PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Effect of the Environment on Processing and Handling Materials at Sea [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1978 **290**, 161-177
doi: 10.1098/rsta.1978.0080

Phil. Trans. R. Soc. Lond. A. **290**, 161–177 (1978) [161]
Printed in Great Britain

Effect of the environment on processing and handling materials at sea

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[Plates 1–4]

Compared with conventional land-based mining and processing operations, the exploitation of minerals from the seabed, particularly in deep water, involves a vast range of new problems in conducting the various stages of mining, transportation, processing and disposal of waste products, in a marine environment.

In all such operations the ways in which local sea and weather conditions and their seasonal variations affect the stability of the vehicle, be it ship or other floating structure or submersible from which the operations are being conducted, have to be taken into account. The resulting motion together with vibration generated by propulsion and other machinery are significant factors in the performance and behaviour of equipment and materials during processing, handling and transportation operations at sea. In deep-sea mining operations at depths of 2–5 km the effects of associated pressure, salinity and temperature must also be dealt with.

The paper reviews the present state of such knowledge as currently practised in continental-shelf operations, and as proposed in various deep-sea mining operations. Associated research requirements for future mineral exploitation in the deep-sea environment are discussed.

Introduction

During the past decade there has been world-wide interest in the sea bed and the ocean deeps as a source of raw materials to meet ever increasing demands or to replace exhausted land-based resources. Earlier papers in this volume have illustrated the tremendous advances and new developments in marine technology which have led to the successful exploitation of offshore oil and gas. Although there has also been widespread prospecting and associated technological activities towards the exploitation of marine minerals, the rate of development by the mineral industries has in general been considerably less sensational than that of the offshore oil and gas industries. This is due to constraints imposed as much by economic factors as by technological problems. For example, the overall viability of an offshore mineral operation must be related to the cost of exploiting equivalent land-based mineral resources, world market values and demand. In deep-sea mining operations, there also remains a lack of agreement on International Law of the Sea relating to the security and rights of concessions.

A number of minerals, including sand and gravel, tin, iron, titaniferous sands (in near-shore operations), calcium carbonate in various forms, barytes and sulphur, are currently being recovered from the sea bed in commercial-scale operations. With the exception of barytes and sulphur, all these operations are carried out by dredging. Inevitably, as near-shore deposits become worked out, future trends and technology must be established for operations to move further and further out to sea, dredging at greater depth and consequently in worsening sea conditions. In this situation there is considerable incentive towards primary processing operations at sea to avoid the need for transportation of large quantities of waste materials which can be rejected on site.

It is recognized that compared with conventional land-based mining and processing operations, the exploitation of minerals from the sea bed, particularly in deep water, involves a wide variety of new problems, including those arising from local sea and weather conditions, their seasonal variations and their effect on the vehicle, be it a ship or other floating structure or submersible, from which the operations are being conducted.

The resulting motion, and vibration generated from propulsion and other machinery, are significant factors, not only in the mining and lifting of material to the surface, but also on the subsequent behaviour of equipment and material during processing, handling and transportation operations at sea. In deep-sea mining operations at depths of 2–5 km the effects of associated pressure, salinity and temperature must also be dealt with.

This paper first reviews the present state of such knowledge as currently practised in mineral operations on the continental shelf and considers what future development trends are likely as these operations move into deeper water. In the continental-shelf operations, marine sand and gravel and marine mineral mining (typically and principally represented by alluvial tin) present distinct problems and are treated separately. Following this, corresponding aspects of proposed operations in the exploitation of deep-sea minerals are dealt with. Finally, associated current and future research requirements relating to all these activities are discussed.

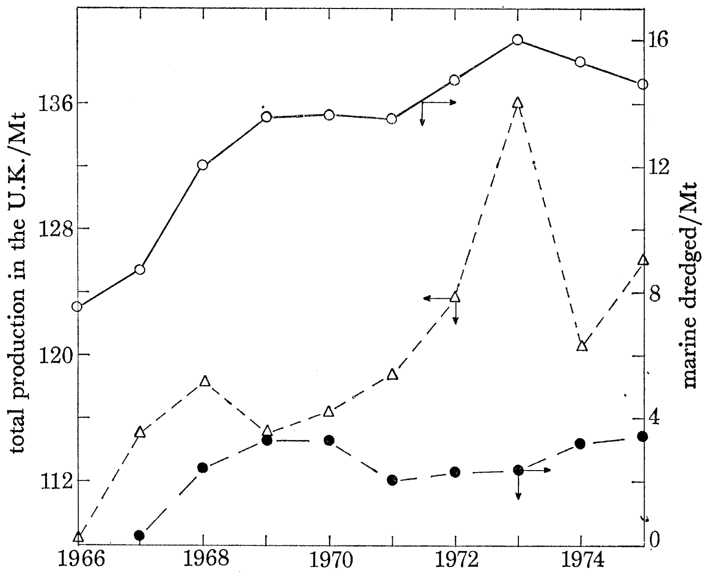


Figure 1. Trends in production of sand and gravel in the U.K. over a 10-year period: △, total production in the U.K.; ○, total marine dredged; ●, export marine dredged.

Marine sand and gravel

The U.K. marine sand and gravel industry is one of the largest offshore mining operations of its kind in the world. It produces various grades of sand and aggregate which are used mainly by the building and construction industries. A maximum annual production of 16 Mt was achieved in 1973 (Institute of Geological Sciences 1977). This corresponds to about 13 % of that produced from land-based sources and is estimated to be a similar percentage of the total marine aggregates produced throughout the world. Since then, the decline in the requirements of the building and construction industries in the U.K. has resulted in a reduced market demand and a shift in the proportion exported to other European markets. The growth rate and trends in these requirements are illustrated in figure 1.

(a) *Dredging methods*

The industry recovers the sand and gravel from the seabed by dredging vessels which vary in size and cargo capacity up to about 7000 tonnes. A typical sand and gravel dredger is shown in figure 2, plate 1.

Suction dredging is almost universally used. In this, the aggregate is transported up a dredge pipe from the sea bed to the vessel from depths of down to about 50 m. The flow is induced either from a centrifugal pump located as low in the ship as possible or from a jet lift system in which a negative pressure is created by high-pressure jets located near the lower end of the dredge pipe. Jet-assisted centrifugal pump systems are also used.

Depending on the type of deposit being worked, either hole digging or tail dredging can be adopted. Hole digging uses a forward-pointing dredge pipe, usually for working deep deposits with the ship at anchor. Trail dredging, as the name suggests, uses an aft-facing dredge pipe. It is usually used for working shallow deposits, whilst the ship is just making way, but can also be used for deep deposits with the ship at anchor.

(b) *Shipboard motion and compensating systems*

Movement of the ship in relation to the seabed is one of the key factors relating to the limits of sea conditions under which it is possible to operate the dredge. A swell compensator is used to remove some of the relative motion between the ship and the head of the dredge pipe. It is a passive type of hydro-pneumatic system which takes in or pays out the wire rope supporting the dredge pipe according to the load on the rope. The pressure in the system is adjustable to give the required level of contact pressure between the dredge head and the seabed. Thus as the ship starts to lift the dredge-head off the bottom, the load on the rope increases and the compensator pays out more rope until contact pressure is restored. Conversely, when the ship sinks into a trough, the load decreases and the rope is pulled in. However, because the compensator has only a limited operating range it is not always able to provide complete compensation for the motion of the ship in heavy seas. In this situation, a very high sense of anticipation is required by the dredgemaster in manually assisted control of the winches, to enable dredging to be carried out without risk of damage. Typical motion data recorded on a dredger operating in conditions of up to Force 5–6 on the Beaufort scale are shown in figure 3.

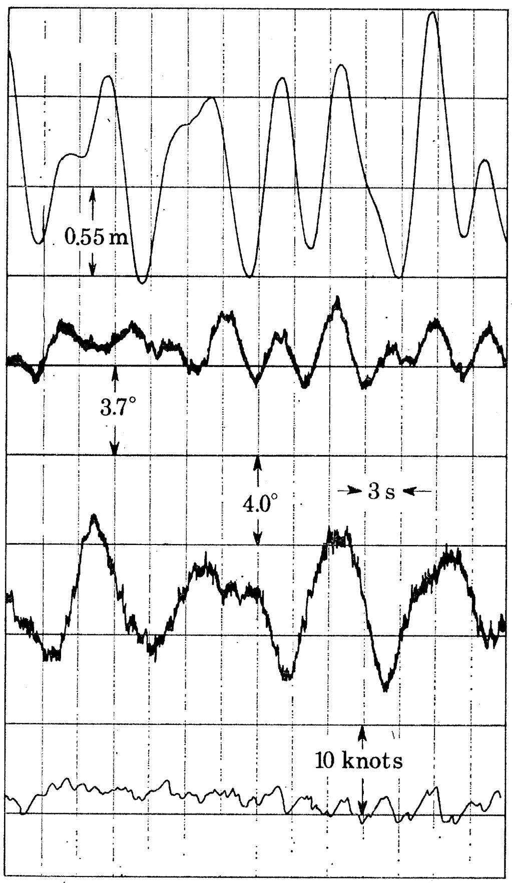
(c) *On-board processing*

The main processing operation which takes place on board the dredger is screening, to reject either the sand as undersize or the gravel as oversize, depending on whether gravel or sand is the required marketable product. In either case, a separation at $\pm\frac{3}{16}$ in (5 mm) is usually aimed for. The screening plant may range from a single static inclined-screen deck (figure 4, plate 1), to either two or four vibrating-screen decks. Where two or more screen decks are employed a feed distributor is needed to ensure uniform volume flow, solids concentration and particle size distribution to each screen deck. Investigations at Warren Spring Laboratory (W.S.L.) have shown that the design of the distribution system is of considerable importance in achieving these aims since the uniformity of volume flow and solids concentration distribution is significantly affected by the configuration of the pipework leading to the distributor. However, the effect of shipboard motion does not appear to alter its overall performance.

(*d*) *Future trends*

One of the recommendations of the Report of the Advisory Committee on Aggregates, *The way ahead* (Department of the Environment 1975, §6.35), was that the Department of Industry, in consultation with the Department of the Environment, should encourage research into improved dredging technology, and in particular dredgers capable of dredging in deeper waters (in excess of 36 m) and methods of moving seabed overburden which overlies gravel.

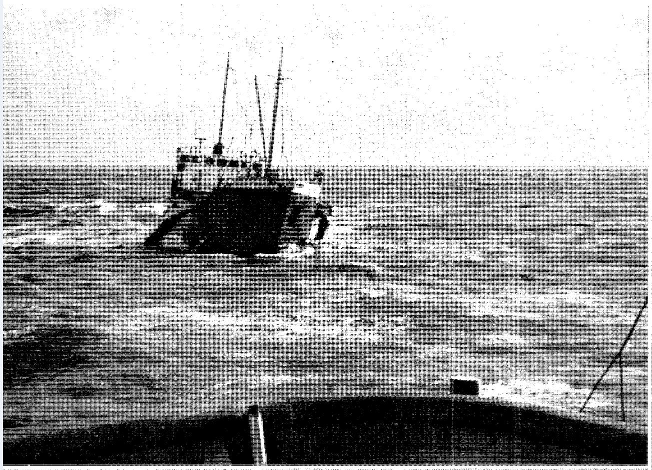
Test 3. Gyro position C, aft on centre line
Conditions: estimated wind direction, NNW; ship's heading, 025°; estimated swell, 1 m



channel	mean	r.m.s.	max.	min.
1: heave/m	0.2217	0.3749	1.3948	−0.9515
2: roll/deg	−1.4714	0.3935	−0.3264	−2.7129
3: pitch/deg	−0.4798	0.6362	1.9650	−2.9190
4: wind speed/knot	13.2828	13.7396	21.9100	5.2850

FIGURE 3. Typical motion data recorded on sand and gravel dredger.

In the present climate of economic constraints, there is little incentive for the industry by itself to conduct development work towards immediate achievement of these aims. Nevertheless, a limited amount of work has already been carried out in this area in terms of design and feasibility studies in which various systems have been considered. These have included suction systems with submerged pumps (G.E.C. Mechanical Handling Ltd 1973) on rigid and flexible dredge pipes, air lift systems, vertical suction pipes with heave compensation similar to that used on drill ships, submersible dredge pods and barges with buoyancy tanks for lifting them to the surface when filled, and underwater processing facilities for rejecting unwanted material



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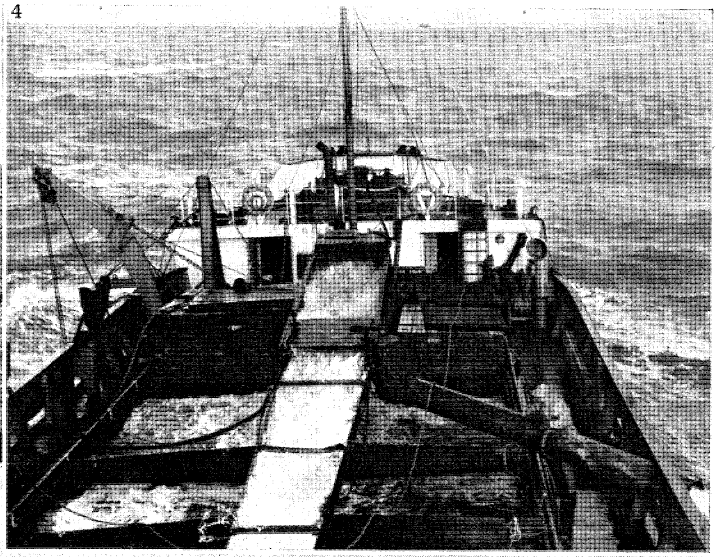

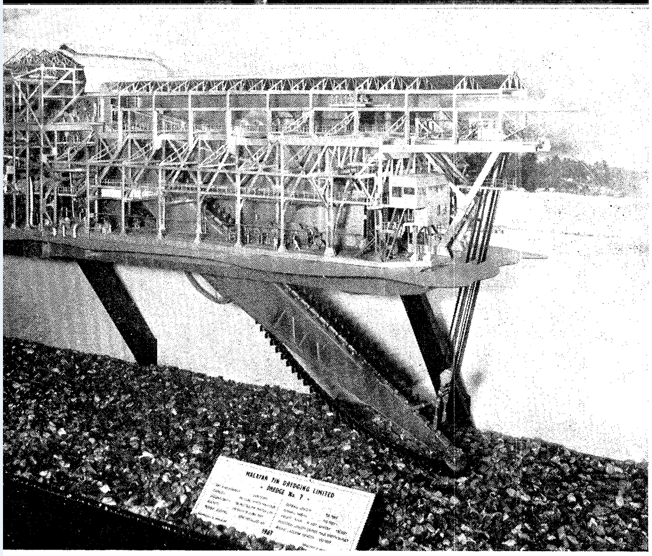

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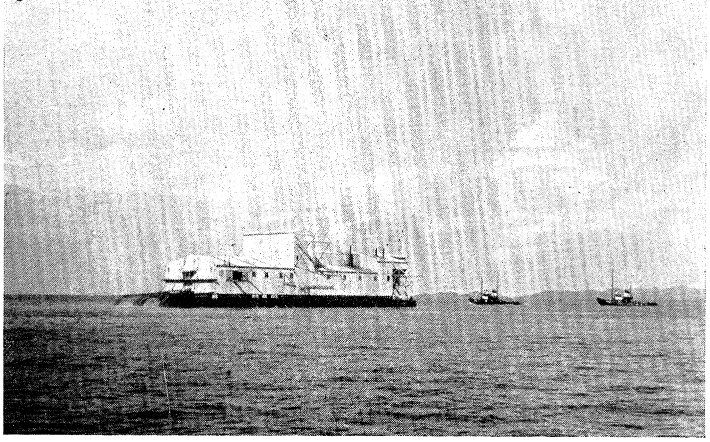

FIGURE 2. Sand and gravel dredger operating in rough seas.
FIGURE 4. Screening plant on board a sand and gravel dredger.
FIGURE 5. Sectional model of a tin dredge.
FIGURE 6. Tin dredge in an offshore operation.

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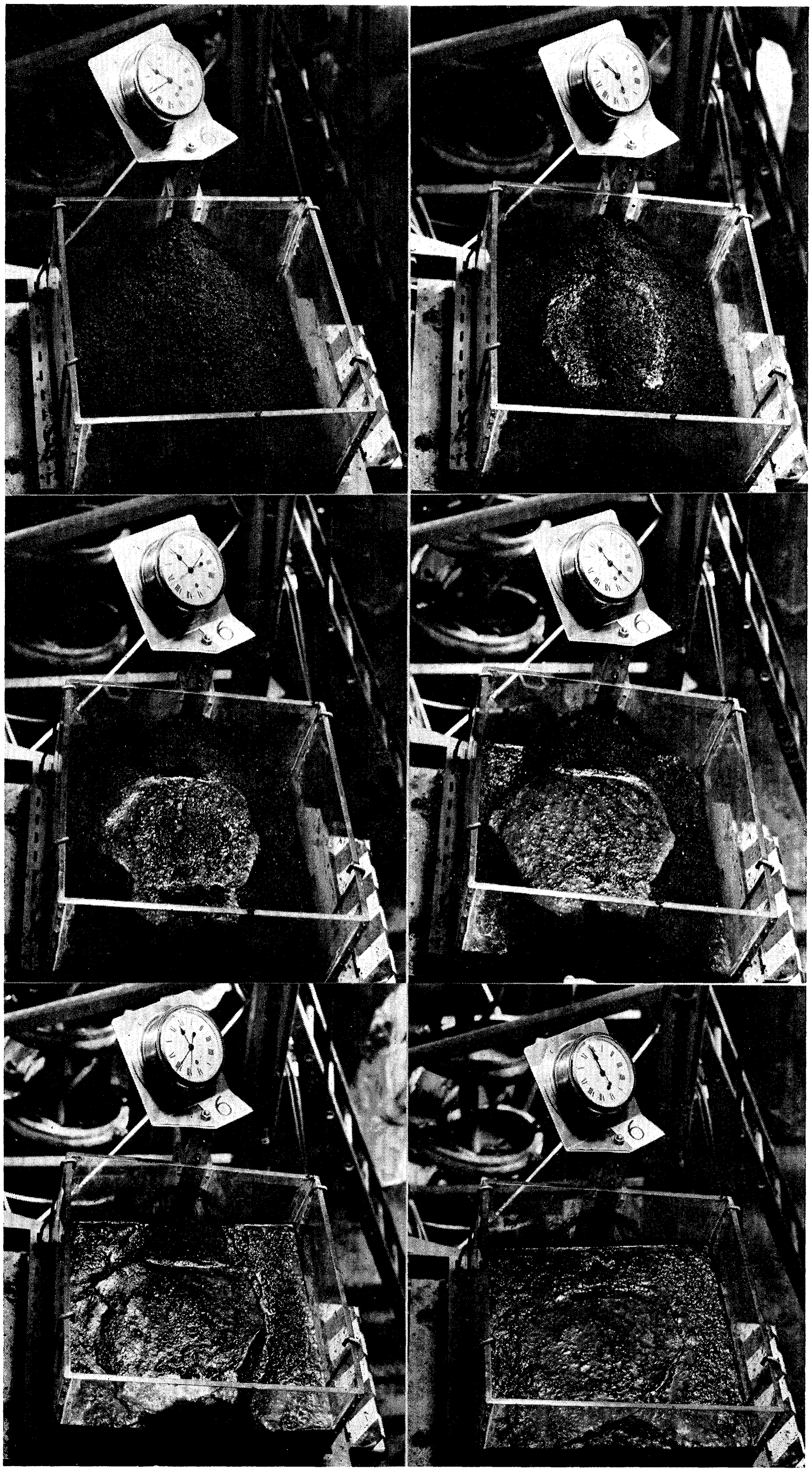

FIGURE 7. Illustration of cargo liquefaction originating from the centre.

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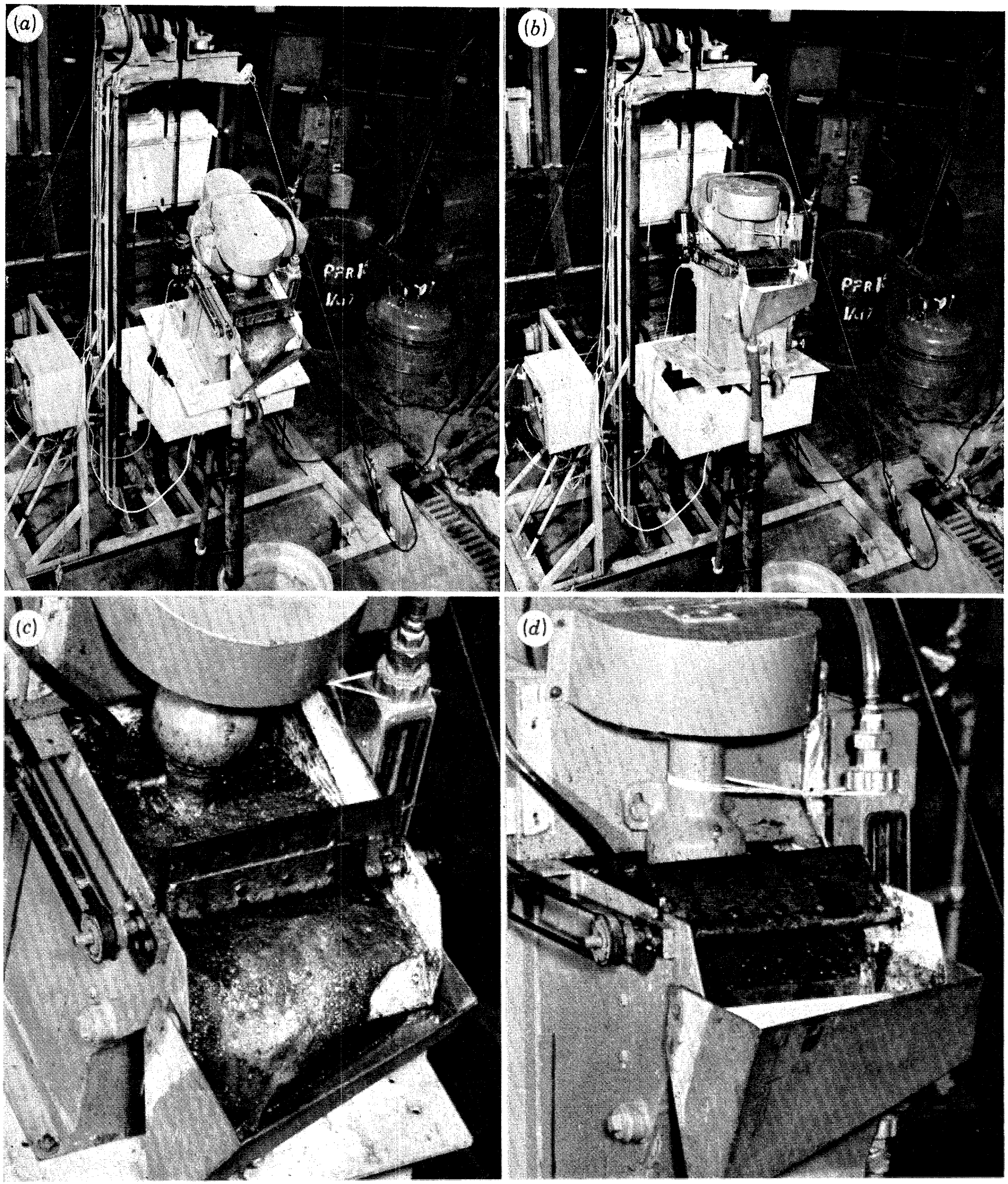

FIGURE 10. Flotation tests on ship's motion simulator, with froth discharge in line with maximum roll motion. (*a*, *b*) Simulator in two attitudes of angular motion; (*c*) overspill with cell tilted forwards; (*d*) no discharge with cell tilted backwards.

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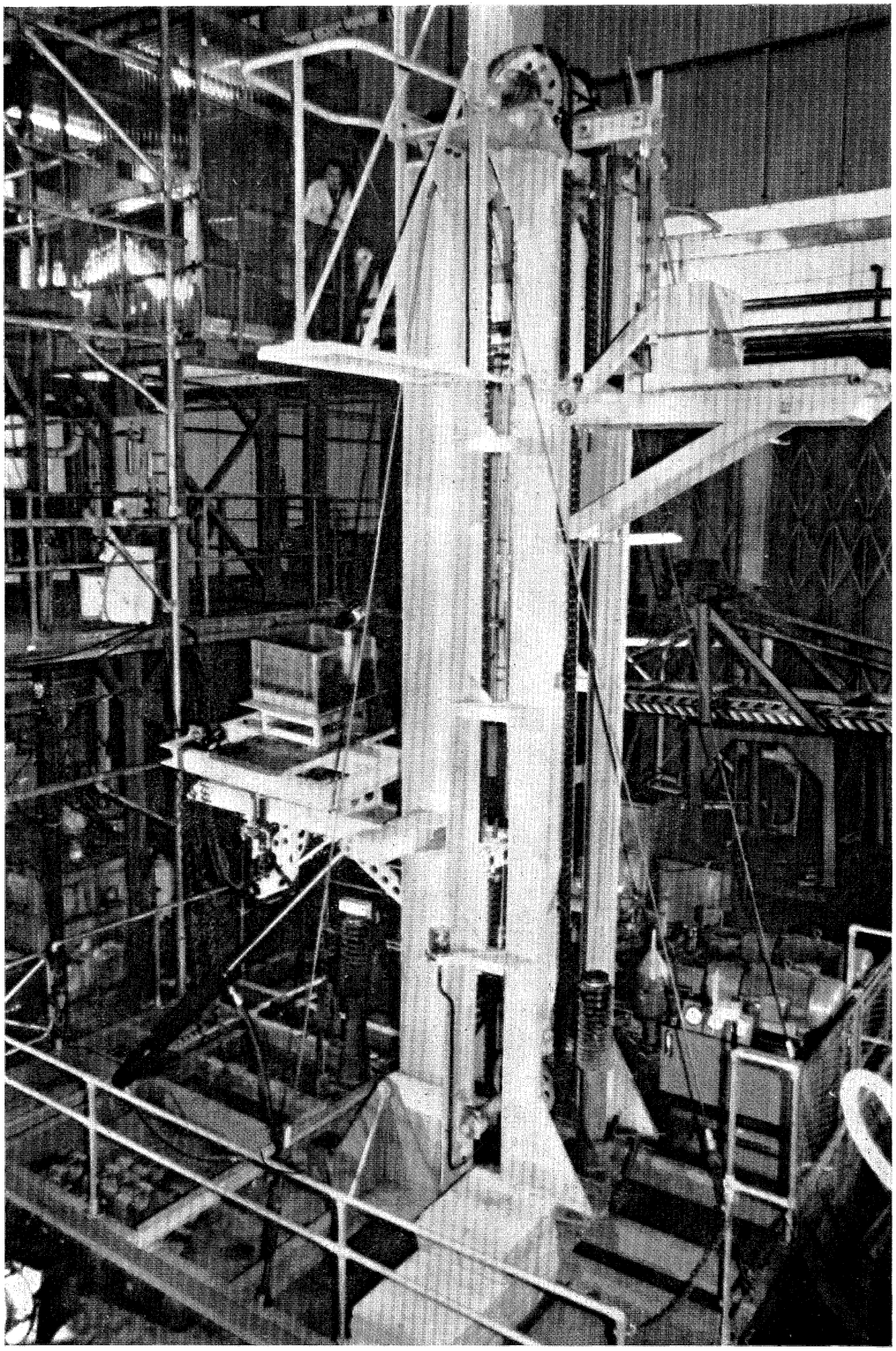

FIGURE 12. Cargo stability testing on largest simulator platform.

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on the seabed. Although the technical feasibility of such systems may have been established, further development of the preferred ones largely depends on costs, market demand and resources. The basic intrinsic value of the product (about £1.75/t) dictates that only relatively cheap and simple systems can be considered compared, for example, with those which might be commercially viable in offshore oil and gas activities.

Market demand depends on the overall economic climate in the U.K. and European countries bordering the English Channel and Southern North Sea, and the corresponding growth rate in their building and construction industries. Future availability of resources is related to demand and thus to the rate at which existing near-shore deposits are used up. Another factor which has to be taken into account is the proportion of these deposits which may be 'sterilized' by fishing and other environmental considerations. An alternative possibility in the medium term is the removal of contaminants such as chalk, shell and clay. Available survey information estimates that approximately 200 Mt of economically extractable gravel, contaminated with small quantities of chalk, exists in U.K. waters.

Finally, the problems of removal and disposal of overburden overlying deep gravel deposits and their consequent effects with respect to erosion and the ecology of the marine environment have to be resolved.

Offshore alluvial tin

Alluvial tin dredging dates back to the early exploitation of inland placer deposits in Malaya about 1913. Since then, the tin dredging industry has developed widely into operations on deposits in riverbeds, estuaries and lagoons in many areas of SE Asia and, more recently, has extended into offshore areas of Thailand and Indonesia. Cassiterite (SnO_2) was probably the first metalliferous mineral to be exploited from the seabed and, up to the present, tin remains the only non-ferrous metal commercially produced by the marine mining industry. The most recent statistics for tin production, on the basis of tin in concentrates, estimates that world production from all sources in 1975 was of the order of 175 kt, of which about 13 % was dredged from estuarine or inland sources and 7 % from offshore dredging operations (International Tin Council 1975).

In relation to overall tin production, the offshore contribution is likely to become greater in the future in the light of prospecting data presented to the Fourth World Conference on Tin, in November 1974, for the offshore areas of Thailand, Malaysia and Indonesia.

Tin dredging operations may resume in the St Ives Bay area of Cornwall in 1977 (Beckmann 1975). It was originally planned that a mobile 'walking platform' be used as a base for the mining and processing plant but more recent information indicates that a dredging vessel will be used for the initial operations.

(a) *Tin dredges*

A tin dredge has little in common with either harbour-clearance or sand and gravel dredgers. It consists primarily of a non-propelled pontoon on to which is built the necessary superstructure for supporting the digging arm, the screening plant for removing the coarse stones, etc., from the feed, and the mineral separation plant which also includes a feed distribution system and a tailings disposal system. The dredge is positioned and fed into the digging face by means of a series of winch-operated mooring lines. A modern dredge can handle up to 1150 $m^3\ h^{-1}$ and operate at depths of 50 m. The general construction of a tin dredge is illustrated in figures 5 and 6, plate 1.

In offshore operations the effect of swell has a significant effect on the overall operation, not only in the stresses imposed on the digging arm but also on the performance of the treatment plant. A number of developments to overcome these problems have been considered including submerged plates to stabilize the pontoon, increasing the length of the pontoon to over-span the maximum expected wavelength, and semi-submersible structures and swell-compensating systems similar to those used on sand and gravel dredgers.

(i) *Bucket-ladder dredges*

These have been used for the past 60 years with few changes in basic concept except for improvements in the pivoting and suspension systems and in articulation of the toe. The mechanical stresses imposed under conditions of swell are very large due to the fact that the ladder assembly may weigh up to 1200 t, particularly when digging near bed rock where the tin concentration is invariably at its maximum.

(ii) *Suction-cutter dredges*

These consist of a cutter head rotating at the end of a ladder or framework. The rotating axis of the cutter is in line with the ladder and discharges into a submerged centrifugal pump also mounted on the ladder. It has the advantage that the supported weight is considerably less than that of a bucket ladder dredge, but for alluvial mining, where the mineral values are not evenly distributed in the material being dug (i.e. deposited on the bed rock), the existing cutters have difficulty in properly cleaning the bed rock and produce wide variations in the solids concentration in the feed to the treatment plant. The same may apply to bucket wheel dredges, as yet not fully developed for this application.

(iii) *Screens*

Trommel screens are almost universally used on tin dredges where the primary objectives in design are maximum capacity with minimum space requirement.

(iv) *Mineral separation plant*

Good distribution of the screen-undersize slurry to the treatment plant has always been a problem on tin dredges. Numerous systems have been tried in recent years. By far the most satisfactory system of distribution to have emerged in the tin dredging industry is a splitter system of distribution, by which the feed to concentrating units is controlled through self-compensating triangular orifices. An important feature of this system is that as well as giving reasonably even flow rates to all units of the treatment plant, it also ensures an even grade of feed. Experiments at W.S.L. (Hughes & Joy 1972) have also shown that this device maintains good distribution performance even under extreme ship-board motion.

The method of mineral separation universally accepted in the tin dredging industry is by jigging, which is one of the oldest of gravity separation techniques. It works on the principle that vertical pulsations of water through a bed of particles will cause separation and stratification of these particles on the basis of their specific gravities. The heavier particles work to the lower part of the bed while the lighter particles are forced to the top, the products being collected separately. In a modern plant this may take the form of either conventional rectangular jigs, 1.07×1.22 m, or radial jigs 7.62 m in diameter. Various opinions exist in the industry on the capacity and performance merits of these two types of jig with respect to cost and space requirements.

(v) *Tailings disposal*

The waste tailings are disposed of either by pumping or gravity discharge through sand chutes designed to convey them as far as possible behind the dredge and away from the working face of the deposit. With the increasing concern of government departments on the effects of mining generally on the environment, ever more stringent controls are likely to be imposed upon tailings disposal to regulate rates of discharge, size distribution and methods of deposition with respect to tidal flows, prevailing currents, etc.

(*b*) *Current designs of tin dredges*

At present, two new tin dredges are under construction, to commence operation in offshore areas of Indonesia on completion. One of these is reportedly the largest offshore tin dredge ever built (Anon. 1977): 110 × 30 × 6.5 m with a bucket capacity of 0.85 m^3 for dredging at a nominal rate of 1836 $m^3\ h^{-1}$ down to a depth of 45 m.

To achieve a high degree of availability in the prevailing wind and sea conditions on site, it is provided with a hydro-pneumatic compensating system in the bucket-ladder suspension. The mineral concentration plant consists of two revolving screens, circular primary jig and rectangular secondary, tertiary and clean-up jigs.

However, other schools of thought in the operating industry favour simplicity in design and maintenance with maximum reliability. The second dredge has been designed to meet these specific requirements. It is 108 × 32 × 4.75 m with a smaller bucket capacity of 0.625 m^3 for dredging at a lower nominal rate of 975 $m^3\ h^{-1}$ but at an increased depth of 50 m (Hewitt 1977). A special feature in its design is provision to obtain optimum fill of the buckets over a wide range of angle at the digging face. The treatment plant consists of two revolving screens and again, illustrating differences of opinion, rectangular type jigs are used throughout for the concentrating operations.

(*c*) *Future trends*

Although current designs of bucket-ladder dredges are generally limited to an operating depth of 50 m, design studies have been carried out for depths of down to 60 m. Limiting factors are bearing design for the main pivot and for the suspension system in view of the enormous basic load imposed by the extended ladder assembly plus shock load safety factors under open sea conditions.

For the future, it seems likely that some departure from conventional designs will be necessary for operations at depths greater than 60 m. For example, it is believed that deep tin deposits exist in the straits of Malacca which could be commercially exploitable if techniques were available to recover them. A number of design possibilities exist towards this end, including continuous dragline bucket systems (Gauthier & Marvaldi 1975) as proposed for deep-sea mining operations, suction dredging systems with submerged pump or air lift as discussed for marine aggregates, systemized clamshell grabs and remotely controlled submersible units for dredging, screening and pumping the feed by flexible pipeline to a surface treatment plant. In common with future trends for marine aggregate dredging, technical feasibility is not the only consideration and the incentives for the tin industry to proceed along these lines will also depend on economic factors, costs in relation to tin prices and future world demand. Continuing increase in the price of tin could, in the long term, lead to the development of alternative substitute materials, at least for some applications, and thus become a disincentive for future developments in offshore tin operations.

Manganese nodules

Smale-Adams & Jackson (1978, this volume) have already dealt with various aspects and problems of manganese nodule mining, lifting, etc., and it remains for this paper to deal with the operational effects of the marine environment on processing and handling these materials at sea.

(a) *Local weather and sea conditions*

Local weather and sea conditions, together with their seasonal variations, are highly significant factors which have to be taken into account in the planning and selection of workships, floating structures and associated on-board equipment for processing or handling operations at sea. These factors must be considered with respect to stability requirements and accepted codes of practice for maritime safety as well as the technical and economic viability of the operations which are being planned.

In order to give an impression of the severity and range of conditions likely to be encountered, seasonal wind and wave characteristics for the area centred around 10° N, 140° W are given (Meteorological Office 1977). This area is one in which nodule mining is likely to take place.

(i) *Wind*

The NE trade winds affect the location from October to July, but during August and September winds are variable and mostly light. Mean monthly speeds vary from 8 knots in August to 17 knots in April with an annual average of 14 knots. Calms are rare as are winds above force 7; however, it is estimated that between July and September the location is affected by tropical storms or hurricanes two years out of three, when, of course, much more severe conditions would be experienced.

(ii) *Waves*

Swell waves are generally larger than wind waves, with a mean height of about 4 m and periods of between 10 and 16 s (wavelengths 150–400 m). During the tropical storm season in particular, swell is often heavy and confused. Significant heights of wind waves mainly vary between $1\frac{1}{2}$ and 3 m but periods are very variable, mostly 5–9 s with 6 or 7 s most common, corresponding to wavelengths of 40–125 m with a mode of about 60 m.

It is not proposed to extrapolate this information in terms of actual ship-board motion since this depends on a wide range of other factors beyond the expertise of the author. However, some comparative indication of ship's motion may be obtained by reference to figure 3. These data were recorded on a sand-and-gravel dredger with principal dimensions: length 79.2 m (260 ft o.a.l.), beam 14.02 m (46 ft) and draught 4.57 m (15 ft) at a position close to the stern of the vessel and on the centre line of the main deck. It will be seen that the mean wind speed conditions were 13.3 knots during this test as compared with the annual average of 14 knots in (i) above. Thus the out-to-out motion recorded on the dredger for heave was 2.3 m, for roll 2.4° and for pitch 4.9°. (The maximum and minimum values for these motions are computed about the mean.)

During these trials, the dredger was under the command of an experienced master, who handled the vessel to minimize motion in order to facilitate continuous and effective dredging. It is likely that ship motion, in this particular area of the Pacific discussed, will be of no less magnitude.

For mining operations, the problems of safety of the lifting systems must be a matter of some concern during periods of tropical storms and hurricane conditions which are predicted.

(*b*) *Ship-board processing operations*

Since the proposed mining sites are over 2000 km distant from land, it is important to consider what processing operations can be carried out on site in order to reject as much waste material as possible and thus to avoid the cost of transporting it long distances. However, work to date indicates that the primary operations of dewatering and removing the ocean bed sediment (ooze) are the only possibilities at this stage. In this respect, the effect of ship-board motion may interfere with classification procedures designed to reject the ooze from fine nodular particles at the lower end of the particle size range. Such effects will depend on the size distribution of the feed to any separation process, the concentration of solids and other factors, including the frequency and amplitude of the ship movement during the operations. The particle size of the nodular material and the percentage of associated ooze will depend, to a large extent, on its previous history and location, friability of the nodules, methods of harvesting and lifting, and any other handling or transfer operations. To maximize the recovery of nodular material in any particular mining operation, it may well be necessary to determine the hydrodynamic behaviour of the feed material, its response to classification processes, and how these are affected by superimposed shipboard motions of varying degrees of severity. Such data, in conjunction with the corresponding mineral distribution with particle size, will have to be used as a basis for selecting appropriate classifying operations and for predicting expected scale-up performance.

(*c*) *Materials handling*

It is conceivable that ship-to-ship transfer systems will be employed where dewatered solids have to be transferred from the mining and processing vessel to a bulk cargo vessel for transportation to the land-based processing plant. Transfer systems which have been developed (G.E.C. Mechanical Handling Ltd 1973) and used for many years in naval and mercantile replenishment-at-sea applications, could readily be adapted for this purpose. For example, such systems incorporate methods for refuelling using self-sealing dry couplings, transfer of stores and ammunition, and the safe transfer of personnel between vessels under way. Hydraulically driven winches and solid-state logic control systems provide the necessary sensitivity and flexibility required for safe operation when two ships, often of very different tonnages, are keeping stations when underway in quite severe sea states.

Similar equipment and methods have been relied on extensively for many years on self-unloading bulk cargo vessels where no shore handling equipment is available.

There seems little doubt that similar systems could be used for ship-to-ship transfer of nodular material either as hydraulic suspensions or partially dewatered bulk solids.

(*b*) *Transportation of damp nodule cargoes*

The transportation of bulk mineral concentrates and other similar fine-grained materials requires their carriage in a manner such as will avoid the hazard of shifting cargo due to liquefaction. The onset of the phenomenon is associated with the moisture content exceeding some critical limit in relation to the prevailing conditions. Such cargoes may appear to be in a relatively dry granular state when loaded and yet may contain sufficient moisture to develop a flow state under the stimulus of vibration and ship's motion, particularly during a voyage in heavy seas. In the resulting fluid state, a shift of cargo can occur in various different ways, from which the vessel may progressively reach a dangerous heel and eventually capsize.

There have been a number of casualties attributed to this cause over the years, in some cases involving loss of life (Green & Hughes 1977). In others, shift of cargo with consequent development of a list condition have been reported but the vessels succeeded in safely reaching port.

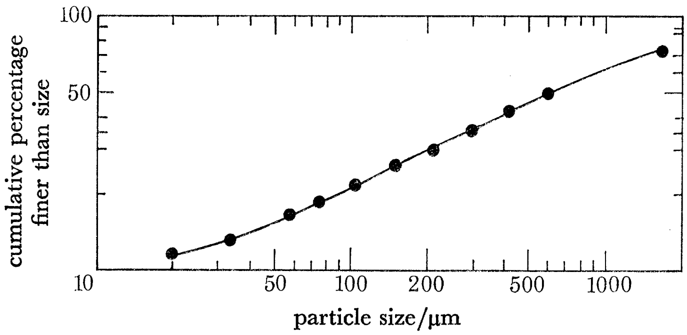


FIGURE 8. Size analysis of anthracite washed duff.

Any damp fine-grained mineral cargo – and this must include damp or wet fine-grained nodular material – is regarded as lying within the category of potentially hazardous material for shipment as a bulk cargo. It should therefore be subjected to internationally recognized flow moisture tests from which its transportable moisture limit for safe transport by sea can be derived (IMCO 1972). Furthermore, since there is no background of experience in the shipment of this material, as, for example, exists for ore concentrates and fine coal, confirmation of its flow moisture characteristics and behaviour under simulated shipboard conditions is advisable.

The effect of simulated ship's motion and vibration are dramatically illustrated in figure 7, plate 2. This shows a model-scale cargo container in which an anthracite washed duff at a moisture content of approximately 21 % is being tested on a ship's motion simulator. The particle size of this sample is shown in figure 8.

It will be seen that even though the cargo appeared reasonably dry when loaded, the onset of liquefaction occurred near the top of the ridge within 3 min and gradually transformed the cargo into a fluid mass inside 1 h. Under real conditions on a bulk cargo vessel this could create a situation of extremely hazardous instability.

Although various test procedures and codes of practice have been evolved with a view to ensuring that such cargoes have sufficiently low moisture content to be transported safely by sea, cargo behaviour during a voyage is far from being fully understood. In this situation it cannot therefore be assumed that because manganese module material in a partially dewatered state may appear dry and safe, it is actually safe to transport as a bulk cargo by sea. The alternative is specially designed ships with compartmented cargo holds to reduce the free surface problems, as in tankers. However, this increases capital and the materials-handling cost and must be considered in relation to dewatering costs to bring the cargo within the transportable moisture limit as a bulk cargo.

Red sea mud

The locations of brine pools and metalliferous sediments along the median valley of the Red Sea have been investigated by different groups of scientists since 1964. Their location is shown in figure 9.

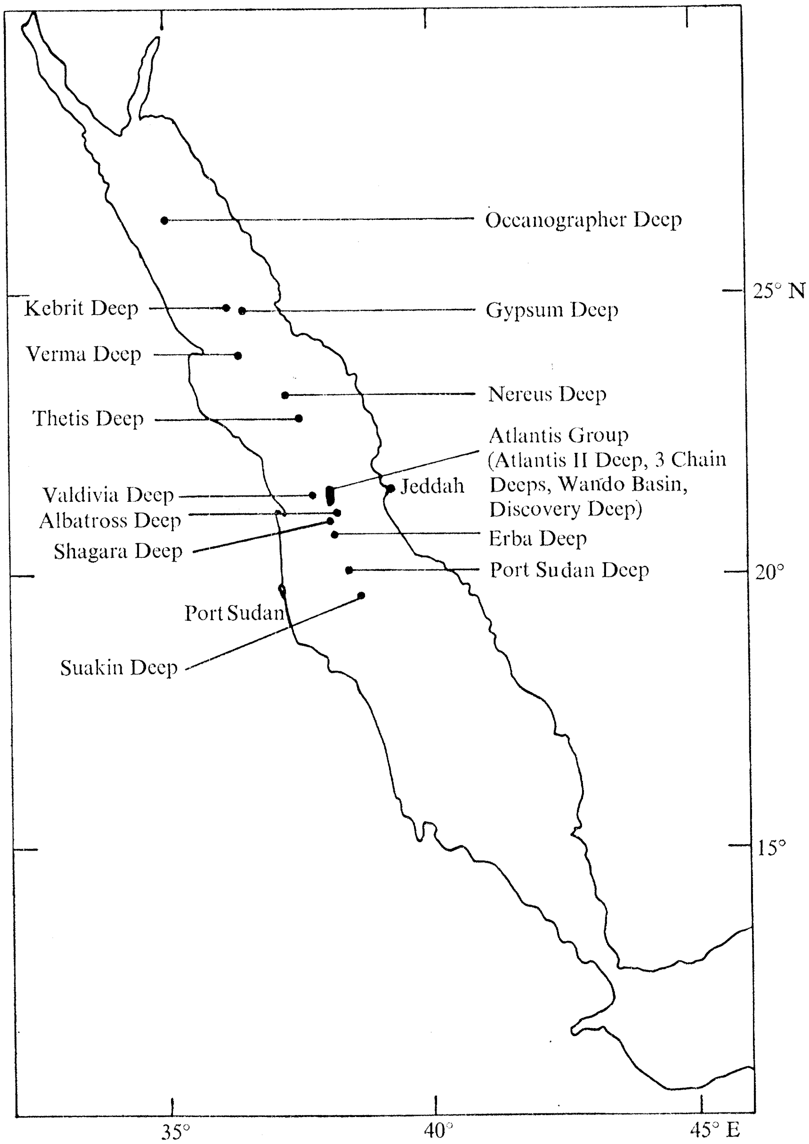


Figure 9. Distribution of brine pools in the Red Sea.

The largest of these pools is the Atlantis II Deep which covers an area of 55 km² and contains the only sedimentary deposits at present of economic interest in the Red Sea. The southern part of Atlantis II Deep (Amann, Bacher & Blissenbach 1973) is estimated to contain 150–200 Mt of dry salt-free mud with an average content of 5 % Zn, 1 % Cu and 33 % Fe (Supp & Nebe 1974). These metals occur mainly as sphalerite, chalcopyrite and iron oxides or hydrates of iron oxide respectively. In the original state, one litre of thermal sediment contains about 90 g of dry salt-free solids and 300 g of salt (99 % NaCl). The deposits are located at a depth of about 2 km in a layer up to 10 m in depth with temperatures up to 60 °C. The solids are characterized by their extremely fine particle size, of the order of 60–70 % by mass finer than 5 μm. This creates considerable problems in developing technical and economically viable processes for extracting the metal values. However, investigations to date appear to indicate that froth flotation (Supp & Nebe 1974) followed by hydrometallurgical treatment (Neuschütz & Scheffler 1977), leaching, solvent extraction and electrowinning processes are possible routes for recovering the mineral values.

In this event and bearing in mind the bulk handling and transportation problems, it seems reasonable to speculate that primary concentration by flotation could take place on site with subsequent treatment of the concentrates on a land based plant. The former would involve processing under shipboard conditions.

Table 1. Wind and sea conditions in the Red Sea

	Dec.–Feb.	Mar.–May	June–Aug.	Sept.–Nov.	year
(i) winds					
predominant direction(s)	N	N (NW)	NW	NW (N)	—
frequency (%)	47	40 (30)	45	33 (30)	—
mean speed (knots)	10.3	10.0	8.3	8.0	9.2
hourly mean speeds expected on average to be exceeded only once in:					
1 year	34	35	31	31	37
5 years	37	39	34	34	41
10 years	38	40	35	36	42
50 years	41	43	38	39	45
(ii) waves					
height ⩽ 2 m (%)	84	81	93	90	87
period ⩽ 7 s (wavelength ⩽ 75 m) (%)	77	75	80	77	77
maximum wave exceeded only once in 50 years/m	10	11	8	9	12

(*a*) *Local weather and sea conditions*

The same general principles apply as those expressed in an earlier section for mining and processing of manganese nodules. However, for the area centred around 21–22° N, 38° E in the Red Sea, there is considerably more information available than for the area where manganese nodules are located. An attempt has therefore been made to predict extreme winds and waves and the data have been divided into four periods roughly corresponding to the northern hemisphere seasons. The results thus obtained are given in table 1 (Meteorological Office 1977).

No specific information is available on swell at the location of Atlantis II Deep but the relatively small area of the Red Sea suggests that this is not a significant factor.

It will be seen that conditions for mining and processing operations in the Red Sea are likely to be more constant and less severe than those predicted for corresponding operations on manganese nodules in the North Pacific.

(*b*) *Mining and shipboard processing operations*

Mining methods for Red Sea muds are likely to be relatively simple compared with those for harvesting manganese nodules. First, the operating depth is of the order of 2 km as compared with 5 km for nodules. Secondly, the deposit is in the form of a deep layer of sediment about 10 m thick as compared with relatively thin layers of nodules deposited on the seabed. Consequently, in principle, much simpler methods can be adopted for lifting the material to the surface, such, for example, as suction dredging. However, materials of construction for both mining and surface treatment plant are much more significant factors in view of the high temperature (60 °C) *in situ* and brine concentration (300 g l^{-1}).

In decisions regarding processing on site, the same general principles apply as for manganese nodules. Similarly, the motion produced by local sea and weather conditions will also interfere with the separation behaviour of the particles which in this case is likely to be by froth flotation. Briefly, this involves selective preconditioning of the particles with surface active reagents in an aqueous slurry and agitation of the pulp, which at the same time induces air as finely dispersed bubbles. The addition of a frothing agent enables the fine mineral particles which rise to the surface attached to the bubbles to be skimmed off by means of a rotating paddle.

Shipboard motion in varying degrees of severity will produce a number of effects on these processes:

(i) Angular motion will reduce the effective volume of the flotation cell due to overspill as the cell is tilted towards the discharge lip. Thus the throughput on a commercial scale will also be reduced for a given size of plant.

(ii) Removal of froth is likely to be less uniform due to the flow of froth towards or away from the discharge lip as illustrated in figure 10, plate 3.

(iii) Directional orientation of the discharge flow should therefore be in the same direction as that of the minimum motion in the prevailing sea state.

(iv) Increased froth volumes can adversely affect the grade and recovery of mineral values in the concentrate.

(v) The speed of the paddle should ideally be arranged to avoid coincident phase relations with the frequency of the predominant wave motion.

(vi) The interaction of heave motion and slamming may also affect performance.

(*c*) *Materials handling and transportation*

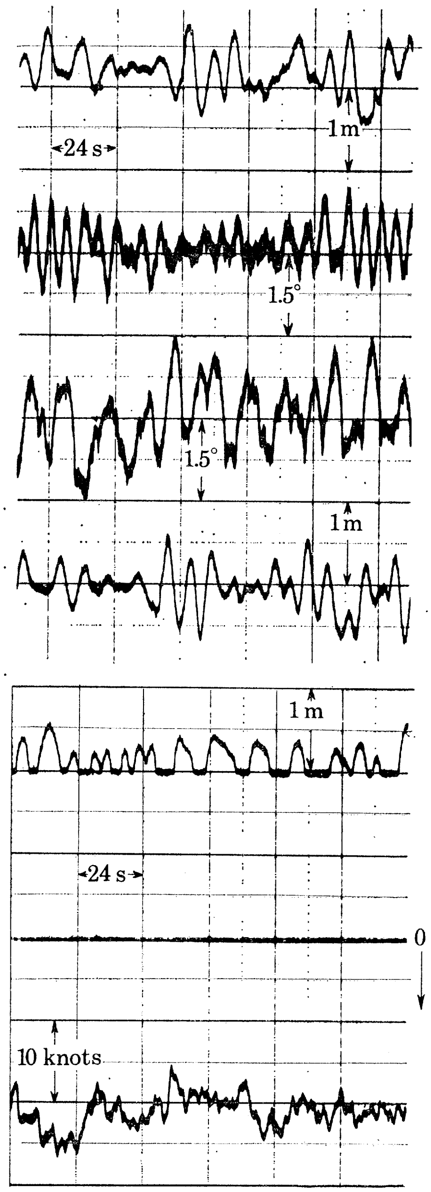
The same general principles and requirements apply as discussed for manganese nodules. However, if a concentration step is carried out at the mining site, the transportation operations will be on a much smaller scale.

Present and future research

In order to investigate the effects of motion on the various processing and other operations likely to be carried out at sea, the first requirements, as part of a research programme at Warren Spring Laboratory, were clearly to have the ability to monitor the sea-board motion of dredging, mining and other types of workships over the full range of operating conditions and then to reproduce them on land-based ship's motion simulators. Thus it would be possible to conduct investigations on how equipment and process behaviour was affected, not only over a range of conditions of varying severity, but also by individual motions, e.g. roll, pitch, heave, etc.

(*a*) *Monitoring and simulation of a ship's motion*

Successive sea trials have led to the progressive development of ship's motion monitoring equipment to meet these special requirements. In addition, a recently developed system allows for submersible applications, providing similar outputs to a depth of 200 m at a maximum cable length, at present, of 400 m. In both these systems, the results produced can be immediately displayed on board ship as well as being recorded for detailed examination when the sea trials have been completed.



channel	mean	r.m.s.	max.	min.
1: heave/m	−0.11	0.26	0.58	−1.22
2: heave acceleration/g	—	—	1.09	0.91
3: roll/deg	5.40	0.57	7.06	4.03
4: pitch/deg	3.21	0.42	4.50	1.56
5: sway/m	−0.07	0.21	0.40	−1.06
6: sway acceleration/g	—	—	0.05	−0.06
8: surge/m	−0.16	0.32	0.50	−1.00
9: surge acceleration/g	—	—	0.12	−0.15
10: wind speed/knot	20.41	2.48	28.78	13.69

Figure 11. Typical set of recordings taken on board a drillship.

Measurements are made of roll, pitch, heave, sway and surge. These, together with wind speed, direction and any commentary that is required, are recorded on magnetic tape. A typical set of recordings taken on board a drillship are shown in figure 11.

Three ship's motion simulators, also developed at various stages of the programme to meet particular requirements, are now available for equipment and process testing. The largest and most recent one, which has a heave displacement of 3.7 m, with a payload of 1.5 t, as well as roll and pitch motions, is illustrated in figure 12, plate 4. Both facilities are described in greater detail elsewhere (Warren Spring Laboratory 1977), but their principal specifications are given in table 2.

TABLE 2. SHIP'S MOTION MONITORING AND SIMULATION FACILITIES

Description of facility
ship's motion monitoring systems
capability of monitoring and recording angles of roll and pitch; vertical, lateral, fore-and-aft accelerations and displacements, also vibration
basic specification:
roll and pitch range of ± 25° to an accuracy of ± 1 %;
heave range of ± 15 m to an accuracy of ± 5 %;
sway range of ± 15 m to an accuracy of ± 10 %
(all of which can be measured over the frequency range of 5–25 s)
vibration can also be measured.
ship's motion simulation facilities
capability:
1. (*a*) Up to 1.2 m heave
(*b*) Up to 15° out-to-out angles of roll and pitch
(*c*) Payload 200 kg
2. (*a*) Up to 1 m heave
(*b*) Up to 25° out-to-out angles of roll
(*c*) Up to 12° out-to-out angles of pitch
(*d*) Up to 6° out-to-out angles of yaw
(*e*) Payload 1 t
3. (*a*) Up to 3.7 m heave
(*b*) Up to 16° out-to-out angles of roll
(*c*) Up to 16° out-to-out angles of pitch
(*d*) Payload 1.5 t

(*b*) *Research applications*

Up to the present, a wide range of investigations have been carried out in relation to the exploitation and transportation of minerals from the continental shelf and from the deep seas, including various studies on mineral processes and equipment such as: sedimentation and flotation; feed and distribution systems, spiral and pinched sluice concentrators, mineral jigs; liquefaction phenomena and the behaviour of fine-grained bulk cargoes at sea; instrumentation and other equipment for the offshore oil industry.

(*c*) *Future research requirements*

Various problem areas and future requirements have been discussed in the preceding sections. However, in the present climate of confidentiality by the different commercial organizations involved in both continental shelf and deep-sea mining activities, it is difficult to specifically state what has been done, what is being done, or what still needs to be done. At best, from what may be regarded as common knowledge, one can only speculate on where the problem areas are likely to be.

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An attempt has been made to summarize some of these in the following list:

(i) Dredging systems for deeper water on the continental shelf. (For the deep oceans this is mainly in the hands of the various consortia involved.)

(ii) Primary underwater processing systems, size classification, gravity separation and possibly comminution if commercially exploitable hard rock deposits are discovered.

(iii) Materials of construction and design systems to withstand salinity, pressure and temperature of the deep sea environment in mechanical, electrical and control applications.

(iv) Evaluation of the effect of shipboard motion – as arising (ongoing at W.S.L.).

(v) Improved compensating systems or alternatively semisubmersibles or submersibles.

(vi) Specially designed mineral processing equipment for operation at sea such as mineral jigs, spiral concentrators and flotation cells (ongoing at W.S.L.).

(vii) Adaptation of ship-to-ship transfer systems for materials handling, as required.

(viii) Further investigations of the factors governing the behaviour of fine-grained bulk cargoes at sea (ongoing at W.S.L.).

(ix) Disposal of waste products and their effect on the environment and ecology.

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Discussion

B. White. (*Department of Mineral Resources Engineering, Royal School of Mines, Prince Consort Road, London, S.W.* 7). I should like to ask Mr Hughes to stick his neck out and make some prediction of the future of marine mining processing systems.

Although it may be easier going into deeper waters when considering oil-pollution problems (see Dr Gaskell's paper, which follows), it most certainly is not when considering mineral processing. We already have the problem of developing new technology for the mining of the nodules, etc., without even considering their processing at sea. Is there not a good case for compensating the operational environment and making use of existing processing technology rather than redesigning all the equipment?

T. H. Hughes. The design of any mineral processing plant is invariably based on previous feasibility studies of the composition, characteristics and behaviour of the constituent minerals in the ore body which has to be processed. However, in addition to the prime technological considerations, a number of other important factors such as capital and operating costs, amortization period, location and site conditions, availability of supporting resources, etc., have to be taken into account before final decisions on the design and selection of the plant are reached.

In general, I think the same broad principles would apply in the design of a concentrating plant for the exploitation of a marine mineral deposit. The use of a compensating system or alternatively redesigned equipment for a particular deposit would be an additional factor for consideration with all the others. Certainly, technology exists for compensating systems or could readily be developed as, for example, from the advanced designs for gun or rocket launching platforms used at sea, to very simple systems tested at W.S.L. (Hughes 1973) for pinched sluice concentrators and subsequently for spiral concentrators. Such systems would need to be evaluated during the feasibility studies.

Therefore, at present it is not possible to advocate one method of approach or the other. However, further studies of the effects of ship-board motion on the various processing operations, leading to new designs of equipment which will operate more effectively in a marine environment than existing types, would enable decisions on final plant design to be reached more conclusively.

Reference

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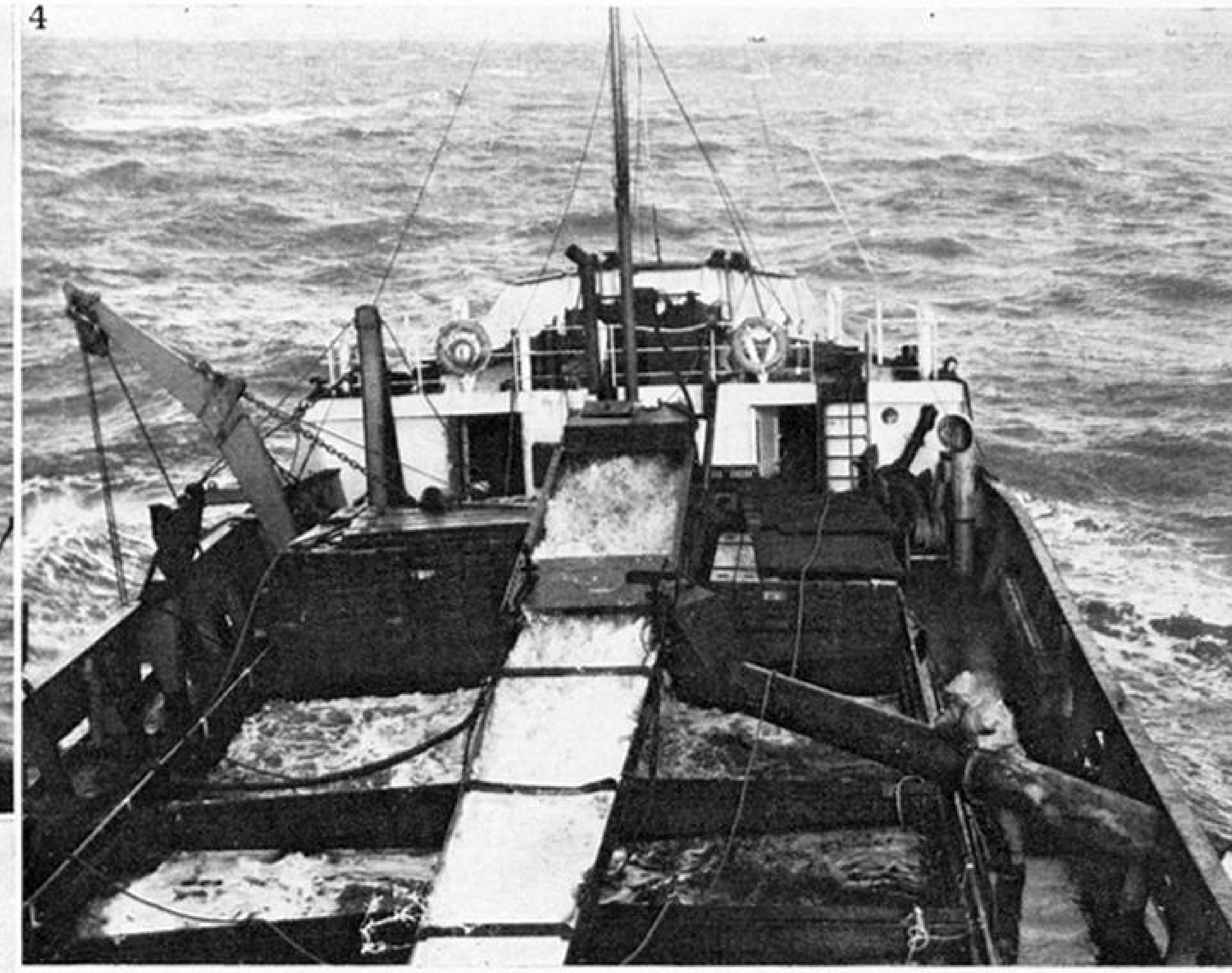

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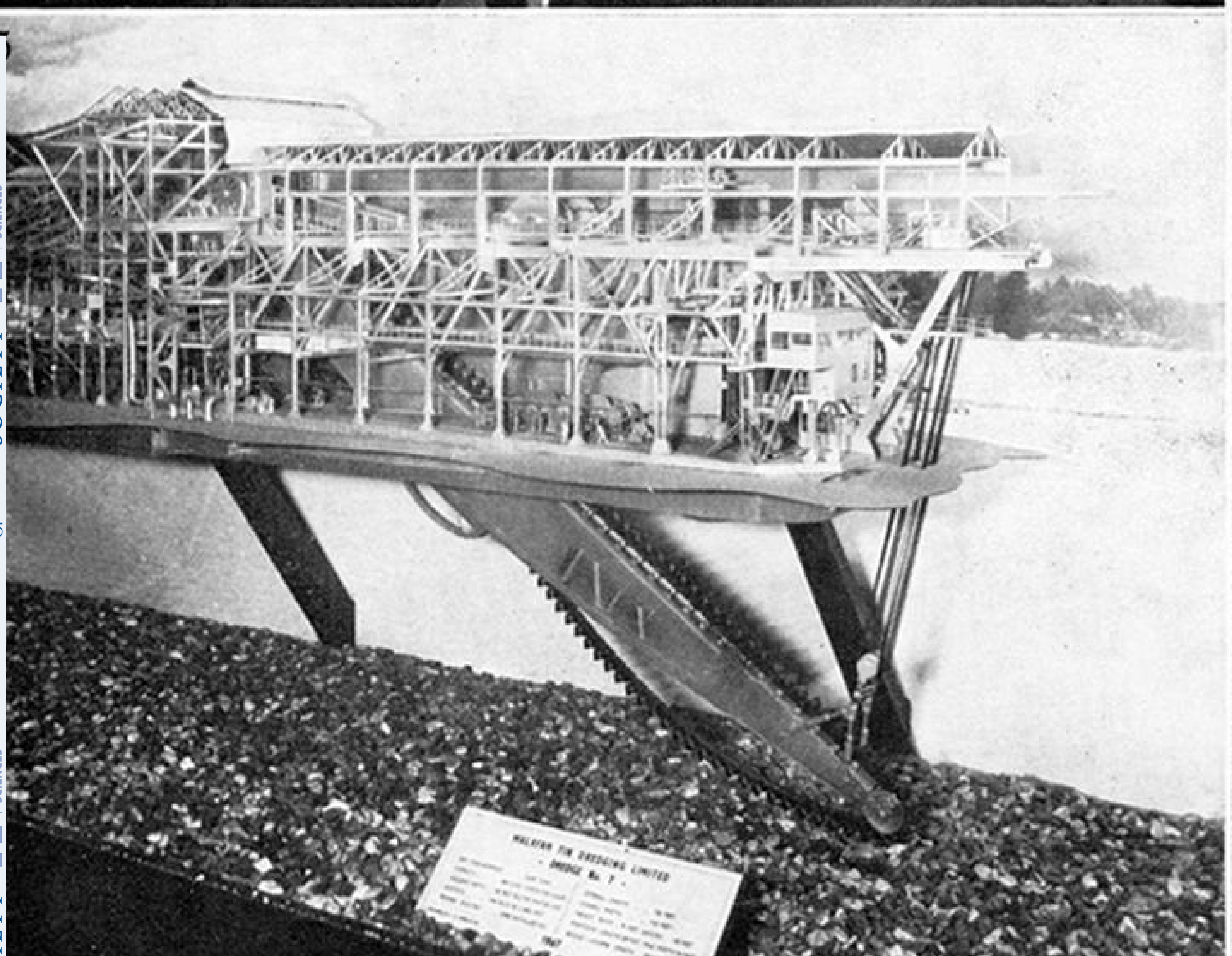

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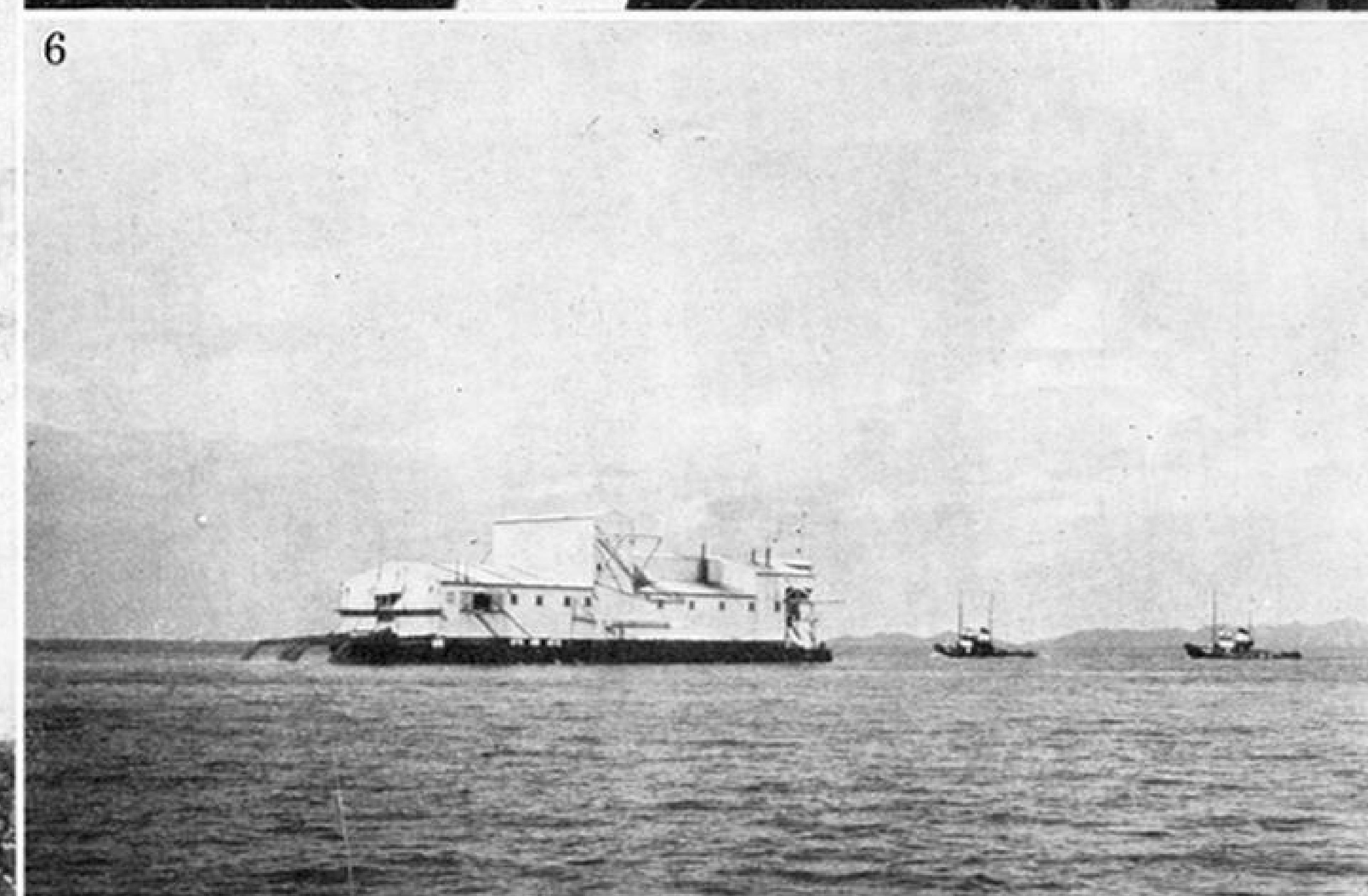

FIGURE 2. Sand and gravel dredger operating in rough seas.
FIGURE 4. Screening plant on board a sand and gravel dredger.
FIGURE 5. Sectional model of a tin dredge.
FIGURE 6. Tin dredge in an offshore operation.

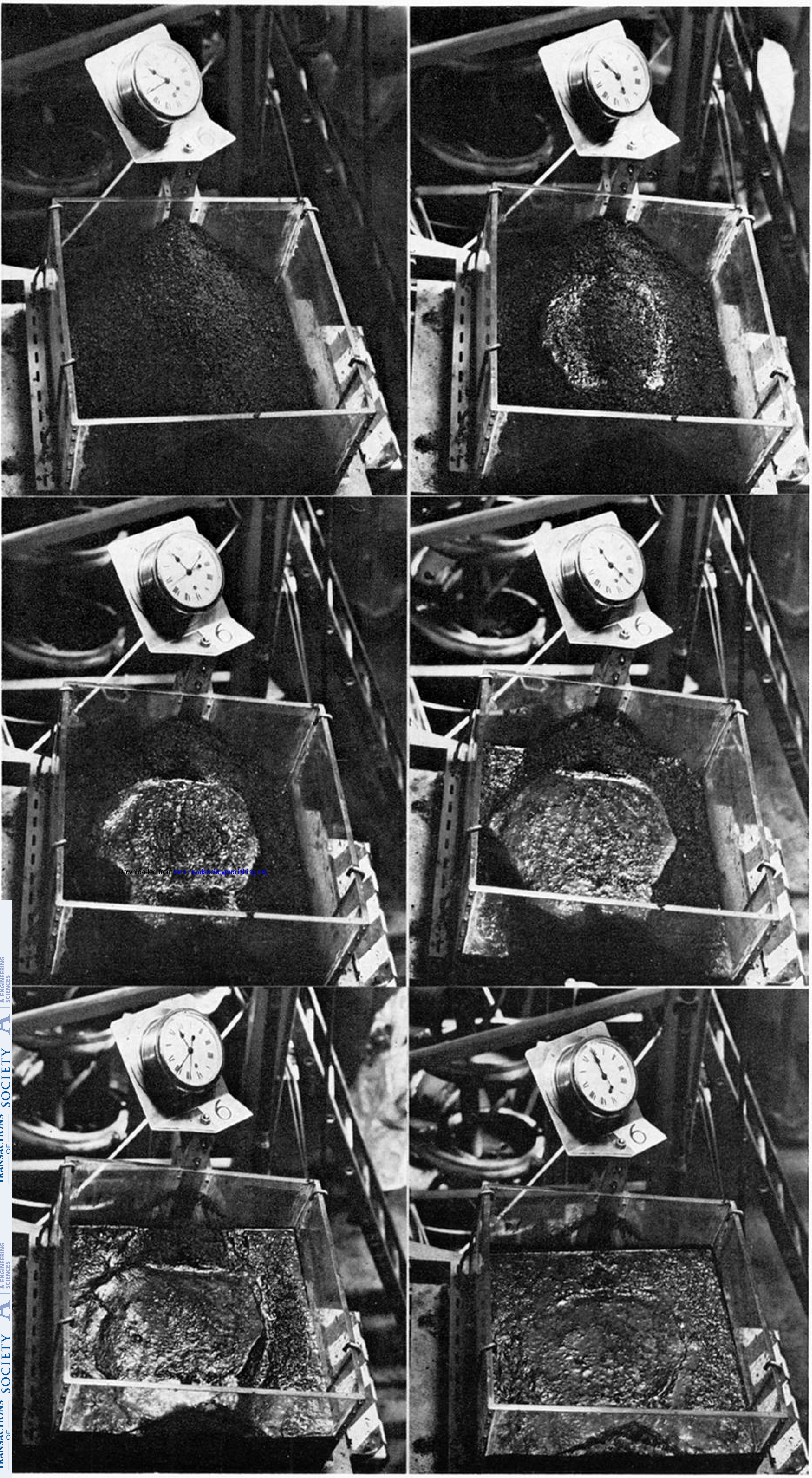

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FIGURE 7. Illustration of cargo liquefaction originating from the centre.

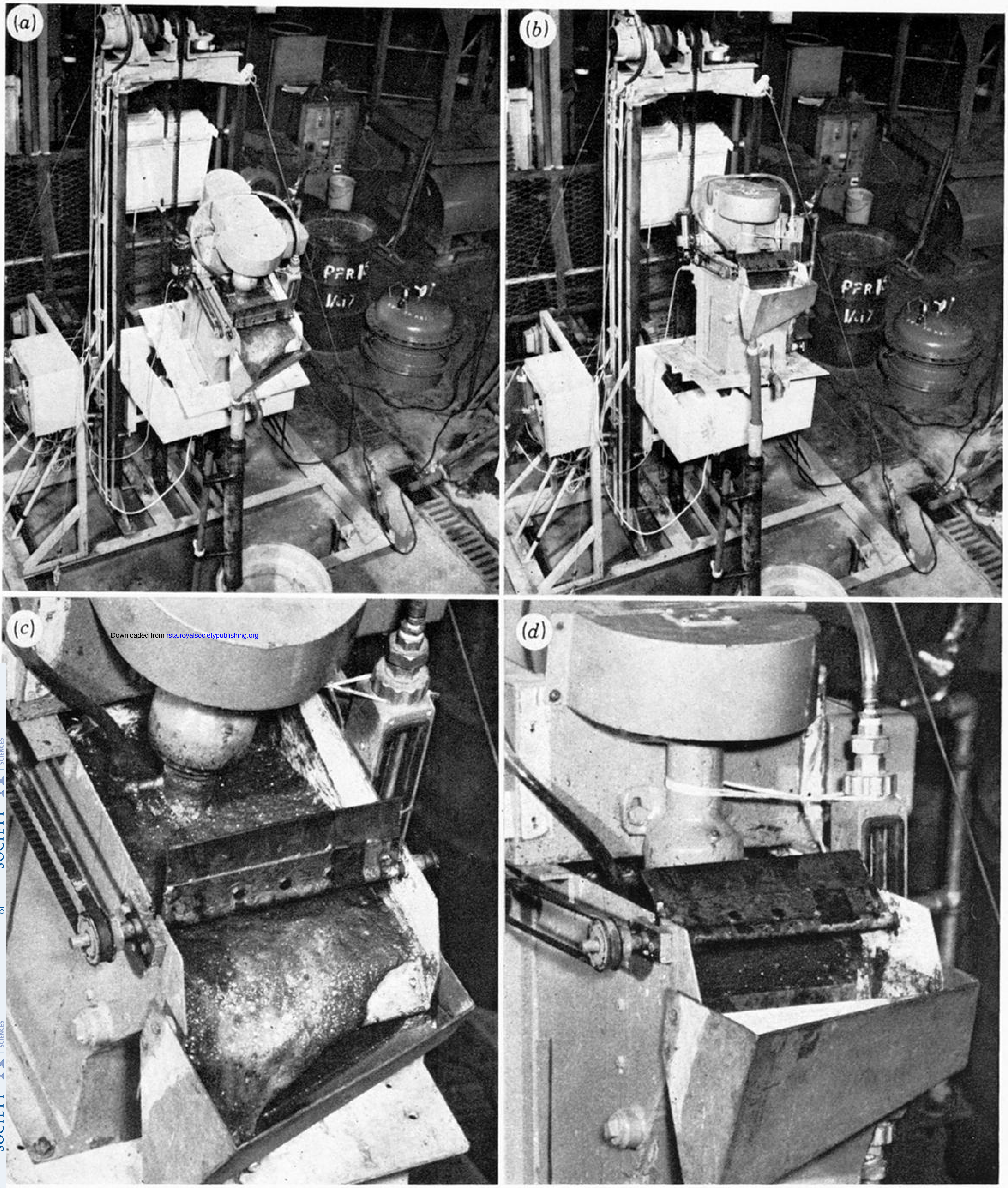

FIGURE 10. Flotation tests on ship's motion simulator, with froth discharge in line with maximum roll motion. (*a*, *b*) Simulator in two attitudes of angular motion; (*c*) overspill with cell tilted forwards; (*d*) no discharge with cell tilted backwards.

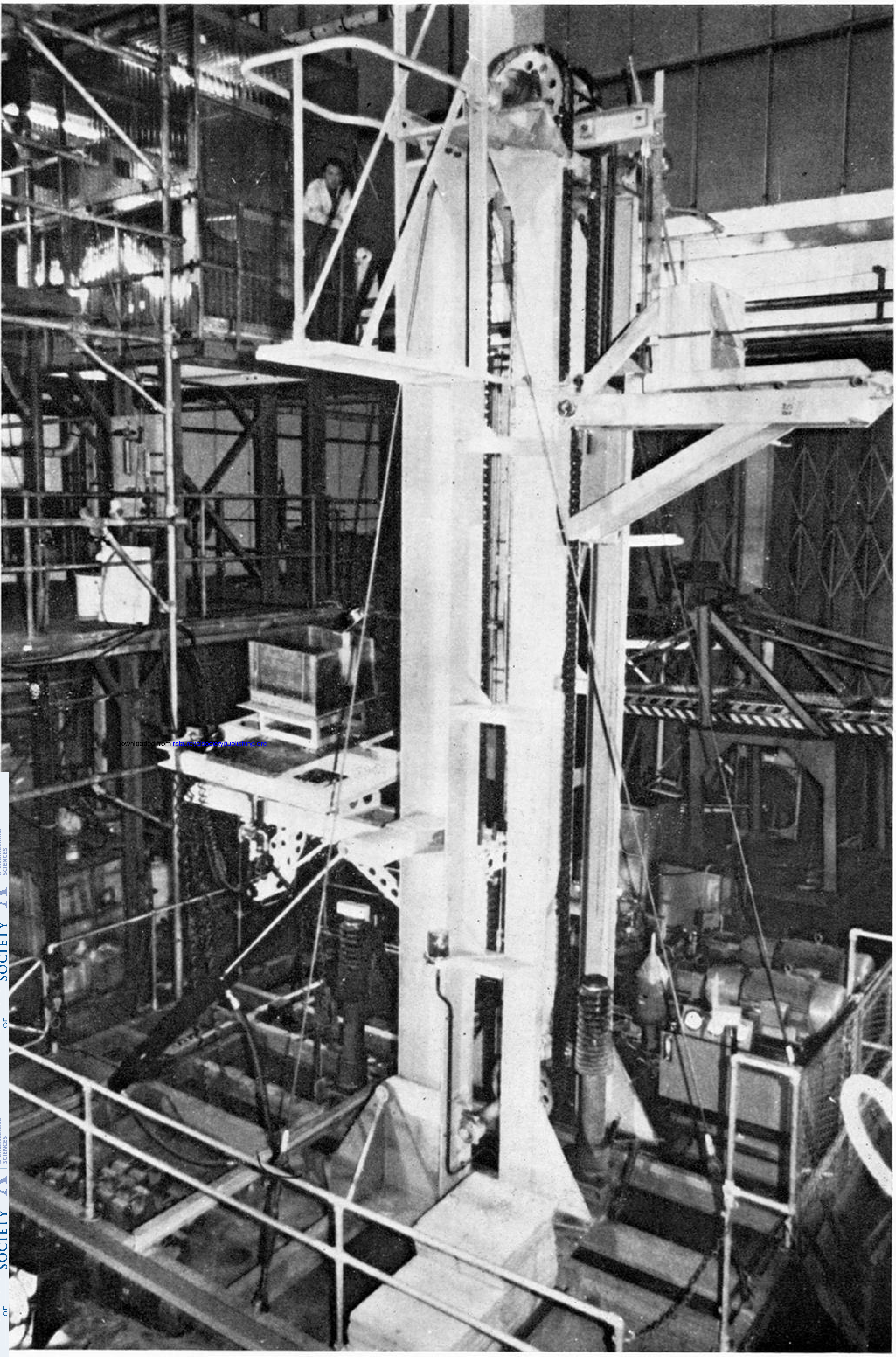

FIGURE 12. Cargo stability testing on largest simulator platform.

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