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# **The Re-alignment Afloat of a Ship's Main Engine Crankshaft Using Liquid Nitrogen: The Original Repair Re-visited.**

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## ***Synopsis***

The failure in service of the crankshaft of the main propulsion diesel engine of a large ocean going cargo vessel is an operational and mechanical disaster.

The author discusses the failure in service of the crankshaft of a 670mm bore Doxford LBD4 marine diesel main engine caused by cooling water leakage through minute cracks in a cylinder liner, adjacent a fuel valve. The water passed into the cylinder combustion space formed by two opposing pistons, in one of the cylinders. The hydraulic shock caused crankshaft journal slippage and major axial misalignment, with consequential main bearing and other damage. This occurred when the engine was wrongly tested using starting compressed air without first checking the main machinery by slowly rotating it once or twice, using the electric driven mechanical crankshaft turning gear.

Any return to service by such an affected vessel usually requires removal of the crankshaft from the engine for its repair or renewal. This would always require a lengthy lay-up of the ship at a dockyard and be associated with great allied costs.

Using four tonnes of liquid nitrogen, the author recounts how the crankshaft of the MV Eastern Rover was successfully restored to operational alignment afloat. The bearing damage was also repaired and realigned afloat, with full cargo intact, at Moji, Japan, where the casualty occurred.

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April 2004

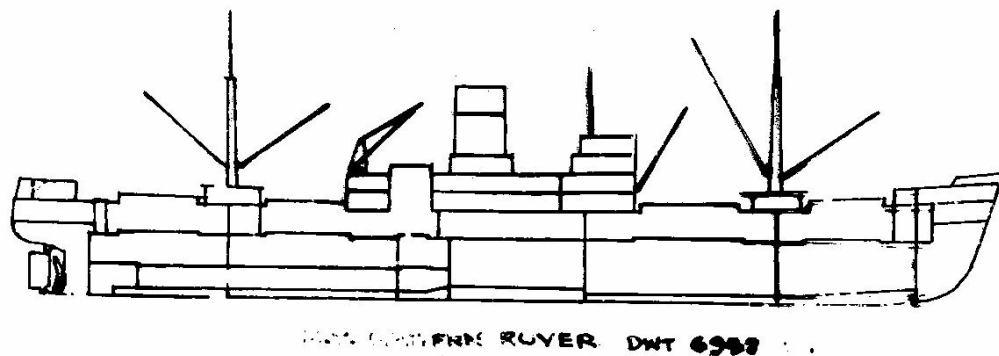
## ***Introduction***

This paper describes the repair of a 67LBD4 Doxford heavy oil main propulsion diesel engine crankshaft using approximately four tonnes of liquid nitrogen. In correspondence (1991), Chief Doxford Engine works designer Dr Finn Orbeck asserts that the repair procedure now described was the first of its type.

MV Eastern Rover, a general purpose cargo ship of 7 000 dead weight tons arrived at Moji Japan quarantine anchorage about 8pm 24<sup>th</sup> July 1968, too late for quarantine authorities to clear the ship. The vessel therefore anchored overnight with instructions to keep the engines on '10 minutes notice'. This instruction was given taking into account the weather conditions, the local spring tides and their associated current flow. Cabled instructions from the Moji Agents were received by the ship at 9pm, advising that movement to a cargo wharf would take place at 0630 hours next morning. The engine rested freely throughout the night without the locking security of engaging the main engine mechanical turning gear. Next morning, in preparation for 'stand by' and movement of the ship under main engine power, the engine was turned in readiness by using the high pressure starting air. Unfortunately, during the night, circulating main engine cooling water had leaked into the number 4 cylinder. In rotating the engine using compressed starting air, the subsequent hydraulic shock caused by compression of the opposing pistons upon the water trapped inside the No 4 cylinder combustion space, caused a section of the crankshaft to slip about its journal shrink fit, thereby rendering the engine useless.

## ***Particulars of ship and engine***

Figure 1 is a profile of the MV Eastern Rover. Together with her sister ship MV Eastern Ranger, these vessels regularly visited the major ports between Calcutta and Japan. The ship had five holds with the lower sections of numbers 4 and 5 holds being cargo carrying deep tanks. On this occasion these tanks held full cargoes of latex, palm oil and edible peanut oil, all of which were very valuable. The ship was built by JL Thompson & Sons Ltd in the United Kingdom in 1962 and was propelled by a 67LBD4 Doxford heavy oil main engine. These diesel engines were of British design. They were of simple but robust construction with many attributes that made them very popular. Figure 2 shows sections through this engine. Easily seen are the opposed pistons and their connecting rods and guides, the air scavenge pump with its associated driving links and the crankshaft top and bottom end bearings. Figure 2A is a transverse section through a 3 cylinder engine. Also easily seen are the crankshaft centre and side rods and top and bottom end bearings and guides together with the top piston transverse beam and bottle guide assembly. Figure 3 is a simpler sketch.



MV Eastern Rover Dwt 6952  
Figure 1 Profile of the ship.

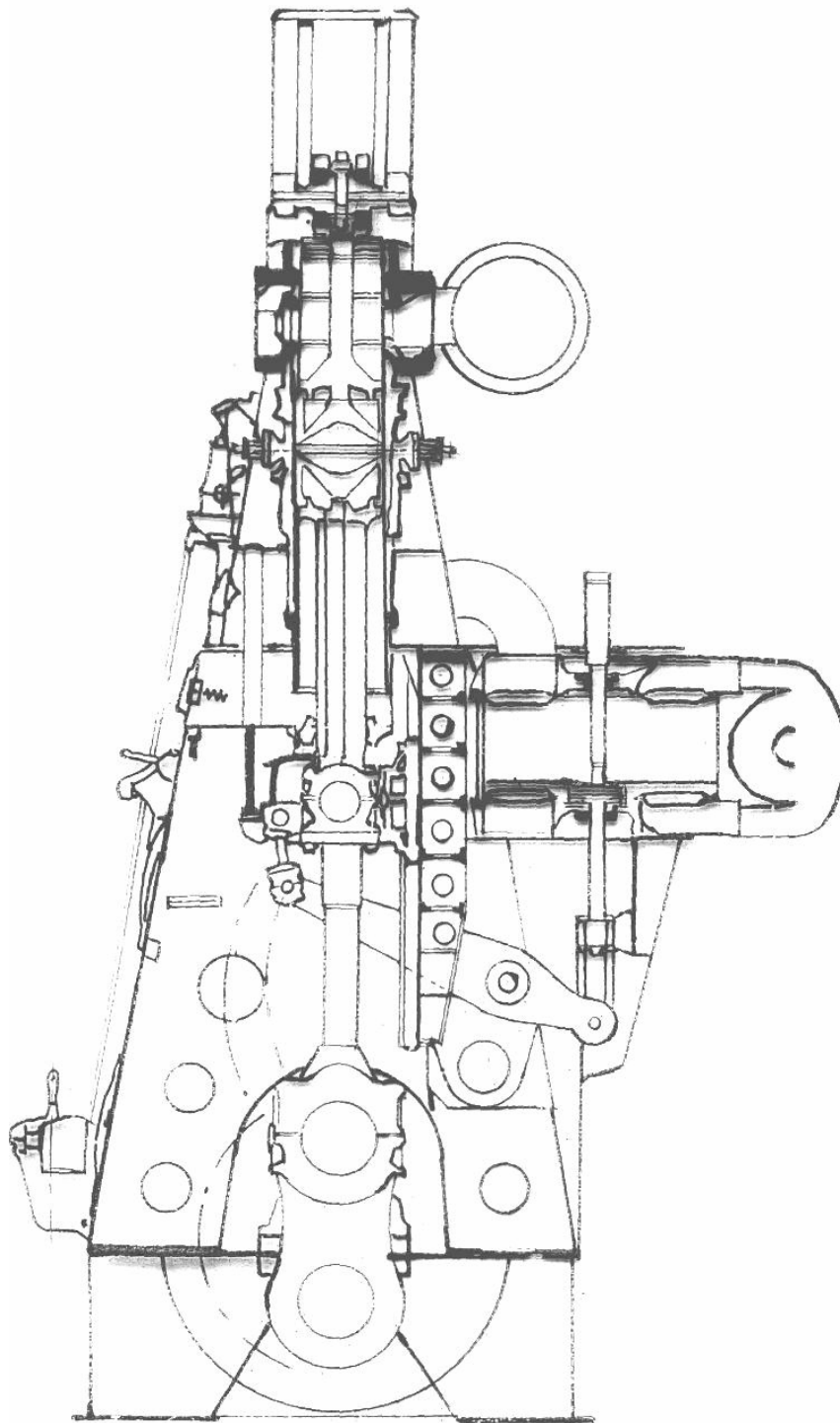


Figure 2. Section through the engine



The Marine  
Diesel Oil Engine.

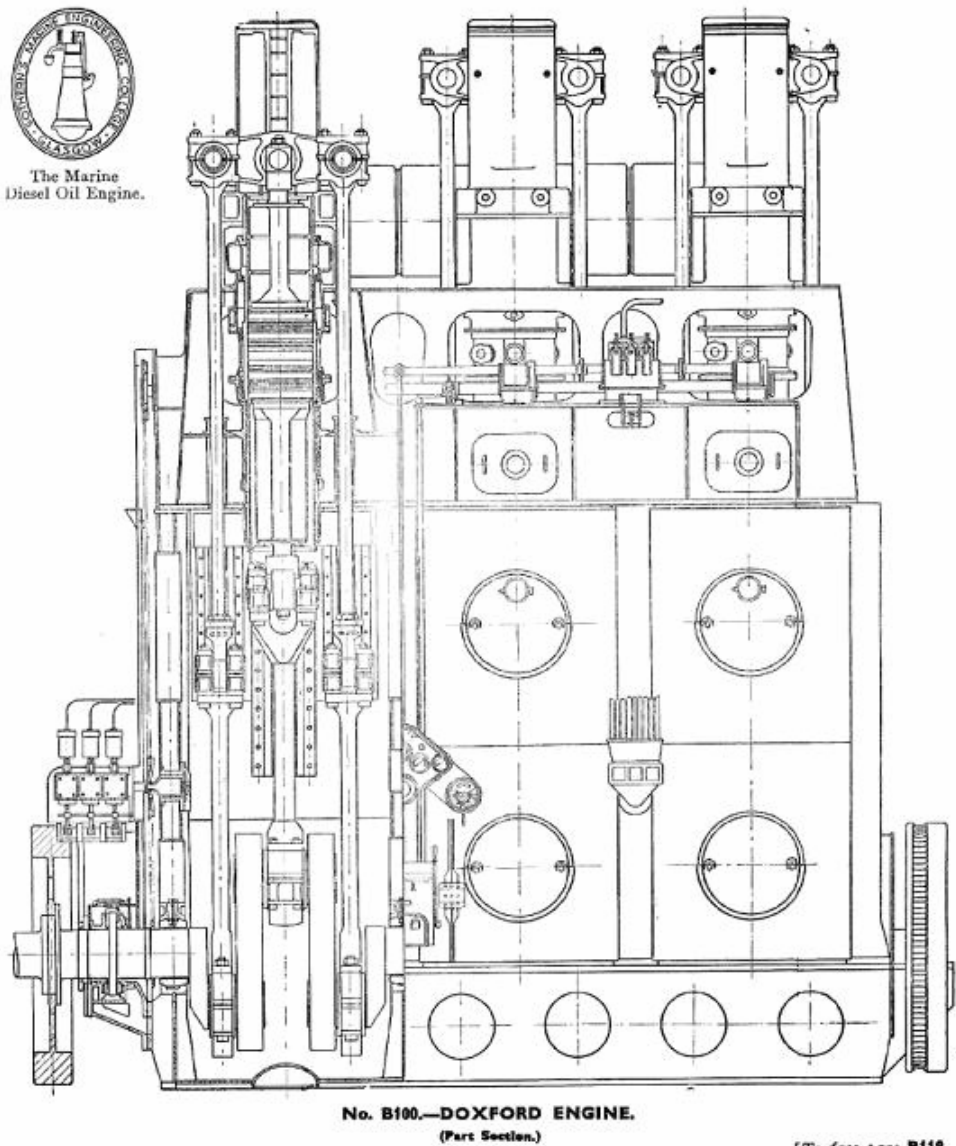
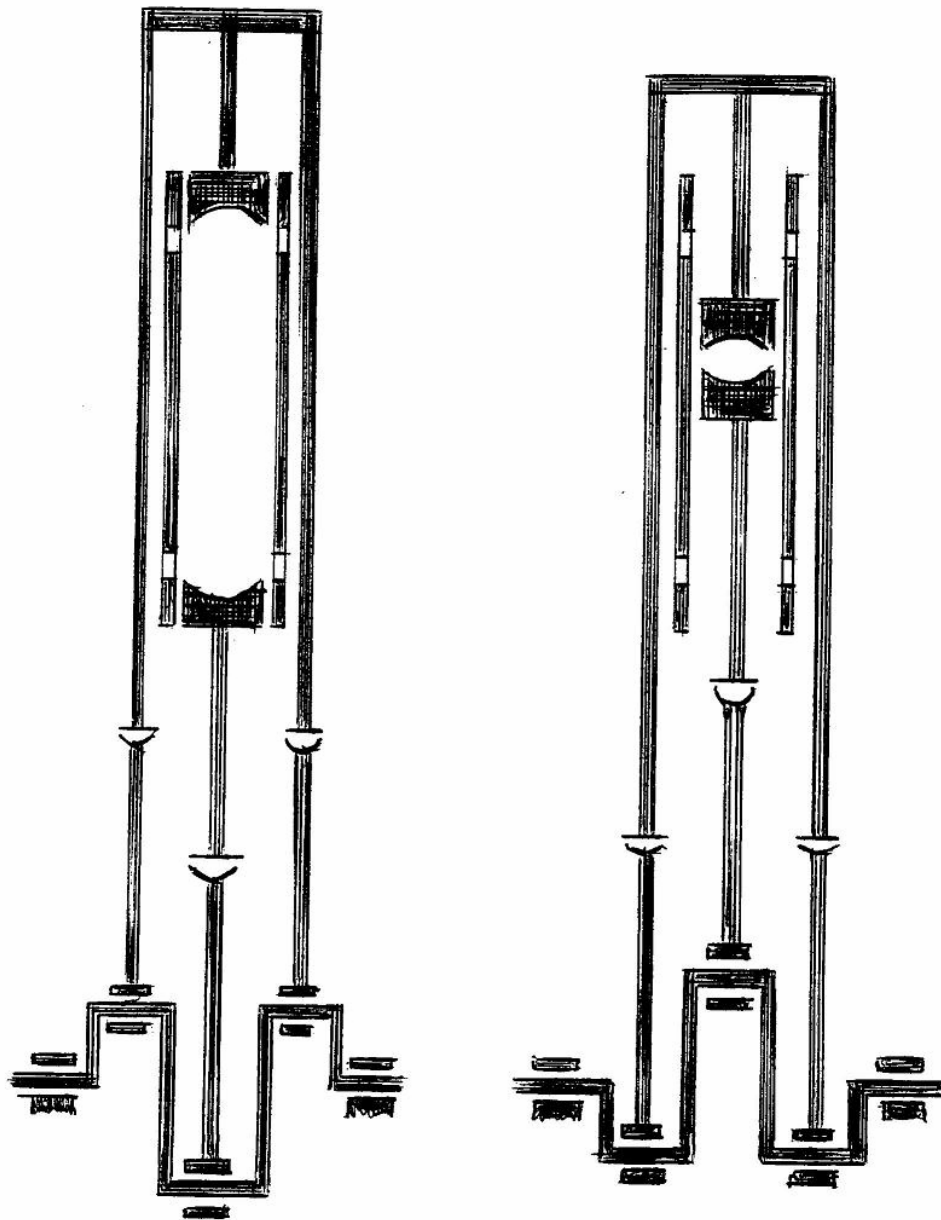


Figure 2A. Transverse Section of a Doxford 3 cylinder engine.



DOXFORD

Figure 3. Simpler schematic sketch of the engine.

**Preamble**

Crankshafts of large modern two stroke crosshead marine diesel engines can weigh over 300 tonnes. Today's engines therefore might well have 30 or more tonnes of revolving crankshaft mass per cylinder. In the early diesel propulsion engines, crankshafts were constructed from separate parts and assembled to make the whole. This fully built method consisted of forging separate webs, crankpins and main journals. The crankpins and journals were machined to final size and their matching holes were axially bored in the webs slightly smaller in diameter. The webs were then heated up and the crankpins and journals fitted into the holes which had expanded to a larger diameter because of the applied heat. Upon cooling down, the webs gripped the crankpins and journals tightly enough to stop them from slipping when the engine was being normally operated. All the diesel powers of the day were accommodated by this design, whether two or four stroke. The method particularly suited Doxford because their opposed piston design shared power between two pistons. This resulted in lighter weights of the individual reciprocating and rotating masses. It also simplified construction.

However it could be shown (Storey and Crowdy)<sup>1</sup>, that engines with fewest cylinders and pistons such as those being manufactured at the time by Sulzer, MAN and Burmeister & Wain, among others, not only were less costly to make, their shorter crankshafts saved shipboard space. Their design was also popularly favoured because of their potential for greatly increased power on the crankshaft.

Forging capacities and the large crankshaft machining lathes available today, now enable engine crankshafts to be semi-built, no matter how big, so the handicap of size and weight has largely been overcome. Today's best practice is to forge the two webs contiguous with the crankpin from one steel billet for each cylinder. To build the crankshaft, each web is axially bored to suit a shrinkage fit with each joining journal. Upon completion of assembly, crankshaft line axial accuracy is obtained by machining each pin and journal of the completed crankshaft in a special lathe. It is instructive to note that the entire engine output is transmitted through the shrink connexion of the last crankweb and its output journal. The effectiveness of the shrinkage construction method is acknowledged as very well proven.



The shrinkage allowance in modern semi built crankshafts is approximately 1/600 of the diameter and key connexions are not allowed. Among other shortcomings, key slots focus unwanted stresses. When a crankshaft is manufactured under survey, as well as stamping his own identifying mark, the surveyor stamps a very fine chisel line across the face of the connexion joint of each crankweb and its associated journal or pin. The marks join across the ends of each pin or journal to the inside flat faces of the webs. The goal therefore was to re-align these fine lines on the web that had slipped. Realignment of these lines would indicate that the shaft had been restored to closely match its original manufactured alignment.

### ***Discussion of the damage to be repaired***

The cause of the damage was self evident to the ship's engineers. Notification of the casualty was received at our Hong Kong head office immediately after it happened. Repairs and dry dockings were the author's responsibility so the author was instructed to fly to the ship immediately and arrived aboard next day. It was a feature of Doxford engines to employ two fuel valves in each cylinder. These fuel valves are positioned one on each side of each cylinder and are cooled by the fresh water that also circulates the main engine cylinder liners and top pistons. The valves themselves are secured in a removable carrier such that both the carrier and the nozzle are in a cooling water space outside the liner. Failure of the nozzle cone to make a watertight seal with its carrier can enable water to leak into the cylinder past the nozzle cone, to thereby accumulate on the concave crown of the bottom piston. Another possibility known from a few cases, was that Doxford liners had developed small cracks in way of their fuel valve pockets. Figure 4 depicts the fuel valve and cylinder liner arrangement. Subsequent inspection showed minor cracks were the cause of the casualty. The combustion space of No 4 cylinder had become slightly filled with water. Contrary to company requirements, the engine had not been given one or two slow test turns by means of the electric driven mechanical turning gear with the cylinder indicator cocks open, as precaution demands before starting the engine. It will be clear by reference to Figure 3 that when starting air at 600psi was applied in one of the other cylinders to turn the engine, the top and bottom pistons in No 4 cylinder made their compressive inward strokes. This was done with such force that the hydraulic shock in the cylinder caused the dislocation of the crankshaft. The forward main crankshaft web slipped its shrink and rotated 9.5mm around the

side rod crank pin, in an astern direction. The length of shafting forward of No 4 unit had continued to travel ahead of the after section, to produce the

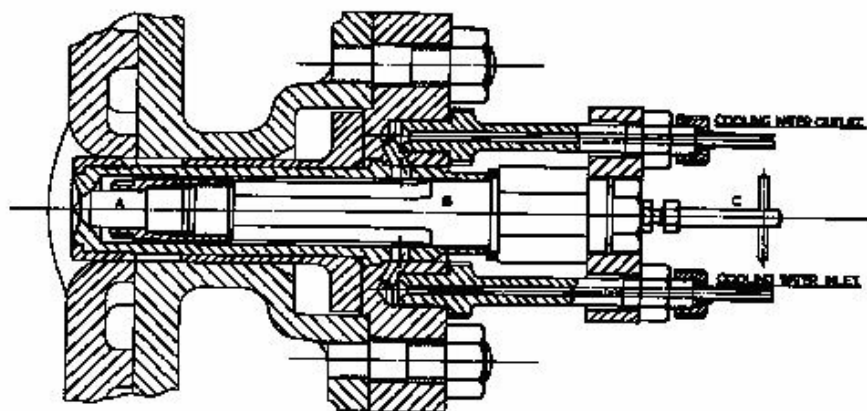


Figure 4. Fuel valve/cylinder liner arrangement

slippage. Before its rotation stopped, no longer in axial alignment, the crankshaft journals on either side of No 4 cylinder proceeded to badly damage their respective bottom half white-metal bearings.

By the time the author reached the ship, the Chief Engineer had a considerable amount of the engine already in dismantled stages. This was to permit a full inspection of engine parts that might also have suffered damage. Unfortunately, during the initial work on dismantling sections of the engine, No 4 portside cast iron bottle-guide was broken off at its base on top of the engine. Bottle guides are a crucial part of the engine and they are installed on the top of each cylinder. They ensure that the top pistons of the engine which partly leave their cylinders on every stroke, are constrained to move centrally up and down the cylinder liners during their reciprocating motion. Each upper piston is connected via a short piston rod to a transverse beam through the use of a lubricated centre pin. The beam also has pins at each of its ends. The tops of the side rods are attached to these end pins by a simple bearing arrangement. The beam's mid length pin is designed to form a self-aligning fulcrum assembly that has a lubricated 'bottle' shoe at each end of the beam's centre pin. The action of a shoe in its associated bottle guide is to mechanically constrain any out-of-line movement of the upper piston. Figure 2A shows the assembly. The accident happened when the main engine was

being turned using the electric motor-driven mechanical turning gear to rotate the crankshaft for work upon No 1 Unit, without first checking that both No 4 unit side-rods were properly released and freely hanging upon bridges installed upon their guides for this purpose. As it happened, No 4 aft side connecting rod had been removed and the weight of this disconnected side rod which was still in position in its guide shoe, with the added weight of the reciprocating and other attached parts above, was supported by resting the side rod crosshead upon a purposely made bridge that was bolted across the guides. The forward side rod of the No 4 unit however, was still fully connected to the top piston transverse beam, and by means of its top end bearing pin connexion it remained joined to the crankshaft. Therefore when the crankshaft was rotated, the forward side rod with its crankpin connexion moved down, pulling the end of the transverse beam down with it to an alarming angle, causing the cast iron bottle guide column to break off. This was an additional major setback.

The ship carried no spare cast iron bottle guide column assembly and there was no chance of getting a replacement for this crucial part in Japan. The availability of a replacement part from the UK was possible but unknown, and in any event its size and weight could pose problems for aircraft transportation.

The repair issues were therefore,

1. To restore the crankshaft to proper working alignment and condition.
2. To effect appropriate repairs to the damaged main bearings and to any damaged side rod and bottom end bearings where found necessary.
3. To align the crankshaft in its relationship to the engine bearings and bedplate and hull. This would be done by adjustment of bearing heights using crankshaft deflexions.
4. To accurately repair the fractured cast iron bottle guide assembly, such as to permit engine operation without excessive bottle clearances, noting that the bottles were whitemetal lined and could not be operated at excessive temperature.
5. To test the repaired engine under sustained full load and other sea conditions to the satisfaction of the attending Lloyd's Register Surveyor, such that the ship could safely re-enter continuous ocean-going service.

Arrangements were made to shift the ship by tugs from its anchorage to a Moji Port dead wharf, to facilitate the repairs.

### Procedure of the repairs

Figure 6 shows how the crankshaft repair was carried out. Brackets made from mild steel plate were welded to the top flanges of the engine bedplate as buttresses for the hydraulic jacks that would be used. The 1mm thick sheet-metal tank was fabricated to surround the slipped side rod crankpin.

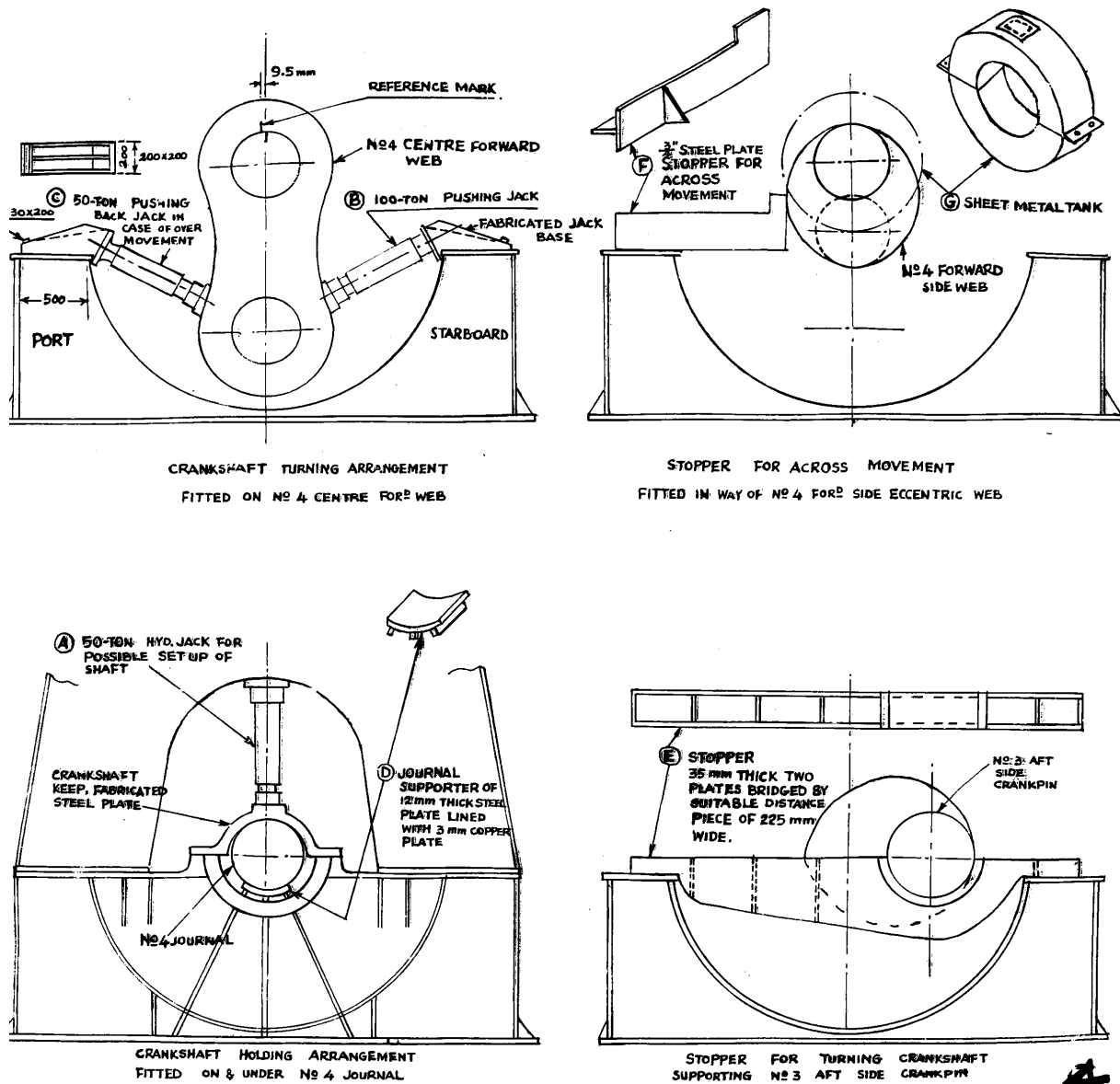


Figure 6. Repair set up

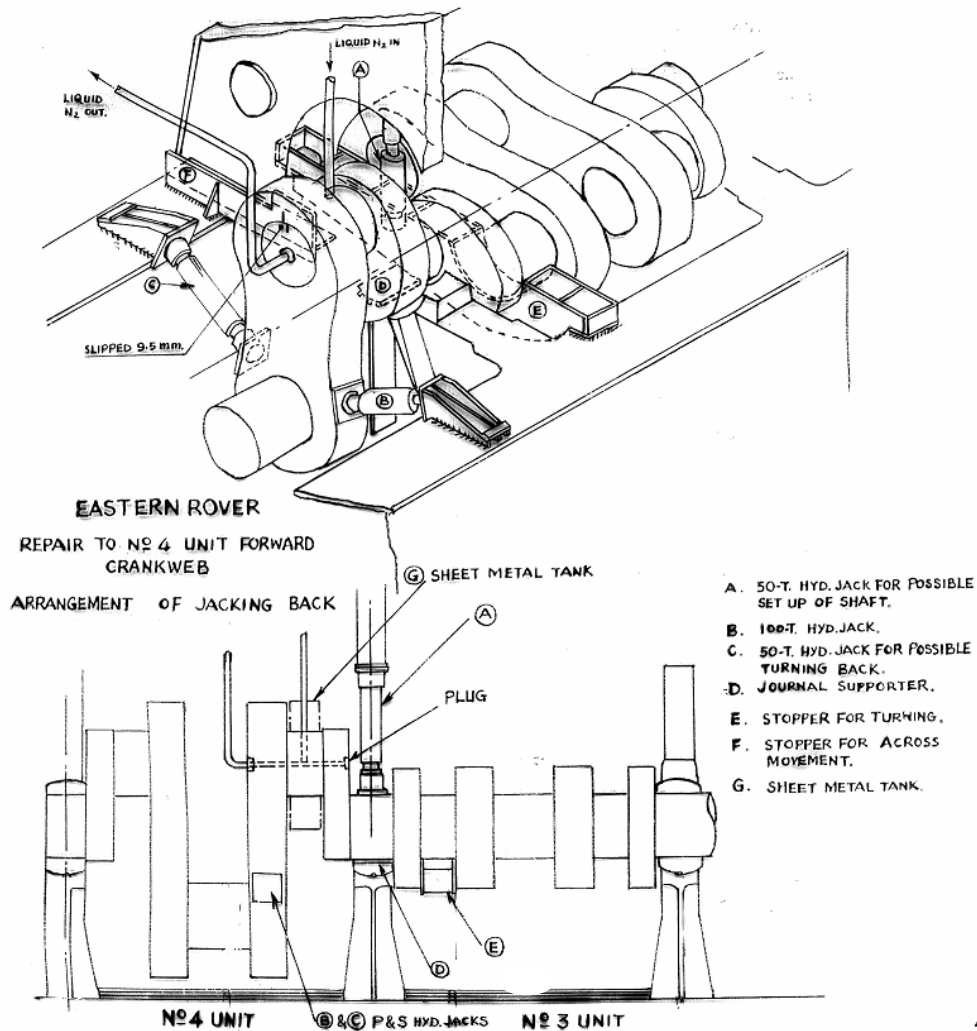


Figure 6A. Repair set up continued.

The purpose of the tank was to hold dry ice, to pre-cool all the parts associated with the crankpin, in readiness for the safe introduction of liquid nitrogen internally through the crankpin lubricating oil hole. Thereafter it would act as insulation. Roughly 30 hours of pre-cooling was done while other work went on. This included removal of the engine casing structure above the engine room, to facilitate the removal of the broken bottle guide assembly by floating crane and thence ashore by barge. The assistance of a shore based mechanical team of excellent and highly cooperative technicians, each wearing 'Honda' on their cover-alls, had been engaged. These friends arranged for the cast iron welding of the broken bottle guide assembly to be done at a workshop ashore. The crucial repair was carried out by a man very skilled in cast iron welding. Not only was the very difficult and extensive cast iron weld done superbly, it was done with such vertical alignment accuracy

that the bottle guides needed only minor clearances correction when the ship was running on sea tests.

Being uniquely British, Doxford engines were not well known to the larger Moji marine engineering works. Further, since ours was a crankshaft casualty of major degree, the local repairers and major shipyards may have thought in terms of intangible side dis-benefits attached to any failure they might be associated with. In any case the small group of eight men mentioned, was all the help that we could find who came forth spontaneously. It was through these friends that we managed to order a tanker-load of liquid nitrogen. Even if repair work of this nature was done ashore, the re-setting of any crankshaft to proper alignment is no easy task. Notwithstanding the clinical conditions of initial manufacture, the work is very precise. During manufacture, closely controlled and specifically designed heating tools and methods are used to build up a shaft piece by piece. The great shrinkage forces produced when each crankshaft web locks upon each pin or journal secures the parts together, and time is of the essence in the work. In the situation now being described, the author did not consider any method based upon full heating of the web, to be practicable or to be safe. Apart from the dangers involved by using very large heating torches in the confines of the crankpit, prolonged heating produces changes in the grain structure of steel. In general therefore, classification societies avoid using uncontrolled heating as an approved method of repair. For these and other reasons, and mindful that liquid nitrogen and dry ice had safe properties, this was the repair course deemed possible. Liquid nitrogen boils at  $-196^{\circ}\text{C}$ , transforming into an inert gas. The dry ice used to initialise the cooling process, sublimates to an inert gas at  $-78.5^{\circ}\text{C}$ . As a gas, nitrogen is slightly lighter than air, while carbon dioxide is heavier. Both gases are colourless, odourless, tasteless and inert. Proper ventilation was ensured by completely opening up the engine crankcase and making full use of the engine room ventilation fans. Because it would be cooler for the work to be undertaken at night, the supply of the nitrogen was arranged for 6pm. The tanker had a volume of 3 700 litres, approximately 3 660 kg. The eventual volume of nitrogen delivered approached 4 222 litres.

An initial calculation showed that a temperature difference of approximately  $150^{\circ}\text{C}$  would produce relaxation of the shrink and this could be achieved by

applying gentle heat to the web in the final cooling stages of the crankpin. Because the alcohol thermometer being used was only graduated to  $-90^{\circ}\text{C}$ , the temperature fall was plotted upon a graph to indicate approximately when the crankpin would reach the projected goal of  $-120^{\circ}\text{C}$ . The graph is shown in Figure 7.

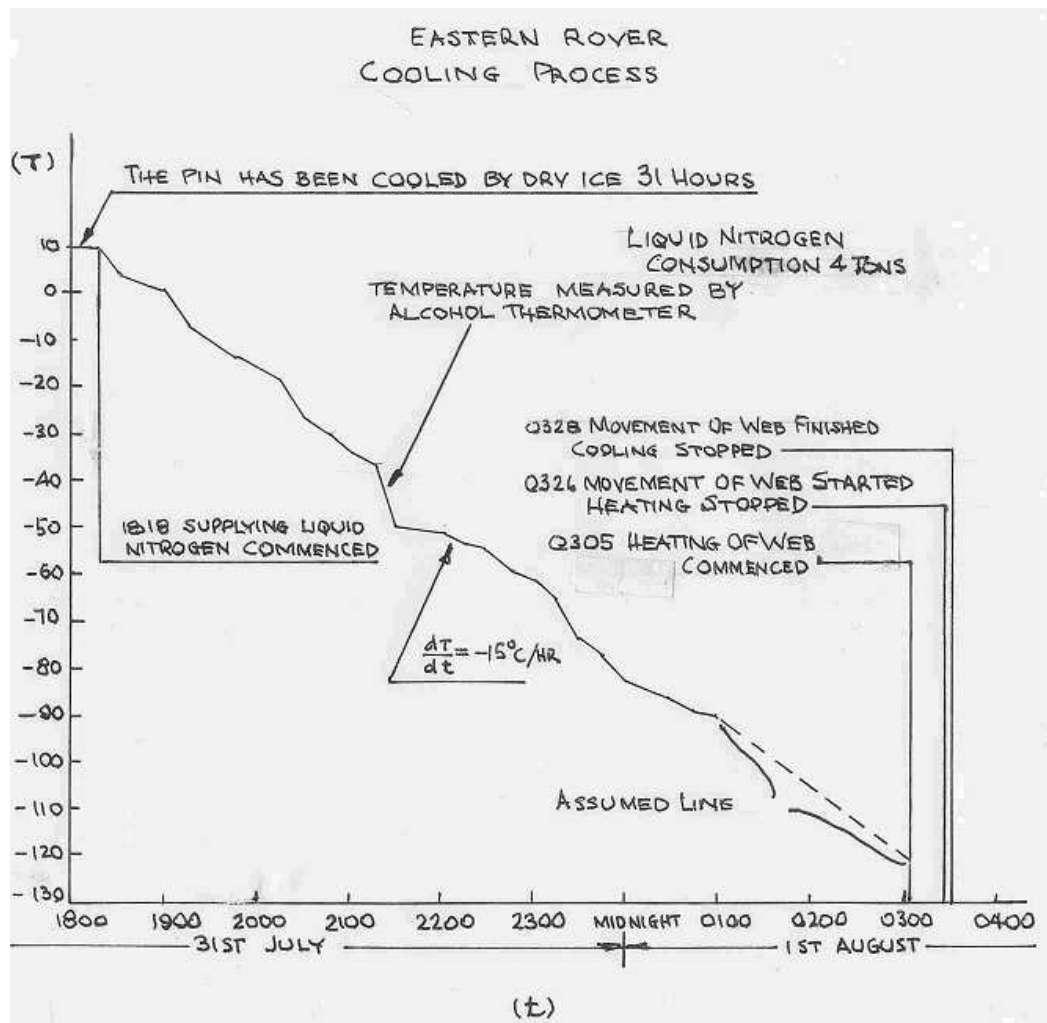


Figure 7. Temperature plot

The 50 ton jack on the opposite side of the crankweb served two purposes. Its first purpose was to provide solid opposition to the movement to be made of the web, to prevent the web being uncontrolled. Its second purpose was that because working conditions in the crankpit were awkward and difficult, accurate observation of the fine alignment of the marks, was likewise difficult, with all the frost and rind, piping, jacks and propane heat, about. If the web unfortunately moved too far, the author wanted to

be able to reposition the web using this jack immediately. Once in position, both these jacks had their bases tack welded to their mild steel brackets. A further 50 ton jack was employed to press the crankshaft down within its bearing pocket. This was to counteract any upward reaction produced by the restoring couple. To support the down-load thrust of this jack positioned in the engine 'A' frame above the bearing pocket, a circular false bearing was fabricated. This was accurately lined with a 3 mm copper plate. The copper plate was to prevent any likelihood of damage to the journal. Also, as shown in the sketch, a girder was fabricated from mild steel plate and tack-welded into position beneath No 3 unit aft side rod crankpin.

This was to prevent the forward section of the crankshaft rotating when restoration hydraulic pressure was being applied. Once the jacks were properly positioned and secured, a small test of the equipment was carried out on the parts.



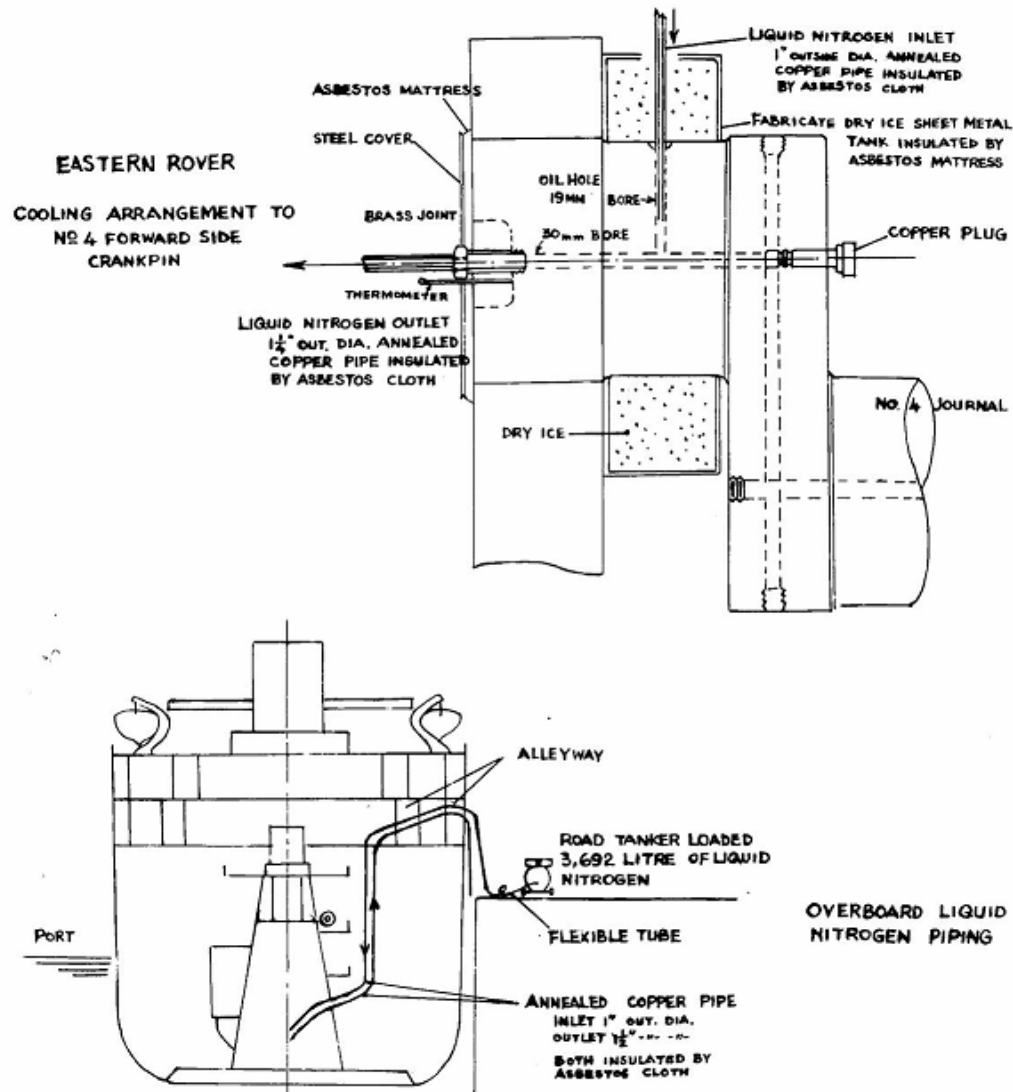


Figure 8. Liquid nitrogen supply connexions.

A copper plug was fitted into the drilled lubricating oil end hold of the side crankpin to isolate the pin from the rest of the system. A copper tube was forced into the lubricating oil hole in the crankpin surface. This was the supply pipe connexion for the liquid nitrogen. A copper outlet tube was fitted into the lubricating oil hole in the centre bore of the pin. Both tubes were connected by screwed nipples to lengths of 20mm and 40mm bore copper pipe which were taped with asbestos insulation and led out to the wharf. The vapour exhaust pipe was led down between the ship and the wharf. A circular plate of 5mm steel cut with a circular centre hole was used to cover the end of the crankpin with asbestos cloth put between the plate and pin end.

A small slot was cut from the plate to permit observation of the two alignment marks.

With all the equipment in position, the nitrogen truck was coupled up at 1818 hours, Wednesday 31<sup>st</sup> August. The liquid nitrogen was passed into the crankpin at a slow rate. Pressure averaged  $1\text{kg/cm}^2$ . After nine hours the temperature (by extrapolation of the plotted recordings), was estimated to be about  $-130^{\circ}\text{C}$  in way of the pin counter-bore, and probably about  $-160^{\circ}\text{C}$  in way of the dry-ice protected pin surface.

Four propane oxygen torches were prepared. Using three rose flame burners, heat was gently applied to the outside of the crankweb at 0305 hours on 1<sup>st</sup> August. After fifteen minutes of heat the gradually receding frost rind on the web was approaching the web/pin interface. The forcing jack pressure was set to  $200\text{kg/cm}^2$ . A minute or two later the jack was pressed to  $400\text{kg/cm}^2$  when instantly and easily the web began to move. The flow of nitrogen was stopped and the torches shut off. A constant pressure of  $200\text{kg/cm}^2$  kept the web moving steadily until the reference marks were re-aligned. Only four minutes were taken to restore the two alignment marks by eye accuracy. Fortunately this proved successful. No readjustment of the web was necessary, and both jacks merely kept firmly upon the web. The shrink re-applied itself through the remainder of the night, assisted by some gentle heat applied to the end of the pin. A static torque test at 355 ton ft ( $1.08 \times 10^6 \text{ N-m}$ ) was applied to the web the following mid-morning, (Thursday 1<sup>st</sup>). The pressure of  $1\,000\text{kg/cm}^2$ , (jack ram dia 95mm, torque arm 1,550mm) was held for 1/2 minute. A pressure of  $700\text{kg/cm}^2$  that is a torque of 250 ton ft ( $0.76 \times 10^6 \text{ N-m}$ ), was held for 10 minutes.

New bearings were required for No 4 and 5 pockets. Adjustments were also necessary to No's 3 and 2 main bearing heights. This was to realign the shaft in the bedplate as accurately as before. All bearings were given about .014 inch (.35mm) shaft clearances and .005/8 inch (.125/.20mm) spherical clearance. No 4 cylinder liner was replaced. The repaired bottle guide assembly was re-installed with carefully adjusted guide clearances.

### ***Pier Trial***

In consultation with the Lloyd's Register Surveyor, a pier trial was held on Saturday 3<sup>rd</sup> August. At 1653 hours the engine was run for a few minutes at 35 rpm, then run at 70 rpm for twenty minutes. Immediately upon stopping the engine, all the running gear was felt by hand and found in order. The reference marks remained intact. All bearings were cold to touch.

### ***Departure Moji***

With the Lloyd's Register surveyor aboard the ship departed Moji for Kobe via the inland sea at 1730hrs, and after various engine movements the main engine was set to 90 rpm at 1830 hours. At 0500 hours, August 4<sup>th</sup>, the rpm were gradually increased to average 112.6. Indicator power cards were taken at these revs and totalled 5000 IHP. For the remainder of the voyage the engine was held at 100 rpm. At arrival in Kobe, the engine was vigorously tested full astern full ahead for about ten minutes. The crankcase was opened up and all bearing were cold. The surveyor checked all bearing and reference marks to his satisfaction and issued the appropriate repair certification with the requirement for re-inspection in one year. The repairs took roughly seven days and other than the schedule disruption, cargo work proceeded as planned.

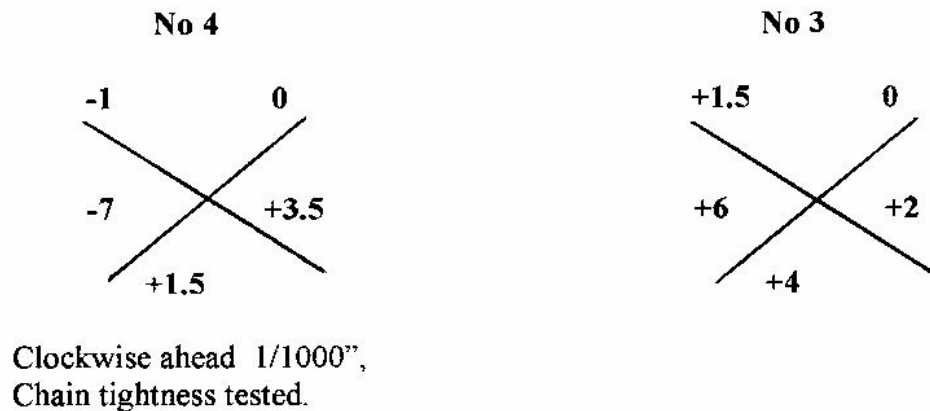


Figure 9

Figure 9 portrays the deflexions of No's 4 and 3 crankwebs after completion of the work, including the adjustment of main bearing heights, prior to Moji departure.

MV EASTERN ROVER  
Lx B x D = 38'0" x 5'1" x 25'3"  
DRAUGHT = 23' 4 1/2" (MAX) 8' 1/2" (LIGHT)  
DWT = 6592 TONS  
BUILT = JOSEPH L THOMPSON & SONS  
ENGINE = DOXFORD 67LBD4  
( BHP = 4600 )

		-	16		15	-	8		-3
DEFLEXION			20		16		18		15
Straight shaft			-4		-1		-20		-18
Actual deflection			-4		-1.2		-34		-18
X Span Factor			-12		-3.6		-72		-54
x <sub>3</sub>									

### EXAMPLE OF THE METHOD OF ALIGNMENT BY DELETIONS

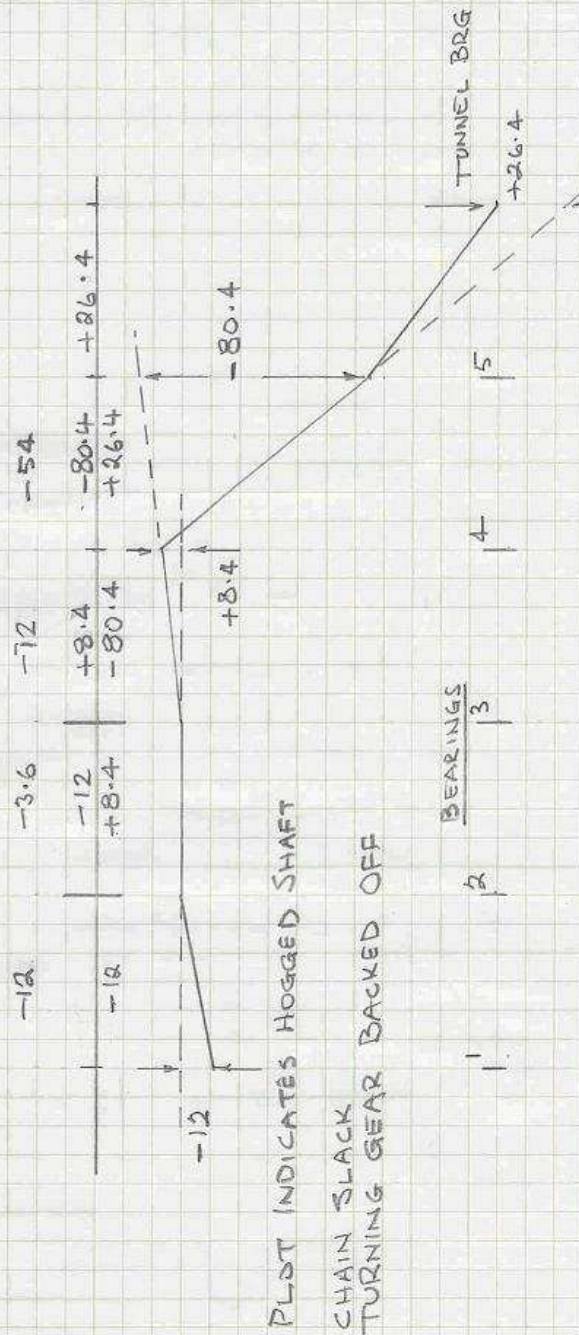


Figure 10 Main engine shaft alignment. Deflexions recorded arrival Kobe 5-8-68

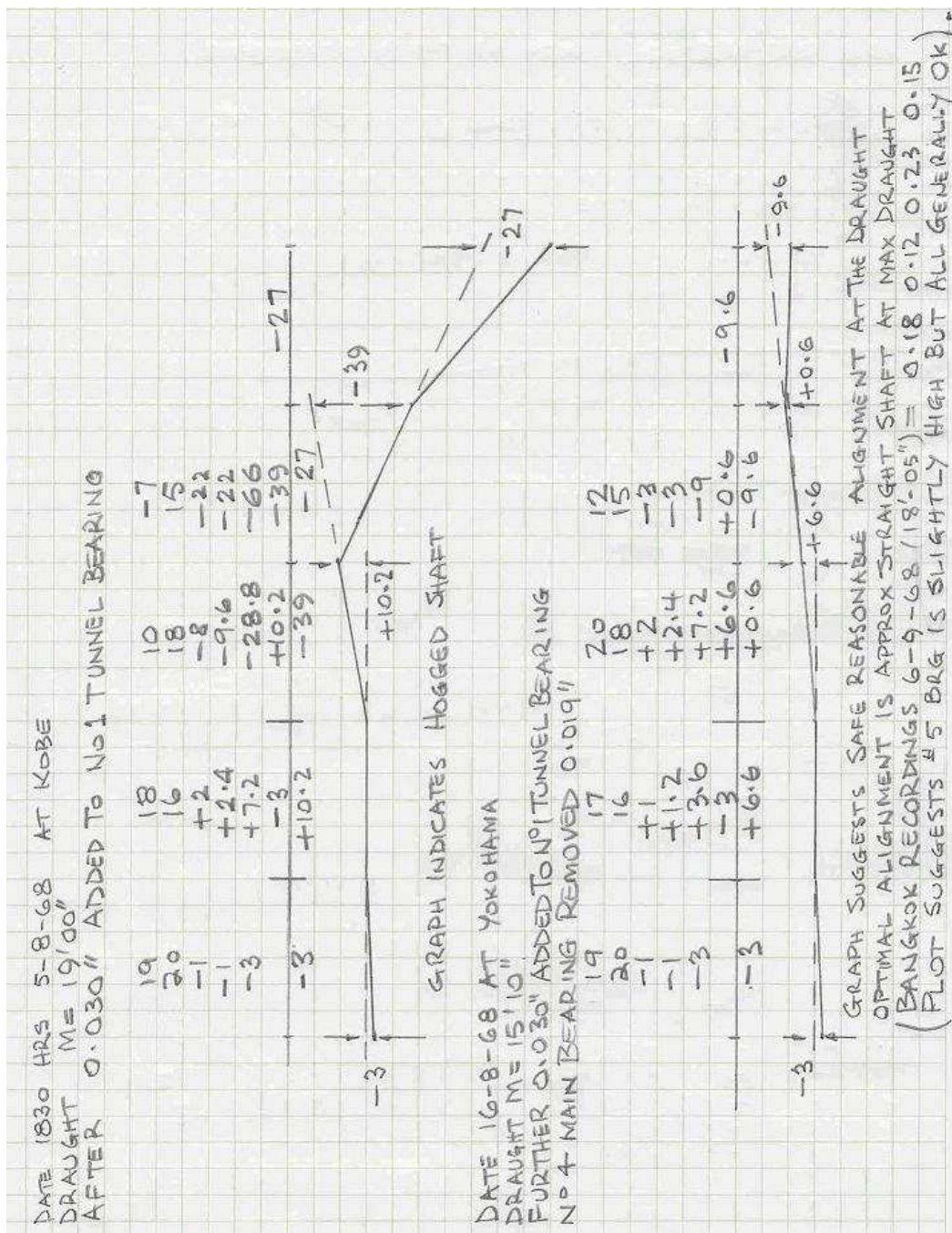


Figure 11 Main engine shaft alignment departure Kobe 5-8-68 after further work and also upon departure Yokohama 16-8-68, following further adjustments.

Figures 10 and 11 portray the alignment of the crankshaft from web deflexions taken at ports succeeding the repair. Adjustments were made to the main bearing heights as shown. The plots indicated that being new, No 4 main bearing was high relative to the other main bearings. This could be expected.



However it was judged that the thrust bearing was being influential in the deflexion readings and so to test this opinion the bearing was raised by 0.030 inch shims and the deflexions retaken. A plot of these deflexions resulted in the further addition of 0.030 inch shims beneath the thrust bearing accompanied by the removal of 0.019 inch from No4 main bearing. The final acceptable position of the crankshaft is shown in Figure 11. Doxford engine builders require that their engines operate with positive deflexions within the range of +0.005 to +0.035 inch (0.125 to 0.9mm). Confirmation of the acceptable alignment can be seen from the later deflexion gauge readings recorded at Bangkok by the ship's engineers. Care must always be taken to factor into the work the alignment of the loaded hull, and therefore the distortion of the bedplate that occurs with changes of ship loading. This change of hull alignment corresponds to the changes in the vessels draught. Doxford LBD4 engine main bearings are uniquely designed, being mounted in spherical housings. This design enables the bearings to change their positions in the bedplate, to suit changes in bedplate alignment, thereby warranting special consideration. It will be seen from the above that alignment of a ship's main engine crankshaft by adjustment of the thickness of the white-metal bearings is considerably complicated. Nevertheless the author hopes that the deflexion graphing technique used by the author and depicted here, to realign the crankshaft and the bearings, has been explained or is otherwise sufficiently self explanatory to be readily understood and perhaps utilised by those whose job it is to continually monitor the main and auxiliary diesel engines of ships both big and small.

### ***Conclusions***

Upon completion of the repairs MV Eastern Rover continued to perform excellent service. The benefits of the repair method described for this type of casualty, as against removal of the shaft if in fact removable is feasible, are manifest. Clearly any such crucial repair is difficult but so long as the necessary temperature difference is obtained between the web and pin, release of the mating components is assured. Additionally, the possibility of worsening any damage to the mating surfaces during the repair is minimised. The type of fully built crankshaft design discussed here ceased production many years ago, but the crankshafts of today's 10 000 hp/cyl (7 400Kw) engines continue to be semi-built, using the same shrinkage. The possibility of a similar type of slippage of a crankshaft shrink fit can therefore never be

discounted. Correct alignment of a ship's main engine crankshaft is crucial to the proper operation of any diesel engine. This usually involves adjustment of the bearing heights relative to each other. In the case of vessels that trade for long periods away from large docking facilities or trade in remote areas, the responsibility falls upon the ship's engineers to provide the correct machinery maintenance. The author therefore suggests to the interested reader that for a comprehensive explanation of the author's procedure of using deflexions to adjust crankshaft alignment, reference be made to the author's paper, "Notes upon crankshaft re-alignment including a method based upon deflexions"<sup>2</sup>.

The method given in the reference paper shows the procedure to realign the modern stiff semi-built crankshafts in the ships of today. As explained in the paper, stiff shafts have a different scale ratio to Doxfords. These big shafts sit in fixed, standard design rigidly supported bearings. The author's alignment method is also applicable to engines of smaller power.

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<sup>1</sup> The Final Years of the Doxford. North East Coast Engineers and Shipbuilders Vol 105 Part 2 (1989)

<sup>2</sup> Hudson, R.J. F. April May (1974) . Marine Engineers Review  
(The Doxford drawings are used by permission of the publisher James Munro & Sons, Glasgow)