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BEHAVIOUR OF DAMP FINE-GRAINED BULK MINERAL CARGOES

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Behaviour of Damp Fine-grained Bulk Mineral Cargoes

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SYNOPSIS

The result of sliding 'liquefaction' instabilities in bulk cargoes can be catastrophic. A research programme, with the aims of understanding liquefaction in ships, developing a universally applicable test for the identification of potentially hazardous cargoes, and considering means of making dangerous cargoes safe, is in hand at Warren Spring Laboratory. Experiments on ships' motion simulators have shown that flow can occur when cargoes are less than fully saturated. Individual parameters are examined in small-scale experiments, the results of which are compared with existing hazard identification tests and the simulator experiments.

INTRODUCTION

Bulk mineral cargoes are generally concentrates, valuable minerals separated from ores at or near the mines, prior to shipment to smelters or refiners. The majority of mineral separation processes involve the use of water and grinding, and the concentrates produced are therefore damp, particulate materials.

During shipment these materials can undergo a 'dry' shift of cargo; or liquefaction, in which the damp cargo becomes temporarily able to flow like a liquid. That such failures do occur, and that they can be dangerous, can be shown by examination of the casualty statistics, the findings of inquiries into specific losses and, more rarely, by reports from ships that have reached safety although cargo failure is known to have occurred.

This paper is concerned primarily with the phenomenon of liquefaction, and much of its content is derived from the research programme at Warren Spring Laboratory (WSL). The objectives of this programme are threefold:

(i) to achieve a fuller understanding of the phenomenon of liquefaction in bulk mineral cargoes;

(ii) the identification of potentially hazardous cargoes, and

(iii) to develop methods for stabilizing such cargoes.

BACKGROUND AND CASE HISTORIES

It is clear from the large and increasing tonnages of bulk minerals that are shipped around the world that the overwhelming majority of voyages are made safely. However, records[1] show that of 46 Scandinavian ships lost between 1907 and 1956 other than in war incidents, 11 were carrying ore concentrates. A more recent survey[2] compiled from Lloyd's Register of Shipping showed that 61 out of 305 ships foundering between 1964 and 1974 were carrying ore, while a further 36 were carrying coal (Table I).

These statistics do not indicate the cause of each of these losses, although Scandinavian records do suggest that movement of the cargo occurred in eight of the 11 cases quoted. That is not to say that liquefaction occurred in all cases, although it was reported that almost all of the cargoes were relatively wet.

The first of the case histories to be considered also comes from the Scandinavian records, although this vessel was not lost. ss *Aquilla* returned to harbour in 1910 after her cargo of 1918 tonnes of iron concentrate liquefied and caused a list. An eye witness account reported 'A thin mud puddle formed on which the rest of the cargo floated .... The cargo moved independently of the vessel. When the ship rolled, the concentrate rose to the deck and remained there'. The twofold change, from damp particulate solid to flowing sludge to restabilized solid, is an important aspect of liquefaction.

The next case history is that of *Burtonia,*[3] which sank off the Suffolk coast in November 1972. The Court of Inquiry into her loss attributed her foundering to the shifting of her cargo of 558 tons damp lead concentrate. Expert witnesses said that they considered the failure of the cargo was caused by the effect of the ships' motion and vibration on the strength of the wet cargo: that is, that liquefaction occurred. One of the experts also said that other vessels had probably been lost because of cargo liquefaction although the official attributions were to 'ingress of water'; he particularly referred to the case of *Traquair,* which was carrying coal slurry which 'changed consistency'.

The Court recommended that the Department of Trade initiate a research programme to establish the laboratory test procedure most suitable for identifying potentially hazardous bulk mineral cargoes. This is the programme carried out on behalf of the Department of Trade by WSL.

In January 1975, *Lovat*[4] sank off the Lizard when her cargo of 1334 tons washed anthracite duff shifted in heavy weather because it liquefied under the influence of ships' motions and vibrations. WSL was involved in test work on samples of material similar to the *Lovat'*s cargo in the course of the investigation into her loss. This makes an obvious point: in cases where a ship sinks, knowledge of the *actual* condition of her cargo is dependent upon any sampling, measurement or observations made before her last voyage started. Any changes in the appearance or behaviour of the cargo may not be observed or reported because of the loss of the vessel, and perhaps the loss of her crew.

One case that is almost unique because of the amount of information available involved a British ship[5] carrying lead and zinc concentrates from Sweden to Belgium in January 1977 (total cargo weight 2200 tons—1250 zinc, 950 lead). While she was in the North Sea, some 30 hours after departure, weather conditions were poor with rough seas and Force 7 winds; the ship began to roll and pitch heavily, and eventually developed a list to starboard (35 hours). The captain decided to examine the cargo and found that about 40% of the

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J.M. Kirby read geology at Nottingham University, and then researched the geotechnical characteristics of colliery tailings for his thesis at Durham University. After a further year as a lecturer in soil mechanics at Durham, he joined the Mineral Processing Division at Warren Spring Laboratory as part of the team looking at cargo stability.

Table I: Ships that foundered while carrying bulk cargo, July 1964–June 1974

CARGO GROUPINGS		TOTAL BY MONTH	
Ore	61	July	18
Coal	36	August	14
Scrap	18	September	24
Miscellaneous	190	October	30
		November	35
Total	305	December	34
		January	49
		February	26
		March	27
		April	18
		May	10
		June	20
		Total	305

Miscellaneous bulk cargoes include: cement, cereals, chalk, clay, copra, earth, fertilizer, graphite, limestone, marble, phosphates, potash, pumice stone, salt, sand, stone, sugar and urea.

Table II: Moisture contents relating to cargo of lead and zinc concentrates in a British ship (%)

	ACTUAL CONTENT AFTER VOYAGE	STATED CONTENT BEFORE VOYAGE	TRANSPORTABLE MOISTURE LIMIT
Lead concentrate	10	8.8	8.9
Zinc concentrate	14.6	11.7	12.6

lead cargo had liquefied at the forward end of the heap of concentrates, and was moving 'like lava'. Attempts to remove water from the cargo by the bilge pumps were unsuccessful.

The list was counteracted by ballasting double bottom tanks but, in view of forecasts of continued heavy weather, the captain decided to divert to the nearest port (150 miles away). A second list developed before safe harbour was reached, this time to the port side, and inspection showed that the cargo had flowed to port. Again ballasting counter-balanced the list successfully and the ship made harbour safely.

Inspection of the hold in port showed that the liquefied section of the lead cargo was level and apparently covered with water, while the remainder of the cargo looked as it had when loaded. By the time pumps were brought to remove the surface water (some 30 min to 1 hour) the water had drained back into the cargo, leaving a flat solid surface. Samples of the cargo were taken and tests showed that the moisture contents were higher than those stated before loading, and higher than the transportable moisture limits for the materials derived from flow table tests (see Table II).

The last case history is the exception in that liquefaction was not involved. The most recently completed inquiry, in which WSL participated, was that into the loss of *Pool Fisher,*[6] a small vessel carrying 1250 tons KCl (potassium chloride for the fertilizer industry) from Germany to Runcorn, which sank off the Isle of Wight in November 1979. In this case the cargo was highly soluble and also tended to absorb water from the atmosphere and 'cake' — two properties which added an extra dimension to the experimental work — but the Court found that the foundering of the ship was not caused by cargo movement, although some slight settling or sliding of the dry cargo early in the voyage might have occurred.

All the cases which have been described so far have involved fairly small vessels with cargoes of between 550 tonnes and 2200 tonnes, probably loaded into one or two holds. There has not, to our knowledge, been a case in which the foundering of a large bulk ore carrier of say 50 – 170 000 dwt has been attributed to instability of its cargo due to either sliding or liquefaction.

Some systems load the ship with cargo in the form of a slurry, i.e. at a high moisture content. As will be shown, such cargoes would normally be considered as potentially liquefiable and therefore a danger to the stability of the ship. Vessels incorporating such systems should be designed to be stable with a slurried cargo.[7] Certainly, no untoward incident involving these ships has come to the authors' attention.

THEORETICAL BACKGROUND

Bulk mineral cargoes comprise solid particles with both air and water in the void spaces between them. The relative proportions will vary from cargo to cargo. As will be shown, the proportion of water, in particular, is of great importance. A cargo is described as dry if the void space contains air only, saturated if it contains water only and partly saturated or unsaturated if it contains both. With the exceptions of systems that load the cargo into the ship's hold as a slurry, most cargoes are loaded in an unsaturated condition.

Once loaded, each element of cargo will experience a stress due to the weight of any superincumbent cargo. However, this stress will continually alter as the cargo is accelerated by the heave and engine vibrations of the ship, and also by the rolling and pitching. When circumstances conspire, a damp particulate solid, acted upon by a continually altering stress, can undergo a change described as liquefaction; the material changes to a liquid, albeit a dense, viscous liquid, and is capable of flow.

Liquefaction of cargoes in particular, and unsaturated particulate media in general, have not received a great deal of attention. The shear strength and compressional behaviour of unsaturated materials under constant or monotonically increasing stress has been extensively studied in chemical engineering[8] and soil mechanics.[9,10]

The response, including liquefaction, of saturated materials to oscillating stresses has been extensively studied in earthquake and offshore engineering. Earthquakes produce short, sharp oscillating stresses which have caused foundations and earthfill dams to liquefy.[11] The foundations of offshore structures (such as gravity platforms) are subjected to oscillating stresses due to wave action; here the duration of large variations in stress during storms is longer, and has a slower build-up and lower frequency. The cargo problem incorporates elements from all these related areas.

In discussing the behaviour of unsaturated particulate materials, a useful starting point is the Proctor compaction curve. Compaction is a term used in soil mechanics to denote the densification of a soil by the expulsion of air. Conventionally, the process is viewed in terms of a graph of the dry density achieved by tamping material into a mould, plotted against the moisture content, for a given compactive effort.

A relationship similar to the curve AOB in Fig. 1 usually results; a maximum dry density is achieved at the optimum moisture content. The explanation for this curve is that, at low moisture contents, the water forms small menisci at grain contacts; surface tension results in considerable suction pressures which increase the strength of the mass, so that it resists the tamping. As the moisture content increases, the average radius of the menisci increases, suction pressures and hence strength are lost; it is common experience that slightly damp sand forms the strongest sandcastles. As the damp sample is less resistant to tamping, the density increases. At the optimum moisture content, the air channels become discontinuous, air can no longer be expelled and the density decreases as more water is added.

By plotting lines of equal saturation (Fig. 1) it can be shown that the optimum point occurs at less than full saturation. The optimum point moves from O towards D with increased compactive effort. Materials that comprise grains all of one size display flat curves with ill-defined optimum points, due to the small difference between the loosest and densest packing which may be attained in such a material.

Turning to liquefaction, the explanation is provided by considering the following hypothetical experiment. The box shown in Fig.

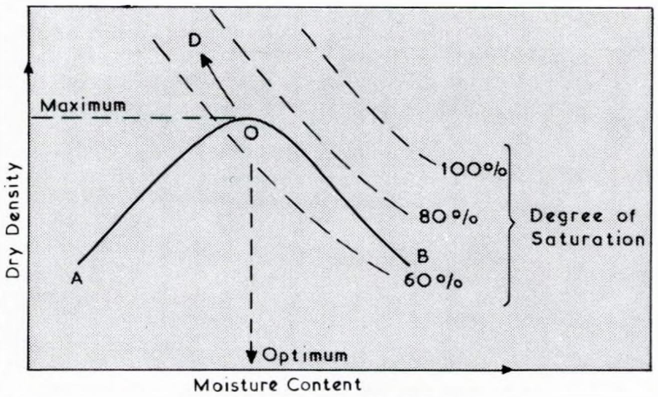
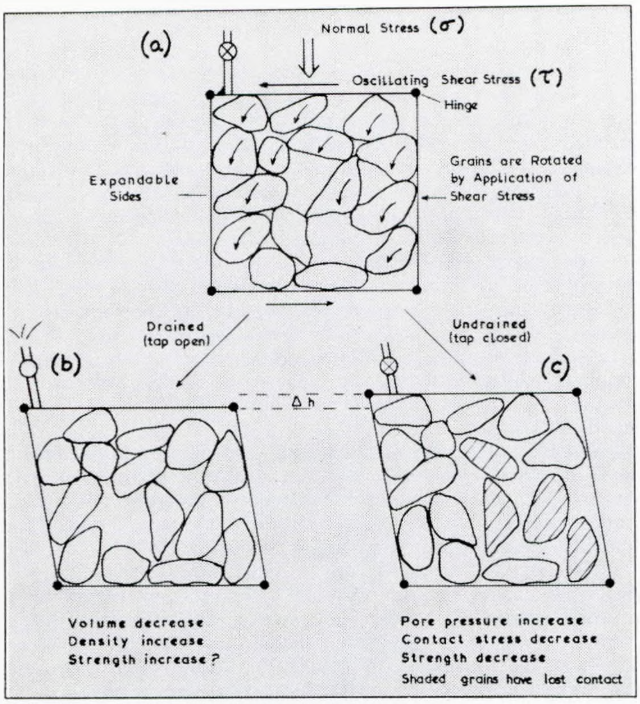


FIG 1 **Compaction curve**



Δh = Reduction in height of cube with drain tap open

FIG 2 Hypothetical shear experiment

2(a) is hinged at the corners and can therefore deform into a parallelogram; the two vertical sides can expand or contract; water may escape through the tap if allowed. In the box is a saturated particulate solid; a normal stress (σ) is applied to the top. When the oscillating shear (τ) is applied, continual small rotations and slippage causes a rearrangement of the grains into a denser packing.

If the tap is open, then water is forced out, the box collapses slightly by Δh per side, and a denser material results as shown in Fig. 2(b). If, however, the tap is closed, the box cannot collapse as it is prevented from so doing by the incompressible water, the pressure of which rises in response. By rearrangement, the grains lose contact and thus little stress is now transmitted via particle to particle contacts, Fig. 2(c). The material has the strength of a liquid rather than a solid, and will flow in response to a shear stress; liquefaction has occurred. Once the oscillating shear stress is removed, the particles will settle once more into a solid arrangement and will resist shear.

In the cargo hold, the role of the tap is taken by the material itself. A substantial proportion of fine particles will retard the flow of water (i.e. it has a low permeability) so that is behaves as in Fig. 2(c).

A saturated material, then, can liquefy if it is of sufficiently low permeability. In an unsaturated material, the air moves through the mass much more quickly than water. Figure 3 shows measurements taken at WSL of the permeability to both air and water of an iron ore concentrate at various levels of saturation. Furthermore, air is compressible and therefore the solid particles can take up a denser packing arrangement, even if they are fine enough to retard the flow of air.

Thus a cargo must be fairly saturated if it is to have the potential to liquefy. This may occur, first, if it was loaded in a very wet condition. Second, the saturation level may start at some value from which it increases due to compaction in response to the oscillating shear. Third, water may migrate downwards under the influence of gravity, causing the base of the cargo to become wetter at the expense of the upper portions. However, in very small voids, the surface tension will hold the water in place and will retard this downward flow. Thus, below a certain moisture content, termed the field capacity, the flow is insignificant because only the smallest voids are full of water.

Given that a cargo becomes saturated enough via one, or a combination, of the three routes outlined above, what are the controls on the liquefaction process? Research in earthquake and offshore engineering has indicated that a great many factors play a part.[12] It is beyond the scope of this paper to dicuss all of these, but the following may be noted.

- Very coarse materials will not liquefy because the pore water always escapes quickly and its pressure never rises. However, if there is a wide range of particle sizes present, the smaller fill the voids between larger, and the material may liquefy.
- The shape, roughness, specific gravity and surface properties may affect the process but these properties have not been well studied.
- The more compacted is a given material, the greater is its resistance to liquefaction.
- The resistance to liquefaction is directly related to the normal stress (σ in Fig. 2).
- The number of cycles required to liquefy a given sample is inversely proportional to the oscillating shear stress. The frequency is usually regarded as relatively unimportant.
- Laboratory tests, such as shear tests simulating Fig. 2, are affected drastically by experimental procedures; for instance, the method of introducing the sample into the shear box can radically affect the results of the test. This is a major difficulty in this field of investigation.
- The few studies on unsaturated materials reach contradictory conclusions. Chaney[13] finds that a small drop in saturation (to below 99%) in the sample markedly increases the resistance to liquefaction. At WSL, on the other hand, it is frequently observed that flow readily occurs at saturation levels as low as 70%.

Liquefaction is not the only mechanism by which cargo can move in the hold. A slope can be formed of a particulate material only below a certain limiting height or slope angle. A slope that exceeds these limits will fail along a preferred surface, with the material on either side remaining as a coherent mass. In a ship's hold, the cargo may be trimmed to be apparently safe, but it must be remembered that rolling will increase the slope. Furthermore, the reduction in strength experienced during the liquefaction process may cause a slope to fail at a low angle of roll, before a state of general liquefaction develops, indeed without liquefaction actually occurring.

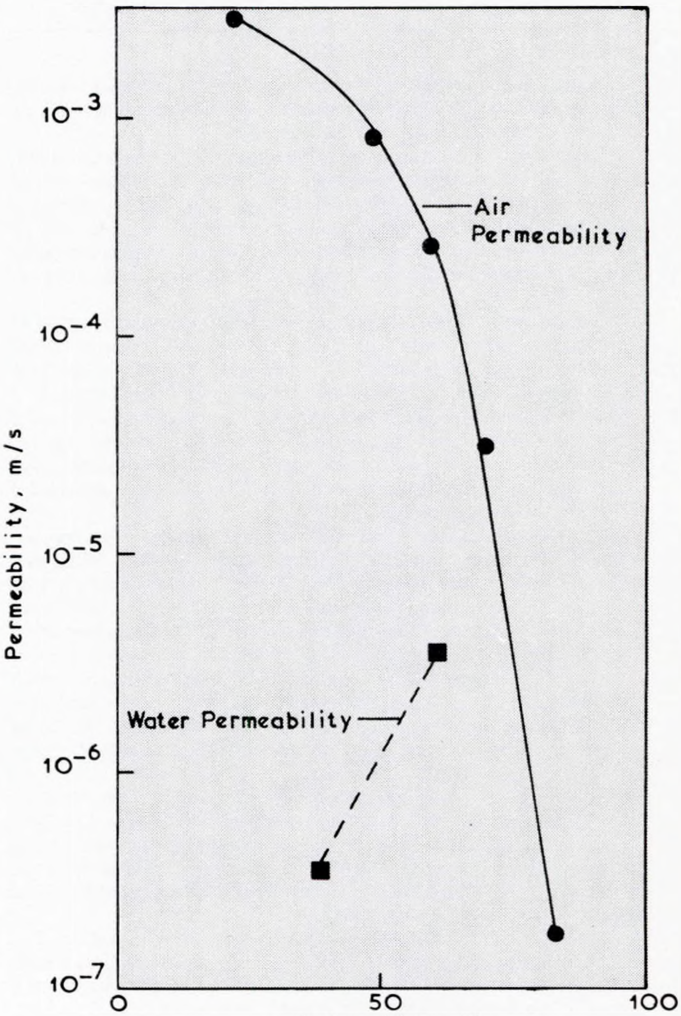


FIG 3 Permeability to air and water of iron ore concentrate at various levels of saturation

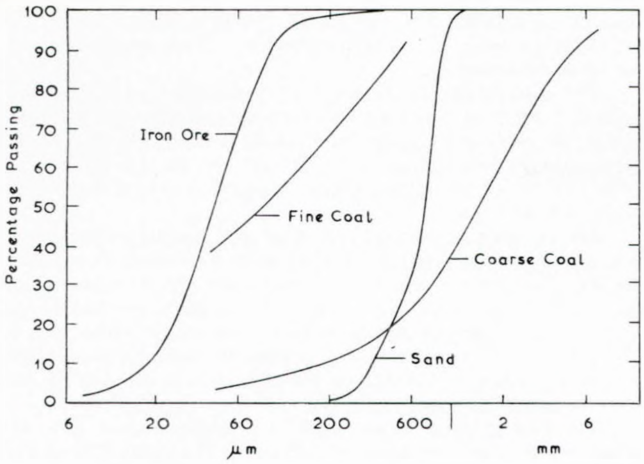


FIG 4 **Particle size distributions of the four materials**

Table III: Index properties, flow properties and field capacities for four materials

	SAND	IRON CONCENTRATE	COARSE COAL	FINE COAL
Specific gravity	2.65	5.21	1.47	1.37
Optimum moisture content (% wet weight)	—[a]	12.5	15.5	25.0
Maximum dry density (tonne/m^3)	—[a]	2.52	0.95	0.81
Flow moisture point (% wet weight)	—[a]	11.4 (dense) 12.2 (medium) 13.1 (loose)	13–17[b]	23.7–24.8
Simulator flow level (% wet weight)	ND	13.5–14.0	ND	ND
Field capacity (% wet weight)	3	4	6.5	21

[a] This uniform grain sized sand does not produce a result in either of these tests.
[b] The coarse coal does not produce a good result in this test.
ND = Not determined.

Ultimately it will be necessary to determine the effect that cargo liquefaction or slope instability is likely to have on the ship. For an individual ship, determining the angle of heel due to a shift in the cargo by slope failure is not difficult. For a liquefied cargo, matters are more complex. First, the free surface effect of a dense liquid in the hold must be taken into account; the density of damp iron concentrates may approach 3 tonne/m^3. Second, the roll of the ship may be adversely affected by the movement of the cargo. Third, liquefaction is a reversible process; the cargo may resolidify and it is sensible to consider the worst case in which the cargo resolidifies with a horizontal surface at an extreme of roll.

To analyse fully these effects would require an assessment of each ship and cargo as an individual case, which clearly is not feasible. Rather it is in the search for comparisons between ships that such analyses are worthwhile, for instance, in determining whether certain types of ship are in more danger than others. It should be noted in this context that suggestions have been made for certain residual stability requirements, assuming a shifted cargo, if a ship is to transport a cargo that could liquefy.[14] Assessing the stability of ships is beyond the scope of the research at WSL.

BEHAVIOUR OF UNSATURATED CARGO

Material characterization

In the previous section it was pointed out that many factors affect the liquefaction process. As a matter of course, therefore, all materials tested at WSL are first indexed by results of various tests. The specific gravity and size distribution are determined; the moisture content/density relationship is measured by a modified Proctor compaction test, the method 'c' of Fagerberg;[15] the flow moisture point is measured by the IMCO flow table test (see below). Four materials are currently being studied in greater detail, these being a sand, an iron concentrate, a coarse coal and a fine coal. The size distributions of these materials are given in Fig. 4, and other index properties are given in Table III.

Surface properties

Among the group of material properties which affect the liquefaction process, the surface characteristics of mineral concentrates deserve special mention. Different minerals have different natural characteristics: the variation in shape, roughness and surface properties have already been mentioned. Coal stands out in that it is naturally hydrophobic whereas most minerals are hydrophilic. (Coal is also very porous which sets it even further apart from most metalliferous ore minerals.)

However, mineral separation is frequently achieved by flotation, in which the valuable mineral is treated by reagents to make it hydrophobic so that it will rise to the surface froth with air bubbles while hydrophilic, wetted gangue minerals sink. This process is widely used in separating sulphide ore minerals (galena for lead and sphalerite for zinc for instance) from gangue, whereas iron oxides (haematite, magnetite) and tin oxide (cassiterite) are frequently separated by gravity techniques, allowing the high density ore minerals to settle differentially from the gangue from pulp streams passing over equipment such as spirals or vibrating tables.

Some preliminary experiments have been done at WSL to investigate the effect of conditioning the grain surfaces of an iron ore, normally hydrophilic, with reagents to make them hydrophobic, and then carrying out compaction or flow table tests. This series of experiments was not conclusive but one reagent did have the effect of increasing the maximum dry density, although the optimum moisture content was the same as for the untreated material. Further experiments in this area are included in the programme but have yet to be carried out.

Phenomenology: simulator experiments

One of the primary reasons for the involvement of the Mineral Processing Division of WSL in research into cargo instability was that ships' motion simulators had been designed and built there in order to test mineral processing equipment for use in offshore mining. In all, the laboratory has had three simulators. One, now dismantled, could generate roll, pitch and yaw movements; the other two both generate heave, roll and pitch, but have different amplitudes of motion and payloads. All three could be fitted with vibration motors so that the combined effects of motion and vibration could be examined.

The ranges of vibration, motion and sample conditions at which liquefaction could develop on the simulator were to be established. Comparison of these ranges — especially regarding sample conditions — with those indicated as significant in characterization and index tests (the flow table and compaction tests, in particular) was an essential part of this first phase.

Shortly after the start of the research programme the loss of *Lovat* put an immediate emphasis on the need to examine the behaviour of fine-grained coal cargoes, and much of the early test work concentrated on these materials. The *Lovat* work established that more violent vibration and motion could generate liquefaction at lower moisture contents than less severe movements.

Another problem then emerged: among the coals that are shipped round the British coast some have relatively coarse particles, although predominantly fine, and these were proving not to be amenable to the flow-table test. A group of five coarse coals was examined in some depth, mainly by simulator experiments in conjunction with characterization tests. These experiments showed that all five coals would flow at moisture contents and densities that correlated closely with the 'optimum' conditions determined in the modified Proctor compaction test. However, those with either a wide size distribution or a relatively fine and single size flowed more readily or for longer than the relatively coarse single-sized samples.

Figure 5 shows the size distributions of three of the five samples: the two with distribution 'A' flowed least readily. In addition, movement stopped in the course of some tests on these two coals, and water movement through the interparticle voids could be seen. Apparently an unstable particle arrangement had changed, with movement, to a stable one.

These tests served to demonstrate that coals that were too coarse to be tested by the currently accepted method were still capable of flow at moisture contents close to significant index test values—a potentially dangerous circumstance. The coarse coal experiments also demonstrated, on a whole-sample basis, that liquefaction occurred at less than full saturation. Overall sample volumes were measured at the start and end of tests and, together with moisture content and weight of solids measurements, were used to determine the initial and final degrees of saturation. Those tests in which flow occurred showed volume reduction and an increase in saturation, although this remained below 100%; while tests in which flow did not occur showed no volume change.

In subsequent series of simulator tests in which an iron concentrate was examined, similar volume decrease and saturation increase results were recorded. However, this material's behaviour was markedly different from that of most of the coals, both fine and coarse, that had been tested. All but two coals had flowed readily under the right conditions and, once mobile, they remained in suspension, moving across the container in response to the simulator's motion.

The two single-size coarse coals and the iron concentrate, although becoming mobile, would then settle out of suspension and restabilize despite continued vibration and motion. In the case of the iron concentrate this settling out of suspension was emphasized by the fact that the solids settled to a dense mass at the base of the container while the major part of the water in the sample was left as supernatant liquor above the solids.

Small scale, specific experiments

The project is now moving into a phase in which specific material parameters are being measured directly. As a first step, the field capacity and permeability to air and water of the four selected materials are being studied in detail. The field capacity is measured by setting up a 1 m high column of the material at a uniform moisture content and leaving it for two days. If, upon dismantling the column, the moisture content is still uniform, then it is below the field capacity; if downward migration of water has occurred, then it is above.

The field capacities are given in Table III; results from samples of various densities indicate that these figures are not sensitive to density. The field capacities of the iron concentrate and two coals are well below the moisture contents at which flow can occur. Therefore, it is possible that these materials could be loaded at an apparently safe moisture content but above the field capacity; subsequent moisture migration could cause some parts of the cargo to become wet enough for flow.

However, it might be argued that the iron concentrate and coarse coal would retain little water in dockside stockpiles because of their low field capacities. Whether this is so will depend on the residence time in the stockpile, drainage arrangements, weather conditions and so on. This work is to be extended to determine the effect of vibrations on the field capacity.

Turning to the permeability of these materials, few results are at present available. For all materials the results are similar to those for the iron concentrate shown in Fig. 3. The permeability to water is extremely low when the material is fairly dry, rising exponentially as the saturation increases.

The permeability to air has been measured by a Rigden apparatus.[16] Material is tamped into a sample container and a certain volume of air forced through by a falling pressure, the time taken being inversely proportional to the permeability. The size distribution of the coarse coal necessitated a larger sample holder than is usual for the Rigden apparatus.

The variation in permeability to air with moisture content was determined at three different densities in each material; the medium density corresponds to that in the various index tests. It is clear from the results in Fig. 6 that there is a sharp fall in the air permeability at about the optimum compaction moisture content, at which flow is also possible. The moisture content at which this sharp fall takes place is inversely related to the density, which is also the case for the optimum compaction point (see Fig. 1).

The flow moisture point varies in a similar manner (c.f. the results for the iron concentrate in Table III). The association of this sharp fall in air permeability with the optimum compaction point has been noted before.[17] The association with the flow point suggests that liquefaction is possible at the optimum compaction moisture content or above, because the air can no longer escape; the material response to an oscillating load becomes similar to that of a fully saturated material. The next phase of the work will be to test this proposition with shear experiments of the type depicted in Fig. 2.

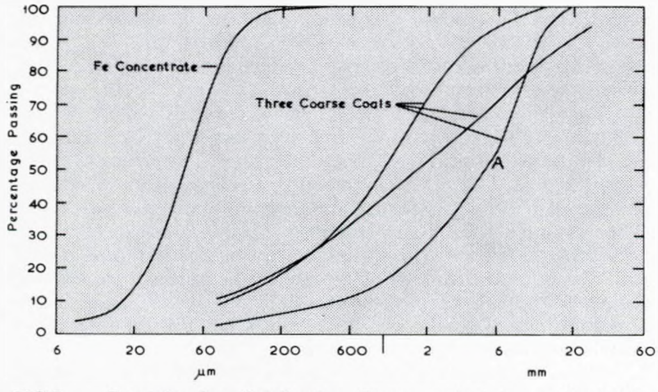


FIG 5 Particle size distribution. Some materials used in WSL experiments

Hazard identification tests

The practical objective of the research programme is the development of a universally acceptable and applicable test, able to identify potentially hazardous cargoes. This could be achieved, once the parameters to be measured are known, either by inventing a new test method, or by modifying one currently in use. A fairly detailed review of some of the methods in use is given by Green and Hughes.[2] In summary, the most widely recognized is that recommended in the IMCO Code of Safe Practice for Solid Bulk Cargoes,[18] the flow-table test. In this a sample is compacted into a mould, the mould is removed, the sample and its supporting table are dropped repeatedly through 0.5 in (12.7 mm) 25 times per minute. While the moisture content of the sample is below the flow point, the sample cracks and crumbles when the table is dropped.

The procedure is repeated with samples with increasing moisture contents, until flow deformation occurs instead of crumbling. The flow moisture point is taken as the mean of highest moisture content at which no flow occurs and that at which flow just occurs. A factor of safety is applied and the material is deemed safe for transportation at 90% of the flow moisture point.

Alternative tests are either modifications of this, such as the Norwegian flow-table test in which the number of drops of the table is correlated with the amount of movement developed by the sample; or they are based on the compaction test used in civil engineering practice. One modified version of this test was developed in Sweden, and is adopted as the standard method of testing cargoes there. Another modification has been suggested in Canada, in which fewer drops of the tamper are used to compact the sample; but, although this has been submitted to IMCO for consideration, it has not been widely adopted.

All of these methods have some advantages to recommend them, and some disadvantages, but while all are empirically derived, usually from other fields of engineering, it is not surprising that each country adopts the test which seems most applicable to the materials handled there. Until a test emerges which can be universally applied, and which is known to be based on a scientific understanding of the potential hazard, it is unlikely that all countries will adopt a single test.

REVIEW

The research which has been presented in this paper is concerned with a hazard which occurs in only a very small percentage of the total number of voyages involving mineral cargoes. However, it seems that when it does arise it can have catastrophic effects: of the cases quoted in which liquefaction occurred, only two returned to harbour. The work has therefore caught the attention of several interested groups.

The various authorities, both national (Department of Trade) and international (IMCO), that advise on, and regulate, the shipment of mineral products are concerned to be helpful and that regulations

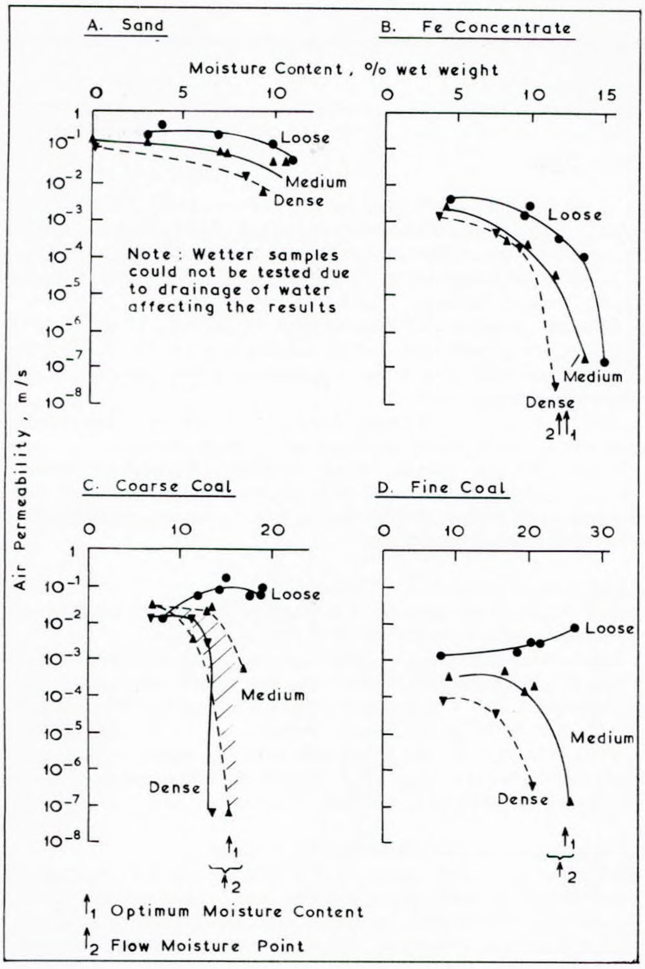


FIG 6 **Variation with moisture content of the air permeability of the four materials**

should be justified and not unnecessarily restrictive. The mineral producers and buyers clearly want to ensure the safe arrival of each cargo at its destination but are concerned to keep costs down wherever possible. The shipping companies have to meet the requirements of the regulating authorities and to ensure safe voyages. They are themselves able to advise on the practicalities of any advice and regulations.

These various groups have generated pressure for the research programme. In turn, the research scientists themselves find they need to draw on existing experience and knowledge in several fields.

Those of earthquake and offshore engineering have already been mentioned as specific aspects of soil mechanics. Ship operators and cargo handlers must be involved in discussions as it is through them that actual cases of liquefaction and cargo instability are reported and described. Without this knowledge the research work cannot be verified; and without the guidance of shippers on the limits of practicality in, say, sampling frequency, the research workers could generate unreasonable suggestions for avoiding the hazard.

In this area, naval architects too have a significant contribution to make. Their advice and cooperation must provide the link between instability of the cargo and instability of the ship.

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Discussion

D. C. GILBERT (Chief Ship Surveyor, Department of Trade): The title of this paper is deceptively innocent, and indeed quite disarming, and I fully approve of the authors starting with the case histories of a number of ship casualties; if only to bring one's attention quickly to bear on the need for this research into the instability of bulk mineral cargoes.

The fact that my Department initiated research as long ago as 1975 (which is still continuing) is an indication that this is not a simple problem to solve. It is by no means a recent phenomenon and our Departmental records show that two ships were lost in 1937 when carrying zinc concentrates. At that time these losses were attributed merely to a shift of cargo as nothing was then known of cargo liquefaction.

The research which my Department asked Warren Spring Laboratory (WSL) to do in 1975 has been directed toward developing a satisfactory laboratory test procedure and establishing necessary margins of safety, appropriate to the conditions under which metallic concentrates and such cargoes are carried in bulk by sea.

The IMCO Code of Safe Practice for Solid Bulk Cargoes (first issued in 1965) recommended a method known as the flow table test for determining the 'safe transportable moisture limit'. The research at WSL therefore began with an appraisal of this method. It became evident that there is an element of subjectivity and, consequently, unreliability in this method; and, in order to develop an improved method, a better understanding of the process of liquefaction was needed. It is known that this phenomenon is related to the degree of saturation of the material; this can vary during a voyage as it is compacted by settlement, ship motions and vibrations due to machinery or wave impact.

In consequence, a ship motion simulator has been used to determine the critical moisture content at which a flow state will develop and to compare this with the IMCO flow table test and other methods such as the Proctor test.

The importance of full-scale data has also been recognized by WSL. Attempts were made 3 years ago to record vibration levels and pore pressures by means of transducers embedded in the coal slurry cargo in the hold of a coaster. This phase of the research was apparently not successful for reasons which, no doubt, the authors can explain.

Shortly after this research started in 1975, the *Lovat* (carrying a cargo of anthracite washed duff) capsized. As a result, a good deal of the research effort has since been directed towards a suitable method of testing such coal cargoes, especially those containing relatively large particles, where the IMCO flow table method is unsuitable.

On this subject there has been extensive collaboration between my Department, WSL and scientists in the National Coal Board (NCB). This again led to comparison tests between the flow table test (as far as it could be used), the Proctor test, simulated tests and the NCB vibrating plate method for determining the critical moisture content. This evidently varies with the coal field from which the samples came, particle size distribution, etc.; which further complicates the problem. Particle size distribution also affects the ability of the cargo to drain.

Some thought has been given to the practicability of using bilge suctions to remove excess water but it is generally believed that this would result in choking the lines. Merchant Shipping Notice M.746, para. 20, advises the Master on this, stating that 'the cargo hold bilges should be regularly pumped to remove any water which may collect'. A feedback from shipowners would be useful as it may be worthwhile developing special drain wells with filters to prevent choking of bilge suctions.

The present phase of the research is directed more towards understanding moisture migration, initially in the laboratory by determination of field capacity, drainage, air and water permeability. There seem to be differences of opinion regarding the direction of moisture migration, i.e. up or downwards. It is clearly important to know this to prevent, if possible, local high saturation levels and consequent progressive shift.

Future research will look more closely at the effect of ship motion and which parameters of the ship (e.g. beam/draught ratio, GM) most influence this and could therefore be controlled. This work would be done in conjunction with a shipowner and make use of knowledge gained and ship motion prediction computer programs that may be developed as part of our SAFESHIP project. The cargo stability and ship motion research projects have so far been progressing separately to avoid over-complication of either project but, at an appropriate time, they will be brought together. Observations at sea of both cargo behaviour and ship motions, properly recorded, will support this work.

G. G. SUMMERS (Shell International Marine Limited): The authors explain very clearly the phenomenon of cargo liquefaction and set out the results of experimental work aimed at understanding the role of different cargo variables on the likelihood of liquefaction occurring during voyage conditions.

As such, the paper well demonstrates the relevance of this topic to safety onboard bulk cargo vessels although, of course, it is not the only hazard; hold swamping, synchronous rolling, explosions and cargo heating could be others.

The case studies presented concentrate on the liquefaction phenomenon experienced on board small vessels. A number of issues relevant to more general cargo instability phenomena remain, however, and these might be particularly important to large ships carrying cargoes such as high density ore. As we see it the principal additional issues are as follows.

Cargo instability due to dry sliding failure

This mechanism was mentioned in the paper and occurs when a cargo is tilted beyond its so-called 'angle of repose'.

The loss of a number of ships carrying scrap iron has been attributed to the instability of the cargo but, clearly, this has not been due to liquefaction. It is therefore emphasized that dry sliding failures should not be overlooked as a potential cause of ship stability problems. Indeed, dry sliding might in some circumstances provide an explanation without the need to invoke the somewhat more 'sophisticated' phenomenon of liquefaction.

The importance of ship's motions and vibration

The work presented shows the sensitivity of the liquefaction phenomenon to both ship's motions and vibrations. Dry sliding failure could be similarly dependent. It is important to bear in mind that motions and vibrations could vary considerably between small and large vessels; indeed between vessels of similar size but differing types (e.g. VLOO or bulker).

Thus, for laboratory work such as that presented to maximize its impact on safe shipping practices, it will be essential for reliable data on ships' motions and vibrations to be collected from ships; or confidently predicted from model studies and used as input to this type of study. With this information it should then be possible to relate laboratory measures of 'cargo instability propensity' to what might actually happen to the cargo onboard ship.

Finally, we should like to advocate the extension of the programme to cover the study of dry sliding failure and, in particular, the relevance of both liquefaction and dry sliding failure to larger vessels.

We fully support the statement made in the last paragraph of the paper concerning the importance of the contribution that naval architects may make to the study. Indeed, we believe that additional contributions from naval architects and operators familiar with trading in this sector will be essential when seeking some answers to a maritime safety issue that has been to the forefront in recent years and, as international trading in bulk cargoes increases, is unlikely to recede unless the advances in our knowledge are made. This will not materialize unless further effort is applied.

N. BROMFIELD (Portsmouth Polytechnic): Having read the paper a number of times I must conclude that the compaction and flow table tests give only poor indications, and perhaps wrong ones, of the liquefaction hazard.

To some extent the authors are to blame for this, for not explaining clearly the relationships between these tests and the ship problem. The significance of the tests is further confused by the hypothetical shear experiment (where, for example, the authors have to switch suddenly to a saturated solid to explain liquefaction) and the authors' inability to identify the important influencing factors.

It is difficult not to be critical when the paper continually indicates that the present research is contributing little to the naval architecture and marine engineering knowledge of the problem. I think I was glad, for example, that the authors did not describe what they were attempting to represent in their simulators, simply on the grounds that I anticipated that these experiments would also be empirical and not directly related to the ship problem.

May I suggest that the present work be discontinued until there is a better scientific understanding of the ship problem. Let us concentrate on an understanding of the problem first: a suitable test will readily follow. It is clear from the paper that the financial support for the necessary work must be given to a research institution where naval architects/marine engineers can ensure that the effort concentrates on the real situation of a ship carrying a hazardous cargo in a sea-way.

What is the alternative? At the present rate we will lose another 305 ships before, if the authors are lucky, they produce a suitable test. I suggest that the potential loss of life makes a solution much more urgent.

Finally, it appears that nothing is being done to develop methods for stabilizing such cargoes.

L. M. GOLL (Head of Cargoes Section, IMCO): IMCO is very appreciative of having received the invitation to attend this lecture.

It, *inter alia,* provides an opportunity to express our gratitude to the Marine Division of the Department of Trade and, indeed, to Warren Spring Laboratories, who have actively contributed valuable material to the Organization's efforts to deal with precisely the problems with which the lecture deals.

As the lecture indicates, there is still a considerable way to go and a number of studies to be made before sufficient knowledge is obtained about cargoes which liquefy or become thixotropic.

The work on safe carriage of bulk cargoes has been going on for a considerable number of years, as manifested by the fact that the first IMCO Code on safe practice for bulk cargoes appeared as early as in 1966.

At this point I should like to mention that there is strong circumstantial evidence of the fact that the existence of the Code has saved life and property as, at least in one instance, a ship that had loaded a cargo of coal in a West British port did not put to sea after having consulted the Code, whereas another ship of similar size and design, having loaded the same cargo at the same time, *did* put to sea and foundered.

Most of the elements touched upon in the lecture still constitute ongoing work in the IMCO Sub-Committee on Containers and Cargoes; and we fervently hope that the continued studies will give such results as will render the maritime transport of the cargoes in question entirely safe, without creating procedures which will prove too cumbersome and comprehensive in practice.

From the practical point of view there are three aspects which are of fundamental importance and should thus be tackled with the highest priority. They are:

1. Provision to the Master, prior to loading, of reliable information on the transportable moisture limit of the cargo in question.
2. Provision to the Master, also prior to loading, of the moisture content of the cargo to be loaded.
3. In order to accommodate and facilitate the requirements referred to in (1) and (2) above, the establishment of reliable methods and procedures for sampling the cargo to be loaded.

These points referred to above are very much in focus of IMCO's activities concerning bulk cargoes, and it is very much hoped that the further research and studies indicated in the lecture will contribute to the expedient solution of the practical problems. The traditional close and positive co-operation between the Marine Division of the Department of Trade and the Warren Spring Laboratory on the one hand, and IMCO on the other, should bode well for the achievement of this goal.

A. L. MILNES (Portsmouth Polytechnic): This paper seems to be very much user-orientated and to have, as its ultimate aim, the formation of simple tests which will detect the difference between safe and unsafe cargoes.

It is probably unrealistic under these circumstances to expect the authors to use an approach designed to cast light on the nature of the mechanism causing a 'phase' change or a 'state' change.

What appears to be lacking is a body of theory enabling hypotheses to be constructed and tested in a systematic manner. To construct conjectural models of the behaviour of the material seems relatively unhelpful and we must ask whether any paradigms can be borrowed from other areas of science/technology.

Certainly we would suspect that such changes as are described in various accident reports have been brought about when the energy flux through the cargo rises above some critical value; this connection is a well-known scientific fact accepted in the more conventional phase changes. Therefore, it seems to me that a better approach would be to look at the variations in the energy field which acts upon the ship and cargo when in a sea-way.

This has the clear advantage of using a dynamic model to investigate the dynamics of cargoes. The difficulty then arises of determining the energy field in an actual ship and attempting to establish dynamic similarity in any model employed. The limited number of degrees of freedom stated in the description of the apparatus makes it unlikely that the true velocity/acceleration/energy field was modelled.

It is worth commenting that the transition from solid to pseudo-fluid is reversed when the energy supply to the ship from the sea is removed.

It seems that a fruitful field of study would be to simulate the ship motions in a computer, so that the vector/scalar fields acting on the cargo can be, at least relatively, determined. This is the procedure we have elected to follow in the work being done at Portsmouth Polytechnic. This work is being done by way of student projects and my student for the current year is present at this meeting and will no doubt give fuller details of the simulation procedure.

The progress is necessarily slow, since the combination of interest, mathematical and computing ability is not commonplace in students.

E. TZANNATOS (Portsmouth Polytechnic): Further to Mr Milnes' contribution, in the current project we are attempting to determine, by computer simulation, the acceleration field induced upon the ship in a storm sea environment.

Random sea conditions have been modelled mathematically by 12 superimposed sine waveforms incorporating different phase, amplitude and period parameters. The resultant waveform defined the linear displacements of the ship at approximately 500 points and, equally well, the pitch, roll and yaw rotational deflections at these points.

An array of four values has been arranged on the computer to accommodate the local velocities with respect to heave, roll, pitch and yaw, as a result of division of successive distances between points of reference by the time interval between them. Furthermore, local acceleration components are determined by dividing successive velocities by the time interval between points of concern and, again, placed in an array of four values.

The derived components of local accelerations and velocities mentioned above are introduced in the acceleration relations for x, y and z direction, leading to the establishment of an acceleration field responsible for the ship's movements.

The approach described above illustrates the main points of the work carried out in our present project.

T. H. HUGHES: To begin with, I should like to mention that I have been involved with this research work since its commencement and up until I retired from Warren Spring Laboratory at the end of September 1980. Also, that the following views and comments are now expressed entirely in my own right.

In this situation you will appreciate what a fascinating experience it is for me to be here for the presentation of this paper and I should like to thank the Institute of Marine Engineers for so kindly inviting me to attend the meeting and to contribute to the discussion.

First of all, I am naturally delighted to see the progress that has been made towards a fuller and more scientific understanding of the various and complex phenomena involved and, particularly, the experimental approaches the authors have now proposed in their paper.

For example, the hypothetical shear experiment illustrated in Fig. 2 is an interesting case in point, where existing soil mechanics technology is to be applied towards a study of the behaviour of the test materials when subjected to stress conditions similar to those prevailing in typical bulk cargo vessels. However, in view of the complex nature of the applied forces, it would be helpful if the authors could provide a fuller description of the actual apparatus on which these experiments are to be carried out.

Regarding the preliminary experiments on the conditioning of grain surfaces (p. 5, col. 2, para. 2), it was interesting to note that one reagent had the effect of increasing the maximum dry density although the optimum moisture content remained the same as for the untreated material. This suggests that, whilst the interstitial zone sizes must be smaller in order to achieve a higher density, they must also be more completely saturated to achieve the same optimum moisture content as the untreated material.

Does it therefore seem likely that the hydrophobic nature of the surface provides a continuous network, linked at the points of contact, for the air to escape around the grain boundaries of the particles? Conversely, with completely wetted surfaces, is it probable that discrete air bubbles will be trapped in the interstices? Confirmation of this could no doubt be obtained by the air-permeability experiments proposed.

Turning now to the field capacity aspects, it is a daunting thought that cargoes loaded at an apparently safe moisture content but above the field capacity can subsequently be subject to moisture migration, which could cause some part of the cargo to flow. In the proposed experiments to determine the effect of vibration on field capacity, will it be possible to extend the length of the column from 1 m to something approaching the depth of the cargo in the size of ships most likely to be at hazard? Direct scale-up experience will otherwise be difficult to obtain. It would also seem useful to confirm that, even though saturation conditions may occur in the lower strata of the cargo, the degree of compaction achieved through the 'hydrostatic' head pressure, combined with vibration, will be sufficient to prevent actual flow or dislocation of the cargo.

Finally, in their review, the authors have identified a number of authorities and organizations with expertise, knowledge and/or various interests in this programme of research. Have any moves been made to form some sort of active working Group other than through the IMCO Sub-Committee on Containers and Cargoes? This could provide necessary input on associated aspects which, as the authors here indicated, may not necessarily be within the expertise of WSL. Periodic exchange of views with such external and independent experts would surely inject additional stimulus in the research work. Perhaps the Department of Trade may also wish to comment on this.

H. BIRD (Department of Trade, Marine Division): I am very interested in this paper for two reasons: I am the Marine Division Project Officer concerned; and I have special responsibilities for improving our understanding of large-amplitude ship rolling motion and capsize prevention, to improve the philosophical basis for future stability regulations.

As Chairman of the UK Intact Stability Working Group, I have been responsible for formulating an elaborate programme of stability research which we call the SAFESHIP project. This was started about 6 months ago.

The WSL research is mainly concerned with the phenomenon of liquefaction. Naval architects, ship operators and my department have to be concerned with the wider problem of cargo shift generally and this requires the means, i.e. computer techniques, to predict large-amplitude rolling motions. This is one of the main objectives of the SAFESHIP project.

The WSL research was initiated by my Department as recommended by the Court of Formal Investigation into the loss of MV *Burtonia* in 1972 and was directed towards developing a satisfactory laboratory test procedure and establishing necessary margins of safety.

The IMCO Bulk Cargoes Code recommends a test method known as the flow table method to establish the critical moisture content. This has been criticized for, among other reasons, dependence on the operator's skill. However, it has a safety margin of 10%, i.e. TML = 90% of FMP. Presumably this is to cover uncertainty in sampling, lack of reliability in testing and uncertainties about moisture migration during the voyage. In my opinion it is doubtful if this safety margin is nearly adequate to do all these things, especially since Merchant Shipping Notice M.746 permits some parts of the cargo to exceed the TML.

Other methods of testing, principally the Proctor test, have been suggested. This appears more scientific and less subjective from my reading of the Fagerberg and Stavang paper (Ref. 15). This paper recommends a 70% saturation level as being safe for general cargo ships but, if this is the turning point on the compaction curve, does this not correspond to the FMP rather than the TML (i.e. no safety margin at all)? Perhaps the authors could comment on this method and say what length of time is required to carry out either type of test.

There seems to be some controversy about the direction of moisture migration during a voyage, especially in rough weather. According to Fagerberg, Ref. 15, water is first formed at the bottom, as one would expect, due to high pressure of cargo. However, he suggests that this is not dangerous as it is displaced upwards to the free surface. I find it hard to believe that the danger is so removed. Can the authors comment?

When this project was first formulated, one of the matters to be addressed was the practicality of de-watering and, while no progress appears to have been made on this subject, I still feel that it is important.

Both the IMCO Code, page 11, and M.746, page 7, imply that the bilges should be capable of being pumped although I have sometimes been advised that this is not practicable because the suctions would become choked. According to my information it is a legal requirement. I feel that the number of drain wells should be increased in ships carrying damp mineral concentrates and some form of suitable filtering medium developed to minimize choking of bilge lines. Do the authors think that filtration is practicable?

According to the IMCO Code, page 12, for cargoes which have a static angle of repose greater than 35 deg, only a limited amount of trimming is necessary. Observing that a number of metallic concentrates are close to this figure (IMCO Code of 1972), do the authors feel that this distinction is a prudent one?

For cargoes having an angle of repose less than 35 deg, these are required to be trimmed 'reasonably level' and M.746, Appendix IV, prescribes a stability criterion. The surface shift angle is to be assumed equal to 35 deg—natural angle of repose. For such angles which are just under 35 deg, and some are quoted in the Code, this could mean a very small hypothetical shift moment. Have the authors any views?

I am grateful to the authors for investigating so thoroughly and explaining so clearly the rheological aspects of the problem. I am also glad to see us moving away to some extent from comparative laboratory tests towards drainage and other tests which may provide a rationale for predicting moisture migration and the means therefore to establish the necessary safety margins. I hope that this laboratory work can be extended to measurements on board ship. An attempt was made to do work on a coaster 3 years ago but then abandoned. Can the authors say whether the prospects for detecting moisture distribution at sea are any better now?

I have to add that these comments and opinions are my own and do not necessarily reflect the official views of the Department of Trade.

G. CAINES, CEng, MIMarE: In my opinion the paper has two disadvantages: it contributes nothing new to the subject; and it lends respectability to the IMCO Code of Safe Practice for Solid Bulk Cargoes.

I was informed by an ex-Chief Officer, who knew the ill-fated *Derbyshire* well, that it would have been loaded with iron concentrates in the amidships holds to a depth of approximately 5 m at the wings and 15 m at the peak. These depths are convenient for calculation purposes as there would be equal volumes of ore above and below the wing depths. They may, however, be too high for the densest ore quoted in Table III (i.e. specific gravity 5.21; maximum dry density 2.52 t/m^3).

Consider 1 m^3 of ore at the maximum density quoted and with a moisture content of 10.26% (i.e. the transportable limit—90% of the flow moisture point of 11.4%). Then:

$$10.26\% = W/(W + 2.52)$$

Thus W (weight of water) = 0.29; and density of wet cargo = 0.29 + 2.52 = 2.81 t/m^3.

If there are 25 000 t in a hold 44.2 m wide and 22.7 m long, the height at the wings for half-volume of cargo is 4.43 m, making the height of the peak 13.29 m. If diagrams are drawn to scale, it can be seen how little water is required to create a water table which, with only small angles of inclination, is liable to break through the inclined surface of the ore.

For 1 m^3 of ore, the volume of solids = 2.52/5.21 = 0.484; and the volume of voids = 0.516. So, the absolute saturation moisture content = 17%. The criterion to determine the height of the water table in the ore is the apparent saturation point, which may be substantially less than the absolute saturation point.

This may be shown by taking the extreme, albeit absurd, case of the particles of ore being identical hollow cubes. Then, a single droplet of water would produce apparent saturation. At apparent saturation, the angle of repose and resistance to shear would tend to zero values.

Is it a coincidence that the authors found that the simulator flow level was 13.5–14%? I suggest that this moisture content was, as near as makes no odds, that of apparent saturation. So, if 14% is taken as the apparent saturation point, an initial average moisture content of only 7% would bring the water table up to the wing levels of the ore in the case under consideration. (*Derbyshire* had, according to my information, 3.59%.)

I know that I have ignored the residual moisture or 'field capacity' referred to by the authors. It has already been established that, after a voyage, the residual moisture content in the upper levels of iron concentrates has been found to be about 1.7%. A prudent naval architect, considering the stability of an ore carrier from first principles and from the aspect of safety rather than acceptable risk, would almost certainly treat the residual moisture content as zero. He would also conclude that, under complex ships' motions, water near the surface of the ore is likely to be thrown above it and possibly erode the sloping surfaces, with dire results. He would then realize that moisture contents of only about 5% could be highly dangerous in wide-hold ships with peaked cargoes.

If the moisture content was 10.26% (as allowed by IMCO), there would be pockets of water at the wings with potential hydrostatic heads of water of the order 44.2 sin 30 deg, 22.1 m, tending to cause a slide of the peak. Can there be any justification for the IMCO moisture flow point, or the even higher simulator flow points of 13.5–14% as found by the authors?

Also, I do not see how the results from a small experimental hold of unknown size, perhaps 1 m wide, can be related to what happens in a 44 m wide hold.

Is it not time that marine engineers declared that the ship's conventional bilge pumping system cannot cope with water contained in fine-grained mineral ores? When I first ask Chief Officers and Chief Engineers what they do about their bilge suctions and sounding pipes prior to loading ore, almost all say 'We block them off'. After a little thought about the implications of this, they change their reply to burlapping the bilge wells. Even if the bilge suction points were burlapped, the bilge lines and pumps would be choked after a few minutes' pumping.

So, we have the situation where (1) the IMCO Code allows much too high a moisture content in the cargoes; (2) the ship's pumping system cannot cope with the water in the cargo as loaded, let alone water which may enter afterwards, and (3) the Masters of ore-carrying vessels are lulled into a false sense of security as they have ostensibly complied with the IMCO Code.

The behaviour pattern I have suggested fits perfectly to the case of the British ship reported on pages 1 and 2 of the paper if the reasonable assumption is made that the cargo had been loaded to give a trim by the stern, i.e. with the cargo shallower at the fore end(s) of the hold(s).

You will have noticed the discrepancies reported in Table II between assessment of actual and stated moisture contents. The seemingly simple task of gauging the moisture in cargoes is extremely difficult and must surely, in general, be potentially dangerous underestimates.

Also, I doubt the reliability of the virtually non-reproducible moisture flow point tests, which depend on the physical strength of the tester; and his ability to select representative samples of the ore to be loaded and to judge when its compaction is the same as that at the bottom of the hold(s).

I suggest a return to basic principles, i.e. restrict, where necessary, the breadth of holds; provide proper drainage of the cargoes; and provide an efficient pumping system. Until this is done, some carriers of damp fine-grained ores with 5% or more moisture content for peak loads, and about 8% or more for trimmed level loads, must be suspected of unseaworthiness despite their probable compliance with the IMCO Code.

P. W. AYLING, BSc, CEng, FRINA: From the work they have done so far, are the authors able to say which of the two main dynamic phenomena—low-frequency, large-amplitude ship motions or relatively high-frequency, small-amplitude, structural vibration—is the most significant in the liquefaction of damp cargoes?

I enjoyed the paper and have a better appreciation of the complexities of the subject although there would appear to be a need for the closer involvement of all the interested parties in the future direction of this important research.

Authors' Reply

The contributions to the discussion touch on so many points that our replies to most of them must necessarily be brief and of a general nature.

First, most of the contributors make some reference to the need to relate the work presented in the paper to the motions and vibrations prevalent in ships. We fully realize the importance of this and considerable effort in this project has been devoted to gathering data, both by direct measurement and by consulting appropriate authorities.

Direct measurements of motions and vibrations have been made both in the Warren Spring research vessel *Sea Spring* and on two voyages of a coaster. On *Sea Spring* a sample cargo was loaded into a large container in a condition which was deemed likely to liquefy, so that the observed cargo behaviour could be correlated with recorded motions and vibrations through the ship, container and cargo. On the coaster the intention was to collect measurements from full-scale cargoes in various sea conditions. On both voyages, however, very calm seas persisted throughout. From both *Sea Spring* and the coastal voyages, the vibration data collected were too complex to permit direct correlation with cargo behaviour.

A major difficulty in such studies is the need to develop general conclusions and therefore to seek generalizations regarding motions and vibrations. Otherwise there is a danger of concluding that each ship (or even each voyage) is unique; piecemeal analysis of unique cases is clearly not feasible. One useful general conclusion would be to answer the question posed by Mr Ayling, that of the relative importance of large-amplitude, low-frequency motions and of low-amplitude, high-frequency vibrations. We do not know the answer to this, but would point out that rotational motions (roll is the most severe) have a large and easily calculable effect in terms of oscillating shear stresses within the cargo; the influence of vibrations is more equivocal, being dependent upon the characteristics of the vibrations and the damping properties of the cargo, about which we currently know very little.

We would, however, take issue with the philosophy of Messrs Bromfield and Milnes, that the study of motions and vibrations in isolation will determine safety levels for cargoes. This implies that all cargoes at all levels of moisture are equally unsafe at a given 'energy flux', which is an unreasonable proposition. The two aspects of the solution, to study both the ships and the cargo, must go hand in hand.

Regarding the explanation for liquefaction given in the paper using the example of a hypothetical shear experiment, neither Mr Bromfield nor Mr Milnes appear to have understood this. This explanation is based on a great body of theoretical and experimental work in soil mechanics on the subject of liquefaction, and we would direct Mr Milnes to Refs 10, 11 and 12 of the original paper. We have constructed a testable hypothesis regarding the transition with changing moisture content from a non-liquefiable to a liquefiable material; Mr Bromfield has clearly missed this point. On a more practical note, Mr Hughes may find a description of the device to be used for the shear experiments in Bierrum and Landva,* modified to allow cyclic loading.

Several contributions refer to the use of bilge or suction pumps, to control the moisture content of the cargo. Potentially, there are two modes of operation of these pumps. Either they may remove water which drains by gravity into the bilges, in which case attempts to remove moisture below the field capacity will not be effective. Alternatively, they may apply a suction directly to the face of the material. However, this requires a special filter capable of supporting the suction between the pump and the cargo. In either case the fine particles must be prevented from entering the pumping system without at the same time blocking any filter medium. The prediction of moisture migration, and the study of the effectiveness of various drainage facilities, are a part of our programme and we therefore hope to be able to answer Mr Bird at a later date.

We are not at all surprised that Mr Caines has discovered an iron concentrate with a field capacity different from that quoted in the paper. We are surprised that he considers that his value should apply to all such cargoes. The two coals referred to in the paper have very different field capacities. It is a parameter that is linked to particle size; the smaller the particle size the higher the field capacity. Mr Caines also expects the prudent naval architect to consider the field capacity as being zero, and therefore drainage to occur, rendering some parts of any damp cargo dangerous, and yet to accept a cargo at a moisture content of 5 or 8% (or more) depending on trimming. This is both a contradiction and totally disregards measurable properties of the cargo. Mr Caines' misconceptions on this point emphasize the usefulness of studies of moisture flow.

Mr Summers and Mr Bird both draw attention to sliding failures—the angle of repose problem—and the distinction drawn between cargoes with an angle of repose above and below 35 deg. We do not

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*L. Bierrum and A. Landva, 'Direct simple shear tests on a Norwegian quick clay'. *Geotechnique*, Vol. 16, pp. 1-20 (1966).

feel that this distinction is in all cases prudent; for one thing, a cargo may start and end a voyage on different sides of the 35 deg boundary due to moisture migration, compaction and so on in the voyage. We fully agree with Mr Summers that liquefaction may not always be the cause of cargo shift and that further work is required on sliding failure phenomena.

Mr Bird and Mr Goll raise the questions of safety margins for any hazard identification test and in the context of sampling whole cargoes. In the case of the compaction test let us, at least partially, reassure Mr Bird. The 70% saturation level suggested by the Swedes is deemed to include a factor of safety against liquefaction failure as, for the metal concentrates examined, the turning point on the compaction curve (comparable to FMP) occurs at saturation levels above 70%.

Until the research into drainage characteristics is complete we cannot be dogmatic but it seems likely that the difference between field capacity moisture content and the flow moisture point for some cargoes is so wide that the 10% factor of safety on FMP may not be sufficient.

It is our opinion that no cargo or part-cargo should be loaded if it is known to have a moisture content above the transportable moisture content, although this is permitted by the IMCO Code, but we recognize the practical difficulties of preventing such part-cargoes, in particular, from being loaded. This brings us directly to the question raised by Mr Goll of sampling cargoes to get representative samples. We have not addressed this question as part of our research to date. It carries certain implications regarding both margins of safety and the economics of sampling the cargoes (not to mention the rejection of unfit cargoes). This question can therefore only be answered by consultation with all interested parties, including shippers and experts in the field of materials handling.

Although the previous paragraph contains a mild criticism of the IMCO Code, it should not be taken as condemnation. We regard the Code as the best available general guidance on the handling of bulk mineral cargoes but, were it perfect, the need for our research would not exist. We hope that the results of our work will permit amendment and improvement of the procedures recommended in the Code.

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