NOTES ON THE "LAURENTIC" SALVAGE OPERATIONS AND THE PREVENTION OF COMPRESSED AIR ILLNESS.

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(With Plates I–V and 5 Text-figures.)

Except in the West Australian pearl fisheries most of the world's diving is done in shallow water, from small boats or piers; and in civil life each diver is independent and controls the situation according to his own lights. In the British Navy the divers work under an officer who directs all the above-water side of things, such as the arrangements for pumping down air, and deciding whether or not it is safe to dive in existing circumstances. Though the officer will have had a short training at the Naval diving school he is not necessarily experienced in under water work; but he will be a seaman possessing knowledge of boat management, weather, and tides, with the authority to give and enforce orders which the young diver lacks. For simple shallow water work the first system is probably the better, though hardly practicable in a disciplined service where the divers are recruited from the lower ratings.

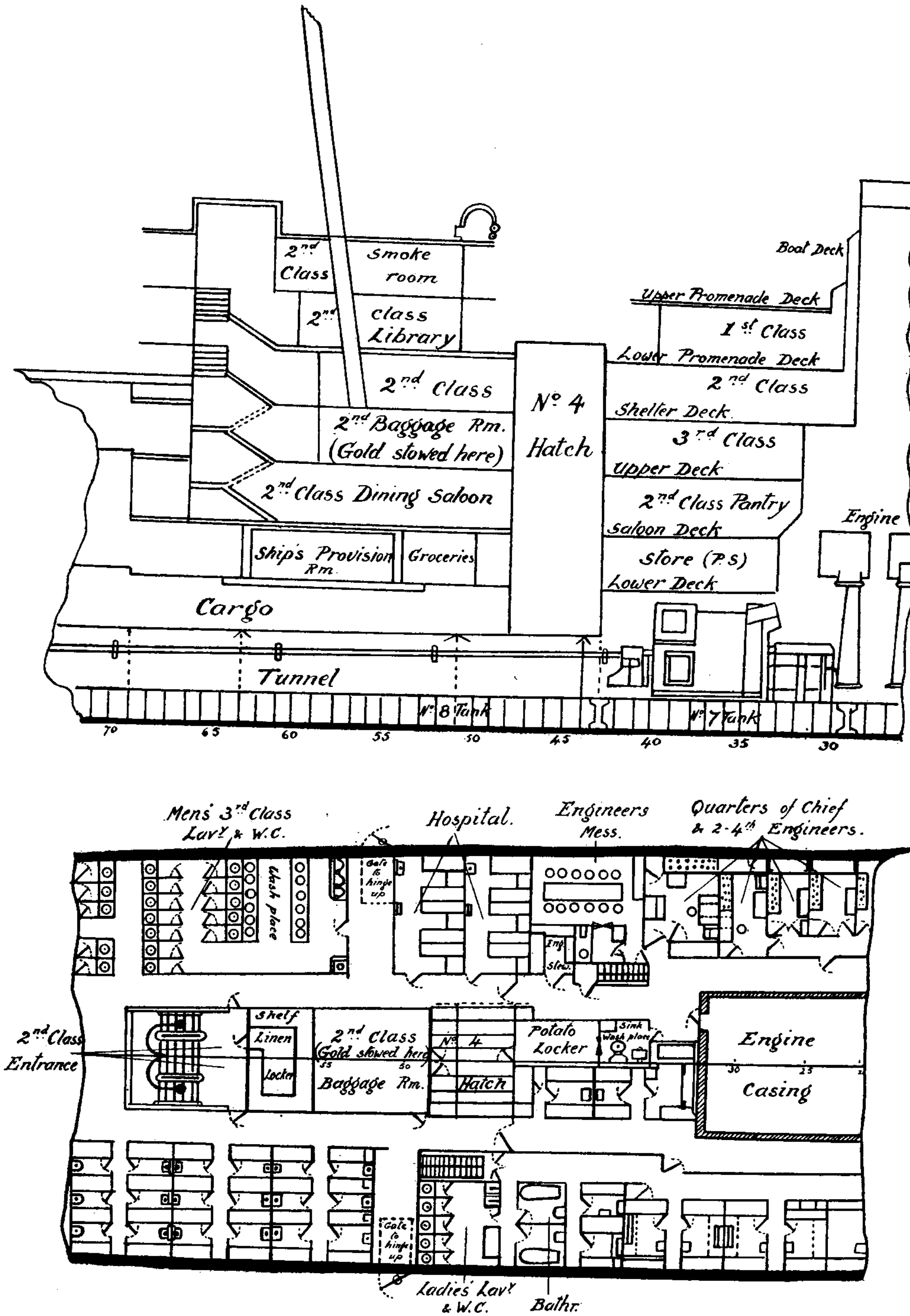
Be that as it may, there can be no doubt that in a large-scale undertaking in deep water, where two or three divers are down at the same time and heavy weights are being hoisted or lowered amongst them, where compressed air illness has to be seriously taken into account, where risks have to be accepted, and the work has to be driven on as a whole, it is necessary to have a single authority giving his orders on deck. This paper, giving some of the experiences and lessons learned by such a one in the course of seven summers' work in 20 fathoms of water in a very exposed situation, is written in the hope that it may help others and throw further light on the prevention of compressed air illness.

The "Laurentic" was a 15,000-ton Atlantic liner which during the war was taken over by the Admiralty and converted into an armed cruiser. In the early days of 1917 she shipped five million pounds worth of bullion at Liverpool and sailed for Halifax, but before clearing the Irish coast she was sunk by enemy mines with heavy loss of life. At this time the gold was very urgently needed, and measures for its recovery were put in hand forthwith. The wreck was located in a position off the mouth of Lough Swilly, with a depth of 20 fathoms or 120 feet, and was exposed to the full run of North Atlantic weather from the Westward and Northward, while any force of wind from the Southward fetched a nasty sea down Lough Swilly. Evidently the diving could only be done from a fairly large and seaworthy vessel, which must be kept in accurate position over the wreck, and not allowed to swing to wind and tide. The use of a ship instead of the usual diving boat necessitates the provision and placing of heavy ground-tackle to hold her moored "at all four corners," and this again demands powerful capstans. Steam or motor air compressors were also needed: for previous experience had shown the inadequacy of the ordinary hand diving pumps for such work. In 1917 we were at war, and the requirements of the job had to be met with such resources as were available.

As the more perfect arrangements of later years will be described below it is unnecessary to dwell on the original shifts and expedients. Fortunately we were able to obtain an excellent recompression chamber for dealing with cases of compressed air illness (see Plate I); and, apart from its value in curing such cases as did occur, the moral support of knowing that it was on board and ready enabled things to be done that would otherwise have been unjustifiably risky.

The first diver found the wreck lying on her port bilge with her masts about 60° from the vertical, so that it was impossible to stand on her deck at all, or on the side except at points where there was something to hang on to. The gold was known to have been stowed in the second class baggage room (Text-fig. 1), and the easiest access to this was by a water-tight door called the entry port about half-way down the ship's side. Accordingly the divers made their way to this spot and marked it by a floating buoy. A free ocean swell makes itself felt at a great depth by creating horizontal surges of water as the crests and troughs of successive waves pass over a given spot, and as this part of the work was done in heavy weather the divers edging along the high starboard rail, like cats on the ridge of a roof, got the full benefit of this phenomenon, having to cling tightly with arms and legs to prevent themselves from being swept away as each sea passed overhead, and then scramble along a few feet in the interval. The "Laurentic's" crew had taken to the boats, whose falls of course remained overhauled from the davits to their full length; and some of these threefold purchases, 60 feet long with heavy blocks at the end, were being lashed to and fro like whips by the scend of the seas. A diver was greatly impressed in the dim light by seeing the huge block at the end of one of these falls fly past within inches of his face glass. This was happening at a depth of about 60 feet from the surface and the same distance above the sea-bed.

The exact position of the entry port being now known, the moorings were taken up and relaid with the mark buoy as a centre, so that the diving vessel might plumb the men and, by keeping their air pipes and any hoisting wires as vertical as the tide would allow, minimise the risk of fouling. A suitable charge of guncotton was then adjusted on the thick steel doors of the entry port and exploded, so that the next diver down found them neatly displaced and resting on something a few feet within the ship. The next step was to get them out of the way, and after some difficulty they were hoisted to the surface. The awkward part of the business for the divers was firstly slinging



Text-fig. 1. Vertical and horizontal sections of "Laurentic" showing position of the gold within the ship.

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them in the dark narrow cross-passage, and secondly guiding them out through the entry port, which of course they almost exactly fitted, while all the time the diving vessel was pitching in the swell and jerking at the hoist.

The opening of the doors released a concourse of casks and cases of stores which had somehow assembled in the cross passage; many rushed to the surface, but others, waterlogged, remained behind, and several hours had to be spent in breaking them out and clearing the passage. Flour in sacks which had been under a head of 70 feet of water for 6 weeks showed the curious property this substance has of resisting immersion: for it was only wetted through a thickness of one or two inches inwards from the outside, the bulk being perfectly dry and sound.

A barred iron gate across the passage had to be blown off its hinges with another guncotton charge; and after two more hours' work at shifting heavy cases and clearing the way diver E. C. Miller reached the steel door of the strong room. Opening it with hammer and chisel he slid down on to a pile of bullion boxes worth about £8000 apiece. Though only a foot square by six inches deep these boxes weighed 140 lbs. and formed an awkward load for one man to get up the sloping slippery passage and round the various corners. This prevented much help being given from above. Miller nevertheless got one of them out that night and three more next morning.

In quiet weather all the operations up to this might have been done in a couple of days; but we were struggling against a succession of mid-winter gales with snow squalls, and could only hang on to the moorings in the short intervals, so a fortnight had elapsed. Yet the back of the job now seemed to be broken, and with ordinary luck a few weeks more should have seen the end of it; as a matter of fact it was going to last 7 years.

With the fourth box the wind came up, veered to the northward, and blew a hard gale for a week. Soon miles of the coast were littered with wreckage from the ship, much of which could be identified as coming from positions below decks, whence it could only have been liberated by extensive tearing of the hull.

When the weather moderated and the moorings, which had suffered badly, had been taken up and relaid, the business of plumbing the entry port was repeated and the significant fact noted that with the divers at the aperture of the entry post the pressure gauge on their air-supply showed the depth to be 103 feet, whereas before the gale the reading at the same point had been 62 feet. This could only mean that the wreck had collapsed to such an extent that her higher side had settled down through 40 feet. Getting in through the entry port the men could only penetrate a few feet along the passage: for, in the general flattening, its roof had closed down within 18 inches of the floor and the narrow space between was jammed solid with crumpled steel bulkheads and wreckage. This was a severe set-back; but a passage had to be forced somehow, and we set out to clear the road inwards by forcing up the overlaying decks with explosives, and shoring up the tunnel as it was made

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good. This policy succeeded, and the strong room was reached again at a depth of 120 feet, *i.e.*, right down on the sea-bottom; but it was empty and its floor gaped in large rents. Evidently the gold had slid away to port and downwards, dropping through decks and bulkheads as they tore asunder during the collapse of the ship. Plate III shows diagrammatic sketches of the condition of the vessel resting on the bottom before and after the collapse.

By now it was clear that the entry port route was too dangerous and must be abandoned; there were five decks above the divers supported by nothing in particular, and settlement was still going on as was evidenced by loud noises and tremors which occasionally disturbed the men as in darkness far inside the wreck they struggled to squeeze themselves onwards through narrow chinks. Moreover this burrowing work was terribly slow, since each obstruction as it was dislodged had to be hoisted out through the narrow aperture of the entry port (see Plate IV, fig. 1). Accordingly it was decided to cut down through the wreck vertically from above the spot where the bullion was judged to have lodged, the structure being removed plate by plate and beam by beam till the gold was exposed. Explosives were used to separate the members, and each piece as it became detached was raised to the surface and slung outside or on board the diving vessel till it could be dumped at a distance.

Though all was open above the divers' heads the hoisting of the big sections of plating to the surface was always anxious work (see Plate V, fig. 1). The derricks in the salvage ship were more than 120 feet above their work, and one may understand the situation by visualising one of those cranes so often seen towering over the sites of buildings in course of erection. Imagine now a dense fog (representing the intervening sea) which prevents the men at the crane and on the ground respectively from seeing anything of each other; add the complication that the crane instead of being fixed relatively to the ground is afloat, and that besides being subject to lateral displacements of several yards under the influence of winds and tides it has the habit of jumping vertically at irregular intervals as the swell passes under it. Again, let us have a furious wind (to represent the tide) which gets hold of any slack line such as the crane wire it is desired to lower to the diver and streams it out nearly horizontal; let the weight to be lifted be five tons of jagged plating which has to be slung and guided up between overhanging decks and structures by one man who is in a clumsy diver's dress, and whose range of vision is about five feet, who can only communicate by telephone, and who depends on a vulnerable rubber air pipe with a tendency to twine itself round the lifting wire at some mid-water point equally inaccessible to himself and those above. All the conditions for an accident are present, and a high standard of attention and discipline is needed to prevent one. That alone does not suffice, however. For instance, while any member of a structure under stress can readily be severed by explosives it is difficult to cut apart portions which by collapsing have relieved themselves of the stresses they are intended to bear. The mainmast was thrown down out of the way with precision and ease, but fallen sheets of decking could only be dealt with (in a reasonable time) by lifting a corner with a wire rope, pushing a charge underneath, and firing while the strain was still on.

One afternoon a plate had been partly lifted in this way and a fresh diver (Blachford), carrying a charge of guncotton, set about crawling under the plate to thrust the explosive as far in towards the "hinge" as possible. The steel wire supporting the plate stretched taut from the drum of the winch along the salvage ship's deck and down over the side. Blachford was giving directions up the telephone as usual, "Lower my pipe and line a little," "Take in the slack of the firing circuit," etc., when with a sudden snap the bight of the wire rope flew into the air and then fell slack along the deck. A flawed shackle had parted, the plate had fallen and our man was underneath it. After several long seconds his welcome voice came back on the telephone, "Give me all the air you can Sir." The valve was opened wider. "That's right, give me more yet, and get another diver down here as quick as possible." A very good man (Clear) was half undressed (in the diving sense) on deck when the shackle parted, and already was being screwed up again, while other hands rove a fresh wire and provided new slings for the plate: but as to giving Blachford more air, the pressure-gauge already showed such a big excess that the danger of bursting his dress presented itself. On the other hand the dress might be torn and partly flooded already, and he needing the extra air to keep the water back from his face as he lay prone. A dilemma, not to be solved by question and answer: for the roar of the volume of air already passing through Blachford's helmet as heard on the telephone all but drowned his voice, and evidently he could hear nothing of ours. When one throttled the supply a little to get better hearing the voice could be heard slowly and deliberately articulating "Give me more air." Balancing the risks, it seemed wiser not to do so. Clear went down, taking the new wire with him and keeping Blachford's pipe in hand for guidance to the exact place. All went well, the plate was slung anew, the weight taken and cautiously raised, and the man got out about nine minutes after he was trapped, unruffled and none the worse. It had felt to him as if the weight of the plate was just on the point of breaking his back, and the extra air inflating the dress seemed to take part of the burden and relieve him a little. The risk of its bursting the dress and drowning him had not struck him in the circumstances.

It may be objected that undue risks were being run, that no divers should have been below while hoists were being raised to the surface, that charges should not have been put under plates in the way described, but laid on top and repeated again and again till disruption was effected, and so on. The answer is that such procedure would have increased the time required for any particular piece of work fourfold. The gold was being sought, not for any selfish purpose but for National needs in war-time by a fighting Service, and the divers recognised that chances must be taken for the sake of quickness, and were proud to take them.

About this time German minelaying submarines were active in the vicinity; and our sweepers, in clearing the channels, used occasionally to explode a mine in their sweeps. This occurred one day at a distance of 2 miles and gave a diver who was under water a most violent and dangerous shock. After that we suspended diving while the minesweepers were working within 5 miles; but later on a similar detonation 6 miles distant gave another diver a severe blow.

It is rather hard to visualise the nature of the damage inflicted on submerged beings at such a distance from a submarine explosion. Fish do not seem to be killed outside a radius of two or three hundred yards, and it is curious to note that those without swim bladders do not seem to be affected at all. When a charge is fired those of the (swim bladdered) fish killed that have a slight degree of positive buoyancy at the moment reach the surface, and the rest sink. When blasting was in progress the decks of the wreck were covered with dead fish, so that the divers often slipped on them. This accumulation attracted shoals of dogfish, and I and other divers have often had to fix charges right in the midst of them. After firing, however, it was never possible to find a dead dogfish: on the contrary they could be seen rising to the surface almost in the foam of the explosion, and tearing at the bodies of the freshly killed teleosteans.

After two months' shipbreaking work, to the relief of all hands we got in touch with the gold again, or rather with an isolated part of it. The "Laurentic" had not been stripped of her passenger fittings, and at this stage the removal of each piece of plating used to expose a fresh bed of lumber, smashed furniture, bedding, wooden decks and panelling, provisions, and so forth (see Plate IV, fig. 2), which had to be pulled out by hand and flung into a large hopper or bucket. This was raised to the surface and emptied at frequent intervals. Among this stuff diver Miller found ten loose bars, and, following up the clue and enlarging the hole bit by bit, more were got daily till by September gold to the value of about £800,000 had been returned to the Treasury. By now wintry weather had set in, and for this and other reasons work was suspended with the intention of resuming in the spring. Before then another and more urgent matter had, however, arisen in connection with which the services of a team of expert divers was required; so our party and their equipment were engaged on other but even more exciting work through the summer of 1918. Thus 18 months elapsed before we returned to the scene, this time with a properly equipped salvage ship, the "Racer."

It was a surprise to find that the general appearance of the wreck had changed but little. The work was taken up in the same way as before: again gold turned up in the debris after a few weeks' work; and before the season ended a further £470,000 worth had been salved. The first part of this was found without much difficulty, but later on bars seemed to grow very scarce, and many tons of debris would have to be hoisted out for each one discovered. As a matter of fact the gold must, during the collapse of the wreck, have divided into two portions which came to be separated by some little distance as well as many thicknesses of plating. The smaller portion which we had hit upon was now practically exhausted. The part of the "Laurentic" in which we were working had been a well deck; *i.e.* both before and abaft it high superstructures rose containing passenger accommodation such as dining and smoke rooms. These had not collapsed like the hull proper, and as the cutting away of the hull between them proceeded their supports became undermined so that they leaned inwards and overhung the excavation in rather a threatening way. So long as gold was coming to hand I was very reluctant, however, to break off the work for the purpose of dealing with these superstructures, which certainly contained none of the bullion. The decision was fortunate, for on resuming work in the spring of 1920 we found that the winter gales had done all that was necessary and a bit more. The near ends of both superstructures had come down into the hole and completely covered it with sheets of steel and planked decks. All our landmarks, such as the heel of the mast, had shifted relatively to each other by as much as 30 feet, so that it was extremely hard to decide exactly where to start blasting again.

On peeling off the uppermost layers of plating a vast mass of rubbish was revealed filling up the crater that had taken two years to make. Evidently as the inner ends of the superstructures settled down their contents had been shot, as it were, into the depression, which was now filled with many scores of tons of broken up wood, cement and iron, the disintegration products of hundreds of saloon chairs, panelling, porcelain baths, and the planking, tiles, and composition which had formerly covered the various decks involved. Another unfavourable change was that the alteration in the profile of the wreck now allowed stones and sand from the sea-bottom to sweep in to the working place; and the mass, as it settled down, caked and hardened like gravel, while the remains of cot frames and spring mattresses running through it in all directions provided reinforcement. Besides this stationary dump there was an almost inexhaustible supply of waterlogged and broken wood drifting about in outlying parts of the wreck; and in bad weather wave action (which can be very violent at a depth of 20 fathoms) washed this stuff to and fro till it came to rest in any excavation the divers might have made since the last gale.

Through the summers of 1920 and 1921 the fight to get rid of this debris was carried on grimly. At one time we would get down a few feet through it and be able to reach a fresh deckplate and blast it away; at another, sand from the sea-bottom would cover up everything afresh. Large centrifugal pumps and dredging grabs were tried but failed, principally because of the constricted and obstructed nature of the space within the wreck where they had to be applied and the shortness of the periods for which the salvage ship could be held in position over the wreck. Hand work (to be described later), which could be started or stopped without delay, was found in the end to be the only reliable method of dealing with the stuff; but progress was so terribly slow that for months it remained questionable whether the inflow of sand from the sea-bed could be overcome. In fine weather the divers gained, and in bad, the sand. Very fortunately a few odd bars of gold turned up and kept hope alive when failure seemed to be threatening.

We may now describe the arrangements that were found best to supply the divers with air in proper quantity and protect them from compressed air illness. The operations described had the great advantage of being carried on in the light of the knowledge gained in a thorough investigation of the physiology of diving which had been carried out under an Admiralty Committee of which Dr J. S. Haldane was the scientific member[1]. At the time this Committee was appointed (1905) it was generally recognised that the difficulties of diving at such depths as 20 fathoms were so great that, except in the case of a very few men of great skill and endurance, the game was scarcely worth the candle. In the first place men could only work extremely slowly, and frequently became unconscious under water. In the second, despite various precautions traditional in the craft, severe or fatal cases of compressed air illness occurred often enough to make the issue of any particularly deep dive quite uncertain. With regard to the first matter the cause was found to be simply CO_2 poisoning. The approved method of supplying air to a diver by one hand-worked pump was so inadequate in deep water that, as a series of samples taken from the helmets showed, divers were often trying to work in an atmosphere in which the partial pressure of CO_2 rose to as much as 10 per cent. of an atmosphere.

The question of compressed air illness was not so simple; but with the aid of a large amount of experimental work a set of rules were evolved by Dr Haldane for controlling the ascent (or decompression) of a diver in an entirely novel way through the application of a new axiom, viz. that however long a man has been exposed to a high air pressure it is always safe to reduce that pressure (reckoned as absolute) by one half, *i.e.*, from four atmospheres absolute to two atmospheres absolute, or from six atmospheres absolute to three atmospheres absolute. At the same time a number of irrational rules and customs which had hitherto obtained and been more or less observed in the Navy were swept away. The theoretical considerations on which the new regulations were based and the experiments by which they were modified and shaped were published in full in this journal[2], and, though the system received some adverse criticism at first, it was immediately adopted by the Admiralty, and has been used in the Navy ever since with entirely satisfactory results.

[1] *Report of a Committee appointed by the Lords Commissioners of the Admiralty to consider and report upon the conditions of Deep Water diving.* (Blue Book. Stationery Office, 1907.)

[2] Boycott, A. E., Damant, G. C. C. and Haldane, J. S. (8. vi. 1908). The prevention of Compressed Air Illness. *Journ. of Hygiene*, VIII. 342–443, with 7 figs. and 3 plates.

The reliability of the Admiralty decompression tables.

Prior to the "Laurentic" operations it had been my general experience that no cases of compressed air illness arose if the Admiralty regulations were adhered to; and there was some reason for thinking that at the lesser depths they gave an unnecessary margin of safety. In 1917, for reasons already stated, safety had to be subordinated to speed, and the official decompression periods were deliberately shortened till the minor symptoms of compressed air illness began to appear among the men. At this stage individual differences in susceptibility among the divers became manifest and were duly allowed for; but it was impossible to foresee and guard against cases where an individual under pressure did an abnormal amount of physical work with his whole body or a particular limb, and so became, generally or locally, more highly saturated with dissolved nitrogen than the average. For instance diver Miller was considered relatively immune, but both on the day he entered the strong room and sent up the first box, and the day 2 months later when he again struck the gold amongst the wreckage, he had bad attacks of "bends" (acute pain, generally in joints). On the latter occasion he had worked for 90 minutes at 115 feet depth and should, by rule, have had a decompression lasting 87 minutes, but actually received one lasting 40 minutes only. As far as Miller knew he had worked no harder than usual, but evidently the excitement and anxiety to get as much gold as possible in the time caused an unconscious but significant increase in work done and consequently in N_2 absorbed. With experience we learned to expect symptoms in cases where a man got foul and had a struggle to clear himself, or was doing exceptionally well in digging out gold, or was experiencing trivial mishaps under water (such as dropping a tool and being unable to find it) which might prevent him from carrying out his allotted task and so injure his proper pride. In slinging plating for hoisting to the surface everyone soon learned for himself that screwing or unscrewing a succession of stiff shackle pins with finger and thumb would surely result in bends in the right forearm. At the time when shortened decompressions were practised, the average amount of physical work done by a diver in his "dip" was less than later on; in the first years each task required a little thinking about; and whilst, for instance, a hoist of plating was being hove to the surface and the man under water was waiting for the derrick wire to be lowered to him again, his exertions, if any, were purely mental. Later on, when it had become apparent that the success or failure of the enterprise depended on whether the divers could shift shingle out of a hole quicker than the sea could put it back again, the task and the method of doing it were standardised so that the men might as far as possible throw all the energies of their bodies into the scale. The quantity of shingle and debris sent to the surface by each, being weighed and recorded, formed the basis of a friendly but keen competition in which (the spells on the bottom being limited to 30 minutes) the divers worked at top speed, as if they were boxing, or running a race, from the time they reached the wreck till they were called up again. When this standard of exertion was attained it was found that no cutting of the Admiralty decompression times was possible, and further, that in the case of specially susceptible individuals, about one man in ten, they had to be increased by about 20 per cent. to secure freedom from bends.

Latterly, as a routine preventive measure, susceptible men used to breathe O_2 from a mask for 10 minutes after their decompression was finished and the helmet had been removed. I believe this to be a useful and very practical way of sweeping excess N_2 out of the body in the interval that nearly always elapses before illness can arise (see *Report* 51)[1]. We had cylinders of O_2 standing on deck, with reducing valve, bag and mask joined up and ready; after being shown how to work the apparatus once the divers could do all that was necessary for themselves. There were no cases of compressed air illness after O_2 had been breathed; but, in the absence of strictly comparable controls this proves nothing, and I was too busy to attempt systematic tests of the value of the method. Still we all came to believe in it; and men who thought they might be going to have bends were free to go to the cylinder and help themselves without fuss or bother to anyone else.

Fortunately I have no serious case to report; but this may be on account of the efficiency of the curative treatment available. Some of the men were in a queer state in the short interval between the first appearance of symptoms and their retreat into the recompression chamber. As noted in the stress of a time when I had many urgent responsibilities, out of 30 cases one was blind, another paralysed in both legs, and two or three more undoubtedly had bubbles in their central nervous systems. I believe these cases were analogous to the "temporary paralysis" of animals (see Boycott, Damant and Haldane, p. 386)[2] and of no very serious import; but of course one could not test the matter by withholding immediate cure. Simple "Bends" constituted the most frequent trouble. Patches of discoloration under the skin (generally abdomen) were often seen, but not counted. Dyspnoea, a most grave symptom (*l.c.* p. 388)[2], never appeared.

As a rule the illness came on within 1 hour of the diver's return to the surface, and only once was it delayed for 2 hours. Occasionally the pain of "bends" began to be felt towards the end of the decompression period; and the divers found that sometimes the attack could be aborted by violent exercise of the affected joint during the remainder of the decompression. Altogether we had 31 cases of illness out of about five thousand dives, the majority of which were at pressures between 53 and 59 pounds per square inch. In one particular it seems clear that the Admiralty rules do not allow a sufficient margin of safety, they say: "*Extra precautions after a second descent.* If a diver descends a second time into deep water with an interval of less than $1\frac{1}{2}$ hours between the two dives, his body will be more highly saturated with nitrogen at the end of the second dive, and extra care is needed in bringing

[1] See footnote 1, p. 34. [2] See reference in footnote 2, p. 34.

him up. The safe rule is to add together the times shown on the bottom in the two dives, etc., etc." going on to give certain rules for decompressing more slowly than usual. As the interval between successive dives of any one of our men was never less than 2½ hours there appeared to be no need for extra precautions; but as time went on and I noticed that practically all the cases of illness were occurring after the second dive, it became clear that the interval was insufficient. We increased it to 4 hours, the maximum that could be conveniently allowed; but even so the second dive showed itself to be definitely more dangerous than the first; and we shortened it by 5 minutes in the half hour, retaining the full decompression time.

Treatment of compressed air illness.

Recompression is the only remedy, and if applied immediately is invariably successful. For applying it the "Racer" had a steel recompression chamber about 8 feet long by 4 feet 6 inches diameter in which a couple of men could lie down side by side comfortably (see Plate II, fig. 1). The valves controlling the air supply were arranged so that the pressure could be controlled either from inside or outside, and 45 pounds per square inch was the highest internal pressure the chamber would support. There was a small air lock by which such things as cups of tea could be passed in or out, and a thick glass light by which one could dimly see what was happening inside. It was used in the following way:

Any man attacked by compressed air illness was bundled into the chamber with as little delay as possible, the door screwed up, and the pressure raised till his symptoms disappeared. In our cases this generally happened rather abruptly at some pressure between 10 and 20 lbs. After waiting a minute or two to make sure that all was well the escape valve was opened and the pressure allowed to fall at the following rate:

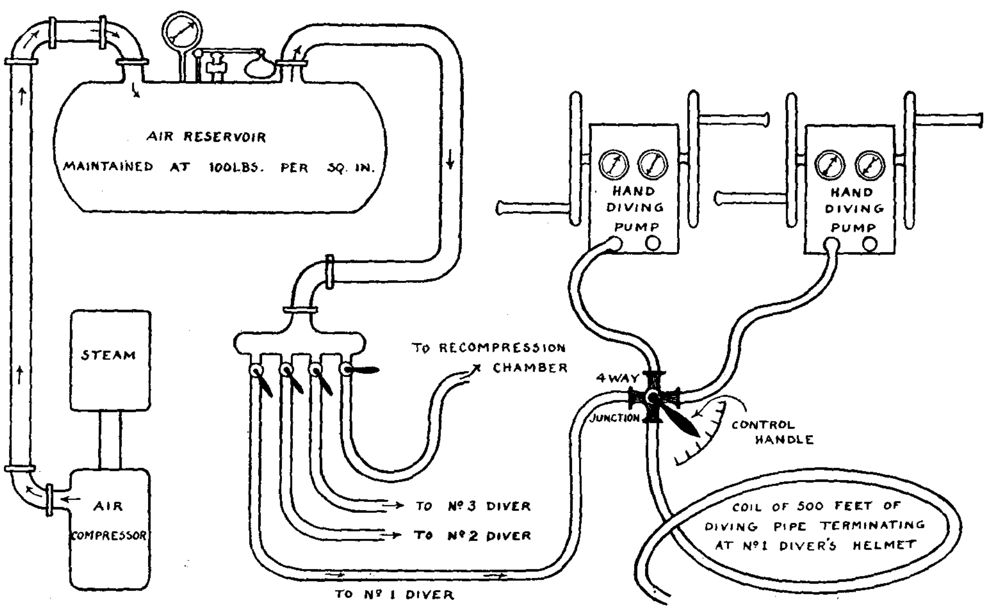
Between 45 lbs. and 30 lbs.	1 lb. in 3 minutes
Between 30 lbs. and 15 lbs.	1 lb. in 5 minutes
Below 15 lbs.	1 lb. in 8 minutes

As a rule (except in the 1917 cases to be mentioned presently) there was no return of symptoms; but when this did occur the escape of air was checked and the pressure raised again till relief was obtained. The decompression was then started again, but at a slower rate than before. It was striking to witness the immediate and certain cure of a man suffering acute pain and perhaps graver symptoms.

As experience increased, the divers, who at the beginning were reluctant to declare themselves ill till they could endure the pain no longer, came to report the first symptom, and were able to go into the chamber alone, manipulate the valves, and cure themselves as a matter of course without fuss or assistance. On one occasion after I had been working in the wreck I found myself beginning to see double an hour after returning to the surface. Unfortunately the chamber was already occupied by a bends case (Miller), who had got rid of his trouble and already decompressed down to 5 lbs., so that another 40 minutes should have seen him out of the chamber. But with my eyes diverging more and more every minute, and other unpleasant head feelings, it was difficult for me to wait so long; and Miller, getting to understand the situation, chivalrously blew off his remaining pressure and admitted the new case at the cost of an immediate return of his own torments. On raising the pressure my symptoms vanished at 10 lbs. and returned no more; but Miller's bends seemed to have acquired a new lease of life, and needed 20 lbs. Moreover on reducing the pressure by scale they returned again at 4 lbs. The pressure was raised again and reduced at a slower rate; but it was no good; and after $6\frac{1}{2}$ hours' trial and error (it was now 1.30 a.m. and we had all had a hard day's work starting at daylight) the temptation to try a warm meal and bed as against the chilly closeness of the chamber overcame the light of reason, with the result that Miller's sufferings continued all night and most of next day. Of course a chamber with an air lock big enough to admit a man would obviate this sort of difficulty; but we had no room on board for such a huge affair.

The diver's air-supply.

A steam air-compressor capable of delivering 100 cubic feet of free air per minute maintained the pressure in a large reservoir at 100 pounds per square inch.



Text-fig. 2. Diagram showing arrangement of the air-supply to divers.

From the reservoir came four branches, of which one supplied the recompression chamber and the others went to the divers numbered 1, 2 and 3 respectively (see Text-fig. 2). Tracing along one of the diver's branches one

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would first come to a 4-way gunmetal junction piece conveniently accessible to the officer in charge. One branch of this junction piece received the pipe from the reservoir, another took the rubber diving pipe from the man's helmet, while the third and fourth took the supply pipes from a pair of hand diving-pumps, which were therefore forked into the circuit and immediately available if the compressor broke down. A 2-way tap controlled this arrangement and by it the diver could be connected to the steam compressor or the hand pumps, and his air-supply increased or throttled down as required. Each diver had 500 feet of flexible rubber diving-pipe between himself and his own fixed 4-way junction on deck. Text-fig. 2 and Plate II, fig. 2 show the system with the piping and hand-pumps of No. 1 diver: divers Nos. 2 and 3 would have the same arrangement.

When a diver was on the wreck not more than half of his 500 feet of pipe would be paid out, the rest being kept in reserve to veer in case of the moorings parting and the ship starting to drive out of position. In such an event the diver, if warned in time, would have a chance of clambering up out of the wreck and saving himself; but it was not much of a chance and naturally the lay out, maintenance and handling of the moorings in bad weather received the most anxious consideration.

Whatever the details, the principle of ventilating a diver's helmet is always the same. An excess of air is forced down, which must escape somewhere and does so, after passing through the helmet, by a valve at the side. If the diver is 132 feet below the surface the hydrostatic pressure on the outside of that valve will be 59 pounds per square inch and the air inside must also bank up to that pressure before it can escape. It follows that, provided air is escaping, the air in the helmet and the incoming air will also be at 59 lbs. Consequently a pressure gauge tapped into the diver's pipe at any point will show what depth he is at.

The diver has control of the escape valve on his helmet. Were he to close it completely, the incoming air, before bursting the dress, would inflate it so as to render him buoyant and cause him to float or rather rush uncontrollably upwards to the surface. This "blowing up" is dangerous and not practised, but by partly closing his valve the diver can modify his buoyancy in such a way as to facilitate certain operations. The matter is complicated by the fact that (even with the valve wide open) the dress can be inflated to a dangerous extent by assuming any attitude in which the valve on the helmet is lower than other parts of the body. In such a case, for obvious hydrostatic reasons, the air will fill up all the higher levels of the baggy dress before getting down to and escaping by the valve.

We had a case of blowing up which might have had serious results. Several hundred bars of gold were discovered buried in sand in troughs or folds formed in the skin of the ship as it crumpled up. Owing to the presence of overhanging plates which could not be blasted away at the time, the divers were only able to reach this gold head downwards (see Text-fig. 3). Taking

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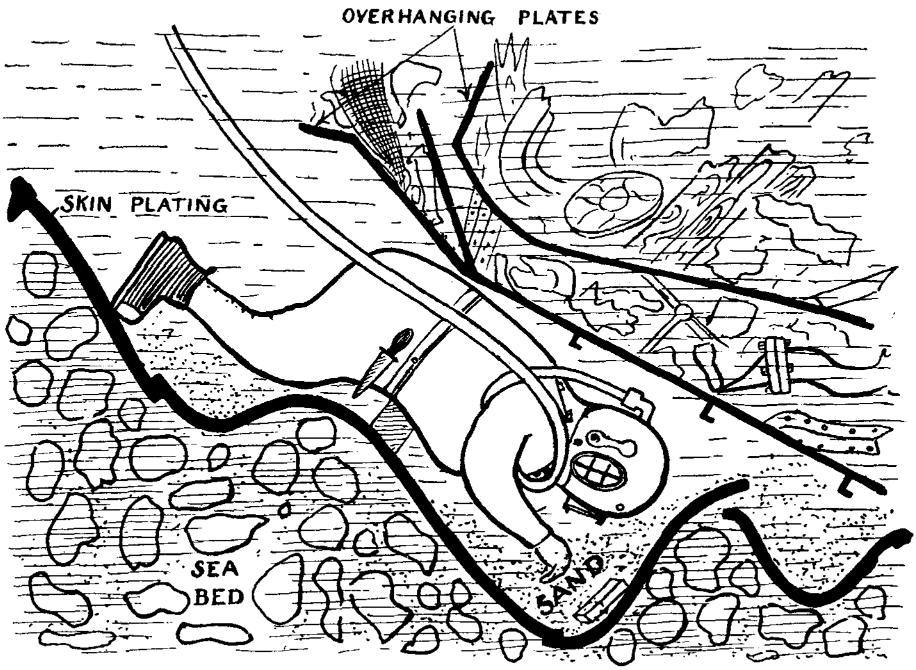
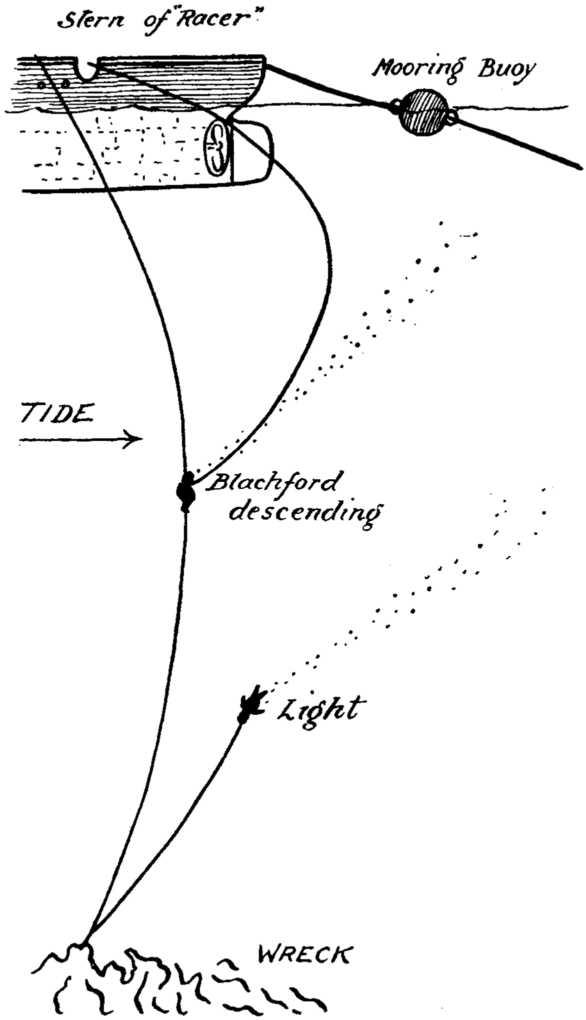
the smallest possible air-supply and often getting that stopped for a minute at a time, they would dig away with their hands till the accumulation of air behind began to lift them, when they would crawl out backwards and raise their heads so as to let it escape, then back again to the job like a terrier at a rabbit hole. In this or a similar place one of our men named Light, who could just feel a bar with the tips of his fingers, remained head-downwards a trifle too long, and his legs floated up to the overhanging plates so that he could not crawl backwards. The air was stopped as he asked, but a moment later he had to let go with his hands, and shot up. But his air pipe had been



Text-fig. 3. Diagram showing diver working head downwards.

stopped (tied) with a lanyard to the wreck, leaving him 40 feet of slack, so that after ascending 40 feet or so he was brought up with a jerk and remained moored like a mine, but upside down. In such a fix the strongest man cannot upright himself, for there is no *point d'appui*, and the buoyancy and stiffness of the distended dress are very great. Light reported by telephone that there was some water in his helmet and he did not know where it was coming from, "only a little" he added reassuringly; but it was evidently necessary to hurry, for though normally a leaky dress is no great matter an inverted man could drown in a quart or so.

Light being in mid-water (see Text-fig. 4) could not be seen either from the bottom or from the surface, so Blachford, who was already under water, was swung over on to the descending part of his pipe and slid down till he reached the lanyard securing it to the wreck. If he had then climbed up the ascending part till he reached the other diver he could probably have capsized him by throwing all his own weight on to the feet; but by an error for which I was responsible he was told to get astride Light's pipe and cut the lanyard with the idea that he would then be able to ease the other up to the surface. This did not come off, for as soon as the lanyard was cut the great buoyancy



Text-fig. 4. Diagram of a diver (Light) "blown up" in an awkward position (refer to description in text, p. 40).

of Light dragged both men to the surface in a flash. Fortunately they came up the right side of the ship, without striking her bottom, and all clear, so it was not difficult to get Light inboard, make sure that he had sustained no injury, and put him under a suitable pressure in the recompression chamber before any ill effects could arise from his sudden decompression, while Blachford was sent down under water to finish decompressing in the usual way.

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The risk of "blowing up" can be greatly reduced by lacing up the legs of the dress so that they fit tightly and afford no air space (*Report*, p. 52)[1]; but this procedure hampers a man's movements appreciably, and my experience is that no skilled diver will voluntarily adopt the precaution for work where much clambering about is involved. Still it would have prevented this particular mishap, and perhaps should have been enforced for men working gold out of this deep trough; but we went on as before and had no more trouble.

The summers' work of 1920 and 1921 had yielded only 50 bars of gold between them, but by the end of the latter season so many hundreds of tons of the wreck's structure had been brought to the surface that the port side of the shaft tunnel and tank tops were beginning to emerge from the confused mass of debris, showing that we had worked right through the ship from top to bottom as she lay, and giving valuable points of reference for orientation in the vast scrap heap.

There was a delightful surprise when we came back in the spring of 1922, for the first diver sent down actually *saw* a number of bars sticking up out of the sand close to where we had been working. For once the winter gales had worked on the side of the Treasury and washed away two feet or so of silted material. Nineteen bars came up that first day; they gave themselves up like lambs, as the men said. Following the clue, a few more were got each working day as the bank of sand and stones was scraped away by hand till the skin of the ship was reached and temporarily cleared over an area of about 440 square feet. After a check the trail of gold was picked up again, leading away to the port side under various layers of plating which still remained to be blown adrift and removed. It was here that the curious longitudinal folds and corrugations of the ship's bottom, which are shown in cross section in Text-fig. 3, were met with. While filled in with sand they puzzled us greatly: for it seemed as though the sheet of skin plating had come to an end and that we were digging down into the virgin sea-bed and finding part of the gold there.

Nearly one and a half million pounds worth was salved between April and October, when the weather became so stormy, and there was so little daylight penetrating down to the wreck, that it was unsafe to prolong the season. The best day's haul was £150,000, when the divers reached a nest of ingots still surrounded by the remnants of the boxes in which they had been packed. Strong though the original boxes had been it was seldom that any trace of them remained; and this was not surprising, for the gold bars themselves bore striking traces of the tremendous crushing and grinding they had received between the frames and plates of the wreck as they twisted and yielded to the swaying shocks of the wave action. Some bars were doubled up into a U-shape, others were squeezed out like so much putty and it was common to see pebbles or rivet heads deeply buried in the substance of the soft gold. I was able to look forward to the spring with confidence; for it was

[1] For reference see footnote 1, p. 34.

established that by concentrating on a small area and working on a carefully organised system the divers could keep ahead of the siltage, and also that the gold was lying on a presumably continuous sheet of skin plating, and could sink no lower.

The system of working.

After the first two years, for reasons which will be explained later, the length of a dive (except for special purposes) was limited to about 30 or 35 minutes on the bottom and 30 minutes more spent decompressing in mid-water: we will now discuss the way in which the time was spent.

In slinging and sending up heavy hoists of steelwork each job differed from the next, and no rules could be laid down; but as it became apparent that success depended on the speed with which sand could be shifted the methods for doing it became more and more standardised, and results improved accordingly, largely, I believe, because on a standard job each diver felt that he was bearing a fair share of the load and was competing with his messmates on equal terms. Let me say here that there were no personal rewards for finding gold; at the end of a season the Authorities used to give for division amongst the whole ship's company, a bonus of about one-eighth of one per cent. of the value of the gold that had been recovered in it. The divers had a share of this bonus; but it made no financial difference to an individual whether he or another found and sent up the gold. Nevertheless the competition was as keen as possible, each diver's score was reckoned up from day to day and the lucky fellow who sent up £45,000 worth on one dive received a prize of a tin of cigarettes.

Human nature being what it is there was a tendency for some men to spend their whole half-hour in poking about for odd bars and getting the derrick wires down to turn over likely plates, leaving the dull sand-shifting to the next fellow. It was odd to find oneself cursing *X* for bringing up untold gold and blessing *Y* for producing a sack of dirty sand and stones; but there was no doubt that the gold would give itself up in greater bulk than ever if only the sand could be got rid of. It cannot of course be shovelled under water: pumps and other mechanical means far too technical for description here had failed; man-power was on its trial and the issue was doubtful, when the corner was turned, as I am convinced, by the simple device of weighing and recording the amount of sand dug out by each diver in his spell below. Here was a new competition, and one with no luck about it. For 10 or 20 working days the weights of sand per man steadily increased as brains came to the aid of muscle, and as new dodges for saving 20 seconds here, and getting an extra 3 or 4 lbs. there with the aid of some queer-shaped scoop made by the blacksmith, came into action. Gradually it became clear that our strongest man, Balson, was unbeatable, after which, no doubt, interest declined. But a standard, and a high one, had been set up which no diver's pride would allow him to fall below; and till the excavations reached a depth point 10 feet below the level of the surrounding sea-bed the sand trouble was overcome.

The implements were simply sacks into the mouths of which had been tied steel scoops resembling the front part of a coal-scuttle (Plate IV, fig. 3), a fire hose carrying a high pressure of water, and the bare hands. Let us follow the actions of one of the divers. He has been dressed and put into the water some minutes beforehand and is waiting just below the surface for the word to go down. Four minutes before it is time for his predecessor to leave the wreck the order is given and he slides rapidly down the thin wire "shot-rope" which is put on afresh daily and leads directly to the spot where the work is being done. To slide down the 126 feet takes a minute or slightly less: the increase in atmospheric pressure of 55 pounds per square inch produces no physiological effect, though of course the descending diver has frequently to force open his Eustachian tubes. On first reaching the wreck he hauls down 30 feet or so of his own air pipe, ties it with a lanyard to some convenient part of the wreck and gives the order by telephone "Haul taut air pipe" Those above pull it up into as nearly a straight line as the tide will allow, so that there is no curving bight of pipe flowing out and liable to catch in distant parts of the wreck. The lanyard of course prevents any of the strain from coming on to the diver, whom it would pull off the bottom. The diver can generally see 20 feet or so, beyond which distance all is vague mist. He has landed in the bottom of a sort of crater the sides of which are formed by jagged shelves of plate, each one piled high with toppling masses of broken wood and indescribable junk.

Near the bottom of the shot-rope stands a large hopper or bucket, painted white so as to be conspicuous in the general gloom, into which a diver is struggling to lift a bulging sack. It is to help him that our friend has gone down early: he stumbles across, gives a heave to the sack, and seeing it flop into the bucket with the raising of a cloud of black mud, turns his back and makes for a canvas hose close at hand. This hose terminates in a specially strong conical metal pipe about 2 feet long. The diver gets down flat on the sandy floor of the crater, grips the metal pipe in his right hand, and asks for the water to be turned on from above. With a powerful jet issuing, the nozzle can be thrust deep into the caked silt and the diver's left hand follows it up, exploring this way and that among the pebbles, chunks of iron and other hard objects buried in the sand. It is now absolutely pitch dark on account of the cloud of mud and dirt raised by the hose; and if a bar comes to hand the diver lays it behind in contact with his leg.

Twelve minutes after leaving the surface he gets the order to start bagging sand and the water is stopped. With one of the bags already described he gets to work on the loosened dirt, scraping it in with his bare hands or a bit of wood. Perhaps during the hosing period he has located bars without being able to work them out, and he will now direct his digging towards them, bringing a knife or a crowbar to bear and working against time: for after 13 minutes on the bag the order to "Come up" is given from above. He has 5 minutes now in which to put his bars, if any, into the bucket, lift in his heavy sack of sand, and gather up into coils the slack pipe between himself and the lanyard. Giving the order "Up pipe" he casts off the lanyard, watches his pipe go up all clear, and then throttles the air-escape valve on his helmet so that in a moment he is sliding rapidly up the shot-rope again. Thirty feet below the surface (the exact spot being indicated to him from above) he checks his ascent, and letting go the wire shot-rope swings through the water to a short hanging rope steadied by a weight at the end.

There he passes through the decompression period. Adjusting his buoyancy so as to be only slightly negative, he can maintain his position on the rope with one hand or one leg while violently exercising his other three limbs and trunk with the object of increasing the circulation and consequently the rate of escape of N_2 from his tissues. After spending 5 minutes 30 feet below the surface he is signalled to ascend another 10 feet, and after spending 10 more minutes in the same way at the new level he is called up to his final stage 10 feet below the surface, where 15 minutes are passed. On getting inboard some 65 or 70 minutes after entering the water he is undressed, in some cases breathes O_2 for some minutes, and then starts deck work, attending to the other diver's pipes and so on. This is hard physical work, but not comparable to the half-hour spent in the wreck.

The gold bars or ingots generally lay 18 inches or 2 feet deep in the sand, so that the men could only reach them with their finger tips. As soon as the hose stopped playing, or one let go of it so as to bring both hands to bear on a bar, the sand would settle down and firmly grip the arms plunged into it. Some layers of deposit were too firm to be broken up by the hose with the highest water-pressure we could apply. As a rule we did not go above 70 pounds per square inch, as the loosened pebbles, etc., in flying about would batter and bruise the diver's hands. Apart from this type of damage the men's hands got into a pitiful state when a spell of fine weather enabled diving to be pushed on for 6 or 8 days in succession. The finger-nails used to get worn down to a strip barely a quarter of an inch wide; and the outer layers of skin on the extremity of each finger would be rubbed away so as to leave a raw surface about half an inch across. The pain of this condition was specially bad at night after the day's work was over, and the less injured skin which had been soaked in salt water all day began to dry and shrink. Hugh Miller (*My Schools and Schoolmasters*, chapter XI.) has left a vivid description of his sufferings from what must have been almost exactly similar damage.

Leathern gauntlets, were available in unlimited quantities, but the men would not wear them as long as they could use their bare hands at all. The reason for this was that they used to distinguish ingots from other hard objects deep down in the sand by touch alone; and the gloves, though by no means stiff ones, baulked this sense. Of course the shape and weight of a gold bar were unmistakeable to anyone who could *handle* it, but here the divers usually

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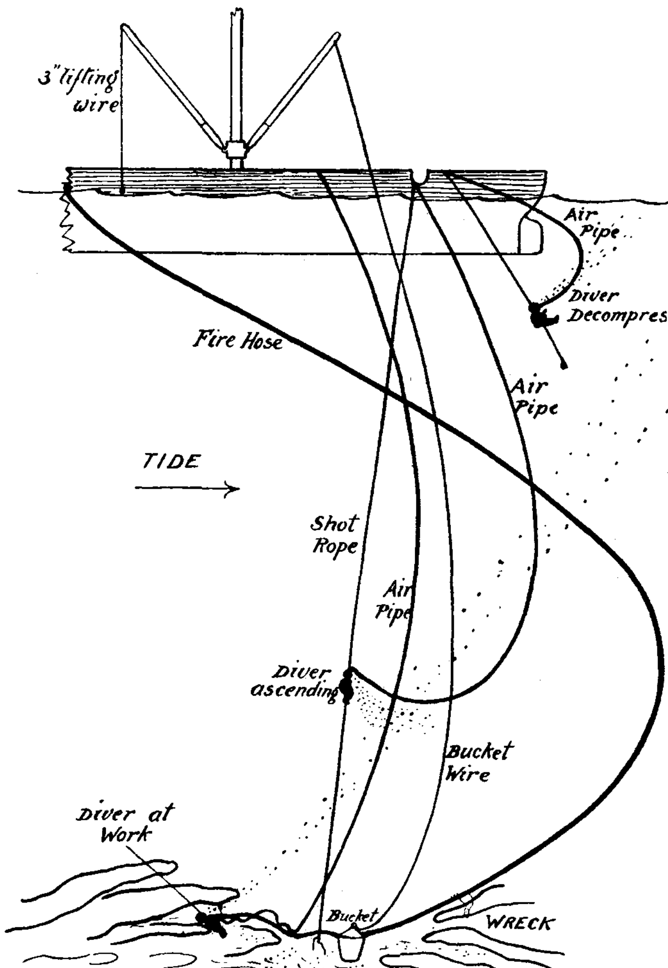
had to make their minds up by what they could feel of one small part of the surface of a deeply buried bar with the tips of their fingers. Experienced divers of the greatest keenness and skill coming to us did not compare favourably with our old hands till they had been working 6 months on the job; and I believe that what they chiefly lacked at first, and were acquiring in the interval, was this delicate finger-tip sense. They missed bars and used to spend time laboriously working out chunks of brass or glazed porcelain ware.

It will probably strike the reader that half an hour on the bottom is rather a short dive; and so it would be for most purposes. At the beginning, when divers good enough for the job were scarce, long dives formed the only possible means of getting anything done; and later on, for special purposes, we sometimes kept a man down in the wreck for a long period. But as we got together a team of experts who could start effective work within a minute of landing in the wreck, and needed no time for making themselves comfortable or thinking how to get over some difficulty, it turned out much better to get a perfectly fresh man to work every half-hour. It somehow quickened activity and mental alertness on deck as well as under water to have fresh news and viewpoints at such frequent intervals; and it nourished the invaluable spirit of competition.

Depth		Pressure pounds per square inch	Time under water, *i e.* from surface to beginning of ascent	Stoppages at different depths in minutes								Total time for ascent in minutes
Feet	Fathoms			80 ft.	70 ft.	60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	
120–132	20–22	$53\frac{1}{2}$–59	Up to 15 mins.	—	—	—	—	—	2	5	7	17
,,	,,	,,	15 to 30 mins.	—	—	—	—	—	5	10	15	33
,,	,,	,,	$\frac{1}{2}$ hr. to $\frac{3}{4}$ hr.	—	—	—	—	5	10	15	20	53
,,	,,	,,	$\frac{3}{4}$ hr. to $1\frac{1}{2}$ hrs.	—	—	—	5	10	20	30	30	98
,,	,,	,,	Over $1\frac{1}{2}$ hrs.	—	—	—	15	30	35	40	40	163

As the above extract from the Admiralty diving tables shows, had we kept each diver $1\frac{1}{2}$ hours on the bottom he would have had to spend a further $1\frac{1}{2}$ hours decompressing, during which time his services would have been lost to us on deck, where probably also when he did appear after 3 hours under water he would not have been much use till he had had another hour's rest. Further it would be unwise to give a man two such dives in the day. Again if a sudden shift of wind or accident obliged us to slip the moorings and run for shelter in a hurry what could be done with such heavily saturated (with N_2) divers? By limiting the liability for decompression to half an hour I felt justified, as the sea got up, in hanging on till the last moment, and in snatching a dive here and there in intermissions.

Text-fig. 5 shows the number of pipes and lines that we usually had over the side and in action simultaneously. The bucket was hoisted up by its own wire rope, and emptied at pretty frequent intervals. In a tideway the descending divers had to be allowed a long bight of pipe; and the fire-hose likewise could not be pulled tight or it would kink and burst. Someone had to keep the probable positions of the submerged, curving, and invisible pipes and ropes in his head, and work them so as to prevent entanglement and sudden death as a hoist of plating or a bucket full of wreckage was being whipped up by the steam winches. As in a marionette theatre there is a limit to the number of strings one person can manipulate physically or mentally, so here; and we never tried more than three divers under water at a time. Of these one or



Text-fig. 5. Diagram illustrating the lay in the water of the air pipes, water hose and wire ropes.

two would generally be on their decompression and comparatively safe. Had the "Laurentic" carried two hoards of gold, three or four hundred feet apart, the whole arrangement could have been duplicated, and both gangs could have worked simultaneously. But in the actual conditions two sets of people working in the same constricted area would have quickly neutralised one another's work by a series of unavoidable accidents.

The end of the work.

During 1923 nearly two million pounds worth of bullion was salved, leaving only 154 bars, worth about £240,000 still to be accounted for. When the "Racer" started work again early in 1924 the sheet of skin plating on which the gold had previously been found resting was almost completely cleared; but there were rents, and apertures such as port-holes, in it; and we had reason for thinking that some of the bars had found their way through these holes and worked down into the sea-bed. A fair number were obtained by digging out the boulders and stiff clay where they could be reached through the rents in the carpet of plating; and as the excavations were deepened and extended, so that divers could pass through and squeeze themselves right underneath the wreck, more gold was discovered several feet from any rent, and beneath continuous side-plating. The explanation of this anomaly is that what we may call the carpet of steel plate had been settling and creeping for two or three years since the bars had passed through the holes. Thus the carpet had slid over and covered many of them. Work in the dark beneath the wreck was difficult and not too safe, so it was decided to cut all the last layer of the wreck into sections and raise it to the surface piecemeal. A very fine spring and early summer favoured this undertaking, and eventually about 2000 square feet of the sea-floor were uncovered and searched, with the result that 129 of the 154 bars were found. With the onset of winter it became clear that further work would not be profitable, as it was getting more and more difficult to keep up with the inflow of gravel from higher parts of the sea-bed. In fact when the work was abandoned there were several feet of siltage over the deepest level the divers had reached.

Year 1917 Number of bars salved	...	542
,, 1918 ,, ,, ,,	...	0 (No operations)
,, 1919 ,, ,, ,,	...	315
,, 1920 ,, ,, ,,	...	7
,, 1921 ,, ,, ,,	...	43
,, 1922 ,, ,, ,,	...	895
,, 1923 ,, ,, ,,	...	1255
,, 1924 ,, ,, ,,	...	129
Total	...	3186
Number of bars that went down in the wreck		3211

It will be seen that more than 99 per cent. of the gold sunk was recovered. The whole cost of the operations amounted to between 2 per cent. and 3 per cent. of value salved, and there were no accidents to life or limb.

DESCRIPTION OF PLATES

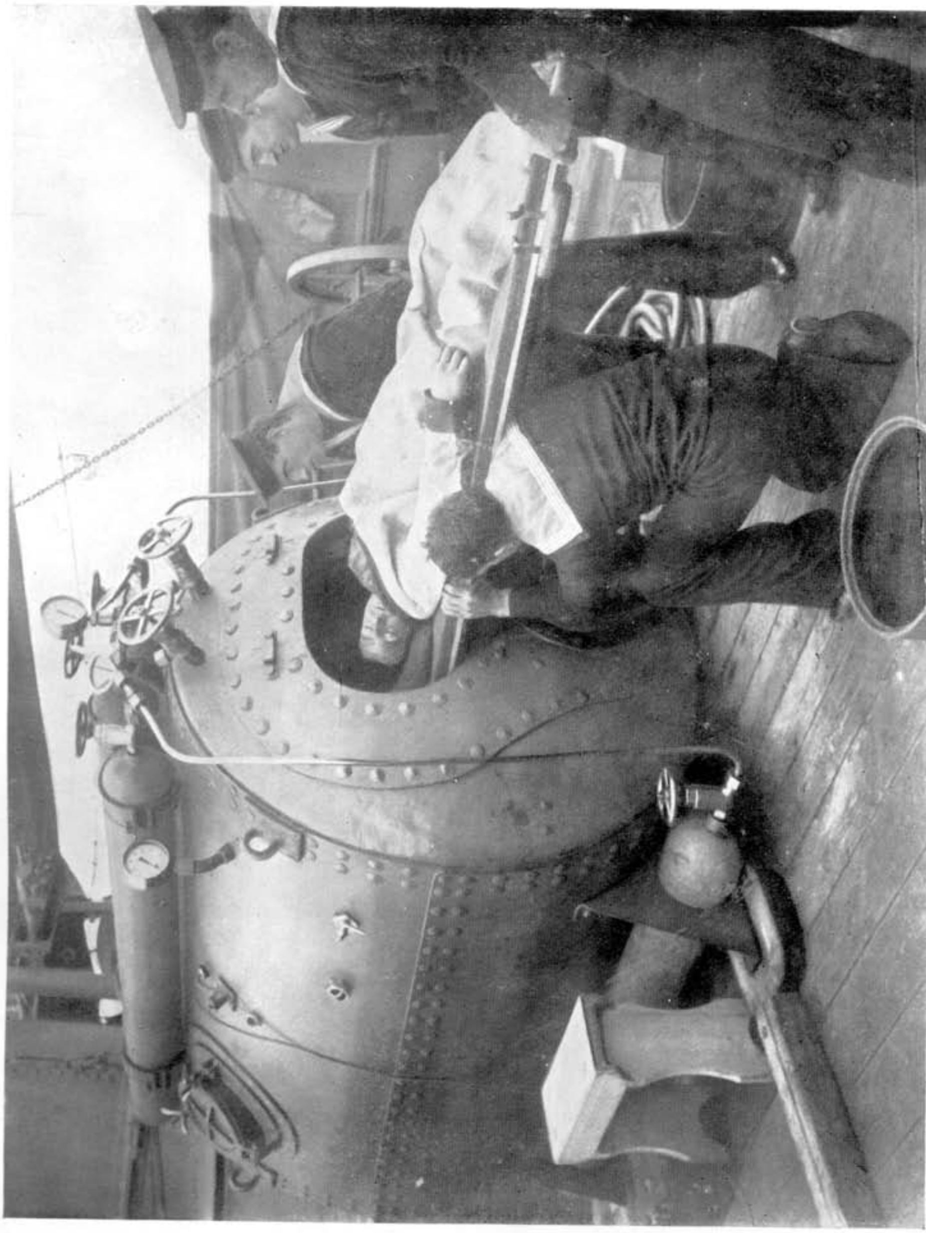
PLATE I.

The recompression chamber which was first used.

PLATE II.

Fig. 1. The small recompression chamber with large door which was used in later years. The diver in the foreground is holding two of the gold bars.

Fig. 2. Showing control taps and air pipe.



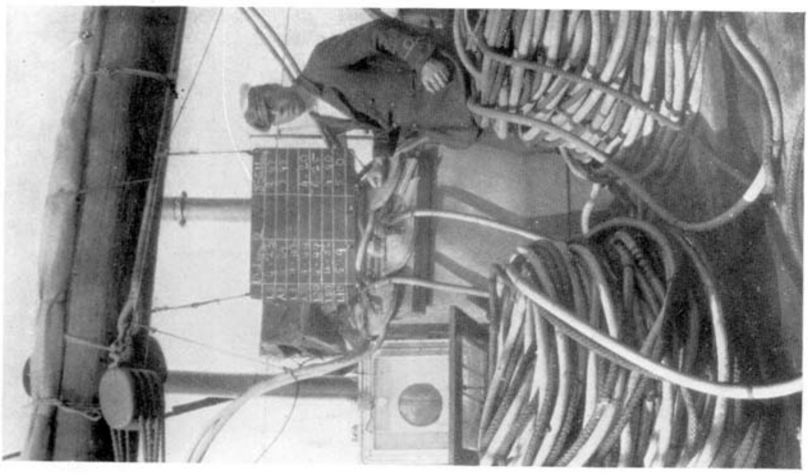


Fig. 2

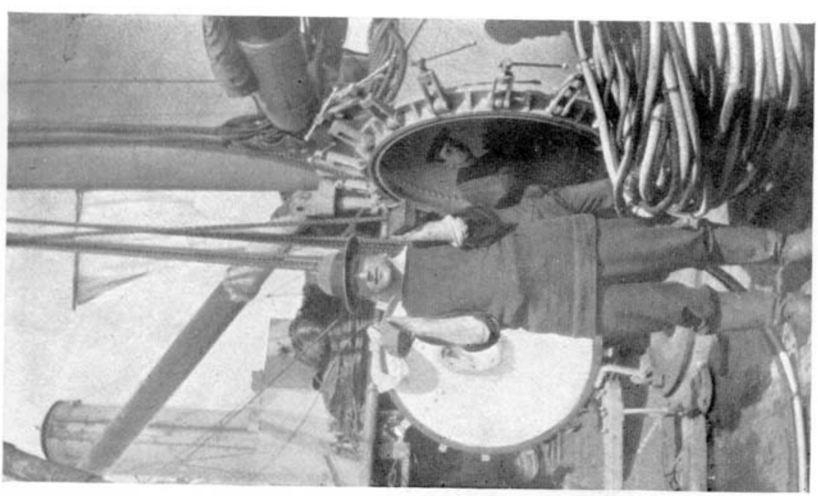


Fig. 1

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PLATE III

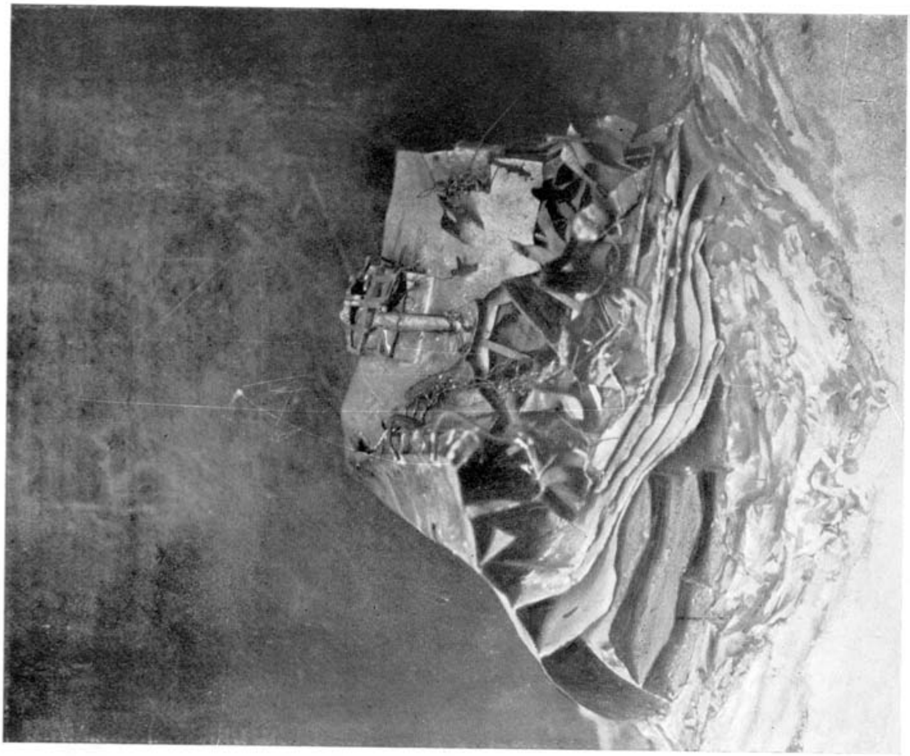

Fig. 2

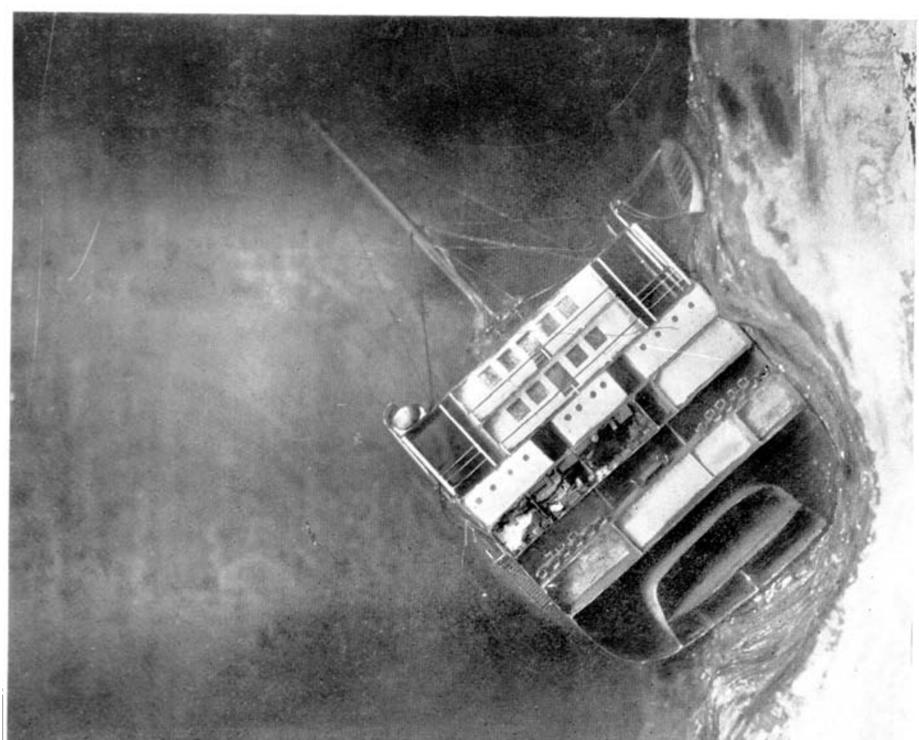

Fig 1

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Fig. 1

Fig. 2

Fig. 3

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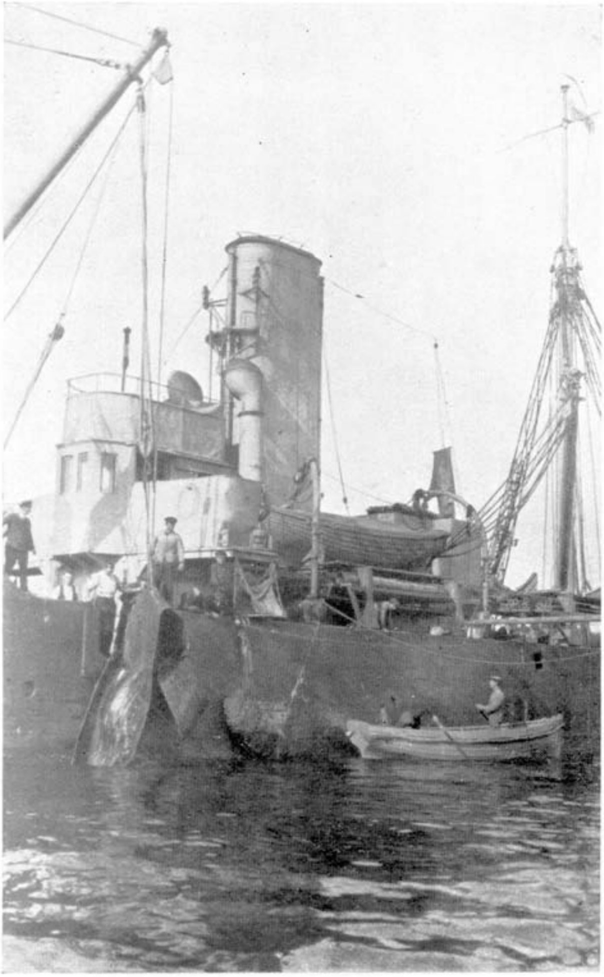

Fig. 1

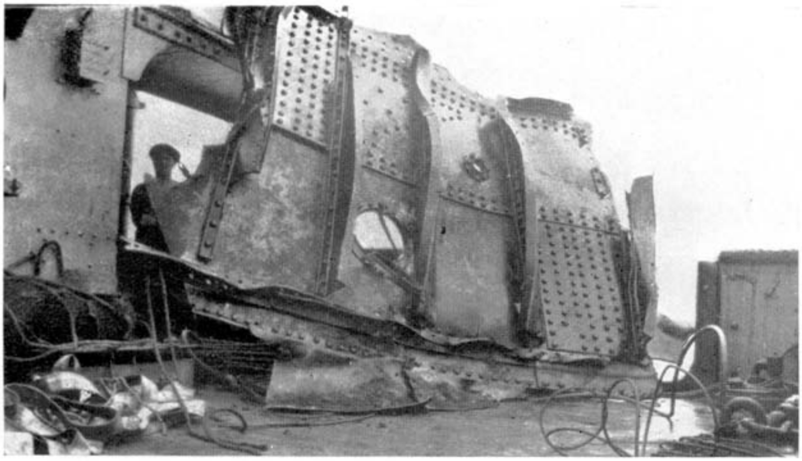

Fig. 2

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PLATE III.

Diagramatic views of the wreck: Fig. 1 before, and Fig. 2 after the collapse.

PLATE IV.

Fig. 1. Small pieces of wreckage hoisted out through the entry port.
Fig. 2. Lumber and debris worked out of the wreck by hand.
Fig. 3. Sacks fitted with scoops as used for bagging sand and gravel.

PLATE V.

Fig. 1. Hoisting plates out of the wreck.
Fig. 2. Section of side plating cut out and raised so as to attain the gold lying between it and the sea-bed.

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