# SUBMARINE PRESSURE HULL DESIGN AND DIVING DEPTHS BETWEEN THE WARS

BY

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The clearing up of the many doubtful points which still await complete theoretical and practical solution must be left to the future. These, however, are mostly of a minor description; the general problem of the submarine boat may be regarded as completely mastered.

*K. Dietz, International Marine Engineering, October 1911*

## Introduction

Until the end of World War I, a submarine was invisible and could not be detected, once submerged. There was little need to go much below periscope depth, though boats (FIG. 1) were usually designed with a capability of 100–150 ft to keep them clear of the keel of the biggest ships and to permit them to rest on the bottom. During the twenties and thirties the introduction of asdic (sonar) and improved depth charge arrangements gave advantages to deeper diving boats which could use temperature layers to avoid distant detection and go below the reach of the standard depth charge settings of that time.

## Diving Depths

Diving depths were usually secret and even now are not easily found for World War II submarines. Even the meaning of 'diving depth' can be unclear as these words can be used to represent at least three very different figures. It is usually possible to distinguish the following depths:

(*a*) *Operational Depth*. This was the maximum depth which should be used in normal operation. There was a considerable margin of safety at this depth and, as will be seen, many boats exceeded this figure by a wide margin.

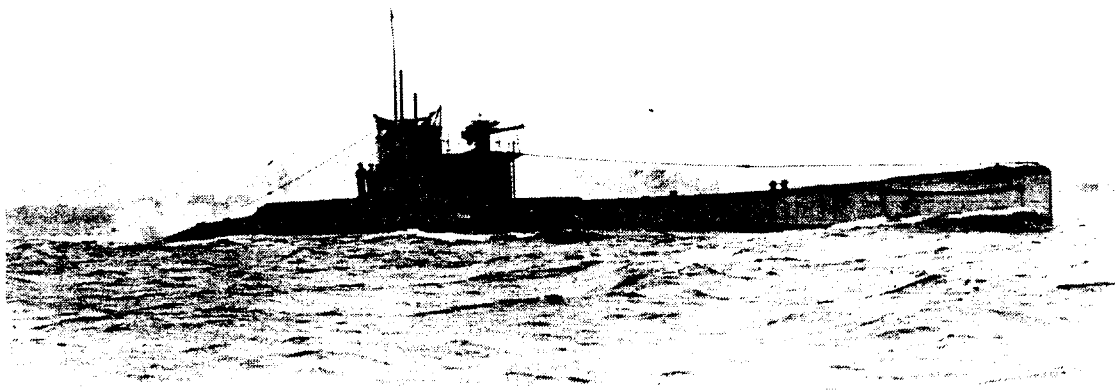


FIG. 1—'L6', AN L CLASS SUBMARINE OF WORLD WAR I

(*b*) *Test Depth*. A new submarine would always carry out a test deep dive, usually to the operational depth. Many commanding officers would go some 10% deeper to give confidence to their crews.

(*c*) *Collapse Depth*. The depth used by the designer at which the pressure of the water would cause failure of the pressure hull. It would seem that British practice (and that of most navies) by the early thirties was to take

$$\text{collapse depth} = 2 \times \text{operational depth}$$

using pessimistic assumptions.

**Modes of Failure**

There are many ways in which a complicated structure, such as that of a submarine, can fail. Brief descriptions of the main failure modes follow; for a fuller description see Daniel and other papers[1]

(*a*) *Overall Collapse* by general instability. This is associated with frames of inadequate strength and would involve collapse of a whole compartment between bulkheads. This mode is very susceptible to out of circularity and hence strong frames are needed to preserve shape.

(*b*) *Interframe Buckling* is a condition in which the plating between frames buckles in a large number of nodes around the circumference. Static pressure did not normally lead to this failure mode in World War II boats but it could be provoked by depth charging. This mode becomes a greater problem when high yield strength steels are used. Riveted construction with butt straps, etc., was less likely to develop a buckling failure mode and more likely to fail by shearing of the rivets.

(*c*) *Yielding of Plating* between frames produces pleats around the circumference of the boat (see FIG. 2).

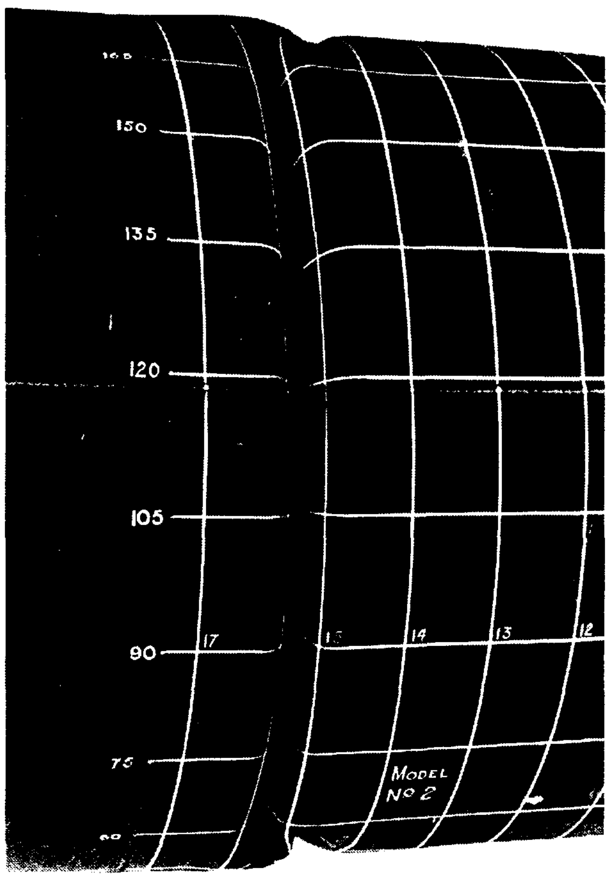


FIG. 2—MODEL TEST SECTION. FAILURE BY INTERFERENCE YIELD

There was general recognition by designers of the different ways in which a hull could fail, from fairly early days. However, not until well after World War II was new and advanced theory wedded to the computer to give useful results, due to work by Kendrick and others at the Naval Construction Research Establishment, Dunfermline.

Design practice was to overdesign the framing, by judgement, so that overall collapse, the most intractible calculation, could be ignored. Inter-frame failure could then be calculated, fairly accurately, using a very simple equation known as the 'boiler formula':

$$\text{stress} = \frac{\text{pressure} \times \text{radius (hull)}}{\text{thickness (pressure hull plating)}}$$

This formula, and the preceding discussion, relate to circular pressure hulls. Many submarines designed before World War II had oval sections forward to facilitate the arrangement of torpedo tubes and aft to suit a twin shaft propulsion system. The circular hull was also broken by hatches, and, in particular, by the torpedo loading hatch. Local structure was usually over-strong in way of such discontinuities, though tests to destruction after the war suggested that the torpedo loading hatch area was often the point at which collapse started. In deep diving trials deflection of these oval sections was always measured and formed a guide to the safety of the boat. The paint on the webs of pressure hull frames would crack on 45° shear lines as another indicator of shear yield.

Stronger hulls were seen in the R.N. more as giving added protection against depth charges at shallow or moderate depth than as a means to increasing operating depths.

The factor of safety also accounted for the recognized inaccuracy in using simple methods such as the boiler formula, as well as for minor errors in design or in building and for the possibility that the hull plates were rolled under thickness. Finally, it was realized that corrosion was inevitable and that the hull would get thinner as it rusted away.

Diving depths for British and some foreign submarines, up to the 1940s, are given in TABLES I and II respectively. It will be seen that, with the exception of Germany, other navies required operational depths very similar to those of the R.N.

TABLE I—*British Diving Depths*

| *Class* | *Date* | *Operational Depth* ft | *Class* | *Date* | *Operational Depth* ft |
|---|---|---|---|---|---|
| L (FIG. 1) | 1917 | 150 | T | | |
| O (FIG. 3), P, R | 1926–30 | 300 | riveted hulls | 1938 | 300 |
| RIVER | 1932 | 200 | welded hulls | 1941 | 350 |
| PORPOISE | 1932 | 200 | U | 1938 | 200 |
| SUNFISH (FIG. 4) | 1936 | 200 | V | 1943 | 300 |
| 1940 S | | | A | 1945 | 500 |
| riveted hulls | 1940 | 300 | | | |
| welded hulls | 1942 | 350 | | | |

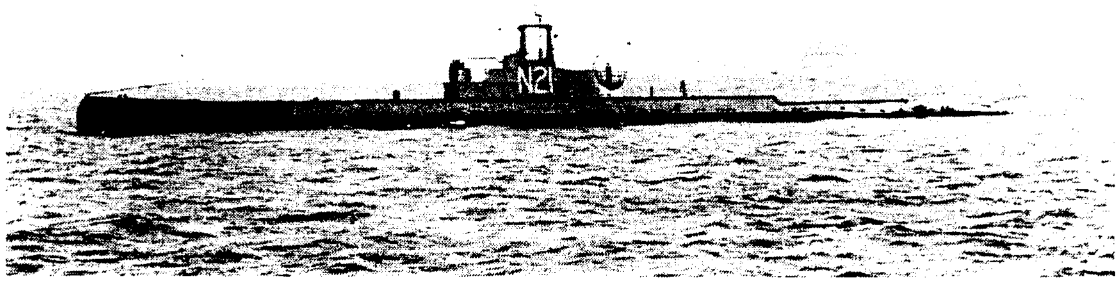



FIG. 3—'OBERON', IN WORLD WAR II CONDITION

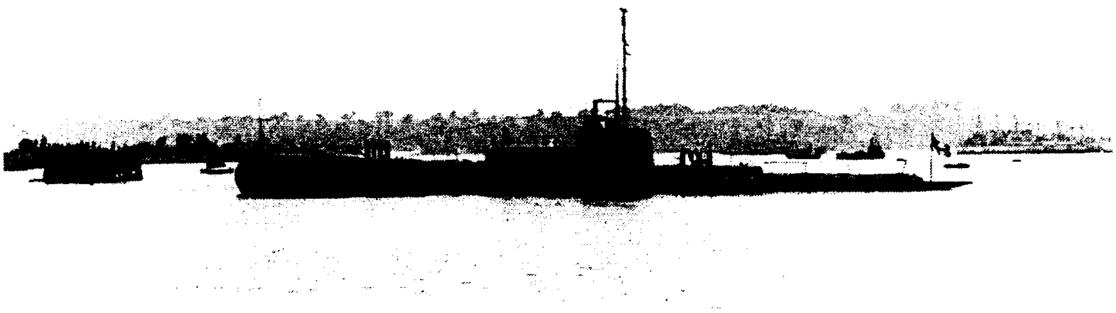


FIG. 4—'STURGEON', AS BUILT. NOTE THE BIG CASING FORWARD OF THE CONNING TOWER FOR A DISAPPEARING GUN MOUNTING

TABLE II—*Some Overseas Diving Depths (mainly based on reference 2)*

| *Country* | *Class* | *Date* | *Operational Depth* ft |
|---|---|---|---|
| France | REQUIN | 1923 | 256 |
| | L'AURORE | 1935 | 328 |
| Germany | 1A | 1936 | 472 |
| | VII C | 1940 | 472-590* |
| | IX | 1938 | 492 |
| | XXI | 1944 | 492-656* |
| Italy | BALILLA | 1925 | 288 |
| | ARCHIMEDES | 1932 | 288 |
| | BRIN | 1936 | 288 |
| Japan | I 153 | | 200 |
| | I 9 | 1934 | 328 |
| | RO 100 | 1941 | 246 |
| USA | BARRACUDA | 1920 | 200 |
| | SALMON | 1936 | 256 |
| | GATO | | 300 (-400 in later boats) |
| USSR | L | 1931 | 288 |
| | K | 1938 | 229 |

*figures vary

When new, test depth was usually the same as operational depth. On some older boats reduced test depths were applied, though operational depth was not always reduced to the same extent.

## Pressure Hull Design

Particulars of the hull diameter and plating thickness for British submarines are contained in TABLE III.

There is still some uncertainty in the understanding of design methods used in calculating the strength of pressure hulls before World War II. The basis was an informed comparison with previous successful designs and it would seem that much importance was attached to L2's dive to 300 ft (twice the design depth) during the first World War. Throughout the twenties the design aim seems to have been to keep the streses in plating and framing to about those of the 1912 E class. With hindsight, this approach is seen as over-cautious since the collapse depth of the main hull of L2 was about 500 ft. The boiler formula was used as a basis of comparison and not as a design criticism.

By 1929, J. H. B. Chapman, later Director of Naval Construction (DNC), had marshalled a considerable body of theoretical and empirical methods and data relating to the design of stiffened cylinders. These formulae were then related to L2's dive and used in the design of the *Sunfish* (and probably *Thames*). He studied the effect on overall hull weight of varying the design collapse depth. For *Odin*, a reduction from 500 ft to 300 ft gave a saving of 35 tons, a saving which was used by Bailey (a constructor lost in *Thetis*) in his design for *Thames* to allow more powerful machinery.

TABLE III—*British Hull Particulars (from Submarine Museum records)*

| *Class* | *Plating Thickness* ins | *Pressure Hull Diam.* ft–ins |
|---|---|---|
| L | 0·5 | 15–7 |
| O, P, R | 0·875 | 16–1¾ |
| RIVER | 0·625 | 18–5 |
| PORPOISE | 0·625 | 17–2 |
| SUNFISH | 0·375 | 14–11 |
| 1940 S | | |
| (riveted) | 0·375 | 14–11 |
| (welded) | 0·55 | 14–11 |
| T | | |
| (riveted) | 0·625 | 16–3 |
| (welded) | 0·75 | 16–3 |
| U | 0·5 | 16–3 |
| V | 0·625 | 16–3 |
| A | 0·85 | 16–0 |

It seems that the boats which formed the bulk of the wartime fleet—1940 S, T and U—were designed in much the same way as just described, though with a more consistent factor of safety. Knowledge of von Mises's work reached the designers in the later thirties, just too late.

The first deep diving trials were carried out in an O Class boat about 1927 or 1928 with A. N. Harrison as the trials officer. Battens were rigged across the hull at various places to measure deflections. Despite additional support from pillars, the oval frames aft showed excessive deflections, as did the oval gun access trunk. The trial was abandoned due to a leak at the forward torpedo loading hatch, later found to be caused by defective welding. The after end and gun trunk were given additional stiffening and no further trouble was experienced (according to a letter to the author from A. N Harrison, later DNC). In these riveted boats, the deep dive was a noisy affair as rivets would slip and pop.

## Welding

The Admiralty had been a pioneer in the welding of ship structures with the publication in 1920 of the 'Portsmouth Rules', the first U.K. standards for welding. Progress was slow. The depressed industry of the inter-war years lacked the money to develop weldable steels, electrodes, equipment and to retrain designers, managers and men.

During the thirties considerable progress was made in welding surface ships but only in 1940 did a weldable, high strength steel, suitable for submarines become available. This was 'S' quality, fairly similar in mechanical properties to the 'high tensile steel' (HTS) which it replaced, though with a yield stress of 18·5 instead of 17 tons/in$^2$ (see Table IV). It was not easy to weld and great care was needed.

TABLE IV—*'S' Quality Steel*

| *Composition* | | | *Strength* | | *Elongation* % |
|---|---|---|---|---|---|
| *C* | *Mn* | *Si* | *Yield* tons/in$^2$ | *Ultimate* tons/in$^2$ | |
| 0·21 max | 0·8 min | 0·3 max | 18·5 min | 30–34 | 18 |

Weight was saved in the welded boats due to elimination of connecting flanges, butt straps, etc., and this enabled slightly thicker plating to be used (TABLE III). In turn, this led to an increase of about 50 ft in diving depths. The first T Class boat with an all-welded hull was tested to 400 ft on completion and *Amphion*, the first A boat, to 600 ft. The hulls were given a high pressure air test before launch to ensure that there were no leaks.

## Diving Depths, as Designed and as Tested

TABLE V compares the operational depth and that calculated from the boiler formula with the maximum recorded (usually inadvertently) during the war. TABLE VI shows the results of tests to destruction. It includes plating thickness and dimensions as measured on the boats, which, because of tolerances, varied from the design figures given earlier and result in modified boiler formula depths. Tests on an XT midget and a large-scale section have been added. By the time these tests were carried out, more advanced design methods were in use and, by these methods, calculated collapse depth was within 5% of the actual depth at which failure occurred. The failure usually started at a discontinuity, often the torpedo loading hatch, but there was clear evidence that predicted failure modes were close or had started. It is interesting to note that *Stubborn*'s wartime excursion to 540 ft was greater than the depth at which *Stoic* collapsed. The margin of safety was less than some commanding officers believed.

TABLE V—*Calculated Collapse Depth and Depth Achieved*
(*18·5 tons/in$^2$ yield steel*)

| *Class* | *Operational Depth* ft | *'Boiler formula' Depth* ft | *Depth Achieved* ft |
|---|---|---|---|
| L | 150 | 520 | 152 |
| O, P, R | 300 | 880 | 400 |
| RIVER | 200 | 550 | 300* |
| PORPOISE | 200 | 598 | — |
| S | 200 | 407 | 300 |
| 1940 S (riveted) | 300 | 596 | 540† |
| T (riveted) | 300 | 626 | 400 |
| U | 200 | 500 | 400 |
| V | 300 | 616 | 380 |
| A | 500 | 840 | 600‡ |

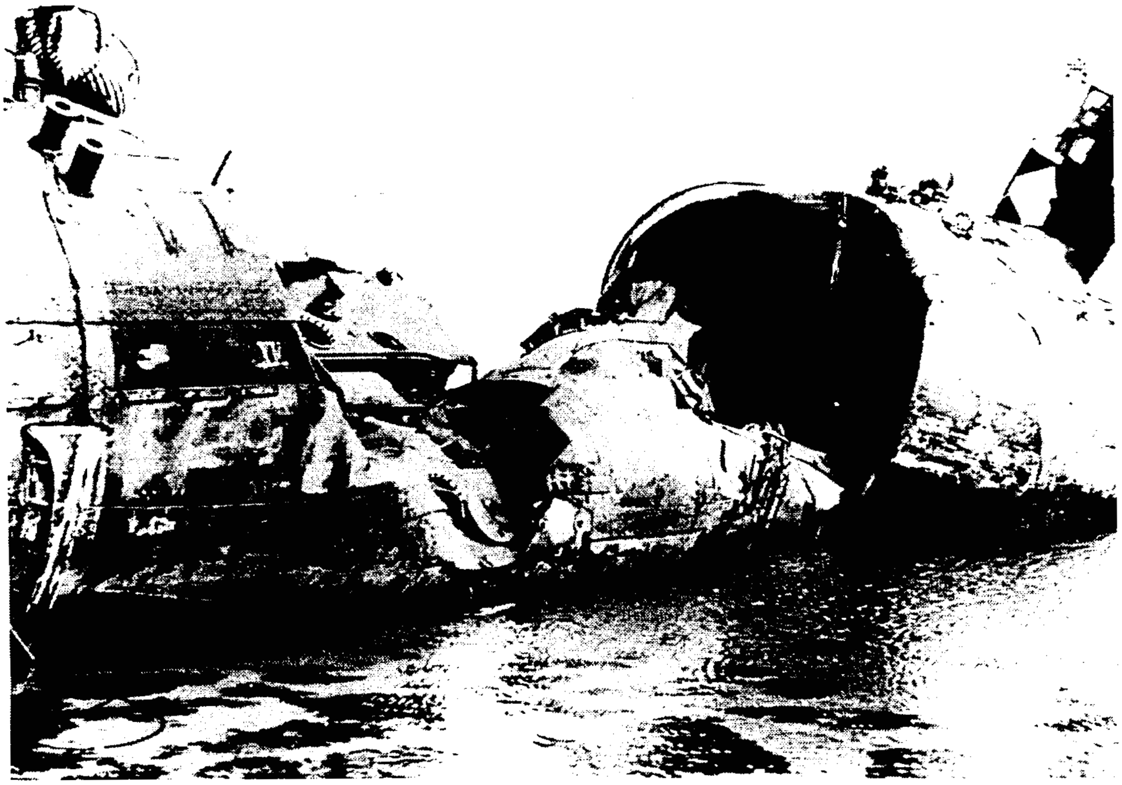
*Only *Clyde* reported any damage—to the oval section aft.
†With the exception of *Stubborn*, none approached collapse depth.
‡*Amphion* trial

There was concern over the variable quality and thickness of 'S' quality plates. The standard deviation on yield strength was 3·1 tons/in$^2$ with a mean less than the specified 18·5 tons/in$^2$. Plates were normally under the specified thickness, though usually within permitted tolerance. Calculations ignored rolling tolerance as lying within the overall accuracy.

TABLE VI—*Tests to Collapse*

| *Name* | *Material* | *Yield Strength* tons/in$^2$ | *Diameter* ft–ins | *Thickness* ins | *'Boiler Formula' Depth* ft | *Actual Failure Depth* ft |
|---|---|---|---|---|---|---|
| STOIC (FIG. 5) | HTS | 17 | 14–11 | 0·54 | 534 | 527–537 |
| SUPREME (FIG. 5) | S | 18·5 | 14–11 | 0·625 | 700 | 647 |
| VARNE | S | 18·5 | 16–7 | 0·614 | 614 | 576 |
| ACHATES | S | 18·5 | 16–0 | 0·875 | 860 | 877 |
| XT midget | | 20·5 | 5–9 | ·227 | 702 | 565 |
| Test Section | S | 18·5 | 5–9 | ·25 | 698 | 563 |

HTS: high tensile steel
S: 'S' quality steel



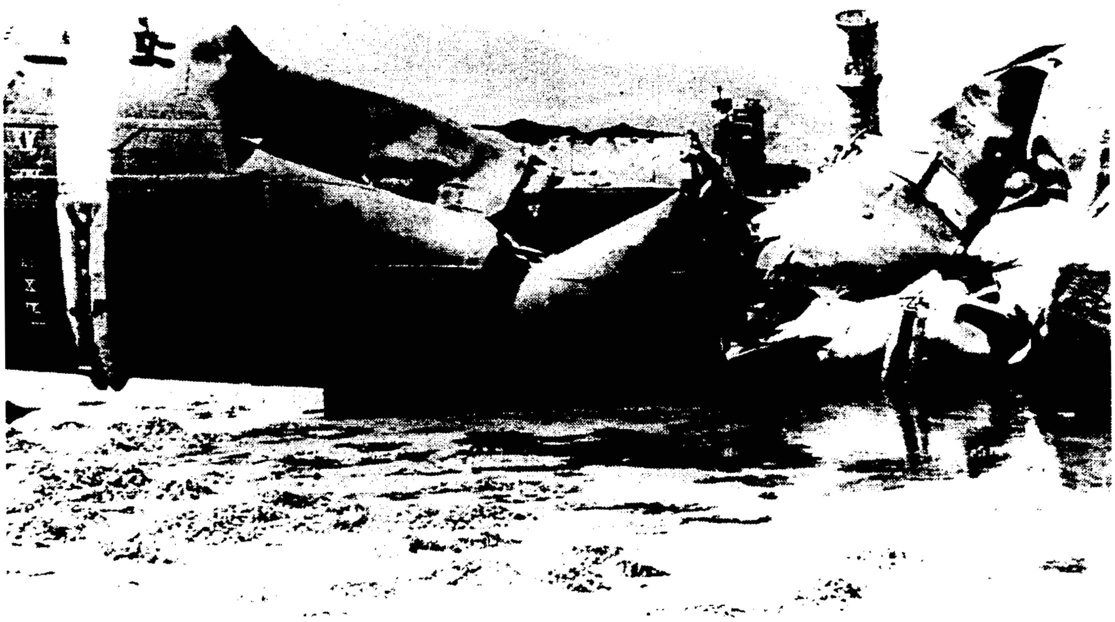


FIG. 5—H.M. SUBMARINES 'STOIC' (ABOVE) AND 'SUPREME' (BELOW) AFTER BEING LOWERED TO COLLAPSE DEPTH

## The Cost of Deep Diving

Increased diving depths could be obtained by using a higher strength steel, by a smaller hull diameter, or by thicker plating. For the Royal Navy the first two options were not available, and increased plating thickness was the only possible route. For the *Oberon* the hull and equipment weight was 794 tons out of a total surface displacement of 1480 tons (54%). An increase in plating thickness would increase the hull weight almost *pro rata*. Either the submarine size would increase or the weight of something else must be reduced. The converse of this situation was seen in the THAMES Class where, to make weight available for more powerful diesels, the thickness of the hull plating was reduced, and with it, the diving depth.

When the DNC, Sir Stanley Goodall, was asked in June 1941 to explain the surprising performance of the '500 ton' U Boats (VII C) he replied 'I believe his battery is lighter, engines run to death and welding saves more than we do, reserve buoyancy is less and perhaps 500 tons is an under statement'. It was. Later in October 1941, Sir Stanley was able to inspect the captured U570 and commented 'Very interesting. A clean hull and welding good. But why such a thick pressure hull in association with comparatively flimsy frames . . .'. In fact, the U boat's frames were quite adequate but small in comparison with the over large British structure.

Since there was no great demand from the Staff for deeper diving boats, design features which restricted diving were often adopted. British batteries were reliable and long-lasting compared with German batteries but were much heavier, and to some extent these remarks apply to the diesel engines and electric motors. The Vickers engines were heavy and fairly reliable whilst the Admiralty engines were about 20 tons heavier and much less reliable. There was, perhaps, an excessive use of non-magnetic bronze plating round the magnetic compass which, because it was high up, added further weight in the form of ballast low down. Escape trunks, sealed in war, were another heavy feature, using weight which could have gone into the hull.

The requirement for six internal bow tubes enforced the use of oval sections forward on small submarines until the much deeper diving A class had to accept a four-tube internal battery.

## The Value of Deep Diving

In World War II deep diving could help the submarine in the following ways:

(*a*) ability to rest on the bottom in deeper waters;

(*b*) reduced risk of asdic detection;

(*c*) reduced risk of a lethal depth charge attack.

Of these, the first is self-evident. World War II sonars were not very effective and were even further degraded by the effects of layers of water of different density. The deeper diving boat had more chance to hide under a layer than one limited to shallow depths.

The standard depth charge, used by most navies at the outbreak of war would rupture a pressure hull at a distance of about 30 ft. Since the precise position and depth of a submarine was not known, patterns of 5, 10 or 14 charges were dropped to straddle the likely positions of the target. Non-lethal hits could still cause small leaks and damage equipment, making the submarine more susceptible to a further attack or even forcing it to the surface.

Since the asdic beam looked ahead and was relatively narrow, contact was lost with the submarine well before the bow of the escort was above the target. Depth charges were dropped from the stern and fell at about 10 ft/sec ($16\frac{1}{2}$ for the later, heavy charge). This lengthy dead time gave the submarine moving at some 2–3 knots (3–5 ft/sec) a chance to evade the attack. Furthermore, depth could not be measured by Asdic until late in the war and rapid depth changing was an effective way of avoiding a slow falling charge. The resistance of the hull increased a little with thicker plating.

To sum up, the staff failed to recognize the value of deep diving submarines during the thirties but, even had they asked for more depth, the means for significant improvements were not available in the U.K. There were no strong steels suitable for welding and batteries and engines were heavy, reducing the weight available for hull strength.

## Acknowledgements

The assistance of R. J. Daniel, A. N. Harrison, J. H. B. Chapman, Commander Compton-Hall, the staff of the Submarine Museum, and of several of my colleagues is acknowledged.

*References*

1. *Royal Institution of Naval Architects Symposium on Naval Submarines, 17–20 May 1983*; particularly a paper by R. J. Daniel, 'Considerations influencing submarine design'.
2. Bagnasco, E.: *Submarines of World War II*; London, Arms & Armour Press, 1977.
3. Harrison, A. N.: *The development of H.M. submarines from Holland to Porpoise* (BR3043); HMSO, 1979.

NOTE

Copies of this paper, with a lengthy appendix summarizing J. H. B. Chapman's work in 1929 and with copies of the letters referred to from Daniel, Chapman and Harrison, have been placed in the following libraries:

R.N. Submarine Museum, Gosport
National Maritime Museum
Royal Institution of Naval Architects
Naval Library, Ministry of Defence.