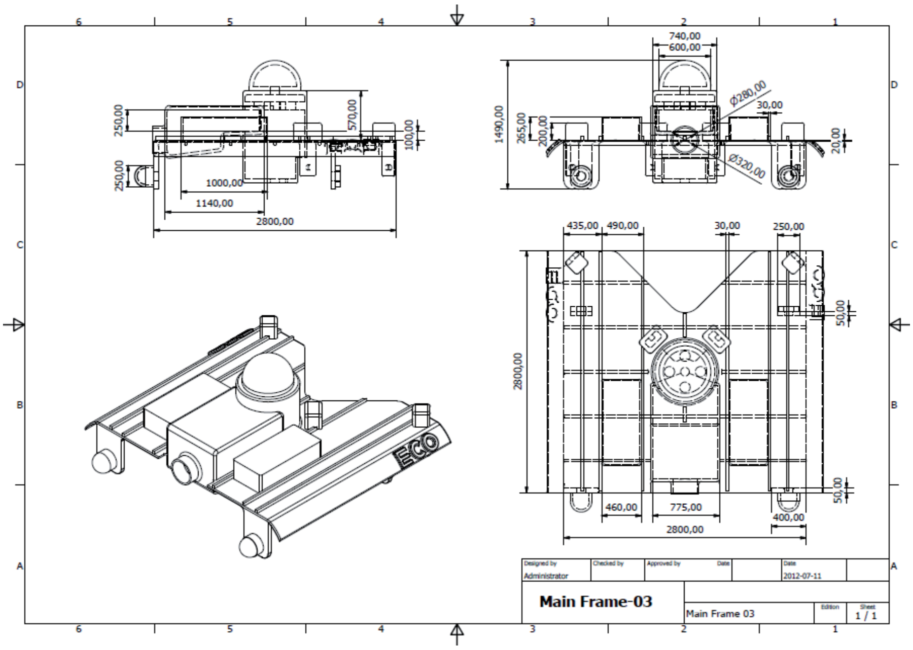


Figure 3.15: Design of main frame of the collector in terms of Design Phase III.

Assembly Design

In the assembly design the mechanical interference and the layout were reviewed. With these processes, the model can be easily modified. Three assembly designs are illustrated in Figure 3.16 to Figure 3.18. The dimensions of the frame, the production rate and the total weight of the collector are presented in Table 3.4 in terms of the Design Phase I, II, and III. The operating rpm of the vertical screw is set to be 20 based on the volumetric calculation. The efficiency of the vertical screw is assumed to be 85% the volume delivered from the surface volume to the vertical screw.

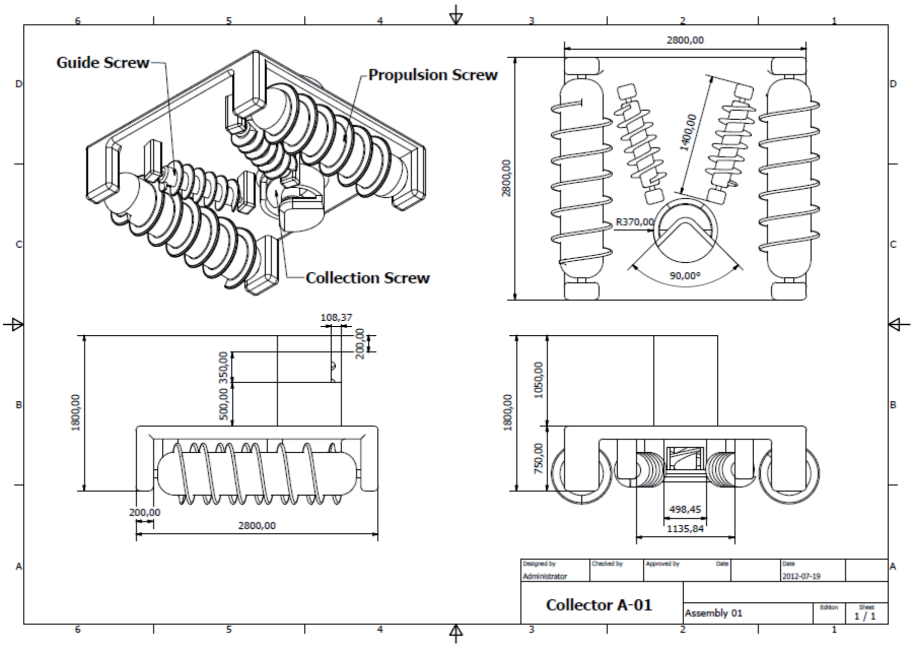


Figure 3.16: Design of the collector in terms of Design Phase I.

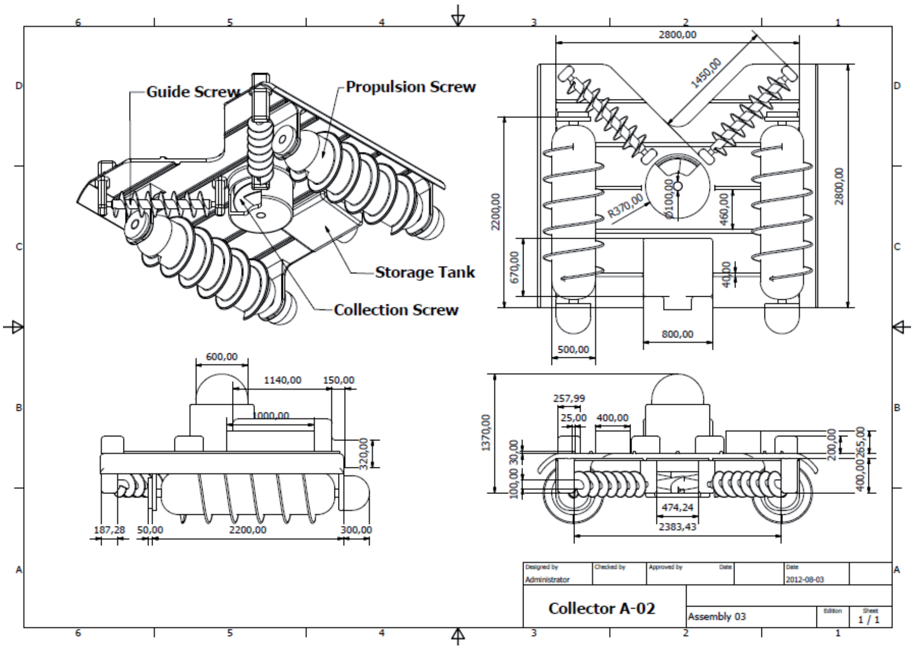


Figure 3.17: Design of the collector in terms of Design Phase II.

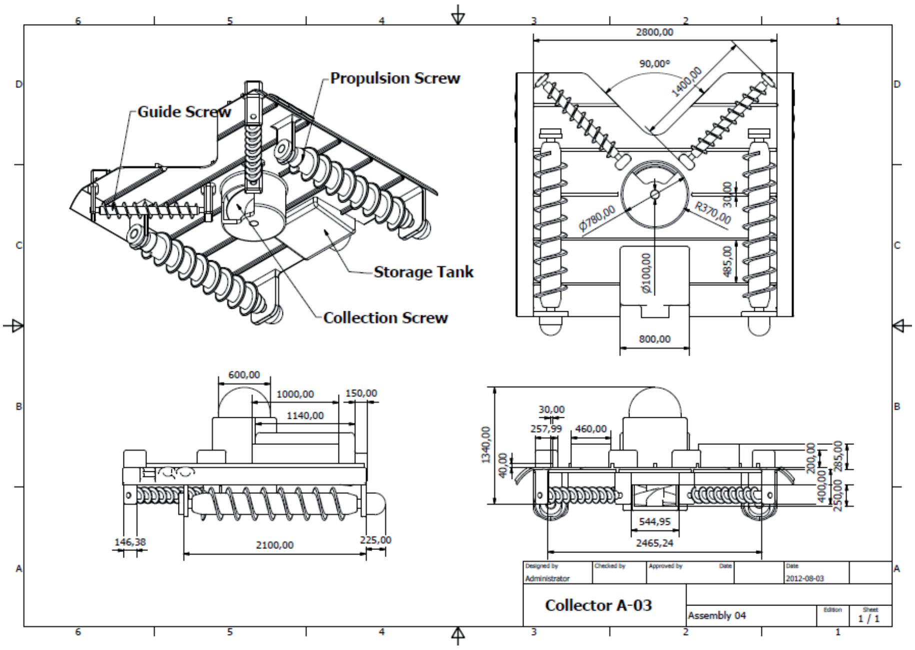


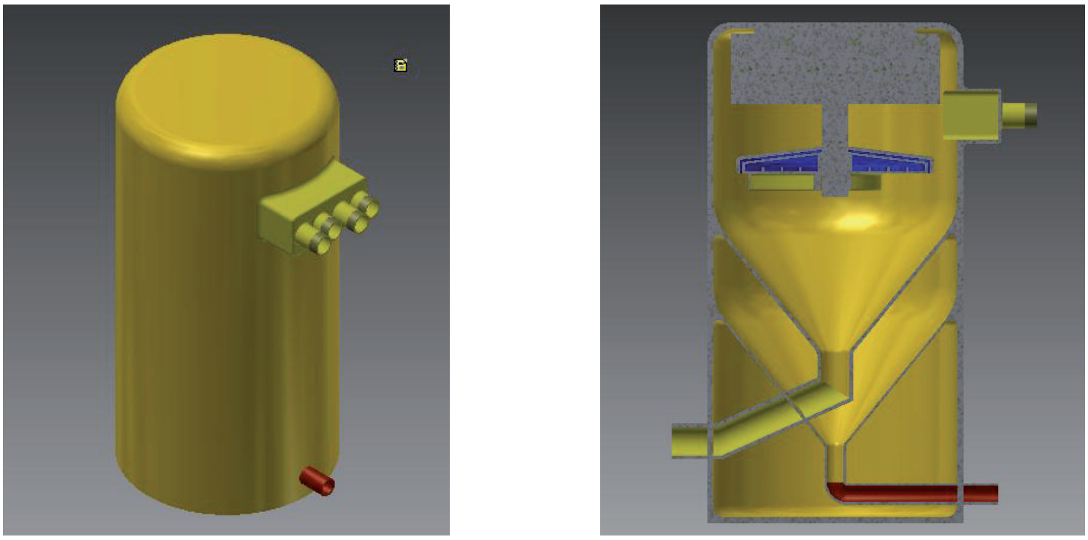
Figure 3.18: Design of the collector in terms of Design Phase III.

Table 3.4: Dimensions, capacities and weights of the collector design in terms of design phase I, II and III.

Model Number			Phase I A-01	Phase II A-02	Phase III A-03
Angle (deg)			30.0	90.0	90.0
Velocity (mm/s)			200.0	200.0	200.0
Horizontal Screw	Inlet	Width (mm)	1,135.8	2,383.4	2,465.2
		Height (mm)	100.0	100.0	100.0
	Outlet	Width (mm)	498.5	474.2	545.0
		Height (mm)	150.0	150.0	150.0
Vertical Screw	Angular Velocity (rad/s)		1.010	3.403	1.894
	RPM		10	32	18
Production Rate	1 Hour (ton)		10.4	21.9	22.6
	1 Day (ton)		208.5	437.6	452.6
	1 Mon (ton)		5,213.5	10,939.9	11,315.5
	1 Year (ton)		62,562.1	131,279.3	135,785.4
Weight	Main Propulsion Screw (ton)		1.298	0.665	0.448
	Horizontal Screw (ton)		0.216	0.080	0.055
	Vertical Screw (ton)		0.728	0.236	0.264
	Main Frame (ton)		13.000	6.724	4.500
	Total (ton)		17.484	8.686	6.034

3.2 Separation System

The sediment from collected nodules is a major issue for seabed mining. When the sediments come to the surface structure or processing unit, a dewatering system is essential. Therefore, in order to decrease the sediment issues a subsea separation system is included in our conceptual design. The conceptual design and the drawings are presented in Figure 3.19 and Figure 3.20.



(a) perspective view (b) side view

Figure 3.19: Conceptual design of the separation system.

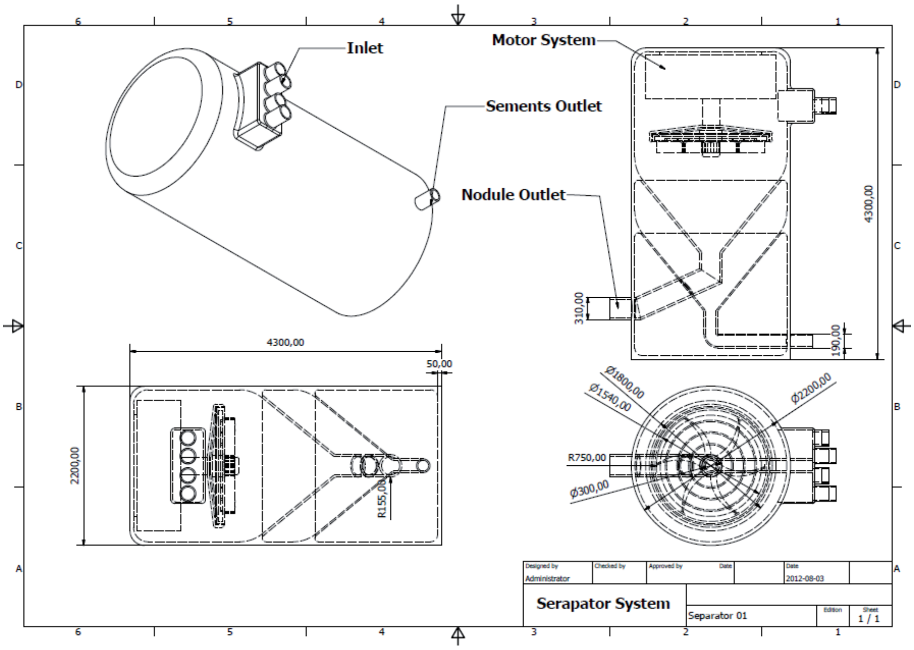
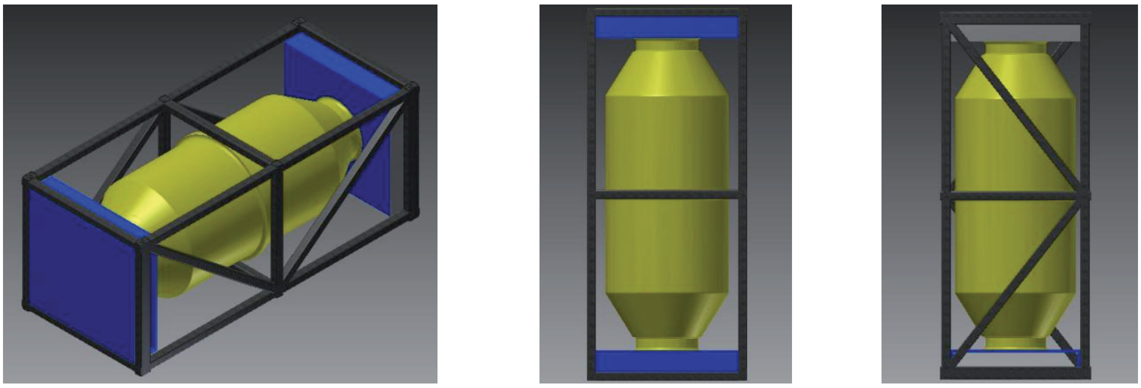


Figure 3.20: Design of the separation system.

3.3 Storage System

In our concept, for the outer dimensions of the storage system we adopted those of a freight container, 20FT and 40FT presented in Figure 3.21 to Figure 3.24. The capacity and weight of the storage systems have been listed on Table 3.5. Each system has two lifting tanks and pressure control valves. When the tank is filled to some level, the lifting systems are activated and filled with a buoyancy media. The storage system can be floated along the guide lines which are linked from the seabed to the surface structure. With the guidelines, the risks of collisions and drifting effect induced by wave, current and wind can be decreased.



(a) prospective view (b) top view (c) side view

Figure 3.21: Conceptual design of the storage system, 20FT size.

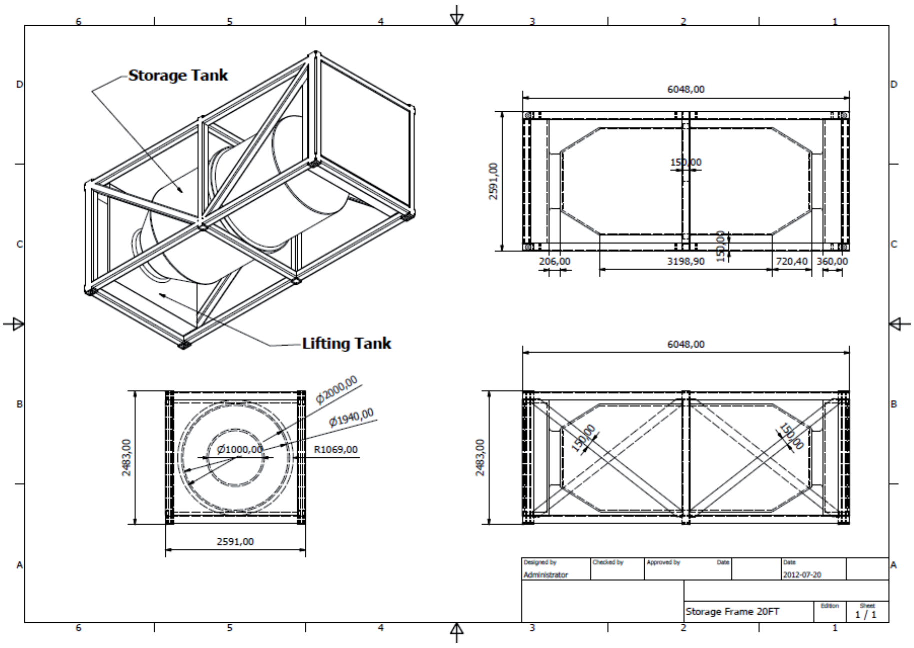
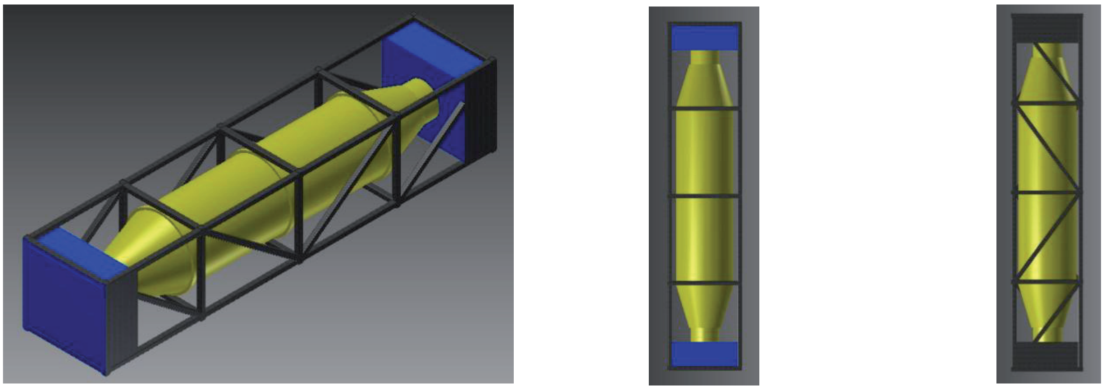


Figure 3.22: Conceptual drawing of the storage system, 20FT size.



(a) perscpetive view (b) top view (c) side view

Figure 3.23: Conceptual design of the storage system, 40FT size.

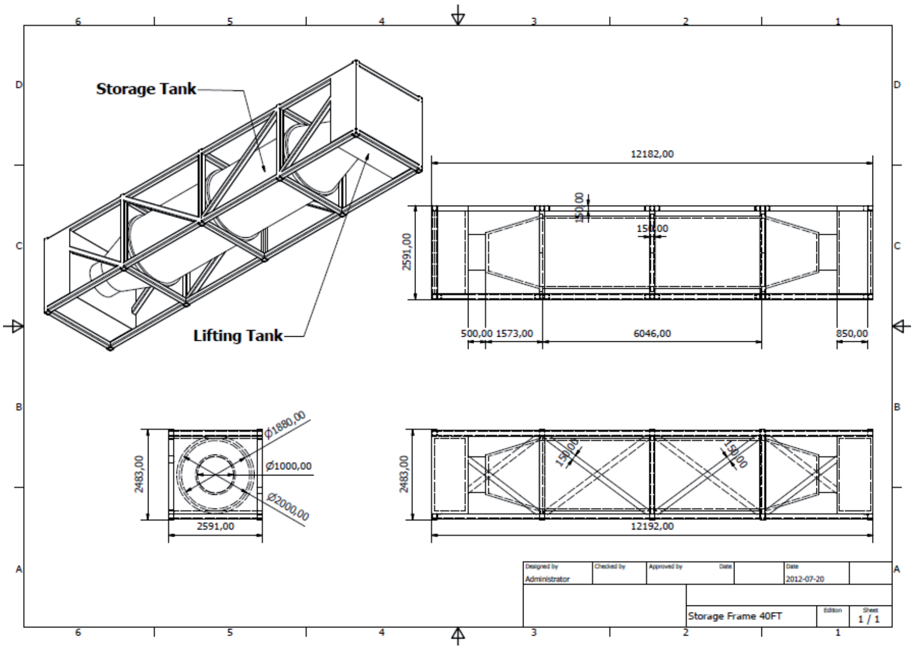


Figure 3.24: Conceptual drawing of the storage system, 40FT size.

Table 3.5: Capacity and weight of the storage systems.

Unit	20 FT	40 FT
Tank Capacity (m^3)	11.0	20.0
Storage Capacity (ton) (with 85% filling ratio for 20FT, 75% for 40FT)	30.0	50.0
Weight (ton)	23.0	60.0

Discussion

The decision to invest in proven technology or research into prospective technology is one of the key issues to confront ventures into new fields (Krishnan 2002). In the context of commercial ventures in general this decision is based on a balance of product performance and price. In the specific context of polymetallic nodule mining with its prohibitive level of technology risk this decision is more appropriately based on the adequacy of existing designs and the potential for new designs to reduce overall technology risk. Thus the model conceptualization and formulation should follow a flexible design approach based on Parallel Path principles as opposed to Sufficient Design. The primary objective of Parallel Path development is to maintain a number of alternative designs when confronting technology uncertainty to increase the chance of success. Sufficient Design development in contrast defines the architecture and the product package early and results in an 'overdesigned' product at a lower cost.

For a new venture like marine mining it is valuable to consider the benefits of maintaining available alternative designs during the R&D phase (Gil 2004). Early commitment to a specific design with little flexibility can impact on the value of the project and the venture as a whole (Oriani, 2008). This may be observed in the reports on previous marine mining systems. Early commitment to one collector design resulted in reduced mining efficiencies in the case of both the OMI and DORD projects. While further collector analysis and development has occurred, the sampling yields from these field tests have contributed to high technology risk valuations for polymetallic nodule mining. By adopting a flexible design approach such as the Parallel Path principle advocated by Krishnan these ventures may have deployed multiple collector designs or adapted design in response to results. Producing a range of yield data for different collectors may mitigate the assessed technology risk.

3.4 Processing subsystem

The third major component of a nodule mining system is the mineral processing plant. Once raw nodules have been collected from the seabed, transported to the surface and on to a processing centre (at sea or onshore) the various metals must be extracted from the nodule ore and purified for sale. Processing is commonly composed of a large number of industrial steps through which ore is converted to useful feedstock for industrial purposes.

Reducing business risk is the most important issue preventing successful commercial seabed mining. Business risk is excessive at all levels of the mining process. Mineral processing is the most costly component of the mining process as depicted in Figure 3.25 below.

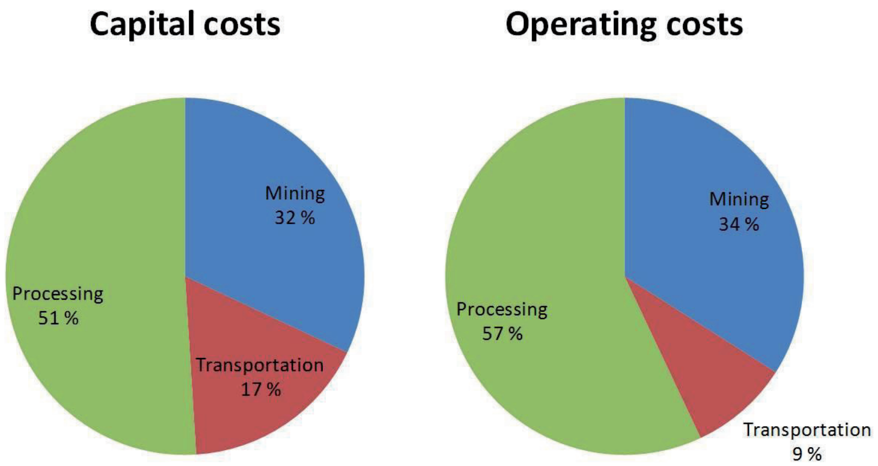


Figure 3.25: Major costs for a marine mining venture, (Graham and Trotman, 1989).

The extraction of four primary metals (Cu, Ni, Co, and Mn) from polymetallic nodules and the rare earth components requires specialized equipment and processes. The construction of a dedicated nodule processing facility requires a large, constant feed of nodule ore. The processing business carries relatively low risk *if* a constant supply of ore is available, but a dedicated plant dependent on the high-risk mining operation means that risk impacts on the larger investment in processing plant and equipment.

Under these conditions risk can be reduced significantly if the processing business can be released from its dependency on the high-risk mining operation. Polymetallic nodules are unique formations, but the metals present in them are relatively common. Many of the processing stages are similar to those of land-based lateritic ores. Some authors have proposed a combined or 'hybrid' processing operation capable of accepting both lateric and nodule ores (Sen, 2010). The Group has reviewed the range of processing techniques tested for polymetallic nodules below and identified the most appropriate processing techniques for incorporating into a combined hybrid system. Based on this review the Group recommends the key components of a hybrid system and some of the innovations necessary for its development in the concept section.

3.5 Five technologically feasible processes

Out of the many processes available the following five are considered technically feasible:

1. Gas reduction and ammoniacal leach
2. Cuprion ammoniacal leach
3. High temperature and high pressure sulfuric acid leach
4. Reduction and hydrochloric acid leach
5. Smelting and sulfuric acid leach

These five processes are described in detail below.

3.5.1 Gas reduction and ammoniacal leach

In this process the nodules are leached in ammonia solution (Caron, 1924). The reaction rate of the metal oxides at atmospheric temperature and pressure is relatively low. For this reason the nodules are reduced by a gas mixture (usually carbon monoxide (CO) and carbon dioxide (CO_2)) before leaching with a solution of ammonia in combination with ammonium carbonate or ammonium sulphate. The resultant processes are illustrated in Figure 3.26.

$MnO_2 + CO \rightarrow MnO + CO_2$ (reduction)

$MnO + CO_2 \rightarrow MnCO_3$ (carbonation)

$Fe_2O_3 + CO \rightarrow 2FeO + CO_2$

$FeO + CO \rightarrow Fe^0 + CO_2$

$NiO + CO \rightarrow Ni^0 + CO_2$

$Ni + 1/2O_2 + 8NH_3 + 2CO_2 + H_20 \rightarrow Ni(NH_3)_6^{2+} + 2NH_4^+ + 2CO_3^-$

$Fe\,Ni + O_2 + 12\ NH_3 + 3CO_2 + H_20 \rightarrow Ni(NH_3)_6^{2+} + Fe(NH_3)_4^{2+} + 2\ NH_3^+ + 3CO_3^{2-}$

$MnO + CO_2 \rightarrow MnCO_3 \downarrow$

$Mn^{2+} + 6NH_3 \rightarrow Mn(NH_3)_6^{2+}$

Figure 3.26: Key reactions in gas reduction ammoniacal leaching process

Table 3.6: Manganese nodule leaching processes in different ammonium medium.

Reference	Reduction medium and temperature	Leaching Condition	% Recovery					
			Ni	Cu	Co	Mo	Mn	Fe
(Fuerstenau and Han, 1983)	CO:CO_2 gas mixture at 600°C	1 hr at 25 °C with NH_3+ $(NH_4)_2CO_3$	65	44	50	-	4	1
(Han et al., 1974)	CO:CO_2 gas mixture at 600°C	1 hr at 25 °C with NH_3+ $(NH_4)_2SO_4$	74	60	50	-	42	0
(Redman, 1973)	Reducing gas at 600°C	3 hr at 25 °C with Aqueous NH_3 /CO_2	91	88	72	83	-	-
(Skarbo, 1973)	Simultaneous reduction and leaching	1 hr at 60 °C with $(NH_4)_2SO_4$+ $MnSO_4$	88	89	92	25	-	-

Table 3.6 demonstrates the variations between ammonia leaching processes and the corresponding metal recovery yields. It can be seen from the table that ammonia leaching processes do not recover Mn except that proposed by Han et al. (1974) where only 42% Mn was recovered.

National Metallurgical Laboratory (NML) at Jamshedpur, India adopted the reduction roast and ammoniacal leach process. Subsequent to leaching in ammoniacal solution the metals are extracted by solvent extraction-electrowinning. The process flow chart is given in Figure 3.27. The maximum metal recovery is reported as 90% Cu, 90%Ni and 60% Co (Puvvada et al., 1997).

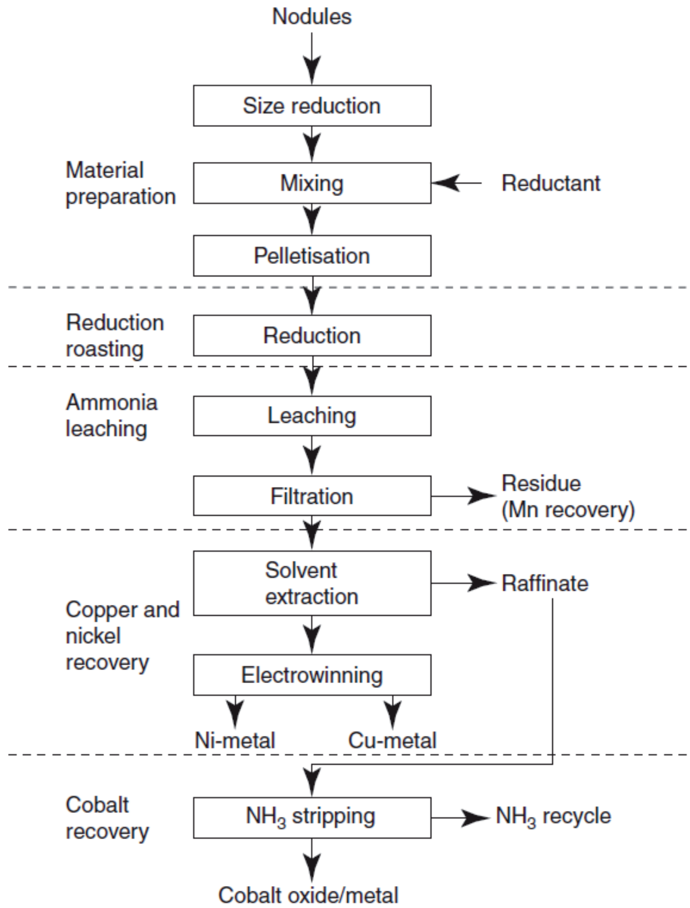


Figure 3.27: NML Process (Mukhopadhyay et al., 2008, Puvvada et al., 1997)

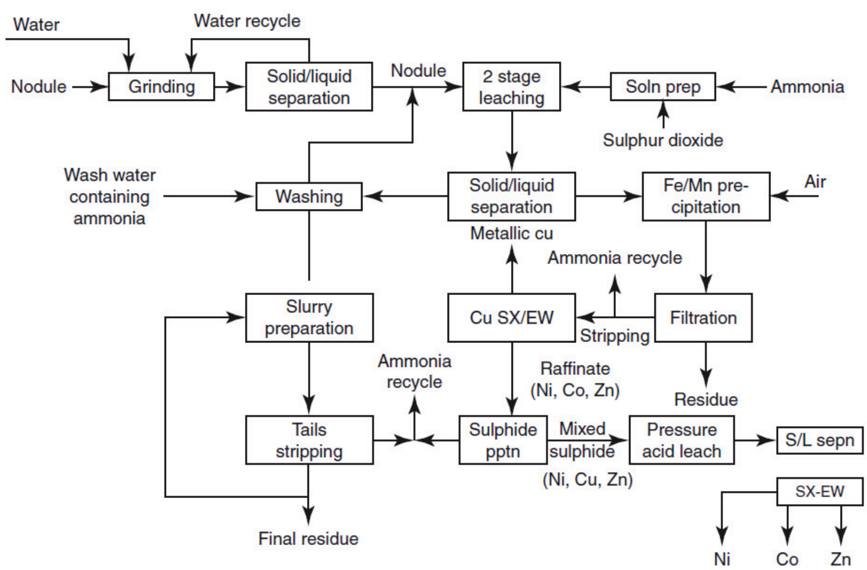


Figure 3.28: RRL Process (Das, 1989, Premchand and Jana, 1999)

Another variation of reduction and ammoniacal leaching is adopted by Regional Research Laboratory (RRL), Bhubaneswar, India, where instead of producer gas sulfur dioxide gas is used as a reducing agent. A two stage leaching process (see Figure 3.28) under pressure is designed to enhance the dissolution rate of Ni, Cu and Zn (Das, 1989).

3.5.2 Cuprion Ammoniacal Leach

Kennecott developed an ammonia leaching process based on the Caron process (originally developed for the processing of nickel laterite ore) (Caron, 1924). In this process the nodules are leached in an aqueous ammonia solution and at the same time reduced in the presence of excess cuprous ions. This process is similar to the ammonia leaching process described in section 3.5.1, with the exception of the high temperature pre-reduction treatment, making the process less energy intensive. However, this process recovers only Cu, Ni and Co and rejects Mo, Mn and Fe.

The cuprion ammoniacal leach process involves grinding and slurrying the wet nodules with a mixture of sea water and recycled process liquor that contains dissolved Cu and ammonium carbonate. CO is injected into the reaction vessel that produces cuprous ions. The cuprous ion reacts with ammoniacal solution to form an amine complex that serves as a reducing agent and reduces manganese oxide in the ore and confers Cu, Ni and CO into the solution. The major reaction is given in Eq.1 and Eq.2

$MnO_2 + 2Cu\,(NH_3)^{2+} + 4NH_3 + CO_2 + H_2O \rightarrow MnCO_3 + 2Cu(NH_3)_4^{2+} + 2OH^-$ (1)

$2Cu(NH_3)_4^{2+} + CO + 2OH^- \rightarrow 2Cu(NH_3)^+_4 + + 4NH_3 + CO_2 + H_2O$ (2)

The net overall reaction is:

$MnO_2 + CO \rightarrow MnCO_3$ (3)

This process is patented by (Szabo, 1976). A flow chart of the process is given in Figure 3.29.

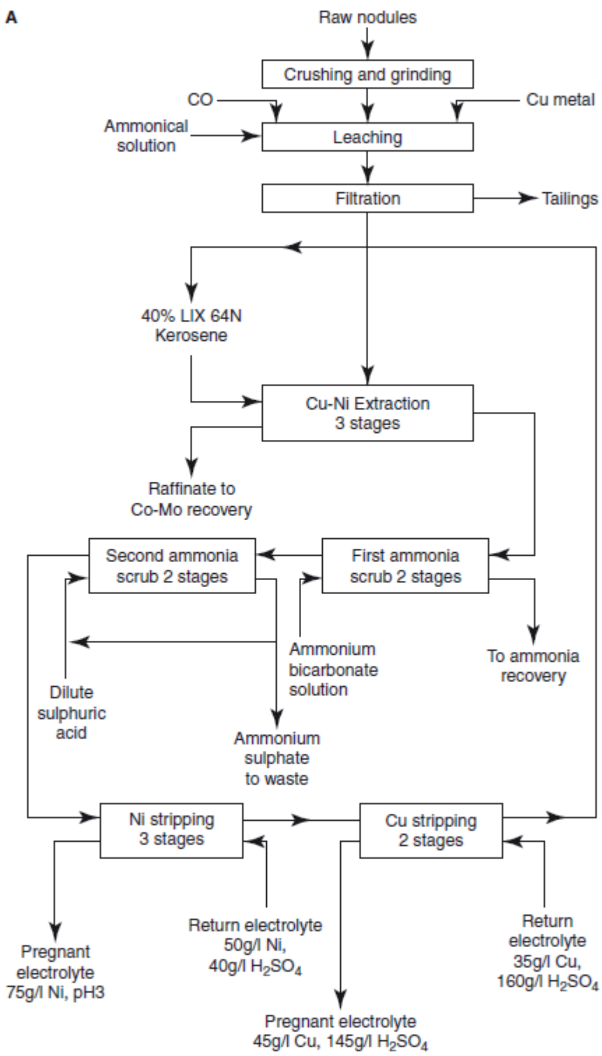


Figure 3.29: Kennecott Consortium Cuprion Ammoniacal Leach process (Szabo, 1976)

3.5.3 High Temperature and high pressure sulphuric acid leach

The high temperature and high pressure H_2SO_4 acid leach is adapted from nickeliferous laterites processing used by Moa Bay, Cuba. This process involves leaching the sea nodules with H_2SO_4 at a temperature of ~200°C and a pressure of 150 psig (Han and Fuerstenau, 1975). Cu, Ni and Co dissolve from the iron and manganese oxide lattice leaving the Mn and Fe rich residue. 93% of Cu, 86% of Ni, 50% of Co, and 23% of Mn recovery is reported. The nodule residue is separated from the acid solution by decantation. The pregnant leachate is then pH adjusted from where Cu and Ni are separated by an organic liquid exchange method and Cu and Ni are separated from each other by an electrowinning method. The pregnant leachate is subsequently reacted with H_2S to precipitate Co. The key reactions are presented below in Figure 3.30.

$$MnO_2 + H_2SO_4 \rightarrow MnSO_4 + H_2O + 1/2O_2$$

$$Mn^{2+} + 1/2O_2 + 2(OH)^- + \rightarrow MnO_2 \downarrow + H_2O$$

$$Fe_2O_3 + 3H_2SO_4 \rightarrow Fe_2\ (SO_4)_3 + H_2O + 1/2O_2$$

$$Fe^{3+} + 3(OH)^- \rightarrow Fee4\ (OH)_3 \downarrow$$

$$NiO + H_2SO_4 \rightarrow NiSO_4 + H_2O$$

$$CuO + H_2SO_4 \rightarrow CuSO_4 + H_2O$$

$$CoO + H_2SO_4 \rightarrow CoSO_4 + H_2O$$

$$Co_2O_3 + H_2SO_4 \rightarrow 2\ CoSO_4 + 2H_2O + 1/2O_2$$

Figure 3.30: High Temperature and high pressure sulfuric acid leach reactions (Haynes et al., 1985)

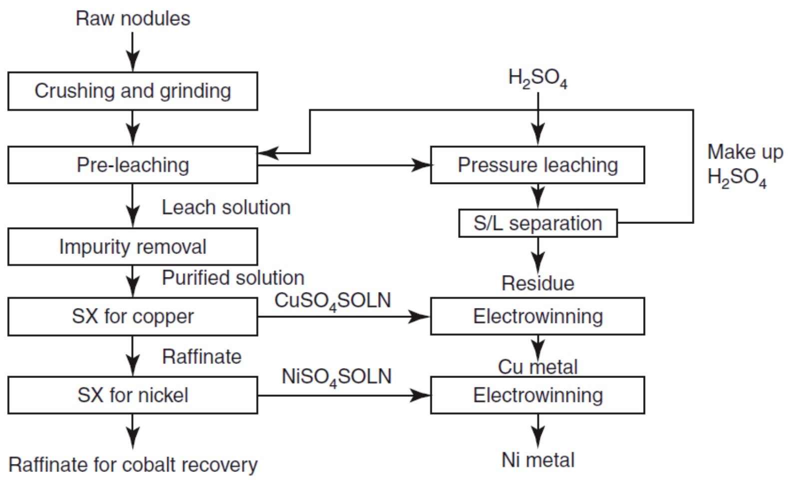


Figure 3.31: Sulfuric acid leach process adopted by Hindustan Zinc Limited (HZL) (Premchand and Jana, 1999).

Hindustan Zinc Limited (HZL), Udaipur, India, developed a sulphuric acid leaching process, as shown in the flow chart given in Figure 3.31 (Basu, 1989, Premchand and

Jana, 1999). In this process Cu and Ni and Co is extracted from the leach liquor using a solvent exchange and electrowinning technique.

3.5.4 Reduction and hydrochloric acid leach

A variety of routes are available for leaching metals from polymetallic nodules using hydrochloric acid. Deep Sea Ventures pioneered this process of extracting metal values from polymetallic nodules (Kane and Cardwell, 1973, Kane and Cardwell, 1974a, Kane and Cardwell, 1974b). Typically the nodules are ground and contacted with hydrogen chloride gas at a temperature of 500°C to reduce the metal oxides. The reduced nodules are subsequently leached with aqueous HCl (pH=1.9) for 60 minutes. The reactions involved in this process are presented in Figure 3.32 below. A very high percentage of dissolution of the metals (up to 90% Mn) can be achieved through this process (Cardwell and Kane, 1976).

$$MnO_2 + HCl \rightarrow MnCl_2 + 2H_2O + Cl_2$$

$$Fe_2O_3 + 6HCl \rightarrow FeCl_3 + 3H_2O$$

$$FeCl_3 + 3H_2O \rightarrow Fe(OH)_3 \downarrow + 3HCl$$

$$NiO + 2HCl \rightarrow NiCl_2 + H_2O$$

$$CuO + 2HCl \rightarrow CuCl_2 + H_2O$$

$$CoO + 2HCl \rightarrow CoCl_2 + H_2O$$

$$Co_2O_3 + 4HCl \rightarrow 2CoCl_2 + 2H_2O + 1/2O_2$$

Figure 3.32: Typical reactions for reduction and hydrochloric acid leach (Cardwell and Kane, 1976).

Metallurgie Hoboken-Overpelt (MHO) also developed a variation of this process where chlorine generated in the reduction steps is recycled and reused in the manganese chloride solution (Van Peteghem, 1977). Metals from the leachate are recovered by a solvent extraction and precipitation method. A flow sheet of the MHO process is given in Figure 3.34.

3.5.5 Smelting and sulphuric acid leach

Another approach to extracting metals from nodules using simultaneous smelting and leaching with sulphuric acid (Halbach et al., 1977, Sridhar et al., 1977). Fe is removed from the leach liquor by a solvent exchange method before the leach liquor is subsequently reacted with H_2S to precipitate Cu and Ni as their respective sulphides from where pure metals are recovered by electrowinning process. Subsequent to the removal of Cu, Ni and Fe, manganese metal is crystallised from the remaining manganese chloride in the solution.

In this process Mn nodules are reduced using CO rich producer gas at a temperature between 625°C and 1000°C followed by smelting in an electric furnace with silica and coke at 1425°C. The reactions in this process are given in Figure 3.31. A molten alloy rich in Cu, Ni, Co and Fe is separated from the Mn slag by gravity. The molten alloy is then re-oxidised with air, separated as slag and taken to the electric furnace where gypsum and coke are used to produce metal sulphide ''matte'' containing Cu, Ni and Co. The matte is then reacted with 5% H_2SO_4 at 110°C and 10 atm pressure and the metal values are selectively extracted by an organic solvent extraction method.

$MnO_2 + C \rightarrow MnO + CO$

$MnO + CO \rightarrow Mn^0 + CO_2$

$MnO + SiO_2 \rightarrow MnSiO_3$

$2MnO + SiO_2 \rightarrow Mn_2SiO_4$

$2Mn^o + O_2 \rightarrow MnO$

$Fe_2O_3 + C \rightarrow 2Fe0 + CO$

$FeO + CO \rightarrow 2Fe^0 + CO$

$NiO + CO \rightarrow 2Ni^0 + CO$

Production of Ferromanganese alloy

$Mn_2SiO_4 + 2CaO \rightarrow MnO + Ca_2SiO_4$

$MnSiO_3 + CaO \rightarrow MnO + CaSiO_3$

$MnO + C \rightarrow Mn^0 + CO$

$Ca2SiO4 + Al_2O_3 \rightarrow Ca_2Al_2SiO_3$.

$SiO_2 + 2CaO \rightarrow Ca_2SiO_4$

Figure 3.33: Reactions for smelting and sulphuric acid leach (Sridhar et al., 1976).

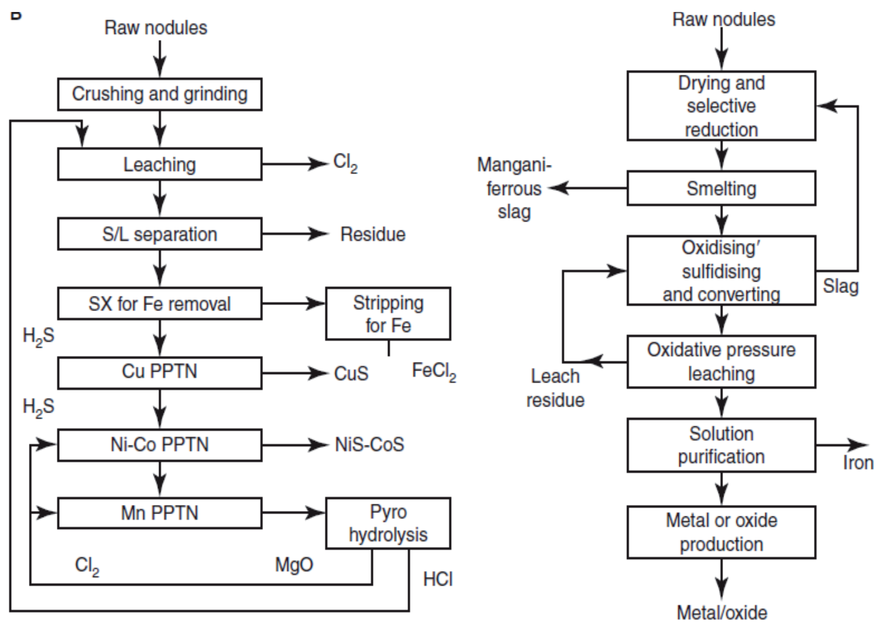


Figure 3.34 MHO hydrochloric acid leach Process (left) (Van Peteghem, 1977) and INCO Process for smelting and sulphuric acid leach (right) (Sridhar et al., 1976).

In contrast to other processes this INCO process route produces a manganiferrous alloy in addition to metals (Cu, Ni, and Co). International Nickel Company (INCO) also utilizes this process (Sridhar et al., 1976). A flow sheet of INCO process is given in Figure 3.34.

3.6 Concept

A marine mining venture based on polymetallic nodules can be divided into the mining operations (retrieving the ore) and processing operations (extracting and refining valuable products from the ore). Processing operations are estimated to represent over 50% of the overall cost of a mining venture and if wholly dependent on feedstock from the mining venture they must be assessed at the same level of risk as the overall operation. However because it is a mature technology processing operations can reasonably be assumed to represent lower risk if they can accept ore feedstock from multiple sources (Johnson and Otto, 1986).

In light of this, authors such as P.K. Sen (Sen, 2010) have proposed processing plants that may accept marine nodule ore as well as land-based lateritic ore, thereby reducing the required rate of return for a processing operation. Additionally, if the processing operation can extract four metals (Cu, Ni, Co, and Mn) from the nodule ore the return on investment is estimated to be at least 30% greater as depicted in Table 3.7, and more environmentally friendly thanks to reduced waste production.

The disadvantage of the process advocated by Sen is the inaccessibility of the Rare Earth Element components of the nodule ore. Figure 3.35 (below) is a flowsheet outlining a process concept proposed by the Group based on that described by Sen but with the additional option of extracting Rare Earth Elements from the leach liquor. The final product of the process is metallic Cu, Ni, Co, electrolytic manganese dioxide (EMD), chemical manganese dioxide (CMD) and a manganese alloy for sale to the steel industry.

As depicted in Table 3.7 the four-metal process is already estimated to provide 15.7% IRR, the additional revenue from the sale of Rare Earth Elements can be estimated at around a further 10% (see financial analysis section3.9). This will increase IRR further, however the final increased IRR must be the subject of further analysis using the appropriate REE extraction process and related increase in costs.

IRR over 15.7% for a mature processing operation that can accept lateritic ore as well as marine minerals is considered financially viable. If realized this reduces the required investment for a marine mining venture by more than 50%.

The proposed concept has the following advantages:

1. 4 metal recovery with a ferromanganese alloy that increases IRR.
2. Financial risk minimization by integrating land-based ores.

3. Unit for processing laterite and polymetallic nodules allowing for continuous production.
4. Potential for Rare Earth Element production.
5. Based on cost-effective reagents.
6. Potential to upgrade an existing lateritic nickel plant such as Weda Bay project is located in Indonesia (Moskalyk and Alfantazi, 2002).

Further work is required before such a process can be commissioned. The challenges for this process include:

1. Establishing a commercial extraction method for Rare Earth Elements from leaching liquor based on Zhang et. al. (Figure 3.36)
2. Leach acid is currently not recyclable.
3. Processing of PMN produces 70% waste, treatment and disposal will incur further costs.
4. High temperatures and pressures make this an energy intensive process.

Table 3.7: From (Sen, 2010) showing processing options and IRRs

	Hillman (1985)	**Andrews et al. (1983)**	**Charles (1990)**	**Lenoble (1990)**	**Lenoble (1990)**	**Ham (1996)**	**Soreide et al. (2001)**
IRR,%	7.4	6.4	12	**15.4**	**15.7**	11.93	9.6
Capacity (DMTPA)*	3.0, three metal	1.5, four metal	1.5, four metal	1.5, four metal	1.5, four metal	3.0, four metal	0.7, three metal
Process route	Cuprion	Reduction smelting and Cuprion processes	Reductio n HCI leach	**Sul-phuric acid leach**	**Smelt reductio n**	Reduction roast ammonia leach	Sulphuric acid pressure leach(PL)

*DMTPA is Dry Metric Ton Per Annum

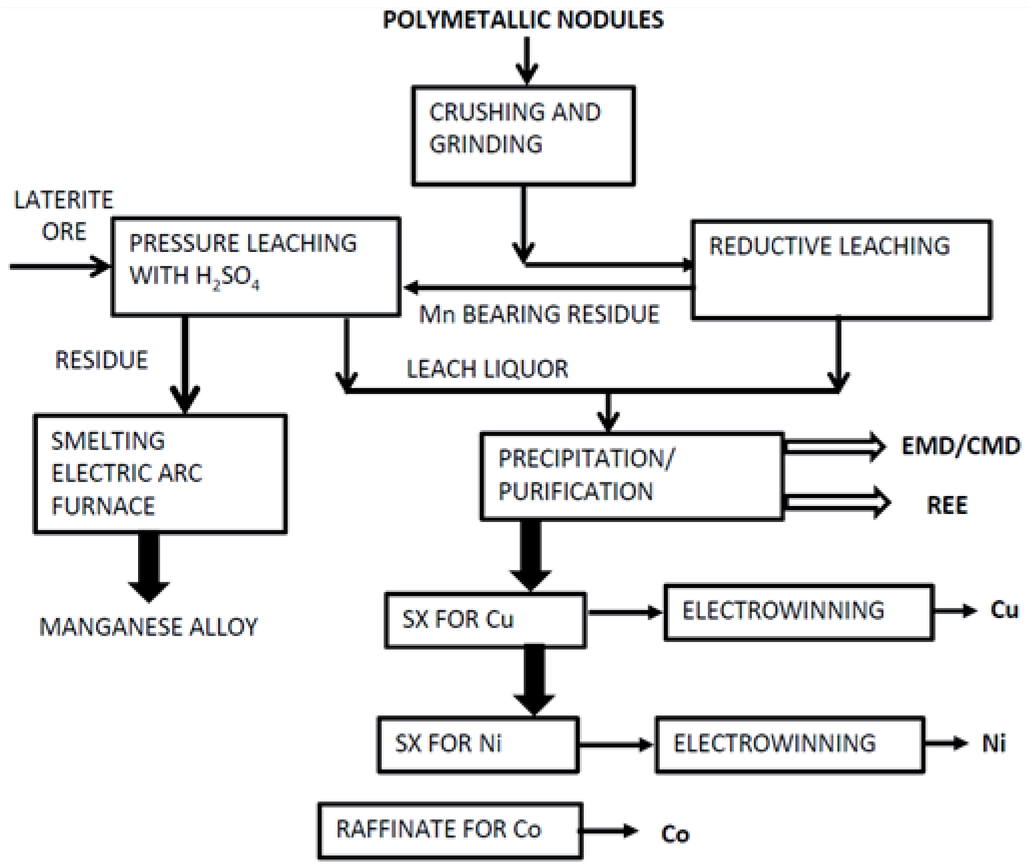
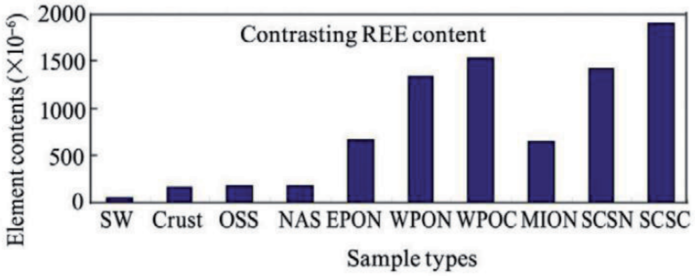


Figure 3.35 Processing concept proposed by the Group with potential for 4-metals and Rare Earth Elements

REE Extraction

It is found in the literature that Scandium is dissolvable in H_2SO_4 from Wolframite slag (Zhong, 2002) (see Figure 3.35). Thorium has also been successfully recovered by H_2SO_4 acid leaching (Gupta and Krishnamurthy, 1992). Since the REE concentration is relatively high in the polymetallic nodules it can be recommended that REE may be successfully extracted from the H_2SO_4 leachate.



Note: In this figure, SW=REE of sea water, Crust=REE of the crust, OSS= REE of offshore surface sediments, NAS= North American shale, EPON=eastern Pacific Ocean nodules, WPON=western Pacific Ocean nodules, WPOC=western Pacific Ocean crust, MION= mid-Indian Ocean nodules, SCSN=South China Sea nodules, SCSC=South China Sea crust

Figure 3.36: REE concentration in various sea based resources (Zhang et al., 2012)

3.7 Ancillary subsystem concepts

Along with the major subsystems described above any marine mining system requires a number of other components to operate. These include power for the nodule collector, a transport system to raise recovered nodules to the surface and a means to mitigate any harmful effects from the mining operation. While the Group has focussed on the development of the two primary concepts above these ancillary subsystems are also a major source of cost and risk to a marine mining venture.

Technical development in these subsystems is essential for reducing the investment risk and improving the profitability of a mining venture. The following concepts have been proposed by the Group to address these issues. These concepts have not been validated to the same extent as the major subsystems described earlier but are included as additional concepts that warrant further investigation.

3.7.1 Subsea power system

In addition to the collector system, another point of failure on subsea operations is the power unit. Modern remotely operated vehicles (ROVs) are commonly powered by electric motors with power provided by an umbilical cord connected to generators on the control vessel (mother ship). This design has been extended to seafloor miners; however seafloor miners require vastly more power than most ROVs (around 2 MW of 3-phase power) and in the case of manganese nodule mining require umbilical power conduits up to 6,000 meters long. The electric motors driving the equipment are very large and must operate at extremes of temperature and pressure. Under these conditions the power units experience a high rate of failure, and as described by IHC Merwede (pers. comm.) the provision of this amount of power over such a distance introduces further difficulties with weight and control; the larger power requirements demand heavier and more complex electrical equipment including a rectifier and power inverter at the seabed. This equipment leads to a substantial increase in weight and further points of potential failure. These elements may be relocated to the mother ship but this requires the provision of variable low frequency power through the long power cable which in turn leads to power reflection, frequency distortion, poor control, heat and wear on the collector motors.

To avoid these problems there are a number of alternatives to provide power to the nodule collector. With further development of the deep seabed the provision of power will become an active area of research and development. One alternative proposed here by the Group is the use of hydraulic power to drive the collector machinery. In comparison to electric motors for high power applications hydraulic motors are lighter, more robust and provide greater torque. These characteristics are particularly advantageous for deep sea applications where weight and reliability are paramount.

Despite their advantages hydraulic motors have not been applied in this environment because traditional designs require two hydraulic lines for provision and return of fluid. Traditional designs are also not optimized for the deep sea environment. The deep sea environment does however offer an abundance of ambient pressure.

The subsea power concept proposed by the Group is a design that utilizes sea water as the working fluid and atmospheric pressure at the seabed (up to 8,000 psi) to drive a hydraulic motor attached to the collector. In contrast to traditional hydraulic motor designs this concept would require only one hydraulic line – a return line to the mother ship. The concept also saves weight by discarding the inverter, rectifier and transformer required for electric power, and is in principle, more robust than an electric system as the materials and complexity are reduced.

Many early engine designs used atmospheric pressure for power, including the Savery and Newcomen engines (Frenken and Nuvolari, 2004). These designs relied on creating a pressure difference across a piston by the condensation of steam, resulting in the surrounding atmospheric pressure causing the piston to move. Such designs were clearly inefficient in part because of the relatively low pressure available in air (1 atm / 14 psi). After 50 years of use James Watt revolutionised the steam engine by using the steam pressure to drive the piston rather than atmospheric pressure. This allowed Richard Trevithick to produce the first high-pressure steam engine operating at 40 psi (Von Tunzelmann, 1978). These early engines produced up to 5 horsepower, while modern hydraulic engines typically operate between 1,000 and 2,000 psi producing between 70 and 300 horsepower (Merritt, 1967).

While the Newcomen-type atmospheric engines have long been abandoned because of the limited available pressure, the extreme atmospheric pressure available at the deep seabed, the abundance of working fluid and the need for a simple, robust design may warrant an investigation into using an atmospheric engine design for power.

In the concept proposed by the Group a simple atmospheric engine similar to current hydraulic designs is used at the collector. The outlet valve of this engine is connected to an expansion cylinder and pipe leading to the mother ship (see Figure 3.37). The water in the pipe and expansion cylinder are maintained at a lower pressure than the surrounding sea by a pump located on the ship and the pressure difference across the engine is used to drive the collector and associated components.

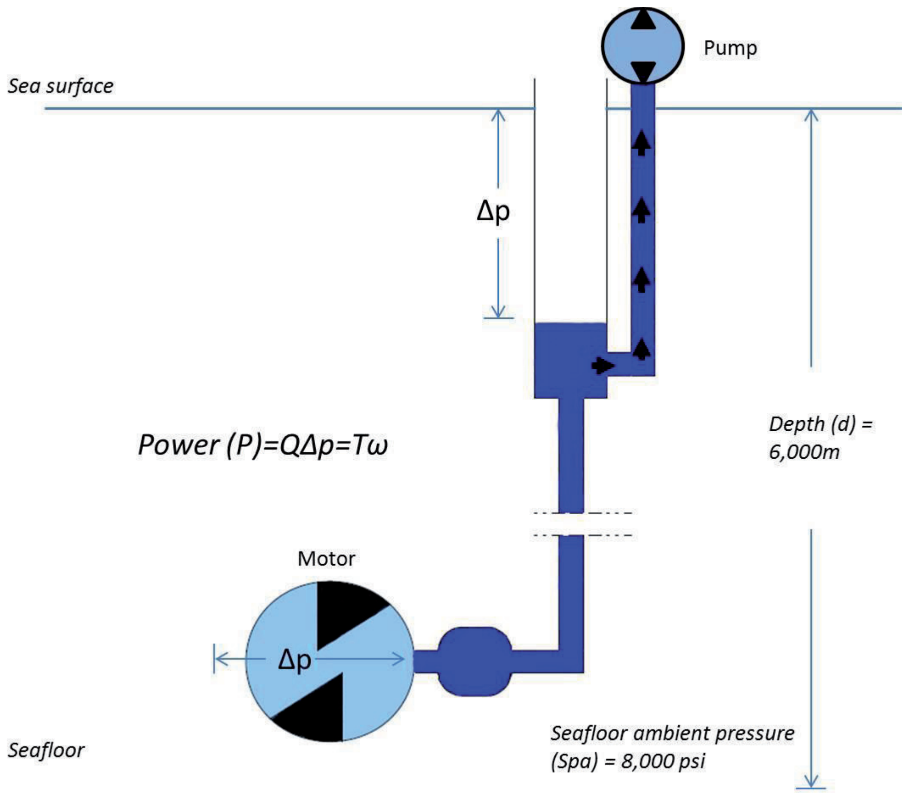


Figure 3.37- Subsea hydraulic power system. Q= flow rate Tω= torque.

Directional ability may be accomplished by the use of a hydrostatic drive and brakes applied to each propulsion screw, or two hydraulic motors operated independently. The engineering challenges of such a design are significant, including appropriate materials and design for operating in the deep sea environment and with seawater as a working fluid, accurate and responsive control, suitable conduits resistant to collapse under pressure etc.

This design does however suggest that alternatives to electric power may be considered for deep seabed mining.

3.7.2 Transport-to-surface design and principles

Every deep seabed mining operation requires an efficient reliable and cost-effective method for transporting ore from the seabed to the sea surface. In considering this problem the Group has proposed using cheaper chemical energy in place of electric or diesel power to raise ore from the seabed. Chemical energy may be used in a simple shuttle system to reduce cost and increase reliability.

Many concepts have been proposed for retrieving nodules from the seabed. Most ventures have applied some form of the riser system described in section 3.3.

Risers for deep seabed mining are an extremely large, complex and expensive component. Riser technology was originally developed for dredging and offshore oil and gas sector, beginning in shallow water and eventually being developed out to around 1,500m depth on the continental shelf. Deep seabed mining requires riser technology to be extended to up to 6,000 m, and conduct heavy, rough nodule slurry. Under these conditions risers are subject to extreme weight and complexity (over 10,000 tons – Brockett in (ISA, 1999)) high energy consumption and high wear. Personal communication with IHC Merwede has identified another emerging problem – plug formation in riser contents. Despite these problems risers are still considered the most appropriate technology for raising large volumes of ore from the seabed.

In its review of the field, the Group found that shuttle-based transport systems have been largely discarded on the basis of their high cost, energy consumption and complexity. Previous shuttle system designs have relied on electrical power to drive thrusters to lower and raise vehicles for the transportation of ore. These systems are complex, expensive, prone to breakdown and demonstrate a low production rate.

The core problems inherent in previous shuttle system designs revolve around the propulsion and navigation systems. The Group considers that alternative designs may be explored to reduce the cost of such a system by eliminating the propulsion system and navigating shuttles using guidelines.

Basket shuttles

Figure 3.38 below is a preliminary hand-drawn sketch of such a system, nominally referred to as the ‘basket shuttle’ system. This design uses steel baskets suspended from cones (similar to a diving bell) from which is suspended a large metal basket with space for collected nodules.

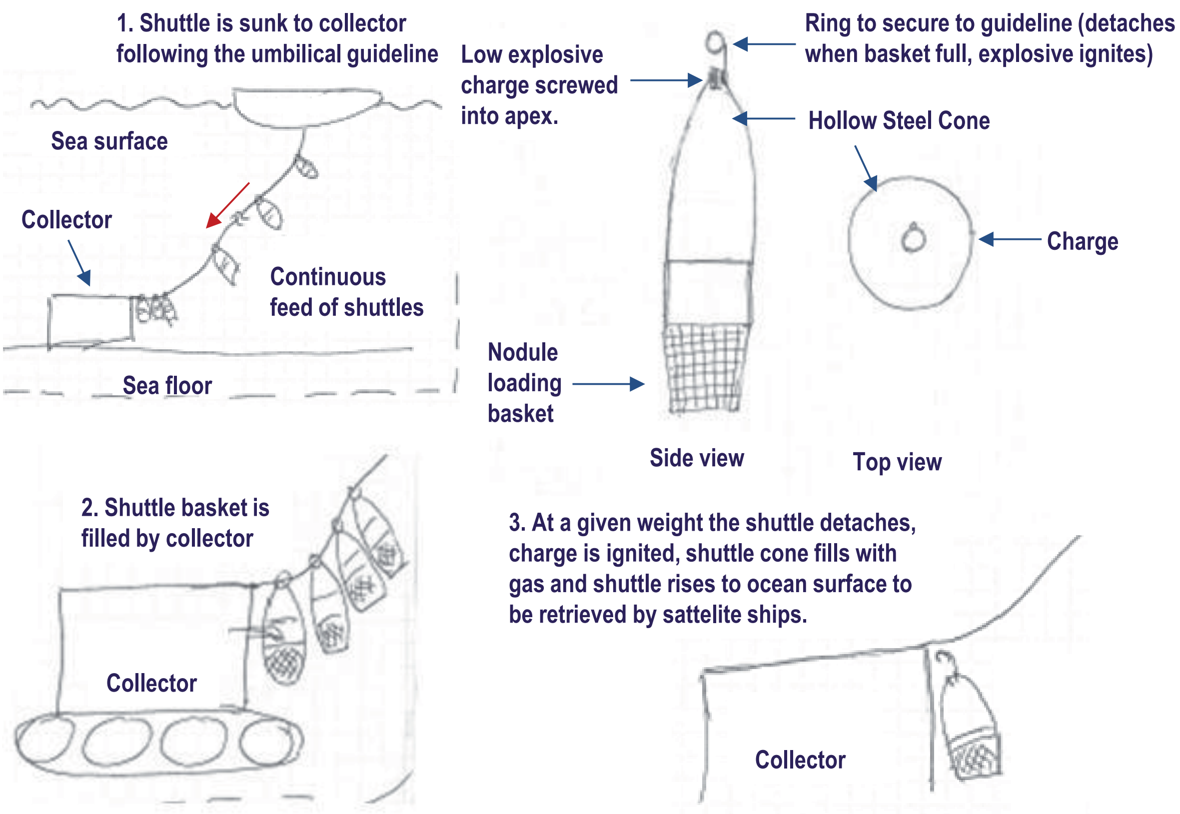


Figure 3.38: Basket shuttle concept sketch

In the apex of the cone is a thread, into which a charge of low explosive can be fixed. The explosive charge fuse is connected to a hook which will disconnect when the basket is full.

The shuttle would be filled with water and sent down to the collector attached by the hook to a guideline. When it reaches the collector it is filled with nodules until the added weight causes it to separate from the hook. On separation the explosive charge is ignited, filling the cone with gas and expelling water. Low explosive produces around 10-15,000 psi, the pressure at 4km depth is around 8,000 psi so it is expected to expel water slowly.

The shuttle becomes positively buoyant and rises to the surface where it can be collected by a satellite ship. Since the cone is open at the bottom as the gas expands it is progressively released so that the speed of the shuttle does not become excessive.

Storage system

As described in the collector system design section, nodule storage designs have also been proposed as a means of transporting nodules from the seabed to the surface. The detailed designs above may use compressed air or other buoyancy media, they are also well suited to using chemical energy to drive water out of ballast tanks. The use of chemical energy is considered attractive as it is cost-effective and uses the hydrostatic pressure at the seabed to drive transport. Consultation with Professor Sunil Shastri (Hull University) (pers. Comm.) has indicated that the design is technically feasible but may present additional problems with collection and containment of shuttles and the impact to the environment from noise, shockwaves and released gas. These issues need to be researched thoroughly prior to proceeding with design and development.

3.7.3 Wastewater treatment and bioremediation

Little work has been done on mitigating environmental damage caused by deep sea resource exploitation, and no published work has been found on strategies or technologies specifically designed for remediating deep sea mining waste.

As discussed in the Environment section (2.7) deep sea mining is expected to have a significant impact on the environment via two primary components; (i) the interaction directly with the seabed, and (ii) the production of waste water from the mining and processing components.

Environmental impact by nodule collectors interacting directly with the seabed must be addressed, at least in part, by collector design. Specifically collectors must be designed to minimize disturbance of the seabed and suspension of sediment.

Waste water produced by the slurry transport and processing components must be treated to avoid any negative environmental impacts. Environmental impact by wastewater is a common issue in many industrial processes. Deep sea mineral exploitation presents a particular issue due to the fact that much of the wastewater is produced at sea.

One very effective and widely utilized route for the treatment of wastewater in industrial processes is bioremediation – the culture and maintenance of an active population of flora and fauna that convert different components of wastewater into a benign product in sequence.

Of the methods for applying bioremediation one in particular presents opportunities for deep sea mineral exploitation; in-situ phytoremediation, or more specifically phycoremediation. Phycoremediation is the use of marine plants to absorb and convert potentially hazardous wastewater materials (Davis et al., 2000). The Group reviewed designs from Industrial Biomass (Australia) for the remediation of marine wastewater in situ and consider them to be particularly attractive.

The Industrial Biomass core technology was originally designed to extract soluble phosphate, potassium and fixed nitrogen from seawater along with fixing atmospheric carbon. These primary substrates are used by marine plants to produce energy products such as biogas and ethanol, and food and chemicals through fertilizer and biochar products suitable for addition to agricultural land.

Two of the most significant pollutants in the wastewater derived from the mineral slurry extracted during marine mining operations are deep-sea nutrients (phosphate, potassium, fixed nitrogen) and heavy metals. High nutrient loads in wastewater result in an increased Biological Oxygen Demand (BOD), which leads to a spike in biological activity at the site of disposal and a consequent crash in dissolved oxygen concentrations. Low dissolved oxygen in turn leads to a crash in biological activity and the death of organisms farther down the food chain, such as fish. This phenomenon is known as eutrophication and is a major cause of environmental damage in many marine and aquatic systems around the world, notably the Gulf of Mexico and the Black Sea (Kideys, 2002).

Heavy metals are derived from the disturbance of the seabed and the target minerals themselves. Heavy metals commonly include members of the transition metals, some metalloids, lanthanides and actinides (Bailey et al., 1999). Variously heavy metals may be essential for biological systems or toxic to biological systems, and this effect may also depend on the concentration of those pollutants in the surrounding environment. In any case heavy metals are a major pollutant and the focus of many environmental regulations.

Heavy metals are commonly absorbed in the carbohydrate cell wall of many species of marine algae. Because they are not readily taken up actively by the cell but rather 'biosorbed' by the cell wall, marine macroalgae such as Sargassum are capable of active growth in wastewater contaminated with heavy metals and are one of the most effective means of its remediation (Davis et al., 2000).

The Industrial Biomass technology (details of which are not disclosed due to intellectual property rights and confidentiality) is a new method of culturing marine macroalgae in open water suitable for the continuous harvest of biomass for conversion into saleable products. The Group found that the Industrial Biomass technology is well suited for integration with deep sea mineral exploitation operations, particularly PMN mining, as much of the wastewater produced by these operations is ideally disposed of on site.

Additionally the Industrial Biomass technology may have the capacity to produce fuel to supplement the mining operations and an additional revenue stream by processing biomass through fermentation or pyrolysis into biogas, ethanol or traditional petroleum. Biochar produced through pyrolysis could also potentially be used as coke for the processing of PMN ore.

3.8 Hazard Identification (HAZID)

The next steps in the concept development are beyond the scope of the current study, however, a Hazard Identification (HAZID) workshop with the participation of all five members of the Group, to project major potential personal, and environmental hazards associated with the proposed conceptual system. The workshop was held on the 21st of August 2012 to identify the major potential safety and environmental concerns of the proposed mining concept. A HAZID is a systematic method to evaluate a system or an operation with the aim of identifying hazards in order to plan for, avoid or mitigate their impact. The workshop was conducted early in the concept phase of the project, and the focus was on the major safety hazards and environmental impacts of the concept. The workshop was conducted using the methodology described in the following section.

3.8.1 HAZID methodology

The hazard identification followed a methodology where the concept design of the whole system was divided into subsystems (see the division scheme below), and a hazard identification of each subsystem was carried out. The HAZID of each subsystem followed the following steps:

1) Present the planned design;
2) Identify hazards, causes, consequences and safeguards by applying a set of guidewords (see list of guidewords below);
3) Record potential hazards, causes, consequences and mitigating strategies;
4) Classify the recorded potential hazards into categories shown in Table 3.8.

Once all the subsystems were reviewed and potential hazards, causes, consequences and mitigating strategies recorded, a hazard identification of the total system as a whole was performed, and the recorded findings are summarised.

Table 3.8: Classification of safety hazards and environmental impacts applied in the HAZID

Classification	Description	
	Safety hazard	**Environmental impact**
1	No potential safety hazard could be identified.	No potential environmental impact could be identified.
2	A potential safety hazard could be identified. The hazard is known from other similar concepts.	A potential environmental impact could be identified. The impact is known from other similar concepts.
3	A potential safety hazard could be identified. The hazard can be estimated from other similar concepts.	A potential environmental impact could be identified. The impact can be estimated from other similar concepts.
4	A potential safety hazard could be identified. The hazard is unique to this concept, and further studies are required to conclude whether it is acceptable.	A potential environmental impact could be identified. The impact is unique to this concept, and further studies are required to conclude whether it is acceptable.

For the purpose of the HAZID the engineering system was divided into the following subsystems:

- Collector
- Lifting system
    - Shuttling tanks
    - Basket
- Metallurgical processing
- Surface ship
- Transport to shore

It should be noted that the subsystems Surface ship and Transport to shore were only covered as part of the total system. This is because these subsystems are thought to be of existing design, with only minor modifications in the present concept.

Two sets of guide words were used during the workshop, a set which addressed safety hazards and a set which addressed environmental impact. These are listed below.

Guidewords addressing safety hazards:

- collisions
- floatability/stability
- loss of position
    - drift off
    - drive off
- dropped objects
    - stuck
    - drag
- fire/explosion
- electricity
- toxicity
- escape and evacuation
- weather conditions
- 3rd party
- other

Guidewords addressing environmental impact:

- noise
- waste
- spillage/release
- disturbance
- other

3.8.2 System description

The HAZID was performed early in the concept phase of the project, with rapidly developing engineering design. A brief overview of the concepts and the status of design which were the basis of the workshop are therefore presented in this section.

Collector

The status of the collector concept design at the time of the HAZID is shown in Figure 3.39. The unique and novel part of this collector design is the collector system. The screw-based propulsion system has already been tested out in some of the existing collector designs. The collector will operate in water depths of 4000 to 6000 m. It will have to be deployed from the surface ship by a gantry crane, and will be connected to the surface ship by an umbilical for power supply and control. The collector will use electric or hydraulic power. During the collection of polymetallic nodules the collector will remove the top 10 – 30 cm of the seafloor, which will be replaced behind the collector, except for the nodules.

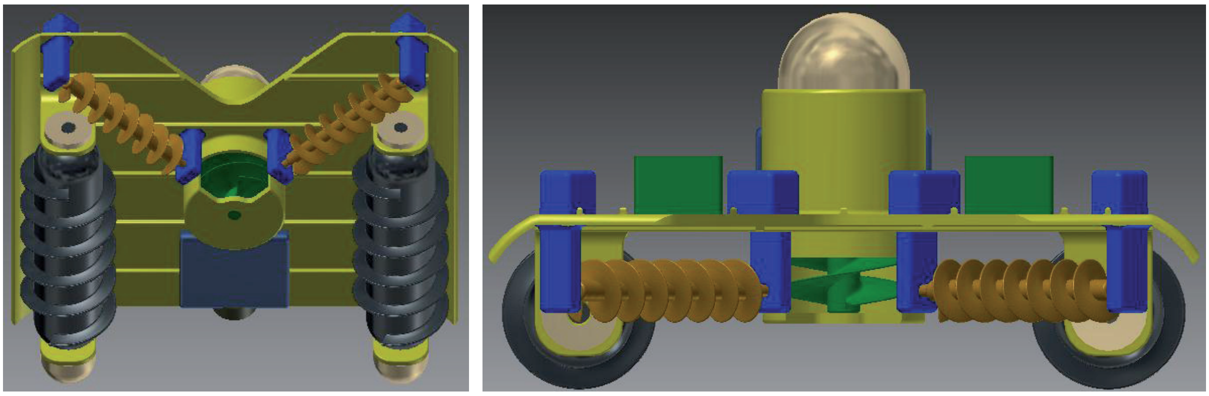


Figure 3.39: Collector design at the time of the HAZID

Container lifting system

The concept of the shutteling container system at the time of the HAZID is shown in Figure 3.40. The concept is based on chemical power for buoyancy purposes and use of mooring lines for guiding purposes. In order to avoid shock waves, low-explosive powder will be used to generate gas for buoyancy of the container. This means that the chemical reaction will be non-violent.

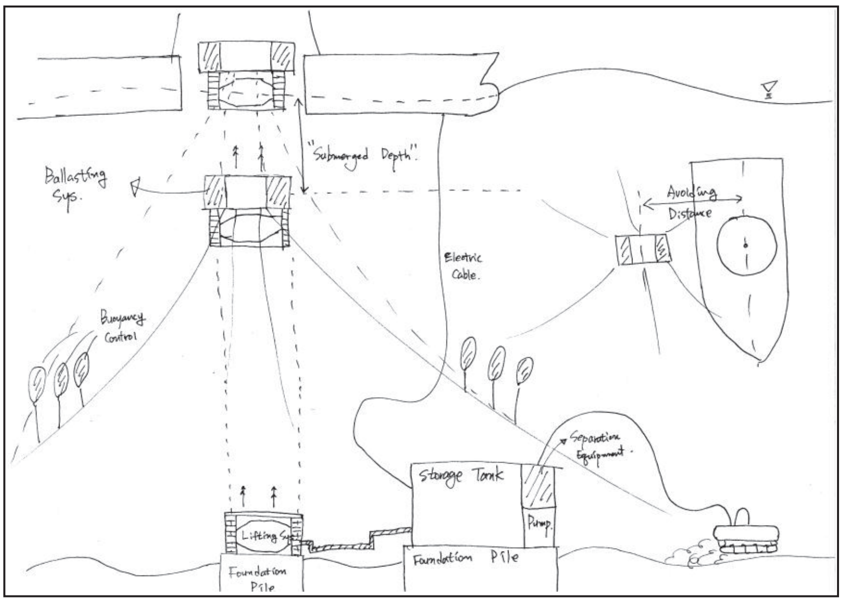


Figure 3.40: Container lifting system at the time of the HAZID

Basket lifting system

The basket lifting concept proposes, similarly to the container shuttling concept, to utilise chemical power for lifting purposes. The concept uses a guideline to descend the basket and free floating buoyancy for ascending. The concept is proposed used without any forms for artificial guiding, therefore the positioning of the surface ship upstream is essential. A top view of the proposed basket lifting concept at the time of the HAZID is shown in Figure 3.41.

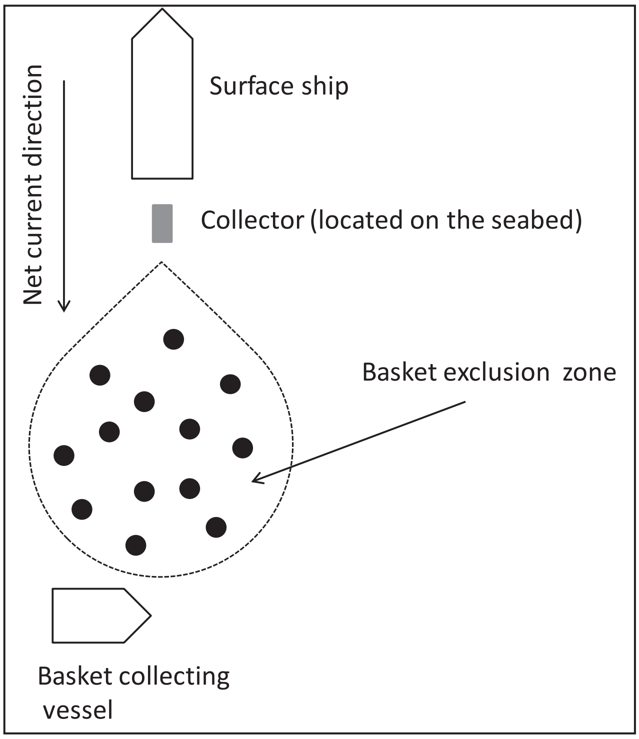


Figure 3.41: Top view of the proposed basket lifting system at the time of the HAZID

Metallurgical processing

The metallurgical processing is a combination of processing land-based lateritic ore (nickel-based ore from land sources) and polymetallic nodules. A flowchart showing the overall proposed process at the time of the HAZID is shown in Figure 3.42.

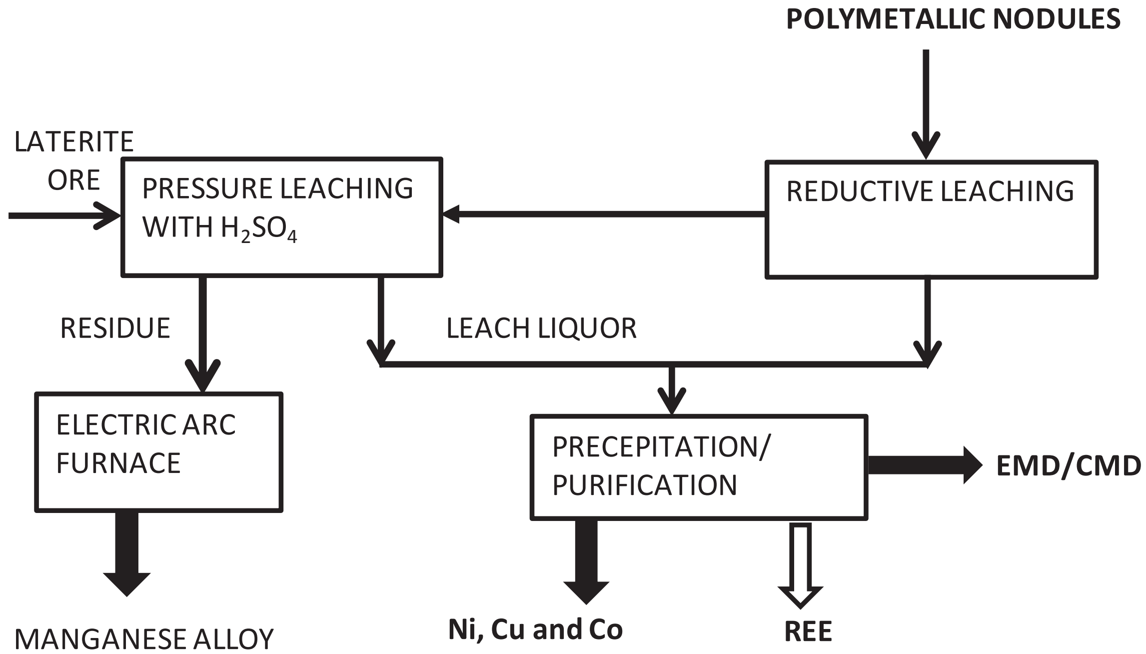


Figure 3.42: Metallurgical processing concept at the time of the HAZID

3.8.3 Hazard identification

The HAZID brainstorming session is documented in the following tables. Table 3.9 addresses safety hazards and Table 3.10 addresses environmental impact.

Table 3.9: Hazard identification – safety hazards

ID no.	Subsystem	Guide word(s)	Description of safety hazard, causes and consequences	Measures or systems implemented to control the hazard	Classification of safety hazard (1-4)	Comments and possible follow-up measures
1	Collector	Jamming Clogging	Rough terrain and obstruction on the seafloor may lead to unwanted stops. Will mainly lead to downtime.	Mitigation strategies: - mapping of the seabed - sensor systems on the collector.	1	
2	Collector	Dropped load Swinging load	Collector acting as a swinging or falling load during deployment and picking up of the collector.	Procedures on the surface ship.	3	Hazard can be estimated from similar offshore operations or ROV deployment/picking up operation on research vessels.
3	Collector	Plume Visibility	The speed of the current may be faster than the speed of the collector, which causes spreading of the plume by the current and reduced visibility.	Mainly a design/reliability issue.	1	
4	Collector	Collision	Collector hitting pipelines and sea cables. Possibility of causing a dent to the pipeline.	Mitigation strategies: - mapping of the pipeline/cable routes prior to start up of the operation - Sensors systems on the collectors (identification of obstacles) - Visual for the operator	3	Hazard and mitigation strategies can be estimated from similar offshore operations.
5	Collector	Drive-off	Causing disturbances to the surface ship in a situation of drive-off of the collector.	The collector will be too light to cause serious damage to the surface ship in such situation. Will be retrieved from the seabed.	1	

ID no.	Subsystem	Guide word(s)	Description of safety hazard, causes and consequences	Measures or systems implemented to control the hazard	Classification of safety hazard (1-4)	Comments and possible follow-up measures
6	Collector	Cable connection	Cable connection to the surface ship will limit the motion of the collector.		NA	Unsolved issue in the design, not a hazard.
7	Shuttling tank lifting system	Collision	Lifting of the ascending containers will be performed continuously. Containers may hit the surface ship during ascending. The anticipated consequences for the surface ship are reparable damage.	Mitigating measures: - Guidelines will be used for guiding the container during ascending - DP positioned ship, which makes it possible to move the ship away from the ascending point of the container - Surface ship design (stability of the ship cannot be affected by container hit/damage).	4	This is an important safety aspect that is not completely solved in this early concept phase of the project. Will have to be investigated further at the later stages of the design.
8	Shuttling tank lifting system	Waste	Handling of waste generated by the chemical reaction in the buoyancy elements.	Removable container to avoid waste collecting inside the container and limit human contact with chemicals.	3	Hazard and mitigation strategies can be estimated from land based mining.
9	Shuttling tank lifting system	Toxicity	Personnel exposure to toxic gasses in the container generated by the chemical reaction.		4	Still unclear at this stage of the design process. Hazard and mitigation strategies will have to be investigated further at the later stages of the design.
10	Basket lifting system	Chemical reaction for buoyancy	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system

ID no.	Subsystem	Guide word(s)	Description of safety hazard, causes and consequences	Measures or systems implemented to control the hazard	Classification of safety hazard (1-4)	Comments and possible follow-up measures
11	Basket lifting system	Collision	The ascending baskets may hit the surface ship. The anticipated consequences for the surface ship are reparable damage.	Mitigating system: - Modelling of flow conditions - Ship position "upstream" basket exclusion zone - Surface ship design (stability of the ship cannot be affected by basket hit/damage).	4	Can possibly be estimated from similar concepts which are under development, (Howard and Martin, 2009)
12	Basket lifting system	Collision	The ascending baskets may hit the basket collecting vessel. The anticipated consequences for the basket collecting vessel are reparable damage.	Mitigating system: - Modelling of flow conditions - Procedures - Surface ship design (stability of the ship cannot be affected by basket hit/damage).	4	The basket collecting vessel will be the most exposed vessel for collision with floating/ascending baskets.
13	Basket lifting system	Collision	Collision of "runaway baskets" with trawlers or other passing vessels.		4	The extent of this hazard is still unclear at this early stage of the concept development. Will have to be investigated further at the later stages of the design.
14	Metallurgical processing	Toxicity Spill/Leak	Exposure to acid.	Similar to conventional metallurgical processing.	2	
15	Metallurgical processing	Leak	Exposure of personnel and possibly also neighbours to CO/CO_2	Similar to conventional metallurgical processing.	2	
16	Metallurgical processing	Fire	Fire in electrical arc furnace.	Similar to conventional metallurgical processing.	2	

ID no.	Subsystem	Guide word(s)	Description of safety hazard, causes and consequences	Measures or systems implemented to control the hazard	Classification of safety hazard (1-4)	Comments and possible follow-up measures
17	Metallurgical processing	Fire Explosion	Fire/explosion in the pressure vessel during pressure leaching.	Similar to conventional metallurgical processing.	2	
18	Metallurgical processing	3rd party		Similar to conventional metallurgical processing.	2	
19	Whole engineering system	Transport of personnel Evacuation Weather conditions	The location of the surface vessel may be some day's travel from shore (~4 days). Not accessible to helicopter without intermediate landing facilities.	Possible mitigating measures: - Possibility for the surface ship to disconnect from the subsea equipment and leave location. - Possibly intermediate landing facilities for helicopter.	3	Will have to be investigated further at the later stages of the design, based on experience from offshore and marine industry.

Table 3.10: Hazard identification – environmental impact

ID no.	Subsystem	Guide word(s)	Description of environmental impact, causes and consequences	Measures or systems implemented to control the impacts	Classification of environ-mental impact (1-4)	Comments and possible follow-up measures
1	Collector	Seabed disturbance	Removal of the top layer of the seabed. The collector will pick up the top 10-30 cm of the seabed and due to this destroy flora and fauna in the mining tracks.	Difficult to avoid this impact in nodule mining. The most impacting part will be the collector. The depth of penetration of the collector is anticipated to be of the same order of magnitude as existing concepts (e.g. hydraulic collector). Compared to seabed mining for other resources (e.g. SMS), nodule mining has gentler impact on the seabed.	4	Novel concept, tests necessary to quantify the impact.
2	Collector	Noise	Low-frequency noise, which may travel long distance, originating from the motor is anticipated to be the biggest issue. Collector and propulsion system are not anticipated to produce high amount of noise due to soft clay substrate. Some noise from nodules crashing can be expected.	Will have to be addressed during later design stages.	3	Noise levels similar to existing concepts are anticipated.

ID no.	Subsystem	Guide word(s)	Description of environmental impact, causes and consequences	Measures or systems implemented to control the impacts	Classification of environ-mental impact (1-4)	Comments and possible follow-up measures
3	Collector	Plume	Moving collector and propulsion screws will generate sediment plumes. Suspended sediments may bury seafloor species outside mining tracks.	Implemented mitigation measures: - Skirts will cover the propulsion screws - Lower speed will lead to reduced disturbance. Design benefits: Lower design speed leads to increased collector efficiency and reduces.	4	Novel concept, tests necessary to quantify the impact. The level of impact is anticipated to be similar as for other existing concepts.
4	Collector	Oil spill	Possibility of releasing of oil into environment.	The collector will contain only very small amounts of oil for cable protection.	1	
5	Shuttling tank lifting system	Collision	Collision with fishes and sea mammals during ascending and descending of the container. Rising and lowering of containers will be frequent operation.	Possibly low speed of the container.	4	This is a novel concept and the impact is difficult to predict at this early concept phase. The biggest issue is anticipated to be the high frequency of the ascending/descending containers. The impact of a single operation can be estimated from other offshore operations or ROV deployment/picking up operation on research vessels.

ID no.	Subsystem	Guide word(s)	Description of environmental impact, causes and consequences	Measures or systems implemented to control the impacts	Classification of environ-mental impact (1-4)	Comments and possible follow-up measures
6	Shuttling tank lifting system	Noise	Noise generated by chemical reaction used to produce gas in the buoyancy elements.	Low-explosive powder will be used, i.e. no violent chemical reaction. No significant noise generation is anticipated.	1	Should be validated during later design stages.
7	Shuttling tank lifting system	Shock wave	Shock wave generated by chemical reaction used to produce gas in the buoyancy elements.	Low-explosive powder will be used, i.e. no violent chemical reaction. No significant shock wave generation is anticipated.	1	Should be validated during later design stages.
8	Shuttling tank lifting system	Release	Contamination of the seawater by the byproducts (e.g. H_2S) of the chemical reaction in the buoyancy elements. Hydrogen sulphide will in contact with water form sulphuric acid.	Low amount within one container.	4	The biggest impact is anticipated to be from the high number of the ascending/descending containers. The level of impact and mitigation strategies will have to be investigated further at the later stages of the design.
9	Basket lifting system	Chemical reaction for buoyancy	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system
10	Basket lifting system	Collision	Collision with fishes and sea mammals during ascending and descending of baskets. Rising and lowering of baskets will be frequent operation.	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system	Similar to the shuttling tank lifting system

ID no.	Subsystem	Guide word(s)	Description of environmental impact, causes and consequences	Measures or systems implemented to control the impacts	Classification of environ-mental impact (1-4)	Comments and possible follow-up measures
11	Metallurgical processing	Waste	Radioactive elements in polymetallic nodules will lead to radioactive contamination of the processing waste.	Mitigation measures: - Compliance with existing regulations	3	This issue is similar as for processes for production of REE from land based resources, but not for leaching processes for production of Mn, Ni, Cu and Co from land based ore.
12	Metallurgical processing	Waste Spill/Leak	Acid waste.	Similar to conventional metallurgical processing.	2	
13	Metallurgical processing	Leak	CO/CO_2			
14	Metallurgical processing	Waste Amount	As 74 wt% of polymetallic nodules is non-commercially valuable material, the amount of waste will increase significantly compared to a plant processing only land based ore.		4	Possible uses of the waste material could be evaluated. En interesting prospect is possible use as fertilizer, as suggested in the reviewed litterature.
15	Whole engineering system	General environmental issues	From the system as a whole, following activities will lead to additional environmental impact: - At-sea dewatering - At-sea drying		4	Impacts are anticipated to be similar to existing concepts. . The level of impact and mitigation strategies will have to be investigated further at the later stages of the design.

3.8.4 Conclusion - HAZID

In order to identify the major potential safety and environmental concerns of the proposed mining concept a hazard identification workshop was performed. The workshop was conducted early in the concept phase of the project, and the focus was on the major safety hazards and environmental impacts of the concept. The HAZID team consisted of the five members of the group.

The identified potential safety hazards and environmental impacts were classified as either known hazards, hazards that could be estimated from known concepts or new hazards specific to the current concept.

Most of the hazards which were classified as new and specific to the current concept were related to the lifting systems concepts, addressing unresolved issues of the buoyancy system and lifting trajectory. This is logical, since the lifting system concepts are the least mature in the proposed engineering system.

In addition, environmental impacts from the collector, such as seabed disturbance and plume generation were classified as novel and requiring tests to identify their impact. Of the metallurgical processing the environmental impact of the large amount of waste material originating from the polymetallic nodule processing was classified as new and specific to the current concept.

3.9 Financial analysis and feasibility study

The risk barrier confronting seabed mining is not isolated to technological factors. As discussed in section chapter 2 inherent risks can be found in the legal/regulatory environment, geo-political context and the product market. To address these risks there are a variety of strategies that may be adopted within the business model for seabed mining. What follows is a discussion on the current state of deep seabed mining from a commercial perspective and recommendations by the Group for alternative strategies, beginning with a review of the financial modelling.

3.9.1 Preliminary financial analysis

A number of analyses have been performed on the financial viability of manganese nodule mining. Table 3.11 lists those reviewed by the Group.

Table 3.11 Financial analyses for PMN mining

Author	Title	Year	Source
(Martino and Parson, 2012)	A comparison between manganese nodules and cobalt crust economics in a scenario of mutual exclusivity	2012	
	New scenarios of the world metal markets and the eventual contribution from deep sea mining.	1993	OTC
(Yamada et al., 2009)	Combined analysis of ecology and economy of manganese nodule mining	2009	ISOPE
(Yamazaki, 2008)	Model mining units of the 20th century and the economies (production requirements, area requirements and vertical integration).	2008	ISA
(Hein et al., 2010)	Seamount mineral deposits. A source of rare metals for high-technology industries	2010	Oceanogra phy
(Agarwal and Goodrich, 2003)	Extraction of copper, nickel and cobalt from Indian Ocean nodules.	2003	CJCE
(Johnson and Otto, 1986)	Manganese nodule project economics. Factors relating to the Pacific region.	1986	Resources Policy
(Hoagland, 1993)	Manganese nodule price trends. Dim prospects for the commercialization of deep seabed mining.	1993	Resources policy
(Sen and Singh, 1999)	Design of flexible configuration nodule pilot plants in the context of evolving metal markets	1999	ISOPE
Handschuh R. et al	Economic simulation for a small scale manganese nodule mining system taking into account new technologies.	2003	ISOPE
(Dick, 1985)	Deep sea mining versus land based mining: a cost comparison. (In The Economics of deep sea mining)	1984	Book
(Lenoble, 2000)	A comparison of possible economic returns from mining deep sea polymetallic nodules, polymetallic massive sulphides and cobalt rich ferro-manganese crusts.	2000	Workshop on mineral resources

Author	Title	Year	Source
(Soreide et al., 2001)	Deep ocean mining reconsidered – a study of the manganese nodule deposits in Cook Island	2001	ISOPE
(Hillman and Gosling, 1985)	Mining deep ocean manganese nodules: Description and economic analysis of a potential venture	1985	US Bureau of Mines
(Andrews et al., 1983)	Economic viability of a four-metal pioneer deep ocean mining venture	1983	US Dept of Commerce
(Charles et al., 1990)	Views on future technologies based on IFREMER-GEMONOD studies	1990	Materials and society
(Lenoble, 1992)	Future deep sea bed mining of polymetallic nodules	1992	IFREMER
(Ham, 1997)	A study on economics of development of deep sea bed manganese nodules	1997	ISOPE
(Little, 1979)	Technological and economic assessment of manganese nodule mining and processing.	1979	Cambridge

All of these analyses either ignore or only briefly mention the additional revenue stream available to polymetallic nodule mining operations through the sale of rare earth elements (REEs) and in many cases manganese alloy. Rare earth elements have recently received a lot of interest in mineral processing due to their limited supply (almost exclusively from China), increasing demand and critical significance to clean energy technologies, the arms industry and national security. Over 11 billion tons of manganese is produced annually (Clark and Neutra, 1983), mostly as a key component of steel.

3.9.2 Additional revenue from Rare Earth Elements (REE)

A number of recent analyses have been made into the REE market, including those listed in Table 3.12.

Table 3.12 Analyses of REEs in PMN

Author	Title	Year	Journal
(Hensel, 2011)	Economic challenges in the clean energy supply chain: the market for Rare Earth Minerals and other critical inputs	2011	Business Economics
(Hein, 2012b)	Prospects for Rare Earth Elements from Marine Minerals	2012	ISA Briefing paper
(Hein, 2011)	Marine mineral deposits as a source of rare metals for high- and green-tech applications: Comparison with land-based deposits	2011	ISA workshop
Okazuki and Tsune (2012)	Polymetallic nodule project: An approach to exploitation	2012	In: Minerals of the Ocean-6 international conference (Russia)
(Spickermann, 2012)	Rare Earth Content of Manganese nodules in the Lockheed Martin Clarion-Clipperton Zone Exploration Areas	2012	Lockheed Martin Corporation

The values for rare earth elements have increased significantly over the past 3 years due to reduced supply from Government-imposed embargos on Chinese exports.

The impact of REE and manganese on the financial models described above will most probably increase the return and Net Present Value (NPV) of a mining venture, perhaps bringing it close to feasibility. The Group recommends a review of all previous financial modelling with the inclusion of revenue from the sale of REE and manganese material (and the concomitant costs of processing) to establish an accurate estimate of the impact on the business case for nodule mining assuming suitable commercial extraction and refining processes are developed.

An indication of this impact is presented below through basic analysis by the Group. Nodule REE yield data from the Lockheed Martin research programme (Spickermann, 2012) is incorporated into the revenue figures of Yamazaki (Yamazaki, 2008) to estimate the maximum available revenue from an example nodule mining venture. This preliminary assessment suggests that a more detailed quantitative review of the financial models is performed with the inclusion of the latest prices and sensitivity analysis for manganese and REE metals.

Table 3.13: Prices for Rare Earth Elements

		c					**b**	**a**	**2011**
	Element	**MW**	**$/ton 1999**	**$/ton 2004**	**$/ton 2006**	**$/ton 2010**	**$/ton 2011**	**CCZ PPM***	**$/ton nodule**
Heavy REEs	Yttrium	89	85000	88000	50000	40000	130000	76	9.88
Heavy REEs	Dysprosium	163	65000	120000	150000	231600	1449800	26.2	37.98
Heavy REEs	Terbium	159	685000	535000	800000	557800	2334200	5	11.67
Heavy REEs	Holmium	165		440000	650000		n/a	4.6	
Heavy REEs	Erbium	167	150000	155000	160000	110000	350000	12.8	4.48
Heavy REEs	Thulium	169	3600000	2300000	2500000		n/a	1.9	
	Ytterbium	173	230000	340000	400000		90000	12.7	1.14
	Lutetium	175		3500000	3500000		n/a	2	
	Gadolinium	157	115000	130000	140000	18000	19000	29.8	0.5662
	Europium	152	700000	990000	1000000	559800	2842900	7.9	22.46
Light REEs	Samarium	150	75000	360000	250000	14400	103400	34.1	3.53
Light REEs									
Light REEs	Neodymium	144		28500	45000	49500	234400	131	30.70
Light REEs	Lanthanum	139		23000	30000	22400	104100	96.7	10.07
	Cerium	140	21000	19200	40000	21600	102000	316	32.23
	Praseodymium	141		36800	50000	48000	197300	31.1	6.14
	Scandium	45		6000000	Na	900000	900000		
	Promethium	145							

All prices from http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/

*nodule concentrations from Lockheed Martin, published by (Spickermann, 2012).

Table 3.14 Manganese nodule revenues (Yamazaki, 2008)

Price($/ton)	*1999*	*2004*	*2006*	*2010*
Cobalt	55,000	58,960	35,200	45,496
Nickel	7,260	13,816	22,000	27,016
Copper	2,200	2,772	6,600	7,788
Revenues($)	*1999*	*2004*	*2006*	*2010*
Cobalt	129,987,396.00	139,346,488.51	83,191,933.44	107,525,574.00
Nickel	133,148,689.47	253,385,990.87	403,480,877.20	495,474,517.00
Copper	30,411,273.45	38,318,204.54	91,233,820.34	107,655,999.15
Total revenue($)	293,547,358.92	431,050,683.93	577,906,630.96	710,655,999.15
Revenue per ton of nodules($)	209.68	307.89	412.79	507.61
Revenue per ton of metals($)	8,502.03	12,484.54	16,737.94	20,582.76

Value of REE in nodules (in USD/ton, 2011) = $(a/1x10^6)*b$ as per (Spickermann, 2012).

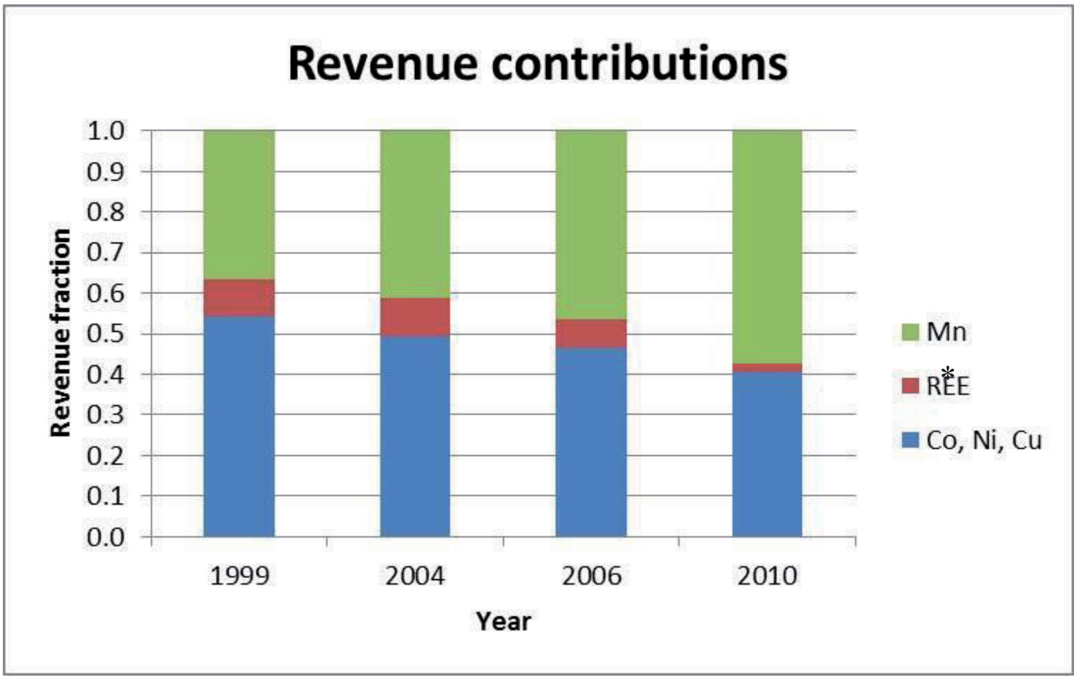


Figure 3.43 Potential impact of REE on revenues used in previous financial analyses

*2010 data for REE does not include values for 4 key elements – it is expected that these would make up for the shortfall in 2010 prices.

Adding the potential revenue from the above REE price table to the financial modelling data from Table 3.15 produces the following (assuming 1.2MT of ore):

Table 3.15 Updated revenue table for PMN constituents

Price ($/ton)	**Tons**	**1999 ($000)**	**2004**	**2006**	**2010**
Cobalt	2363.4	55	58.96	35.2	45.5
Nickel	18340.04	7.26	13.81	22	27.02
Copper	13823.31	2.2	2.77	6.6	7.79
Manganese	360000	550	1000	1600	2800
Yttrium	91.2	85	88	50	40
Dysprosium	31.44	65	120	150	231.6
Terbium	6	685	535	800	557.8
Holmium	5.52	n/a	440	650	n/a
Erbium	15.36	150	155	160	110
Thulium	2.28	3600	2300	2500	n/a
Ytterbium	15.24	230	340	400	n/a
Lutetium	2.4	n/a	3500	3500	n/a
Gadolinium	35.76	115	130	140	18
Europium	9.48	700	990	1000	559.8
Samarium	40.92	75	360	250	14.4
Neodymium	157.2	n/a	28.5	45	49.5
Lanthanum	116.04	n/a	23	30	22.4
Cerium	379.2	21	19.2	40	21.6
Praseodymium	37.32				
Revenues ($m)					
Cobalt		130	139	83	108
Nickel		133	253	403	495
Copper		30	38	91	108
Yttrium		7.75	8.03	4.56	3.65
Dysprosium		2.044	3.77	4.72	7.28
Terbium		4.11	3.21	4.8	3.35

Holmium	n/a	2.43	3.59	n/a
Erbium	2.30	2.38	2.46	1.67
Thulium	8.21	5.24	5.7	n/a
Ytterbium	3.51	5.18	6.10	n/a
Lutetium	n/a	8.4	8.4	n/a
Gadolinium	4.11	4.65	5.01	0.64
Europium	6.64	9.39	9.48	5.31
Samarium	3.07	14.73	10.23	0.59
Neodymium	n/a	4.48	7.07	7.78
Lanthanum	n/a	2.67	3.48	2.60
Cerium	7.96	7.28	15.17	8.19
Total Revenue ($m)	**540.70**	**871.84**	**1243.77**	**1760.06^**
Revenue per ton nodules ($)				
Revenue per ton metals ($)				
Total Revenue (metals)	293(54%)	430(49%)	577(46%)	711(40%)
Total Revenue (REE)	49.70(9%)	81.84(9%)	90.77(7%)	41.06(2%)^
Potential Revenue Mn	198(37%)	360(41%)	576(46%)	1008(57%)

**Data based on assumed nodule content published by Spickermann (2012) (w/w): Ni(1.4%), Cu(1.3%), Co(0.25%), Mn(30%), total REE(0.08%) and yield assumed from Yamazaki (2008): 1.2Mt dry nodules.*

^2010 price data for Ytterbium, Thulium, Lutetium and Holmium was not available. This has decreased the Total Revenue and share of revenue for REE in 2010.

Discussion

Previous financial analyses on proposed manganese nodule mining ventures have included only 3 metal products; cobalt nickel and copper. In the period since much of this analysis was performed the price of manganese and rare earth elements has increased dramatically. At the same time technological advances in extraction and recovery of such metals from PMN has advanced. The impact of these increases on the revenue from a marine mining venture has been estimated through a preliminary assessment using new data from Lockheed Martin (Spickermann, 2012).

This estimate raises two points of interest; (1) that the contribution of a Rare Earth revenue stream to nodule mining has the potential to increase the estimated revenue by 10%, and

(2) that revenue from the sale of manganese may have the potential to increase overall revenue by 100%, and that the share of overall revenue from manganese production has been increasing steadily for over 10 years.

Processing of REEs and manganese material from nodule ore will undoubtedly incur additional processing cost. The additional cost and exposure to risk combined with the relatively low increase in revenue from REE makes the decision to move from a four-metal system to REE processing more complex. It is recommended that the advantages and disadvantages be incorporated into a Pareto Frontier for analysis to further define the decision.

If REEs are to be targeted as part of a mining system this may raise the possibility of state-sponsored investment. In light of the low IRR values for nodule mining systems (5-15%) government support for such operations is crucial. Under certain circumstances a nodule feed can be integrated with a lateritic plant (Sen, 2010) for four-metal production. Investigations into the form and recoverability of REEs throughout this process is highly recommended. If integration with lateritic processes is possible the economic viability of an independent processing operation is improved. Government funding, in whole or in part might be sought for such a proposal.

A detailed review of manganese nodule mining by Arthur D. Little (Little, 1979) first established that an IRR of 30-35% is required for a venture to offset the overall risk to investors. Other authors have since attempted to advocate a lower IRR assessment on the basis of separating the low-risk processing business from the high-risk mining business, on the basis of resource security or technological advancement. Incorporating REE revenue and the ability to process lateritic ore is an essential part of this separation.

4 Conclusions and Recommendations

This report has reviewed the field of polymetallic nodule mining and identified some major barriers to its commercialisation. Most of these are related to the high investment risk inherent in deep sea mining.

In part 3 a number of new and reprised concepts have been proposed to reduce investment risk by increasing reliability, independence and decreasing cost of marine mining systems. These include;

- a new PMN collector design
- processing routes for combined marine/laterite ores
- hydraulic subsea power system
- shuttle transport systems
- on site bioremediation

The application and specific design of these concepts may be novel but they are based on established principles and many have been applied previously in some form. The specific concepts proposed in this volume are not claimed to be superior in design, but the principles on which they based are a valuable consideration for future technology development. Below is a summary of each concept and a discussion on the fundamental principle behind them. It is hoped that the presentation of these principles and examples of their application might serve to broaden the research of deep sea mining technology.

Nodule collector

The nodule collector is the unique component of a PMN mining system. Nodule collectors must be designed from the beginning for their purpose and existing designs have contributed to high risk through downtime and reduced efficiency. In their review of the literature the Group found that downtime and efficiency can be improved through careful design and development. A design concept has been described here based on the use of Archimedes screws in the collector, elevator and propulsion system. Screw-based designs are not new but their application to the nodule collection apparatus is. The core principle behind this design is reduced complexity to avoid problems caused by interaction with the seabed material. Comparison with research management literature confirms that maintaining multiple designs is critical when dealing with new development into unfamiliar fields. Further reflection on the design principles suggests that design for new nodule collectors should maintain as broad as possible portfolio of options and to avoid committing to a particular design until absolutely necessary. In terms of specific nodule collector design this process has highlighted the need for robust design with careful consideration of the point of interaction with the seabed. Given the difficulties of testing designs in the field and the lessons learned by previous programmes it is advisable to base designs on primary tools that have been proven to work well.

Processing routes

Discussion within the Group and with other groups at the 2012 LRET Research Collegium highlighted the pressure that a dedicated extraction and processing plant places on the mining operation. The construction and operation of a dedicated PMN processing plant requires significant capital outlay. To make this operation profitable requires a minimum feed of nodules (up to 2,500,000 tonnes per year – G). Mining operations have so far proven to be incapable of providing such a high supply of nodules. At the same time the commercial feasibility of nodule mining depends on the market for key metal products. Shifts in the market can eliminate the viability of a mining operation, with serious impacts on a dedicated processing operation.

In light of this the Group considered the advice of a number of researchers who advocate for combined processing operations that can accept land-based laterite ore as well as nodule ore. This necessitates new processes and equipment that can convert nodule ore to suitable feed for a laterite plant, but it allows for an independent processing operation that can maintain viability during periods when mining yields are low. Additionally it removes the mining operation from the burden of meeting a minimum production rate, an important consideration for the first nodule mining venture. The Group has presented an alternative process suitable for a combined operation and identified a potential location to adapt an existing lateritic plant to accept nodule feedstock.

The philosophy behind this concept is taken from authors such Hoagland (1993) who point to the lower IRR requirement for the processing operation compared with the mining operation, and the cost of the processing operation is more than half of the entire system.

The principle illustrated by this concept is a need for independence between the mining and processing operations. At these early stages of a high-risk venture in a new industry it may be implied that dividing risk between multiple smaller operations is preferable to incorporating a number of risky businesses under one banner.

Hydraulic subsea power system

Another key point of failure in marine mining systems is the power supply to the nodule collector. This component presents particular challenges, requiring large electrical power through a very long cable to complex, heavy electrical equipment (motor, transformer, inverter, rectifier). Not only are these components complex and vulnerable to breakdown, they also significantly increase the weight of the seabed machinery.

To address this problem the Group revisited hydraulic power systems for seabed equipment, specifically in an atmospheric engine design. The use of an atmospheric engine allows for a cheaper, lighter and more robust drive system. Concept development and validation was beyond the scope of the 2012 LRET Research Collegium so this element remains only a conceptual proposal, but the underlying principles behind the hydraulic power system are worthy of note.

Reducing complexity and eliminating key points of failure is a fundamental strategy for reducing downtime. Downtime is particularly important for deep sea mining due to the time required to retrieve, fix and return to service critical machinery. This downtime reduces mining yields and contributes to the high assessed investment risk for marine mining ventures. Additionally the weight of electrical drive equipment on seafloor mining vehicles requires downsizing of critical collector machinery, reducing their effectiveness.

At its core the hydraulic drive concept aims to address these issues by moving complex power systems to the mother ship and reducing the equipment located on the sea floor to its minimum. The generators and pumps that provide power to the system are therefore less prone to breakdown and readily accessible for maintenance, and the weight of the drive system at the collector is reduced, allowing for larger, more effective collector machinery. This principle may also be applied to electrical systems where heavy components may be moved to the mother ship, but this also requires the delivery of variable low-frequency power along the length of the cable, introducing further problems.

The Group wish to emphasize that this conceptualization should at least suggest that the extension of ROV power systems to deep sea mining is not the only option, that alternative approaches may be considered and have significant benefit.

Shuttle transport systems

The transport of nodule ore to the surface in a marine mining system is a major technical issue and cost for mining ventures. Various different designs have been proposed but current technology still relies on riser systems designed for shallow water adapted for use in the deep sea. Shuttle systems have been largely abandoned due to their high cost and complexity, but this report introduces two concepts for raising nodule ore with a shuttle system using chemical energy in place of electrical energy. This alternative allows for a far simpler design and more cost-effective technology. Like the other ancillary concepts proposed in the course of the LRET Collegium 2012 this proposal is limited to the early conceptualization stage, but it illustrates an alternative to one of the most complex and costly components of a marine mining system, as well as a reminder to maintain an open research programme with active parallel projects in a variety of technology alternatives.

On site bioremediation

The environmental impact of marine mining is an emotive topic with widespread implications for large public stakeholders such as governments and major mining companies. Current mining of SMS deposits in ecologically sensitive areas with high biodiversity has engendered opposition to the marine mining field. The ISA has also instituted a strict environmental policy that requires mining ventures to monitor, report and manage environmental hazards with financial penalties for failure to adhere. While the impact of PMN mining is lower due to the relatively sparse marine life in these remote locations it is still critical to ensure that waste water is appropriately treated and environmental impacts are avoided, mitigated and offset.

On site bioremediation offers tangible potential to remediate waste water and at the same time reduce costs by displacing some of the fuel required for mining. While such systems require significant capital outlay they also provide an opportunity to develop sustainable technologies for harvesting soluble minerals (potassium, nitrogen, phosphorus) from ocean water and an important niche opportunity for next generation clean energy and bio-refinery technologies.

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Appendix

Appendix A: Collecting pattern

A Appendix A

A.1 Collecting pattern

The collector sweeps a two dimensional seafloor for seabed manganese nodules. And its path should be planned for maximizing of sweeping coverage efficiency. We assume the collected area has the following condition.

1. The mining site is minable area by the exploration. We have enough information about the target area. So this is a known environment.
2. The target area is a free space for moving the robot. In this area, we could plan any directions. There are no unknown obstacles and no restriction for driving.
3. The collector can track on a desired path without any problems.

Now, our purpose is to find the adaptable method for the operation of the collector. The collector should perform the complete, non-overlap, minimizing operation cost, and maximizing coverage efficiency coverage path.

For an area, a square, rectangle, relative complex area, a gradient and a complex area where there is an obstacle, the sweeping patterns may follow the following types, shown in Figure A.1 to Figure A.**5**.

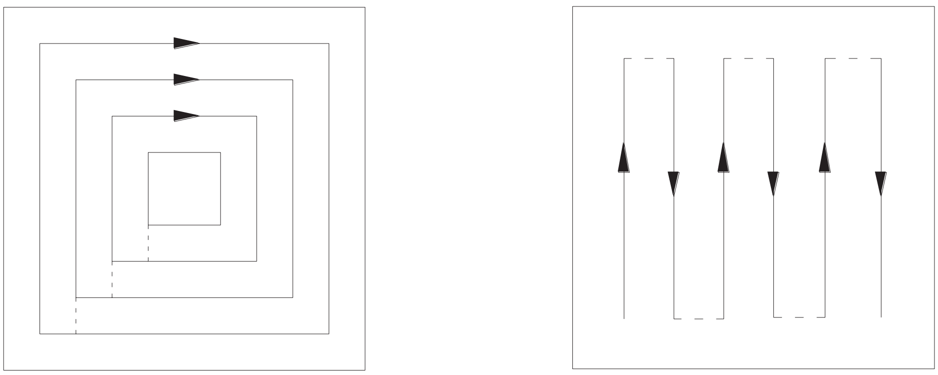

Figure A.1: Basic idea of path generation.

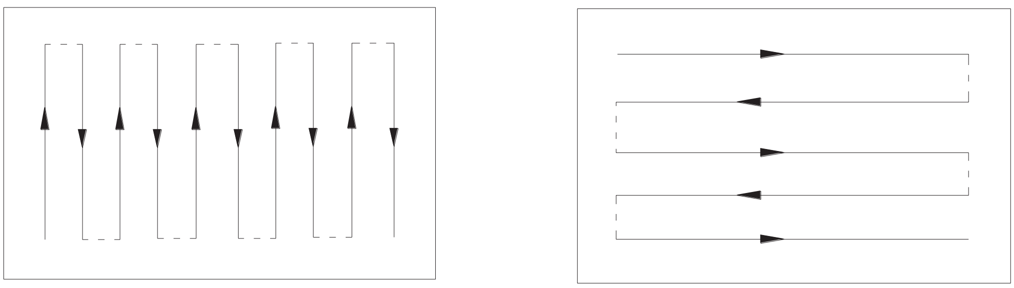

Figure A.2: Different Path direction for a rectangle area**.**

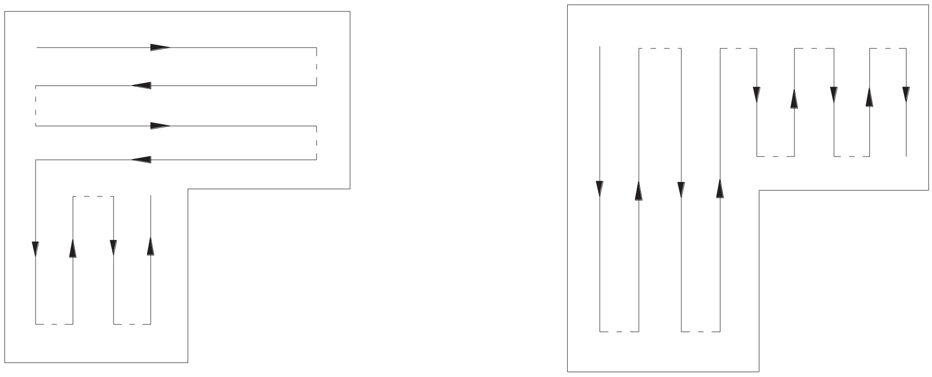

Figure A.3: Different path direction for a relative complex area

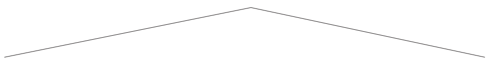

Figure A.4: There is a slope in the path. Different path directions will result in different efficiences of the collector.

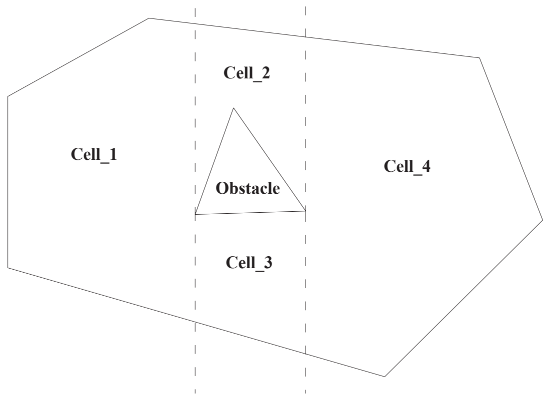

Figure A.5: Path direction decomposed while there is an obstacle

When a collector meets a turn, it must slow down, make the turn, and then accelerate. When a collector is collecting polymetallic nodules on a gradient seabed, a proper routine should be determined, because the collector goes down along the gradient it will accelerate, while when the collector climes the gradient it will need more power. Then we should wish to minimize the number of turns required when we design a sweeping path. And when a collector is going to collect polynmetallic nodules, input information such as path requirements, vehicle information, vehicle performance information and target environmental information should be confirmed. Then the collector will define the configuration space to find out whether there is an obstacle. If there is an obstacle, the first thing for a collector is to decompose the area into different cells, select the start cell and define the path direction and calculate the collecting efficiency to find an optimal path. After all these steps, the collector starts to work. A flow chart of the collector sweeping method is shown in Figure A.6.

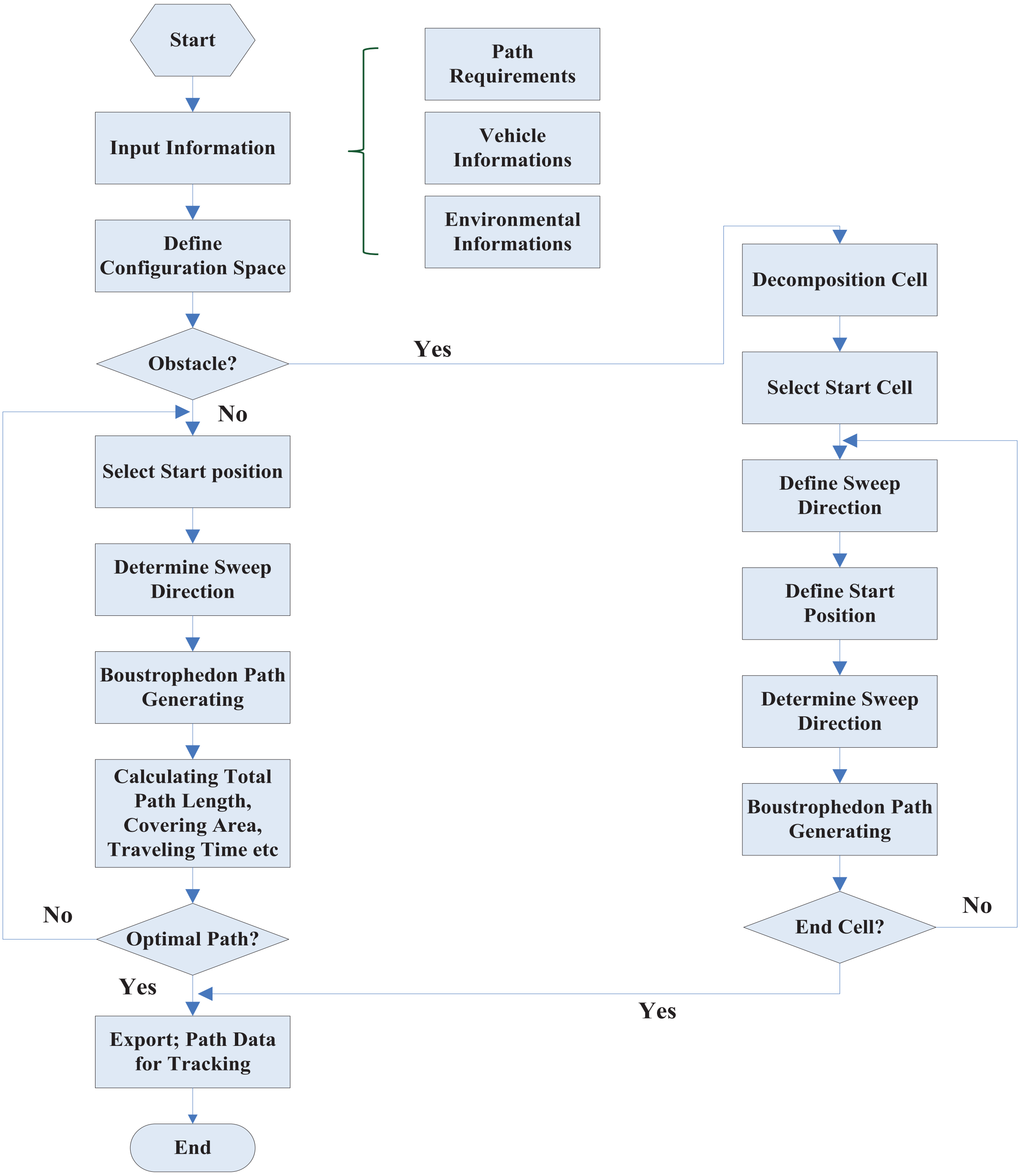

Figure A.6: Flow chart of collector sweeping method

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