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THE RED SEA PRE-PILOT MINING TEST 1979

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1. Abstract: Development of Ocean Mining in the Red Sea

The occurrence of metalliferous sediments of the Red Sea has induced considerable scientific and industrial interest. The Saudi-Sudanese Red Sea Commission and its main contractor Preussag AG cooperate in exploring the deposits and developing new technologies to produce metals from the sediments. The main event of the project so far, has been a successful mining test performed in the Atlantis II Deep including concentration of the sediments and disposal of tailings. Two ships were involved in this operation from March to June 1979, SEDCO 445, the first dynamically positioned drillship in the world, serving as a test production platform, and VALDIVIA, the German ocean exploration vessel, performing environmental and geologic research and supply services for the test mining ship. Some 200 scientists, engineers and technicians from Arabic countries, Europe and the US took part in the operation, many more in the preparation and evaluation. This multinational project, encompassing many different technical and scientific disciplines, continues to generate new information on the natural history of the Red Sea and valuable know-how on technologies for raw material production.

2. Goals of the Pre-Pilot Mining Test 1979 (PPMT)

They had been identified in three different fields of offshore resource technology:

a) ocean mining, here to establish the technical feasibility of mining semi-solid metalliferous sediments in 2,000 m of waterdepth by means of a suction-vibration head and pumping the dissolved sediments through a deepwater submerged radial pump,
b) offshore processing, here to establish the beneficiation of a new and complex type of ore by means of ultrafine grain flotation in seawater on board of a rolling ship,
c) ocean environment, here to test the feasibility and environmental consequence of discharging tailings of flotation into the sea.

Related to these tasks were the following quantitative goals:

- produce 3,000 - 5,000 tons of undiluted sediments (about 6,000 - 12,000 tons of diluted sediments) for the production of several tons of concentrates of sufficient quality to feed a subsequent metallurgical development program (zinc content above 25 %),

References and illustrations at end of paper.

- determine quantitative results of parameter variations of the mining system, such as percentage of dilution water/solids content of the flow, frequency and amplitude of vibration, power input to the pump, different sediment inputs such as strata, depth of sediment, type of sediment,
- test technical design characteristics of the mining system and its components such as pump impellers, suction head configuration, instrumentation, data transfer,
- arrive at handling and operational procedures for mining, flotation, thickening, storage, pipe transfer and disposal,
- establish the effects of parameter changes of an offshore flotation plant such as residence time, level, head flow (volume, solids content), reagents on recovery and concentration factors,
- test different flow schemes and try to optimize the flotation plant,
- discharge of tailings through a 400 m deep discharge pipe, monitoring the discharge stream and the built-up of a dilution cloud, monitoring the movement of the discharge cloud into varying directions under the prevailing currents,
- monitor the effect of the discharge on the marine environment: plankton, benthos, fish, water chemistry etc.,
- predict eventual effects of the offshore discharge on coastal reefs.

After the accomplishment of these scientific and technical tasks an economic pre-feasibility evaluation of the Red Sea metalliferous sediment deposits should be undertaken.

3. Results

The technical feasibility of mining, pumping and concentrating metalliferous sediments of a complex character in 2,200 m of waterdepth has been proven for the first time and the main goal of the PPMT has thus been attained. From May 1 to June 3, 1979, approximately 15,000 m^3 of metalliferous sediments, diluted sediments and brines have been mined at four different mine sites, pumped to the surface and partly stored, processed and discharged, table (1), mining data.

The technical principles of mechanical action on and dilution of the sediments in situ also proved to be valid although different technical realizations of the principles were achieved. Mechanical action was transferred to the suction head by slow vertical movements of the pipe string and positioning set-offs of the drill ship controlled by dynamic positioning according to a predetermined mining pattern. The effects of vibration are limited in range. The necessity of a pressure water system for dilution became questionable. Inflow of brines into the mining depression - be it a trough, cone shaped pit or cylindrical hole - was sufficient to dilute the mechanically broken sediments into optimal rheological conditions: 40 - 70 g/l solids content for the design parameters of the PPMT pump.

The precise dynamic positioning capacity of SEDCO 445 helped to determine very exact mining patterns, sometimes a relative precision of 1 m was observed! (relative within the coordinates determined by two mine site beacons). Together with this precision of lateral movement an adequate precision of vertical movement was effected by readings of the length of the installed pipe string. Vertical and horizontal precisions of suction head movements permitted some degree of selective mining. This may eventually help to improve the economics of mining the layered deposit. The suction head was usually dragged 10 - 20 m, sometimes 30 m, behind the center of the ship.

Instrumentation and electronics onboard ship worked satisfactorily but the submerged parts needed special attention, care and test work. A measurement section for mud flow (flow rate, solids content, density, pressure, temperature) at the suction head needs to be developed for future pilot and commercial operations.

Increasing know-how of flotation resulted in concentrates of about 20 % Zn for mine site 1, 25 - 30 % Zn for mine site 2, 35 - 40 % Zn for mine site 3 and even above 40 % Zn for one extended run at mine site 4. The latter two results were achieved from sediments assaying 3.5 % Zn on average and with a recovery rate of 55 - 65 %, table (2), processing data.

Sediments stored in the drill water tanks did not attack the ship steel to any noticeable extent, presumably due to the lack of oxygen in the sediments/brines. The sediments influenced the old paint in some tanks (coal tar epoxy) which was already damaged and blistered when the project was started. A fresh coating of the slider bins applied before the beginning of the test with coal tar primer plus normal top coat, however, withstood the extended filling with sediments without any damage.

Disposal of tailings, brines and surplus fresh muds was done via the 6" disposal pipe attached to the bow anchor line. No technical problem was encountered when installing, operating and retrieving the pipe. The plume behaviour was monitored by VALDIVIA. It should be summarized here that the discharge usually descended from the 400 m deep mouth of the pipe in a gravity flow/jet flow to 800 - 1,200 m of waterdepth. From there, a large and very diluted diffusion cloud, drifting apart and settling slowly (5 - 10 m/h), built up. A harmful effect of tailings discharge on the Red Sea marine environment (coastal reefs, surface plankton) could so far not be observed and seems not to be probable.

4. Performance of the Mining System

Subsequently the mining test, its equipment and components are described and results are evaluated, fig. (3) to (6).

4.1 Site preparation, further exploration

The precise test site bathymetric survey was one important prerequisite for mining. Depth sounding was done with the aid of the already well proven 30 kHz gyro-stabilized narrow beam echo sounder of VALDIVIA. Maps of the seafloor with only one meter iso-bath contours were established with the aid of a newly developed amplifier added to the 30 kHz sounder. Positioning reference for bathymetric mapping was achieved with chains of 6 to 8 ATNAV transponders laid out by VALDIVIA. Reception of acoustic signals from the positioning transponders was good although acoustic interference from other sources occurred, such as from the sediment thickness sounder installed above the mining head. It was thus possible to design bathymetric charts of a so far unknown vertical and horizontal resolution and precision. Actual test mining proved the validity of depth sounding with deviations of less than ± 2 m, or one per mil of the waterdepth.

Two positioning release pingers, compatible with the dynamic positioning system of the mining test ship, were set at each mine site, tethered above the brine layers. One of the two pingers was used as the actual positioning beacon, the second as back-up. Despite fears of failures of the first beacon and the need to switch over to the second beacon, failures never occurred. Neither acoustic interference nor acoustic clouding by disposal of tailings disturbed signal reception by the ship's hydrophones. The horizontal range of proper signal reception was about 50 % of the waterdepth although longer ranges could be achieved. The two beacons were usually spaced at 500 - 1,000 m one to the other so that the test site covered 2 - 4 km^2. Four test sites were thus identified, test site map in fig. (3). Retrieval of the eight pingers was successfully accomplished by VALDIVIA with the exception of only one pinger which had to be abandoned on the seafloor.

In addition, coring with a long box corer helped to predetermine the sediment layers at the test sites. Good coincidence of the two to four cores sampled per mine site and subsequent test mining was observed. The vertical coincidence was usually better than one meter and sometimes better than one third of it.

Further to test site coring, VALDIVIA took fourty long box cores (8 - 10 m), especially in the eastern and northern parts of the deposit where sampling, so far, was rather scarce. This will help to calculate new deposit values which is being performed at the time of writing this report.

4.2 Suction head, pump and pipe string

Dissolution of the hardened layers of metalliferous sediments in situ should have been effected by vertical oscillation (f = 14 - 16 c, a = 5 mm) of a vibration/suction screen. Mechanical action was assisted by high pressure sea water, sucked in by a high pressure pump in the main pump module and ejected from a pressure water ring around the suction head, fig. (5). This method was adopted after testing various possibilities of mining sediments sampled at earlier exploration campaigns. The sieve was designed to suck up all particles below 10 mm diameter. Mechanical dissolution by vibration aided by pressure sea water proved to be of limited influence, laterally and vertically, however. Other methods of mechanical action had to be adopted in the course of the test and proved to be ultimately efficient.

After a crack occurred in the seawater pressure hose it was found out that brine was a sufficiently good dissolution medium.

The suction head was designed to withstand vertical loads of 5 tons and would thus be sufficiently stable to penetrate intercalated anhydrite layers. It was slightly damaged when set on such a layer or, possibly, on the more consolidated lower sediments, fig. (5).

The pump was a six stage radial pump with a capacity of 30 - 50 m^3/h for high viscosity flows. The high head of 750 m was achieved by the back to back design of the 3 x 2 stages. The pump impellers were made of three different alloys to test the influence of erosion/corrosion of different materials in different pressure stages. Maximum power requirements of the pump at 500 kW and optimum performance were to be achieved at a flow of 50 m^3/h. The pump was turned by a 535 kW Pleuger underwater motor which was capsuled and seawater-filled. Energy from the specially designed generator installed onboard ship was transferred to the pump at 3,000 V via a shielded coax. Control of the pump/pump motor was achieved by automatic and/or manual frequency control, ranging from 48 to 60 cycles. At the beginning of the test series, when the highly diluted sediments (average 25 g/l) were flowing at 100 m^3/h and sometimes more, the pump motor load was below 300 kW only. It was subsequently learnt how to control a solid content of 40 - 80 g/l. This resulted in optimum load performances: 400 kW at 55 Hz and approximately 3,000 V transmission voltage.

A 5" drill string, with tool joints, temperature treated for improved notch toughness (tempered and subsequently annealed), served as connection and flow line between the sea bottom and the test ship. No problems of installation or operation occurred, such as the anticipated clogging due to fallout from a salt-saturated sediment flow.

4.3 Work platform, equipment handling, storage

SEDCO 445, the first dynamically positioned oil exploration drill ship in the world, served as a test platform. Its technically well proven components greatly helped to achieve proper handling of equipment: the automatic pipe racker, derrick and drawworks above a wide moonpool (ø 9 m). The 500 t drawworks was more than sufficient for the 100 t load made up by 2,200 m of 5" drill pipe, suction head, pump module and instrumentation. A 20' stroke heave compensator was occasionally used when mining in heavy sea. The sea keeping capacity of the vessel was excellent. High winds were encountered three times with wind forces of 6 - 8 and maximum wave heights up to 8 m when installation of equipment had to be stopped. As soon as all equipment had been installed and lowered to sufficient depth, however, operations continued in all weather. Mining was successful continued in seas up to 6 m max. wave height when the center of the ship heaved 1 - 2 m. The sediment flow on board ship, piping instrumentation and storage is represented in the p+i diagram of fig. (7).

4.4 Instrumentation

The main tasks for the rather comprehensive instrumentation system were to monitor the main characteristics of the mining process and the sediment flow as well as to store equipment parameters on magnetic tape. Instrumentation was also extensively used to assist in preventing clogging and, last not least, to produce data for the design of an eventual pilot mining system. Sensors were installed at or behind the suction head, at the pump module and on board deck, fig. (6). All data were digitized, transferred via pulse code modulation in coax data transfer cables and fed into the 32 K ship board computer for processing, display via printer and/or screen, and storage on magnetic tape. In addition to the transducers being directly or indirectly related to the sediment flow, a pipe string control system was installed. Horizontal accelerations were monitored and interpreted as well as temperatures for thermal correction at 7 locations along the pipe string.

A sediment thickness sounder was developed to obtain a constant and accurate reference control for penetrating the sediment layers. It consisted of four high power output transducers (10 kW) with variable frequency (1 - 10 kHz) installed between the suction mining head and the pump unit. A cutter head positioning beacon was attached to the pipe string above the suction head for constant control of the suction head relative to the ship's vertical axis.

Summarizing the extended experiences with the instrumentation system one can say that most of the deeply submerged transducers were working partly only, such as the flow meter at the suction head, the flow density meter and the differential pressure meter. All onboard instrumentation worked satisfactorily. It will thus be a development task of considerable significance to have a sediment flow meter, designed for application in about 2,000 m of waterdepth, directly behind the suction head.

The sediment thickness sounder ultimately produced good acoustic soundings of the various sediment layers, fig. (6), although a true acoustic correlation has yet to be established. The vertical position of the suction head was determined indirectly. An active acoustic reference, such as a pinger, installed at the suction head should serve, in future, to exactly locate the suction head's position above or within the sediments.

Mechanical and electrical problems occurred with the shielding of the pipe string control cable consisting of an already earlier used underwater television cable. Despite these problems valuable data for pipe string movements could be concluded from the final evaluation of the magnetic tapes. Coincidence of the lateral movements found by the pipe string control system and visually observed with the aid of the mining head beacon was within a few meters.

4.5 Dynamic positioning

Two seafloor tethered beacons per mine site served as reference point and back-up for SEDCO 445, frequencies were between 22.5 and 24.5 kHz. Reception of acoustic signals by the ship hydrophones was good, failure due to acoustic clouding as a result of tailing disposal was never observed. The limits of absolute precision as to one given point on the seafloor were considered to be 10 - 15 m due to physical properties of the positioning system and equipment ranges. It was, however, found that positioning within the range of some meters and even down to one meter was possible. Movement of the ship (and the mining system, hanging usually perpendicular beneath the moonpool) was performed by "set-off" steps of about one to two meters: one set-off usually took 4 and 5 minutes when trenching. Due to the large mass of the ship a stepwise, semi-continuous progress was thus achieved in either west-east or north-south directions.

Various dredging patterns could be achieved by this method: rectangular, square, parallel lines or even random lines (if this should prove to be the most economical way of mining metalliferous seafloor sediments). It is important to note that available technology of dynamic positioning adopted to this greater waterdepth will permit precise and reliable orientation of the ship and the mining equipment. This very satisfactory result could not at all be reasonablly anticipated when planning the test as considerable difficulties for proper positioning in the rough and dangerous subocean terrain were expected.

4.6 Conclusions

Ocean mining of metalliferous seafloor sediments of the Red Sea type is well feasible. Deconsolidation of the sediments by mechanical action and dilution with brine and seawater can be achieved. Pumping through a steel pipe which can be comparatively easily handled and scaled up to pilot and commercial dimensions proved to be an adequate method. The radial pump worked well. Problems with erosion/corrosion in small slitses between the pump stages can be overcome by improved design and material selection. Alternatively, axial-radial designs with more stages are at hand. Scale-up to pilot and commercial dimensions are possible. Mining can be performed in well defined and controlled patterns.

Feasibility and reliability of deepwater data monitoring is one major area of technical improvement for deep ocean mining. Measuring the flow, sediment and brine content and density of the mining stream shortly behind the mining head in 2,000 m of waterdepth needs to be developed. By eventually improving the existing radio-nuclear analysis it may be even possible to obtain readings of metal content in situ. Data transfer by PCM and ship board computer processing, storage and control by available methods and technology do not represent major problems. Better installation and handling characteristics of the instrumentation system can be achieved, however, by improving the deepwater junction boxes and cable connectors. The acoustic sediment thickness meter is being further improved. Correlations of the acoustic readings with sediment properties for direct measurement are calculated.

5. Performance of the Concentration Plant

5.1 General layout and conditioning

The flow scheme of the concentration plant, consisting of the conditioning tanks, flotation plant, thickening and filtering station, together with the appropriate pipes, pumps, instruments etc., is given in fig. (8). The drill ship's four mud mixing tanks with a total capacity of 420 m³ were used as homogenizing tanks. Homogenization was performed with the mud mixing impellers in the tanks and with the mud mixing pumps between the tanks. It usually took 24 hours until a fairly homogeneous input for the flotation plant was achieved at, for example, 40 g/l sediment content. The flow was then pumped to the flotation plant, diluted to 25 g/l, conditioned, floated and the concentrate fed to the thickener and ultimately to the small vacuum drum filter for final dewatering tests by filtering.

5.2. Flotation of marine metalliferous sediments

The plant consisted of six rougher cells (500 l) for bulk material handling, three double cleaner cells (200 l) for concentrate treatment and one scavenger cell series (4 x 50 l) for eventual concentrate scavenging. The process diagram and one flow sheet alternative, programmed on board ship on the basis of test findings, is shown in fig. (8). The flotation plant was designed and built according to specifications arrived at in lengthy laboratory test work on methods how to float the fine-grained sediments. Specific characteristics of the flotation cells were: high speed of the rotary impeller ($v \sim 10$ to 20 m/sec), special arrangement of stationary blades at the cell bottom and vacuum pumping of air into the cell. These factors produced a high velocity turbulence of the pulp flow mixed with small air bubbles, homogeneously distributed over the total cell volume, and the resulting high level of activation of surface energies of the fine grain sediment particles. Together with proper selection and adjustment of flotation chemicals a sufficiently good flotation behaviour of the freshly mined sediments had been expected. Very good flotation characteristics of the especially surface active fresh sediments were found. Taking Zn as guiding parameter it was found from the outset that concentration factors of 8 - 10 were possible. Preliminary and rather tentative optimization resulted in concentration factors of about 15. Recovery varied considerably at the beginning but was stabilized in the range of 60 - 70 %. Summarizing the many different test runs one may say that encouraging results for further development work have been achieved. It now seems possible to continuously produce concentrates of more than 40 % Zn and corresponding values of Cu and Ag at a recovery rate of about 70 %. Standard chemicals were used: xanthates as collector, $CuSo_4$ as activator for ZnS, NaOH for pH control and NaS for sulfidisation. When the stocks of NaOH were depleted it was found that flotation without addition of NaOH is well feasible, probably due to the natural alcalinity of seawater, another cost saving characteristic of seawater flotation. In addition it was found that Na_2S is not necessary for the freshly mined and surface active sediments.

5.3 Dewatering, thickening and filtration

The thickening equipment consisted of standard conical and lamellar thickeners from which the thickened tails should have been pumped off upon ultrasonic gauging of a thickened flow of 130 g/l (input about 50 g/l). Coagulants such as Praestol were tried to speed up the thickening process. Due to malfunctioning of the ultrasonic gauge, however, thickening rates of 80 - 100 g/l were achieved only by manual operation. Furthermore, high froth formation on the concentrate pulp surface prevented frequently proper functioning of the thickening plant. The same results and better ones, however, were obtained by natural sedimentation. A properly designed thickening plant, therefore, will eventually deliver the anticipated results. The same holds true for filtering. Although no filter cake was built up on the test plant onboard ship, later tests with filter presses resulted in filter cakes of 50 - 60 % solids content.

5.4 Conclusions

Having found that metalliferous sediments can be well floated and thereby concentrated it is certain that flotation constitutes an important factor to improve the economics of an eventual ocean mining venture. Investment costs and operating costs for flotation are comparatively low. The increase of recovery rates to 70 % and concentration rates of more than 40 % Zn and corresponding rates for copper and silver will decisively determine the economics of the project. In addition it will be necessary and possible to further decrease the content of iron in its oxidic mineralization in the concentrate. Goethite and other oxidic iron compounds consume larger amounts of acids in metallurgical treatment of the concentrate and should thus be eliminated by flotation as much as possible. Although dewatering tests on board ship did not satisfy one may anticipate proper dewatering equipment for any pilot and economic operation. Dewatering will have a significant impact on the economics of transport of concentrates to shore.

6. Protection of the Environment

6.1 General concept

One of the main prerequisites for the ultimate feasibility of ocean mining is the environmentally neutral disposal of tailings from the concentration plant on board ship and of effluents from any onshore metallurgical plant. The PPMT had thus to show whether and in which way flotation tailings and other residues from mining and concentration could be disposed off without endangering the unique and delicately balanced environment of the Red Sea.

Four conditions had to be satisfied:

- The tailings should not disturb for an extended period and to an extended amount the surface near plankton

layers or other surface near bioactive strata of the sea,
- The tailings should not touch in any concentrated form the active reefs on neither the Sudanese nor the Saudi Red Sea coasts,
- Influence on any other form of marine life should be limited,
- The tailings should not "rain" back on the deposit and thereby deteriorate mining.

6.2 Disposal arrangement for the discharge of tailings

Having engineered various complicated alternatives for the disposal of tailings the following simple technique was adopted: a 6" pipe, made up of 6 m long and 6" wide sewage steel pipe sections, was attached to the ship's bow anchor line and lowered to 400 m of waterdepth, the anchor serving as weight. This depth was chosen to be certainly below the biologically active zone. Installation, operation and retrieval of this simple disposal pipe was efficient, fast and without problems and could well be adopted in future. Greater installation depth of 600 to 800 m would be feasible. Movement of the ship in dp mode with the system installed is possible at speeds of up to 2 kn, depending on current speed and direction.

6.3 Various discharge tests performed

Different discharge tests were performed. Discharge of tailings mixed with sediments and brines were performed at all four mine sites. In addition, a controlled discharge test was done with 400 m^3 of tailings, being impregnated with a tracer and homogenized for 36 hours, at a special disposal site north of the Atlantis II Deep deposit. Iridium in the form of IrO_2 was used as tracer. The iridium oxide was melted in quartz and ground to particle sizes with sedimentation characteristics similar to those of the tailings particles. Neutron activation of tracer impregnated samples of bottom sediments (Ir 191 Ir 192) would permit detection down to a limit of 10^{-9} g of tracer material directly, and to 10^{-11} g if chemically treated. Finally a surface disposal test was performed with 400 m^3 of surplus sediments, at a site between the Atlantis II Deep and Jeddah, on June 12, 1979, which was monitored by satellite (Landsat).

The function of the disposal pipe can best be compared with an "inverted chimney". The residues would drop down in a jet/turbulence-flow from the mouth of the disposal pipe some hundred meters to subsequently form a large dilution cloud drifting apart with the various currents. Dilution within the cloud was anticipated to be very low.

Acoustical methods for monitoring the disposal flow were applied as well as methods for light attenuation and sampling of seawater and sediments from VALDIVIA. It turned out that the most efficient means to detect and monitor the dilution cloud was the 30 kHz narrow beam echo sounder of VALDIVIA which produced good records of the cloud, fig. (9). It was usually possible to detect and follow the various disposal clouds with the exception of the tracer disposal test when weather conditions (sea states 6 - 8) did not permit proper acoustic soundings. Further research campaigns (Meseda 3 and 4) will thus help to sample the seafloor. Nuclear activation of the samples retrieved will eventually help to identify the ultimate settlement of the disposal cloud.

The tailings dropped to 800 - 1,200 m of waterdepth, fig. (9), mainly due to the higher density of the salt rich tailings and due to the pump pressure, more than anticipated in mathematical model calculation. A new model (combination of turbidity flow and gravity flow) may have to be adopted. The subsequently developing dilution cloud spreaded into various directions, depending on the current direction of the particular site, waterdepth and time.

The surface disposal test of June 12 showed the development of a large surface cloud mainly generated by the ship thrusters which would slowly drift to the SE. Sinking was very slow, some 5 - 10 m per hour were estimated, following observation and documentation from the test ships. Satellite monitoring did not indicate any hazards at all from the surface disposal test (pending further and more detailed information from NASA).

6.4 Short summary of oceanographic research and its present results

Ocean current measurements performed during 1977 and 1978 and during the PPMT and supported by CDT probes in the Central Red Sea have resulted in many, often contradictory current profiles which could not yet be synthesized into a useful and correct model. The old model, ref. (5), of the prevailing north-westerly inflow of fresh surface water all along the Red Sea axis and the subsequent slow drift back of bottom water towards the Straits of Bab el Mandeb needs to be corrected and detailed, however. Especially in the Atlantis II Deep area where tropical influences from the south and subtropical weather from the North exchange, remarkable regional, seasonal and even monthly variations and variations with waterdepth have been observed.

Pending the results of the ongoing evaluations, subsequent computer model testing and further measurements one may summarize the present knowledge on the current regime in the Atlantis II Deep area as follows: While strong currents (up to 2 m/sec) and changing directions, SE predominating, however, at the sea surface have been observed, mainly as a consequence of prevailing winds, the current velocity decreases to below 10 cm/sec in waterdepths of 200 m to about 1,000 m to values of 0.5 - 5 cm/sec in the central graben, close to the brine pools. Current directions at the surface and further down vary considerably, a prevailing direction along the axis of the Red Sea, namely to SSE and vice versa have been observed. It was found that the water masses in the central graben usually moved slowly to the SSE, as expected, but that occasionally, about once per month, this movement was reversed. A possible explanation could be seen in lunar tidal influences. In addition, morphological influences of the central graben have been observed which result in slow shearing currents to the NNW and to the SSE.

The already established remarkable layering of the Red Sea water was again corroborated, even in coastal areas. There is very little upwelling. Vertical exchange of water is thus apparently restricted to diffusion and advection processes which are very slow. Helium/tritium and C 14 methods were therefore applied to assess the long term vertical exchange movements of water masses in the Red Sea. It should be remembered that model predictions vary between 20 and 200 years. First results indicate that the shorter time span is more likely than the centennial.

6.5 Outline of environmental baseline studies and some preliminary results

Further to investigations of the physical oceanography rather extended baseline assessments on the Red Sea biology: plankton, benthos, neston and reef environment were needed as well as research of possible repercussions of tailings disposal, ref. (8) to (12). Baseline investigations were performed with the aid of various sampling methods such as multiple net trawls for plankton, box grabs, photo sleds, photo traps and closing fish trawls for benthos, neston and fish population. The 30 kHz echo sounder of VALDIVIA proved to be a valuable tool to detect the vertical movement of the main plankton layers between 200 and 300 m and 450 - 500 m waterdepth. Sampling and analyses on fauna and flora was supported by sampling and analysis of the water chemistry. The aim was to assess the regional and seasonal daily distributions of the various populations together with their nutrient supply, feeding and growing rates and possibly already existing contaminations with heavy metals. In addition, ecotoxicological experiments in situ and in various laboratories were performed in order to obtain knowledge on tailings disposal at dilution rates of 1 : 100 to 1 : 100,000. The in situ observations were performed in plastic foil bags of 7 - 17 m length and 5 - 10 m^3 volume suspended under a raft. Growth and mortality of plankton and epizoic hydroids were especially observed.

The in-situ tests produced significant influences at low dilution factors of chemicals (up to 1 : 100) in the tailings on the fauna observed while only tentative observations could be made at high dilution factors (1 : 100,000). Adverse weather and sea conditions prevented extended in situ testing. Laboratory tests with highly diluted tailings performed in late 1979, however, indicate a measurable influence on certain species living at or close to the sea surface, such as epizoic hydroids which are known to be most sensitive. After an exposure of 96 hours of these animals to a solution containing 0.1 mg of solids per liter of seawater, a mortality of 50 % was observed. It should be noted, however, that such dilutions would in reality only occur in or near the disposal flow while dilution in the cloud would still be 100 - 1,000 times lower and that the test fauna lives much higher up in the water column, close to the sea surface. Marine life in 1,000 m of waterdepth was found to be very scarce.

6.6 Conclusions

The prediction of a concentrated vertical tailings flow from the mouth of the disposal pipe to a certain waterdepth and the subsequent formation of a laterally spreading highly diluted diffusion cloud was correct. As the tailings dropped much deeper down than anticipated the computer model needs to be adopted. A combination of gravity and turbulence flow needs to be incorporated in order to predict more exactly the flow behaviour.

The built-up of a highly diluted diffusion cloud in a waterdepth of about 1,000 m seems to exclude influences on the surface-near plankton layers and the reef areas. Environmental repercussions are thus restricted to an area of lower or even negligible biological activity. Dilution will be such that a "concentrated" disposal of tailings on the deposit can be excluded, especially if a disposal depth of 600 - 800 m will be chosen.

7. Research on Metallurgical Treatment of Red Sea Concentrates

Comprehensive engineering analyses on methods of metallurgical treatment of concentrates had indicated the feasibility of cyclone smelting. Technological risks of this new method of pyrometallurgical smelting became apparent in 1977 and 1978 when pilot operations with somewhat similar bulk concentrates encountered problems in the fields of material preparation, process kinetics and recovery. In addition, the need for salt-free washing, or at least, reduction of salt content, constituted a considerable problem for the operation of a smelter in the Red Sea area.

It was thus decided to abandon this route and investigate the applicability of recently developed methods of metal chloride leaching. It is known since some time that metal chlorides such as Fe^{+++} and Cu^{++} are strong oxidizing agents, especially if certain conditions such as temperature, (slight) pressure and pH can be adjusted. Leaching of non-ferrous metal sulfides with Fe^{+++} and/or Cu^{++}, however, resulted in two major problems, one being the corrosion of equipment and the other being electrolytical production of the metals from a chloride solution. Recent progress to comply with both problems make metal chloride leaching an attractive alternative for treating Red Sea concentrates.

First tests with various compositions of $FeCl_3$ and $CuCl_2$ have all indicated good to very good recovery rates for Zn and Ag, although insufficient solubility of Cu (probably due to cementation) still needs to be investigated. Metallurgical research is being done internationally in a test program presently performed with Red Sea concentrates produced at the PPMT 79 with specialized organizations in Norway, UK, France, the US, Spain and West Germany. Emphasis is laid on methods of treating the leach liquor with solvent extraction and electrolysis. First results are encouraging, technically and economically. The test program should be terminated by spring of 1980 and evaluated technically and economically in 1980.

8. Outlook

Pending the ultimate results of the test evaluation and especially the outcome of the metallurgical research it should be noted that ocean mining in the Red Sea has been considerably advanced with the 1979 test series. The Red Sea Commission will decide to carry out a pilot operation if the present tendency for a profitable venture continues to materialize.

There are, already now, some important aspects of the project which give an eventual ocean mining venture a positively economic direction if compared with land deposits in the area. The transport infrastructure to support ocean mining and to transport products to the market appears basically favourable. The ports of Jeddah and Yanbu are very close at a shipping distance of 6 and 20 h for normal vessels. No extra roads need to be built. Economics to supply goods or products (concentrates) by sea transport is superior to that on land. Due to the climate and oceanic environmental condition it seems probable that a continuous operation can be achieved. Ocean mining, furthermore, does not necessitate any expensive mine development such as shaft sinking or open pit mining. Last not least the metalliferous sediments lend themselves readily for beneficiation, no milling and grinding is necessary which requires usually large amounts of investment and operation capital.

Another factor of major influence will be the further development of the markets for silver, zinc and copper. Assuming a price of silver of 800 DM per kg - a conservative assumption at the beginning of 1980 in the light of the prior price increases for this metal - and a recovery of only 50 % of silver in the deposit, ocean mining of metalliferous sediments in the Red Sea looks definitely better than in 1978 when the price of silver stood at about half.

The scope of a pilot operation would be determined to some extent by metallurgy. A pilot plant should process a minimum of 10 tons of concentrate per day. Operation of the pilot metallurgical plant would last 8 - 12 months. The offshore operation would accordingly last for 200 - 250 days. Beside operational know-how to be gained in such a novel exercise - know-how which would ultimately determine the scope of economics as well - technical scale-up experience is also very much needed before a commercial venture could be started. The scale-up factor of a pilot operation would be about 10 compared with the pre-pilot test and again about

10 compared with an eventual commercial project. Provided that the decision to start a pilot operation is arrived at by mid 1980, the mining operation could begin by the end of 1982 and then take most of 1983 when the onshore pilot plant for metallurgy could be commissioned.

The start of a commercial ocean mining venture producing eventually 50,000 - 80,000 tons of Zn and corresponding amounts of Ag and Cu per year should therefore be expected for some time in the mid eighties. The overall economic repercussions for the economies of the sponsor countries Saudi Arabia and the Sudan would be considerable: diversification into new industries, such as production of metals and chemicals, offshore services and engineering, utilization of the readily available infrastructure at Yanbu, creation of some 2,000 long-term employments ranging from the unskilled to highly qualified and managerial functions and the eventual utilization of the technology developed in the Red Sea for ocean mining ventures in other parts of the world.

The authors want to acknowledge their thanks to all those who have generously sponsored this unique project, especially the Members of the Board of the Red Sea Commission. The authors also want to thank all those who have so actively contributed with their know-how, skill and hard work to make the project a success.

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TABLE 1
Results Mining

	Period of stay of ship			Duration of pumping			Appr. quantity mined/pumped (m^3)	Appr. quantity stored (good muds)(m^3)	Appr. quantity processed (m^3)
	from	to	hours	from	to	hours			
Mine Site 1	11.4.	6.5.	613	1.5.	2.5.	21.46	1,800	1,400	700
	(9.00 - 22.00 h)								
Mine Site 2	7.5.	17.5.	264	9.5.	10.5.	17.04	1,400	900	600
	(1.00 h)								
Mine Site 3.1	18.5.	24.5.	154					400	200
	(9.00 - 19.00 h)			23.5.	25.5.	21.5	1,500		
3.2	24.5.	25.5.	19					200	150
	(21.00 - 14.00 h)								
Mine Site 4	25.5.	4.6.	233	26.5.	27.5.	31.5	2,800	200	140
	(18.00 - 11.00 h)			30.5.	3.6.	103.6	8,280	200	160
Total			1283			195.1 + 8 (seawater/brines)	15,780	3,300	1,950

TABLE 2

Results Flotation

	Duration from	to	hours	Total quantity muds processed (tons)	Total quantity conc. produced (kg)	Solids contents (grams/liter) heads	tails	conc.	Zn contents (percent) heads	tails	conc.
NE Site 1	4.5.	9.5.	102	700	1400	25	35	35	2.0	0.9	18
	11.5.	14.5.	61								
E Site 2	18.5.	22.5.	86	600	1500	23	15	43	5.5	2.4	27
	25.5.	26.5.	20								
E Site 3.1	24.5.	24.5.	8	200	400	40	22	32	3.65	1.7	37
	26.5.	27.5.	35								
E Site 3.2	31.5.	2.6.	34	150	300	45	24.5	22	2.9	1.2	40.8
E Site 4.1	29.5.	30.5.	29	140	400	48	26	36	3.4	1.45	33
E Site 4.2	2.6.	4.6.	34	160	400	48	16	23	3.4	1.35	42
Total			409	1950	4400						

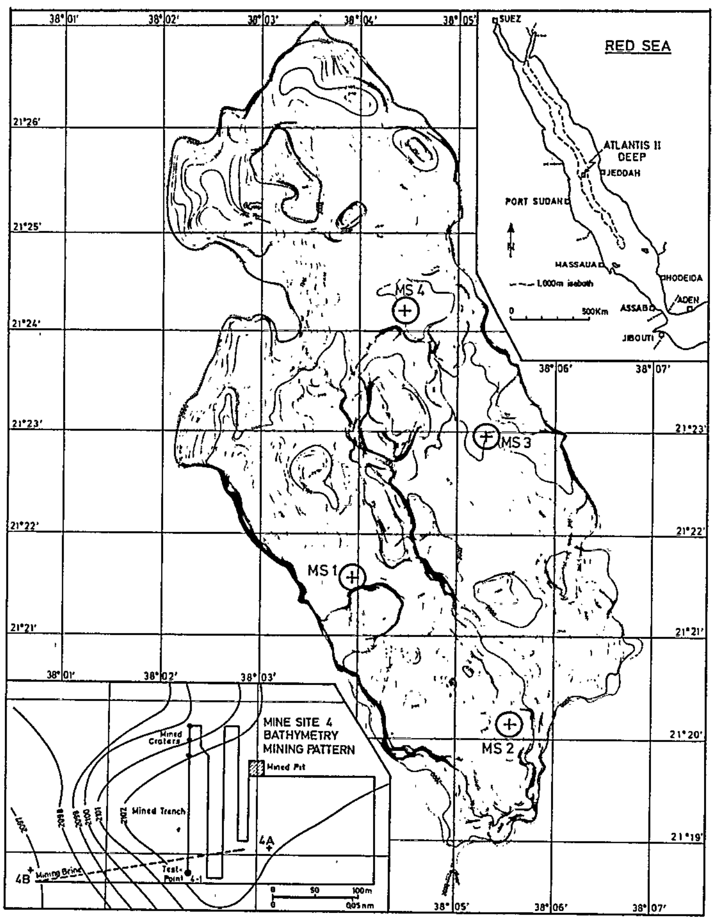


Fig. 3 - Red Sea, Bathymetry of the Atlantis II deep, mine site 4.

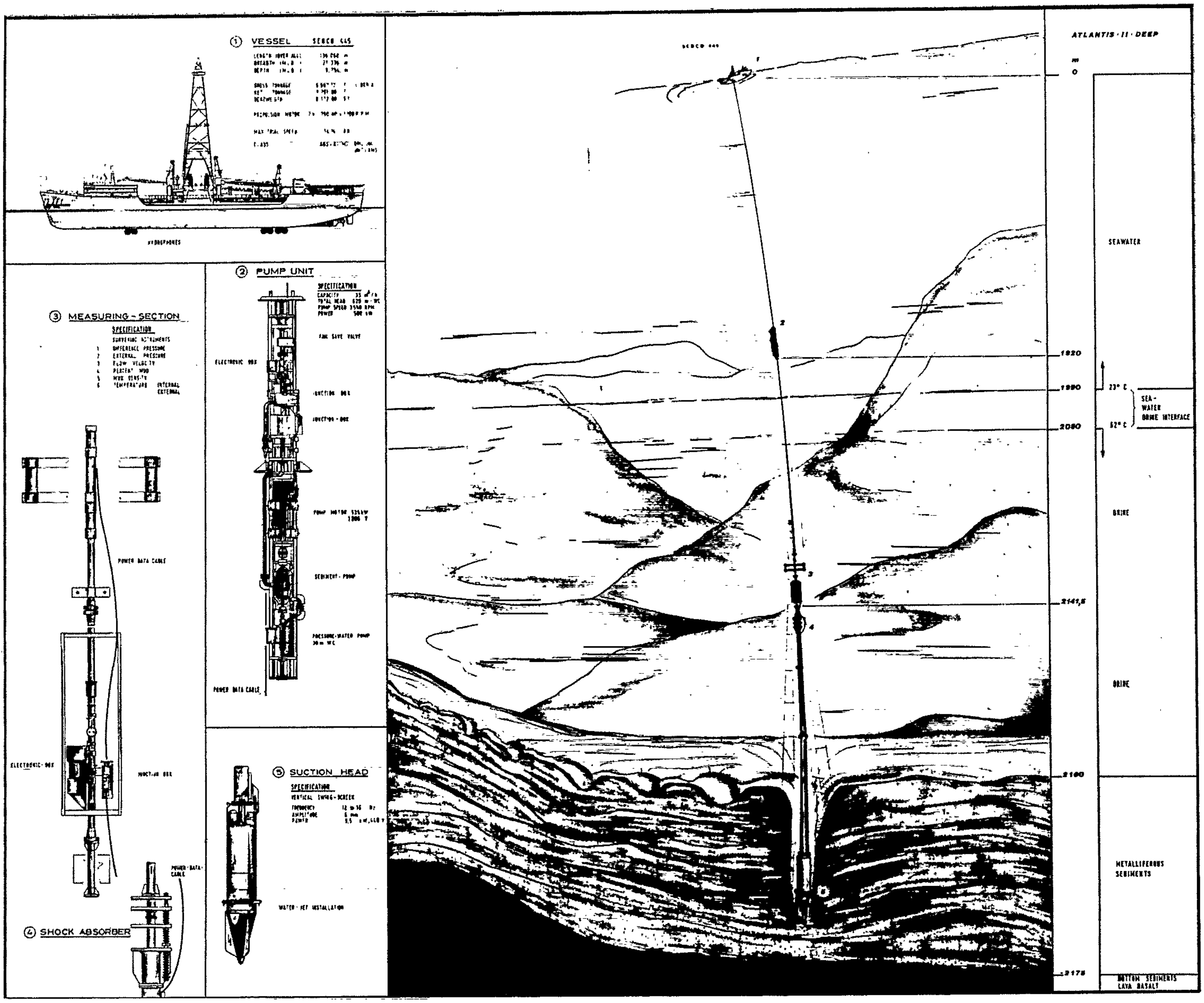
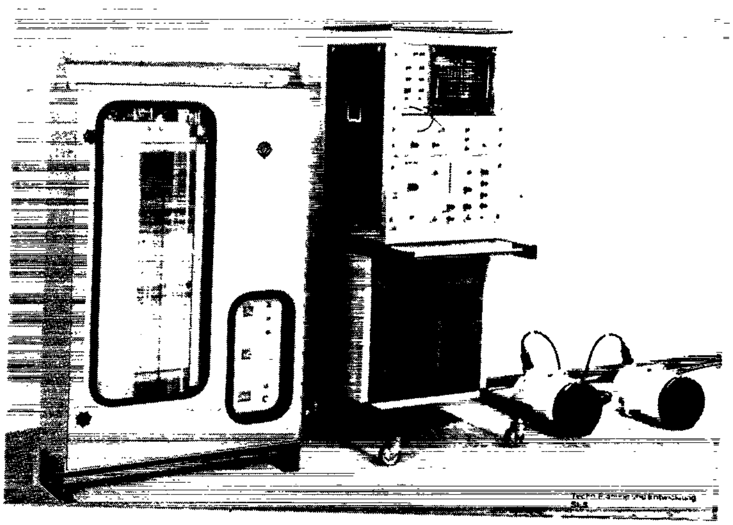


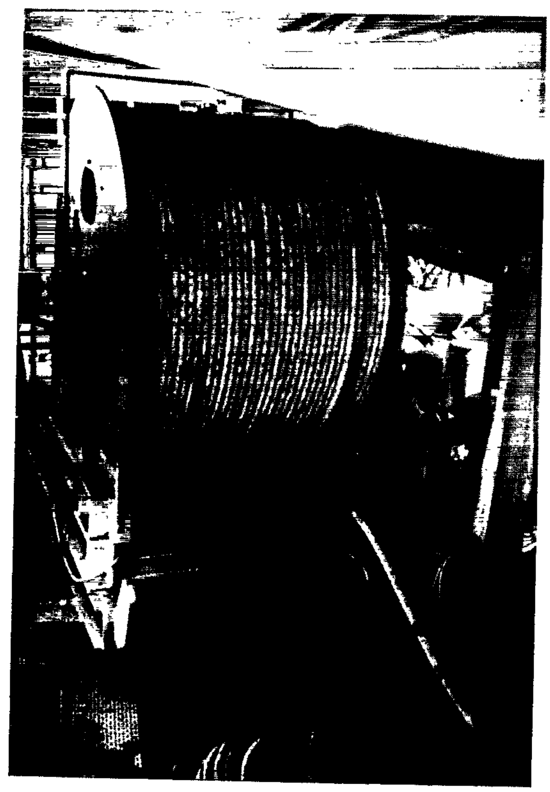
Fig. 4 - General arrangement of the mining system.

(a) Suction Head

(b) Pump

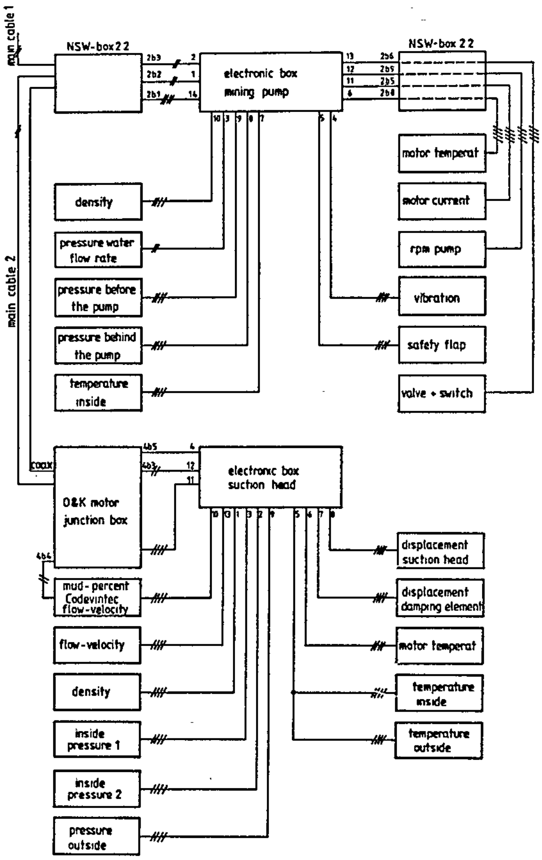


(c) Sediment Thickness Meter

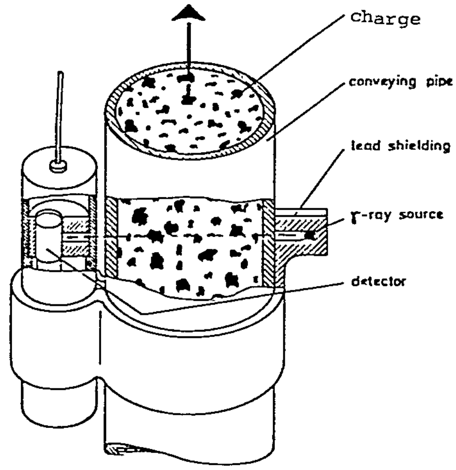


(d) Cable Winch

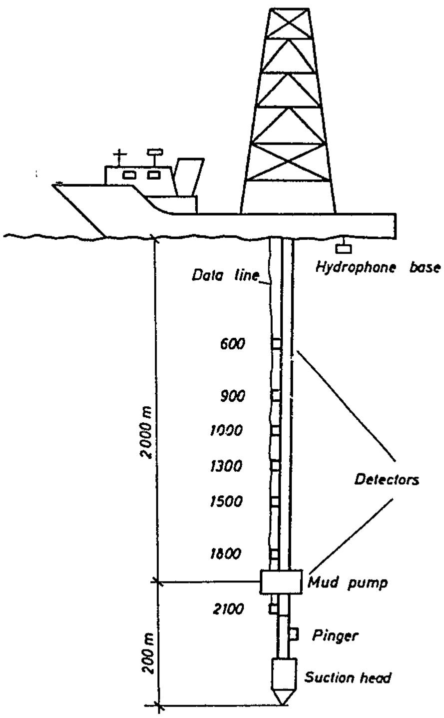
Fig. 5 - Mining equipment.



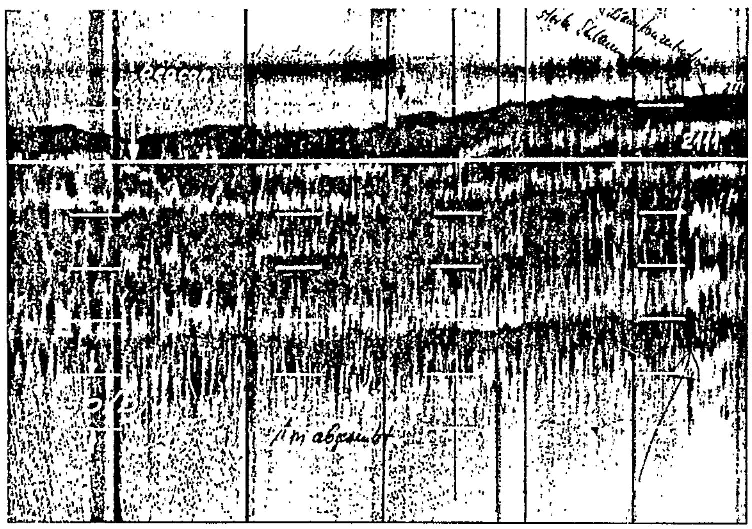
(a) Instrumentation Layout



(b) Radioisotopic Flow Meter



(c) Pipe String Control



(d) Reading Sediment Thickness Meter

Fig. 6 - Instrumentation.

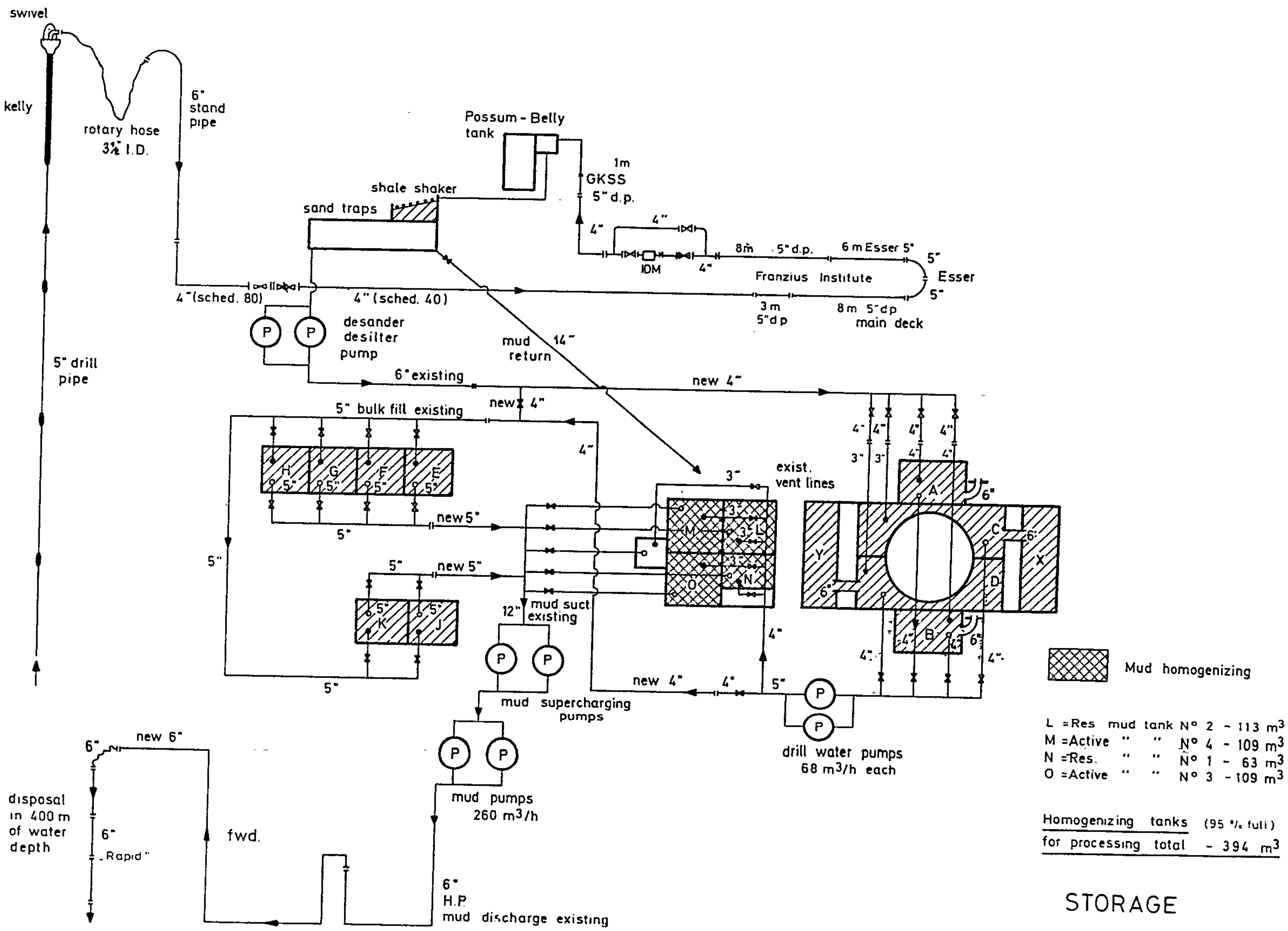
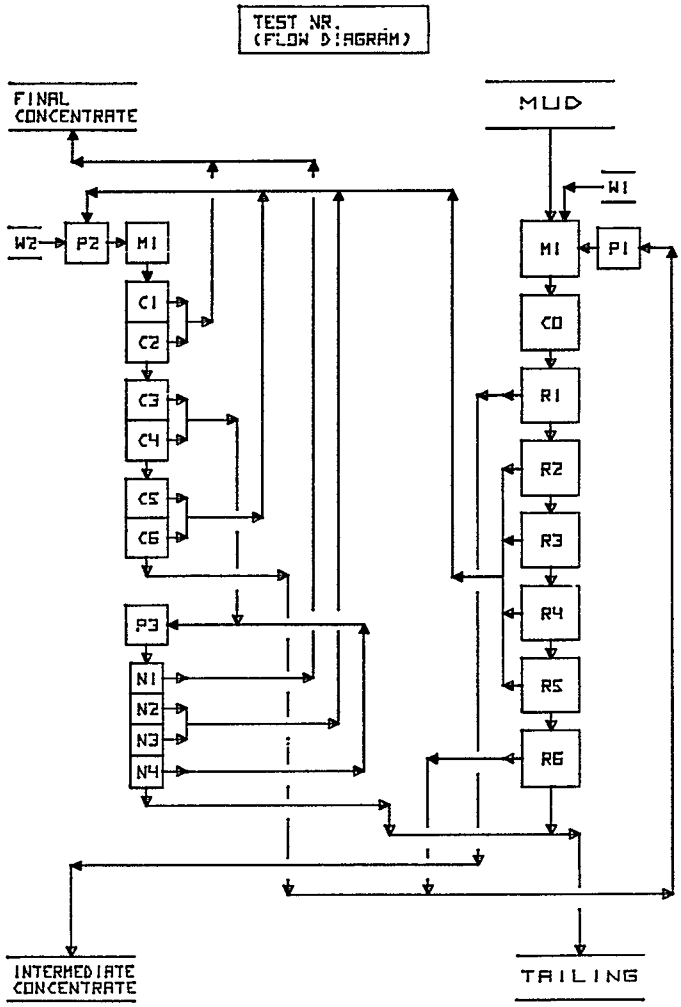


Fig. 7 - Pipe and instrumentation diagram of sediment handling and storage.

(a) Overall View of Flotation Plant

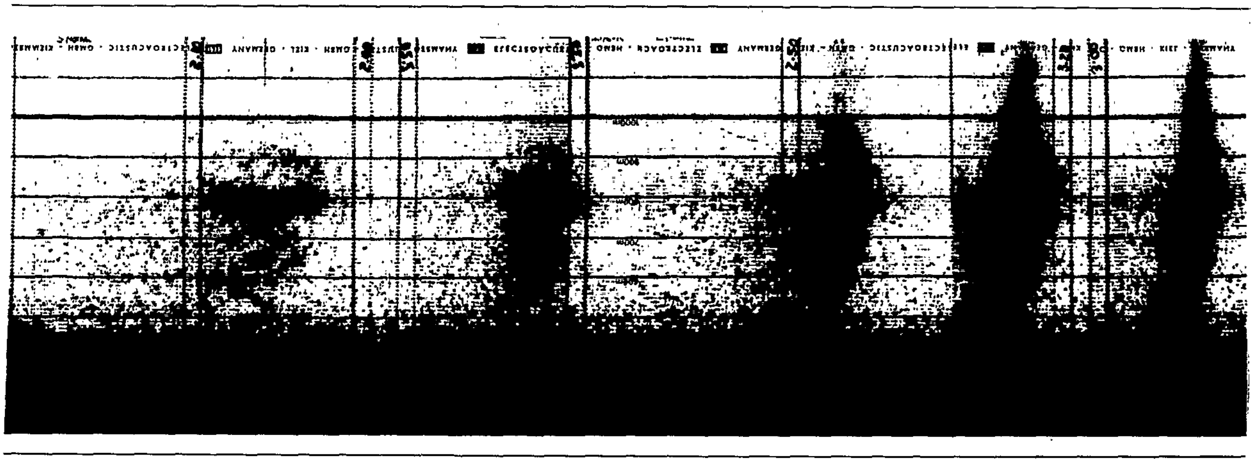


(b) Flow Sheet

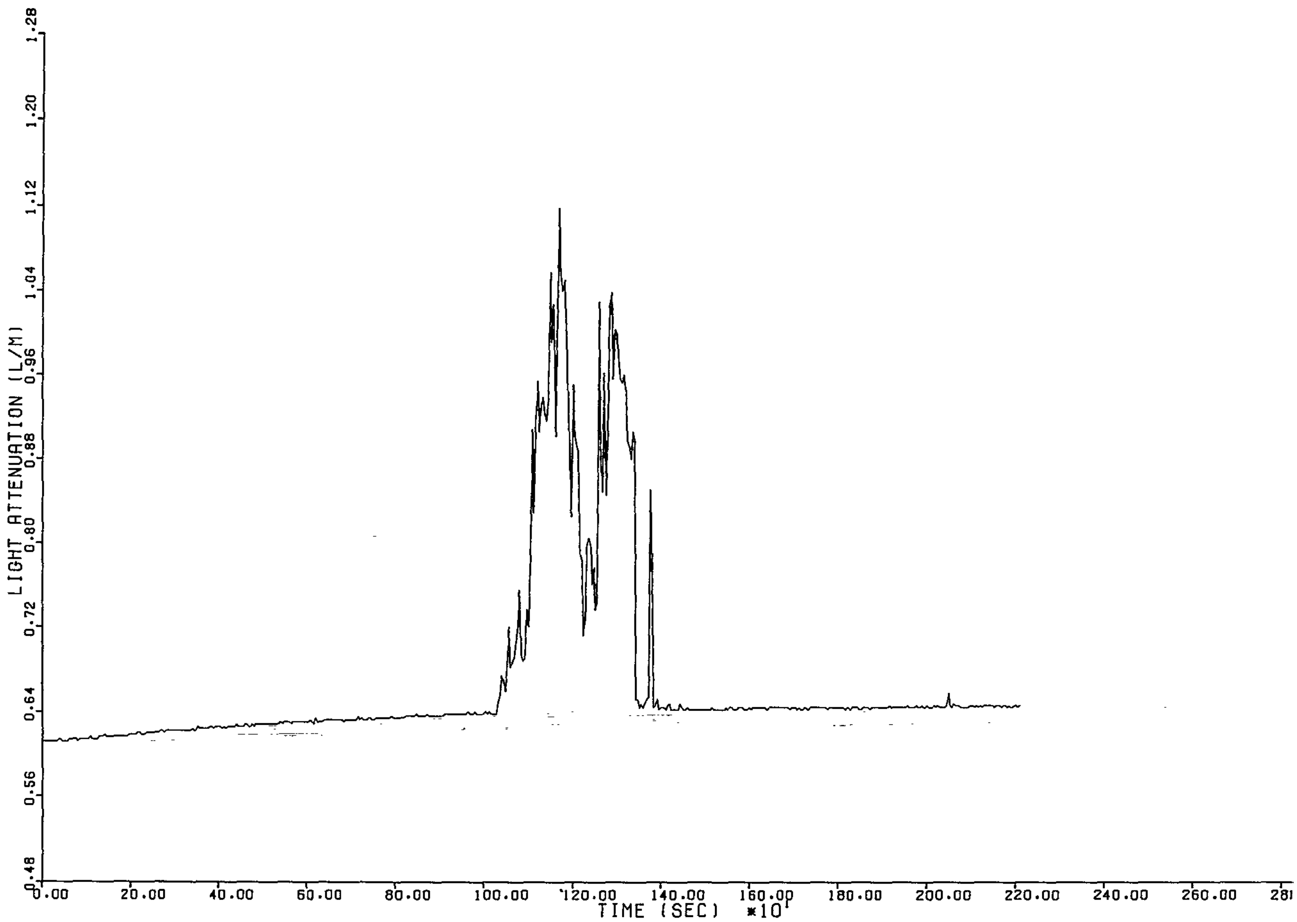
(c) Intergrowth of Chalcopyrite and Sphalerite Crystals

(d) Flotation Cell

Fig. 8 - Flotation plant.



(a) Ēcho Sounding of Disposal Plume



(b) Light Attenuation Sounding of Disposal Plume

Fig. 9 - Disposal of tailings.