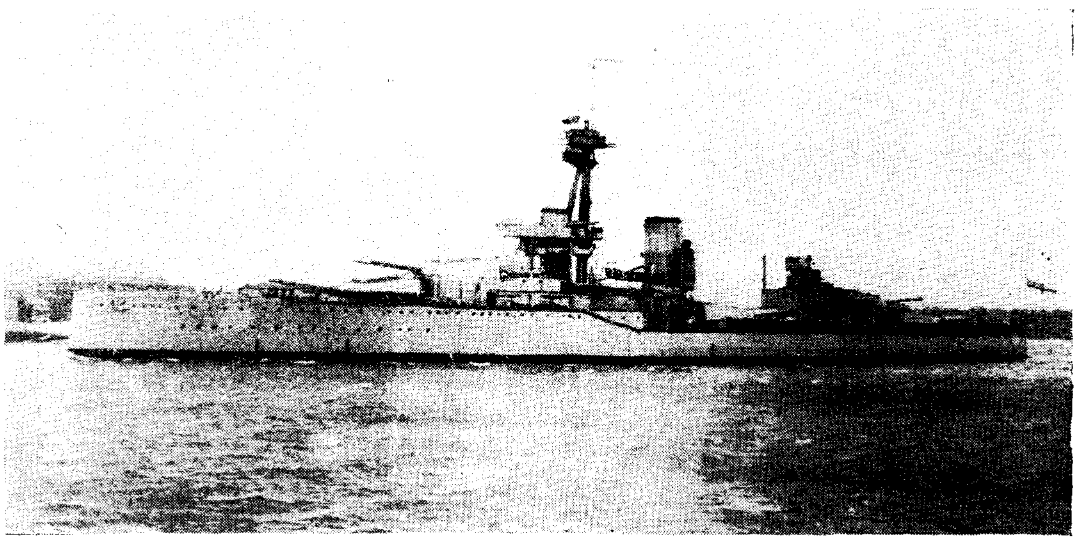


FIG. 1—H.M.S. THUNDERER

SOME NAVAL ENGINEERING CALAMITIES

BY

COMMANDER A. J. H. GOODWIN, O.B.E., R.N., M.I.MAR.E.

The following paper was presented to the Scottish Branch of the Institute of Marine Engineers in October, 1964, by the author who is now the Senior Manager of the Yarrow-Admiralty Research Department. The naval calamities he describes are those with which he has had personal contact and the events are associated with the ship in which he was serving at the time. Many of these events provide some lessons in engineering both on the technical side and even more on the administrative side.

H.M.S. 'Thunderer'

After the first world war, H.M.S. *Thunderer* was used for many years as a training ship for cadets and I served in her in 1922. Although she started as a coal burning ship, she had by that time been converted to burn some oil fuel as well. She was therefore typical of the leap-frogging technique which occurs so often in the Royal Navy. For many years there was sail combined with steam, then as in this ship, coal combined with oil. More recently we have seen steam combined with gas turbines, and it may not be long before we see gas turbines combined with nuclear power.

On every such occurrence it seems to be inevitable that a nostalgic reaction is set up in favour of the motive power which is on its way to being superseded. It is a matter of history that the old sailing captains did not take kindly to the introduction of steam. I forget what the arguments used against steam were but no doubt they included messiness and the lack of character building. However, in the case of the coal *versus* oil controversy, coal had one very formidable advocate in the person of a naval captain, and his arguments centred largely on the neglect of the nation's coalmining resources and the dependence on foreigners for our oil supplies; this was some thirty years before our similar

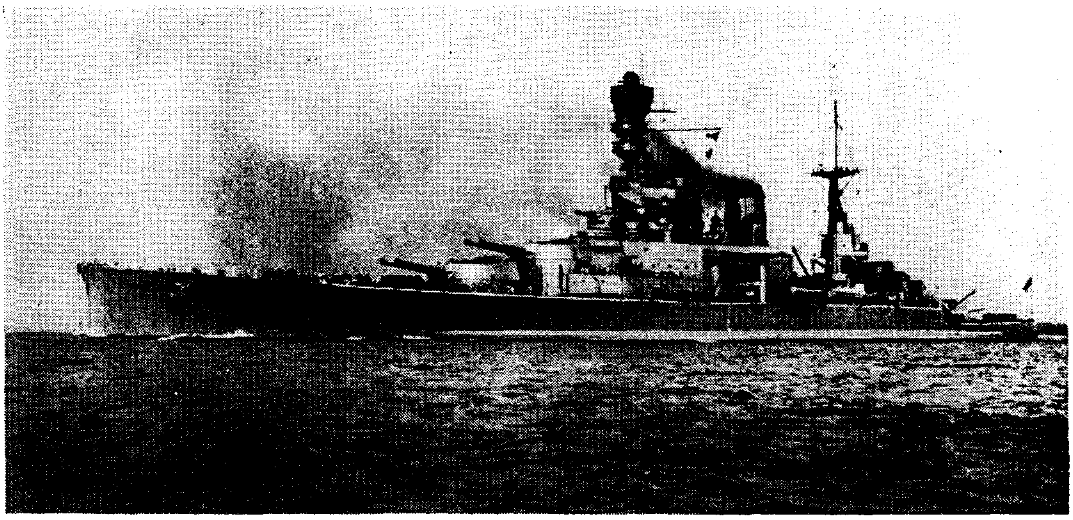


FIG. 2—H.M.S. RENOWN

scare in the Suez incident. He was a man of very strong views on other subjects as well, and I remember his theory of the migration of birds being explained to me as that the emigration of birds was entirely unintentional; they always tried to fly towards their birthplace, but at certain times of year the prevailing winds were so strong that they inevitably went backwards. I do not know if this matter has been satisfactorily resolved, but that of coal and oil certainly has. Recently there has been in some quarters a revulsion from the naval gas turbine to an all-steam arrangement, but we are more likely to move on to Diesels and gas turbines before a widespread introduction of nuclear power.

The nearest I can get to a calamity in connection with H.M.S. *Thunderer* is seasickness. Naturally, on first going to sea almost all of us suffered for a time from this, but the Navy's way of dealing with it was simply to ignore it, and insist on everyone getting on with this work as though no problem existed. This works very well with human beings but, as will be shown later, is a disastrous attitude to adopt on technical problems.

H.M.S. 'Renown'

My next ship was H.M.S. *Renown*, and here a real calamity arose which might have led to very serious consequences. This was a very big fire in the boiler rooms, and it occurred in 1927 when we had on board the Duke and Duchess of York who subsequently became King George VI and Queen Elizabeth. They had been visiting Australia and New Zealand and the ship was on her way home about half way between Australia and Africa, in fact, in about the position that S.S. *Trevessa* had sunk a year or so previously when an epic voyage was made by her boats to reach Mauritius.

The upper part of FIG. 3 shows the arrangement of the machinery compartments at that time, and the lower part the re-arrangement when she was re-engined, completing in 1939. It will be seen that at the time there were 42 boilers arranged in six boiler rooms—A containing three, B seven and C, D, E. and F eight each. The fire broke out early in the afternoon watch in D boiler room, while the ship was steaming on C and D boilers. It subsequently transpired that the cause of the fire was oil fuel that was being transferred from forward to one of the double bottom tanks in D boiler room. The filling arrangements were a stand pipe with an open-ended funnel and a filling valve above. The stoker who was tending this valve made the cardinal error of sounding the wrong tank, so that as he could see no rise of level, he kept opening the valve wider and wider until the tank and its stand pipe were completely full and the oil overflowed, some of it striking the hot boiler front and catching fire.

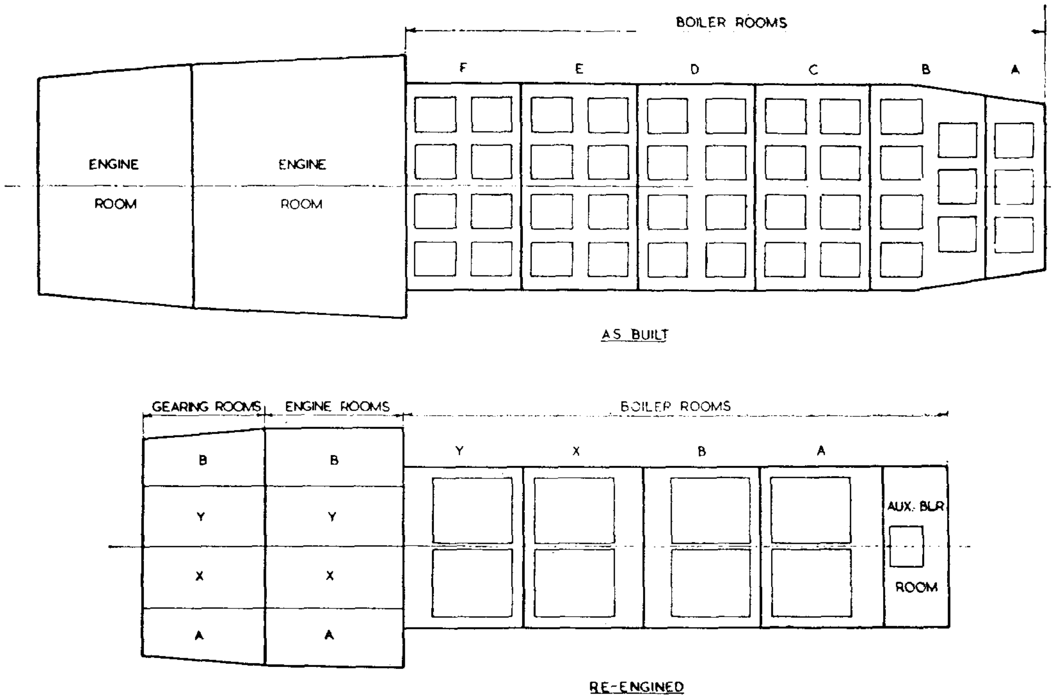


FIG 3—ARRANGEMENT OF MACHINERY SPACES—H.M.S. RENOWN

The stoker then completely lost his head and as he described later, 'Some of the oil came over me and I thought I was on fire, so I rushed up on to the upper deck to put it out'.

No one else in the boiler room was aware what was happening, so the oil continued flowing at full bore into the boiler room so that the whole of the bilges were soon alight, and the steaming crew were driven out of the boiler room. Unfortunately, the boiler fans were still running and providing all the air necessary to keep the fire raging. Very soon news of the calamity spread round the ship and officers and men off watch came rushing to help. The Officer-of-the-Watch at the time (he subsequently became Engineer-in-Chief of the Royal Canadian Navy) concentrated on keeping the forward four boilers in C boiler room alight and this was no mean task as the after bulkhead was red hot and desultory fires kept breaking out in the bilges there.

The main problem of course was to stop the source of air to D boiler room, because by now the oil fuel transfer pump had been shut off but not before there was a layer of three or four feet of oil in the room. The Senior Engineer had taken charge and insisted on shutting off the steam to each of the eight fans himself. Unfortunately, in the literal heat of the moment, he didn't foresee that the wing fans ought to be shut off first then the next outer ones and so on working in at last to the inner ones where the only access to the fan flat from the deck above was. As it was he shut off these inner ones first so that the flames from the boiler room were able to come out through the fan inlets into the fan flat. Hoses which had already been rigged were turned on into the fan flat to try to make conditions tolerable for the Senior Engineer, who was wrapped in wet towels, as he tried to battle his way past these flame spots to shut off the remaining fans. He would not accept assistance in what was now a very dangerous task and wore himself out in repeated and unsuccessful attempts.

Before going on to describe the subsequent events, I should like to interject that I learnt that day two very important lessons in leadership, the first being that the natural leader should deny himself the dangerous and exhausting jobs and concentrate on directing others in these, and to do them justice, there

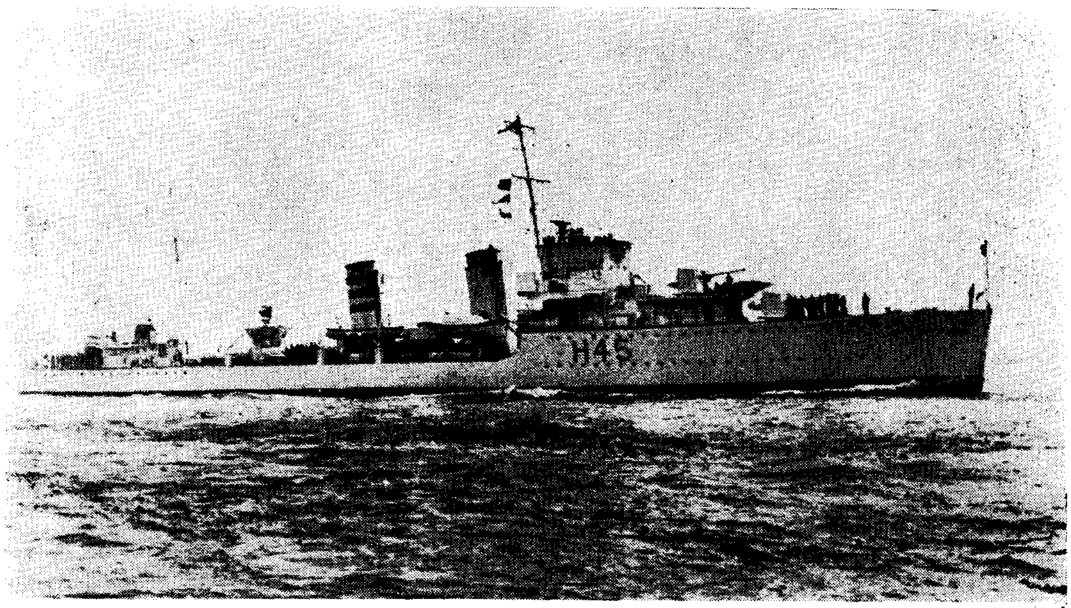


FIG. 4—H.M.S. ACHERON

were and always are plenty of volunteers available and eager to take them on provided that they know they are being competently directed. The rest of us badly needed direction from the Senior Engineer who had a complete and devastating knowledge of the whole engine-room department. The second lesson was that in an emergency it is the man with knowledge who inevitably takes command; in a later stage of the fire when we were trying to make sure that none of the innumerable oil fuel tanks had caught fire, it was the Stoker Petty Officer of the Double Bottom party who had to direct our efforts. A fine 'power of command' is of no use if one hasn't a clue what to command.

While indulging in that little homily, we have left the fire raging away with water from the hoses pouring in through the fan eyes, so that the layer of burning oil was rising steadily up the boiler fronts. It eventually reached to just below the steam drums and of course the contents of that boiler room were completely ruined. Although we never succeeded in shutting off all the fans we did eventually manage to fit shutters and canvas screens that almost completely blocked the passage of air from the air intakes on the upper deck.

In case anyone is wondering why we did not use the master shut-off valves for fans and oil fuel pumps and oil supply to boilers fitted outside the machinery space, the answer is, of course, that there were none at the time and it was because of this fire in *Renown* that thereafter they were fitted in all ships.

The Senior Watchkeeper had been told off to light up the boilers in F boiler room and was busily employed there, since it took several hours in those days, and even in this emergency it was over two hours before these boilers were connected to take the load off the four remaining boilers in C boiler room. Incidentally, and rather comically as it appeared afterwards, steam was also raised in the Royal Barge, although we were thousands of miles from anywhere. The forward bulkhead in E boiler room was naturally red hot and an alarming sight, but after we had rigged hoses to keep it under control, I went down to the engine room to be greeted by the Warrant Engineer with the words: 'You're just in time, sir, the steering gear is broken down, the last drop of water has just gone out of the main feed tank, there's no steam for the main engines and the Bridge keeps ringing down asking when we will be ready to proceed.' However, it wasn't as hopeless as it seemed, and when at last F boilers were connected I was able to reply to a further Bridge enquiry 'Now'! We were in fact underway before the end of the afternoon watch and I remember meeting a Warrant Engineer, who had had the middle watch and had had his head down prior to the first dog watch, emerging from his cabin and seeing hoses everywhere saying: 'What's going on? Has some silly idiot been having a fire practice?'

The only real trouble we had after that was our fortunately ill-founded suspicions that oil fuel tanks were on fire, and the difficulty we had in opening up D boiler room, since due to the stored heat every time we let air in the fire broke out again. So we had to let it cool off for some time.

As a result of the Board of Inquiry that was held, alterations and additions were carried out and new construction modified so that:

(1) Open ended funnels for tank filling were barred from boiler rooms

(2) External shut-off arrangements were made for steam to boiler room fans, steam to oil fuel pumps and heaters, and the oil fuel supply to each boiler.

H.M.S. 'Acheron'

It is now generally accepted in naval circles that H.M.S. *Acheron* was a calamity in that she halted naval engineering progress for years, and left us to fight the 1939–1945 war with machinery technically a long way behind that of the American Navy and hence ships with unduly limited endurance.

H.M.S. *Acheron,* when she was ordered in 1928, was a bold step into the future with steam pressure 500 lb/sq in. and temperature 700 degrees F. She had four turbines on each shaft, an H.P., two I.P.s and an L.P.

I joined her in 1936 when she had returned from the Mediterranean in disgrace as a notorious cripple. She had spent quite a proportion of her time out there under repair alongside a dockyard wall, and the rest as a lame duck of the Flotilla with her speed limited to about 20 knots. The trouble was that the Navy had tried to treat the machinery as it treated its cadets who were seasick, by ignoring the problems which her novel machinery created, and insisting that she was just one of the A Class Flotilla and had to perform immediately as the rest of them did.

The technical troubles that she had were leaking joints, which was largely a matter of workmanship with the higher pressure, some material problems due to the higher temperature, and principally H.P. turbine vibration above a certain speed. The first two had been cured before I joined her, but the turbine vibration was the reason that she had been consigned to the Local Flotilla at Portsmouth, the duties of which were such that high speed was desirable but not essential.

Several attempts had been made to diagnose the turbine trouble but whenever Admiralty officers were present to observe the trials she refused to produce the symptoms and the Admiralty officers were able to go away saying whatever the trouble was it seems to be cured now, and you can cancel the limitation on your speed. Of course, after their departure the very first attempt to use high speed produced vibration and the limit was put on again. The very intermittance of the trouble gave the clue that it was a transient temperature condition that was causing the vibration, and very soon we were in a position to inform the Admiralty that if they would send observers, we could guarantee to make the turbine vibrate. How nice it is to be in a position of being encouraged to make a thing go wrong rather than being blamed if it doesn't go right. Basically, it was a loosening of the H.P. turbine shrunk joint which occurred for a time after opening the first of the two by-pass valves. When heat had soaked through thoroughly the joint tightened up and the ship could then run at full power quite happily. During the time when the joint was loose there was a tendency to touch in the labyrinth gland, overheat locally, and distort sufficiently to prolong the vibration.

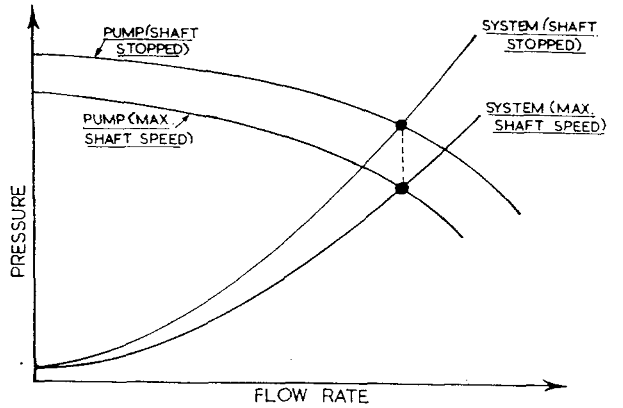


FIG. 5—PRESSURE/FUEL RATE CHARACTERISTICS OF CENTRIFUGAL PUMP AND SYSTEM

By the time war started in 1939 H.M.S. *Acheron* was a thoroughly reliable destroyer and remained so until sunk by enemy action, but the harm had been done and when naval rearmament started seriously just before the war, no advantage was taken of the technical progress of which H.M.S. *Acheron* had been intended as the prototype. The American fleet which had two years' grace before entering the war, was able to standardize on 600 lb/sq in., 825 degrees F, with double reduction gearing, and her ships had considerably greater endurance than ours.

It is gratifying to be able to state, however, that the lesson of *Acheron* has been learned, and that when H.M.S. *Ashanti* was commissioned as the first warship with gas turbine boost, her programme allowed for a six months' shake-down period during which she could be put through all her paces and any mechanical failings could be put right. Care was also taken to train an engine-room staff in the philosophy and detail of the design so that they could nurse the machinery through the teething stages. This has resulted in the gas turbine being warmly welcomed in the Fleet despite some technical flaws having to be discovered and put right.

One special feature I remember from *Acheron* was that the machinery ran quite satisfactorily at full power with no lubricating oil pressure showing at the bearings. Since there were four turbines feeding into the gearbox the number of bearings was large compared with that in ships contemporary with her; this led to a low system resistance and at high power the pumping effect of the bearings and thrusts further reduced the pressure at entry to the bearing. The net result was zero readings at some of the pressure gauges to the bearing inlets, but a large number of flow indicators was fitted which restored confidence about the amount of oil reaching each bearing. With regard to the pumping effect of bearings, since the war we have made measurements on the Y.E.A.D.1 installation at Pametrada, and on the *Devonshire* gas turbine installation at A.E.I., and in each case we found that even with centrifugal lubricating oil pumps the total flow quantity varied little between full speed and stopped, but that the oil pressure at bearing inlet was substantially reduced at high speed, as was the pressure at pump discharge. Aeration of the oil pumped lowered the whole characteristic at high speeds, so that one effect counteracted the other and the total flow altered very little. (See FIG. 5.)

It is rather disheartening even to this day to find so many engineers wedded to the idea that high pressures must be maintained in the lubricating oil system, even to the extent of starting an extra unnecessary pump, whereas the thermocouples fitted in the bearing near to the load line give the best possible guide as to whether the oil flow is sufficient. Thermocouples in the metal of the bearing positioned at the full power estimated point of minimum oil flow thickness, where the maximum temperature should occur, were introduced into the *Whitby* Class frigates partly because they give a more reliable and sensitive measure of the bearing conditions than thermometer readings of the oil outlet temperature, and partly because it was clear that they needed development prior to relying upon them in later ships when control room control and monitoring would be required. It has, however, been difficult to educate engineers into accepting the perfectly satisfactory metal temperatures of about

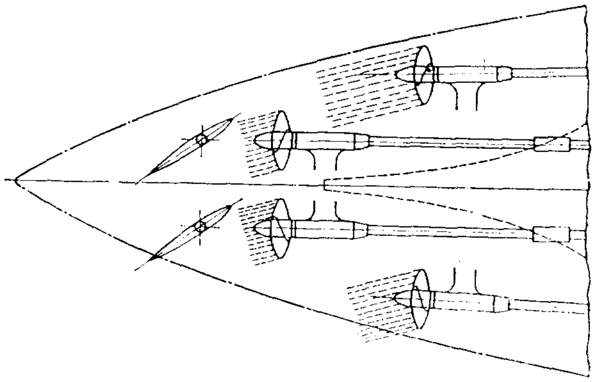


FIG. 6

250 degrees F. rather than the oil temperature figures around 180 degrees F. to which they are accustomed. The instrumentation has been considerably improved since the first attempts in the *Whitby* Class, and has enabled us to introduce refinements into bearing design such as grading the clearance ratio to the bearing speed, current figures ranging from 0·0025in. per inch diameter for primary pinions to 0·0007in. per inch for main wheel bearings.

H.M.S. 'Renown' Re-engined

Shortly before the 1939–45 War when I was at the Admiralty in the Battleship Section, H.M.S. *Renown* carried out her contractors' sea trials on completion of re-engining. We had considerable difficulty with these because she refused to maintain her vacuum during the astern trials, the vacuum dropping steadily until we lost our nerve at about 20 inches of vacuum and stopped the trials. On a repeat of these trials we went a little further and there was a resounding bang from one of the L.P. turbines. Even before we could shut down we noticed some recovery of vacuum, and on opening up the turbine we found that one of the ties retaining the inner cylinder in place had fractured, and investigation showed this to be a redundant member which had been distorting the casing, and opening the horizontal joint. The remedy was to leave it broken and to cut the similar ties in the other three L.P. turbines, and after that we had no further trouble with the vacuum when going astern. This was an excellent example of the adage 'If you can't break a racket, join it'.

Axial Vibration of Propeller Shafting

When war broke out in 1939 we were attempting to deal with a problem for which we knew a cure, but didn't know what the disease was, namely, axial vibration. When the battleship H.M.S. *Warspite* was carrying out full power turning trials after completely re-engining in 1938 severe vibration developed in the vicinity of the flexible couplings between the turbine and the gearboxes. When opened up, the teeth of the male and female parts of the coupling were found to be welded together. A number of abortive trials were carried out before it was established that this vibration and welding together of couplings was occurring in a shaft set, the propeller of which was running in the slip stream of another (FIG. 6), and that if the slip stream could be reduced in intensity, the trouble did not occur. It was apparently a trouble that any of our battleships or aircraft carriers with three or four shafts might suffer from, and the fact that only *Warspite* had been observed to have this trouble was due to her having done these full power-turning trials, other ships being careful to use very little helm during their six-monthly full power trials in order to prevent spoiling the performance figures.

A set of instructions had to be produced for the reductions in power required on the outboard engines on the outside of a turn for all our three or four-shafted ships together with warning systems from the bridge when high speed turns had to be made. Some measure of the serious view taken by the Admiralty of the danger to the engines in the Fleet will be realized from the fact that, in the week before war was declared, the personal signatures for the instructions were obtained from the Director of Naval Construction, the Engineer-in-Chief of the Fleet and the Director of Navigation in a single morning. This should be placed on record because of the stories that used to go around during the

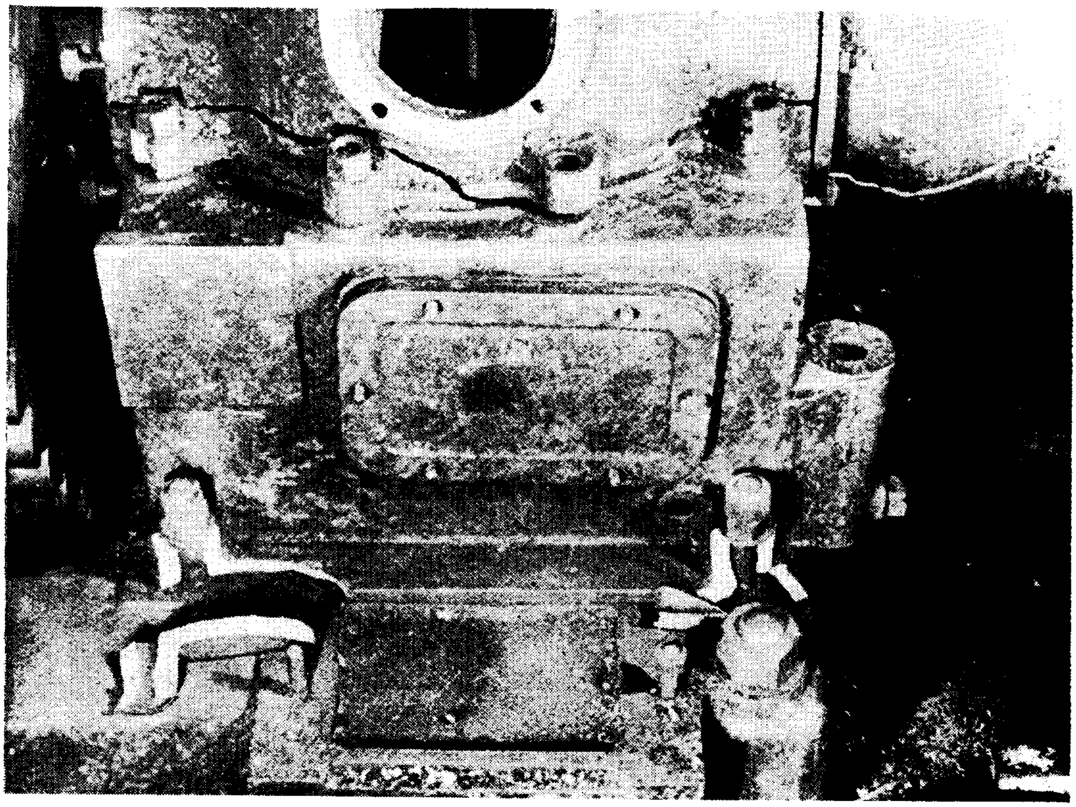


FIG. 7

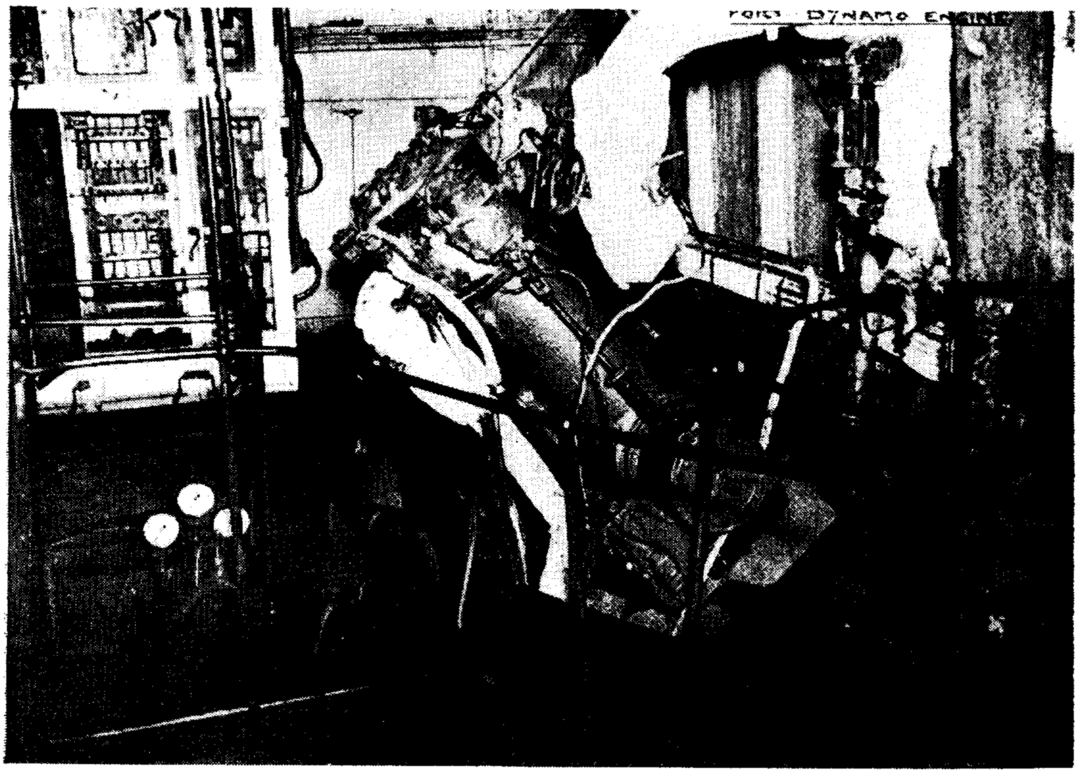


FIG. 8

war, such as: the man who asks the policeman in Whitehall 'Is the Admiralty on this side?' and gets the reply 'That's what we'd all like to know'.

By a coincidence, the problem of axial vibration was again looming large when I rejoined the Admiralty in 1949. By then Mr. Rigby, of the R.N.S.S., had diagnosed the problem as one of axial resonance in the propeller shaft system that caused high speed relative axial movement in the flexible coupling, hence heating up and eventually fusion. I had the satisfaction of developing for H.M.S. *Eagle* and subsequent ships a resonance changer fitted to the thrust block which damped down the vibration and made it unnecessary to have any restrictions on turning at high speed.

Some readers may from time to time have come across instances of flexible couplings welding up their teeth. This is not usually an axial vibration problem but merely one of alignment, and measurements in one case showed that a mal-alignment as small as 0·050in., which represented an angular mal-alignment of 9 minutes of arc, may cause this welding to occur. Such a mal-alignment entails a sinusoidal relative velocity at the teeth with a maximum value of 0·7 ft/sec. at full speed. To obtain the same relative velocity in *Warspite* at the axial resonant frequency would need an amplitude of relative movement of 0·1 inches. In all probability the amplitude in *Warspite*, particularly when thrust reversal was taking place was well in excess of this figure, as in fact was the damage to the flexible coupling teeth in excess of that in the ship referred to.

Shock

One of the greatest calamities which was not just an engineering calamity but was nearly disastrous to the Navy and therefore to the whole country during the last war, was the effect of shock from non-contact underwater explosions. On 21st November, 1939, H.M.S. *Belfast* exploded a magnetic mine beneath herself when entering the Firth of Forth, and the effects were devastating in the machinery compartments. To give some idea of the magnitude of the damage done, it took until 1943, over three years later, for the repairs to be completed and for *Belfast* to become a fighting unit again.

This was the first and best known case of crippling of the machinery due to shock although the hull remained watertight, but it was followed by innumerable casualties due to this cause either from magnetic or acoustic mines or near-miss bomb explosions. Typical examples of such failures are shown in Figs. 7, 8 and 9.

Before going on to describe the measures taken to compete with this new menace it is desirable to say a few words about what, on looking back, seem to be administrative failures in letting ourselves become vulnerable to this, the first of Hitler's 'secret weapons'.

There was, of course, nothing secret about the possibility of using magnetism to set off non-contact explosions, and in fact a lot of our time in H.M.S. *Acheron* had been spent in acting as target for or firing magnetic torpedoes. In the former case if the triggering mechanism had worked correctly, a couple of ping-pong balls were released which came bobbing to the surface. The cure for the liability to set off magnetic weapons leaps immediately to the mind of any engineer, and I can remember on the morning that the disaster to H.M.S. *Belfast* became known in the Admiralty everybody walking round the corridors with the thumb, first finger and second finger all at right angles to one another in the way we had been taught to relate magnetic lines of force to the flow of electricity. Undoubtedly a wonderful administrative and technical effort was made in fitting 'de-gaussing' to so many of our naval and merchant ships in such a short time after the *Belfast* disaster, but observing that so much had already been known in certain sections of the Admiralty about the offensive possibility of magnetic weapons, plans at least ought to have been drawn up and better still implemented for the countermeasures required.

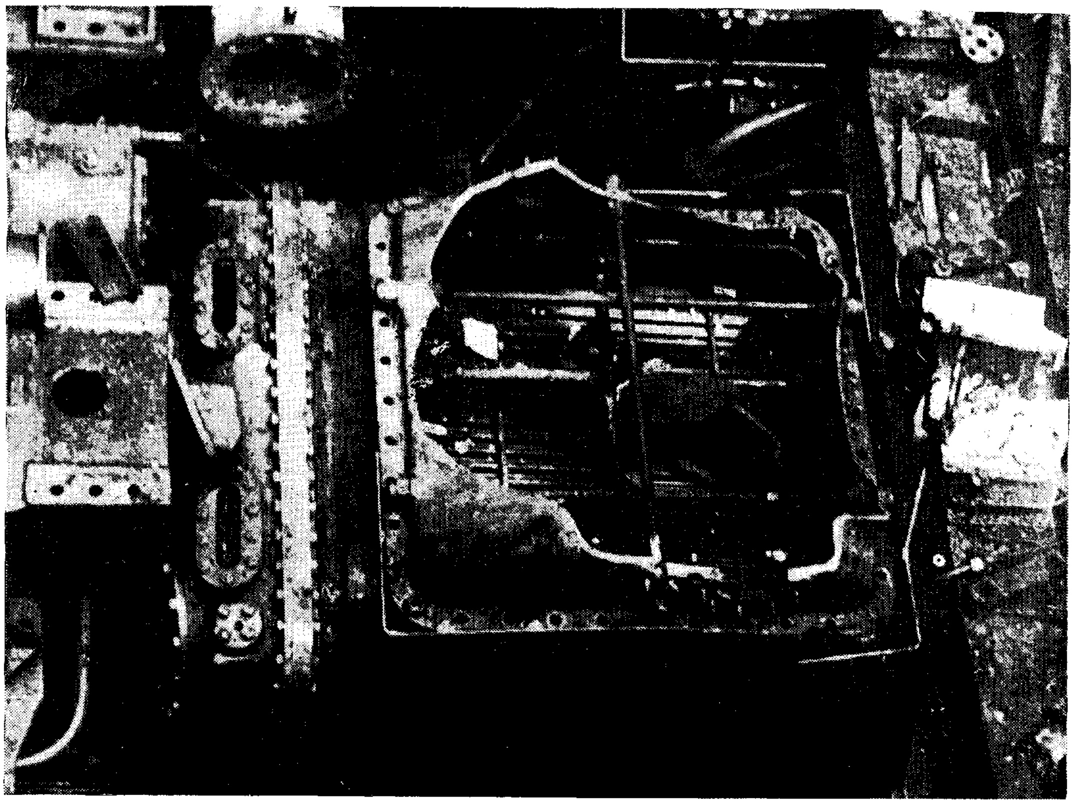


FIG. 9

Similarly, on the constructional, engineering and electrical sides it was basically an administrative failure that had caused us all to be so totally unprepared for the effects of shock from underwater explosions. Responsibility for the carrying out of trials to test the possible effects of every weapon on our ships lay with the Director of Naval Construction and although that department consulted other departments concerning their special requirements for such trials, 'departmentalism' was such that the proper liaison never developed. When the enemy forced a crisis upon us, co-operation between the departments of the Director of Naval Construction, the Engineer-in-Chief, the Director of Electrical Engineering and the then Director of Scientific Research developed very rapidly and in a fairly short time a 'Shock in Ships Committee', was formed to develop constructional techniques to resist the effects of shock and to carry out any tests necessary to guide them in this work. I like to think that this was a small-scale prototype of the recent reorganization of the Technical Departments into the Department of the Director-General Ships.

However, before going on to describe the work done under the auspices of the Shock in Ships Committee, it should be recorded that in 1937, D.N.C. had informed E.-in-C. that cast iron tended to fracture as a result of underwater explosions, and that its use should be avoided where possible. Unfortunately, two misunderstandings seem to have been associated with this: firstly that it was entirely a stress wave consideration, and secondly, that direct contact with the water in which the explosion occurred was a necessary ingredient in such failure. As a result the Royal Navy, but glaringly not the Merchant Navy, had substituted ductile materials for cast iron on all sea valves and also on condenser doors. Incidentally, a vast effort had to be devoted early in the war to concreting up the cast iron sea valves in merchant ships.

The question of stress waves was very interesting because the more scientifically minded were very alive to the possibility of a comprehensive stress wave

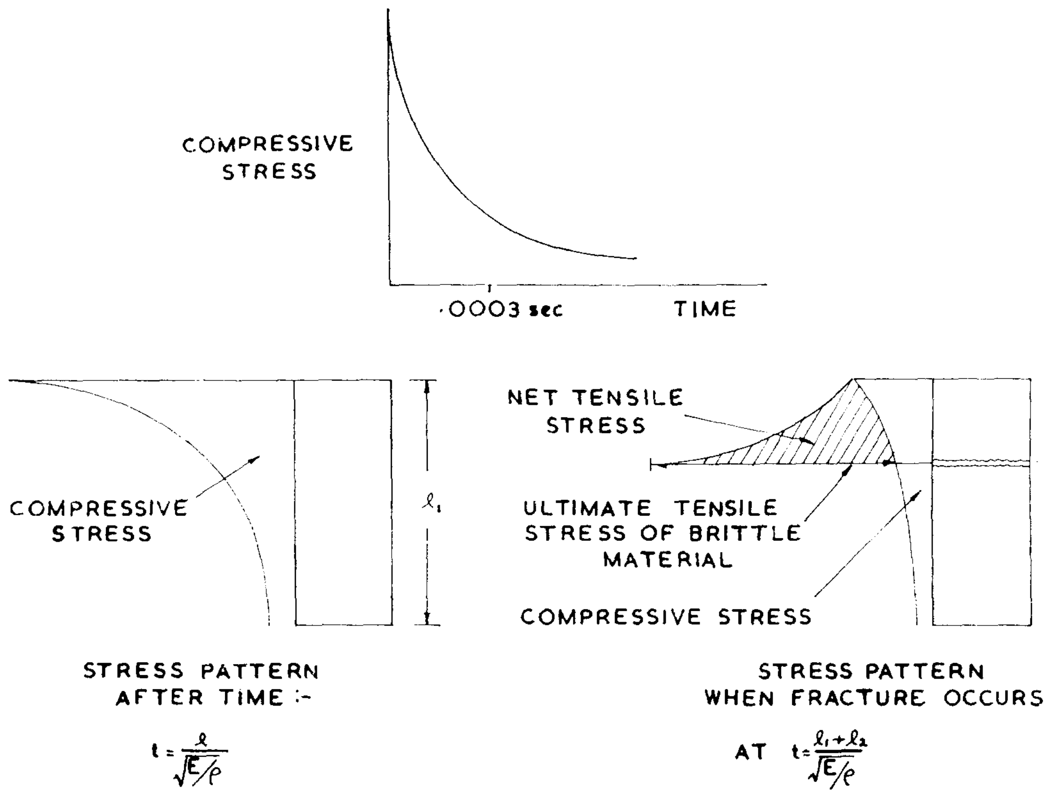


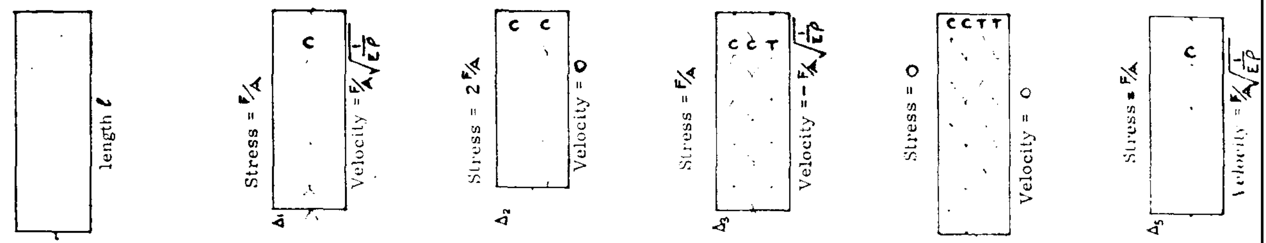
FIG. 10

being reflected at a free surface as a tensile wave. FIG 10 shows what occurs if the stress wave is very short-lived, and it can be seen that a material such as cast iron with good resistance to compressive stress can withstand the upward passage of the stress wave but due to its weakness against tensile stress will fail in tension at a point when the tensile wave is returning and the net tensile stress exceeds the ultimate tensile stress of the material. The fact that it was obvious that a majority of failures of machinery items occurred during deceleration rather than acceleration lent some mistaken credence to this reflected stress-wave theory of the fractures that occurred in ships. For a little time even the great Professor Haigh, who was naturally called in by the Admiralty as a consultant, was misled in this matter; however, he was thereafter invaluable in assisting us to reconcile stress wave theory with what was actually occurring. In a pressure pulse the particle velocity is directly proportional to the stress intensity and in a compressive stress this velocity is in the direction in which the stress wave is proceeding, while in a tensile stress wave the velocity is in the opposite direction to that in which the stress wave is proceeding.

$$\text{The particle velocity} = \text{stress} \times \sqrt{\frac{1}{E\rho}}$$

At an interface between two sections of different stiffness or mass the velocity and the forces must be common. To encompass this some of the stress wave is transmitted on and some reflected back either as a compressive or a tensile wave.

The effect of a suddenly applied continuous force on a fixed body and on a free body is shown in FIGS. 11 and 12. The pattern of the stress wave in the ship's frames as a result of non-contact underwater explosion is not as simple as that assumed for these examples, but consists of two parts:



$t = 0$

Suddenly applied load F

Compressive Stress $F/_A$ starts upward at speed $\sqrt{\frac{E}{\rho}}$ with particle velocity $F/_A\sqrt{\frac{1}{E\rho}}$

$t = \frac{\ell}{\sqrt{E/\rho}}$

$\Delta_1 = F/_A\sqrt{\frac{1}{E\rho}} \times \frac{\ell}{\sqrt{E/\rho}} = F/_A\ \ell/_E$

At this point front of stress wave is reflected from infinitely rigid support as compressive stress. Particle velocity is in opposite direction to existing particle velocity and starts to cancel it out.

$t = \frac{2\ell}{\sqrt{E/\rho}}$

$\Delta_2 = F/_A\sqrt{\frac{1}{E\rho}} \times \frac{2\ell}{\sqrt{E/\rho}} = 2F/_A\ \ell/_E$

At this point front of stress wave is reflected from free end as a tensile wave with downward particle velocity.

$t = \frac{3\ell}{\sqrt{E/\rho}}$

$\Delta_3 = 2F/_A\ \ell/_E - F/_A\sqrt{\frac{1}{E\rho}} \times \frac{\ell}{\sqrt{E/\rho}} = F/_A\ \ell/_E$

At this point front of tensile stress wave is reflected from infinitely rigid support as tensile stress. Particle velocity is upward and starts to cancel out existing particle velocity.

$t = \frac{4\ell}{\sqrt{E/\rho}}$

$\Delta_4 = F/_A\ \ell/_E - F/_A\sqrt{\frac{1}{E\rho}} \times \frac{\ell}{\sqrt{E/\rho}} = 0$

At this point front of tensile wave is reflected from free end as a compressive wave with upward particle velocity.

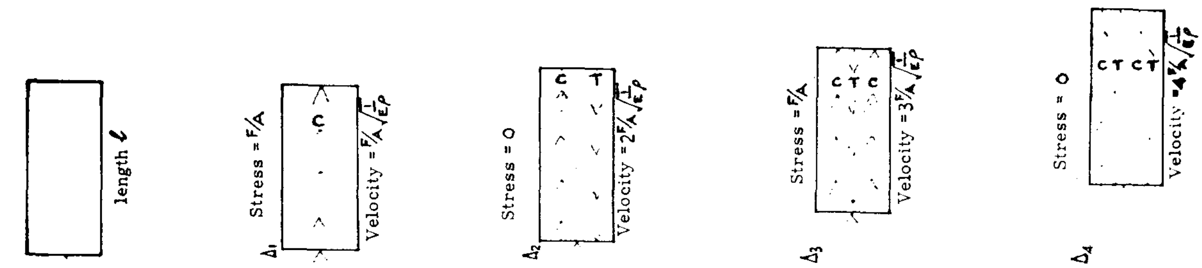
$t = \frac{5\ell}{\sqrt{E/\rho}}$

$\Delta_5 = \Delta_1$

Conditions are an exact repea[t] of these at $t = \frac{\ell}{\sqrt{E/\rho}}$ and subsequen[t] events are similar to thos[e] at $t = \frac{2\ell}{\sqrt{E/\rho}}$ e[tc.]

This shows that taking stress wave into account the overall effect is the same as that obtained from conventional theory with a suddenly applied force, *namely, an oscillation about a mean compression of* $\frac{\text{stress}}{E}$ x length.

FIG. 11



$t = 0$

Suddenly applied **load F.** **Compressive** stress $F/_A$ **starts** upward **at speed** $\sqrt{\frac{E}{\rho}}$ **with particle velocity** $F/_A\sqrt{\frac{1}{E\rho}}$

$t = \frac{\ell}{\sqrt{E/\rho}}$

$\Delta_1 = F/_A\sqrt{\frac{1}{E\rho}} \times \frac{\ell}{\sqrt{E/\rho}} = F/_A\ \ell/_E$

At this point front of stress wave is reflected from free end as tensile stress. Particle velocity in tensile wave is existing particle velocity.

$t = \frac{2\ell}{\sqrt{E/\rho}}$

$\Delta_2 = F/_A\sqrt{\frac{1}{E\rho}} \times \frac{2\ell}{\sqrt{E/\rho}} = 2F/_A\ \ell/_E$

At this point front of stress wave is reflected from free end as compressive stress. Particle velocity in compressive wave is upwards and additive to existing particle velocity.

$t = \frac{3\ell}{\sqrt{E/\rho}}$

$\Delta_3 = 2F/_A\ \ell/_E + 3F/_A\sqrt{\frac{1}{E\rho}} \times \frac{\ell}{\sqrt{E/\rho}} = 5F/_A\ \ell/_E$

At this point front of stress wave is reflected from free end as tensile stress. Particle velocity in tensile wave is upwards and additive to existing particle velocity.

$t = \frac{4\ell}{\sqrt{E/\rho}}$

$\Delta_4 = 5F/_A\ \ell/_E + 3F/_A\sqrt{\frac{1}{E\rho}} \times$ … $= 8F/_A\ \ell/_E$

At this point front of stress wave **is** reflected from **free** end as **compressive** stress, etc. etc.

This shows that taking **stress** wave into account, the overall **effect** is the same as that obtained by conventional theory with a **suddenly applied** constant force, namely, the whole body moves off with an acceleration of $F/_A\sqrt{\frac{1}{E\rho}}$ per $\frac{\ell}{\sqrt{E/\rho}}$ seconds or an acceleration of $\frac{F}{\rho A \ell}$ that is the force divided by the mass.

FIG. 12

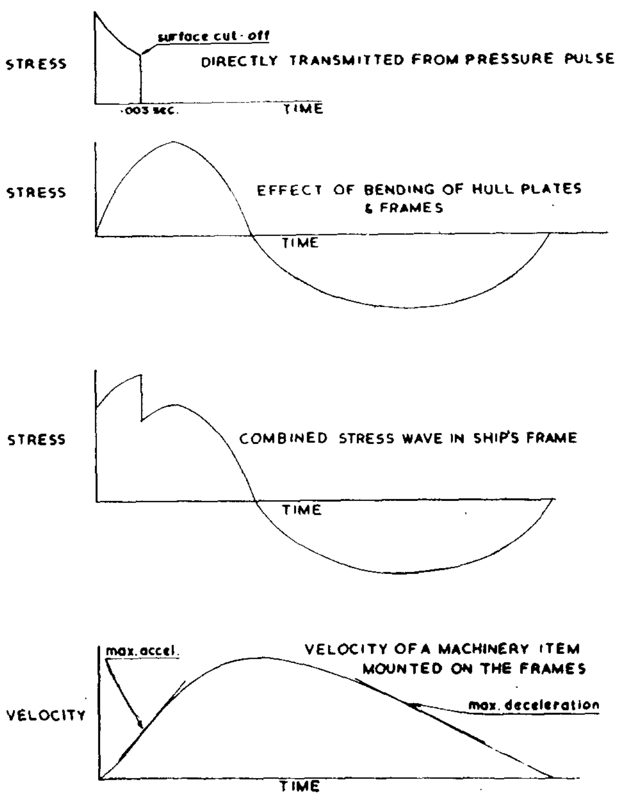


FIG. 13

(*a*) That directly transmitted from the pressure pulse in the water, which is sharp-fronted with an exponential fall-off for about 0·003 secs. when 'surface cut-off', reduces it to zero.

(*b*) That caused by resistance to the inward bending of the hull plates between the ships' frames due to the action of the pressure pulse in the water on these plates, and modified by the frames' own resistance to bending.

The resultant stress wave is as shown in FIG. 13. It can be seen that this remains positive for a time which is long compared with the time taken by a stress wave to traverse a machinery item, i.e., half a millisecond for an eight-foot height, and the concept of bodily acceleration and deceleration is justified. For the reflected stress-wave theory to be justified as the cause of damage, the stress wave in the ship's frames would need to vanish in under a millisecond.

Referring back to the photographs of damage, it can be seen in FIG. 7 that fractures have been caused by the bending moments set up in the cast iron crankcase by the pull of the holding-down studs during the decelerating phase. I cannot remember whether the fourth stud had been missing or was itself fractured, thus saving the crankcase in that vicinity. FIG. 9 illustrates a failure in the accelerating phase, and again, bending moments have played a large part in increasing the maximum tensile stresses in the cast iron to above its U.T.S.

This matter has been gone into at some length because of course, if the short-lived stress-wave theory prevails, the whole basis of our accepted design against shock would be erroneous, which it is not, and it was a major hurdle early in the war to obtain acceptance of the idea of bodily acceleration and deceleration as a design basis.

The commonsense practical engineer had no difficulty at all in this connection (perhaps he had never heard of stress waves!) and when the Engineer-in-Chief invited inspection of the damage in *Belfast* by prominent main and auxiliary machinery contractors, they all wrote in most shrewd and practical suggestions for dealing with the problem of building in resistance to the effects of non-contact underwater explosions. Only the other day I had another look through these letters sent by the contractors who visited *Belfast*, and they still read extremely well.

Besides inviting the suggestions of machinery contractors, the Engineer-in-Chief set up a Damage Section, consisting, in the first place, of myself alone, to study all damage to machinery caused by enemy action and to make proposals for minimizing it. Although this covered fires, direct hits in machinery spaces, the effects of the unit systems and so on, by far the major part of the work devolved on shock. If someone were to ask me to define 'shock', I would

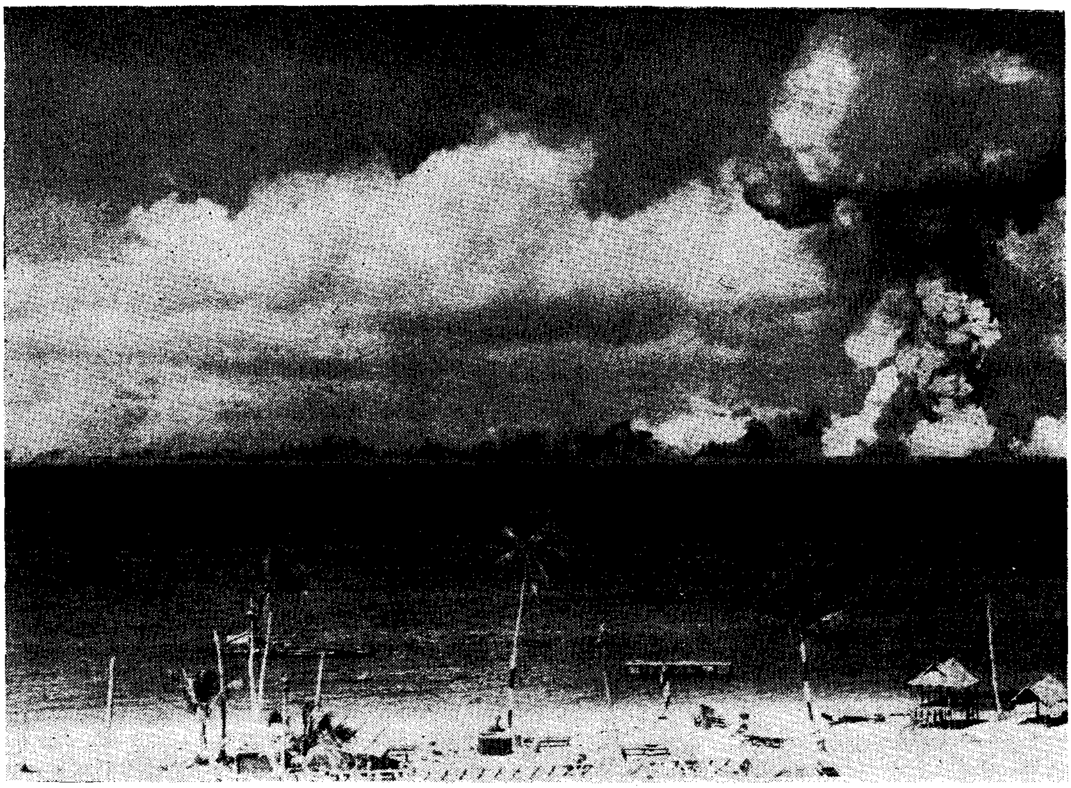


FIG. 14—AIR BURST ATOMIC EXPLOSION AT BIKINI

point out that although a large number of intelligent people applied themselves to finding a satisfactory definition, they never succeeded, although we all know precisely what we mean by the word. The sort of phrase that one ended up with was 'Shock is a non-periodic vibration characterized by suddenness and significant magnitude'!

Each of the Controller's Departments had their own immediate problems as a result of *Belfast* and subsequent casualties; D.N.C.'s being the whipping of the ship as a whole to such an extent that the ship's back was frequently broken at one of the nodes; E.-in-C.'s being the devising of protective measures such as yielding bolts and keeps and resilient and rigid-resilient mountings for existing ships machinery and the laying down of design-rules for new construction machinery; while D.E.E.'s main pre-occupation was perfecting shock-testing machine construction and operating techniques to reproduce as faithfully as possible failures that had occurred in ships, either malfunctioning of switchgear or breakages. A small team of D.S.R. personnel at H.M.S. *Vernon* (the home of torpedo officers who were at that time responsible for the electricity in ships) set about developing instruments suitable for measuring the motions imposed on various components in a ship as a result of shock. It is gratifying to be able to state that within a matter of months each of these activities produced results which saw us through the war, and even now, after all the refinements which have been introduced as a result of years of full-scale testing and analysis, do not seem too naive.

In the case of E.-in-C.'s instructions for a new design, an ability for auxiliary machinery to withstand very substantial upward accelerations and decelerations was postulated. Incredulous horror was the first reaction of the manufacturers, coupled with a desire to have me certified. However, in course of time they learnt to live with these figures and now will accept even higher values without flinching.

As mentioned earlier, the Departments got together to form a Shock-in-Ships Committee on which all interested parties were represented and many

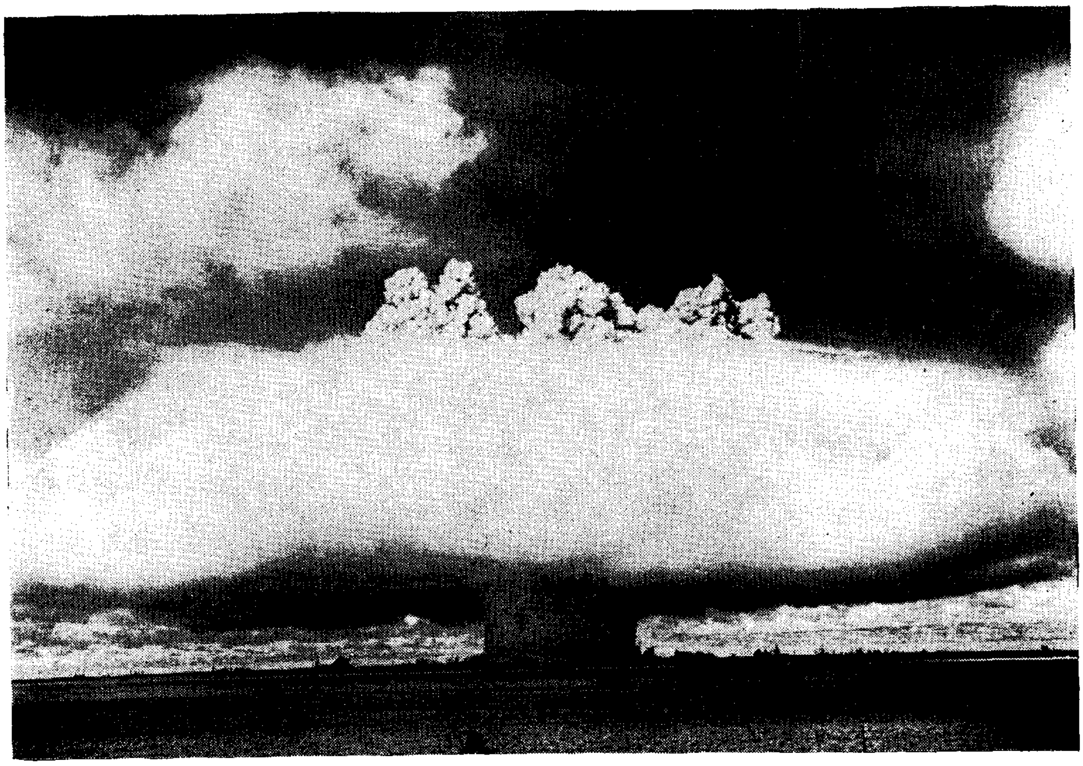


FIG. 15—UNDERWATER BURST ATOMIC EXPLOSION AT BIKINI

series of full-scale shock trials were carried out on destroyers and submarines to substantiate the validity of palliative methods and design instructions, and this work has continued right up to this day developing larger and better shock-testing machines, and closer specification of the precise requirements for items in particular circumstances. The inclusion of anti-noise mountings with requirements conflicting with those for shock protection has added to the complexity of the problem.

Leading on from the war-time experiments was the dramatic full-scale experiment staged by the Americans to test the effects on ships of atomic bombs exploded both in the air and underwater at Bikini. I was privileged to attend these tests as one of the small team of British observers, but I have never been able to discover what the connection was with or how the name has managed to be usurped by its more glamorous popular use.

The main outcome of these trials was that they showed that although the scale was completely different, the principles of shock resistance remain much the same. They did show, however, the need for control rooms isolated from the machinery compartments from which operation of the machinery could be carried out leaving the machinery compartments themselves unmanned.

Control Rooms and Remote Control

In view of the intense interest nowadays in remote and automatic control, some of the back history of the use of control rooms and remote control in the Navy may be worth stating.

In the early 1930's the Royal Navy steamed two battleships around the oceans completely unmanned and remotely controlled by radio control from an accompanying destroyer some three miles away. These ships, the *Agamemnon* and the *Centurion*, were used as target ships for gunnery practice with shells up to 8in., but not, of course, lyddite-filled.

The control of *Agamemnon* was rather crude and she was soon replaced by *Centurion* which operated as target ship for several years. A friend of mine was the Senior Engineer of *Centurion* so I am able to give some not-widely remembered details of her operation.

The remote control was operated by a dialling system rather similar to that used on the Post Office Telephone Dial System and up to 100 different instructions could be radioed to the ship. The ship carried out these instructions and then radioed back the instructions received.

The main orders were given to:

(*a*) The ahead manœuvring valves which were operated by geared electric motors, and could be instructed to open or close so many fractions of a turn at a time.

(*b*) The oil fuel spring-loaded by-pass to suction valve which could be increased or decreased in steps of 20 lb/sq in.

(*c*) The steering gear which could be instructed to steer any given gyro course in 10-degree steps of angle. An ingenious automatic anti-swing device, provided 'meeting' rudder to prevent overswinging the desired course.

The ship itself signalled when the boiler steam pressure was about to exceed 210 lb/sq in. or to fall below 180 lb/sq in. so that the destroyer could direct correcting oil fuel pressure signals. The ship could also signal its shaft r.p.m. back to the destroyer by a series of bleeps, one for each 2 r.p.m., which could be counted on the destroyer bridge.

The main safety device was a re-set gear which had to be re-set by the destroyer every twenty minutes or other pre-determined time. Three minutes before this time elapsed, the ship would send a warning signal, and if the re-set gear was not operated within three minutes the automatic shut-off gear would operate and stop the ship.

With the turn-down available on the simplex fuel system the ship's speed could be varied between 10 and 15 knots, but she could be brought down to 8 knots by the automatic operation of a boiler blow-off to the main condenser at boiler pressures greater than 210 lb/sq in.

This speed of 8 knots was used when the ship's company transferred from the ship to the destroyer, which came alongside for the purpose, and back again to the ship on completion of the exercise. Before leaving the directing dial was first tried out in the engine room, then on the upper deck and again immediately the control officers reached the bridge of the destroyer. I understand it was a wild scamper transferring from the *Centurion* to the destroyer, the main concern in everyone's mind being not to lose control of the ship during the process and not to drop the gin bottles.

Observing that this was all in the early 1930's, it was an incredible achievement, which makes some of today's attempts to work with unmanned machinery compartments seem fairly puny.

Control rooms were built into the Royal Navy's battleships and aircraft carriers designed just before the last war starting with the *King George V* Class and the *Ark Royal*—that was so frequently sunk by Lord Haw Haw. These consisted mainly of observation rooms, where the Engineer Officer could watch the performance of the various units from one central position, but in some of the aircraft carriers there was also the ability to operate the main throttles and to instruct the boiler rooms on the number of sprayers to use and the appropriate oil fuel pressures. Cruisers had also a machinery observation position in damage-control headquarters. In all of these ships, however, the engine and boiler rooms had to be fully manned to operate the machinery.

One of the lessons of the war was that not only did failure of the ventilation arrangements make operation of the machinery quite intolerable, but also that heat exhaustion in the Tropics detracted from the mental and physical ability to cope with emergencies. The sinking of H.M.S. *Prince of Wales* in the Gulf

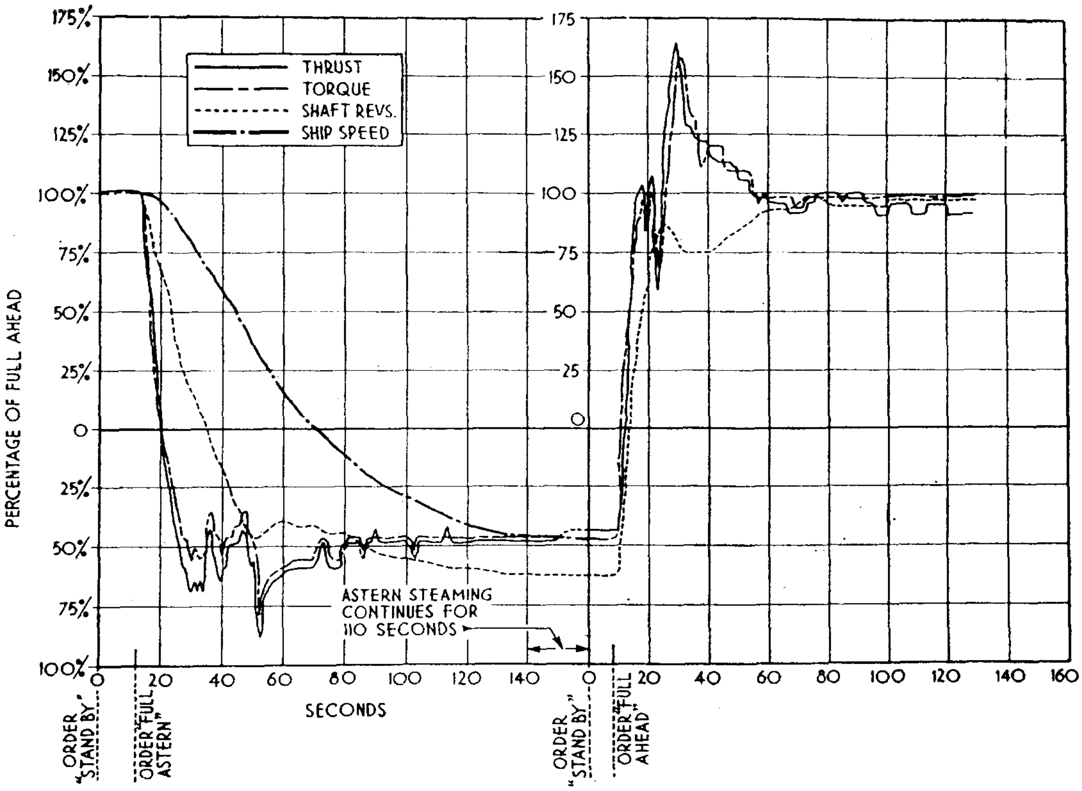


FIG. 16—H.M.S. SAVAGE—FULL AHEAD—FULL ASTERN—FULL AHEAD TRIALS

of Siam at Christmas, 1941, by Japanese torpedo bombing aircraft furnished many instances of this. There was therefore a case on its own for introducing air-conditioned control rooms from which the machinery could be fully operated with the machinery compartments unmanned, and from which sorties could be made by personnel physically and mentally competent to cope with crises. The advent of the requirement shown by the Bikini experiments, for control positions immune from radio-active fall-out clinched the matter and Admiralty policy thereafter was to introduce fully air-conditioned control rooms with ability to leave machinery compartments unmanned for considerable periods. *Devonshire* and *Ashanti* Classes were designed with this in view and *Hermes* and *Tiger* Classes had it introduced during construction.

Before leaving this subject, it was interesting to observe at Bikini that the Japanese warships used as targets had control rooms fitted within each boiler and engine room. The present advanced thinking in the Japanese mercantile ships on automatic control is obviously no new growth.

H.M.S. 'Savage'

My next calamity is rather an anti-climax after nearly losing a war but it is introduced because we were in the unique situation of having instrumented the transmission system and having the instruments working when the propeller blades fell off. This was in H.M.S. *Savage* which carried out a whole series of propeller trials during the years 1950–1953. Before going any further, I should like to mention that although the turbines reached an overspeed of nearly 190 per cent, they did not burst. Due to the centrifugal load, however, the H.P. rotor swelled out and jammed in its casing at about the time that steam was shut off by quick-thinking watchkeepers, so no great damage was done.

Some readers may remember a set of curves I produced in Vol. 6, No. 2 of the *Journal of Naval Engineering* in April, 1953, showing the transient torque and thrusts that occur when manœuvring from ahead to astern and *vice versa* (FIG.

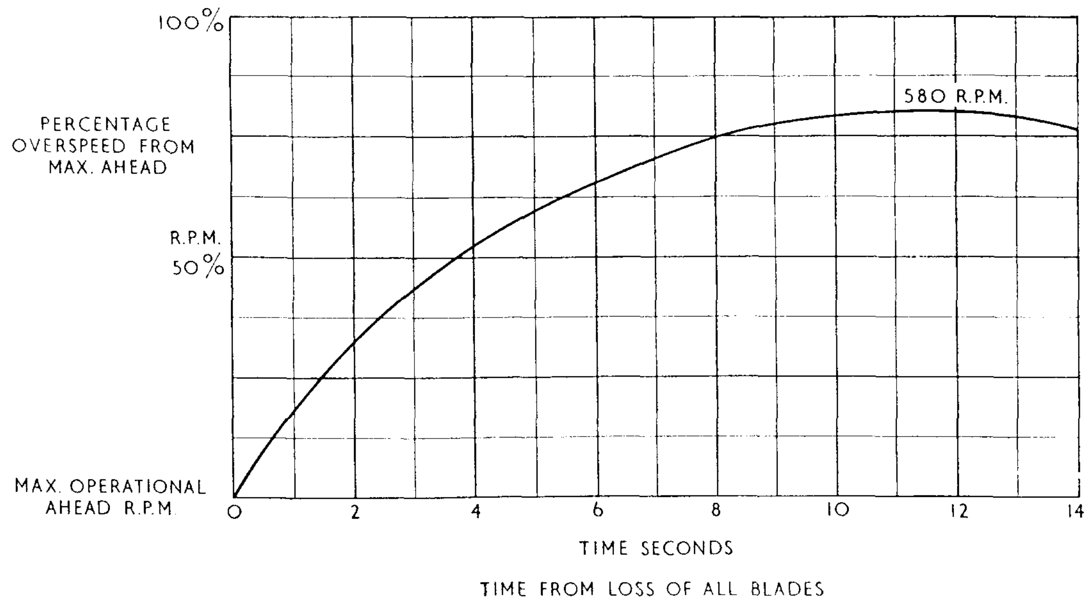


FIG. 17—H.M.S. SAVAGE—LOSS OF PROPELLER

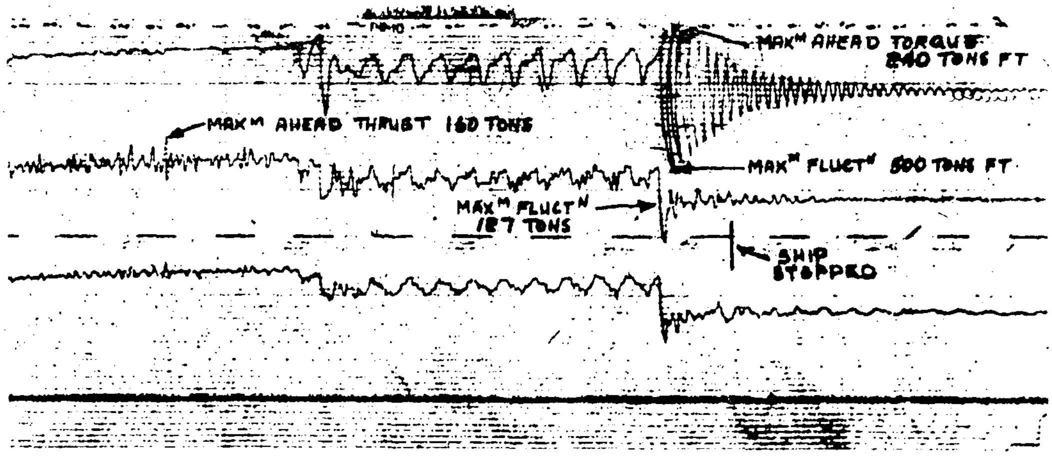


FIG. 18

16). From these it can be seen that some of the highest stresses are liable to be caused in the propeller during these transient conditions, and since one of the objects of the trials was to establish whether propulsive efficiency could be improved by thinning the propeller blades, it was necessary to establish that such thinned blades would retain sufficient strength. We did, in fact, continue thinning until a point was reached where the bronze propeller blades were bent by fierce manœuvring. With a well trained crew we were able to go from one to eight sprayers in 12 seconds; present day automatic boiler control systems can just beat this speed.

The propeller from which the blades fell off (FIG. 17) was an 11 per cent chrome, 0·15 per cent nickel stainless steel propeller thinned 20 per cent below that normally used for bronze propellers. The real trouble, however, was that the casting technique had not been properly mastered and, in fact, one propeller of this type was left overnight seemingly intact in the factory and was found next morning with one of the blades fallen off. The fact that the blades fell off the propeller in question while manœuvring should not be regarded as a black mark for stainless steel propellers, but only for our particular technique at that time.

Analysis of the pen recorder traces of this propeller shown in FIG. 18 produces the following results:

(1) It appears that one blade fell off initially then the other two approximately 12 seconds later.
(2) Shafting reached a maximum overspeed of 90 per cent in approximately 12 seconds from total loss of propeller. (FIG. 18.)
(3) Natural frequency of the main shaft minus propeller blade approximately 17 c/s.
(4) Sudden release of 'wind up' in the main shafting caused a considerable transient torque condition; the maximum peak to peak value being 500 ton ft. A similar release of 'wind up' is indicated in the thrust, but presumably the instrument response was not good enough to keep up with the resulting damped oscillation.

N.B.—The notation 'Ship Stopped' should be disregarded; no doubt some credulous scientist accepted an optimistic estimate from the above mentioned quick-thinking watchkeeper as to when he shut the ahead manœuvring valve!

Nuclear Propulsion

Finally, to round off this series of calamities which word, incidentally, my thesaurus classifies among disaster, catastrophe, casualty, reverse, contretemps, and setback and I think the ones I have referred to cover this range, we come to something which tends to be polemic, that is our failure so far to build any surface nuclear ships in this country. I believe that this must come via the Navy where a very strong case can already be made for any warship of 5,000 tons or more in displacement having nuclear power. There is historical precedent for revolutionary changes such as this coming about in the first place in the Royal Navy, and spreading into the Merchant Navy as they become better developed, as in the case of water-tube boilers, oil firing and steam turbines. If in five years' time we are not well along the road of introducing nuclear surface warships, I think that this, too, would rank as a major naval engineering calamity.