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OPERATIONAL PERFORMANCE AND SAFETY ASPECTS OF LNG SHIPS

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Operational Performance and Safety Aspects of LNG Ships

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SYNOPSIS

By the end of 1981 the Shell fleet of seven 75 000 m^3 LNG ships, operating between Brunei and Japan, will have transported more than 1000 cargoes since the project began in 1972. The authors describe the service performance of these ships, particularly machinery and cargo system reliability, operational problems and modifications carried out. Operational changes dictated by project requirements or developed from experience are discussed, and the part these have played in optimizing project performance. The importance of ship safety aspects is emphasized, with details on risk areas, the measures taken to ensure reliability and safety; and the casualty contingency planning.

INTRODUCTION

The seven 'G' class 75 000 m^3 LNG ships have been in service on the Brunei–Japan project since 1972 and have transported more than 1000 cargoes. The outline particulars of these ships are shown in Table I.

The spearhead of Shell Tankers (UK)'s commitment to the operation of these ships is the service organization known as IMR within Shell Kosan, Tokyo. The function of IMR is to ensure the safe, reliable transport and delivery of LNG cargoes to the customers in Japan. This is achieved by maintaining close liaison with ships' staff and customers and by organizing planned maintenance on items for which the Classification Society requires continuous survey; and also considerable on-board maintenance. STUK has a service contract with Mitsubishi Heavy Industries for the drydocking and refit of all 'G' class ships: they also provide a depot for the storage of the very substantial spare parts inventory.

In addition, IMR act as a clearing house for information: first, by keeping all the ships fully informed of possible operational trouble spots within the fleet; and, second, by keeping STUK in London abreast of all significant events so that policies and practices can be co-ordinated.

Finally, STUK and IMR liaise closely with the Japanese government organizations responsible for enforcing safety and structural standards, namely the Maritime Safety Agency and the Ministry of Transport.

The initial design concepts and early operational experience have been described in earlier papers.[1,2] However, in almost 9 years of continuous operation, valuable performance data have been obtained, problems have been encountered and operation and safety have required equipment modification and improvement in the light of experience. This process will certainly continue in order to avoid complacency—which cannot be tolerated in an LNG project of this nature.

The following outlines the operating experience, problem areas and safety considerations that have occurred to date, with particular emphasis on the special features that distinguish LNG carriers from more conventional ships.

SERVICE PERFORMANCE

General

The seven ships have consistently displayed a high reliability, in that every year the required number of cargoes have been delivered. Due to the prohibition on movements in Japanese ports between sunset and sunrise, minor delays of an hour or so can result, on rare occasions, in a ship having to anchor overnight. The greatest delay in delivery of a cargo has been 48 hours, caused by exceptionally high winds preventing berthing. The ships have speed in reserve on the ballast voyage so that, over a number of voyages, their schedule can be regained.

The special features required by the LNG cargo, including the containment, pipelines and valves, loading/discharge system, cargo monitoring and safety systems, have so far given no more problems than have the conventional hull and propulsion. The fact that periods between refits, initially one year, have gradually been extended to two years and are now planned for two and a half years, indicates the degree of reliability which has been achieved.

Cargo boil-off

The boil-off on the loaded voyage of these ships averages 0.31% per day, with no measurable difference between the two membrane designs.

Table I: Brunei–Japan ship particulars

CONTAINMENT	SHIP	BUILDER[a]	PARTICULARS		ENTERED SERVICE	CARGOES DELIVERED[b]
Technigaz	*Gadinia*	CA	Capacity	75 000 m^3	Dec. '72	194
	Gadila	CA	L	231.4 m	Aug. '73	178
	Gari	CA	B	34.75 m	Jan. '74	168
	Gastrana	CA	d	9.45 m	Aug. '74	156
	Gouldia	CNC	SHP	15 300 kW	Aug. '75	135
			Speed	19.0 knots		
Gaz Transport	*Geomitra*	CNIM	Capacity	77 700 m^3	May '75	140
	Genota	CNIM	L	230 m	Nov. '75	128
			B	34.75 m		
			d	9.45 m		
			SHP	15 300 kW		
			Speed	19.0 knots		
Total						1099

[a] CA —Chantiers de l'Atlantique.
CNC —Chantiers Naval de la Ciotat.
CNIM—Constructions Navales et Industrielles de la Mediterranee.
[b] As of July 1981.

Table II: Average consumption of fuel oil per round voyage (tonnes)

YEAR	TONNES USED
1975	500
1976	360
1977	235
1978	173
1979	141
1980	100
1981	180 (Est.)

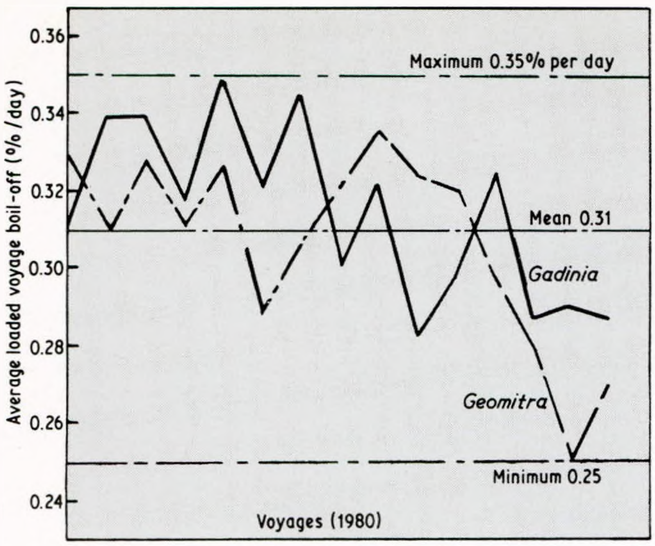

FIG 1 Loaded voyage boil-off variation

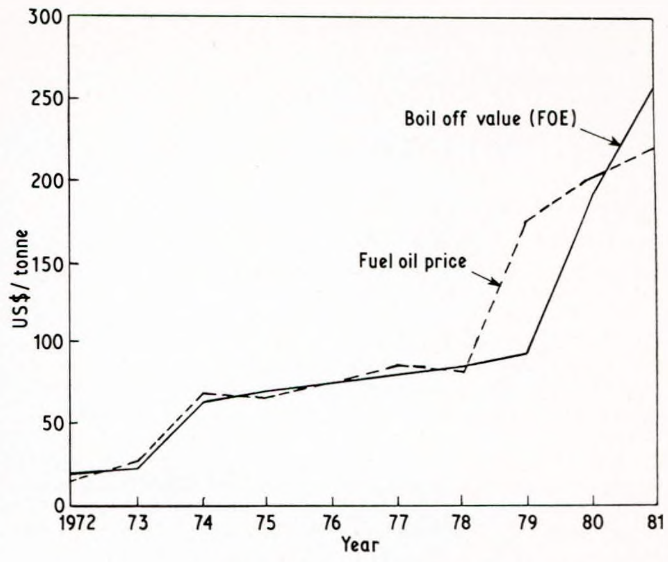

FIG 2 Fuel oil price vs. boil-off value (FOE)

However, although the average boil-off has remained substantially constant over the years, the fluctuations from voyage to voyage are significant, as illustrated in Fig. 1 over a typical 1980 consecutive voyage period for the two ships *Geomitra* and *Gadinia*. This indicates that the minimum and maximum daily boil-off can range from 0.25% to 0.35% per day. The reasons for this relatively wide variation are not completely understood. Certainly sea conditions, ambient temperatures and, to a lesser extent, measurement errors play a role, but analysis of considerable data over the years has failed to show clear trends and influences.

In the early years of the project, spray cooling of cargo tanks with residual LNG remaining on board was carried out only during the final stages of the ballast voyage. This was predominantly because vapour returned to shore during loading at this time had to be flared and, in order to minimize these losses and avoid the cost penalties for arrival at the loading terminal with warm tanks, this procedure appeared the most favourable. However, it did involve venting gas to atmosphere during spray cooling, with consequent energy wastage.

In recent years the Brunei shore system has been modified to allow loading boil-off to be returned to the liquefaction plant. As a consequence, spray cooling may be now carried out intermittently on voyage so that no more vapour is generated than can be used as fuel for the boiler on the voyage. With this system, the ballast voyage boil-off has varied from about 60% of loaded voyage boil-off to a minimum of 35% with no spray cooling at all. The amount of spray cooling carried out has depended on the relative values of LNG and fuel oil.

Propulsion fuel

These ships began operation in the period before energy prices began to rise to levels hardly credible at that stage. Since 1972, the bunker prices in Japan and the fuel oil equivalent price of LNG on a basis of equal calorific value have followed the trends shown in Fig. 2. The sharp increases in energy prices in 1973/74 and, more recently, in 1979/80 are clearly shown. The relative variations in value between fuel oil and LNG boil-off have largely influenced the philosophy adopted in meeting the 'G' ships' fuel requirements. During 1972–78, fuel oil and LNG values were closely in step and both relatively cheap, by today's standards.

The 'G' ships have always suffered from excess boil-off during the loaded voyage and the principal efforts during these early years were directed towards maximizing the utilization of this boil-off by methods to be described later. The desire to reduce fuel costs became more acute in the period 1978–80 when bunker prices rose very sharply and faster than LNG prices, to the extent that serious consideration was given to vaporizing additional LNG cargo specifically for use as fuel. While this was not done, the overall reduction in round-voyage fuel consumption achieved over the years without reduction in LNG cargo delivery has been quite dramatic, as shown in Table II.

Since 1980 the situation has changed again, in that LNG prices have, at least temporarily, overtaken fuel oil costs and current efforts are aimed at maximizing cargo delivery at the expense of somewhat higher fuel oil consumption.

In practice, appreciable flexibility exists on many voyages since deliveries are adjusted to suit customers' requirements within the overall annual delivery programme. Consequently, it is often feasible to operate at slightly slower speeds on the loaded voyage, burning virtually no fuel oil; and, similarly, to adjust the ballast voyage speed to suit the loading requirements and thus minimize fuel oil consumption. This method of operation is a complete justification, if such is required, of careful planning and co-operation between the producer, carrier and customer.

Nitrogen consumption

It has been normal in LNG carriers, at least up to the present time, for each ship to have storage capacity for liquid nitrogen. This is used primarily for purging of insulation spaces.

Consumption has remained substantially constant over the years, between 0.6 and 0.8 m^3/day for each ship. It is the normal practice to replenish the nitrogen storage so that sufficient nitrogen is always on board to inert the largest cargo tank. Topping up is normally done whilst discharging cargo, about every third or fourth round trip.

Serious consideration was given to fitting a nitrogen generator together with a small shipboard air separation plant to produce nitrogen for immediate use and to keep the storage vessels topped up. However, an air separation plant has been built adjacent to one Japanese receiving terminal, which uses the 'cold' from the LNG installation. This made shipboard production of nitrogen uneconomic since the

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L. R. Prew served an apprenticeship at HM Dockyard, Devonport, and studied at Kings College, Newcastle upon Tyne, graduating in 1951 with a BSc (Marine Engineering) and an endorsement to BSc (Naval Architecture). He joined Shell Tankers (UK) Ltd in 1951, rising to Chief Engineer in 1959. He was then appointed ashore with Shell International Marine Ltd. As a Senior Project Engineer he has been concerned predominantly with the design and development of LPG/LNG ship cargo systems and safety research, including the Brunei/Japan LNG ships.

liquid nitrogen produced in the shore plant could be obtained at very competitive prices. It may be, however, that a ship designed from the outset to be self-sufficient in nitrogen could show overall economic gain.

OPERATIONAL PROBLEMS

Main propulsion plant

The seven sets of propulsion machinery have generally proved to be very reliable. The boilers, as expected, remain very clean because of the high proportion of gas in the total fuel consumed.

The only major problem with the main engine occurred in the first ship *Gadinia,* and was initiated prior to the ship entering service. It was discovered after five years' service, during a refit when the main gearing was being surveyed. This was the first of the epicyclic gears to be opened for survey and it was decided that it should be stripped for complete examination.

During the inspection some cracks were found at the inner ends of several teeth on the sunwheel coupling. The teeth affected were in two distinct groups, eight in one group and nine in the other, positioned as shown in Fig. 3. The cracks were localized mainly in the roots and extending on to the end faces of the teeth. The two groups of cracks were on opposite flanks.

Clearly, it was essential to try to determine the cause of this damage and ensure, if possible, that it was not symptomatic of a common problem. Accordingly, the gear was returned to the manufacturers (the depot stock spare having been fitted to *Gadinia*) for a comprehensive examination. This revealed that the cracked teeth had been bent slightly, consistent with some abnormal load during assembly or disassembly.

The fact that the two groups of bent teeth were disposed 22.5 deg either side of the centre line supported the belief that it had happened whilst the gear was stationary. As the contact angle of the teeth is 22.5 deg, the teeth in these positions would mate first, if one component is tipped relative to the other. It was finally concluded that, at some time, the total weight of the gear had been supported from the sunwheel coupling teeth, deforming them and leading to cracking during the subsequent 5 years' operation. Close examination of the remaining six gears have confirmed the belief that this was an isolated failure, caused by initial physical mishandling.

Auxiliary machinery

No significant delays have occurred due to the auxiliary machinery. Some difficulties have been experienced but have been contained by the use of depot spares.

The high-pressure hydraulic pumps used for steering gear and cranes have been troublesome. The problem has usually been traced to minute particles of foreign matter in the hydraulic oil. High-speed, high-pressure pumps of this type require clinical cleanliness, a condition very difficult to achieve in practice.

High-speed centrifugal pumps have suffered the usual corrosion and erosion, and the tendency has been to introduce non-metallic impellers and wearing rings.

Probably the most costly units in terms of repairs have been the diesel engines which drive the 1.2 MW alternators. Of the six engines fitted, two have suffered major failures. In one engine, one main bearing out of seven failed and damaged the crankshaft so much that it had to be renewed. On the other, a valve guide fractured and the resultant pieces of metal were hammered into the alloy piston, expanding it and causing seizure. This led to a broken piston which freed the connecting rod; subsequently, the rod so damaged the engine entablature that it had to be replaced.

On a third engine of the same type, which fortunately sustained only minor damage, a valve stem broke and the valve, and part of its stem,

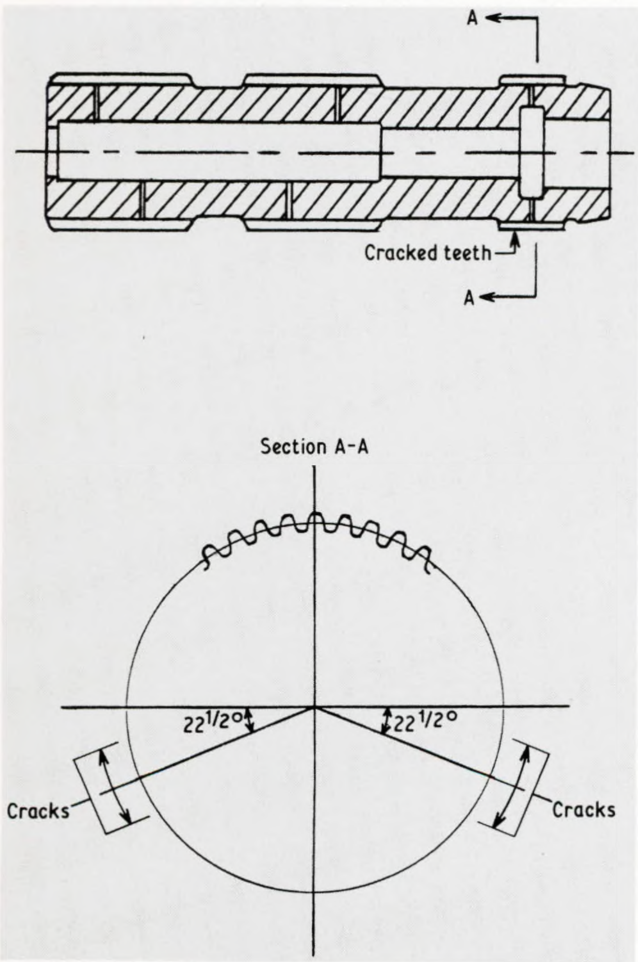
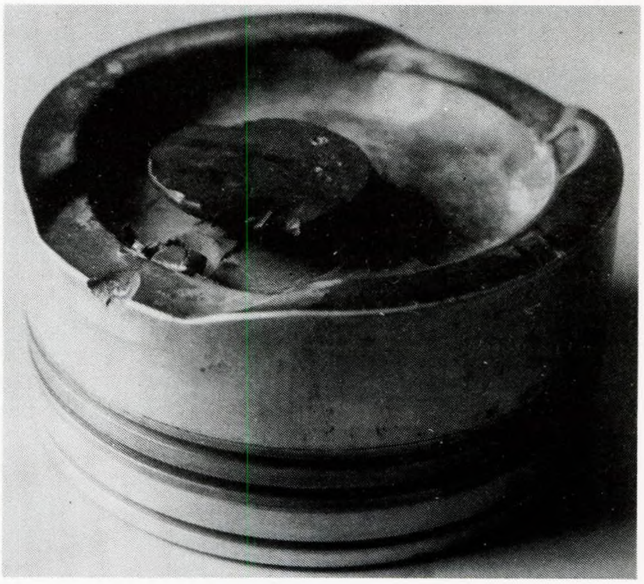


FIG 3 Damaged sun wheel gearing

▼ FIG 4 Diesel generator piston failure



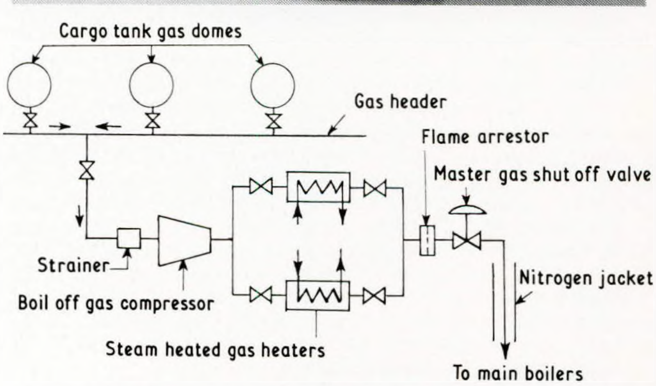


FIG 5 Schematic of boil-off gas supply to main boilers

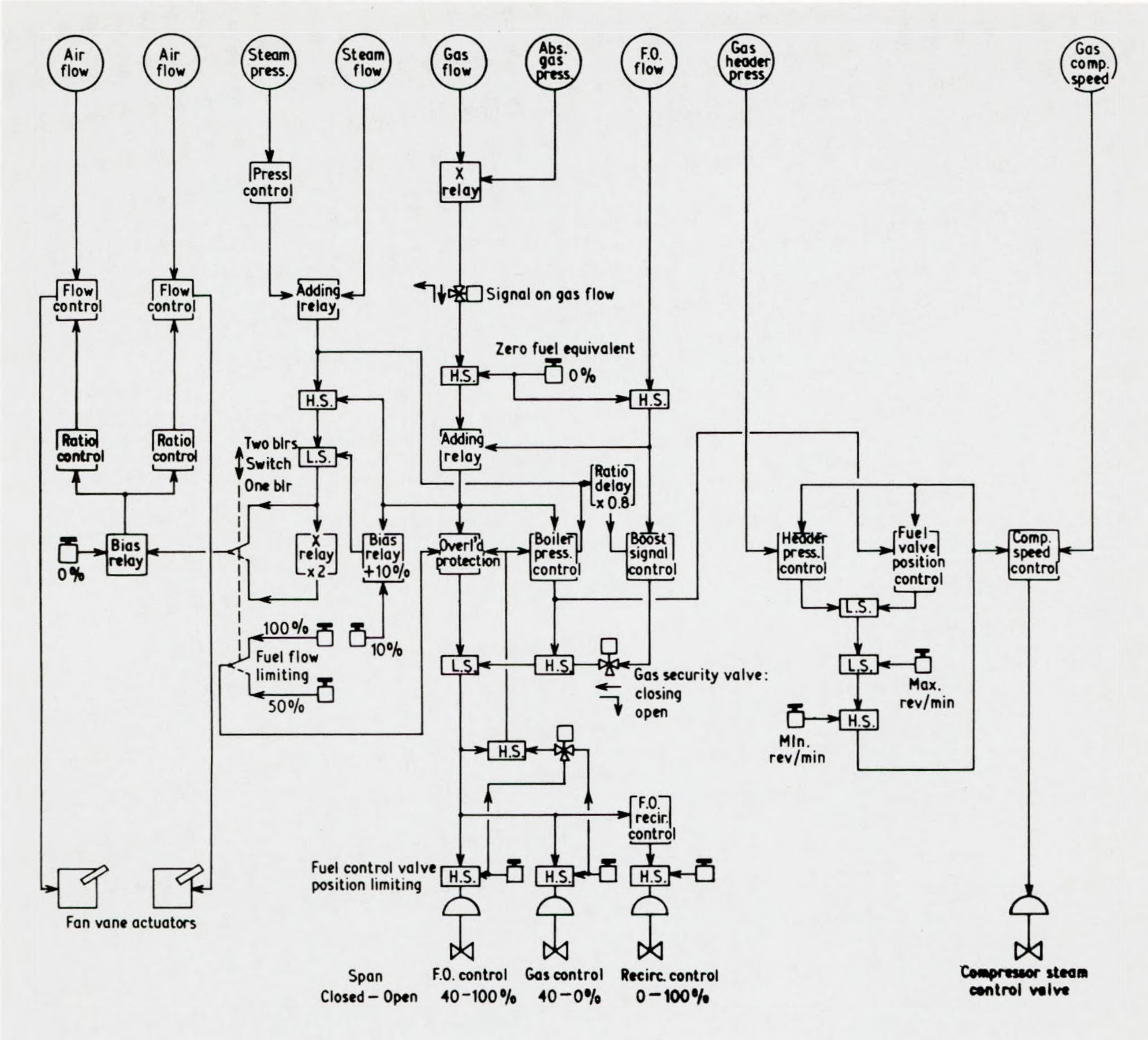


FIG 6 Combustion control system

fell into the cylinder. Figure 4 shows how the valve inverted, with its stem driven into the piston.

These engines were originally designed as traction engines and it will not be difficult to imagine the marine engineers' reaction when the instruction book for the engine recommends, as a prerequisite to any crankcase work, that the engine should be inverted!

Gas burning and combustion control (Figs 5 and 6)

As is normal in LNG carriers, the cargo boil-off gas in these ships is used as fuel for propulsion. Figure 5 shows, in simplified form, the essential elements in the gas-handling system whereby a centrifugal compressor takes suction from the vapour space above the cargo and delivers the compressed gas via a heater and master shut-off (trip) valve to the boiler combustion system.

The gas-burning compressor was initially designed to handle 0.26% boil-off per day, but in practice it has been found that the average loaded boil-off was about 0.31% per day. By a change of materials, the permissible operating speed of the compressors was increased to provide some 10% increase in capacity but, in the long term, with the compressors operating at maximum output continuously, the maintenance load has been high. In an effort to increase the density (and hence the mass flow) of the gas which the compressors had to handle, the insulation on the gas-suction lines on deck has been renewed and improved, to provide colder gas at the compressor suction. This did improve matters but could not solve the problem completely.

Nothing more can be done to increase the capacity of the existing units, short of a complete rebuild, and serious consideration is being given to fit a machine of larger capacity to each ship, while retaining the original compressors as standby units.

Choosing the capacity of the gas-burning compressor is one of the most important decisions to be made in connection with the boil-off gas system since the loss of efficiency, when the compressor operates at a point significantly different from its designed duty, can be substantial.

Early in the operational life of the ships it became evident that the two Gaz Transport ships had significantly better turn-down on fuel oil than the remaining five. Thus they were able to maintain a very stable flame with boil-off gas as the main fuel. Experiments indicated that stable fuel flames could be maintained with oil below 5% of total fuel.

Investigations showed that, though the burner registers were the same in all ships, the two better performers used burners fitted with the Admiralty-designed skew-jet atomizers. Their performance was so much better that the other five ships were converted. All seven ships now use the skew-jet atomizers with excellent results.

The problem of flame failure detection has not so far been completely solved. Ideally, the scanners should be able to detect the presence of an oil flame within the gas flame envelope. Though the wavelengths of the peak levels of emitted light from an oil flame are different from a gas flame, in practice it is found that the gas flame overwhelms the oil flame and discrimination is not possible. Twin ultraviolet scanners, fitted on each burner, have been found to offer the best protection against flame loss or malfunction.

The combustion control system has been developed and improved considerably during the life of the ships; the system shown in Fig. 6 represents the current, and probably final, position. This system has consistently demonstrated the ability to change smoothly from a 100% gas flame to a 100% oil flame within the time taken for the master gas trip-valve to close (typically 7 s).

Particular care has been taken, in the system illustrated, to fit signal selectors so that, when there is any change of fuel, no controllers go into a saturation condition. In fact, all changes can take place without any manual adjustment. Obviously, this introduces additional components and adds to the complexity of the control system but, in an installation which has to manage two fuels, either independently or in almost any combination, this is inevitable.

Probably the most important requirement which distinguishes this from a system using only oil is to cope with a shut-down of the gas supply initiated by the safety system. There are a number of conditions to be met before gas may be used as fuel: adequate pressure, nitrogen blanketing of the gas line, gas temperature, etc., all of which are monitored and each of which must be in a safe condition before the master gas shut-off valve may be opened. Should any monitor detect an unsafe condition, the master valve trips and it is then essential for the fuel oil flow to be increased rapidly to avoid loss of steam pressure or, in an extreme case, a 'black furnace'.

This is achieved by feeding forward a boost signal to the fuel oil controller, which then decays as the fuel oil is modulated by the boiler load signal. At the same time, the supply steam to the gas compressor is shut off to prevent surging.

Following any interruption of the gas supply, restoration of gas burning is not automatic, but it can be initiated remotely from the control room when the problem has been rectified.

The system has operated very satisfactorily and, with the co-operation of the Classification Society, the ships are permitted, on a special dispensation basis, to burn up to 100% gas when in a 'full away' condition, provided all safety checks are operational and healthy. This can result in a significant fuel oil saving when the gas availability matches the required propulsive power.

Cargo loading valves

The special system of loading over the stern of the ships demanded an integrated loading and emergency shut-down and disconnection system which could function without manual intervention. Obviously the possibility of even small spillages of LNG could present a hazard if these were caused by any malfunction of the emergency system.

Accordingly, valves with axially-moving pistons were built into the loading arm since their axial movement provided a ready means of operating a non-return valve (Fig. 7). Unfortunately, soon after the ships entered service, seizure of these valves caused problems. It was found that particles of ice, which had entered them during disconnection, melted, and caused sufficient corrosion for seizure to occur.

Following discussions with the manufacturers, the materials of various parts were changed to prevent corrosion in the critical areas. This sounds much simpler than it was, since the material most resistant to corrosion was useless in a rack gear, essential to the design of the main valve spindle. Finally the spindle had to be made in three sections and screwed together. Some apprehension was felt about these connections remaining tight through temperature cycling from ambient to cryogenic, but fortunately the modification has proven completely satisfactory.

A further difficulty with these valves was increasing stiffness in operation; this was traced to basic wear and tear caused by overtesting. It is the normal practice to test every emergency shut-down trip mechanism which protects the loading system, prior to a ship berthing at the loading port. The end point of each test was the closure of the loading valves. It was realized that each valve went through 14 open/close cycles during a full test sequence. Modifications have been made to cycle the valves only during the first and last test in each sequence, with a consequent significant reduction of wear.

Cargo pumps

In all, 63 main cargo pumps are fitted to all ships. A complete spare pump is retained ashore and the fact that this has rarely been used is a good indication of their reliability. They are of the close-coupled, electric motor driven, submerged type. Initially, it was the practice to renew all the bearings during each refit. However, the replacement cost of the specially selected and matched ball bearings has encouraged careful and cautious extension of the bearing life to the current four years. This appears to strike a reasonable balance between economy and prudence.

The only other pump problems of any consequence have been two cases of broken inducers (Fig. 8), propeller-like screws which assist the flow of LNG into the eye of the main impeller, minimizing cavitation. No explanation of this failure has been forthcoming but, as it only had a significant effect on the pump performance during final tank draining, it was not a serious situation. The small pumps fitted to spray LNG into the upper parts of the cargo tanks to cool them have given trouble-free service.

Cargo level instrumentation

Each cargo tank is fitted with three methods of measuring cargo level. The primary system consists of a capacitance probe with remote digital readout, the secondary is a tape and float with local readout, and, third, there is a directly visible ullage gauge, viewed locally via a porthole in the liquid dome. It is operational when the tank is near maximum fill levels.

As the ship's gauges are used for custody transfer, reliability is of extreme importance. In general, reliability is very high and not until last

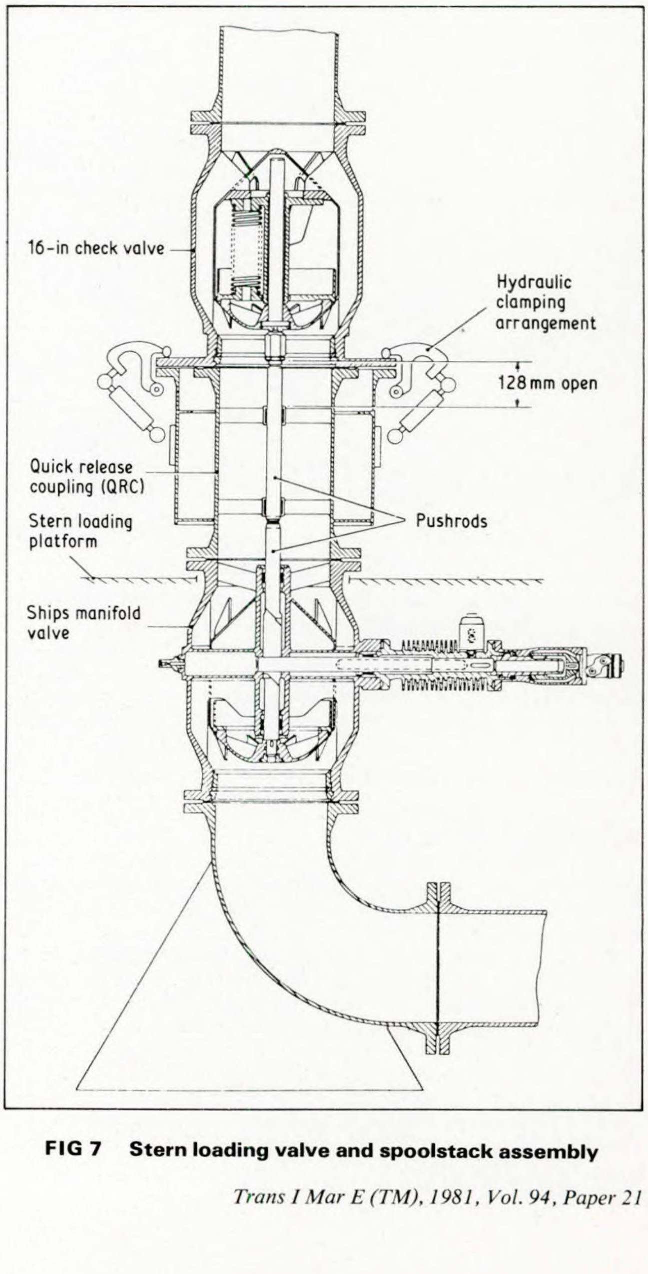


FIG 7 Stern loading valve and spoolstack assembly

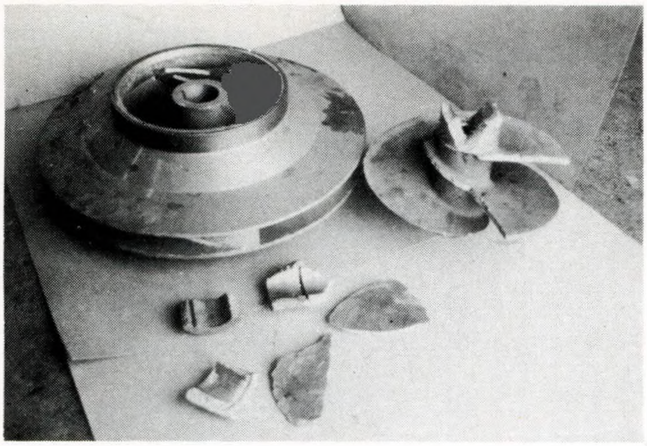


FIG 8 Cargo pump inducer failure

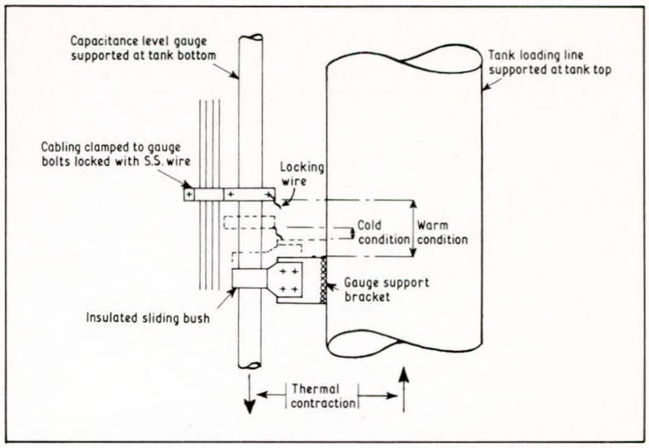


FIG 9 Capacitance level gauge support system

year did one ship have a problem with the capacitance gauge. In this case it was not a failure of the equipment as such that caused malfunction, but an earth contact of the locking wire which secured the clamp bolts holding the capacitance gauge cable to the gauge column (Fig. 9).

The problem arose from the fact that the capacitance probe does not contract in the same direction as its support column; thus, adequate initial separation of the support clamps is vital. In this particular case the locking wire had contacted a column support in the cold condition.

The minimum safe separation distance for these components is now known and routine checks ensure that sufficient margin exists to permit movement during cool-down without earthing of the capacitance probe clamps or any part thereof.

Gas detection systems

Two types of gas detection equipment are fitted. The first is an infra-red detector which monitors various points in the insulation spaces of the cargo tanks and other parts of the cargo handling system. This is based on the infra-red radiation absorption characteristic of methane gas. A single detecting cell sequentially analyses samples drawn from each point monitored.

Second, catalytic sensors are fitted which detect methane in air on a continuous basis. These provide an electrical output proportional to the amount of gas present. This system monitors the machinery spaces and the accommodation.

The gas detection systems are regularly tested and checked for accuracy. They have proved to be reliable, following initial problems with the small diaphragm pumps which draw the samples into the infra-red unit. The original pumps fitted suffered frequent diaphragm failures, but a change to an alternative make of pump has solved this particular problem.

Certificate of Fitness

Following the 1975 IMCO resolution A329 (IX) which set out the code for existing ships carrying liquefied gas in bulk, a comprehensive survey was carried out to check what modifications were required to meet the code. It was satisfying to find that these ships, which had been designed in 1969, met the vast majority of the requirements.

By far the most significant addition required was the fitting of a water-drenching system for the accommodation house. This takes the form of a series of pipelines at various levels round the accommodation which are fitted with spray nozzles. The water flow required was such that an additional pump had to be fitted specifically for the drenching system—an impressive sight in operation.

Additional fire detection was required by the new code, particularly at the liquid and gas domes on each cargo tank and at the loading and discharge manifolds which for the 'G' ships are separate stations. The detection is achieved by fitting fusible plugs in a line pressurized by nitrogen via a flow-restricting orifice. In the event of a plug melting, the pressure in the line falls and that operates a pressure switch linked to the emergency shut-down and alarm systems.

The other modifications can be described as minor, including, for example, extension of the fire alarm to include the gas compressor room; and fitting of gas-tight doors at the two points of access to the accommodation from the deck.

Cargo discharge strainers

Until 1977 the 'G' ships operated satisfactorily without any form of discharge strainers. The only strainers in the LNG delivery chain were those in the Brunei loading lines which were fitted, essentially, to protect the ships during the initial commissioning and build-up period of the project.

Similarly, *Methane Princess* and *Methane Progress* have operated from Arzew to Canvey Island since 1964 without discharge strainers. Since the unfortunate *Hilli* incident in 1977 when problems were caused by debris in the ship's cargo system, there has been a growing insistence for discharge strainers on all LNG ships discharging at Japanese terminals.

The 'G' ships were immediately fitted with conical in-line wire mesh strainers at the liquid discharge manifolds to ensure compliance with customer requirements. The strainers were ASTM 18 mesh (nominal aperture 1.0 mm) and currently these are fitted only during the first one or two discharges after drydocking. Apart from cutting the manifold spool pieces and welding additional flanges to accommodate the strainers, this caused no particular problem since these ships use the stern manifold for loading and only the midships manifold for discharge.

For conventional gas carriers with the normal dual loading/discharge manifold midships, however, the problem is more complex because the strainers must be designed for dual flow conditions, and possibly high surge pressures. In addition, there is a tendency to require fine-mesh strainers, i.e. 60–80 mesh (nominal apertures 0.25–0.18 mm, respectively). These strainers require large surface areas to limit pressure losses to acceptable levels, thereby increasing the installation problems. Also, access to the strainers for inspection can be difficult with the limited access facility normally available at the manifolds.

With normal tank and pipeline inspection standards during ship construction and refitting and—apart from the one incident referred to—the excellent record established in the trade overall, the demands being made, particularly for new projects, appear in our view to be an over-reaction. If it is accepted that the receiving terminal should have some protection against gross contamination then 18 mesh strainers appear to be adequate. They should be limited, possibly, to temporary insertion on entering service and immediately after drydocking, as currently practised on the 'G' ships or, alternatively, installed in the shore receiving lines.

However, an industry standard recommending mesh sizes and the general disposition of strainers, acceptable to both ship and terminal operators, would be of mutual benefit in allowing strainers to be incorporated in the preliminary design stages and avoiding re-negotiation of this item for each new project.

Secondary barrier testing

In the Brunei 'G' class ships and also, to our knowledge, in all LNG ships built to Technigaz and Gaz Transport designs, no failures of the primary barrier membranes have occurred that were attributable to in-

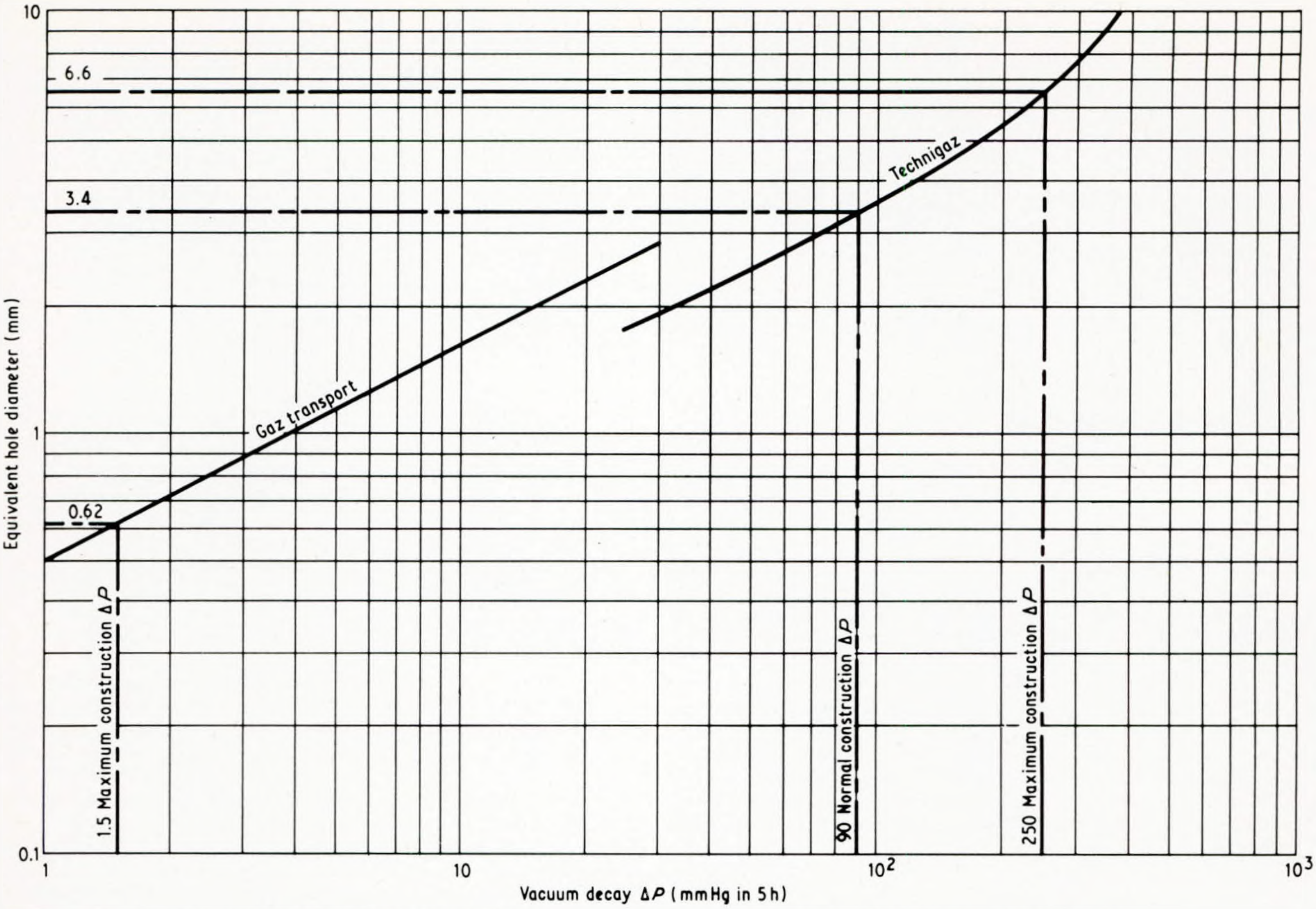


FIG 10 Gaz Transport and Technigaz secondary barrier construction vacuum decay tests

service stresses. By 'failure' is meant LNG leakage through the membrane above normal anticipated gas permeation levels.

Nevertheless, for LNG containment systems of the membrane type, the IMCO Code (Resolution A.328 (ix)) requires the provision of a full secondary barrier. The Code defines the prime requirements of the secondary barrier in paragraph 4.7.4. as:

(a) 'be capable of containing any envisaged leakage of liquid cargo for a period of 15 days
(b) prevent lowering of the temperature of the ship's structure to an unsafe level in case of leakage of the primary barrier.'

In addition, paragraph 4.7.7. requires that 'the secondary barrier should be capable of being periodically checked for its effectiveness by means of a pressure/vacuum test, visual inspection or another suitable method acceptable to the Administration'.

Since in current membrane designs the secondary barrier is normally inaccessible for visual inspection, checking has historically been based on a vacuum test with air.

This test consists of creating a vacuum in the void space between the secondary barrier and the inner hull steel, sealing the space and measuring the decay in vacuum over a period of several hours. The test has been formulated by the system licensors, prior to the existence of IMCO requirements. Its main purpose is to establish that the system meets good constructional standards of global integrity, determined from laboratory work and full-scale ship experience. It does not necessarily test the ability of the secondary barrier to perform satisfactorily in a situation when the primary barrier has failed.

Nevertheless, there is a tendency to adopt the vacuum test as the means of periodic checking of the secondary barrier in service, and comparing these results with the test during construction as an indication of the deterioration, if any, of the barrier. This has caused some problems in interpreting the results in terms of the IMCO requirements and in establishing suitable criteria for the acceptability of the secondary barrier. The problem lies in attempting to relate the results of the vacuum decay test in air—indicating the global porosity/permeability of the system—to the potential leakage of liquid cargo through the barrier and the consequent risk of unacceptably low hull steel temperatures.

For the Gaz Transport secondary metallic membrane, this technique is reasonably realistic, as the acceptability standards are relatively clear cut for a barrier of normally low permeability. Any significant increase in the vacuum decay rate can virtually only mean a weld failure. Such failures, because they are localized penetrations and because the secondary insulation is not liquid- or gas-tight, can provide a potential leakage path for liquid cargo and consequent cold spots in the hull steel. However, for the Technigaz plywood/balsa wood secondary barrier, the situation is less clear. This barrier, in common with most non-metallic systems, has a relatively high permeability to gas even in the 'as new' condition compared with a metallic membrane.

The comparative vacuum decay performance of both Gaz Transport and Technigaz secondary barriers, in relation to construction acceptance criteria, is shown in Fig. 10, specifically for the 'G' cargo tanks but generally applicable to all ships to these designs. In Fig. 10, the vacuum decay ΔP over a period of 5 h from an initial vacuum of 360 mmHg absolute has been plotted against the hypothetical single hole diameter required to cause this vacuum loss, and indicates the normal construction acceptance criteria applied to each design.

From these results, it is clear that the global permeability, as expressed in equivalent hole size, is an order of magnitude greater for the Technigaz system compared with Gaz Transport. The situation with the Technigaz barrier is further complicated by the fact that the initial high permeability can increase even further in service due, predominantly, to micro-cracking of the numerous glued joints through thermal cycling of the system.

This effect does not necessarily compromise the effectiveness of the barrier in meeting the IMCO requirements for containing liquid cargo and hull steel protection, as the total permeability will normally be spread uniformly over the total barrier area and the probability of a concentrated fault through the barrier is very low. However, it does mean that, with the high background permeation, it is difficult to distinguish between a localized fault and global permeation, and also difficult to set realistic acceptability criteria based on vacuum decay test results for this type of barrier.

A programme of secondary barrier testing has been initiated for all the 'G' ships, to be carried out as and when they become available for routine docking. To date, three Technigaz ships have been tested, i.e. *Gastrana*, *Gari* and *Gadila*, using the vacuum decay test with air. Unfortunately, the only Technigaz ship vacuum-tested at the time of construction was the *Gouldia* and, consequently, no 'as new' records for comparison exist for the ships so far tested. For these ships, the results have been similar and generally very satisfactory, as typified by the *Gastrana* results (Fig. 11).

If it is assumed that all the Technigaz ships had secondary barrier constructional test results similar to those of *Gouldia*, the deterioration in service has been small and all tanks are still below the maximum construction limit set by Technigaz. However, with more than 10 years' project life still to run, it is not clear at present what further increase in permeability may be expected with these ships, or what vacuum test acceptability criteria should be applied. Technigaz are currently investigating the long-term effects of thermal cycling in laboratory-scale tests on typical secondary barrier panels. This should give some insight into the further deterioration to be expected, if any.

However, for non-metallic secondary barrier systems with normally high and possibly variable permeability, it is in our view questionable whether the vacuum decay test so far adopted is a reliable means of integrity testing. More discerning test procedures, that can differentiate between relatively harmless global gas permeability and potentially serious localized through-faults capable of allowing the passage of liquid, may be more suitable.

For the Gaz Transport ships *Genota* and *Geomitra*, no comprehensive checks on the secondary barriers have yet been carried out since, with the present programme, the first is not due to dock until the end of 1981. However, while no operational problems have occurred, spot checks carried out on *Genota* in service indicate that secondary barrier weld failures may have occurred. The degree of failure will not be known in detail until the full tests have been completed. Assuming that secondary barrier repairs will be required, however, plans are now being made to ensure that adequate special materials and suitable personnel will be available to effect the repairs as quickly and efficiently as possible.

SHIP SAFETY

Careful design and planning are essential to any LNG project—not least to the LNG ships themselves. The following outlines the attempts made to achieve and maintain the highest standards of marine operations on which the continued success of the project depends, particularly in the area of safety, by concentrating on the identification of the principal marine hazards that are seen and the steps taken to reduce risks. This is a constantly evolving process encompassing the ships, those who sail and manage them, and all concerned with harbour

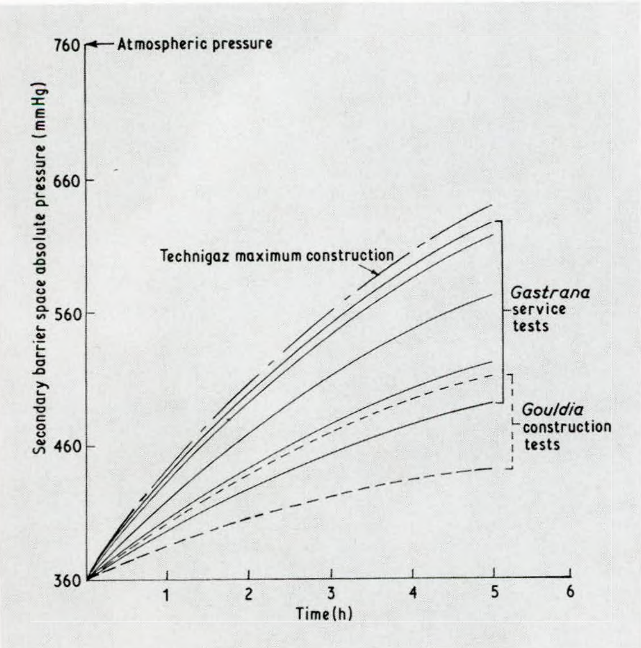


FIG 11 ***Gastrana* vacuum decay tests**

and terminal operations. It requires periodic re-evaluation and up-dating of equipment and procedures in the light of current knowledge.

Special attention has been given to the main risk areas of navigation, staff and crew training and cargo transfer emergency shut-down systems; the development of contingency plans for the type of accident that can occur; and the development of casualty procedures and services to provide an organization for the provision of equipment and technical advice in accident situations.

Risk areas

Navigation

Navigational procedures and equipment have been periodically reviewed since the project commenced in 1972. These cover coastal and port navigation. Most deck staff have undertaken advanced navigational training on simulators and training vessels at navigational schools. Navigational Superintendents periodically visit the ships for onboard training and to ensure strict compliance with procedures. Arrangements are made for 'G' class ships' Masters to visit the Tokyo port radio and traffic control centre, normally prior to an appointment in Japan, to give them a clearer understanding of the procedures and facilities.

The Commodore Master sails periodically on the gas carriers to perform navigational audits and to conduct navigational training exercises to complement shore-side training courses. Close liaison is maintained with the Japanese Maritime Safety Agency (MSA) to discuss and resolve any areas of mutual concern.

The ship's satellite navigator equipment has recently been replaced by more reliable modern instruments and the ship's radar is also in the process of being replaced. The aim is to ensure that the ships are provided with practical and reliable equipment to assist ships' staff to deal with the navigational problems which they may face.

The equipment provisions include satellite navigators for the voyage, particularly navigation in the Palawan passage; satellite navigators and Loran C equipment for the approaches to Japan; radar for navigation at sea and in port using the parallel indexing technique; radar with a plotting aid for collision avoidance; and facsimile receivers for taking weather charts to assist in routeing and avoidance of typhoons.

Advanced collision avoidance systems are also being evaluated. All these instruments are, however, regarded as aids only. The major safeguard against navigational casualties lies in the experience of the staff and their compliance with the correct procedures.

Staff and crew training

Officers normally join the Company as Deck or Engineer Cadets. Apart from the academic qualifications for entry to the training schemes, candidates have to pass aptitude tests and personal interviews. Training alternates between sea service and college periods for some 4 years before their appointment in the Fleet as either Third Officers or Fifth Engineers.

Subsequently, careers are developed through appointments to various types of vessels and by training either 'in house' or in conjunction with nautical colleges. Courses in electronic instrumentation and controls are also run for both Deck and Engineer Officers, specifically aimed in the case of the former for service in the LNG ships. General Purpose Chinese crews are, amongst their general training, instructed in firefighting.

The responsibility for safety rests with all the ships' staff. Onboard ship, immediate responsibility is vested in the Ship's Management Team, comprising the four senior officers under the chairmanship of the Master. The Master is accountable to the Head of Operations, a Director of STUK. Additionally, in accordance with the UK Health and Safety at Work Act, there is a Safety Committee in each ship and an Accident Prevention Officer.

Safety procedures and manuals are the responsibility of the Safety Adviser who is a Senior Superintendent accountable to the Head of Operations. Under the Safety Adviser is a shore-based Safety Officer and a team of three Fleet Safety Officers. These are experienced Chief Officers or Second Engineers who sail in the ships performing audits and safety training.

Navigational training is the responsibility of the Company's Operations Director. He supervises the work of the Commodore, a sea-going Navigation Superintendent and the Training Division. The latter is largely engaged in guiding shore-based training courses.

Cargo operations

Comprehensive operational guides cover all aspects of cargo handling. In addition, extensive use is made of checklists—from small ready reference lists for cargo operations, to comprehensive lists of safety devices. These are used to ensure that the procedures are being carried out correctly and to confirm that safety devices which are not required to operate for long periods are effective when needed.

The cargo operations involving perhaps the most risk are loading and discharging. Whilst the ship is alongside the terminal and is physically transferring cargo, she remains vulnerable, depending on the location of the berth, to any other activities that may be taking place in her immediate vicinity. Security in the berth, in terms of adequate moorings, the reduction of risk of ramming by another vessel and exposure to the effects of wind and waves, is considered essential if the danger of serious LNG spillage is to be minimized.

With this security provided, it remains necessary to consider the maximum spill which could occur during cargo transfer. This requires detailed analysis of the system, to establish which components may fail, the consequences of human failure and then to quantify the spill which could result before flow is stopped.

The possible failure of the ship/shore loading arms justifies special attention. The development of emergency shut-down systems (ESDS) to minimize the consequences of such a failure has been a high priority since the initial design stages of the Brunei project.

Emergency shut-down system (ESDS)

The ESDS developed specifically for the loading system at Brunei[1,2] is, to our knowledge, the first fully-integrated system of its kind. The system allows either the ship or shore to stop LNG transfer quickly and safely, i.e. without creating excessive surge pressure in the loading system, and also to initiate manually or automatically a rapid spill-free disconnection of the loading arms from the ship under emergency conditions. Such a system was considered essential at Brunei to protect the loading crane from overstressing and damage due to excessive ship movement at such an exposed loading berth.

Apart from some teething troubles with the ship/shore signal cable connections and the problems with the ship's stern loading valves described earlier, the system has worked extremely well. Once, when a mooring rope failed, the system saved the ship and loading crane from possible serious damage. At the Japanese discharge terminals, ESDSs were also incorporated to allow ship or shore shut-down of the ship's pumps and closing of ship and shore manifold valves, but without any loading arm quick-release facility.

In recent years it has been considered within Shell that, with the increased knowledge of LNG spill and consequential vapour cloud behaviour, loading arms quick-release systems could advantageously be standardized for both loading and discharge. This would allow the ship to break out of the berth quickly in an emergency and reduce the possibility of sizeable LNG spillage due to loading arm rupture caused by excessive ship ranging alongside.

While the stern loading system quick-release system (Fig. 7) has worked extremely well, it has some disadvantages over more conventional loading/discharging systems. First, it is a complex and costly system that is not readily adaptable to normal midships manifold layouts. Second, it requires the bulk of the specialized equipment, e.g. the quick-release coupling itself, to be incorporated into every ship in the project. The system currently being incorporated in all Shell newbuilding LPG and LNG loading and discharging terminals is shown in Fig. 12. This system is incorporated into the loading arm and requires no special modifications to the ship's manifold.

The discharge terminal ESDS (Fig. 13) is based on two steps. The first step (ESD-1) consists of shutting down the cargo transfer. This covers a first-stage emergency situation where the operators may doubt the safety of continuing operating, and enables fast controlled shut-down of the flow. The ESD-1 system must enable quick resumption of cargo operations once the cause for concern has been identified and acted upon.

The second step (ESD-2) covers a potentially worse situation, in which the ship may be at risk, or if there is a major spill on the jetty. ESD-2 consists of flow shut-down (ESD-1), plus uncoupling of the loading arms. This covers the specific case of potential loading arm failure, e.g. any movement beyond the design envelope of the loading arms, and also allows decisions to be made regarding the safety of the ship, without the additional time required for loading arm manual disconnection.

The three main features of ESD-1, specifically for a discharge terminal, are as follows. First, because flow originates from the ship, stoppage of flow requires ship's pumps to be stopped and ship's manifold valves to be closed. Normally there is a shipboard safety system by which this may be achieved. Figure 13 shows one system, in which depressurizing of a ship's air main, possibly initiated by ship tank high high level alarm, causes shut-down. This also enables crew members to carry out an ESD-1 by opening vent valves at strategic points on the ship.

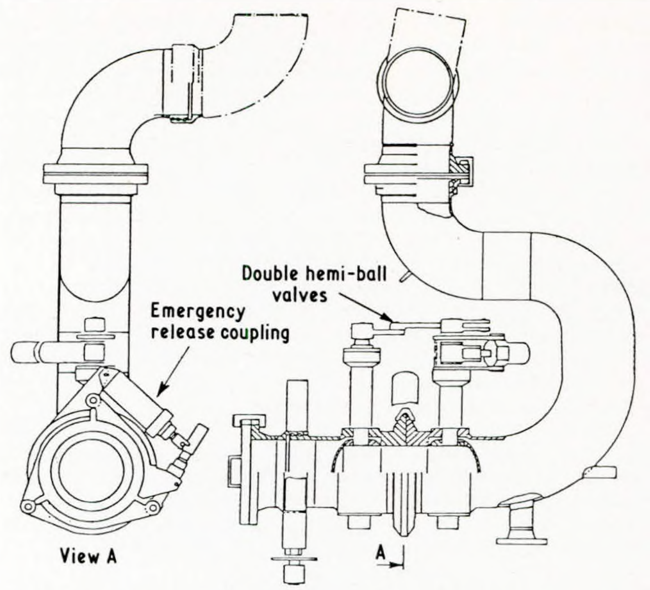


FIG 12 Loading arm with emergency release system

Second, in order that ESD-1 may also be initiated from the shore, a ship/shore link is necessary. Figure 13 shows one such link, which consists of an air hose connecting the ship's air system to a vent valve on the jetty. The vent valve may be opened by a signal from the shore ESD-1 logic system, which can be initiated manually by push buttons at strategic points.

Third, automatic shore initiation of the ESD-1 system can also be achieved from the receiving tank high high level and high high pressure sensors. These signals will also close the valve leading to a specific receiving tank. This valve must be slow closing in order to avoid surge pressure problems and should be designed to reach the fully-closed position after the ship's system has shut down completely.

Similarly, the main features of the ESD-2 system are as follows. First, the loading arms are specifically designed with dry break emergency release coupling installed in the outboard arm (Fig. 12).

Second, the emergency release coupling can be broken automatically by a signal from the loading arm excess angle sensor (XEA). The coupling can only be released after the ball valves on either side of the coupling are closed. If the arm is in danger of being extended beyond its design envelope an alarm will be given, which, if not acted upon, will at the next stage give a signal to the ESD-2 system to initiate uncoupling.

Third, simultaneously with the ESD-2 signal, the ESD-1 flow shut-down will also be initiated, thus causing flow to cease at the same time as the loading arm ball valves close.

Fourth, manual initiation of the ESD-2 action can be also achieved from push buttons located at strategic points on shore.

For a loading terminal the general principles are similar, except that in this case ESD-1 initiates preferential shut-down of the shore loading pumps and valves and also opens a drain valve to a surge tank if necessary to limit surge pressures in the loading lines.

Contingency planning

With every reasonable precaution being taken, the nature of marine LNG operations is such that all risks cannot be totally eliminated. Accordingly, consideration is given to action that can be taken in the event of an accident. An effective contingency plan can only be based on a sound appreciation of the type of accidents that can occur; the possible consequences that can result; and the action that can be taken to contain, or at least reduce, the consequences.

Contingency planning for the ocean leg of the voyage clearly lies within the remit of the ship operator. Within the port the responsibility for safety, insofar as it affects the public and other port users, lies predominantly with the authorities.

From the ship point of view the following equipment has been or is being installed for all the 'G' ships.

Ship-to-shore communications

The first requirement in any casualty situation is the ability to pass data without delay or atmospheric interference between ship and shore. The 'G' ships are now fitted with high-quality satellite communication equipment that will allow direct link via the Indian Ocean and Pacific satellites to ground stations in Japan and the USA, and thence into the general telex system.

Ship refloating equipment

In the event of a ship grounding and rupturing a ballast space, the use of compressed air may materially assist in refloating by reducing draft and changing trim. Each ship has therefore been provided with a diesel-driven air compressor able to deliver 1000 m^3/h at 2.5 bar. The compressor will be stowed aft and will deliver via the ship's fire main and standard fire hoses to individual ballast tanks. Flanges are supplied to secure the ballast tank vent pipes and will incorporate fittings for a fire hose and a pressure gauge manometer.

Ship-to-ship cargo transfer equipment

The ability to transfer safely LNG cargo from ship to ship may be required in order to refloat a stranded ship, or to free a damaged ship of cargo before entering port. Based on Shell's experience of ship-lightening operations at sea, arrangements have been made to position a full set of equipment both in Japan and Brunei capable of allowing an alongside LNG cargo transfer.

The Japanese-based equipment comprises:

- Four foam filled fenders each 2.5 m × 5.0 m, capable of being hoisted by the ship's crane.
- Slings and moorings for fenders.
- One hose rig with manifold connections and slings for liquid transfer.
- One 200-mm flexible stainless steel type hose for vapour transfer.
- Electrical cables for connecting the power supply to five cargo pumps in the relief ship into the corresponding electrical connections in the damaged ship.

This equipment is in store at the Honmoku Shipyard in Yokohama.

Equipment for ship-to-ship transfer operations is also held by Brunei Shell Petroleum (BSP) in Seria. This is similar to the Japanese-based equipment apart from the fenders and the vapour transfer hose and includes two secondary pneumatic fenders each 1.0 m × 2.0 m, and two primary pneumatic fenders each 3.3 m × 6.5 m which already form part of BSP's marine equipment.

The primary fenders are too heavy to be hoisted by the LNG ships' cranes but would be transported and placed alongside by craft. A Compoflex liquid transfer hose rig and electrical cables are also provided. Fortunately this equipment has not yet been required for any incident involving the 'G' ships.

Floating cargo transfer hoses

The ship-to-ship cargo transfer equipment and procedure currently available will allow emergency lightening of a stricken LNG carrier only in fair weather conditions and where the relief vessel is able to moor alongside. While none of the 'G' ships have yet been involved in such incidents that have so far occurred, these conditions have been met and cargo transfers have been successfully carried out. It is, however, possible to envisage circumstances where such a transfer would be extremely difficult if not impossible. Such circumstances may occur when bad weather prohibits the alongside mooring; when the stricken ship cannot be refloated from a grounding situation and consequently the relief ship cannot get alongside without risk of grounding also; or when part of the cargo system of the stricken ship has been ruptured to the extent that an alongside transfer operation would imperil the relief ship.

In these situations the only alternative to alongside cargo transfer as a salvage operation so far available is to jettison cargo.[3] While this operation is viable under open sea conditions, a grounding collision accident in harbour approaches is more probable, where jettisoning cargo could create an environmental hazard.

Due to the consequential vapour cloud, discharging cargo on the sea may not be an acceptable solution; jettisoning also of course is a loss of valuable cargo. A method that potentially would not suffer these limitations is a system that will allow a ship-to-ship cargo transfer to take place at a distance, through floating flexible hoses.[4] 'At a distance' in this context means about a ship's length, i.e. 300 m.

Hoses suitable for this duty need to fulfil the following main requirements. Buoyancy must be sufficient in the 'LNG full' condition to float at or near the sea surface. Fatigue strength must be adequate to withstand the sea motion induced bending stresses under operating conditions. Their flow capacity must be sufficient to allow anticipated cargo transfers in a reasonable time. Frictional pressure losses should allow transfer within the capabilities of the ship's cargo pumps. Their insulating properties should enable limitation of transfer boil-off losses to acceptable levels.

The hoses must also have an empty weight that can be handled by normal ship's manifold derricks; they must be light enough and in convenient lengths that will allow ready transportation to the accident site; and also must be robust enough to withstand emergency handling without significant damage.

As far as is known no flexible hoses are commercially available to date that have a proven capability of satisfactorily meeting all these requirements. Consequently, Shell in collaboration with T.I. Flexible Tubes undertook the development of such a hose in 1979, based on the well-known Compoflex design. Considerable development and testing of materials and construction techniques have been carried out, culminating in the prototype hose design shown in Fig. 14, currently undergoing strength and wave motion flexing tests prior to shipboard handling trials.

This 250-mm bore hose design has been developed to achieve an LNG transfer rate of about 700 m^3/h over a total length of 300 m, with a heat influx of less than 250 W/m^2 through the hose wall while floating on the sea surface. Subject to the satisfactory completion of trials the present intention is to provide suitable hose lengths at strategic positions in a similar fashion to the existing ship-to-ship transfer equipment.

Casualty procedures

In the event of a casualty the satellite communications equipment will be used to pass notification immediately and thereafter to enable a rapid data flow. This will provide

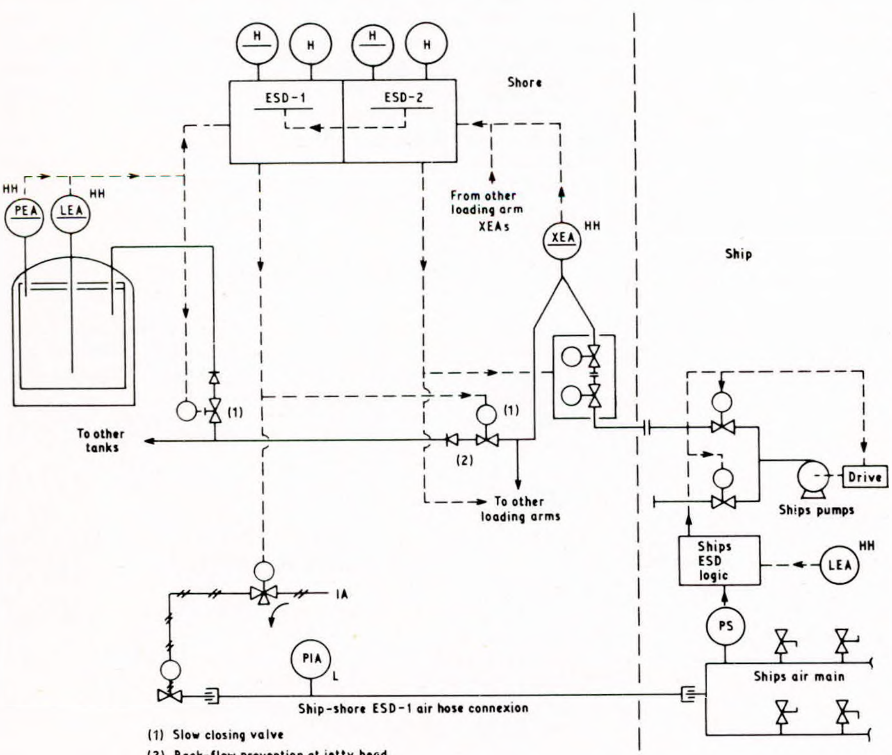


FIG 13 Discharge terminal ESD system

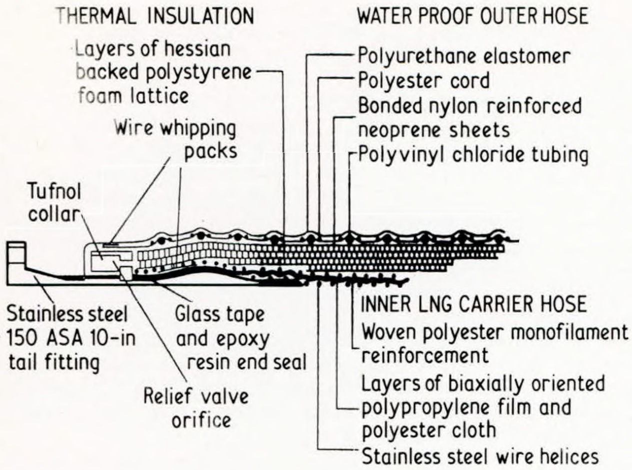


FIG 14 Design of first 10-m length of 250-mm bore prototype

essential input to the damage control computer program in London from which plans can be formulated for refloating a grounded vessel, based on damage stability calculations and hull stress data.

The first-line casualty assistance will be provided by Shell Kosan (IMR) Tokyo, or by Brunei Shell Petroleum (BSP) with prompt support from IMR and possibly Singapore if a casualty occurs in the southern part of the trading route. In both cases a team of specialists and a senior STUK executive will provide support from London and on site if required. On receiving advice of a serious casualty, Casualty Centres will be set up in Shell Kosan and in Shell Centre (London).

Specific communication arrangements will depend on whether the casualty vessel is within Japanese territorial waters and within areas of Tokyo and Osaka Bay; at sea; or at Brunei. Lines of communication for each of these contingencies have been developed.

Following a major casualty involving damage to an LNG vessel it is vital that accurate information be obtained from the ship, regarding position of vessel; nature of accident and details of any personnel casualties; weather condition and tides (if relevant); details of structural damage as known; and amounts of cargo, ballast and bunkers contained in each tank.

The information in this last item would be passed to Shell International Marine Damage Control Group who will immediately use prepared computer runs and recommend any action required to maintain stability and acceptable stress levels. The vessel will keep the Casualty Centre fully up-dated on all changes affecting stability.

The priorities in dealing with any accident are to (1) protect lives; (2) protect environment; and (3) protect property.

If the casualty has occurred in Tokyo or Osaka Bays, the Japanese Marine Safety Agency and Ministry of Transport must be kept fully informed of its extent and action being taken in accordance with the priorities stated. The function of the Japanese members of the Casualty Group would be to establish and maintain communications between the Casualty Centre and MSA/MOT. In this way, assistance to the vessel would be co-ordinated.

The Casualty Centre Group, in the event of a major accident to an LNG vessel, will give immediate advice to the Master and co-ordinate rescue, salvage and damage control efforts through the various authorities and agencies.

CONCLUSIONS

The operating experience and safety aspects described in the paper are of necessity selective in the hope that the items chosen are those of major interest to other owners and operators of LNG shipping. Some of the subjects could, in themselves, form items for lengthy discussion. Nevertheless, some central points, which in our opinion form the nucleus of what has been learnt to date, can be summarized as follows.

The overall performance and reliability of these ships has been excellent in the sense that no out-of-service delays have occurred that have jeopardized the required delivery schedules of the project. This achievement is in no small measure due to the setting up of the Shell Kosan marine department IMR who maintain a close 'on the spot' liaison with the ships and customers, and ensure that all potential problem areas are identified and averted as far as possible and that high maintenance standards are maintained.

The special features, i.e. the cargo containment and handling system, have not so far incurred any major repair and maintenance costs. The secondary barrier repairs anticipated for *Genota*, and possibly *Geomitra*, will be the first major cost item due to the cargo systems.

Demonstrating the integrity of the secondary barriers, particularly for high gas permeable barriers, such as Technigaz Mark I, has caused some problems in interpretation of the standard vacuum decay test and the acceptability criteria to be applied. It is suggested that a different test technique may help to resolve the present uncertainty.

Continuous efforts to reduce operating costs by reducing the energy consumption on voyage have shown quite dramatic results. This has been achieved predominantly by maximizing the utilization of the cargo boil-off on both loaded and ballast voyages. The overall effect has been a reduction of fuel oil consumption per round voyage from 500 tonnes in 1975 to approximately 100 in 1980, while at the same time increasing the net cargo delivery. With the recent increases in LNG value, however, this trend may be modified to maintain optimum fuel cost in relation to cargo delivery.

In the realms of operational safety the emphasis has been and will continue to be on maintaining a well-trained staff and crew assisted by the best procedural guidance and equipment available. Further research into the physical behaviour of LNG spills, in terms of resultant gas cloud behaviour and combustion characteristics, should give invaluable assistance in formulating more effective contingency planning. Similarly, the experience gained with the Brunei emergency shut-down loading system has been the foundation for the further development of integrated loading and discharge systems for new projects. This should significantly reduce the risk and potential size of spillage during cargo transfer operations.

Ship salvage by alongside ship-to-ship transfer of LNG cargo has been demonstrated to be practical and safe under favourable conditions and provides an alternative to jettisoning. Equipment to facilitate this type of transfer is now held at both Brunei and Japan. In our view, however, other techniques allowing cargo transfer or safe disposal with fewer restrictions than currently possible are desirable. The floating cryogenic hose system will hopefully help to broaden the scope for this type of operation.

If the ships were being designed today, it is our view that apart from taking advantage of improvements in design and performance of equipment and machinery it is unlikely that major changes would be made. Different suppliers may be chosen for some equipment but the overall concept of the ships has proved to be well founded. The possible exception to this conclusion is in the attitude towards fuel economy.

With the benefit of hindsight and the present trends in energy prices, greater attention would inevitably be paid to the reduction in the total energy consumption in transportation. Certainly greater consideration would be given to more efficient steam cycles, such as reheat, and possibly even to diesel propulsion. Lower fuel requirements also entail more efficient cargo insulation systems to limit cargo boil-off to within the shipboard consumption potential for steam plant; similarly, in the case of diesel machinery, to reduce the required capacity and power of the boil-off reliquefaction plant to an acceptable level.

ACKNOWLEDGEMENTS

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The authors also wish to acknowledge the support and part-sponsorship of the cryogenic floating hose development given by T.I. Flexible Tubes Ltd, and the Mechanical and Electrical Engineering Requirements Board of the Department of Industry.

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Discussion

M. W. ANKETELL-JONES (BP Shipping Limited): I congratulate the authors on their fine paper and presentation—one of great interest and one which should evoke a considerable response.

The paper did not seem to make clear the relationship between the boil-off rate (BOR) and the power plant design, although it was mentioned that the mean BOR had been 0.31% in service. A design BOR of 0.25% is implied. For example, it is mentioned in the paper that there were six 1.5 MW diesel alternators, presumably running on diesel fuel. The implication is that at the time of design it was thought that the boil-off would be of higher value than diesel fuel and, hence, this expensive solution was decided upon. Reference to Fig. 2 suggests that this decision may have been justified although it is not consistent with the high design BOR. An indication of the design philosophy from the authors would be appreciated.

In practice, however, it turned out that in both the cases of the Gaz Transport and Technigaz designs the effectiveness of the insulation appeared to be below expectations and excessive boil-off resulted. The insulation problem must have been significant as it is understood that it is now necessary to apply heating in the ballast tank spaces.

Could the authors confirm that there was a specific insulation problem or, on the other hand, could they give other reasons for the high boil-off rate; and could they indicate whether or not an insulation guarantee was given to the owners by the shipbuilder as insulation contractor?

Fuel oil consumption

At 0.31% BOR, the excess boil-off on loaded passage is calculated to be equivalent to about 15 tonnes of fuel oil per day. It must be assumed that this boil-off was either vented as gas or was converted to steam and dumped. Alternatively, on the ballast leg at 19 knots there must have been a substantial demand for oil supplementing. It is noted from the text of the paper that great care was given to the question of fuel conservation. Could the authors confirm that objectives in this area were achieved?

Observation of Table II indicates that, in 1980, 100 tonnes of fuel per round voyage were consumed, whereas in 1981 this figure increases to an estimated 180 tonnes. It is noted from Fig. 2 that 1980 is the cross-over point between the boil-off value and the fuel oil price and it is assumed that this is the reason for the increased fuel usage in 1981. Can this be confirmed, please?

Secondary barriers

It is understood that in the Gaz Transport vessels there are cracks in the welding in the support 'chairs' in way of the secondary barrier. It is believed that the first of the Gaz Transport ships is drydocking at Mitsubishi Heavy Industries at the present time. Could the authors say what has been found in way of second barrier; in fact, have the expected cracks appeared? Could they also indicate how long these repairs will take and whether they have been more complex than expected?

In the case of the Technigaz membrane design it is understood that Technigaz is carrying out laboratory tests on thermal cycling of the secondary barrier and, further, that some results may now be available. Can the authors give any information on this aspect?

Safety/contingency planning

It is clear from the paper that Shell Tankers (UK) Limited has developed some first-class contingency planning procedures and that these are implemented effectively. However, no comment has been made on major spill contingency planning and it is presumed that there is no specific arrangement in this regard.

It is understood that Shell has been conducting large-scale tests at Maplin Sands on vapour behaviour resulting from fairly large spills. It is also understood that a simulated live liquid transfer has been carried out between two ships at Brunei. Can the authors give any information on the results of these trials?

On the subject of emergency shut-down, it has been observed from Press reports and other sources that there have been four serious LPG spills in the last 12 months and that these have been due to faulty operation of the ball valve shut-offs. It is clear that all operating companies are, or should be, carefully investigating this serious area. Can the authors say whether the ball valve shut-offs in the discharge systems associated with the 'G' class operation have given any indication of the sort of faulty performance described in this paragraph?

The paper does not cover the case of a significant spill of the sort mentioned in the preceding paragraphs. Clearly an experienced operating company such as Shell must have a good idea of what they would do in the event of a serious spill on board, with particular regard to controlling the ingress of gas into accommodation and machinery spaces. Can the authors give any information on what shut-down procedures would or could be used?

The future

The Australian NW Shelf LNG Project has four participating shipping companies, including both the authors' company and mine. My company has had the duty of performing the optimization studies for the ship design and development of the projects requirement document. In the course of carrying out the optimization study, it was concluded that boil-off rates in the range of 0.15–0.18% were most suitable for the project. This implies a very high performance insulation requirement and, of course, an improved thermal performance on the propulsion plant itself.

The optimization study indicates that, in the course of arriving at these conclusions, it will be necessary to install nothing more sophisticated than an improved steam cycle with four-stage feed heating and, possibly, gas air heating. It was also concluded that for the particular service a re-heat system would not be cost-effective. Investigation into the use of diesel plant with reliquefaction indicates that this approach is not yet ready for use in current projects.

W. H. MARSDEN (Lloyd's Register of Shipping): How refreshing it is to read a paper on the operational performance of tankers carrying high-risk cargoes, and be told that over a period of 9 years a high operational reliability has been consistently displayed.

The success of this achievement to date was measured by the amount of cargo which has been safely transported. This is a simple fact sometimes forgotten in this era of regulations. The authors and their company are to be congratulated in attaining this fitness-for-purpose standard, which the marine industry seeks to achieve in its many conferences and debates.

During these 9 years of operation, changing statutory regulations had to be complied with, in addition to the Classification Survey requirements. The authors have explained how co-ordination, planned maintenance and close liaison with ship's staff, gas producer, customer, government agencies and Classification Society have played an active part in the safe and reliable transportation of cargo. In view of this experience, the authors' opinion would be appreciated on the following two points.

Whilst the LNG trade can be considered as a very specialized operation and, generally, on a fixed trading pattern, can the authors give us their experienced opinion as to whether a small company, having one or two LNG tankers, could organize itself effectively with the type of planned maintenance, operational procedures and contingency planning as described in the paper, or would the cost be prohibitive in such a small company?

It was interesting to hear of planned maintenance works on certain machinery items in association with the Classification Society's continuous survey cycle. It is considered that this type of survey enables planning; but some owners view its extension to hull survey with suspicion. Such owners consider that the continuous survey provides a means by which the surveyor will always be examining the ship, i.e. extending his examination as a consequence of the survey results found during the previously agreed part of the survey cycle.

Taking into consideration the safety aspects of structural integrity, especially with the inner hull, which supports the secondary membrane, can the authors advise on experience associated with continuous hull surveys and its usefulness for refits now planned for at two-and-a-half year intervals?

Turning now to comments under the heading of 'Secondary barrier testing', the authors have given recognition to the valuable service experience that has been obtained with the membrane systems. Service experience has in fact been accumulating since 1969, when the LNG ships *Polar Alaska* and *Arctic Tokyo* are taken into account.

It must also be recognized that, in the design of membrane systems, very extensive prototype testing was carried out. This provided a level of confidence in the secondary containment when such a system is constructed in accordance with the approved procedures and quality control processes. In trying to quantify the knowledge gained by the service experience it is recognized that this could be enhanced by the frequent global examination of the secondary barrier. Such an accumulated record of testing will provide a guide to performance and also indicate whether a particular system, or part of a system, has developed a minor discrepancy which is not significant enough to form cold spots on the inner hull. This regular type of testing during service would maintain the measure of confidence in the system as finalized at the prototype testing.

When the vacuum decay method is to be used for global examination, frequent testing should ideally be carried out by the ship's operators to establish the records and pattern of deterioration in service. Under these circumstances, the projected deterioration of the decay can be established for a particular route, which requires to take into account the ambient temperatures, number of loaded and ballast conditions and sea states associated with the route. However, the authors explained that only three of their five Technigaz ships have had such a test after a number of years of continuous service, and therefore I share the authors' hesitation in being able to define accurately the acceptable criteria for their route when considering the natural ageing of the type of material used. The original 'fingerprint' taken from *Gouldia*, together with the tests presently being carried out, will, however, provide an envelope for an acceptable criterion.

Where the projected range of 'in-service' vacuum decay record is exceeded, then additional investigation should be considered. Detailed search by acoustic detection, trace gases and thermographic cameras are some techniques which are available and being developed. It was interesting to hear this evening from the authors more details of global test procedures, as mentioned on page 9 of their paper, which they consider may be more suitable; and would certainly seem to be more practical than some of the tests I have just mentioned as a detail search, such as thermographic cameras which can only satisfactorily be used in a limited search.

The authors have indicated on page 8 that a secondary barrier type which has a higher level of general porosity in comparison with another type with a lower porosity level need not mean a compromise of safety. Under these circumstances, the reliability engineer would then have to make a technical assessment between two such systems: one with a smaller porosity level but with failure when a defect occurs; or the other, with a larger porosity level but with only a possibility of failure if a defect occurs.

Certain composite materials used for secondary barriers, like plywood and balsa wood, will, due to the cellular structure and temperature difference through the material, restrict the passage of liquefied cargo even under a full working head. This has been confirmed in the testing of recent new materials of closed-cell construction, where a radioactive trace was added to the liquefied gas to establish the ingress of vapour under pressure both in the newly-constructed stage and following long-term thermal cycling effects on the material. In general, the defects in such secondary barriers would only result from the possibility of a continuous passage formed by the micro-cracking of the glue connection.

Referring now to the Gaz Transport ships *Genota* and *Geomitra*, the authors refer on page 9 to secondary barrier weld failures which may have occurred. For record purposes, can the authors please clarify whether the suspected weld failures refer only to the fillet welds of the closing washers which maintain gas-tightness where structural tubes penetrate the secondary membrane? Such fillet welds, with a throat thickness of about 0.7 mm, have been the subject of extensive fatigue investigations in various countries and a number of LNG ships of 125 000 m^3 capacity have already had reinforcement in these areas.

Finally, referring to the impressive section on ship safety, which highlights risk areas, casualty procedures, emergency and contingency planning, the shipowners should be commended for their responsible attitude when considering the extensive technical research involvement of such achievements.

The authors are equally to be commended for placing this responsible and valuable paper on the record of the Institute.

C. A. SINCLAIR (The Salvage Association): The authors have provided details of the practical experimental work carried out by their company in order to evaluate the problems which are likely to arise in an emergency situation, where liquefied gas has to be removed from a vessel which has become a casualty. It is commendable that the results should be made available to both other operators and seagoing personnel.

It is the cause of some concern that the degree of training, and indeed selection, of personnel practiced by the author's company is unlikely to be available to small operators so that, when a number of the older vessels are sold on the market, the good, casualty-free history of the industry is likely to change. This change can be attributed to three main factors: age, maintenance and crewing. Could the authors give us the benefit of their experience and ideas as to how these factors can be mitigated?

Recently there have been some major casualties where the transfer of cargo from the disabled vessel has been effected but, in each case, the weather was favourable and an alongside situation between vessels was possible. It is too much to expect that this state of things will continue. Would the authors please indicate how the proposed floating line would be moored or controlled in a coastal breaker or swell condition with the vessels, say, 300 m apart? In order for the receiving vessel to be safely afloat, it may well be necessary for the hose to be subject to seas at right angles and the forces may be quite large. The delicate link in the chain has always been the cryogenic hoses and the danger of kinking, etc. The new type of hose proposed appears much more rugged but the connecting pieces between lengths may well be a weakness; however, further opinions would be appreciated.

It is noted that the authors' experiments amounted to a dry run and we note that they feel some risk is attached to performing the actual transfer. It would be interesting to hear where they feel responsibility lies for continuation or aborting in the real-life situation; if with the Captain, of which vessel? We note what has been said about the Casualty Centre Group and would consider it should be emphasized that this group is advisory only; the final decisions and actions must be the responsibility of the man on the spot. Will all the vessels have available on board a suitable check list, such as the one included in the gas carrier 'Ship to Ship Safety Guide' issued by the International Chamber of Shipping and the Oil Companies Forum; and will the responsible Master be requested to fill this in and sign it before commencing operations?

Recent casualties have indicated that the vessels can sustain extensive bottom damage without perforating the cargo space. The use of compressed air, to dispel the water from ballast and the void spaces, has been responsible for refloating operations being successful. Do the authors mean to imply that each vessel operated by their company will have the necessary blanks, hose fittings and manometers with connections, or are they to be kept available in strategically-placed dumps? It is noted that a suitable air compressor is to be fitted; this is a step forward, as the logistics of supply and placement in remote places is, to say the least, difficult.

D. St. J. SEIGNE (Department of Trade, Marine Division): The authors describe the emergency shut-down system (ESDS) developed for the Brunei service and mention that further development is taking place. I wish to comment particularly on the ship-to-shore control and communication arrangements for these systems in general.

It is widely accepted, I think, that ESDS systems add materially to safety and should be encouraged. In fact, discussions are currently taking place at IMCO with a view to standardization. The alternatives being discussed are pneumatic and electrical. The former, I understand, suffers from drawbacks due to slow transmission of signal over long lines, possible icing problems and inability to carry messages, etc.

An intrinsically-safe electrical system would seem the best solution but there is one major difficulty in my view, particularly where a mutually acceptable standard is to be considered. The difficulty arises because the rules for intrinsic safety are so very strict. Every part of the system must be subject to painstaking attention to detail at the design and installation stage. The certification documents often lay down severe limitations concerning 'field' wiring and interconnection of other apparatus.

When a ship presents itself at a terminal, the ship's equipment will be connected to that on shore, to form one intrinsically safe system. If any one component is incompatible or incorrectly installed, the whole system becomes uncertified and, worse still, may not be truly intrinsically safe.

I suggest that a simple way round all these problems of interconnections is to introduce an optical isolator between the ship and shore circuits. There is then no electrical interconnection to worry about. Further, if the ship/shore cable is fibre optic then there need be no metal connection at all. This eliminates a possible conflict between the requirements of the port authorities and the rules for intrinsic safety concerning earthing and bonding.

T. W. BUNYAN BSc, FEng, FIMarE: The authors are to be congratulated on a most remarkable success story with their LNG fleet, which they have described in the paper without any claims to fame. They report a number of original developments and we all await, with great interest, the practical demonstration of the ship-to-ship transfer of LNG cargo at sea, a highly dangerous emergency procedure which, we trust, will not be to Shell's account!

I was particularly interested in the paragraph describing the performance of the LNG cargo pumps since the early days of the Shell LNG fleet. The safety factors with the ball and ball bearings, particularly with cargoes of ammonia, had been very low and the sudden and dramatic disintegration of these parts was a most disturbing and costly feature. Critical attention to balancing the internal load reactions of the pumping process has finally produced the solution. The authors have not had to be involved at all with this problem and now run their pumps on LNG ships for 4 years before renewing the bearings. Their cautious initial approach suggests that the notoriety of one pump design—not theirs—had been bad news.

The large, foam-filled fenders, which the authors have said provide high internal damping, I find most interesting. Is this achieved with a short life but a gay one?

Finally, the stainless-steel cargo manifold, produced as a casting without flaws and cheaper than the fabricated alternative, is a most remarkable achievement in a material that is notorious for its propensity to prefer sponginess to soundness, when cast. I remember being involved with some stainless-steel bucket-castings for large Pelton-wheel water-turbines and have the indelible impression that this material was highly temperamental and one which required a high degree of special casting skills—skills which were quite obviously absent at the time and place I was involved.

J. C. HARRISON (Lloyd's Register of Shipping): It seems almost superfluous to congratulate the authors on their paper. Its quality speaks for itself. A very informative document which might well be subtitled 'All you ever wanted to know about LNG operations but never had the courage to ask'.

Most of the points which I had intended to raise when I offered to contribute to the discussion have already been dealt with by the authors, or raised by other speakers, and I do not want to go over the ground again. However, I would like to take this opportunity to explore the topic of the economics of this type of operation a little.

The authors' company is clearly well alive to relative fuel costs and adjusts the ratio of gas to liquid fuel, burnt for propulsion purposes, to give them the best returns; but I have never understood very clearly exactly who owns 'boil-off' gas. Presumably the shipper is reconciled to the fact that he is going to lose something between 0.2 and 0.3% of his cargo per day, through circumstances which are really beyond anybody's control. If the shipowner is astute enough to make use of this 'lost' gas, is he really expected to pay the full market rate for it? And are the FOE prices shown in Fig. 2 strictly relevant? On the other hand, if the liquid cargo is to be broached for purposes of propulsion, as has been considered, clearly this is cargo which would otherwise be delivered, and would be expected to command the market price.

The case for reliquefying boil-off on board ship has received attention over many years, and at least one manufacturer offers such a plant, but I think that, to date, no one has been tempted. I do not have figures as to the likely efficiency of the process in terms of the ratio of the necessary energy input into the compressors, etc., to the calorific content of the recovered cargo. However, liquefaction plant is going to be expensive to install and the power consumption will be very large. Prima facie, it would appear to have little appeal if, after having gone to great expense to preserve that part of the cargo which would otherwise be lost, the owner is still faced with buying oil fuel for propulsion purposes.

The equation is evidently more complex than these factors alone might suggest. Presumably there are increased freights to be gained for more cargo delivered. The savings in the cost of boiler maintenance, which result from burning methane, have been mentioned in the paper, and these would be forfeit. On the other hand there is the energy potential of the 'cold' which would be produced by the liquefaction process.

The delivered gas has to be vaporized at some stage. If further fuel is used as the heat source, this represents an additional energy expenditure. However, if facilities are available ashore which allow the 'cold' to be utilized for cooling cold stores—or in some industrial process such as the liquefaction of nitrogen or oxygen, or even power generation—this represents a gain to offset against the energy expended in reliquefaction. It is quite likely that facilities to make use of this 'cold' are, or will be, available in Japan. The economics of the matter would thus seem to be dependent not only on the relative prices of gas and oil, but on a more complex combination of factors.

Many of those present will be aware that Moss Rosenberg Verft have recently given a good deal of publicity to a new 'economy' design of LNG carrier, with diesel engine propulsion and on-board reliquefaction plant.

Do the authors feel that for their trade, or possibly for the projected Australian North West Shelf trade, the case for the diesel-powered ship with reliquefaction plant is becoming more attractive *vis-à-vis* the type of ship under discussion; or could be made so with an integrated operation involving the interests of the producer, the shipper, the consumer and, possibly, users of the 'cold energy'?

J. McNAUGHT CEng, FIMarE: During a recent visit to Australia I was told about the successful sea trials of a 1500 BHP diesel ship which had been designed to run on diesel or gas.

To operate LNG ships economically, the requirements for propulsive power had to be minimized in order that the boil-off from the cargo could provide a substantial proportion of the daily fuel consumption. What success has the authors' company had in reducing hull drag by using self-polishing paints on the hull and maintaining the propeller with smooth surfaces? What roughness values for hull and propeller are unacceptable and how do they maintain their standards?

J. PAUTHIER (Technigaz): Invited to do so by Mr Prew, and to answer Mr Anketell-Jones' question, I am pleased to explain to you in a few words the tests that Technigaz is performing in relation to the control of the secondary barrier integrity.

The first test is performed on a full-scale model representing the junction of four panels. The intent of these tests is to demonstrate that, even if there is an increase of secondary barrier permeability during the life of the ship due to thermal shocks, the secondary barrier is still able to fulfil its function of temporary liquid containment system after 25 thermal shocks (equivalent to 25 drydocking operations).

The testing sequence includes 25 thermal shocks with liquid nitrogen and then a 15-day test with liquid nitrogen, followed by a 15-day test with liquid nitrogen at 1.5 bar pressure. This pressure is equal to the hydrostatic head of liquid on a 125 000 m^3 LNG carrier. During this 15-day test the inner hull temperature will be carefully checked in order to detect any cold spots. We have just completed the test comprising 25 thermal shocks and we will soon start the test with liquid nitrogen under pressure.

The second test concerns the use of a thermographic camera to locate defects. Full-scale experiments onboard ships have shown the practicability of the method but we still had to demonstrate that the camera will detect defects which are below the critical size. We first determined the minimum defect which can easily be detected in shipboard conditions and we are now in the process of demonstrating that this defect is not critical; i.e. it will not give way to a cold spot on the inner hull if liquid nitrogen at 1.5 bar pressure is applied on the secondary barrier in way of the defect.

Both tests will be presented next week to representatives of Lloyd's Register of Shipping and Bureau Veritas.

D. L. SAUNDERS-DAVIES (Ewbank & Partners): The authors' eminently clear and absorbing account of Shell's LNG ships in operation reflects the very high level of competence and expertise which has existed from the inception to the execution of the Brunei/Japan operation. The record speaks for itself and is one of which the Shell Group and all those associated must be justly proud.

In the 'G' class ships, considerable use is made, both for engine and for cargo operations, of centralized controls and automation. One or two instrumentation problems were described in the paper but the impression given was that, in general, instrumentation and controls worked satisfactorily. This being the case, perhaps the authors could elaborate on how continuous reliable performance has been achieved with extensive and, in some areas, sophisticated equipment. The ships operate on a liner trade and this, of course, makes the setting up of a maintenance scheme rather easier.

It would be interesting, however, to learn how much shipboard maintenance and calibration is undertaken and whether ships' engineers, officers and crew receive special training in this respect.

In considering future plants of increased size and complexity, feedback of operational experience from the ships to the manufacturers of equipment is believed to be valuable. Has this been found possible and would the authors agree that there is still a communication gap here, not only in respect of marine but generally in industry?

R. G. BODDIE FIMarE: In the case of an LNG spill, what specific instructions are given to the Master with relevance to crew and ship safety?

M. Z. NAVAZ (Lloyd's Register of Shipping): Salvaging the cargo as a safe handling exercise is very important, as the authors have so rightly pointed out. Such operations should be a vital part of the initial design concept of the ship and considered long before ship construction has commenced. This was highlighted in a paper which I presented before this Institute in 1972, entitled 'The carriage of hazardous cargoes by sea requiring environmental control'.

With regard to cargo pumping requirements, I refer to the IMCO Code requirement, para. 5.5.1., where at least two separate means of pumping out the cargo are called for. I sincerely hope, in the light of what has been said in the paper, that a deeper and more practical approach to the reasoning expressed by this simple code requirement is adopted by future designers and operators of LNG vessels—or indeed any bulk hazardous liquid cargo carrier. A few years ago I was involved in a situation where every cargo pump was out of commission and inaccessible for repair and a portable compressed-nitrogen driven pump had to be made use of to remove the cargo.

I am glad the authors have raised the issue of secondary barrier testing. I have, as a member of the working party concerned with the drafting of the Code at IACS and a member of the UK delegation at IMCO, etc., voiced strong reservations about the oversimplified words associated with the Code requirements on this subject. The Code attempts to oversimplify the concept of safety by instituting testing as a naive criteria without taking into account any of the enormous amount of research and prototype testing that was carried out prior to approval being given to a system. Such initial investigation should be considered for acceptance in lieu of testing.

In engineering, there are many examples of establishing low-risk profiles associated with a design on the above basis. In the Code itself there are many areas of cargo containment design using this concept. An attempt to consider a 'tank within another tank' concept has historically never been the safety concept associated with secondary barriers. The proposed testing requirements go against the terms of reference of the working party mandate to draft a Code around design standards associated with existing LNG ships sailing the high seas. Nevertheless, the subject matter would sooner or later have to be re-examined.

Finally I would like to refer to Tables I and II, and Figs 1 and 2. The pricing of LNG is still a much-discussed subject. During the first week of December 1981 the *Financial Times* reported that a new price of \$6.11 per 10^6 BTUs was being agreed, to bring about a 43% rise in the price paid by France for Algerian gas. It is said that the USSR piped-gas price is now between \$5 to \$5.70 per 10^6 BTUs. This trading pattern is likely to be the trend towards the end of this century. In Indonesia, it is said that the income from LNG alone in the next 20 years will exceed that earned from all other hydrocarbon fuels, including crude oil. It also appears that the gap between fuel oil price and LNG will widen, as Fig. 2 shows. All this will have a significant role on the size of LNG ships, containment systems, insulation designs and boil-off handling.

As regards Fig. 2, a more detailed horizontal axis would have been helpful indicating the time of the year and thus the ambient temperature when these measurements were taken with reference to the figure. It is misleading to evaluate the mean boil-off, because the two ships have different insulation systems. Further, if we disregard the two or three extreme readings, the mean boil-off for *Geomitra* is likely to be nearer 0.33%—as originally estimated in the plan approval stage of the design. It also appears that this figure is likely to be exceeded since we are only halfway through the life expectancy of the ships.

Insulation deterioration appears to be a big problem in the light of the foregoing comments and the authors' comments on the following points would be appreciated:

- What consideration should now be given to the installation of reliquefaction units on board LNG ships, either as a zero-loss system or as a partial boil-off burning system appropriate to the economic parity between fuel oil prices and LNG prices, possibly with reduced speeds to equate to annual shipment demands?
- Should we look more critically at a water segregation bulkhead adjoining insulation spaces?
- Should a void space be created between a water ballast space and an insulation space?
- Should a *controlled*, low, intermediate ambient temperature be considered in the design stage so as to reduce the boil-off rate to acceptable levels, using, say, 0°C or −20°C as the controlled intermediate ambient temperature level—by a simple refrigeration system?
- Should the insulation system be so designed so that it could be renewed after a period of time; or even removed and regenerated to its original state by drying?
- Should we not look at sloshing other than as a damage criterion but as a natural phenomenon that will occur at intermediate levels; and then mechanically engineer a system to minimize the heat input of this mechanical energy?
- Should we look at tank design more critically, to reduce the free surface of the liquid's movement in the tank?

A. LAREDO (Chantiers de l'Atlantique): I should like to congratulate the authors on the clarity of the paper and above all on the valuable operational data rarely found in other publications on LNG. Figure 1, for example, is very useful in giving the variation of boil-off in 1980.

Four of the ships ordered in September 1969 were built at Chantiers de l'Atlantique and, in all cases, initial contractual deliveries commencing in October 1972 were maintained. This was made possible by the excellent collaboration of the Shell technical team which proved competent and efficient. It is with some satisfaction that I now hear of the good service performance of these ships—a thousand cargo deliveries in 10 years is the proof! We have been particularly impressed by the importance given by the owners to safety aspects, especially staff and crew training.

The aspects of secondary barrier integrity are very interesting. Given the excellent reliability of the primary barriers, one can question whether the IMCO Code requirement of a secondary barrier is really justified for the membrane design of ship. The authors will be interested to learn that shipyard research is currently in hand to develop non-destructive means of detecting secondary leaks based on thermographic camera and radioactive tracer gas techniques. Finally, I should like to ask the following questions:

- What is the maximum filling level used by these ships in service?
- Figure 2 represents the variation of fuel oil and boil-off values. If the 1980 trend should continue, do the authors foresee an increase in the voyage fuel oil consumption?
- Would it be possible to know, with 10 years' operating experience, if the size and speed of these ships remains the optimum? In other words, if the owner undertook the same project today, what size, speed and boil-off would be chosen?

Author's Reply

In reply to Mr Anketell-Jones, the design philosophy adopted for the 'G' class ships did not differ significantly from that employed for present-day LNG projects, i.e. to design ships that would minimize transportation costs without knowingly taking technical risks that could jeopardize ship reliability.

Extensive simulation modelling of the shipping phase, together with the best projections of future fuel oil and LNG values available at that time (1968–69), led us to the conclusion that the seven 75 000 m^3, 19 knot ships comprised the optimum solution based on an assumed design loaded boil-off of 0.25% per day. Normal at-sea electrical load is met by turbo-alternators and only high port load, such as cargo discharge, is met by the additional diesel alternator: i.e. virtually the same philosophy being proposed today by Mr Anketell-Jones' own company for the NW Shelf scheme.

The only flaw in this decision was in the assumption of the 0.25% boil-off figure which, in the absence of any operating experience of these designs at that time, had been based on theoretical predictions that have subsequently been found in service to have been optimistic. The actual average loaded boil-off is, as stated in the paper, 0.31% in service. This level, with the benefit of hindsight, is to be expected for the tank surface area/volume ratios and insulation conductivity values employed in these ships. From this point of view there have been no insulation problems as such with either ship design, in that boil-off values have remained substantially constant and no significant deterioration in insulation effectiveness has been detected since project start-up in 1972.

We would also point out that the only external heating applied to these ships is in the transverse cofferdam spaces during the loaded passage. This is a normal requirement for any membrane design ships and has been practised on all the 'G' ships as routine since commissioning; it is by no means a recent requirement.

The interpretation of loaded and ballast fuel oil and boil-off consumptions is broadly correct in that, during the loaded voyage, excess boil-off is vented to atmosphere and on the ballast voyage additional make-up fuel oil is required. In terms of energy conservation, the aims have been to minimize venting losses on the loaded voyage by increasing the boil-off compressor capacity and also increasing the boiler gas-burning capability. On the ballast voyage, conservation has been achieved predominantly by slow steaming to match more nearly the energy requirement with boil-off availability and also providing the flexibility in cargo delivery required.

Within the available limits of commercial operation these aims have been largely achieved, as indicated in Table II of the paper. These aims are being constantly reviewed in the light of relative fuel oil and LNG values; this has led to the increased fuel oil usage in 1981.

Since the paper was written, *Genota*, the first Gaz Transport ship, has entered dock at Yokohama for the inspection and repairs to the secondary barrier. Careful testing and inspection has indicated that secondary barrier sealing washer failure had occurred in the three central cargo tanks. These failures have taken the form of partial or complete circumferential weld failure in way of the washer/tube welds, to the extent of between 5 and 10% of the total washers per tank.

All failures have occurred on the flat bottom area of the cargo tank. This fact, together with the concentration of failures within the central tank section, confirms in our view that this problem is a function of hull bending fatigue stresses, aggravated in many cases by poor-quality initial welding of the washers. The total repair time for *Genota* is anticipated to be about 5 months.

In the case of the Technigaz membrane, we refer Mr Anketell-Jones to the written contribution of Mr Pauthier, who describes the laboratory tests being carried out by Technigaz to demonstrate secondary barrier integrity in service.

On the safety side, Shell have carried out extensive gas cloud dispersion and ignition tests at Maplin Sands, simulating the instantaneous and continuous spillage of LPG and LNG on to water. Details of these tests will be presented to the Institute of Marine Engineers in May 1982 and we shall not attempt to pre-empt the paper by detail discussion here. However, we would make the general comment that the data obtained largely confirm previously suspected behaviour characteristics of cloud dispersion, in terms of Shell theoretical dispersion model predictions, and that no real surprises occurred during the tests that gave rise for concern.

In a similar vein, an alongside ship-to-ship transfer of LNG has been simulated at Brunei using two of the 'G' ships, as we disclosed during the presentation of this paper. The purpose of this trial was to check the procedures and contingency equipment described in the paper under realistic operational conditions. While no cargo was actually transferred during this test, we are glad to report that it was a complete success in all other respects.

While the emergency shut-down system philosophy adopted at Brunei and as proposed for newbuilding terminals is similar, the hardware and system design to achieve these ends are completely different, as can be seen by comparing Figs 7 and 12 in the paper. No accidental spillages have occurred in service with the Brunei system. Shell have not been alone in adopting the loading arm emergency release system as a safety measure to reduce the risk of accidental spillage during cargo transfer operations. Unfortunately, during the last year, several incidents have occurred at non-Shell installations where the system has malfunctioned causing premature opening of the release coupling with resultant spillage and, in one case, the death of personnel.

Regrettable as these incidents have been, they do not in our view alter the philosophy that such a system is desirable provided that it is properly engineered and maintained. The fact that some systems currently commercially available have design weaknesses does not absolve the terminal operator from doing his utmost to improve safety standards and provide and maintain systems that are inherently reliable and failsafe. This the authors feel can be and is being achieved and organizations such as IMCO, ICS, OCIMF and SIGTTO, recognizing the advantages, are formulating recommendations for their use.

Regarding Mr Marsden's comments, it is felt that a small company, with perhaps two LNG carriers, could well operate in a reasonably economical way, though it can never be said that these are cheap ships to build and operate. It would, however, seem possible to operate two ships with three crews, one of which would in effect be a 'relieving' crew.

Thus the advantages of continuity in knowledge and skill would remain and there seems no reason why the continuous machinery survey and continuous hull survey (CHS) system could not be adopted as well. Adequate supervision is also a vital need, but should be possible even for two ships, where one superintendent could readily cope with their needs and become totally familiar with the ships and their systems.

Regarding CHS, it must be said that this has worked well for the ships referred to in the paper. It confers some flexibility with regard to refit dates; and for ships which have, of necessity, to be maintained to a very high standard, it does not produce any particular problems.

It is in our view questionable whether testing of primary and secondary barriers at sea is a completely practical proposition. Frequently, time is not available on a ballast passage for such a test. On the more specific question of the defects in the Gaz Transport system, it is confirmed that these were confined to the fillet welds of the closing washers on the chair penetrations through the secondary barrier.

In answer to Mr Sinclair, the difficulty in monitoring the performance and operational integrity of a marginal ship operator is recognized. A possible method of running a small number of ships was mentioned in the reply to Mr Marsden. Hopefully, some self-regulation of the industry through such organizations as SIGTTO will be widely enough practised to help in this regard.

It must be emphasized that, in our view, any LNG transfer, be it from ship to ship with the ships tied alongside one another or via a floating hose, must be a fair-weather operation. The risk of making matters worse by undertaking such an operation in adverse conditions is unacceptably high.

In the event of any casualty, the final decision rests with the Master. However, the intention would be to provide him with the best possible advice from a team of experts sent to the scene as rapidly as possible, backed up by another team who would remain continuously on call in the head office.

The provision of a salvage compressor to each ship was considered to be advisable since this is usually the first unit required in a casualty situation. All the necessary blanks, hose fittings, manometers and relief valves are provided to enable air to be introduced into any or all ballast spaces as required.

In reply to Mr Seigne, the possible methods of providing a reliable emergency shut-down signal link between ship and shore have been considered in some detail. Some of the options studied have been:

- A fibre optic link.
- A dedicated radio link.
- An electrical link.
- A pneumatic link.

The fibre optic link, as proposed by Mr Seigne, has a number of attractions as a transmitter of interference-free signals. Our shipboard experience has been confined to its use as a signal medium between room and bridge and also from ballast monitors in a pumproom to the cargo control room. As a fixed installation the capabilities of such systems are impressive. However, as the ESDS ship–shore link is essentially a temporary plug-in system and no plug-in joints or connectors are available as yet in fibre optics, this system has been discounted at least for the immediate future although it holds out considerable promise in the longer term.

Similarly, a radio link using dedicated frequencies is possible but is subject to interference from outside sources and this could cause maloperation of the ESDS. International certification was also considered to be difficult and, similarly, has been discounted at least for the time being.

There are a number of ship/shore ESD systems in existence that use an electrical link. These are almost exclusively on the liner trade liquefied gas projects and sometimes incorporate modern electronic alarm processing systems. Certification of intrinsic safety is of course achievable where both halves of the circuit, ship and shore, are known. However, for an international ESDS where one-half of the circuit may have to be certified by a national authority without the knowledge of what the other half may contain, certification would be difficult if not impossible.

Consideration of the above systems has led generally to a preference, at least in the short term, for a pneumatic link. Even though it is recognized that pneumatics can lead to possibly long and variable response times in the ESDS, the pneumatic link has the overriding advantages of being already in use in a large number of the world's gas carriers; it is simple and reliable; the connections are easy to standardize or adapt; conversion to and from an electric signal is simple, and it does not require safety zone certification.

The foam-filled fenders referred to be Mr Bunyan are in fact expected to have a longer life than pneumatic fenders since, if they are punctured, they do not immediately deflate since the foam has closed pores with a very minimal (0.07%) permeability.

In answer to Mr Harrison's comments, whilst it may not be typical for all LNG schemes, the Brunei/Japan scheme operates on the basis that all propulsion fuel is for the charterers' account and, as he also owns the gas which is boiled off, the question of payment for the boil-off by the shipowner does not arise.

The 'cold' in the LNG is indeed sometimes used in adjacent process plants; for example, there is an air separation plant close to the main Brunei LNG-receiving terminal in Japan that uses the cold from the LNG in an air liquefaction cycle. While the potential economic advantages of this have been recognized since the mid-1950s, in practice it has generally proved difficult, if not impossible, to reconcile the commercial and technical differences between the two businesses. Such differences are exemplified by the fact that the ideal geographical location for an LNG-receiving terminal is not necessarily the optimum distribution centre for liquefied oxygen and nitrogen or as a cold storage facility. Also, the seasonal load factors for the two types of plant tend to be diametrically opposite. Nevertheless, the incentive to minimize energy consumption is increasing daily and the tendency to make the best use of the LNG cold must surely increase.

We are aware of the Moss Rosenberg proposals for diesel engine propulsion and onboard boil-off reliquefaction plant and tend to sympathize with the views expressed that this system is becoming more and more attractive, at least in theory. The successful commercial exploitation of such systems, however, will depend largely on the long-term reliability of reliquefaction plants being demonstrated; and also on the commercial cargo containment systems being able to achieve very low 'boil off' levels to minimize power consumption for such a plant. At this stage we consider that neither qualification has yet been achieved with sufficient degree of assurance to warrant inclusion in imminent ship tender specifications such as the Australian North West Shelf project. In addition the size, power requirements and complexity of reliquefaction plant required to recover boil-off on existing ships makes retrofitting of this plant almost certainly economically unattractive.

To answer Mr McNaught, both self-polishing antifouling paint and propeller polishing has been carried out on the ships under discussion. There is no doubt that these innovations have reduced the fuel consumption, but we are not yet able to apportion the amount of saving to each item. However, monitoring equipment is being developed which should enable us to quantify these savings.

Standards are difficult to maintain once a ship has been in service for two-and-a-half years. Of course, it is possible to clean off fouling and re-polish a propeller but we have not yet set levels of unacceptability.

We should like to thank M. Pauthier for his very interesting contribution and look forward to hearing the results of the Technigaz tests in due course. The tests should give a better insight into the increase in secondary barrier permeability with the number of thermal shocks and also the technique to locate the failures should they occur.

In our view, however, a simple periodic test procedure that will reliably differentiate between global porosity and local through-faults would be of considerable interest. One such test is illustrated in Fig. D1 where the inter-ground space (IGS) is maintained under a vacuum, while air or nitrogen plus a tracer gas is admitted to the inter-barrier space (IBS) to maintain it at atmospheric pressure.

Flow from the inter-ground space is monitored for concentrations of the tracer gas. The principle of the test depends on the fact that normal global diffusion or permeation of the tracer gas through the secondary barrier is slow and will take many hours, days or even weeks, depending on the diffusion coefficient of the barrier materials. Consequently, over the test period of a few hours, no tracer gas concentration should be detected. On the other hand, any through-fault in the secondary barrier will allow tracer gas to pass by normal capillary flow, so that the response to tracer gas detection will be almost immediate. The advantages of such a test for permeable secondary barrier materials are:

- With a suitably high molecular weight tracer gas to reduce diffusion rates, and a gas that is not normally present in the atmosphere or containment system materials, the distinction between global permeability and localized through-faults should be evident.
- The test can be carried out quickly and efficiently, i.e. within 2 or 3 hours compared with vacuum decay tests of 5–10 hours per tank.
- A constant pressure differential is maintained across the secondary barrier during the test, thus eliminating errors in the vacuum decay tests due to extraneous piping and valve leakages.
- The test is insensitive to atmospheric pressure and temperature variations during the test, a major source of error with vacuum decay testing.
- The test is a relatively simple go/no-go test where, if no tracer gas is detected within a limited period, the secondary barrier may be considered free from through-faults and consequently acceptable, irrespective of global permeability.

In reply to Mr Saunders-Davies, the instrumentation has generally worked well, with most maintenance and calibration being done by ships' staff. To facilitate this, a range of test equipment is available which can be sent to whichever ship has a need for it. Such items as a calibrating oven, precision pressure gauges, printed circuit test and fault diagnosis unit are available. With the ships' outfit of meters, oscilloscope, etc., these enable quite comprehensive checking and calibration to be carried out.

Of course, any defect which cannot be handled by staff is dealt with by calling specialist help as necessary and it is true that the ships' regular schedules help greatly in this regard.

Engineers and Electronics Officers are given training in electronics as applied to the marine plant, and Engineers also receive training on pneumatic control equipment. This training is always kept in mind when selecting staff for these ships.

Feedback remains a problem which should be soluble; but efforts to discuss problems with manufacturers have, in general, been disappointing. Most suppliers do not really want to discuss failures of their equipment, probably because they fear the possibility of claims, and no doubt occasionally because the model in question is no longer current.

Mr Boddie raised a question on spill procedure. As no cargo operations are carried out at sea, any spill is likely to take place when loading or discharging so that the ship would almost certainly be in port. The ship is fitted with many gas alarms, several of which are in the accommodation.

The procedure is to extinguish any naked lights, eliminate the cause of the spill and carefully monitor any spread of gas. Two favourable factors apply. First, natural gas is very light (about half the density of air) and so it disperses very quickly; second, as it is cold it causes the moisture in the air to condense and form a vapour cloud. The limits of this could represent a safe, easily-recognized limit to the spread of gas, i.e. areas outside the vapour cloud will be safe.

Concerning shipboard reliquefaction, Mr Navaz is referred to our reply to Mr Harrison. The water segregation bulkheads adjoining insulation spaces have always been a source of concern for this type of ship, as

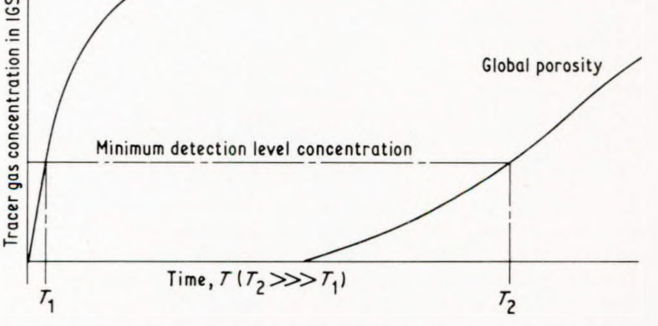

FIG D1 Simple periodic test procedure to distinguish between secondary barrier global porosity and local through-faults

sea-water leakage into the insulation can be an expensive and time-consuming exercise to put right. In our view, however, with the availability of finite element techniques during design and good-quality hull construction and supervision, the risk of bulkhead failures should be remote and sufficiently small not to justify a void space between ballast and insulation spaces. Certainly no ballast leakages have occurred with the 'G' ships in more than 50 ship-years of operation.

The creation of a controlled intermediate ambient temperature as a means of reducing boil-off is an interesting concept. However, to obtain effective cooling of some 5000 m^2 of tank surface would in our view call for something more than a 'simple' refrigeration system. Even if a uniform inner hull temperature of −20°C could be achieved this will only reduce boil-off by about 20%. This figure can almost certainly be achieved more effectively and cheaply by a modest increase in insulation thickness, particularly for the newer foam-insulation systems. Regarding the insulation systems employed in the 'G' ships, there is no evidence to date that there has been any significant deterioration in insulating efficiency in service.

We agree with Mr Navaz that tank designs that minimize free surface have some advantages, not only in the reduction of sloshing but also in reducing fluid kinetic energy and hence boil-off. However, while difficult to prove, we consider that the boil-off generated by fluid motion is a relatively small component and that boil-off induced by the ship's motion is due more to the disturbance of the normal subcooled liquid surface layer.

In answer to M. Laredo's contribution, the filling level on loading for these ships is 98%. It is considered that the trend shown in Fig. 2 over the period 1980–81 is probably temporary and that boil-off value and fuel oil price will tend to return to approximately equivalent values. Even if this occurs, it is felt that the present method of operation, i.e. maximizing cargo delivery and minimizing boil-off on the ballast voyage, will remain economically attractive so that voyage fuel oil consumptions will remain around the 200 tonne figure.

As stated in the conclusions to the paper, it is inevitable that, with the benefit of hindsight, changes would be made if the Brunei project were to be started today. Economy of scale applies to LNG carriers as to any other marine transportation so that the maximum ship size technically and commercially acceptable would be chosen, i.e. a ship size in the range 120 000–140 000 m^3. This choice could well be tempered by the peculiarities of the Brunei loading terminal: this would require a considerable seaward extension to accommodate the additional 1.5 m of draft required. The associated ship's speed and boil-off would depend on the result of optimization studies for the project but would be expected to be in the range of 18–18.5 knots and 0.15–0.18% boil-off.

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