SUBMARINE CARGO SHIPS AND TANKERS

F. H. Todd
National Physical Laboratory

INTRODUCTION

The naval architect has always had to battle with the twin elements of wind and water, and these have provided very powerful barriers to any great increase in the speed of ships. Because a ship is floating at the boundary between two elements of very different densities, it creates waves on the surface as it moves and any increase beyond a certain speed leads to an excessive increase in the wavemaking resistance and consequently to an uneconomic rise in costs of construction and operation. This situation may be thought of in some respects as being analogous to the "sonic barrier" in aircraft design. Much research has been carried out into the reduction of wavemaking resistance, both by experiment and theory, and this has led to the adoption of very fine waterlines forward, U shaped sections and bulbous bows, which has enabled the speed of surface ships to be raised appreciably in the course of the years.

The effect of the wind is not only to increase the drag of the ship by its direct effect, but by creating rough seas or storm conditions forces the ship to slow down to avoid the excessive pitching and heaving motions and the damage to the structure which would eventually ensue. Such slowing down means loss of time or subsequent expenditure of extra power to make up schedules, since in general no owner wishes to do other than make full use of a very expensive investment. Again, research has done much to help the naval architect combat such conditions. The adoption of fine entrances, high freeboards, and good flare above water have, for example, enabled designers to improve the seagoing qualities of trawlers almost beyond recognition, while the perfecting of antirolling fins has reduced this motion to almost negligible amount in those ships fitted with them. There remains the problem of reducing pitching by similar means, and the bulbous bow does present some advantages in this way also.

The naval architect may well have envied his aeronautical colleague who, faced with similar weather problems, has taken the modern aircraft to very high altitudes where atmospheric conditions are calm and stable. He has long been aware of the possibilities of lifting a ship above the water surface on foils to reduce its own wavemaking and avoid the surface wind-generated waves, and of the advantages of taking a ship below the surface to escape both rough weather and wavemaking resistance.

The perfecting of the internal combustion engine, which enabled the aeronautical engineer to achieve his desires by giving him a source of power having a high power/weight ratio and a relatively high efficiency, also allowed the naval designer to build hydrofoil boats which can attain the same speed as a high-speed conventional motor boat for about half the power. These are not new in conception, for the first such hydrofoil craft "flew" in Italy as long ago as 1906, attaining a speed of some 38 knots [1]. Of recent years the interest in hydrofoil boats has greatly increased, many new foil configurations have been evolved, and passenger-carrying hydrofoil craft are now in use in a number of sheltered waters. It is natural that efforts should be made to extend this principle to larger ships, but the difficulties in the way are considerable – the foils and their supports become more massive and heavy, detracting from the deadweight carrying capacity, they are a source of trouble due to the large draft they cause when the boat is on the surface coming into port, and since they are essentially high speed craft the large powers necessary must be transmitted from the hull to propellers a long way below the hull. Studies of such designs are going on, and we shall doubtless see much larger craft of this type built for specialised services, but their use for carrying the bulk cargoes of the world seems unlikely. Moreover, such boats still have to contend with the ocean waves on the surface of the sea, and therefore for any given size have limitations as to the sea state in which they can operate. By going below the surface, both wavemaking resistance and bad weather can be avoided altogether, and with the advent of nuclear propulsion the naval architect for the first time is in a position to seriously contemplate such a procedure. The use of nuclear reactors as a source of heat has freed the ship from dependence on the atmosphere and made possible the true submersible, which would spend all its seagoing time deeply submerged and only surface near the ends of its voyages. The hull can therefore be shaped for minimum resistance under deep-submerged conditions, with little concern as to its surface performance. The benefits to be gained are, of course, the elimination of surface wavemaking resistance, the reduction of form resistance to a minimum by streamlining the hull, and escape from the effects of bad weather.

The availability of nuclear propulsion for ships, as in the case of other new inventions, has led to a search for useful and practical applications. So far as the navies of the world are concerned, there is no doubt as to the value of nuclear propulsion in submarines to enable them to remain submerged almost indefinitely and in other ships in order to maintain fleets at sea for long periods without refueling. Nuclear-propelled submarines, apart from their military use, could be of extreme value for the delivery of fuel and supplies to combatant ships or to beleaguered islands or ports. From the national safety point of view, also, submarine tankers and cargo ships would be of inestimable value because of their relative immunity from enemy attack. A considerable number of military nuclear-propelled submarines are now in commission and it may well be that the first nuclear-propelled submarine supply ship will also be built by one of the navies of the world. The Russians, because of their particular geographical problems, have made the first application of nuclear propulsion to a surface ice-breaker which can, as a result, stay at sea for long periods to keep the lanes open throughout the winter.

The spectacular voyages of the USS NAUTILUS and SKATE under the North Pole in 1958 have also shown that submarines can be navigated for long distances under water without having to surface for sights of the sun or stars. This fact has led to much speculation regarding the possible use of such ships on routes which are closed by ice for part or all of the year.

As we shall see later, the submarine ship must operate at fairly high speeds to show material advantages over the surface ship, perhaps 30 knots or above. This fact may have some attraction to passengers who suffer from travel sickness but enjoy the restful atmosphere of a ship, and limited passenger accommodation may become a feature of such vessels. True, the passengers would not see the sea, but neither do many travellers today, who divide their time between dining saloon, bar, and cabin, and there is certainly no less to see than in the upper atmosphere!

When we come to consider such ships for commercial use, however, a number of operating problems are introduced, and it is the purpose of this paper to review these and, it is hoped, to stimulate discussion and draw forth new ideas. One of the main advantages of nuclear-propelled ships is the saving in space no longer required for bunkers, and the consequent increase in carrying capacity. The weight of the shielding around the reactors cancels out much of the saving in weight by the elimination of fuel, and this would suggest that such machinery is most suitable for long-haul voyages. The average dry-cargo ships have been developed largely along the requirements of certain trades, and these are not likely to alter materially in type. Moreover, the oil fuel is very often carried in the double bottom, and such space is not of use for additional cargo. These considerations lead to the general conclusion that the ships most suited to nuclear propulsion are those carrying bulk cargoes such as ore, grain, and oil. In the case of the latter, with a liquid cargo the ease of handling is such that the ships could just as easily be submarines as surface ships, and it is this aspect of nuclear propulsion which seems to have caught the public imagination.

Economic nuclear propulsion in the strictly commercial sense is as yet some time away, but if it is eventually to be applied to submarine cargo ships, then there are without doubt many difficult problems to solve, and it is certainly not too early to begin research into them if we are to be ready to design and build such ships.

HYDRODYNAMIC ADVANTAGES OF SUBMARINE SHIPS

Although this symposium is supposed to deal with the field of naval hydrodynamics, it would not be realistic to treat this particular problem purely from that standpoint. There are so many practical limitations which would come into the design of a submarine cargo ship or tanker that they must be given consideration, as only in this way can we give due weight to all the conflicting claims. In this section the question of powering will be considered and estimates made for both surface and submarine ships. These will be used later in the paper as a basis for discussion when we come to deal with the problems of operating and maintaining such craft.

From the hydrodynamic point of view, the two greatest savings that we can expect by going under water are the elimination of the wavemaking resistance and the escape from the effects of rough weather. Owing to the good hull form which one can design for a real submersible, it is reasonable to expect that the form resistance would also be reduced.

The wavemaking resistance is a relatively small part of the total resistance for surface ships at low speeds, and therefore one would not expect any great savings in power by its elimination at low speeds of operation. Indeed, the submarine under such conditions begins with a considerable handicap in that the wetted surface will be considerably greater than that of the equivalent surface ship and therefore the skin-friction resistance of the submarine will be considerably higher. Only if this can be offset by a corresponding reduction in form resistance will the submarine be able to break even with her surface counterpart. At higher speeds the wavemaking resistance of the surface ship begins to increase very rapidly (in the order of V^6) and to attain these higher speeds a continual fining of the hull is necessary together with an increase in ship dimensions in order to carry a given amount of deadweight. Eventually we reach a speed at which it is no longer economic to drive the surface ship, and it is here that the submarine would show a very real advantage in terms of power. We can thus conclude on purely general grounds that the elimination of wavemaking resistance by using a submarine ship will only begin to give substantial returns when used at comparatively high speeds.

In order to have some actual figures on which to base a discussion, calculations have been made of the horsepower required for both surface and submarine ships of displacements from 25,000 tons up to 150,000 tons. From these figures estimates have been made of the powers required for surface and submarine ships of the same deadweight, as this is the only fair way of assessing their respective merits. This particular range of displacement was chosen because the lowest figure represents the smallest ship for which marine nuclear installations at present envisaged would be suitable and the highest figure is comparable with the largest tankers at present being built and having deadweights in the neighbourhood of 100,000 tons.

For the surface ships the results have been taken from the David Taylor Model Basin Series 60 [2]. For a number of displacements within the above range the EHP has been calculated for Series 60 models having block coefficients of 0.60, 0.70, and 0.80. The ships all have a length to beam ratio of 6.5 and a beam to draft ratio of 3.0. The ship powers have been estimated from the model results using the A.T.T.C. 1947 line with a correlation allowance ΔC_F of +0.0004. In designing ships of different speeds, it would be natural to use a finer block coefficient for the higher speeds, and the comparisons have therefore been made at a speed appropriate to each fulness. These speeds have been determined from the modified Alexander formula

$$V/\sqrt{L} = 2\ (1.06 - C_B).$$

In order to convert these EHP values into DHP at the propeller, it is necessary to make certain assumptions regarding the propulsive efficiency and appendage allowances. In the first place, it has been assumed that where the DHP is less than 40,000, the ship will be propelled by a single screw, where it is between 40,000 and 80,000, it will have twin screws, and above this higher figure, will have four propellers. For the single screw ships a quasi-propulsive coefficient of 0.72 has been used, in accordance with the experiments with Series 60, and no allowance has been made for appendages. It is assumed, in effect, that with modern large ships of all-welded construction, the allowance of $\Delta C_F = +0.0004$ will be sufficient to take account of any ordinary appendage resistance as well as any hull roughness effects. In such cases, therefore, the DHP has been taken as equal to the EHP divided by the QPC. For the twin and quadruple screw ships, the QPC has been taken as 0.68 and an appendage allowance of 10 percent and 20 percent respectively has been added to take account of the bossings or shafts and A-brackets in these arrangements.

For the submarines, estimates have been made for two different prismatic coefficients, namely 0.60 and 0.65, using various published works by Weinblum, Amtsberg, Crago, etc. These apply to streamlined bodies of revolution having their maximum diameter at a point 40 percent from the nose. Again, the skin-friction resistance of the ship has been estimated by using the A.T.T.C. 1947 line and including an allowance of $\Delta C_F = +0.0004$. The length/diameter ratio has been taken as 7.0, which is approximately the optimum for vessels of this form having the appropriate tail surfaces to give adequate directional stability.

The dimensions of the surface ships and submarines for the displacement ranges covered are shown in Tables 1 and 2 and Fig. 1, and charts of EHP/V^3 in Figs. 2 through 6. The EHP values for submarines of different displacements are also listed in Table 3, and those for surface tankers in Table 4. This latter table also includes estimates from NPL data, which show close agreement with those made from the Series 60. As will be seen in making the comparison for vessels of equal deadweight, the use of a circular submarine form leads to very unrealistic dimensions as regards draft. In order to be able to assess the

Table 1
Dimensions of Surface Tankers
$L/B = 6.5;\ B/d = 3.0;\ V/\sqrt{L_{BP}} = 2(1.06 - C_B)$

Δ (tons)	L_{BP} (ft)	B (ft)	d (ft)	WS (sq ft)	$V/\sqrt{L_{BP}}$	$V/\sqrt{L_{WL}}$	V (knots)	EHP including +0.0004
$C_B = 0.60;\ \Delta/(L/100)^3 = 135.3;\ L = 100\sqrt[3]{\Delta}/5.14$								
25,000	569	87.5	29.2	58,000	0.92	0.912	21.93	17,800
50,000	716	110.2	36.7	92,000	0.92	0.912	24.60	39,200
75,000	820	126.2	42.1	120,600	0.92	0.912	26.30	62,200
100,000	903	139	46.3	146,200	0.92	0.912	27.65	87,150
125,000	962	148	49.3	166,000	0.92	0.912	28.50	110,000
$C_B = 0.70;\ \Delta/(L/100)^3 = 160;\ L = 100\sqrt[3]{\Delta}/5.43$								
25,000	538	82.8	27.6	57,300	0.72	0.715	16.73	7,230
50,000	678	104.4	34.8	91,000	0.72	0.715	18.78	15,870
75,000	777	119.6	39.9	119,500	0.72	0.715	20.10	25,250
100,000	855	131.5	43.8	144,800	0.72	0.715	21.10	35,000
125,000	921	141.7	47.2	168,000	0.72	0.715	21.90	45,300
$C_B = 0.80;\ \Delta/(L/100)^3 = 180.4;\ L = 100\sqrt[3]{\Delta}/5.65$								
25,000	518	79.7	26.6	57,500	0.52	0.516	11.83	2,430
50,000	652	100.2	33.4	91,200	0.52	0.516	13.30	5,340
75,000	747	115	38.3	120,000	0.52	0.516	14.22	8,500
100,000	821	126.3	42.1	144,800	0.52	0.516	14.90	11,660
125,000	885	136	45.3	168,000	0.52	0.516	15.50	15,180

Table 2
Dimensions of Submarines with Circular Cross Section

Δ (tons)	L (ft)	D (ft)	Wetted Surface (sq ft)
$C_p = 0.60$; $L/D = 7.0$; $L = 15.37\,\Delta^{1/3}$			
25,000	450	64.3	65,200
50,000	567	81.0	104,000
75,000	649	92.7	136,000
100,000	714	102	164,600
125,000	770	110	191,200
150,000	817	116.7	216,000
$C_p = 0.65$; $L/D = 7.0$; $L = 14.98\,\Delta^{1/3}$			
25,000	438	62.5	65,400
50,000	552	78.9	104,000
75,000	632	90.3	136,200
100,000	695	99.3	164,800
125,000	750	107.1	192,100
150,000	796	113.7	216,000

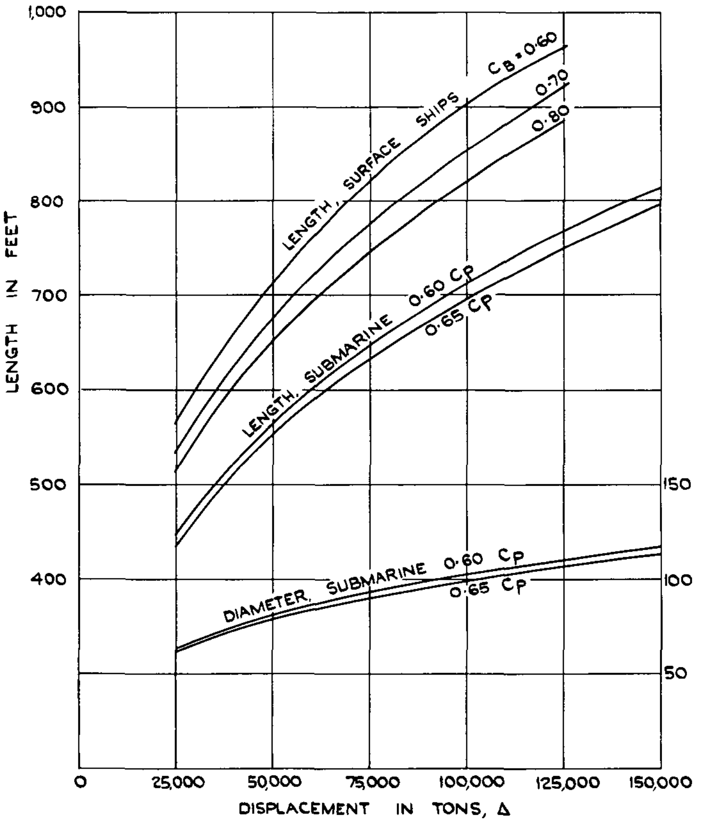


Fig. 1. Dimensions of surface ships and submarines

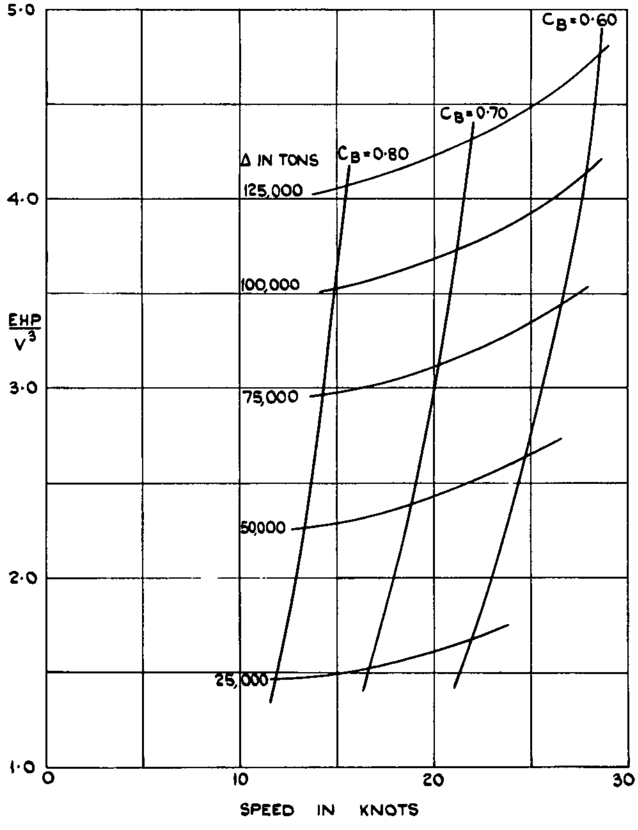


Fig. 2. EHP values for surface ships relative to speed

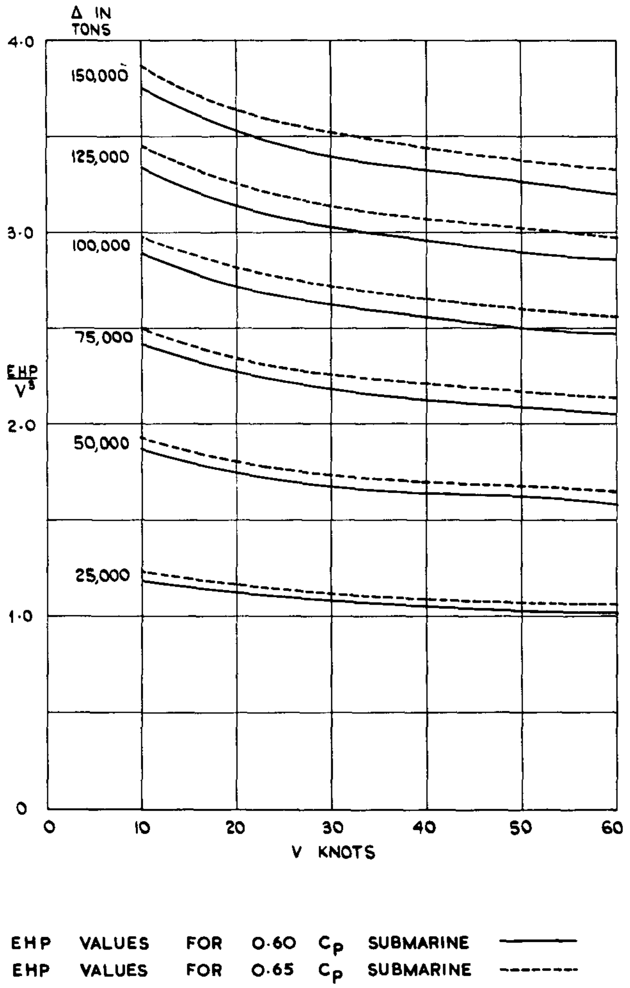


Fig. 3. EHP values for submarines relative to speed

646551 O—62——24

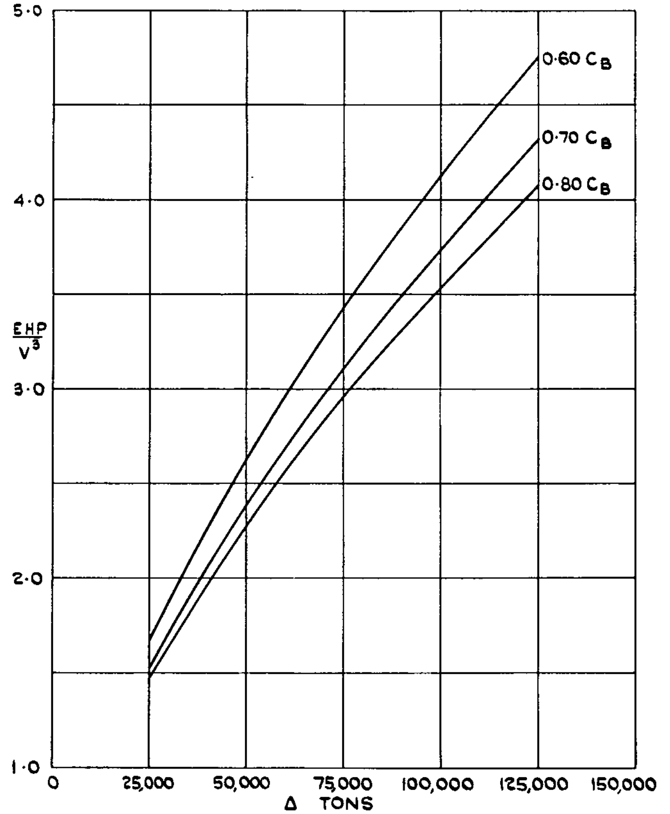


Fig. 4. EHP values for surface ships relative to displacement

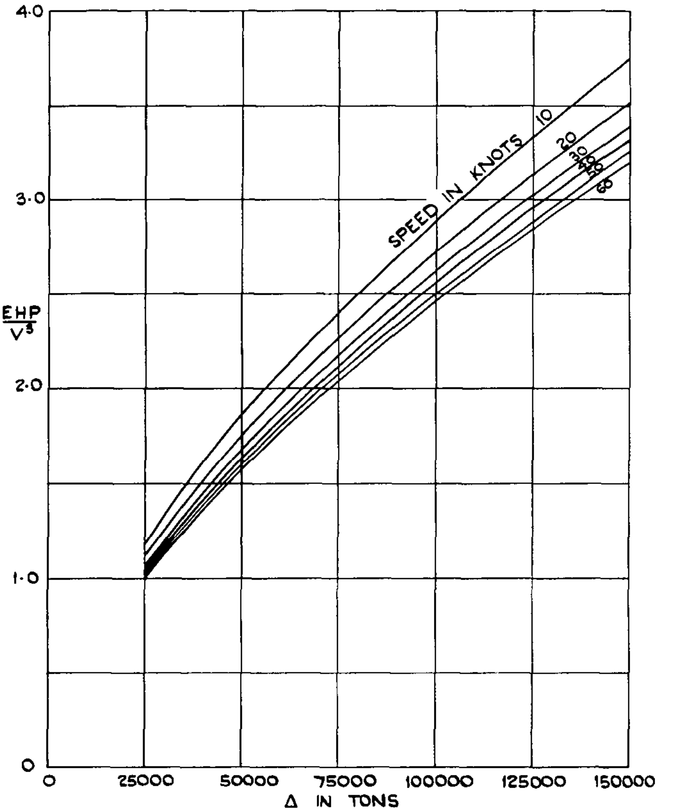


Fig. 5. EHP values for 0.60 C_p submarine

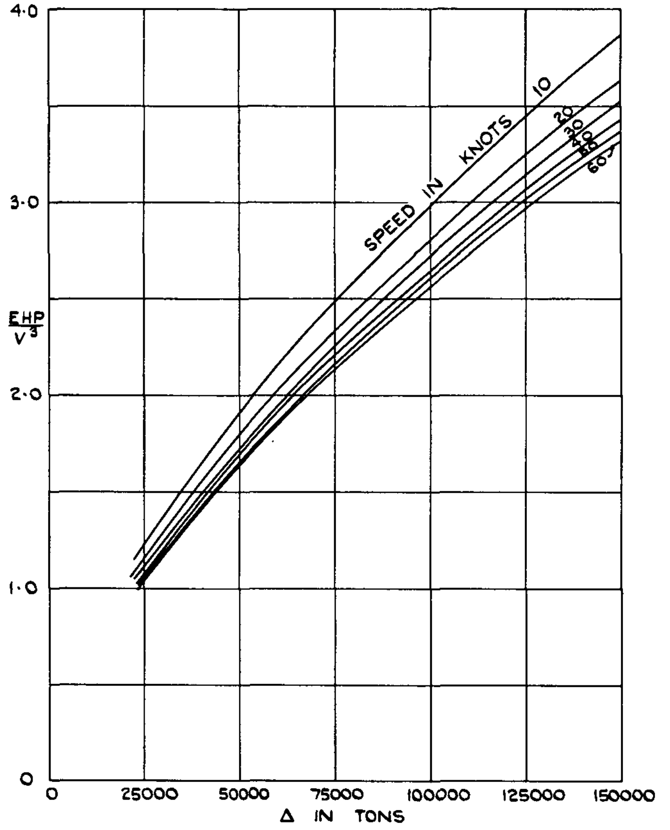


Fig. 6. EHP values for 0.65 C_p submarine

Table 3
EHP Values for Submarines with Circular Cross Section
(based on A.T.T.C. 1947 line + 0.0004)

V (knots)	EHP (for displacement in tons)*					
	25,000	50,000	75,000	100,000	125,000	150,000
C_p = 0.60						
10	1,194	1,870	2,407	2,885	3,335	3,748
20	8,960	14,000	18,120	21,700	25,080	28,180
30	29,040	45,500	58,920	70,530	81,480	91,540
40	67,400	105,100	135,900	163,500	188,900	212,200
50	128,800	201,800	261,500	312,200	360,500	407,300
60	220,100	342,800	443,200	533,246	615,800	691,600
C_p = 0.65						
10	1,236	1,920	2,498	2,985	3,450	3,865
20	9,260	14,430	18,750	22,400	26,000	29,130
30	30,200	47,000	61,000	73,300	85,000	95,120
40	69,800	109,000	141,500	169,000	196,000	219,500
50	134,000	208,700	271,000	325,000	377,000	422,000
60	227,600	356,500	462,000	552,000	640,500	717,000

* Figures below lines require DHP of more than 200,000.

Table 4
Comparison Between EHP Values for Surface Ships Derived from NPL Data and Series 60

Δ (tons)	L_{BP} (ft)	B (ft)	d (ft)	C_B	$\frac{V}{\sqrt{L_{BP}}}$	V (knots)	EHP	
							NPL*	Series 60†
25,000	569	87.5	29.2	0.60	0.92	21.93	17,820	17,800
50,000	716	110.2	36.7			24.6	39,360	39,200
75,000	820	126.2	42.1			26.3	62,500	62,200
100,000	903	139.0	46.3			27.65	87,440	87,150
125,000	962	148.0	49.3			28.5	110,710	110,000
25,000	538	82.8	27.6	0.70	0.72	16.73	7,170	7,230
50,000	678	104.4	34.8			18.78	15,830	15,870
75,000	777	119.6	39.9			20.10	25,190	25,250
100,000	855	131.5	43.8			21.10	35,110	35,000
125,000	921	141.7	47.2			21.9	45,310	45,300
25,000	518	79.7	26.6	0.80	0.52	11.83	2,343	2,430
50,000	652	100.2	33.4			11.83	5,196	5,340
75,000	747	115.0	38.3			13.30	8.226	8.500
100,000	821	126.3	42.1			14.90	11,400	11,660
125,000	885	136.0	45.3			15.50	14,800	15,180

*Model results extrapolated by Froude frictional coefficients, no allowance.
†Model results extrapolated by A.T.T.C. 1947 line with an allowance ΔC_F = +0.0004.

effects of this, estimates have also been made for submarines having elliptical cross sections in which the maximum beam was four times the maximum draft. For a circular-section submarine the draft could also be decreased by an increase in the length/diameter ratio, but this would involve a progressively greater increase in drag and also a considerable penalty in the form of extra hull weight.

In order to convert the EHP values for the submarines to DHP, the same assumption as for surface ships has been made regarding the range of powers for one-, two-, and four-screw arrangements. The QPC has been assumed to be 0.80 for the single-screw designs and 0.67 for the twin- and quadruple-screw. The propulsive efficiency for the single-screw arrangement has been taken somewhat higher than that for the corresponding surface ship because of the better wake conditions attained behind the body of revolution form. For appendage resistance, 20 percent has been allowed for the conning tower, rudders, stern and bow diving planes, flooding holes, and similar items not present on a surface ship, a further 10 percent for bossings or shaft brackets on the twin-screw ships, and 20 percent for the quadruple-screw ships. These figures give total allowances of 20 percent, 30 percent, and 40 percent for the one-, two-, and four-screw arrangements respectively.

The above figures for the submarine are based on the assumption that it is sufficiently deeply immersed below the surface that there is no residual wavemaking. This means as a rough guide that it is immersed to a depth of at least half its length or some 4 or 5 diameters. The effects of depth of submersion have been investigated by model experiments in the Saunders-Roe tank. Models representing an 80,000-ton-displacement submarine were run at various depths below the surface from 100 to 300 feet and over a corresponding ship speed range of 20 to 50 knots [3]. The values of the resistance for a length/diameter ratio of 7 are shown in Table 5 and plotted in Fig. 7. There is certainly some depth effect still in evidence at the deepest depth of submersion, namely 300 feet, as is shown by the increase in resistance with speed at that depth. As the depth is decreased it is seen that the increase in resistance for the lower speeds does not increase very rapidly until the depth reaches something approaching 100 feet. For the higher speeds, however, the increase is much more rapid and for 50 knots, for example, the increase between 300- and 100-foot submersion is no less than 200 percent. It is therefore evident that if we are to obtain the full benefit from the elimination of wavemaking resistance any large submarine of this type must

Table 5
Effect of Depth of Submersion on Resistance
for a Submarine of 80,000-Ton Displacement, $L/D = 7$, and Maximum
Section 40 percent L from Nose (from Ref. 3)

Depth of Submersion (ft)	Speed (knots)						
	20	25	30	35	40	45	50
	Values* of $R/V^2 \times 10^{-4}$						
100	0.100	0.160	0.233	0.338	0.437	0.451	0.445
150	0.062	0.104	0.144	0.187	0.244	0.262	0.272
200	0.062	0.080	0.111	0.122	0.150	0.183	0.192
300	0.075	0.096	0.100	0.098	0.113	0.134	0.144

*R = resistance in pounds; V = speed in knots.

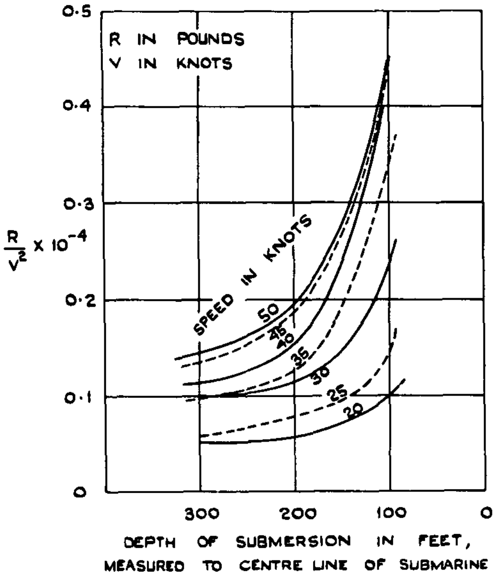


Fig. 7. Effect of depth of submergence on a submarine of 80,000-ton displacement, L/D = 7.0 (from Ref. 3)

run at a considerable depth below the surface. From these same model experiments Mr. Crago has shown that if the submarine is running in shallow water there can be a serious bottom effect also. For the same submarine of 80,000-ton displacement, for example, at 50 knots in water 300 feet deep, the resistance is some four times as great as in deep water when deeply immersed. For a ship of this size this figure is somewhat academic, as no one could ever contemplate driving such a ship at 50 knots in such a depth of water! But the results serve to indicate the problems that are likely to be met with when a large submarine is approaching shallow water on the continental shelf or when coming into estuaries. In fact, for a vessel of this size we must revise our ideas of what we mean by shallow water.

Before leaving this question of resistance, it is worth while pointing out that in a submarine of this type the resistance would be almost wholly frictional, and to obtain the full benefit in power reduction it would be essential to keep the hull clean at all times, since any penalty due to roughness and fouling would be considerably greater than in the corresponding surface ship. This points to the need for frequent dockings, and as we shall see when discussing the operation of such a ship, this poses considerable problems. For a vessel of this type running deeply submerged in the comparatively calm conditions a long way below the surface of the sea, it is interesting to consider the possibility of maintaining laminar flow over the hull to a greater or lesser extent. The benefits to be derived from such a possibility are, of course, great. For a submarine 650 feet in length with a displacement of 75,000 tons running at a speed of 20 knots, the corresponding Reynolds number is 1.7×10^9. The values of C_F for turbulent and laminar flow are 0.00144 and 0.00010 respectively, and if we assume that the laminar flow hull is *perfectly* smooth and omit the ΔC_F allowance of +0.0004 in this case, but add 20 percent in each for conning tower, etc., then the ratio of total resistance for laminar and turbulent flow is 0.25. This is an ideal condition, of course, for a number of reasons. To encourage laminar flow over the hull, the shape would have to be modified, in particular by moving the maximum diameter further aft, and this would increase the form drag. The hull would have to have certain fittings like conning tower, bow planes, flooding holes, anchors, etc., and no matter how these might be housed in recesses with covering doors, etc., they would inevitably act to some extent as turbulence stimulators, and the actual resistance would in fact be much nearer to the turbulent figure. While the idea of maintaining laminar flow is therefore extremely attractive, the practical difficulties of maintaining the requisite smoothness over the whole surface of a steel structure of this kind immersed in salt water and subject to all the effects of corrosion and fouling present almost insuperable difficulties. Of recent months other devices to maintain laminar flow have been suggested, such as the use of a soft skin of rubber with liquid backing which would damp out the onset of turbulence and so prevent transition. Not enough is yet known of these ideas to be able to express any real opinion about them but they would certainly be expensive both to fit and to maintain and, unless they were immune to surface deterioration and fouling, it seems would soon lose their efficiency.

COMPARISON OF SURFACE AND SUBMARINE SHIPS OF THE SAME DEADWEIGHT

A considerable number of papers has been written giving comparisons between conventionally propelled and nuclear propelled surface tankers. These have shown in general that the nuclear propelled tanker cannot yet compete economically with one having conventional machinery unless the capital cost of the nuclear plant and the cost of nuclear fuel become considerably less than their present values. This paper is not concerned with the relative merits of conventional and nuclear machinery, but since the submarine cargo ship or tanker can only be contemplated on the basis of nuclear propulsion, any comparisons made are on the basis of nuclear machinery for both ships. In this way the weight of the machinery will be comparable in both cases and will therefore affect the deadweight available equally in each case.

Several authors have given values of the deadweight/displacement ratio for nuclear propelled surface and submarine tankers, and values of this ratio are shown in Figure 8. Although there is considerable scatter in this diagram, it is considered that if we take a

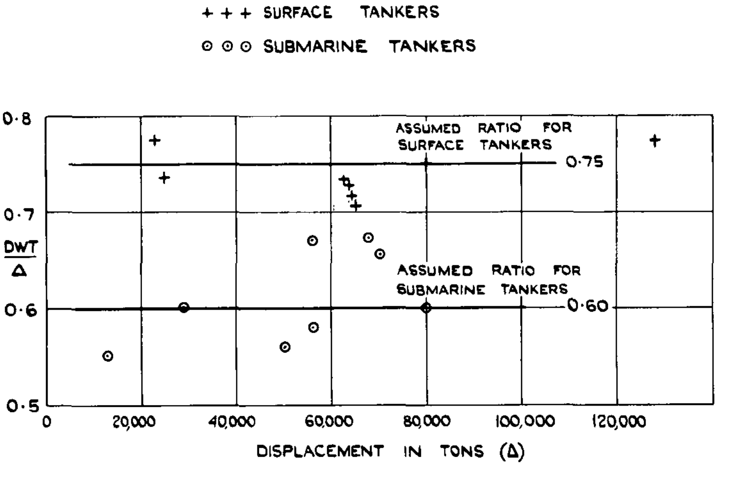


Fig. 8. Deadweight/displacement ratios

value of deadweight to displacement ratio equal to 0.60 for submarine tankers and 0.75 for surface tankers, a fair comparison between the two types would be obtained. A comparison between surface and submarine tankers is shown in Table 6 for ships having deadweights of 18,750, 56,250, and 93,750 tons. Using the appropriate deadweight/displacement coefficients from Fig. 8, the displacements have been calculated and the ship dimensions, EHPs, and DHPs have been taken from the curves obtained as described in the preceding section. The results for three of these cases are shown in Figs. 9, 10, and 11, where curves are given of DHP to a base of speed in knots for a surface tanker and two submarine tankers having respectively circular and elliptical sections. The submarine tanker throughout has a prismatic coefficient of 0.60. On the other hand, the block coefficient of the surface tanker has been varied to suit the speed/length ratio, being 0.80 at the lower end of the speed range and 0.60 at the top end. The figures for the surface tanker do not include any allowance for the effect of rough weather, and the following remarks therefore apply to smooth water conditions for the surface ships, and are favourable to them in this respect. Making the comparison in this way, however, enables certain other points to be brought out.

Looking first at the results for the circular section submarine and the surface tanker, we see that at the lowest speeds in question, namely 10 to 15 knots, there is practically no difference in the power requirements between these two types of ship. Since there is very little wavemaking in the case of the surface ship at these speeds we can infer from this that the reduction in form drag for the streamlined submarine as compared with that for the surface ship is sufficient to compensate for the increased frictional resistance of the submarine due to its augmented wetted surface. At higher speeds the circular section submarine tanker always requires less power. For vessels having a deadweight of 18,750 tons the difference in power is some 5000 on 25,000, and this is about the smallest ship for which a nuclear propulsion plant could be designed at present. For the largest ship having a deadweight of 93,750, which is comparable with the largest tankers built today, the power for the surface ship at 27 knots is some 190,000 and this is reduced to about 140,000 in the case of the circular submarine. It is also worth noting that there is no appreciable difference in power for these two designs up to a speed of 23 knots and to get the benefit from the submarine design one needs to go to higher speeds; however, at 27 knots the figures just quoted show that we are faced with a power plant comparable with those of the "Queens," and this of course would involve many problems regarding the housing of nuclear reactors, heat exchangers, etc., within reasonably sized containers for fitting in a submarine. When allowance is made for the effects of weather, the comparison would be much more favourable to the submarine, either from the point of view of the greater power and fuel consumption to maintain speed on the surface ship or from the loss in speed of the surface ship at the same power. Opinions as to the weather allowances necessary on different trade routes vary, but the tables and curves given here will enable anyone interested in this problem to make his own estimates in these matters for any desired weather conditions.

Curves are also shown in these three figures for a submarine of the same deadweight but having a beam equal to four times the draft. The only factor which has been taken into account in making the estimates for these elliptical section ships is the increase in wetted surface necessary to obtain the same volume within the elliptical section. Doubtless in such a design the displacement would have to be increased to a considerable extent to allow for the effect of the different shape of hull upon steel weight, and it is probable that the residuary resistance coefficient would also be considerably increased as compared with that for the circular section. For both these reasons, therefore, the power curves shown are likely to be an underestimate.

Teasdale has published similar curves for surface and submarine tankers, both nuclear propelled, having a deadweight of 45,600 tons including the weight of the reactor [4].

Table 6
Comparison of Tankers of Constant Deadweight*

Type of Tanker	Δ (tons)	C_B or C_p	L_{BP} or L (ft)	B (ft)	d (ft)	V (knots)	EHP§	No. of Screws	DHP
Deadweight = 18,750 tons									
Surface	25,000	0.60	569	87.5	29.2	21.93	17,800	1	24,730
Surface	25,000	0.70	538	82.8	27.6	16.73	7,230	1	10,050
Surface	25,000	0.80	518	79.7	26.6	11.83	2,430	1	3,380
Submarine									
Circular†	31,250	0.60	484	69.1	69.1	11.83	2,238	1	3,345
Circular	31,250	0.60	484	69.1	69.1	16.73	6,190	1	9,260
Circular	31,250	0.60	484	69.1	69.1	21.93	13,400	1	20,100
Elliptical‡	31,250	0.60	484	138.2	34.55	11.83	3,260	1	4,880
Elliptical	31,250	0.60	484	138.2	34.55	16.73	9,025	1	13,510
Elliptical	31,250	0.60	484	138.2	34.55	21.93	19,550	1	29,320
Circular†	31,250	0.65	472	67.4	67.4	11.83	2,288	1	3,420
Circular	31,250	0.65	472	67.4	67.4	16.73	6,315	1	9,530
Circular	31,250	0.65	472	67.4	67.4	21.93	13,900	1	20,860
Elliptical‡	31,250	0.65	472	134.8	33.7	11.83	3,336	1	4,990
Elliptical	31,250	0.65	472	134.8	33.7	16.73	9,300	1	13,900
Elliptical	31,250	0.65	472	134.8	33.7	21.93	20,280	1	30,400
Deadweight = 56,250 tons									
Surface	75,000	0.60	820	126.2	42.1	26.3	62,200	4	109,900
Surface	75,000	0.70	777	119.6	39.9	20.1	25,250	1	35,060
Surface	75,000	0.80	747	115.0	38.3	14.22	8,500	1	11,800
Submarine									
Circular†	93,750	0.60	698	99.7	99.7	14.22	7,765	1	11,650
Circular	93,750	0.60	698	99.7	99.7	20.1	21,200	1	31,800
Circular	93,750	0.60	698	99.7	99.7	26.3	46,200	4	96,600
Elliptical‡	93,750	0.60	698	199.4	49.85	14.22	11,300	1	17,000
Elliptical	93,750	0.60	698	199.4	49.85	20.1	30,950	2	60,000
Elliptical	93,750	0.60	698	199.4	49.85	26.3	67,500	4	141,000
Circular†	93,750	0.65	680	97.1	97.1	14.22	8,050	1	12,080
Circular	93,750	0.65	680	97.1	97.1	20.1	21,930	1	32,950
Circular	93,750	0.65	680	97.1	97.1	26.3	47,850	4	100,000
Elliptical‡	93,750	0.65	680	194.2	48.55	14.22	11,750	1	17,620
Elliptical	93,750	0.65	680	194.2	48.55	20.1	32,000	2	62,000
Elliptical	93,750	0.65	680	194.2	48.55	26.3	69,800	4	145,800
Deadweight = 93,750 tons									
Surface	125,000	0.60	962	148	49.3	28.5	110,000	4	194,000
Surface	125,000	0.70	921	141.7	47.2	21.9	45,300	2	73,300
Surface	125,000	0.80	885	136.0	45.3	15.5	15,180	1	21,080
Submarine									
Circular†	156,250	0.60	828	118.3	118.3	15.5	13,780	1	20,680
Circular	156,250	0.60	828	118.3	118.3	21.9	37,800	2	73,400
Circular	156,250	0.60	828	118.3	118.3	28.5	81,050	4	169,300
Elliptical‡	156,250	0.60	828	236.6	59.15	15.5	20,100	1	30,200
Elliptical	156,250	0.60	828	236.6	59.15	21.9	55,150	4	115,300
Elliptical	156,250	0.60	828	236.6	59.15	28.5	118,100	4	247,200
Circular†	156,250	0.65	807	115.3	115.3	15.5	14,230	1	21,380
Circular	156,250	0.65	807	115.3	115.3	21.9	38,900	2	75,500
Circular	156,250	0.65	807	115.3	115.3	28.5	83,600	4	175,000
Elliptical‡	156,250	0.65	807	230.6	57.65	15.5	20,800	1	31,200
Elliptical	156,250	0.65	807	230.6	57.65	21.9	56,800	4	118,700
Elliptical	156,250	0.65	807	230.6	57.65	28.5	122,000	4	255,200

* Deadweight/displacement ratio taken as 0.75 for surface tankers and 0.60 for submarine tankers.
† Streamlined body of revolution, circular sections, $L/D = 7.0$.
‡ Streamlined body, elliptical sections, $B/d = 4.0$.
§ EHP based on A.T.T.C. 1947 line plus 0.0004.

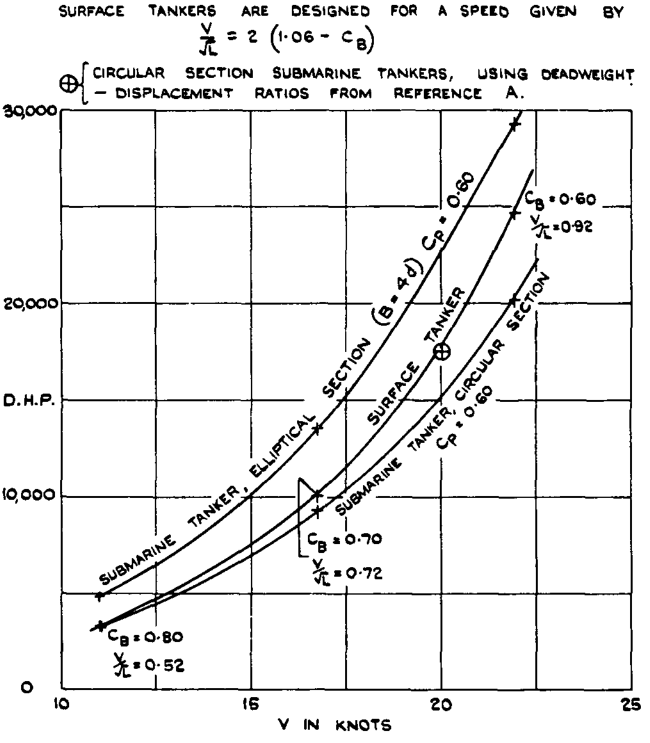


Fig. 9. Comparison of surface and submarine tankers of 18,750 tons deadweight

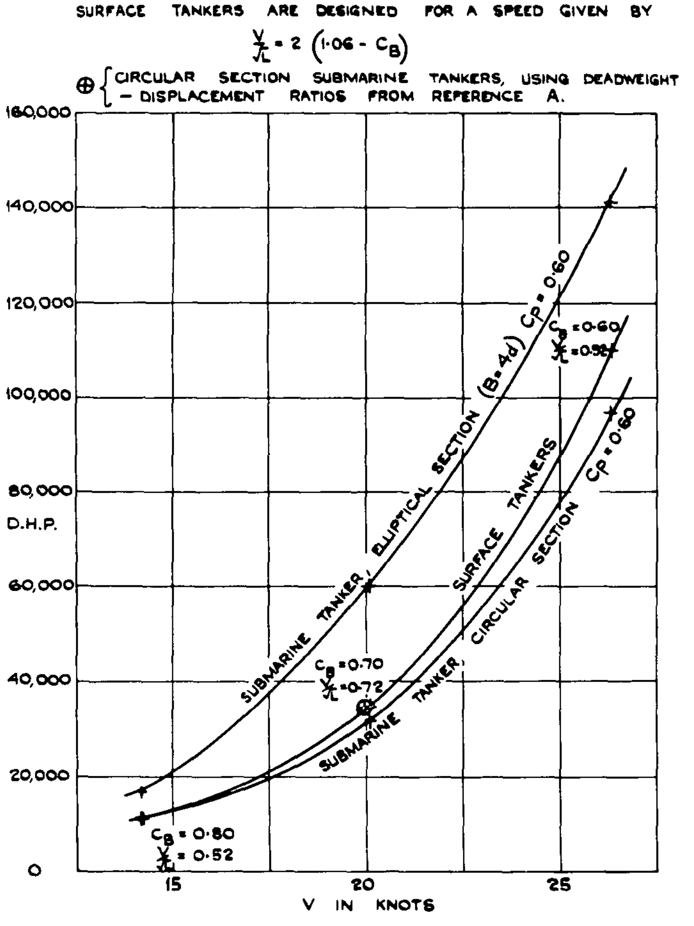


Fig. 10. Comparison of surface and submarine tankers of 56,250 tons deadweight

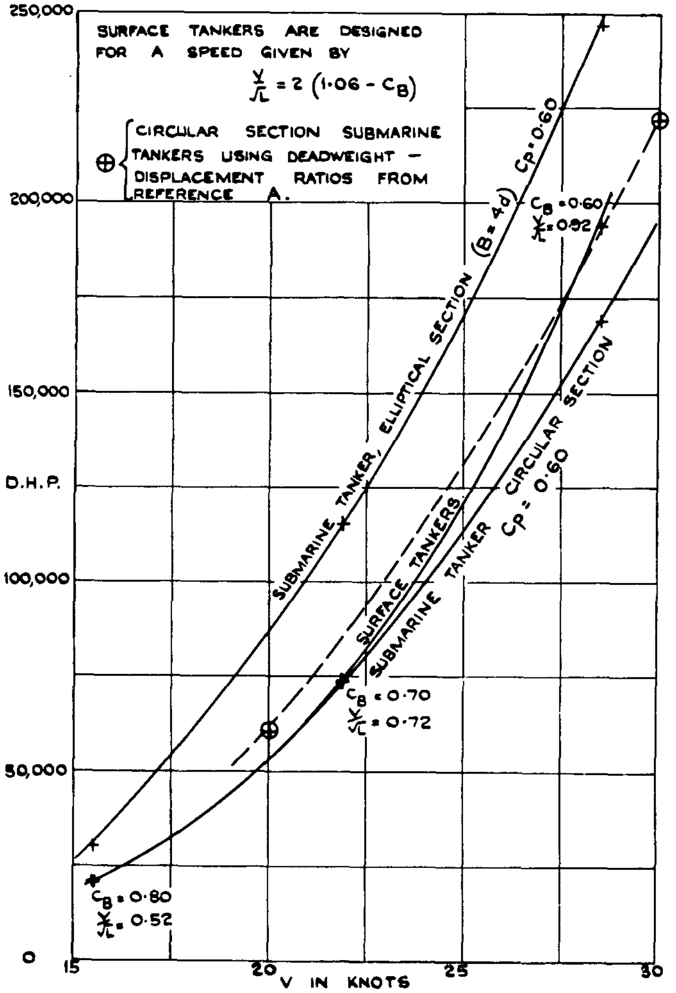
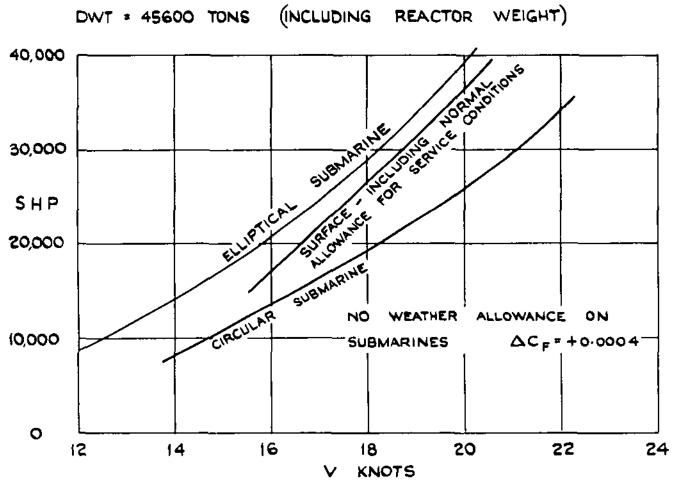


Fig. 11. Comparison of surface and submarine tankers of 93,750 tons deadweight

His power curves are reproduced in Fig. 12 and show the same general relationship between the circular and elliptical section submarines although the estimates are based on quite independent data. The principal difference between his curves and those shown in the present paper is that the power curve for the surface ship is considerably higher and much nearer to the elliptical submarine than to the circular one. This difference can be accounted for by the fact that Teasdale included a "normal" allowance for service conditions, in other words, for the effect of wind and rough seas.



TYPE	SURFACE				SUBMARINES	
SHP	16,000	22,000	30,000	40,000	UP TO 40,000	
SHAPE	HULL FINED TO SUIT HIGHER SPEEDS				CIRCULAR	ELLIPTICAL
L FT	710	743	761	785	538	800
B FT	102·5	103·5	104·3	108·1	108	160
d FT SURFACED SUBMERGED	38·0	38·0	38·0	38·0	90 108	45 50
LOADED Δ TONS SURFACED SUBMERGED	62300	62850	63650	64490	67860 74650	69860 76850
WS SQ FT	110,000 AVERAGE				125070	204120
C_B	0·785	0·754	0·738	0·700		

Fig. 12. Comparison of nuclear propelled surface and submarine tankers (from Ref. 4)

OPERATING PROBLEMS

The strength of submarine cargo ships and problems of manoeuvrability are both extremely important factors in the design of such ships. The first is not strictly "hydrodynamic" and the second is to be discussed in another paper, so the present remarks will be confined to very general aspects of these two problems.

It has been said that in the case of submarine tankers carrying liquid cargoes of one sort or another, they need only have a central pressure hull containing the machinery, living spaces, and buoyancy tanks, the external cargo spaces being of very light construction since the liquid pressures inside and outside could be equalised. It has been claimed in fact in a study conducted in Japan that this could result in an actual reduction in steel weight. But can we indeed accept this conception? There is always the possibility of a power failure or other mishap which would force the ship to surface at sea and possibly in bad weather, and it would seem that under these conditions the submarine would need to possess longitudinal strength comparable with that of any surface ship. This would seem a hazard particularly to be catered for in any pioneer submarine tankers, because in these early ships there will doubtless be many precautions taken to ensure a shutdown of the reactor in the event of any unforeseen or unacceptable faults in the equipment. It may even be that a shutdown could follow a mere fault in the controlling instrumentation. Moreover, with the very large draft of such a vessel, she may in many cases have to load or unload at a deep water terminal in a relatively exposed position where the conditions of the sea may be quite rough as compared with those normally existing in harbour. Also in approaching port when the water depth becomes less than some 400 or 500 feet such a submarine would undoubtedly have to surface and do the last part of the journey as a surface ship and therefore subject to the effects of rough weather. Taking all these possibilities into account, it seems extremely doubtful whether the conception of a very light structural hull for submarine tankers would be acceptable, at least until considerable experience had been gained in their operation. For a cargo ship there is no question but that a pressure hull would be necessary throughout. The Mitchell Engineering Company have carried out an investigation into such a cargo submarine and have come to the conclusion that the hull would need to be made of mild steel up to 3 1/2 inches in thickness amidships in way of the machinery and compensating tanks, and vary down to 1 inch in thickness toward the end. On this basis they estimated the deadweight/displacement ratio to be 0.56 for an ore-carrying submarine of 50,000-ton displacement [5]. There are many other problems involved in the construction of a hull of such dimensions. As has already been pointed out when discussing the resistance qualities of different designs, the circular hull submarine leads to very large drafts such as could not be catered for by any existing docks or terminal ports. On the other hand, the circular hull is the only economical one from a structural point of view and any departure from exact circularity will mean the provision of extra stiffness and greater thickness of plating [6]. Although liquid cargoes could be handled very easily from a submarine, other types of cargo could be very awkward in their demands for large hatches which would have to be pressure resisting and which would, in fact, form another weakness in the strength qualities of the hull. It is probable from a strength point of view that the only reasonable cargoes would be bulk ones such as iron ore or similar high-density materials.

Two of the most important qualities in such a ship would be its directional stability and controllability. If we consider a submarine some 800 feet in length travelling at an immersion of 400 feet and built to resist pressures up to twice this depth, we are asking the crew virtually to fly the vessel in an atmosphere whose depth is only equal to the length of the submarine. This would probably give any air pilot nightmares! Since in order to compete commercially on a power basis with the surface ship the submarine would also have to travel at some 30 knots or more, it is easy to see how by the accidental occurrence of even a moderate trim by the bow the ship could very soon exceed her safe diving depth. The question of providing adequate directional stability and controllability is therefore a paramount one in the whole design.

In order to obtain adequate transverse and longitudinal stability, it will be necessary for the submarine to carry permanent ballast, as is done in military craft. It is also imperative to have some surplus buoyancy when on the surface, and in any commercially operated craft the amount of such reserve buoyancy would almost certainly be controlled by legislation. It is probable that these two items together would amount to not less than 25 percent of the displacement. Although such a vessel would not have to carry bunkers, there would be little if any saving of weight in this respect since the shielding for the reactor would be of the same order of magnitude. All these considerations add up to the fact that a submarine cargo ship or tanker would require considerably greater displacement than a surface ship to carry the same deadweight.

Any nuclear propelled ship will call for a much greater skill in the engine room crew than does a conventionally powered ship. If in addition the nuclear propelled ship is also a submarine, then the navigating crew must also be very highly skilled and undergo long periods of training comparable with those of similar navy crews. The additional cost of this skill could be considerable and may be an important factor in the overall comparison.

At least in the single-screw designs it will be necessary to have some means of auxiliary propulsion such as motors and batteries or diesel engines for use on the surface in an emergency. If a single-screw submarine were designed for use under ice, it would seem almost essential to have electrical auxiliary propulsion since in these circumstances it would be impossible to bring the ship to the surface until she was clear of the ice. In the case of a twin-screw ship with two entirely separate propulsion plants, auxiliary propulsion could probably be dispensed with.

Considering in more detail the operation of the circular and elliptical submarines and the surface ships for which the estimates of power are shown in Figs. 9, 10, and 11, we see that the circular section submarine requires a lower power than either the surface ship or the elliptical submarine. However, we see that the advantage is not large unless we contemplate speeds of 25 or 30 knots and it is a question of the economics of the oil industry whether it is justifiable to carry a commodity such as oil or indeed any other nonperishable bulk cargo at such high speeds. It is not proposed here to enter into these economic questions, but it may be sufficient to point out that these will vary from time to time, as witnessed by the fact that during the Suez crisis the cost of transporting oil via the Cape rose to £19 per ton as compared with the normal freight rate of £2 per ton via Suez. In addition, it has been estimated that the capital cost of a submarine tanker would be of the order of twice that of the equivalent surface ship [7,8]. It would appear, therefore, that the advantages from a commercial point of view would not be large enough at commercial speeds to counteract the increased capital cost of the submarine and the increased costs of maintenance, crew, insurance, and the large expenditure which would be necessary for research and development before such a ship could be built. Beyond these operational problems is the further one that a circular hull submarine large enough to justify nuclear propulsion and competition with similar surface ships would have a very large draft and would require new building facilities, new dry-docking facilities, and new terminals. It would also be very limited in respect of the world ports in which it could be accommodated and would certainly not be able to pass through the Suez or Panama Canals for many years to come. If such a ship to carry oil from the Middle East to Europe had to go via the Cape, then this would far outweigh any advantages it might have in regard to lower power requirements.

If we restrict the draft of the submarine to a figure comparable with that of the equivalent surface tanker, then we are forced into accepting a submarine having elliptical sections. As an extreme case the figures have been calculated for such submarines of different deadweights having a beam/draft ratio of 4:1 and the power curves for these have been given in Figs. 9, 10, and 11. It is at once seen that from a power point of view, even after making some weather allowance for the surface ship, there is no longer any overall benefit to be derived on the basis of power. If the thesis is accepted that for a submarine tanker the structure carrying the oil can be of light scantlings, then there would not be a very great

646551 O—62——25

penalty on weight in going to the elliptical section. However, in a cargo-carrying submarine or a tanker in which the whole hull was built to resist pressure, then there would be a very substantial penalty in weight through such a change in shape. The comparison between the submarine and the surface ship is therefore seen to be more unfavourable to the submarine when we consider a hull with elliptical sections.

The outcome of this whole discussion points to the fact that from a commercial point of view there is little attraction in submarine cargo ships or tankers so long as we restrict our thoughts to speeds within the limits for which economic surface vessels can be designed. However, if we wish to go beyond these speeds, then the submarine would be the only answer for the carriage of bulk cargoes. For lighter specialised cargoes, it may well be that the answer is to go the other way and use hydrofoil craft. If submarine ships were justified by a sufficient demand for the transport of bulk cargoes at such high speeds, the figures that have been given for the powers required, even when we are not compelled to make provision for surface wavemaking and rough weather, still mount rapidly and very soon attain astronomical proportions. In Table 3 a line has been drawn showing where the power required exceeds 200,000 DHP, which means a propelling installation of the same order of magnitude as that of the QUEEN ELIZABETH, and of course to house any such nuclear plant in a submarine would be quite a task. The containing vessel for the 20,000-shaft-horsepower nuclear plant for the American cargo ship SAVANNAH is 50 feet long and 35 feet in diameter, and one can imagine that with 200,000 horsepower together with the space required for permanent ballast, trimming tanks, buoyancy tanks, living quarters, and so on, the deadweight/displacement ratio would be rather small.

From time to time it has been suggested that a smaller tanker of the nuclear propelled submarine type might be competitive with a much larger surface tanker. Such a comparison has been made by Teasdale [4] between a 47,000-ton-deadweight surface tanker and a 26,000-ton-deadweight submarine tanker of circular cross section and having dimensions which do not exceed those of the surface ship. He estimated that if the submarine were travelling at a high enough speed to deliver the same quantity of oil per year as the surface tanker, the fuel consumption would be about four times as great. From his analysis he doubted whether the capital cost of the submarine would be sufficiently less than that of the surface ship to offset such a penalty.

TERMINAL PROBLEMS

The draft of water in many ports and harbours today does not exceed 35 feet and in very few does it exceed 50 feet. This would impose many problems on the building and subsequent dry-docking of submarines of the size we have been discussing. The draft problem could be overcome by going to an elliptical section shape for the hull, but this would give a submarine of excessive beam for most dry docks and would also bring in the other problems which we have mentioned in the previous section. For the ordinary routine loading and unloading processes, it would be necessary to build offshore loading terminals or use feeder services to bring the oil in to the refineries. This would mean that the ship might be subject to rough weather and therefore would have to be designed with normal longitudinal strength and not be able to have a light scantling outer structure. Another point of some interest for such large ships approaching the shore is the fact that once the depth of water was reduced much below 600 feet they would have to surface and do the last part of their journey as surface ships. To achieve the high efficiency of underwater propulsion which has been the aim of all these designs it is necessary to go to a streamlined body of revolution with the very minimum of appendages. However, when such a vessel has to come to the surface it has about the worst possible shape for good performance. The maximum speed under these conditions would probably be quite low, and if the approach to the terminal ports runs for long distances over a continental shelf or similar shallow water, this could add appreciably to the time of passage and so offset to some extent the better submerged performance. Such a large craft would be exceedingly difficult to manoeuvre in shallow water, and would be quite unwieldy at the terminals, and especially if made of light scantlings would be liable to serious damage and during berthing operations would need the assistance of tugs. In common with nuclear propelled surface ships, it would also be necessary for the port authorities to monitor continually for radioactivity and to maintain the equivalent of a fire-fighting service to give warning and to cope with any such accident. Even voyages under ice can be fraught with considerable dangers other than those of navigation. According to information resulting from the voyage of the NAUTILUS, the ice over the North Pole is some 9 to 13 feet in thickness but with occasional ridges penetrating some 100 feet below this. In addition, from time to time icebergs were met with which were imprisoned in the surface ice and reached no less than 1000 feet below the surface. The use of a polar route into the Pacific is also subject to the limitation that water in the Bering Straits is only some 150 feet in depth. It is obvious that extremely careful navigation would be called for to cope with such hazards.

CONCLUSIONS

The general conclusion which can be drawn from all the above evidence is that submarine cargo ships and tankers of circular cross section could be designed to compete with surface ships of the same deadweight as regards their power requirements, especially when one takes into consideration the effects of rough weather, from which the submarine would be immune. Such submarine ships would have excessive drafts, however, and if this is avoided by using elliptical sections, then the submarine's superiority soon disappears. However, up to such speeds as those for which an economical surface ship can be designed, say of the order of 25 to 30 knots, the capital cost of the submarine, of the necessary docking facilities, and of the provision of offshore terminals could not at present be justified on economic grounds. At the very least it would be necessary for a consortium of owners to combine in the building of terminals and dry docks for common use before a fleet of such submarines was put into service. At higher speeds, above 30 knots, the submarine begins to have very appreciable advantages as regards power, but of course at these high speeds the price to be paid in terms of fuel consumption is also high and the propelling machinery would begin to take up more and more of the volume of the ship, thus reducing her deadweight. Whether such ships would be a good financial proposition or not would depend on the interplay of capital cost, insurance, maintenance, fuel and operating costs, the freight rate obtainable for oil or other bulk cargoes, and the route on which the ship is employed. If this were between the Middle East and the United Kingdom, for example, a submarine tanker of circular section of anything greater than about 25,000 tons deadweight would be unable to use the Suez Canal in its present form. The economic advantages of large size in the carriage of bulk cargoes could therefore only be realised in this trade so far as submarine tankers are concerned by routing them around the Cape, with all the attendant disadvantages. These would not, of course, enter into other routes, such as Venezuela to Europe. The first marine nuclear propulsion plants will certainly be expensive, but the ingenuity of the engineer will undoubtedly reduce these as time goes on. Nuclear fuel costs, which at present are perhaps twice those of conventional fuels will also come down in the course of time and with the more widespread use of atomic energy in other fields.

So far we have restricted ourselves to a comparison between nuclear propelled surface and submarine ships. The case for the submarine would be even less favourable at this time if we were to compare it with a conventionally propelled surface tanker. The British Shipbuilding Research Association has compared surface tankers having respectively conventional and nuclear propulsion plants and has shown that even on the assumption of economic parity between capital and fuel costs there is no commercial attraction in installing in a surface tanker a nuclear plant of higher power than the conventional ones being installed at present [9]. It has also been shown, in the case of a tanker of 65,000 tons deadweight with 25,000 shaft horsepower employed on the Middle East-United Kingdom route, that while the cost per ton of transporting oil via the nuclear ship might be within 15 percent of that for the conventional ship, the cost for the nuclear ship begins to rise again at speeds above 17 knots [10]. This means that from the point of view of economy there is really no inducement to fit higher powers in nuclear ships than are at present fitted in conventional ships. The greatest commercial incentive for submarine ships at the moment would appear to be their use on special routes where surface ships cannot be used and on which there might be the attraction of making special profits. One such route which has been mentioned on many occasions is that from Canadian ports carrying out ore in winter underneath the ice, and another has been the suggestion put forward in the London Times that by going under the polar ice it is possible to halve the distance between London and Tokyo [8].

Leaving aside economic questions, there is no doubt as to the extreme advantage of having such craft for military use and for the transport of valuable cargoes in wartime. It may well be that some government will build a craft of this type very soon, both for its military potential and national prestige, and to gain experience in the operation of such ships. Something of the magnitude of the tasks facing the designer of such submarine cargo carriers as we have been discussing may be realised when it is recalled that the largest submarine built to date is the USS TRITON, which has a length of 447 feet, a displacement of 5900 tons, and two nuclear reactors. This is the longest and most powerful submarine yet built and it is a very long way to go from this to tankers of the order of 60,000 or 80,000 tons. Although the tasks are formidable, there is no doubt as to the challenge they present and the extreme interest which they engender in the mind of the designer. Using a completely submerged hull of ideal form, the propeller designer is presented with wonderful opportunities of realising his ideal propeller—a circumferentially uniform wake, the chance to apply impeller theory to marine problems, and the knowledge that at such deep depths cavitation will no longer be a paramount inhibitor always looking over his shoulder. To the hull designer, the challenge will be to eliminate all possible sources of parasite drag by attention to hull form, appendages, and smoothness of surface and to ensure adequate directional stability and control, while tantalisingly in the offing will be the lure of someday, somehow, achieving laminar flow over some of the hull surface. Inevitably progress will be made only by small steps, and the development of a successful submarine cargo ship or tanker will involve many years of research and development and much money. From the scientific and technical point of view, such a vessel presents a great challenge to the naval architect and marine engineer, who will doubtless continue to dream of the possible solutions until the day comes when they are given the opportunity to translate their ideas into reality.

ACKNOWLEDGMENTS

The work described in this paper forms part of the Research Programme of The National Physical Laboratory and is published by kind permission of the Director.

REFERENCES

[1] Crewe, P.R., "The Hydrofoil Boat; Its History and Future Prospects," Instn. Naval Architects Trans. 100:329 (1958)

[2] Todd, F.H., Stuntz, G.R., and Pien, P.C., "Series 60 – The Effect upon Resistance and Power of Variation in Ship Proportions," Soc. Naval Architects Marine Engrs. Trans. 65:445 (1957)

[3] Crago, W.A., "Test Results on Submarine Tankers," Impulse, No. 4, Mar. 1958

[4] Teasdale, J.A., "Characteristics and Performance of Nuclear-Powered Submarine Cargo Vessels," North East Coast Instn. of Engrs. and Shipbldrs. 57:461 (1958-59)

[5] Mitchell Engineering Co., "Nuclear-Powered Submarine 'Moby Dick'," 1960

[6] McKee, A.I., "Recent Submarine Design Practices and Problems," Soc. Naval Architects Marine Engrs., paper 11 for meeting Nov. 12-13, 1959

[7] Article on submarine tankers, Journal of Commerce, Jan. 17, 1957

[8] Shipping Correspondent, "Undersea Voyages," The London Times, Aug. 13, 1958

[9] Smith, S.L., and Richards, J.E., "Nuclear Power for the Propulsion of Merchant Ships," Instn. Engrs. Shipbldrs. in Scotland 100(pt7):698 (1957)

[10] Norton, E., "Future Trends in Marine Engineering," Shipbuilding and Shipping Record, International Design and Equipment Number, 1958

DISCUSSION

R. N. Newton (Admiralty Experiment Works)

We should all be grateful to Dr. Todd for presenting what seems to me to constitute the most comprehensive review of this popular topic, to date. He has dealt with almost every aspect of the general problem and I would like merely to place more emphasis on some of the points which he has made and which militate against the opinion, frequently expressed, that submarine tankers offer great advantages in the commercial field.

In that part of his paper which compares the two types of tanker on the basis of the same deadweight, Dr. Todd assumes, from data provided by other authors, a ratio of deadweight to displacement in a nuclear propelled submarine of 0.6 (see Fig. 8). With this value of 0.6 the DHP curves of the circular sectioned submarine tanker in Figs. 9, 10, and 11 lie below those of the surface tanker at all speeds worth considering. The crossover points beyond which the submarine tanker has the advantage over the surface tanker are 11, 14, and 22 knots for equal deadweights of 18,750, 56,250, and 93,750 tons respectively. This paints a rather rosy picture for the submarine, but if the ratio of deadweight to displacement for the submarine tanker is less than 0.6, a very different picture would be obtained. It is not clear from the paper how the authors concerned arrived at their figures for this ratio, but it is significant to remark that the values indicated in Fig. 8 show a much wider scatter than those for surface tankers. Immediately I notice that Dr. Van Manen gave in his paper a figure of 0.41 for a 100,000-ton tanker and 0.50 for a 43,000-ton tanker. There is only one way to arrive at a realistic figure, viz., by carrying out a detailed design, and, speaking with some experience in the design of military submarines, I venture to suggest that a more realistic figure would be nearer to 0.5 than 0.6, for several reasons. The most important of these is the inherently unsuitable shape of the pressure hull to accommodate machinery and equipment with a degree of compactness consistent with good maintenance such as is possible in a surface ship. Others include the weight and space necessary for additional ship services such as trimming and compensating systems, special air-conditioning apparatus, three sets of control gear (two hydroplane gears and one rudder gear), additional navigational and operational aids, and the fact that many of the ship services must be designed to much greater pressures than in the case of a surface ship. The effect of a lower deadweight/displacement ratio would be to raise the submarine curves in Figs. 9, 10, and 11 and to greatly increase the speeds at which the submarine gains the advantage over the surface tanker to such values as to raise grave doubts as to whether the machinery to drive the vessel at such speeds could be accommodated. In the case of the 56,250-ton tanker in Fig. 10, for instance, if a deadweight/displacement ratio of 0.5 were used the crossover point would rise to the region of 27 knots and the DHP required to 118,000.

Immediately the question arises "could the machinery and propellers to provide this power be accommodated in any reasonable size of pressure hull to suit other requirements?" I am strongly of the opinion that it could not. If this opinion is correct, it follows that, if for any reason a submerged tanker of such size became necessary, then with the present means of propulsion and types of fuel it would be necessary to accept a very heavy loss in deadweight ratio compared with a surface tanker.

Against this, however, must be weighed the distinct advantage of being able to operate with impunity in any weather except when approaching the terminal points of the voyage, as pointed out by Dr. Todd.

In the section of the paper dealing with operating problems, Dr. Todd has called briefly, but very effectively, to the need to take account of dynamic stability and control when submerged. Even with the comparatively small military submarines now being built, the problems involved are both complex and numerous. Compared with the submarines of the last war, underwater speeds have doubled and trebled. The speed beyond which the submerged tanker begins to gain over the surface ship is in this region. Consequently the time available to the commanding officer, and to whatever control apparatus with which the submarine is equipped, to take corrective action is very much shorter—not more than one-third of that in an orthodox submarine of the last war.

Fortunately much has been learned regarding the dynamic stability and control of normal sized submarines. By the application of theory and model experiments correlated to the results of full scale trials, it is now possible to determine stability criteria and to design and use automatic control systems to suit the stability and the response of the submarine. For such large submerged tankers as those under discussion similar investigations would have to be carried out and would, in fact, be vital since the margin of safety involved in terms of time and the depth range is obviously much smaller.

On the question of structural design it is fair to state that the unpressurized structure which may contain liquid cargo offers no insuperable design or constructional difficulties, but, as Dr. Todd points out, it is indeed a grave assumption that it could be of light scantling. On the other hand the problem of designing the pressure hull and the consequences which could result from the application of incorrect principles are much more serious. Sudden collapse of the hull can arise from elastic failure of the structure or plastic failure of the material, so that the problem involves not only the theory to avoid one or both of these but also the development of special steels. This development work becomes more and more difficult as the thickness of the steel increases, i.e., as the size of the pressure hull increases. Construction of the pressure hull is a highly specialized technique. Not only must the hull be built to a small degree of ovality, or "out of circularity," but it is necessary to employ highly specialized welding techniques. Local weaknesses brought about by poor design or bad workmanship introduce a danger factor since they could lead to early local failure and sudden collapse of the hull.

Merely to emphasize the vital nature of these two problems of stability and strength let us take Dr. Todd's example of a submerged tanker 800 feet long with a pressure hull say 600 feet long and a collapse depth 800 feet. Let us also suppose, as he does, that the tanker is proceeding at about 30 knots at 400 feet depth in order to gain the advantage of not generating waves, and then let us suppose that for some unforeseen reason it takes on a bow-down angle of 10 degrees for just 40 seconds. In that short space of time the fore end of the pressure hull would have exceeded the collapse depth and complete disaster would follow. It is as well to stress that this is by no means a hypothetical case but a real possibility.

It is for such reasons as those which I have attempted to emphasize, and many others which Dr. Todd has mentioned, that I incline to the opinion that, although the possibilities of submarine tankers as cargo vessels for commercial use present a great challenge to the naval architect and marine engineer, there are many equally challenging and important aspects of surface ship propulsion which require our immediate and undivided attention in the near future. Not the least of these is the design and construction of hull forms capable of maintaining higher speeds in rough weather.

F. H. Todd

Mr. Newton rightly points out that the relative merits of the surface and submarine tankers in the matter of power depend very greatly upon the values assumed for the ratio of deadweight to displacement, and stresses that only detailed design calculations can give reliable guidance on this point. At the time of writing this paper, no such data appeared to be extant, but recently the results of such detailed weight estimates have been published in the U.S. by Russo, Turner, and Wood.* Detailed designs have been made for a number of submarine tankers with nuclear machinery having streamlined, body-of-revolution hulls, with

* Vito L. Russo, H. Turner, and Frank W. Wood, "Submarine Tankers," Society of Naval Architects and Marine Engineers, New York, Nov. 1960.

and without parallel body, and rectangular hulls having rounded corners. The deadweight/displacement ratios depend upon the size of the ship and its speed, and some representative figures taken from the reference are given in Table D1, as they are of general interest.

Table D1
Deadweight/Displacement Ratios (from Russo, Turner, and Wood)

Speed (knots)	Section	Parallel (%)	Length (ft)	Beam (ft)	Depth (ft)	Dwt. to Surf. Displ.	SHP	Power Increase for Rect. Section (%)
Deadweight = 20,000 tons								
20	Circle	0	525	75.5	75.5	0.546	16,900	–
20	Rect.	59.5	555	80	40	0.527	27,400	62
30	Circle	0	560	79.0	79.0	0.467	68,600	–
30	Rect.	58	570	90	40	0.460	95,400	40
Deadweight = 30,000 tons								
20	Circle	0	600	85.5	85.5	0.559	22,100	–
20	Rect.	60.8	650	100	40	0.536	38,900	76
30	Circle	0	625	89.5	89.5	0.490	87,200	–
30	Rect.	55.5	625	120	40	0.478	128,000	47
Deadweight = 40,000 tons								
20	Circle	0	660	93.5	93.5	0.566	26,800	–
20	Rect.	60.6	710	120	40	0.546	48,400	80
30	Circle	0	680	98.0	98.0	0.500	104,400	–
30	Rect.	64.1	780	120	40	0.489	152,000	45

For the tankers having circular sections the ratio at 20 knots varies from 0.546 at 20,000 tons deadweight to 0.566 for 40,000 tons. At 30 knots the corresponding figures are 0.467 and 0.500. These ratios are referred to surface displacement. If we convert them to submerged displacement, which is the one used in my paper, the values become 0.496, 0.515, 0.425, and 0.455 respectively. These values are all appreciably less than the figure of 0.60 used in the original power estimates. The latter have therefore been revised, using the new deadweight/displacement figures as derived above, but otherwise they are upon exactly the same basis as the earlier estimates. The calculated powers are shown in Table D2 and the appropriate spots have been added to Figs. 9, 10, and 11. For the smallest tanker, of 18,750 tons deadweight, the circular-hulled submarine now requires exactly the same power as the surface tanker at 20 knots, so that the crossover point (for smooth water operation) has been raised from about 11 knots to 20 knots. The same applies to the intermediate 56,250-ton-deadweight tanker, the crossover rising from 14 knots to 20 knots. For the largest ship, of 93,750-ton deadweight, the submarine tanker does not become less resistful than the surface ship (in smooth water) until the speed is some 28 knots.

These figures substantially agree with those suggested by Mr. Newton. I was aware at the time of writing the paper that the assumed value of 0.6 for the deadweight/displacement ratio was probably high, especially as many of the examples originated from the protagonists of the submarine cargo ship. Indeed, in an earlier paper* I had used a value of 0.5, but felt it necessary to err on the side of optimism rather than to run the risk of being charged with pessimism and lack of foresight! This comparison is for circular-hulled submarines, which, of course, suffer from the extreme drafts noted in the paper. In the American paper referred to, power requirements are also given for rectangular section submarines, some of which are shown in Table D1. While this type of section enables the draft to be kept within reasonable bounds (not greater than 40 feet for 40,000 tons deadweight) the price to be paid in power is very considerable, varying from 60 to 80 percent increase at 20 knots and 40 to 50 percent at 30 knots. These powers are higher than those given in my paper for elliptical sections, but, of course, they have the advantage of less beam. With limitations on beam, draft, or both, forcing us to adopt elliptical or rectangular sections, it is obvious that the commercial merits of the submarine tanker as compared with those of her surface sister will be hard to find, even when allowance is made for rough sea effects upon the surface ship, as long as there is no demand for the high speed (and therefore high cost) transport of bulk cargoes across the oceans.

In view of Mr. Newton's experience in submarine design problems, his remarks on the difficulties inherent in providing adequate strength in such large submarines will be of great value to all interested in this subject, and we are indebted to him for his penetrating analysis of the problem.

Table D2
Power Calculations for Submarine Tankers
(Body of Revolution Hull, No Parallel Body, C_p = 0.60, L/D = 7.0)

Deadweight (tons)	18,750		56,250		93,750	
Speed (knots)	20	30	20	30	20	30
Dwt./Submerged Δ	0.50	0.425	0.515	0.455	0.530	0.485
Submerged Δ (tons)	37,500	44,100	109,500	124,000	177,000	193,500
Length (feet)	513	543	735	766	862	887
Diameter (feet)	73.3	77.6	105.0	109.4	123.1	126.7
E.H.P., naked	11,680	41,580	23,040	81,000	31,040	106,110
Number of propellers	1	2	1	4	2	4
Appendage allowance	20%	30%	20%	40%	30%	40%
Q.P.C.	0.80	0.67	0.80	0.67	0.67	0.67
DHP at propeller	17,520	80,500	34,500	169,200	60,200	222,000

H. Lackenby (British Shipbuilding Research Association)

I should like to make a few general remarks on the strength of the author's conclusions, especially as I have since ascertained that they have a bearing on remarks I made on Dr. van Manen's paper on Monday which touched on the same subject. As I said at that time,

* F. H. Todd, "Submarine Tankers," Shipbuilding and Shipping Record, Aug. 21, 1958.

when comparing the performance of surface and submarine vessels one has to be careful about the basis of comparison. Although for a given deadweight of say 25,000 tons the break-even point as regards power for certain designs may be as high as 25 or 30 knots, one has to bear in mind that a surface tanker of 25 knots would not be really economical compared with a commercial tanker which would have a speed of about 15 or 16 knots. As I said before, I am speaking here of economy on the basis of cost per ton-mile of cargo carried under present conditions. This was one of the findings arising from freighting calculations carried out by the British Shipbuilding Research Association in conjunction with ship-owners in connection with extensive nuclear energy studies, reference to which the author has made in the paper. This point is really covered by the second paragraph of the author's conclusions with which I certainly agree. Incidentally it might be of interest to mention that I understand that freighting calculations have also shown that, if anything, the speed of some recently built conventional tankers is perhaps a little on the high side as far as economic running is concerned. From the military point of view, of course, the situation could be quite different as the author has clearly explained.

What I am really saying here is that in my remarks on Dr. van Manen's paper on Monday I anticipated these particular aspects of the author's conclusions, although I was not aware of this at the time.

I should also like to say that I agree with the author's conclusions generally, in addition to those to which I have referred already. There is just one point of detail I should like to raise, namely, the limit of power for a single screw surface ship which the author has taken as 40,000 SHP. Some years ago we looked into this at BSRA in connection with the nuclear studies for tankers referred to earlier and we were advised that for a number of reasons and in particular the possible incidence of excessive cavitation erosion, 20,000 to 25,000 SHP was about the practical limit at the time. Perhaps the author may care to comment on this point.

F. H. Todd

The British Shipbuilding Research Association has carried out a great deal of research into the subject of nuclear propulsion, and it is therefore gratifying to know that Mr. Lackenby is in general agreement with my conclusions as to the commercial merits of its application to submarine cargo ships and tankers. With reference to the use of an upper limit of 40,000 horsepower for a single-screw ship, such power absorption is, of course, fairly common on multi-screw ships. In single-screw surface ships the wake variation conditions are considerably more onerous, and as Mr. Lackenby has said this introduces the danger of cavitation erosion. In the submarine this is not nearly such a serious problem since the circumferential variation can be kept quite small by paying good attention to the shape and location of appendages. Moreover, we are here talking of the future, and with the advance in knowledge about propeller-excited vibration and the necessary stern shapes and clearances to reduce the forces to a minimum, we may look forward to a steady increase in the maximum power we can put through a single screw.

J. M. Ferguson (John Brown and Co., Limited, Glasgow)

I do not wish to discuss at all the technical side of Dr. Todd's paper but I wish to express a thought which has caused a great amount of discussion between my colleagues and myself, mainly during lunch periods. We have been discussing the possibilities of these submarine tankers because at the moment at Clydebank we have been building such a number of present day modern large tankers. Now, as you are all aware, in these present-day tankers a great deal of attention is being paid to the amenities for the crew. The very rapid turn round of these tankers, both at their loading port and at their delivery port means that the crew generally get very few advantages of leave or of getting home and the conditions on board the tankers are made all the more pleasant and congenial for these men. When you come to the submarine tanker, I would like you to think of the psychological aspect of the environmental conditions. These people are to be living in artificial conditions, with no daylight for days and weeks at a time, and the financial cost of making these conditions congenial and tolerable would add very considerably to the economic aspect of running these ships. In the case of the American submarine NAUTILUS, which did that epoch-making trip under the ice in the Polar regions, the crew, when you read the description of the voyage, had quite extensive arrangements made for their entertainment and to keep them happy; but they were doing a special job, they were being filled with a feeling of prestige attached to the job. To maintain, as would you call it, an equally high standard of "esprit de crew," then, quite a lot of money is involved. I would like that thought to be kept in mind because I do feel that when such craft do come along that aspect of it which apparently has not been considered so far will require quite an amount of attention.

F. H. Todd

Mr. Ferguson has called attention to a very important point in the operating of submarine cargo ships and tankers – the maintenance of the health and happiness of the crews. This would without question involve owners in a considerable increase in running costs. As mentioned in the paper, the operation of such craft will call for very highly skilled personnel, both for navigational and engineering purposes, and this also will add still further to the costs, and these two factors together may be of importance in the overall economic comparison.

M. F. Gunning (Netherlands United Shipbuilding Bureau)

We have made some fairly detailed investigations into a 20,000-ton tanker with a moderate eccentricity of the ellipse of the midship section with proper diving depth, reasonable strength of outer hull, etc., and we find that we come well above 0.6, closer to 0.65, deadweight ratio. Here, I am sorry, I am very much at loggerheads with my very good friend Mr. Newton.

F. H. Todd

The question of deadweight/displacement ratio has been discussed at length, and Mr. Gunning's figure of 0.65 seems to be very much higher than those quoted by people with experience in the design of naval submarines and those given as the result of a very thorough study of commercial submarines by the Maritime Administration in the U.S., which I have referred to. Mr. Gunning is himself a submarine designer, and I can only leave this point to the experts in this field to sort out!

J. A. Teasdale (Furness Shipbuilding Company, Limited, Billingham)

The largest known military submarine has a displacement of only one-fifth that of the smallest vessel considered in this comprehensive paper and so far no fully commercial submarine has been in service. The author, therefore, is to be congratulated upon his approach to the comparison between surface and submarine merchant vessels and the interesting presentation of the results of his work.

In order to properly compare these results with other works on the same subject a little more information is required on the data used in the study. Firstly, is the displacement referred to in Tables 2, 3, and 6 and Fig. 8 one of surface or submerged condition? Secondly, what form drag allowance has been assumed for the submarines? Various sources put this allowance as high as 15 percent of the skin friction value. Thirdly, the method of determining the deadweight of the submarines seems to be very approximate and perhaps misleading. The deadweight/displacement ratio is unlikely to be constant for a range of displacement of over 100,000 tons and a range of horsepower of more than 200,000 DHP.

Since these designs of submarine tanker are intended to be of relatively high speed compared with conventional submarines and accurate depth control at low speeds is not so important, there should be no necessity for bow diving planes. Even without these it is doubtful whether the appendage allowance would be less than 25 percent of the EHP of the bare hull.

The author states, "If we restrict the draught of the submarine to a figure comparable with that of the equivalent surface tanker, then we are forced into accepting a submarine having elliptical sections." The writer would venture to suggest that if ever a submarine tanker project becomes fact, then the practical design is likely to have a substantial parallel body of rectangular section with radiused corners. The ends, of course, would be as streamlined as possible.

R. Brard (Bassin d'Essais des Carènes, Paris)

Undoubtedly, the question that Dr. Todd has chosen for this Symposium is an interesting one. Numerous papers have already been written on this subject, that is, a consequence of the promises of atomic propulsion. But the problem of submarines, cargo ships, and tankers is quite different from that of navy ships and there is no evidence that the excellent navy solution is excellent for merchant marines. Dr. Todd made a very acute analysis of the various parts of the problem. He examined them not only from a hydrodynamical point of view, but also from others that are to be considered, and particularly those of the operating problems, terminal problems, and economical problems. I think that the values of the main parameters on which Dr. Todd grounds his analysis, should not give rise to discussion, but in a final synthesis, the weights of each aspect could be somewhat subjective. The conclusion of Dr. Todd seems, however, prudent and full of sense. Many studies are necessary before submarine cargo ships and tankers become practical, but those concerned with this question will find in Dr. Todd's reflections many very useful materials.

F. H. Todd

I am grateful to Admiral Brard for his remarks, and agree completely with his opinion that military and commercial submarines are two quite different propositions. It was my principal aim to give sufficient hydrodynamic data covering a variety of sizes of submarines for anyone studying the subject to make his own power estimates and draw his own conclusions. As power is only one of many factors, however, I did endeavour to call attention to other features in such ships, and, as Admiral Brard says, the relative importance of each of these will vary from ship to ship according to the purpose it is to serve.

In conclusion, I would like to make a few remarks on the philosophy of the theme of this symposium – high performance ships. I have tried to show in the paper that the naval architect and naval scientist have long been aware of the possibilities – and problems – of using submarines for commercial purposes, and how they have to a large extent been waiting for a propulsion plant independent of atmospheric air. From time to time – and indeed in the introductory proceedings of this conference – comments are directed against us to the effect that we have only increased the speed of ships twofold in a hundred years, whereas our aerodynamic friends have done it tenfold in fifty years. I would like to suggest, nevertheless, that we have made some progress in that time – from the old SAVANNAH to the new SAVANNAH in a hundred years seems quite a step, as does that from the old Cunard BRITANNIA of 1840 to the QUEEN ELIZABETH of 1940. As a naval architect and scientist, I feel that we have not altogether failed in developing our science.

One of the great problems from which we have always suffered, and which I have tried to bring out in the paper, is the continual insistence in our particular art or science, whichever you like to call it, that ships must always pay for themselves in the economic sense. This, I think, is where our aeronautical friends have had a terrific advantage. We have striven for years to get just one research ship of our own on which to carry out the many full-scale experiments necessary for the progress of our science, but to no avail. The aeronautical engineer designs an aircraft, and builds one, two, three, or more prototypes for development testing, and is undeterred if some of these, and many millions of pounds, go up in smoke in the process. I believe that if we were given similar opportunities in the way of government support for research and development, and if our steps were not continually dogged by this attitude that every ship built must be a commercial success, we would make a great deal faster progress.

* * *