take what amounted to a complicated laboratory experiment as well, was almost the last straw.

Another remarkable development used in one version of the system was the device of making the enemy echo itself as a spot which grew wings as the enemy approached, moving up or down to port or starboard, just as the appearance of the enemy itself would have done had it been visible. On many occasions successful interceptions were marked by, first, the appearance of the telltale green spot somewhere away from the line of flight of the fighter ; then the pilot's rapid adjustment of his course and altitude to bring the spot seen by his observer ahead and centred ; then the appearance of wings as the distance lessened. Finally the pilot would see the real enemy, a dark shape in the night sky, in a position corresponding to the green patch which hovered in the miniature Radar "picture."

The Radar-controlled Army searchlights were also extensively used to assist the fighters to intercept. Great skill was shown by the operators of these searchlights in illuminating the enemy and keeping him in the beam in such a way that the fighter could close to the kill without himself being illuminated while having every opportunity to see and surprise the enemy. The $1\frac{1}{2}$-m. Radar in fighters was limited in range, however. Reflections from the ground obscured target aircraft at ranges greater than the flying height, and it was necessary to develop a pencil beam to probe the sky, avoiding the ground. That could only be done by much shorter waves, and the solution was to come with centimetric Radar.

CENTIMETRIC RADAR

During the war a group of research scientists at Birmingham University devised the modern magnetron valve, which proved to be the gateway to the great new fields of centimetric Radar. It was, in fact, the outstanding development since the original chain took shape, and it remains the keystone of the greater part of modern Radar. Until 1938, the single research team working on valves specifically for the three Services' use, had been that at the Admiralty Signals School, but the pace quickened towards the outbreak of war and in the autumn of 1939, extra teams were called in for work on behalf of all the Services, still sponsored by the Admiralty, on what appeared then to be the distant goal of designing valves for centimetric Radar. The Birmingham team's achievement was such that the magnetron is now used as the transmitter in all the centrimetric Radar equipment which makes possible the present applications in the air and sea war.

Centimetric equipments not only solved the problems of the range and definition needed by night fighters' Radar ; the new techniques brought in their train such inventions as the moving map-like device which served our bombers in obliterating German targets, and they have served similarly to increase radically the accuracy of equipments used in hunting the enemy at sea and in many other branches of warfare. Centimetre waves have enabled the target data to be fed into A.A. predictors and coastal artillery batteries with such great precision of range measurement, and accuracy of bearing and elevation, as to surpass the inherent accuracy of the guns themselves. The success of these methods can be gauged from the story of the flying bomb attacks, by the end of which Radar-aided anti-aircraft guns were accounting for between 80 and 100 per cent. of the bombs reaching them.

It was appreciated, right from the start of this war, that the detection of surfaced submarines demanded some means other than ASDIC ; but Radar equipment designed for the detection of aircraft was inadequate in this case, and for detection of submarines both from the air and from surface ships, it was the centimetre-wave equipment which provided a decisive solution. The problem it solved was no less than finding, on a pitch black night in an area of many square miles of sea, a piece of metal projecting from the surface of the water by little more than the height of a man.

Before that time it had been apparent that for most naval purposes small aerial systems, capable of producing narrow beams, would be essential ; intensive research into the use of shorter wavelengths by all Services which was applied to naval problems bore an early fruit in 1938. At that time experimental equipments for the detection of aircraft were installed in a battleship and a cruiser and it immediately became apparent that the Navy could provide its own cover against air attack, a factor of vital importance in maintaining our sea power.

Still other centimetre-wave devices can, as already indicated, find towns for our bombers on the darkest, cloudy night and even display a moving map of harbour details, railway lines, and similar features. The immediate success which followed the application of centimetre-wave Radar to long-range bombing deserves particular mention.

The sound strategic decision to withhold the use of such devices until enough had been produced to make a succession of devastating attacks on Germany's great industrial centres, was well repaid. The premature loss of one such equipment to the enemy might have destroyed that element of surprise which, in fact, made impossible any effective reply by the enemy. The proportion of bombs falling on worthwhile targets was greatly increased, and the other offensive and defensive functions of aircraft fitted with Radar devices made more effective by centimetre techniques. It has been shown by statistical analysis of operations that airborne Radar apparatus multiplies by more than five times the value of an air fleet costing ten times as much as itself, quite apart from reduction in the numbers of crews needed and the safeguarding of valuable lives.

At sea and in the air, Radar navigation by these and by other longer-wave devices is now possible with an accuracy which makes the finest achievements of stellar navigation seem inaccurate by comparison. A ship's navigating officer can fix the position of a ship at sea by the stars or solar observation to within about a mile of her true position ; an aircraft can seldom rely on better position finding by astronomy than to within 10 miles of her true position. Yet it is now possible, by various devices, to have continuous indication of the position of a ship or aircraft to within a few tens of yards of her true place on the earth's surface. Indeed, no map or chart can be printed with sufficient accuracy or permanency to vie with the accuracy possible with the equipment.

(To be continued)

Plastic Armour

By DR. J. P. LAWRIE,*

THIS is the story of "plastic armour," a product of naval scientific ingenuity which saved thousands of lives and tons of steel.

In the grim days of Dunkirk, it was observed on some of the "little ships" with bituminous flooring, that bullets from attacking aircraft failed to penetrate, but were retained in the deck composition. Examination showed, that although these stopped bullets were probably almost spent, or had arrived at an angle, the composition of the deck sheathing tended to prevent penetration, and an investigation of the possibilities of developing a "plastic armour" was begun.

The deck sheathing mentioned is usually a form of mastic asphalt, consisting primarily of bitumen and limestone powder to which is added some grit. Heated, the ingredients form a soft paste, which, spread in position, hardens when cool. In peacetime it is mainly used for covering flat roofs, floors, or as a road surfacing.

In August, 1940, the Admiralty requested the Road Research Laboratory of the Department of Scientific and Industrial Research to carry out an investigation to ascertain whether a bituminous mixture of this nature could be produced which would provide superior protection against aerial attack to the sand-cement concrete slabs then in use on merchant ships. Concrete, used thus to protect wheel-houses and gun positions, was found to be ineffective and very dangerous, on account of flying fragments.

Experience with bituminous road materials and in the development of structural materials to resist attack by shell splinters and projectiles provided a valuable background for the investigation. Their research on concrete led the laboratory to the belief that the use of larger particles of stone would improve the resistance of plastic armour. Trials showed that, using a larger stone in the ratio of 50 per cent. to the asphalt, 0·303 armour-piercing bullets were stopped by a protection weighing only $38\frac{1}{2}$ lb. per square foot, compared with 50 lb. per square foot for concrete.

As the weight of solid mild steel to give protection against 0·303 A.P. bullets is 36 lb. per square foot,† it was apparent that in view of the acute shortage of steel and armour plate then prevailing a stone-filled mastic asphalt offered good possibilities as a protective armour.

Further investigations were conducted to ascertain whether plastic armour would give the same protection at extremes of temperature, whether high temperatures affected its resistance to flow, and whether it was likely to catch fire during an attack.

Satisfactory results were obtained, a working specification was drawn up, and under the joint supervision of the Admiralty and the Laboratory, exactly one month after the research had been begun work was commenced on the armouring of vital parts of a merchant ship.

This first *in situ* plastic armour had the following composition :—

	Per cent. by weight.
$\frac{5}{8}$ in. granite chippings	55
Limestone powder	37
Soluble bitumen	8

The "plastic" for plastic armour is made by mixing the stone and bituminous mortar in a normal 4 to 8-ton capacity mixer, as used in the asphalt industry, for three to four hours, after which the mixture is run off and poured into the space between wood or steel shuttering and the surface to be protected. Removal of the shuttering, leaves the plastic in position. In the early days of plastic armour prefabricated $2\frac{1}{2}$in. slabs with a $\frac{3}{16}$in. mild steel backing, were produced by spreading the plastic in horizontal wooden moulds. These slabs were used around wheel-houses, radio rooms, machine gun posts, or any other position requiring protection, especially where vision slots, ports, or vents were required. The steel walls of deck-houses provide ready-made backing for *in situ* plastic armour, but when precast slabs are used a steel backing plate is provided to the slab.

Towards the end of October, 1940, when initial difficulties of manufacture and application had been overcome, a more detailed investigation into the principles of design of plastic armour was begun. The first tests were chiefly concerned with stopping A.P. shot, but tests were later made with bomb and shell splinters and 20 mm. H.E. shells.

Plastic armour consists of a packed mass of stone particles held together with a bituminous mortar and backed with a mild steel plate. The stone particles break or turn the bullet or projectile, and the ductile steel back plate stops the relatively slow fragments of shot and stone which would otherwise be projected from the back of the plastic. The bituminous mortar plays little part in the protection beyond holding the stones in position.

PLASTIC PROTECTIVE PLATING

It was soon obvious that the type, size, and amount of stone were the most important factors affecting the protective qualities of plastic armour. Experimental targets of plastic armour were first made therefore with some fifty different types of stone. The results of tests made with 0·303in. A.P. bullets showed that

* Royal Naval Scientific Service.

† About $\frac{7}{8}$in. Thick—Ed., THE E.

certain flint and quartzite gravels gave the best protection. The granite, which was then in use, was immediately superseded by these new materials.

The next factor investigated was the best size for the stone particles. Tests were made with 0·303in., 0·55in., and 20 mm. A.P. shot on plastic containing as wide a range of stone size as possible. It was found that best protection was obtained when the size of the stone particles was twice the diameter of the shot to be stopped. Later tests with bomb and shell splinters showed that against this type of attack the size of stone in the plastic had no effect on the efficiency of protection.

When tests were made to find how the proportion of stone to bituminous mortar affected protection, it was found that, when special methods of consolidation were used, 70 per cent. by weight of stone could be packed into the plastic, resulting in a considerable improvement in protection over the existing plastic, which contained only 55 per cent. of stone. Unfortunately, plastic with such a high stone content, could not be consolidated behind shuttering or by hand in moulds. Advantage was taken of this discovery, however, in the development of a new form of plastic armour, known as "plastic protective plating."

Plastic protective plating is made by consolidating the hot plastic by vibration into "trays" of thin sheet metal, and then bolting on the back plate to the open side of the tray. In this way the plastic is totally enclosed in metal. This gives the plastic protective plating a much greater resistance than plastic armour to incidental damage from attack and during transport, and, what is more important, it allows the best proportion and size of stone to be used.

Special Light-Weight Plastic

In 1942, at the time plastic protective plating was introduced, it became desirable to reduce imports of bitumen, and the problem arose as to whether pitch could be used in its place. When tests were made it was found that the use of pitch allowed better consolidation of the plastic. Advantage was taken of this fact to develop a special light-weight plastic consisting of pitch, fine sawdust, and lime for use in plastic protective plating.

Plastic protective plating was not only lighter in weight and more efficient and of better appearance than plastic armour, but it lends itself particularly to factory mass production; by the end of 1942, the majority of gun positions were being protected by plastic protective plating instead of *in situ* plastic armour. Since then the proportion of plastic protective plating used has increased steadily.

Plastic protective plating first went into action in the Dieppe raid, when 2½in. non-magnetic plastic protective plating with ¼in. brass backing, used to protect the helmsman, was hit by small arms A.P. shot, 20 mm. H.E. shells, and at least one 4in. mortar bomb. Only one splinter from the mortar bomb perforated the protection and everything else was stopped. This result confirmed the suitability of plastic protective plating for use on landing craft and resulted in its wide use in preparation for D-day.

The protective qualities of plastic protective plating compared with steel armour plate varies to some extent according to the type of weapon with which it is attacked. Against A.P. shot it is better than mild steel, but not as good as armour plate. For example, if the weight per square foot of plastic protective plating required to stop A.P. shot is represented by 100, the weight for armour plate is 75 and that for mild steel is 116 and that for plastic armour of the original type 122. (The actual weight of plastic protective plating required to give protection against 0·303in. A.P. bullets at muzzle velocity, is 30 lb. per square foot.) Against bomb splinters the degree of protection varies with the speed of the splinter, *e.g.*, for splinters at 5000ft. per second, say, from a 500-lb. bomb or large shell, plastic protective plating is more efficient than an equal weight of steel armour. Against splinters striking at 3000ft. per second, say, from a German S.D.2, butterfly bomb, plastic protective plating and steel armour would give equal protection; at a striking velocity of 1500ft. per second, such as would be expected from fragments of an "S" mine, plastic protective plating gives equal protection to mild steel, but is inferior to steel armour.

The good resistance shown to splinters from large shells and bombs has been proved on a number of occasions on ships passing through the Straits of Dover during the shelling.

By May, 1943, approximately 100,000 tons of P.A. and P.P.P. were being produced annually, and it was being made in Canada, South Africa, India, and the Middle East. In 1941, officers specially instructed in its manufacture were sent to the U.S.A., where production was immediately begun.

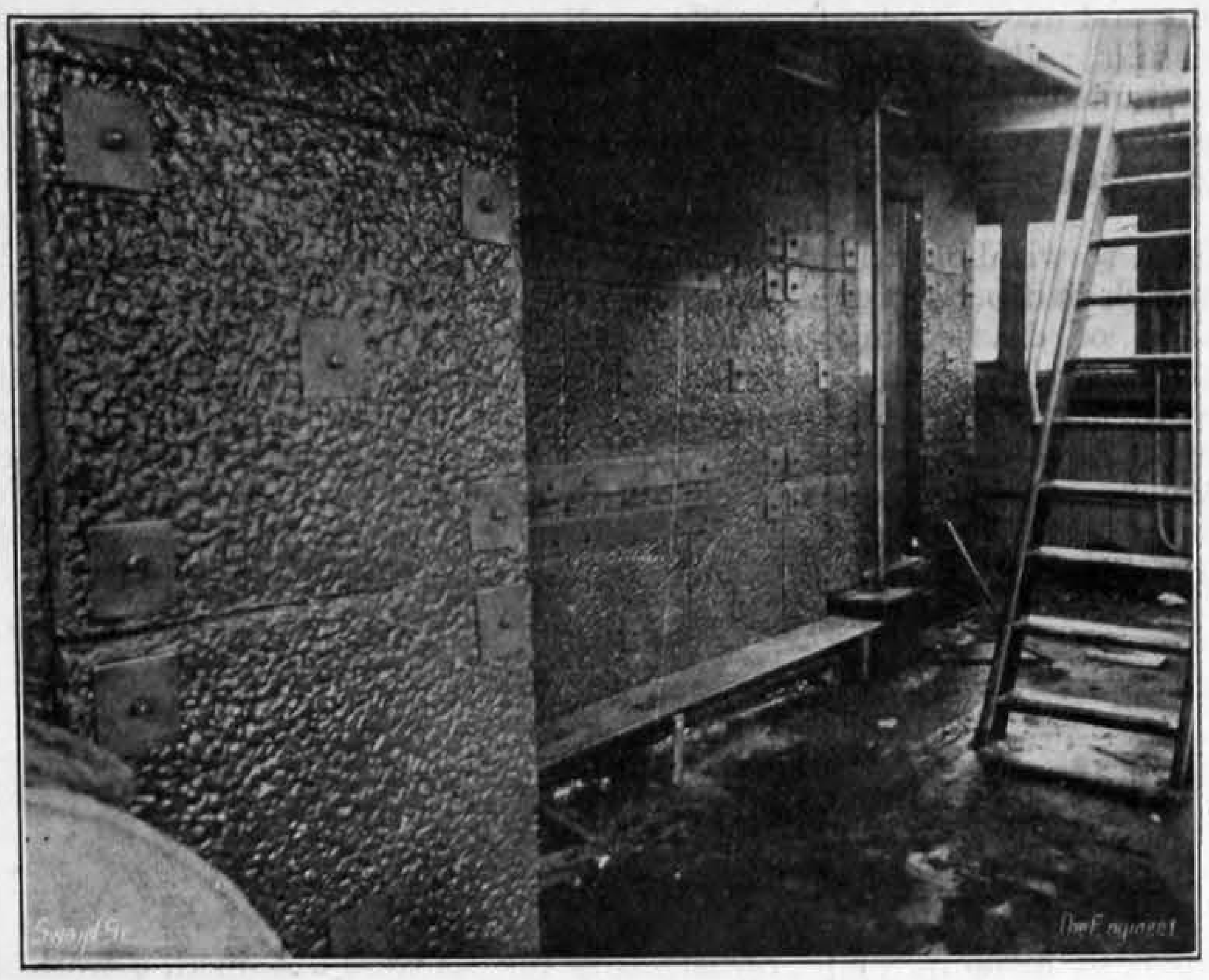
Preparing for D-Day

During the "Battle of the Atlantic" the plastic armour used was of the *in situ* variety, while P.P.P. was installed on ships in preparation for D-day in enormous quantities. Special plates were made for use on bulldozers and flame-throwers to give protection to their drivers. In practice it has been found that the protection offered is in excess of that anticipated. Parts of "Mulberry" prefabricated harbour were also fitted with P.P.P. and there have also been land uses, such as portable blockhouses, for which 137,000 plates were made.

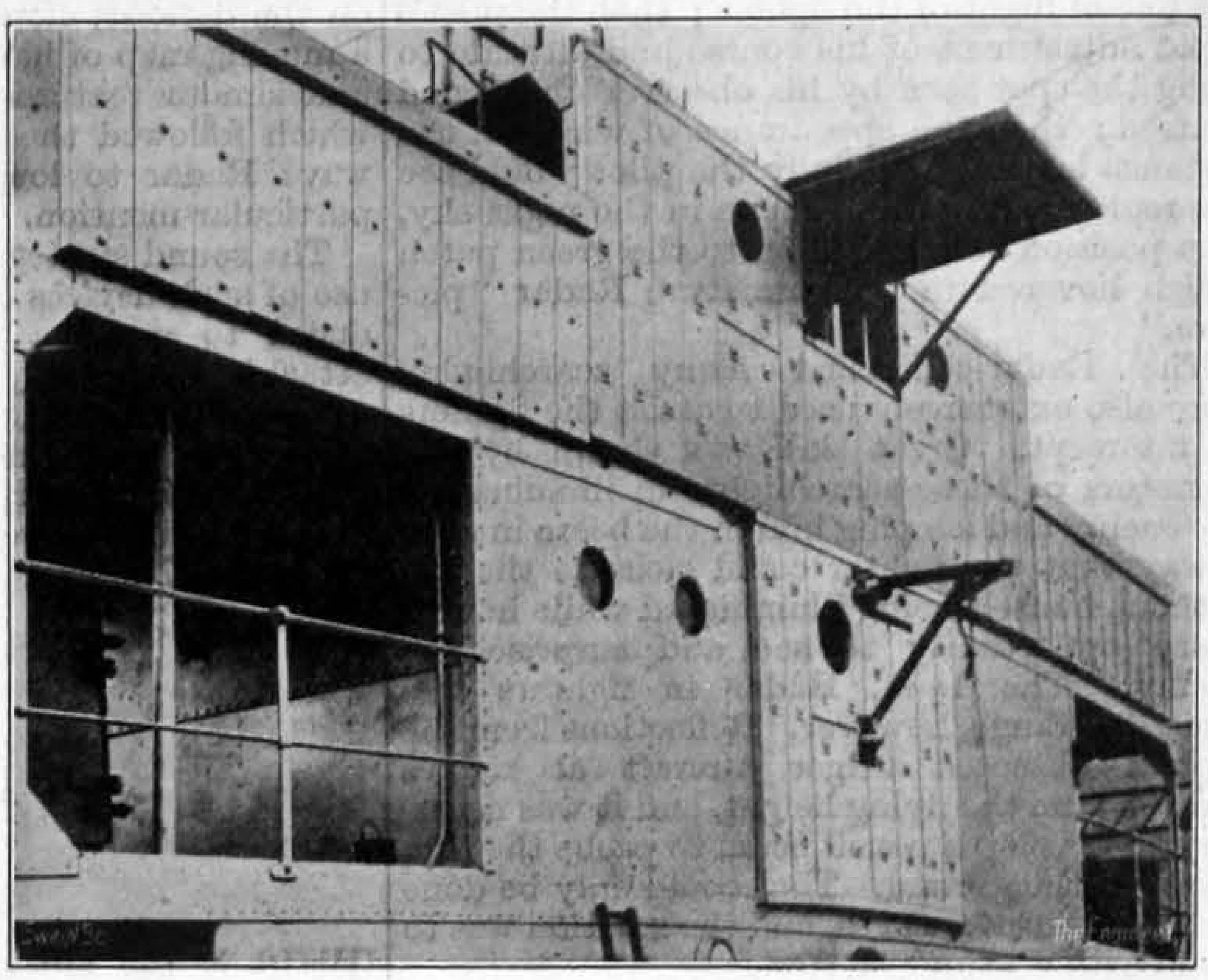
Special barges fitted with large tanks for carrying petrol and water were protected by a framework of steel carrying P.P.P. over the top part of the tanks and with large quadrant slabs at the ends.

As enemy aircraft were sneaking over and firing at our coastwise railway engines, experiments were made to protect the locomotives, and at Eastleigh the cab of the engine "King's School, Wimbledon," was fitted with 2½in. P.P.P. special size slabs, but the matter was not furthered as these raids ceased during December, 1942.

It is highly satisfying to record, albeit briefly, this history cycle of a development sponsored by the Royal Navy, which, while saving lives and steel, has done much to foster and maintain the high morale of the Merchant Navy.

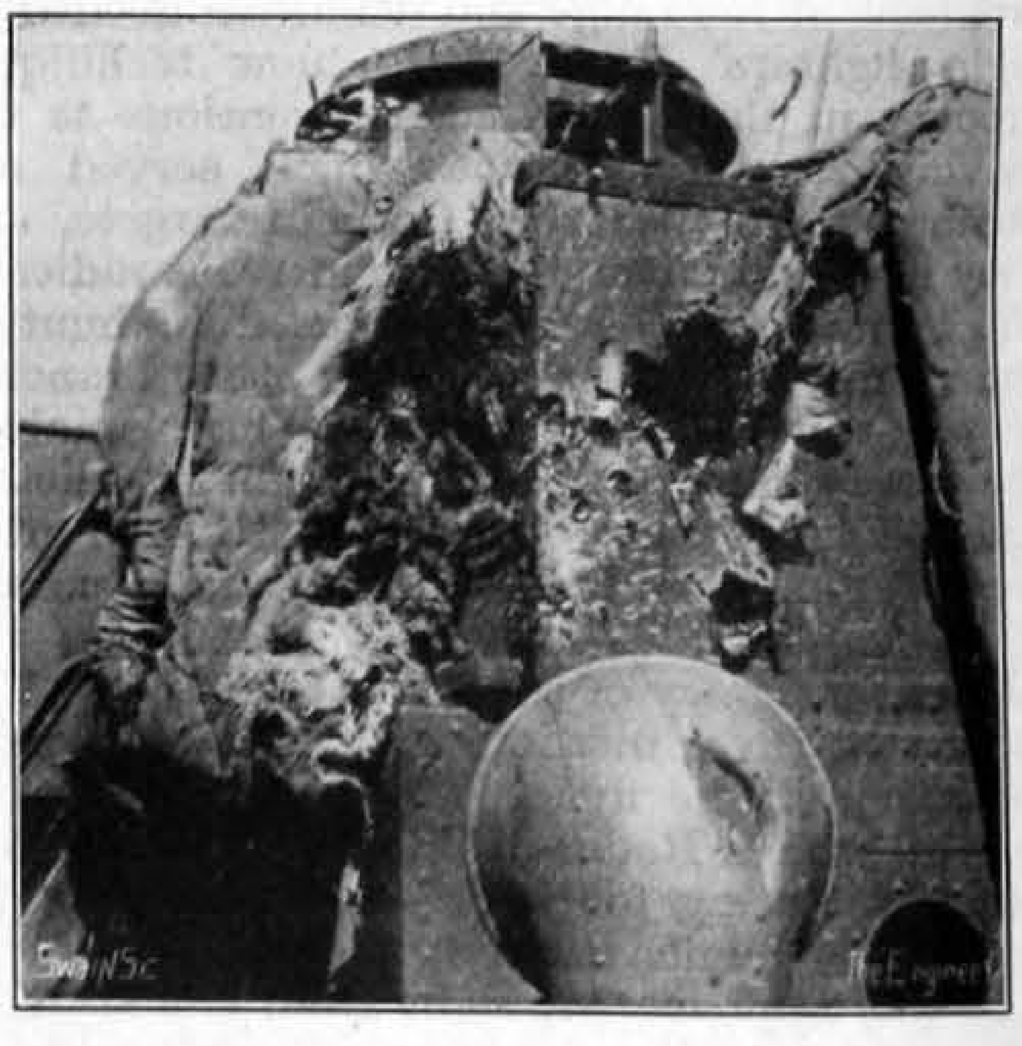


PLASTIC ARMOUR SLABS FOR BRIDGE PROTECTION



PLASTIC PROTECTIVE PLATING FOR BRIDGE PROTECTION

PLASTIC PROTECTIVE PLATING FOR LORRY



DAMAGE TO P.P.P.—NO CASUALTIES