Status of India’s Polymetallic Nodule Mining Programme

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Introduction

- Deep Sea is viewed as potential source for meeting the increasing demand of metals in this century.
- Deep Sea Minerals rich in Copper, Cobalt, Nickel, Manganese, Zinc, Lead, Barium, Silver, Gold are present in the deep seas.
- Mining minerals from such depths is a major technological challenge.
Deep-sea Mineral Resources

Polymetallic nodules

- Copper, Cobalt, Nickel, Manganese,
- Lead, Zinc, Gold, Silver, Tin

Polymetallic Sulphides

Cobalt

Black smokers in the Lau Basin (Peter Herziv)

ISOPE-2011 Maui
Distribution of marine minerals

- Fe-Mn Sulfides
- Fe-Mn Crusts
- Phosphorites
- Placers

Geological features:
- Rift Valley
- Abyssal Hill
- Seamount
- Abyssal Plain
- Continental Rise
- Continental Slope
- Continental Shelf
- Mid Oceanic Ridge
- Ocean Basin
- Continental Margin
Polymetallic Nodules – Relevance to India

- Cobalt, Nickel and Copper are important materials for the industry.
- India has no proven source of cobalt in land.
- The proven source of Nickel (laterite overburden) and Copper in India are small (1.6 million tons of Nickel and 9.4 million tons of Copper).
- Manganese nodules in Central Indian Ocean Basin (CIOB) are potential resource of these metals.
Introduction (contd...)

- India is carrying out the exploration and technology development for exploitation of polymetallic nodules under the Polymetallic Nodule program (PMN) of the Ministry of Earth Sciences (MoES) (erstwhile Department of Ocean Development (DoD)), Govt. of India.
- India was registered as Pioneer Investor in 1987 along with Japan, France and (formerly) Soviet Union. India is the only country with mining site allocated in the Indian Ocean. Other sites are claimed in the Pacific Ocean.
MoES has drawn up a long term plan aiming to fulfil its obligations as Pioneer Investor as well as reach the stage for seeking production authorisation as quickly as possible.

MoES has entrusted the task of Exploration, Environmental Impact assessment, Mineral Processing, Metallurgy and development of Deep Sea Mining Technology to different institutes in the country.

India has carried out extensive exploratory surveys, conducted Environmental Impact Assessment Studies, demonstrated extraction of metals in Pilot Plant Scale and demonstrated a flexible riser mining system concept at 500 m depth.
Chronology of Events

- First nodule sample collected by Indian scientists: 26 Jan. 1981
- First metal from nodules extracted and 3 million sq. km area explored: August 1983
- India Registered as Pioneer Investor and allocated Pioneer Area in CIOB: December 1987
- 20% area relinquished: July 1994
- India Ratified UNCLOS: June 1995
- 10% area relinquished: October 1996
- Completion of the 1st phase of subsea mining experiments (500 m): September 2000
- Final 20% of area relinquished to the International Seabed Authority: April 2002
Chronology of Events (contd...)

● Major Augmentation (DP Systems and LARS) of Research Vessel for Long Term Mining Demonstration  Dec. 2005

● Demonstration of the subsea mining system for long term operations (500 m)  July 2006

● Development and Testing of In-situ Soil Tester for 6000 m  Nov. 2006

● Demonstration of Remotely Operated Artificial Nodule Laying System  August 2007

● Demonstration of Remotely Operable Vehicle at 3000 m depth  April 2009

● Demonstration of Remotely Operable Vehicle at 5280 m depth  May 2010

● Demonstration of Underwater Mining System with Collector and Crushing Systems and testing in shallow waters  October 2010
Multi-institute networking

Survey and env. data collection
- Nat. Inst. of Oceanography

Chemical & mineralogical analysis
- Geological Survey of India
- Indian Bureau of Mines
- Hindustan Zinc Ltd.

Metallurgical processing
- Regional Research Lab.
- Nat. Metallurgical Lab.
- Engineers India Limited

Mining Technology Development
- Central Mining Research Inst.
Nodule program launched

- Onboard RV Gaveshani (Cruise 86-87)
- Under the leadership of Dr. SZ Qasim
- First nodules recovered on 26 January 1981 from Equatorial Indian Ocean
First nodule to first mine-site

Schedule of activities

- Jan, 1981 : First nodule picked from Eq. Indian Ocean
- April, 1982 : India recognised as Pioneer Investor
- August 1987 : Area allocated to India (150,000 sq. kms)
- July 1994 : 20% area relinquished
- October ’96 : 10% area relinquished
- May 2002 : 20% relinquishment

Press cuttings of nodules from Indian Ocean
Followed by state of the art technology / ships utilisation

RV Skandi Surveyor (Norway)

RV Farnella (UK)

RV AA Sidorenko (Russia)

ORV Sagar Kanya (India)

No. of ships = 8, expeditions = 72 x ~35 days = 2520 days = 7 years at sea

(Source: NIO/PMN data bank)
Satellite navigation for position fixing

GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination
Multibeam sounding for seafloor mapping

Total bathymetry Survey (30,000 km x ~10 km swath)

(Source: NIO/PMN data bank)
Equipments for nodule sampling

Total locations sampled = 2500
Total samples collected = 11000

(Source: NIO/PMN data bank)
Seafloor photography

Profiles: 19
Photos: > 50,000

Deep-tow profiles in CIOB

Polymetallic nodules on seafloor
Nodules resources in the ‘Indian’ claim area (150,000 sq.km.)

Wet Nodules 759.00 MMT
Dry Nodules 607.00 MMT
Manganese 144.00 MMT
Cobalt 0.85 MMT
Nickel 7.00 MMT
Copper 6.50 MMT
Total Metal 158.35 MMT

Grade (Cu+Ni+Co %) ranges

(Source: NIO/PMN data bank)
Location of India’s Mining Site

Area covered by the nodules in the Indian Ocean – 10-18 million sq.km.
Total estimated reserves in the Indian Ocean - 0.15 trillion tons.
In situ resources of Poly metallic Nodules in the Pioneer Area

- Nodules: 380 MMT
- Manganese: 92.59 MMT
- Cobalt: 0.55 MMT
- Nickel: 4.70 MMT
- Copper: 4.29 MMT

Nodule dredged by NIOT onboard Boris Petrov
Deep-sea Mining – Technological Challenges

1. Nodules lie on the seabed at 5000-5700 m water depth.
2. The seabed is extremely soft (2.5 to 7.5 kPa shear strength) to support any heavy equipment.
3. Mining equipment has to traverse through ocean floor of varied topography without getting damaged.
4. The equipment has to be sweep large areas and collect nodules with high efficiency to obtain economical production rates.
5. The mining system has to be highly reliable.
6. The mining system should be capable of being deployed and retrieved easily (during storms, other emergencies.)
7. Environmental disturbance must be minimum, both in the ocean floor and in the surface.
8. Collection and lifting nodules to the surface and power intensive%
Flexible Riser System

- Multiple mining machines connected to mother station.
- Self-propelled mining machine that pumps nodules through a flexible riser using a single positive displacement pump.

**Advantages**
- Failure in one system will not affect total operations.
- Less cost intensive.
- Ease in deployment, retrieval.
Deep Sea Mining System using Flexible Riser Concept

Underwater Mining System 500 m

Underwater Mining System 6000 m
Developmental Phases of Flexible Riser System

- First phase of validation of the flexible riser concept at 400-500 meters water depth for sand mining operations.
  - Long Term Operations: 2002-2006
  - Development of In situ Soil Tester: 2002-2006

- Second phase of validation of nodule collection pick up and crusher systems using underwater mining machine developed in the first phase: 2006-2010

- Third phase of validation of the flexible riser concept for manganese nodule mining operations in the Central Indian Ocean Basin using one mining machine and other subsystems: 2010-2015

- In situ soil testing and mining area survey for identification of areas of low bearing strength: 2008-2012
Development of Deep Sea Technology using Flexible Riser System

- Technology development for nodule mining started initially in year 1997 at NIOT.
- NIOT has been working on a concept having a crawler based mining machine and a flexible riser system.
- Institut für Konstruktion (IKS) of University of Siegen, Germany and NIOT, India teamed up and jointly developed the crawler based underwater mining machine.
- Initially the demonstration was proposed for 500m depth.
- Successful testing could enable the team to proceed to development of systems for 6000m water depth with higher confidence.
### Mining System Description

- **Crawler based, Remote Controlled, Electro-hydraulically operated machine.**
- **Specially designed rubber track belt with external teeth of in volute profile to compact the soft sea bed while the crawler is in motion, to minimize eruption of bottom sediments.**
- **Equipped with Underwater Cameras, Altimeter, Doppler Velocity Log, MRU, Depth Sensors, Speed Sensors, Solids Concentration meter, and position transponders.**
- **Pumps mined sea floor material through flexible riser using a twin cylinder positive displacement pump.**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length</td>
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<tr>
<td>Overall Width</td>
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<tr>
<td>Weight in air</td>
<td>10 tons</td>
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<tr>
<td>Weight in water</td>
<td>8 tons</td>
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<tr>
<td>Depth of operation</td>
<td>500 m</td>
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<tr>
<td>Operational speed</td>
<td>0.5 m/s</td>
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<tr>
<td>Max speed</td>
<td>0.75 m/s</td>
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<tr>
<td>Max slope</td>
<td>8.5°</td>
</tr>
<tr>
<td>Slurry Discharge</td>
<td>upto 45 m³/h</td>
</tr>
<tr>
<td>Concentration</td>
<td>30% (max.)</td>
</tr>
<tr>
<td>Mining Output</td>
<td>12 t/h (max.)</td>
</tr>
<tr>
<td>Particle Size (max.)</td>
<td>8 mm</td>
</tr>
<tr>
<td>Flexible Riser System</td>
<td></td>
</tr>
<tr>
<td>Hose size</td>
<td>75 mm</td>
</tr>
<tr>
<td>Hose Spool length</td>
<td>100 m</td>
</tr>
<tr>
<td>Hose-cable joints at 6m intervals</td>
<td></td>
</tr>
<tr>
<td>Hose Winch</td>
<td>500 kg (SWL)</td>
</tr>
<tr>
<td>Hose Spool Speed</td>
<td>0.5 m/s (max.)</td>
</tr>
</tbody>
</table>
| Power Supply, Control and Instrumentation System | |}

- **Electro-mechanical multi-conductor**
- **Cable Breaking strength** 400 kN
- **Power** 120 kW at 3000 V
- **Signal Transmission** 2 optical lines TCP/IP
- **Data Acquisition** PXI based system
- **Transducers** Velocity, heading, pitch, roll, vision
- **Winch for Cable** 1.6 m dia.x 1.4 m length
- **Cable Spool Speed** 0.5 m/s
Other main systems, Infrastructure developed

Umbilical Cable Winch

Integration Bay
Sea tests on Underwater Mining System

- The mining trials were conducted using Ministry of Earth Sciences’ Research Vessel ORV Sagar Kanya and the underwater mining system was successfully tested during year 2000 off Tuticorin coast at 410 m depth.

- Total No. of Tests: 4 (1 off Goa coast and 3 off Tuticorin coast)

- Demonstration of Pumping of Slurry during the tests from 500 m depth validated the flexible riser concept.
Dynamic Positioning System (DP) is the system to automatically keep ship at the fixed position with the thrust of propeller and without using anchors.

Transducers for measurement of wind, wave, heading and other related parameters.

Controller takes the parameters and using specific algorithms controls the Bow thruster and Azimuth thruster to keep the vessel in position within a limited area.

- Heading accuracy: ± 10 deg
- Sea state: 3
- Wind speed: 25 knots
- Significant wave height: 6’ (1.83m)
- Current: 0.5 knots
- Positioning accuracy: 15 m
Launching and Retrieval System

Specifications

- Working Radii
  - Minimum 3.5 m
  - Maximum 14.5 m
- Slewing range 360 degree
- Safe Working Load 12 t
- Dynamic vertical force 40 t
- Dynamic over turning moment 358 tm
- Hoisting speed 40 m / min
- Self weight of the LARS
  - Dry weight 22.2 tonnes
  - Wet weight 22.8 tonnes
- Power
  - Main Power 90 kW
  - Auxiliary power 2.5 kW

- The Co-ordination between the Crawler and Vessel
- Performance of pressure compensated hydraulic system
- System temperature rise and stabilization underwater
- Performance of data acquisition and telemetry system
- Performance of High voltage system, FITA and Slip ring assembly
- Traffic ability of crawler and position keeping of vessel
- Mining and Slurry Pumping Operations

Depth: 451 m
Underwater duration: 3 days
Slurry Discharge: 10-45 m³/h
Maximum density: 1170 kg/m³ at 22% conc. by weight
Results and Graphs

ANGRIA BANK, WEST COAST OF INDIA

Latitude 16°, 14.5° North
Longitude 72.04°, 25° East

Sand mining
Development of In-situ Soil Tester

- An Remotely Operable in-situ soil tester capable of operations at 6000m depth has been developed jointly with Sevmorgeo, Russia.
- Measurement of in-situ properties of soft sea floor possible (<2.5 kPa)
  - Accuracy: +/- 2% of full scale
  - Cone stroke: Maximum 6 m
  - Three cones to cover ranges:
    - 0.05 to 10 kPa,
    - 0.1 to 25 kPa
    - 1 to 50 kPa
  - Rod diameter: 45 mm
  - Vane Range: -0 to 10 kPa

- Experiment 1: 1272 m depth (off Mangalore)
- Experiment 2: 5200 m depth (CIOB)
Development of Collector and Crusher

- The manipulator of the existing crawler to be replaced with a nodule collector
- Involves development of pick up devices, cleated belt conveyors, crushers
- Assembly integration of developed subsystems with underwater mining machine
- System is being designed for mining rate of 8 tons/hour of wet nodules with nodule abundance of 5 to 10 kg/m² in sea floor
- To qualify the system at 500m depth, an artificial nodule site will be created using Artificial nodules.
Underwater Mining System with Collector crusher

Overall length 6200 mm
Overall Width 4200 / 3400 mm
Weight in air 18.5 tons
Weight in water 7.9 tons
Depth of operation 500 m
Operational speed 0.5 m/s
Max speed 0.75 m/s
Max slope 8.5°
Slurry Discharge upto 45 m³/h
Concentration 30 % (max.)
Mining Output 8 t/h (max.)
Particle Size (max.) 10 – 20 mm
Flexible Riser System
Hose size 75 mm
Hose Spool length 100 m
Hose-cable joints at 6m intervals
Hose Winch 500 kg (SWL)
Hose Spool Speed 0.5 m/s (max.)

Power Supply, Control and Instrumentation System
Cable Electro-mechanical multi-conductor
Breaking strength 500 kN
Power 120 kW at 3000 V
Signal Transmission 2 optical lines TCP/IP
Data Acquisition PXI based system
Transducers Velocity, heading, pitch, roll, vision
Winch for Cable 1.6 m dia.x 1.4 m length
Auxiliary Winch 12 Tonnes - 2 Nos
Cable Spool Speed 0.5 m/s

- Crawler based, Remote Controlled, Electro-hydraulically operated machine.
- Specially designed rubber track belt with external teeth of in volute profile to compact the soft sea bed while the crawler is in motion, to minimize eruption of bottom sediments.
- Equipped with Underwater Cameras, Altimeter, Doppler Velocity Log, MRU, Depth Sensors, Speed Sensors, Solids Concentration meter, and position transponders.
- Pumps mined nodules through flexible riser using a twin cylinder positive displacement S-transfer tube pump.
Collector and Crusher System

**Status**

- Development of Main Sub Systems like collector, crusher and pickup systems were completed.
- Studies have been carried out on the developed crusher using both manganese nodules and artificial nodules.
- Integrated tests of the collector and crusher system was completed on a test frame.

![Bentonite tank for testing Pick up devices](image)

![Pick up device Testing](image)

![Experimental set up for studies on Manganese Nodule Pick up Devices](image)
Pumping System and Hydro transport Facility

**PUMPING SYSTEMS**

The Enhanced S-transfer Piston pump has been realised for transportation of large solids slurry.

Twin cylinder positive displacement piston pump

1. Delivery Pressure : 30 bar
2. Discharge : Variable in steps of 10, 20, 30 and 45 m$^3$/h of slurry
3. Concentration : 30 % by weight
4. Drive : Electro-hydraulic
5. Flow rate (max.) : 45 m$^3$/hr
6. Power (motor) : 80 kW
7. Max. Nodule size : 30 mm

### Performance Chart for Clear water test

<table>
<thead>
<tr>
<th>S.No</th>
<th>Control Voltage (V)</th>
<th>Flow rate (m$^3$/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>10.2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>20.7</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>41.4</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>49.6</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>59.58</td>
</tr>
</tbody>
</table>

**Hydro transport Facility for**

- Conducting plugging and pressure loss studies on the flow of large solids through hoses.
- Testing Positive Displacement Slurry Pumps.
- General arrangement for testing of S-shaped profile.
- The set up has been commissioned and used for experimental studies.
Electrical and Control Systems

Sub-sea motor - 75 kW, 3000 V, 3-phase AC submersible motor.

Slurry pump - 80 kW, 3000 V, 3000 rpm AC submersible motor.

Sub-sea electro-optical cable 800-m long

The Data Acquisition and Control System (DACS) used for the mining system is of a modular type with stand-alone controller, which is more versatile for system configuration, programming and avails more local service support.
Facilities - Overview

- Hyperbaric Test Facility for 900 bar (first in S.E.Asia)
- Dynamic Positioning System, LARS and Launch Platform in ORV Sagar Kanya
- Winch Load Test Setup
- Test Pond for Underwater Vehicle Testing
- Hydraulic Valve Test Rig
- TDV Sagar Nidhi
Products Developed

- Underwater Transformer
- Underwater Thruster
- Underwater Multiplexer Connector
- ARGO FLOAT (Array for Real Time Geotropic Oceanography)
- Artificial Manganese Nodules
- Underwater Encoder for 6000 m depth (under development)
- Hydraulic Load Cell for 6000 m depth (under development)
- Remotely Operable Boat
- Echo-Sounder
- Fiber Optic Connector for 6000m
Artificial Nodule Laying System

- The sea trials of underwater collector and crushing system was done at Angria bank.

The following major activities were carried out during the tests:

- Site Survey for sea floor profile and Collection of Gravity Core Samples
- Laying of Artificial Nodules using Remotely Operated Artificial Nodule Laying System
- Artificial nodule were laid on the seabed to create 50 m nodule tracks using Remotely Operable Artificial Nodule Laying System
Underwater collector and crushing system

✓ The collector and crusher system was tested at Angria bank, off Malvan Coast, India.

✓ Underwater mining system with Collector and Crusher was launched to reach the seafloor at 512 m depth using a combination of auxiliary and main umbilical winch.

✓ The machine was operated to mine artificial nodules by following the set track.

✓ All major system like Collector, Crusher, Solid pump, Undercarriage, Crawler tracks, Hydraulic systems, Electrical systems, Sensors, Telemetry and Control systems were qualified.

✓ Details will be presented in Session 96 (Ocean Mining IV)
Future Plans- (2010-2011)

Future plans (2011-2012):

- Demonstration sea trials of collector crusher system on a regular basis combining with Soil Tester Project at 500m depth or deeper waters.
- Detailed design and development of integrated mining machine for 6000 m depth operations.
- Development of new in situ soil tester.
- New proposals for inter institutional R&D programmes.
ENVIRONMENTAL
MINING IMPACTS

Surface discharge affecting turbidity, photosynthesis & productivity

Subsurface discharge changes water column characteristics

Sediment plume behind the miner

Mortality of organisms on the seafloor

MINING SHIP

LIFT SYSTEM

NODULE MINER
Statement of environmental impact assessment from the contractor, includes:

- Baseline data in the proposed mining area
- Test and reference sites for env. monitoring
- Results of simulated impact experiment
- Expected environmental impact due to mining
- Critical parameters for monitoring impacts
- Proposed measures to minimize the effects
Collection of baseline water column data in CIB

Data collection
- Areal
- Seasonal
- 3-dimensional

Parameters
- Meteorology: 600x900 km
- Temperature, salinity: 600x900 km
- Currents (3 levels/locations): ~200 days
- Bottom currents in test area: ~200 days
- Productivity and chlorophyll: 600x900 km
- Chemical characteristics: 600x900 km
  (metals, DOC, POC)
Collection of baseline benthic data in CIB

- **Sounding:**
  300 km x 5 areas = 1500 km

- **Sediment + nodule + benthos:**
  12/13 x 5 = 64 stations

Selection of test & reference areas for impact experiment (with similar features)

<table>
<thead>
<tr>
<th>Area</th>
<th>Av. Abund. (kg/sqm)</th>
<th>Av. Depth (m)</th>
<th>Av. Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1.94</td>
<td>5217</td>
<td>1.1</td>
</tr>
<tr>
<td>R1</td>
<td>1.14</td>
<td>5330</td>
<td>1.4</td>
</tr>
<tr>
<td>A1</td>
<td>2.10</td>
<td>5327</td>
<td>1.1</td>
</tr>
<tr>
<td>T2</td>
<td>3.41</td>
<td>5217</td>
<td>1.7</td>
</tr>
<tr>
<td>R2</td>
<td>5.05</td>
<td>5297</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Simulated ‘mining’ experiment (1997)

Hydraulic suction device used
- No. of tows: 26 tows
- No. of days: 9
- Operation time: 47 hrs
- Operation distance: 88 km
- Sediment resuspended: 580 t (dry)

Experimental site
- * Area: 200 x 3000 m
- * Depth: 5400 m depth
- * Location: Central Indian Basin
Schematic of sampling in experimental mining’ area

- Disturbance site
- Sediment traps
- Sediment cores
- CTD & water samples
Alterations in seafloor conditions

- Vertical mixing of sediment
- Lateral migration of sediment

Changes in physico-chemical conditions

Reduction in biomass
## Stages and parameters for environmental study

<table>
<thead>
<tr>
<th>Stage</th>
<th>Year</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1996</td>
<td>- Sediment thickness</td>
</tr>
<tr>
<td>Pre-mining</td>
<td>1997</td>
<td>- Sediment sizes and mineralogy</td>
</tr>
<tr>
<td>Post-mining</td>
<td>1997</td>
<td>- Shear strength and water content</td>
</tr>
<tr>
<td>Monitoring-1</td>
<td>2001</td>
<td>- Sediment geochemistry</td>
</tr>
<tr>
<td>Monitoring-2</td>
<td>2002</td>
<td>- Porewater geochemistry</td>
</tr>
<tr>
<td>Monitoring-3</td>
<td>2003</td>
<td>- Sediment biochemistry</td>
</tr>
<tr>
<td>Monitoring-4</td>
<td>2005</td>
<td>- Bacterial diversity and abundance</td>
</tr>
<tr>
<td>Env. Variability-1</td>
<td>2003</td>
<td>- Fungal diversity and abundance</td>
</tr>
<tr>
<td>Env. Variability-2</td>
<td>2005</td>
<td>- Meiofaunal diversity and abundance</td>
</tr>
<tr>
<td>Env. Variability-3</td>
<td>2006</td>
<td>- Macrofauna diversity and abundance</td>
</tr>
</tbody>
</table>
1. Assessing the potential impact of nodule mining on environment in test and reference areas

- Benthic conditions getting restored
- Degree of restoration is different
- Natural conditions taking over

2. Natural variability in nodule area
   Water column: 34 stations
   Physical, Chemical, Biological
   Benthic: 20 stations
   Geological, Biological

Findings
Significant seasonal and annual variability observed
Major inputs (EIA studies – contd.)

3. Environmental inputs for nodule mining

- **Atmospheric**
  - wind, rainfall, cyclone

- **Surface**
  - waves, temperature, currents

- **Water column**
  - currents, temperature, pressure

- **Seafloor**
  - topography, micro-topography, slopes

- **Sub-seafloor**
  - sediment thickness, shear strength

- **Mineral characteristics**
  - abundance, grade, size

- **Associated substrates**
  - sediments, rocks, crusts

4. Environmental measures for ‘safe’ mining

- Minimize sediment penetration
- Restrict sediment dispersal to seafloor
- Minimize nodule-sediment transport on surface
- Discharge tailings below oxygen minimum zone
- Treat tailings before discharging
- Induce high rate of sedimentation
# Major outputs (EIA studies)

<table>
<thead>
<tr>
<th>Tangible outputs</th>
<th>Nodule mining</th>
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<tbody>
<tr>
<td>Publications</td>
<td>60 (+10 comm.)</td>
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<tr>
<td>Symposia</td>
<td>46</td>
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<tr>
<td>Patents</td>
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<td>Reports</td>
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<td>Trainings - PAs trained</td>
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<td>Foreign students</td>
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<td>Ph.D students</td>
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<tr>
<td>Dissertations</td>
<td>77</td>
</tr>
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</table>

Special issues of int'l. journals

## Intangible outputs

- Development of multi-disciplinary research group for deep-sea environment studies
- Providing advisories to International Seabed Authority (UN) for formulation of ‘Guidelines’
Major outputs (EIA studies – contd)

Creation of environmental database

**Features**

- Interactive data retrieval and comparison
- Multi-disciplinary data set
  - Water Column
  - Benthic
  - Photo/Video

**Applications**

- Ecological models
- Mining design
METALLURGY
Development of metallurgical extraction process

1983-1986: Lab scale work with different routes

1987: Three routes chosen

NML - Reduction-roasting-ammonia-ammonium carbonate leaching
RRL - NH3-SO2
HZL - Acid pressure leaching

2006: Pilot plant established with 500 kg/day capacity
Modified Flow Sheet in PMN Pilot Plant

- Make-up Ammonia
- Recycled Ammonia
- Ground Nodule
- Sulfur Dioxide
- Recycle
- Discard (To ETP)

Leaching → Filter Press → Demanganisation

Leach Residue → Oxygen

Bulk Sulfide Raffinate → Nickel SX & EW → Cobalt SX & EW

Bulk Sulphide Dissolution → Impurity Removal

Impure Zinc Sulphate Solution (ETP)

Nickel Metal → Cobalt Metal

Nan Cake

Impurities Removal → Bulk Sulphide precipitation → Copper SX & EW → Copper Metal

Sodium Sulfide

Sulphuric Acid → Oxygen

Recycled Ammonia → Ammonia Stripper

Copper SX & EW

Metallurgy
Comparative Recovery Performance

Recovery %

Copper  Nickel  Cobalt  Manganese

Design  10 % PD  15 % PD

- Copper: 85, 96
- Nickel: 86, 92
- Cobalt: 92, 82
- Manganese: 30, 24, 17
Major outputs from IMMT

(a) No. of publications in SCI journals, 86 till 2008
(b) No. of patents, 5
(c) No. of reports 43 till 2010

Contribution to human resource development

(a) No. of Research fellows/PhD students : 7
(b) No. of Project Assistants trained: ~70
(c) No. of students for dissertations: ?
(d) No. of foreign students : 1

Major events organized

Development of extraction process at NML

1981: First sea nodules analysed from Indian ocean.

1983: R & D activities in extraction of metals from sea nodules following two routes:
   - Reduction roast – ammonia leaching – solvent extraction – electrowining
   - Cuprion process

1985: EIL appointed to monitor R&D work of NML on metal extraction from sea nodules.

1987: DOD – EIL shortlists 1 out of 2 NML’s processes for extraction of metals from sea nodules. The process selected: Reduction roast – ammonia leaching – solvent extraction (SX) – electrowining (EW)

1990: NML establishes the process on 10 Kg scale

1993: NML builds up a semi-pilot plant with facility of continuous reduction roasting (100 Kg/day), batch leaching (12 Kg/batch), continuous solvent extraction – electrowining (1000 Lit./day equivalent to 100 Kg nodules processing)

1996: NML completes 12 campaigns on semi-pilot scale
1997: NML demonstrates the process on semi-pilot scale for extraction of metals from sea nodules following Reduction roast – Ammonia leaching – SX – EW route

2000: NML starts the R&D work on leached residue treatment to produce Fe-Si-Mn

2004: NML sets up a pilot plant to producer Fe-Si-Mn from leached sea nodules residue on 350 Kg/day scale (equivalent to residue generated from 500 Kg nodules processing)

2007: NML completes 10 campaigns on pilot scale for production of Fe-Si-Mn and demonstrates to MoES
2008: New activities on improvement of NML’s process starts
2010: NML develops a reduction roasting process using more economic Talchar coal as reduction instead of L.D. oil
• Selective dissolution of Cu, Ni & Co.
• Process tried at 100 Kg/day (Recovery: Cu-90%, Ni-90% & Co-53%)
Facilities in sea nodules pilot plant at NML

Leaching Unit in Sea Nodules Pilot Plant

Solvent Extraction Unit in Sea Nodules Pilot Plant

Ammonia Stripping Unit in Sea Nodules Pilot Plant

FLOW SHEET FOR THE PRODUCTION OF Fe-Si-Mn
FROM LEACHED SEA NODULE RESIDUE BY TWO STAGE SMELTING ROUTE

1st Stage Tapping

2nd Stage Tapping
Detailed unit operations of NML process

ROASTED NODULES

WASH LIQUOR

WET GRINDING

PRECONDITIONING

LEACH: I

Air

LEACH: II

Air

WASHING

Wash Liquor

Wash Solution

Fresh Ammonia Solution

Pregnant Leach Liquor

Fresh Ammonia Solution

RESIDUE

TWO STAGE LEACHING FLOW SHEET OF NML
CONTINUOUS SX – EW FLOW SHEET OF NML PROCESS

25 % LIX 64 N (OA)

RAFINATE (Co)

REGENERATED LIX – 64N AFTER WASH

LEACH LIQUOR

ROASTED NODULES

EXTRACTION

NH3 SCRUB - A

AMMONIUM BI-CARBONATE (17 gpl NH₃)

SCRUBBED SOLUTION FOR RECYCLE

DILUTE ACID

NH3 SCRUB - B

SCREBBED SOLUTION FOR RECYCLE AFTER pH ADJUSTMENT

Ni - STRIPPING

ORGANIC (Cu)

Ni - METAL

Cu - STRIPPING

CPS

CPE

Cu - EW

Cu - METAL

BLEED-OFF

BLEED-OFF

NSE

ELECTROLYTE MAKE-UP

BLEED-OFF

CPS

ELECTROLYTE MAKE-UP

10 % LIX (OB)

AFTER WASH

Ni - EW

Ni - METAL

Ni - STRIPPING

Cu - REMOVAL

NPS

ORGANIC (Cu)

Cu - STRIPPING

CPS

CSE

ELECTROLYTE MAKE-UP

BLEED-OFF

NPE

Ni - EW

Ni - METAL
FLOW SHEET OF Co & NH3 RECOVERY FROM RAFFINATE OF NML PROCESS

1. RAFFINATE
2. HEAT
3. STRIPPING
   - SLURRY OF BASIC COBALT CARBONATE
4. FILTRATION
   - BASIC CARBONATE CAKE OF COBALT
5. DRYING
   - COBALT CALBONATE
6. CALCINATION
   - COBALT OXIDE
7. CONDENSED NH3 & CO2
8. ABSORBED NH3 & CO2
9. SPENT LIQUOR FOR RECYCLING
10. CO₂
MANPOWER AT NML
(a) No. of permanent scientists (18) and technicians (9) at the beginning of the project
(b) No. of scientists recruited for the project at the time of initiation: 1
(c) No. of scientists (18) and technicians (6) recruited during the project (after initiation)

Major outputs from the project
(a) No. of publications in SCI journals: 29
(b) No. of patents: 06
(c) No. of reports: 45

Contribution to human resource development
(a) PhD completed: 01; PhD student: 01
(b) No. of Project Assistants trained: 30
(c) No. of students for dissertations: 01
(d) No. of foreign students: nil

Collaborations / networking with other organisations
(a) national: 02
(b) international: 01

Events organised: 1 national workshop
### Status in mining and metallurgy among Pioneer Investors

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Pioneer Investor</th>
<th>Mining technology</th>
<th>Processing technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>France*</td>
<td>Model studies on self-propelled miner with hydraulic recovery system</td>
<td>Tested pyro and hydro-metallurgical processes for Ni, Cu, Co.</td>
</tr>
<tr>
<td>2</td>
<td>Japan**</td>
<td>Passive nodule collector tested At~2200 m depth</td>
<td>Developed a process to recover Cu, Ni, Co.</td>
</tr>
<tr>
<td>3</td>
<td>India***</td>
<td>(a) Design includes flexible riser and multiple crawlers (b) Crawler tested at ~410 m depth in the sea</td>
<td>(a) Tested 3 possible routes (b) Pilot plant set up for 500 kg / day for Cu, Ni, Co.</td>
</tr>
<tr>
<td>4</td>
<td>China***</td>
<td>(a) Includes rigid riser with self propelled miner (b) Tried different concepts of collector and lifting mechanisms</td>
<td>Developed a process to recover Mn, Ni, Cu, Co, and Mo.</td>
</tr>
<tr>
<td>5</td>
<td>Korea***</td>
<td>(a) Design includes flexible riser system with self propelled miner (b) Developed 1/20 scale test miner</td>
<td>(Not known)</td>
</tr>
<tr>
<td>6</td>
<td>Russia***</td>
<td>Collector and mining subsystems in conceptual stage</td>
<td>Recovered Mn, Ni, Cu, Co from nodules</td>
</tr>
<tr>
<td>7</td>
<td>IOM***</td>
<td>Conceptual design includes nodule collector, buffer, vertical lift system.</td>
<td>Economic assessment of different schemes</td>
</tr>
<tr>
<td>8</td>
<td>Germany***</td>
<td>Considering innovative concepts for mining</td>
<td>Considering different options for processing</td>
</tr>
</tbody>
</table>

(Source: *Herrouin et al, 1991; **Yamada and Yamazaki, 1998 (for mining technology); ***ISA, 2008)
## Overall scientific and human resource contributions

<table>
<thead>
<tr>
<th>Component</th>
<th>Publications</th>
<th>Patents filed</th>
<th>Project assistants trained</th>
<th>Ph. D. students</th>
<th>Disertations</th>
<th>Foreign students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey</td>
<td>250</td>
<td>1</td>
<td>20</td>
<td>2</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>Environment</td>
<td>60</td>
<td>4</td>
<td>25</td>
<td>3</td>
<td>77</td>
<td>5</td>
</tr>
<tr>
<td>Metallurgy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- IMMT</td>
<td>90</td>
<td>5</td>
<td>70</td>
<td>7</td>
<td>?</td>
<td>1</td>
</tr>
<tr>
<td>- NML</td>
<td>30</td>
<td>6</td>
<td>30</td>
<td>2</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Mining</td>
<td>10</td>
<td>3</td>
<td>8</td>
<td>1</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>440</strong></td>
<td><strong>19</strong></td>
<td><strong>153</strong></td>
<td><strong>15</strong>*</td>
<td><strong>148</strong></td>
<td><strong>6</strong></td>
</tr>
</tbody>
</table>

* excluding ~30 scientists who have also done on the job Ph.D.  
(as of March 2010)
Spin offs - Exploration for new resources / areas EEZ Mapping

Area: 2.2 million sq. km
Total surveys: 7500 line km
Outputs: Contours and 3-D models
Seafloor characterisation
Sediment properties
Phosphorite occurrences

(Source: Biswajit Chakraborty, NIO, India)

Surveys for Gas Hydrates

Bathymetry, seabed temperature and geothermal gradient data yielded GHSZ thickness map as a precursor to predict the gas hydrate zones (1997)

Drilling confirmed the presence of gas hydrate deposits in KG, Mahanadi and Andaman Basins (2006)

(Source: T. Ramprasad, NIO, India)
Spin offs - Exploration for other minerals

Co crusts

Afanasiy Nikitin seamount

Co content ~0.8 %

(Source: V.K. Banakar, NIO, India)

Studies on Hydrothermal Sulphides

Areas of study
Carlsberg Ridge,
Central Indian Ridge,
Andaman Backarc Spreading Center

(Source: K A Kamesh Raju, NIO, India)
International assistance to island countries

Seychelles (1984)
• Around Seychelles islands - 4000 km survey done
• Geological, chemical, biological, physical data collected
• Sediments, nodules and biological samples analysed
• Report on data and samples giver to Seychelles govt.

Mauritius (1987)
• Polymetallic nodules in Mascarene Basin (~11,900 sq. km. area)
• Morphology, internal structures, composition, growth rates
• 1-10 kg / sq. m abundance, rich in Fe and Co.

(Source: Nagender Nath and Shyam Prasad, NIO, India - 1991)
Inter-governmental collaborations

Indian – Myanmar joint oceanographic studies (2002~)

- Training of scientists from Myanmar
- Joint cruises for sample collection, data analysis, interpretation
- Geological, Geophysical, chemical, biological data
- Exchange visits and Joint publications

India- Iran cooperation (2006~) between NIO and

- Marine Geology Division, Geological Survey of Iran, Tehran.
- Iranian National Center for Oceanography, Tehran, Iran

For training of scientists and Joint cruises in Gulf of Oman and Persian Gulf

(Source: V. Ramaswamy, NIO, India)

Hands on training in analytical techniques for students from

Vietnam, Sri Lanka, Saudi Arabia, France, Ghana, Germany

(Source: V. Ramaswamy, NIO, India)
Technical Assistance Program (TAPMAR) for developing countries

Conducted interactive sessions on

- Marine surveys for inter-disciplinary research
- Exploration of marine minerals and resource evaluation
- Marine ecosystems and biodiversity
- Environmental impact assessment of offshore projects
- Law of the Sea

At
NIO Goa for 8 weeks

For
Marine Scientists from developing countries

Sponsored by
International Seabed Authority, Jamaica
Available metal reserves/resources and average growth rates

<table>
<thead>
<tr>
<th>Metal</th>
<th>Reserves on land* (million tonnes)</th>
<th>Resources in CIB** (million tonnes)</th>
<th>Avg. consumption growth rate*** (% per annum)</th>
<th>Price growth rate*** (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>~ 142</td>
<td>73.00</td>
<td>5.22 (1950-1980)</td>
<td>2.56 (ore)</td>
</tr>
<tr>
<td>Co</td>
<td>No reserves</td>
<td>00.49</td>
<td>2.64 (1966-2000)</td>
<td>3.56</td>
</tr>
<tr>
<td>Ni</td>
<td>No reserves</td>
<td>03.20</td>
<td>2.42 (1980-2003)</td>
<td>2.97</td>
</tr>
<tr>
<td>Cu</td>
<td>9.4</td>
<td>03.00</td>
<td>2.15 (1980-2003)</td>
<td>2.49</td>
</tr>
</tbody>
</table>

* in India  
** in likely mining area of 75,000 sq. km.  
*** global

Nodule mining is likely in future considering

- average growth rates globally  
- no / low land reserves in the country  
- availability of metals from nodules

(Source: Sudhakar and Das, 2009)
World metal prices will determine the timing of mining

Copper prices ($/Kg) and Nickel prices ($/Kg) from 2003-2008

Cobalt prices ($/Kg) and Manganese prices ($/Kg) from 2003-2008
Major outputs of different components (in brackets)

- **Exploration** (Mine-site)
- **Mining** (Mining technology)
- **Metallurgy** (Extraction process)
- **PMN program**
- **EIA** (Environmental data)
## Tasks ahead under each component

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration</td>
<td>Identification of mine sites and preparation of detailed bathymetry maps</td>
</tr>
<tr>
<td>EIA</td>
<td>Development of environment management plan for mining</td>
</tr>
<tr>
<td>Metallurgy</td>
<td>Disposal of waste material (&gt;75%) after processing</td>
</tr>
<tr>
<td>Mining</td>
<td>Up-scaling and integration of sub-systems for operation under extreme conditions</td>
</tr>
</tbody>
</table>