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Sir FREDERICK J. BRAMWELL, F.R.S., President,
in the Chair.

“Forms of Ships.”

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As it was the object of the Council in instituting these Thursday lectures to bring before the Institution not such mere summaries of subjects as could be readily compiled from books, but rather such discourses as would embody the results of the personal investigations and experiences of those who were charged with their preparation, I need offer no apology for the form which I propose to give to the present Lecture. It will not be either possible or desirable to avoid reference to some well-known principles and familiar facts, or to keep out of view the experiments of others; but these will be referred to only for the purpose of facilitating the discussion of the forms of ships from the points of view from which I intend to regard the subject.

As I desire this evening, in the first place, to bring into prominence the doctrine—as yet but imperfectly realized—that the form of a ship should be very largely influenced by the weight of the materials which enter into its construction, and vary in amount with the extent of the ship's surface, I will first ask my audience to consider for a few moments one of the simplest cases of a floating body adapted for propulsion which can well be imagined. This is the case of a body formed, as we may suppose it to be, out of a smooth sea, by the solidification—as for example, by freezing—of an envelope of water enclosing within its outer surface the required displacement of the proposed ship. It is obvious that, if we simply desire a vessel of a given displacement, say for instance, one of 6,000 tons, we shall have an infinity of forms to select from. We may, for example, imagine our vessel to be excessively long and narrow, say a mile long, a couple of feet wide, and twenty feet deep; or we may imagine her to be of the same depth, but of a circular form 120 feet in diameter; but we may also, and with much more regard to ordinary experience, imagine her of dimensions and form very different from, and lying some-

where between, these extreme cases. From the most recently established, and now generally accepted, laws of fluid-resistance, we may at once infer that the ice-ship a mile long, with any ordinary roughness of the ice-surface, would, if moved through the water at high speed, be subject to the resistance of enormous surface-friction while performing next to no wave-making and eddy-making work; we may as readily infer that the circular ice-ship of 120 feet diameter would, at like speed, be subjected to enormous resistances due to wave-making and eddy-making, while her surface-friction would be comparatively small. Between the extreme forms suggested, there will be an indefinite number of forms of equal displacement, but of varying dimensions, and it is but reasonable to suppose that among these there will be one in which the proportions of the elements of resistance just adverted to are so adjusted that the aggregate resistance will be the least possible for the speed to be attained. What this "form of least resistance" in water at that speed may be, it is no part of my present intention to inquire, for, as will presently appear, it is not a form suitable for practical adoption in ships. There was a time, it is true, when the search for an abstract "form of least resistance" was a familiar pursuit of the designers of ships; and it is not impossible that I might have myself regarded it with more respect, but for the circumstance that I have had much to do with the designing of armour-plated vessels of war, and that is a branch of naval construction of much too concrete and ponderous a character to admit of any dalliance with abstract or fancy forms.

Let us, nevertheless, suppose for a moment that, either by an act of supreme science, or by a freak of fortune, we have secured that form and those dimensions for our ice-ship which, while giving us our displacement of 6000 tons, admits of the desired speed being attained with the least resistance, and, therefore, with the minimum amount of propelling power. The thickness of our ice-skin may be anything we please (neglecting the difference of specific gravity in ice and water), without at all disturbing the conditions of our problem; we will take it to be one inch thick. But now let us imagine that we have to pass from this fragile ice-hull to a hull of steel, and it is obvious that our conditions of equilibrium will disappear, and the excess of weight of the steel hull, as compared with the hull of ice, will sink the ship. In order to induce it to float, we must hasten to depart from the form of least resistance, and bend our steel skin into a different form, which must be such as to embrace within its outer surface a displacement equal to the weight of the steel hull, plus the

weight of the contained water, which weight of contained water we will suppose to remain unaltered, and to constitute the load carried by the ship. The new form of the ship must clearly be such as will comprise within its outer surface a larger volume than before, and this practically involves a decrease of length and an increase of breadth, if the depth remain the same.

Similarly, if our steel ship were required to be of a greater uniform thickness, it is plain that we should then be driven to a still shorter and broader hull, and so on until we came to a circular ship. That form once reached, and the vessel with a given thickness of skin and its given load of water on board, just floating, it is obvious that we should have been driven very far indeed from the form of least resistance, and should have been so driven solely by successive increases of thickness and weight of hull.

Thus far we have considered the variations of form imposed upon us by these increases in thickness and weight of hull, subject only to the necessity of floating a given load; and it is pretty obvious that at every step we have increased the resistance of the hull to forward motion, and have reduced the speed which would be imparted to the ship by the exertion of a given propelling force, simultaneously increasing, of course, the amount of force requisite if the original speed is to be sustained throughout. If we now introduce the idea of the ship carrying in each case its own propelling machinery as part of its load, it is obvious that if we presume the speed to have been always the same, the weight of that machinery must have been increased at each step of the process, and the remaining available load therefore proportionately reduced. A little consideration will show that, in keeping up that speed, the whole load-carrying power of the hull will have been absorbed by the machinery long before the circular form is reached, after which, as the thickness of the hull is increased, the speed must undergo continual reduction.

The foregoing elementary mode of viewing the subject is in itself quite sufficient to establish the fact that there is no such thing as an abstract best form for a ship, apart from the thickness and weight of its structure. In order to further illustrate this, let us consider a specific problem; the following, for example: Let it be our object to produce a ship of the thickest material possible within reasonable limits of size, which shall steam at 14 knots, carrying a deadweight of 1,000 tons, and a coal-supply equal to twice the weight of the machinery requisite to ensure the given speed; and let us assume that the weight of the machinery is to

be $2\frac{1}{2}$ cwt. per indicated HP., and that the draught of water is 24 feet in all cases. In order to obtain at first some general guidance as to the form and proportions which it is desirable to adopt, we will take the Admiralty displacement formula,

$$\text{Constant} = \frac{\text{Speed}^3 \times \text{Displacement}^{\frac{2}{3}}}{\text{Ind. HP.}}$$

as sufficiently approximate to the truth for our purpose, and select from the records of ships which have been tried, the constants of performance of a fine-lined ship, a medium ship, and a very full ship, these being respectively, say, 230, 160, and 80. A ship must be of very full form indeed to have so low a constant as 80 at 14 knots speed, but I take it as an extreme case, and for the sake of obtaining a contrast. We will further assume for our purpose—as the object in view is not quantitative, but only illustrative—that the same constant holds in each case for all sizes of ships of similar form. The following Table gives the results of calculations made upon ships of ordinary forms, the whole weight of hull in each case being represented in inches of uniform thickness of shell-plating. For the sake of simplicity, I have dealt with the under-water part of the ship only, and have assumed that the weight of the hull above water is so light as to be left out of consideration.

TABLE I.—SPEED 14 KNOTS.

Thickness of Hull in Inches.	Fine Ship.	Medium Ship.	Full Ship.
	$S^3 D^{\frac{2}{3}}$ I. HP. = 230.	$S^3 D^{\frac{2}{3}}$ I. HP. = 160.	$S^3 D^{\frac{2}{3}}$ I. HP. = 80.
	Displacement.	Displacement.	Displacement.
5	Tons. 3,300	Tons. 3,600	Tons. 8,500
6	3,900	4,100	9,700
7	4,700	4,800	11,100
8	5,700	5,600	13,000
9	7,200	6,600	15,200
10	9,200	7,800	18,000
11	12,400	9,400	21,500
12	17,200	11,400	26,000
13	24,000	14,000	31,400
14	37,300	17,400	37,800
15	63,700	22,000	46,500

These results are shown graphically in Figs. 1 and 2, Plate 6, of which Fig. 2 is part of Fig. 1, with the scale of displacement increased. From the Table and diagrams we see at once that, throughout the whole range of the thicknesses from 8 inches upwards, the ship of medium form is smaller, and should therefore be preferred to either the fine or the full ship, if size and first-cost alone had to be considered. But as it is obvious that the shorter and smaller ship will, for any given displacement, require greater steam-power than the finer and larger ship, the question will arise, at what point will the ships present equal advantages. In determining this, we clearly shall have to decide for ourselves where to draw the line between a saving in first-cost and a saving in fuel-expenditure. It is unnecessary to attempt this here; the more so as we shall, as the weight of the hull increases, sooner or later reach a point at which the short bluff ship will be driven at the given speed with no more power than the long fine ship requires, owing to the former being of so much less size than the latter. For the moment, however, I wish to neglect the question of steam-power and fuel-expenditure, and point out the relation that exists between the different types of ship as regards the size requisite for constructing hulls of equal mean thickness, and capable of steaming at the 14 knots with the given load. As compared with the fine ship, the medium ship is inferior in this respect at thicknesses below 7 inches, and the fine-lined ship therefore shows to advantage at that end of the scale, as was to be expected. They are about equal for a 7-inch hull, but for hulls above 7 inches the advantage is with the medium ship, and increases rapidly with further increase of thickness. For a hull 12 inches thick, while the fine ship requires a tonnage (displacement) of 17,200, in order to accomplish the object, and the full ship requires about 26,000 tons, the medium ship fulfils the condition with 11,400 tons. Were a hull of 14 inches mean thickness required, the medium ship would satisfy the condition on less than 18,000 tons, while both the fine and the full ship would each require to be of more than 37,000 tons, or more than double the size. At about this tonnage the ship of very bad form (with constant of 80 only) has overtaken the ship of fine form, and now begins to gain an ever-increasing advantage over her, the amount of steam-power required being still left out of consideration. It is unnecessary to pursue the comparison further, it being completely manifest that a fine form of ship which is desirable when the hull is lightly constructed, may be a very bad form indeed for a very heavily-built ship; and *vice versâ*. It is equally plain that,

while the introduction of steel should tend to increase the fineness of the lines of properly-designed vessels, the use of armour should have a contrary result. The practical importance of this principle has been illustrated in the Royal Navy by the substitution, as will presently be seen, of the "Bellerophon," "Hercules," "Sultan," and other succeeding short ironclads, for the long fine-lined ships of the "Agincourt" type which preceded them.

It now becomes necessary to take into consideration the amount of power required for propelling the respective types of ships. It would not be a very judicious thing in most cases to save moderately in the size and cost of the ship itself, when that saving would entail a large and more or less continuous increase in the cost of the fuel consumed. This consideration is not of such great importance in the case of war-ships, which are but very seldom driven at their full speed; but it is of supreme importance in all ships which are intended to sustain their full speeds for long periods. Keeping this in view, let us now see how the respective types of ships, chosen for our illustrations, are related to each other. The accompanying Table II., shows the relation between the thicknesses of hull, and the horse-power required for driving the corresponding ships at 14 knots. Of course no Table is necessary to show us that for any given displacement the steam-power required for propulsion at the given speed will be in inverse proportion to their constants. For example, the medium ship will only require, per ton of displacement, one-half the steam-power of the full ship, because her constant is double that of the latter. Similarly the horse-power requisite for the full ship will be to that required for the fine ship as 230 : 80, or nearly three times as much. But employing the Tables for our purpose, we shall see that within the limits of the Tables, the full ship never becomes unquestionably entitled to preference, because, although for a 15-inch hull, she would require to be of only 46,500 tons displacement, against the 63,700 tons of the fine ship, she would nevertheless require such an enormous excess of power—44,400 I.H.P. as against the 18,400 of the fine ship—that the preference would scarcely be accorded to her. For the 15-inch hull the medium ship is indisputably preferable to either of the others, being of only half the size of the full ship, one-third that of the fine ship, and requiring only 13,500 I.H.P. against the 18,400 and 44,400 respectively. Even for a 13-inch ship the medium form is unquestionably the best, requiring only the same steam power as the fine ship, and being but $\frac{7}{12}$ of her tonnage.

TABLE II.—SPEED 14 KNOTS.

Thickness of Hull in Inches.	Fine Ship.		Medium Ship.		Full Ship.	
	Displacement.	I. HP.	Displacement.	I. HP.	Displacement.	I. HP.
	Tons.		Tons.		Tons.	
5	3,300	2,700	3,600	4,000	8,500	14,400
6	3,900	3,000	4,100	4,400	9,700	15,800
7	4,700	3,300	4,800	4,850	11,100	17,400
8	5,700	3,700	5,600	5,350	13,000	19,200
9	7,200	4,300	6,600	6,000	15,200	21,200
10	9,200	5,200	7,800	6,700	18,000	23,400
11	12,400	6,400	9,400	7,600	21,500	26,400
12	17,200	8,000	11,400	8,700	26,000	30,100
13	24,000	10,100	14,000	10,000	31,400	34,200
14	37,300	13,400	17,400	11,600	37,800	38,700
15	63,700	18,400	22,000	13,500	46,500	44,400

In order to illustrate the relations that arise between the medium and the full types at enormous dimensions, the fine type having dropped out of the running, I may say that for 1,000,000 tons of displacement the medium ship would be 23·18 inches thick, and would require 171,500 I.H.P. (for the 14 knots), while the full ship would be 22·8 inches thick, and would require double that power.

The principal object which I have in view in unfolding and inviting careful attention to this aspect of the form-of-ship question is to show how necessary it is to be on our guard against a misuse of Constants of Performance. There was a time, and not very long ago, when the opinions formed of the respective merits of ships, even by many professional men, were based almost entirely, or quite entirely, upon comparisons of these constants. Without any regard to their character in other respects, ships were praised or blamed just in proportion to the value ascertained by putting their midship section, displacement, and indicated horse-power into the Admiralty formulas, or some other formula of the kind. The Table that I have given makes the error of this proceeding apparent. The ship with the constant of 160 is, at every point in the Table above 5,000 tons, as we saw, superior in thickness

and strength to the ship of equal displacement with the constant of 230; or if ships of equal strengths be compared, the advantages of the ship with the lower constant becomes immense in the case of the heaviest hulls recorded there. If the form associated with the higher constant 230 (which is that of the fast unarmoured frigate "Shah") were preserved in a ship with a uniform thickness of side and bottom of 15 inches, she would require to be of 63,700 tons displacement to carry the weight and steam the speed required; whereas if the bluffer form associated with the inferior constant is accepted, a ship of 22,000 tons would perform the same service.

Table III. has been worked out with different displacement constants, viz., 250 for the fine ship, 175 for the medium ship, and 130 for the full ship, a given weight (1000 tons), being carried in each case in addition to the steam machinery. The present thickness of the ship's hull varies from 25 inches up to 500. It will be seen from this Table that while the steam-powers requisite for the fine ship, and the medium ship respectively, roughly agree pretty well throughout, the advantage in point of size and first cost are always with the medium ship, and enormously so as the thickness of the hull is increased. Further, the full ship is superior to both the others; for a hull of 50 inches thick, she requires both less size and less power than the medium ship, and although of somewhat greater I.H.P. than the fine ship, is of but little more than half the size. For 200 inches and upwards, the short blunt ship, giving a constant of only 130 at 14 knots, is cheaper both in first cost and in working cost than either of the finer ships with higher constants.

TABLE III.

Thickness of Hull in inches.	Fine Ship.		Medium Ship.		Full Ship.	
	Displacement.	I. HP.	Displacement.	I. HP.	Displacement.	I. HP.
25	Tons. 17,000	7,400	Tons. 10,000	6,800	Tons. 12,800	11,000
50	50,000	15,000	28,000	19,200	27,000	18,000
102	200,000	37,800	116,000	37,000	82,000	51,000
201	775,000	93,500	500,000	99,700	280,000	89,300
302	1,638,000	153,000	1,000,000	157,000	573,800	145,000
402	2,800,000	217,000	1,700,000	225,000	969,500	215,000
510	..	..	2,750,000	305,000	1,625,000	276,000

It must not be thought that owing to the large thicknesses and tonnages here mentioned, the principles involved may be without any practical application of importance to ships of ordinary kind. The ships of small displacement in the Tables are significantly and seriously affected by it, although the advantages and disadvantages are not in the same proportion, or even associated with the same form, in these thinner and smaller ships as in the large ones.

Having now set before you some of those considerations which appear to me of very great importance in determining the forms of all such ships as, from whatever cause, have the weights carried by them varying considerably with their dimensions and proportions, and more especially with their surfaces—whether those weights so carried either form part of them, or are otherwise borne by them—I wish to point out that a due regard to these considerations is very likely to bring upon the best of designs the censure of those who think but superficially upon the subject. I shall be excused if in this connection I derive an illustration from my own practice and experience. The first iron-built iron-clad ship built from my design was the “Bellerophon,” already referred to, and she was constructed with a primary regard to those considerations, and although more than successful in every particular, I believe, drew upon herself no little complaint on the ground that her “constants of performance” were much inferior, as they undoubtedly were, and were bound to be, to those of the ships which she was built to supersede, viz., the ships of the “Minotaur” type. There were great differences between the “Bellerophon” and “Minotaur” in armament, armour,¹ &c., but the novel ship was not found fault with on those grounds, as, in point of fact, she carried thicker armour, much heavier guns, was very much handier, and so forth.

For the purposes of the comparison which I am about to make—and which, as you will see, is made solely with the object of illustrating a principle—we may take it for granted that, differing greatly in size as they did, they were about equal in their offensive and defensive powers. But while the “Minotaur” was made 400 feet long in order to obtain fineness of waterlines, the “Bellerophon” was made only 300 feet long, my view being that it was better, when building an armoured hull, and therefore a hull

¹ The “Bellerophon” had the thicker armour of the two, but it was more concentrated. Had this concentration not existed, the average strength of side would have been nearly identical.

of great average weight per square foot of surface, to accept shorter and bluffer waterlines, and give the two ships about equal power. In Table IV. I have brought together the principal particulars of the two ships.

TABLE IV.

	"Bellerophon."	"Minotaur."
Length	300 feet	400 feet.
Breadth	56 „ 1 inch	59 „ 4 $\frac{3}{4}$ inches.
Draught of water	26 „ 7 inches	26 „
Midship section	1,330 square feet	1,300 square feet.
Displacement	7,550 tons	10,000 tons.
Indicated HP.	6,199	6,193
Speed in knots	14.05	14.16
S ³ D $\frac{3}{4}$		
I.H.P.	172	213
S ³ Mid. Sec.		
I.H.P.	595	596
Cost	£342,701	£456,830

On looking superficially at this Table one's first impulse would be to say that we have in the "Bellerophon" a very inferior steamship to the "Minotaur"; for, being a very much smaller ship, she required about the same steam-power to drive her at about the same speed. But now let us consider the matter more closely. The two ships are of equal value, we will presume, for their intended purpose, but the one has cost, as we see, £114,000 more than the other. It would be easy, no doubt, to improve upon the form of the "Bellerophon" in so far as the Displacement Constant of performance is concerned, but as the two ships do the same work, and burn only the same fuel, while the shorter ship is immensely the handier of the two, it would surely be not a very wise proceeding to spend the extra £114,000 by preferring the big ship with the high Displacement Constant to the other. When the "Bellerophon" was tried at the measured mile at Portsmouth, owing to her shortness and fulness, and the certainty of her being a bad performer from the steam-constant point of view, all the authorities at Portsmouth decided in their own minds that she never could steam at more than 11 knots. As a matter of fact, she steamed at 12 $\frac{1}{4}$ knots with half her power, and exceeded 14 knots with full power. That involved a revolution in the naval design of the country, because, as you are probably aware, there never has been another ship yet built—an iron-clad ship—of the proportions of the "Minotaur" and "Agincourt" class, and probably there never will be.

TABLE V.

Ships.	Length.		Breadth.		Length Breadth.	Displace- ment.	I. HP.	Speed Knots.
	Ft.	In.	Ft.	In.		Tons.	Tons.	Per hour.
New armour-clads .	340	0	70	0	4·86	10,470	10,000	17·0
New belted cruisers	300	0	56	0	5·36	5,000	8,500	18·0
New "Scout" . .	225	0	36	0	6·25	1,600	3,500	16·0
"Oregon" . . .	520	0	54	0	9·63	11,270	12,380	20·0
"Umbria" . . .	500	0	57	0	8·77	12,000	12,500	21·0
"Aurania" . . .	470	0	57	0	8·25	11,000	10,000	18·7
"America" . . .	440	0	51	0	8·63	9,500	9,000	18·25

Before proceeding further, I may be allowed to direct attention, in illustration of the remark that I have just made, to this Table (Table V.). I have here brought together about half-a-dozen ships of quite recent character, to show you in what manner this principle is now recognized. Here are some of the fast Atlantic steam hotels: the "Oregon," the "Umbria," the "Aurania," and the "America," and you see their proportions of length to breadth; the "Oregon," 9·6; the "Umbria," 8·7; the "Aurania," 8·2; the "America," 8·6. The Admiralty have ordered some new iron-clad ships, which also go at the high speed here given. The armour-clads are to go at 17 knots. Look at the proportions: 4·8 is the proportion of length to breadth in the new 17-knot armour-clads. And if you take the belted cruisers, which are to go at 18 knots (fortunately, by the force of a little outside pressure, we have got them up to that), you will see the very moderate proportion of 5·3. My own opinion is that they are right enough in those proportions. But perhaps a more remarkable case is to be found in the little vessel, the new "Scout": it is a torpedo-vessel, and at the same time carries armament, and she is to go at 16 knots. I do not know why the speed is only 16 knots, because the new ships building for all other Governments are going at 18 and 19 knots; but with 16-knots speed in an extremely thin ship, the proportion is only 6·25. I cannot speak with the same approval of that, from the speed point of view, as I do of the others, but I will not doubt that, for considerations of handiness and so on, the Admiralty constructors are right in keeping the proportion down as they have done in that case.

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I have already pointed out that if you follow these views and depart from the form of least resistance, which has a fascination for some minds, you are very liable to incur considerable criticism and censure. There are people who cannot get away from formulas which express in their judgment the value of ships; and it is most natural that in cases of steam performance they should be regulated by the indications of a formula. But I do hope I have sufficiently justified my conviction, which is this: that the merit of a naval constructor may often be that he cuts a bad figure in constants of steam performance: that fact may show that he has kept more important objects fully in view.

In making the preceding comparisons between fine, medium and full forms of ships I have employed the Admiralty Displacement Constant of performance, as you know; and it will be obvious to you that whatever may be the measure of the error which that formula involves it can hardly be such as to do more than modify in some degree those comparisons. If we possessed a simple formula based upon a general and correct law of aggregate resistance—at present we have no such formula—we should doubtless be able to deduce from it the same lesson as that which I have drawn from the Table previously given.

The next consideration to which I invite attention is the larger extent to which the breadth and midship section of a vessel, in relation to her other dimensions, may be carried without the sacrifice of the steaming performance. Both the Mercantile and the Royal Navies have of late furnished repeated illustrations of this. The instance which I have selected is that of a contrast between two gunboats of comparatively recent date, viz., the “Medway” and the “Snake,” the particulars of which are set forth in the accompanying Table VI., and in Fig. 3, Plate 6:—

TABLE VI.

	River Gun-boat “Medway.”	Gun-boat “Snake.”
Length	110 feet	160 feet.
Breadth	34 „	25 „ 4 inches.
Proportion of length to breadth	3·24	6·32
Mean draught of water . . .	5 feet 8 inches	9 feet 7 „
Area of midship section . .	172 square feet	179 square feet.
Displacement	350 tons	482 tons.
Indicated HP.	314	460
Speed in knots	9·5	10·3
S ³ Mid. Sec.	472	425·8
I.H.P.		
S ³ D ₃		
I.H.P.	136	146·2

In this comparison the "Snake" gets some advantages from the increased size (being about one-third larger) and almost double draught of water. The much smaller and shallower boat has nearly an equal section owing to her excessive breadth, and nevertheless, with a length only $3\frac{1}{4}$ times her breadth, exhibits, at a speed not very much below that of the other, a steam performance on the whole decidedly superior to the other's. I may mention that when about to build the "Medway" class of river gunboat the Admiralty constructors at first thought of making them 110 feet long, but of only 26 feet in breadth. A doubt arising in their minds upon the subject, the late Mr. William Froude—a man whose memory will ever be respected in connection with this subject—performed some experiments upon models which satisfied the Admiralty officers that a substantial gain, rather than a loss, would result from giving them much greater beam, and his anticipation was certainly verified.

Another and more striking instance of the advantage of combining great breadth and section with fine water-lines as a means of obtaining a given displacement under certain circumstances, is shown in another experiment conducted by the late Mr. Froude. This experiment was described by his son, Mr. R. E. Froude, in a Paper appended to the Report of the Inquiry into the condition of H.M.S. "Inflexible." H.M.S. "Ajax" is a vessel of the "Inflexible" type, but smaller, and the object of the experiment was to ascertain what would have been the effect upon the speed of those ships had their beams been greatly increased for the purpose of increasing their stability, their midship sections being also much increased, but their lengths, draught of water, and displacements, all remaining unaltered in each case. A model of the "Ajax" on the scale of about $\frac{1}{32}$ of the full size was made, and for comparison with it a model of an imaginary ship of equal displacement on the same scale. The dimensions of the models were as follows :—

	"Ajax" Model.	Imaginary Ship Model.
Length	7.78 feet	7.78 feet.
Breadth	1.83 foot	2.48 "
Draught of water (mean) .	0.632 "	0.632 foot
Displacement (in fresh water)	384 lbs.	385 lbs.
Area of midship section . .	152 square inches.	196 square inches.

I am not able to give the diagrams showing the correct forms of these models, but you will be able to conceive a general idea of them from the figures just given, aided by Fig. 4, Plate 6, in which the continuous line represents a water-line of the "Ajax" model

at half the immersed depth, and the broken line represents approximately a water-line similarly situated on the model of the imaginary ship. These models were towed in the Torquay water-trough or tank with the following results, as transferred to more than the full-size scale, giving the two designs the same displacements, or thereabout :—

TABLE VII.

Type of Ship.	Length in Feet.	Beam in Feet.	Mean Draught in Feet.	Midship Section in Square Feet.	Displace- ment in Tons.	Resistance in Tons.		
						12 Knots.	13 Knots.	14 Knots.
Enlarged "Ajax"	320	75·4	26	1,788	12,240	22·2	27·8	38·1
Imaginary ship	320	102·1	26	2,306	12,260	21·8	26·4	32·1

It will be seen from this Table not only that the ship of much greater beam and midship section is subject to less resistance than the other, but that her resistance increases with increase of speed at a lower rate than that of the other vessel.

It is almost incumbent upon me now to notice, however briefly, the position in which we at present stand as regards those doctrines of fluid resistance, &c., to which I have but very lightly adverted in what has gone before. And marvellous indeed are the transformations and extensions which some of those doctrines have undergone during the life-time of many of us now present—marvellous not only in their results, but likewise in the modes and processes of thought by which they have been reached. For it is to be observed, that the nature of the resistances which water opposes to the motions of ships have really been arrived at by aid of very abstract considerations indeed, viz., those dealing with the imaginary movements of those perfect fluids which are themselves imaginary. A perfect fluid would be one of which the particles were free to move among each other, or past an immersed surface, without friction. Such a fluid, if of indefinite extent, would undergo increases and diminutions of pressure in places on a deeply-immersed solid body being moved from rest within it, and would continue to experience differences of pressure all the time the body advanced with accelerated motion. It would respond to these differences of pressure by imparting velocity to certain of its own particles which lay in or near to the path of the advancing body. These particles, moving with varying velocity on lines now called stream lines, would close in behind the disturbing body as it passed onward, coming to rest when excess of

pressure ceased to operate upon them. If now we suppose the body to advance with uniform velocity in this perfect fluid, the positive and negative pressures upon it will, as we know by the laws of fluid motion, be precisely equal; therefore no loss of energy will result; no inducement to the body to stop or slacken its progress will exist; and it will move steadily forward without any reduction of speed whatever. Bring such a body from the deep interior to the surface of a perfect fluid, however, and this state of things will no longer exist. The vertical reactions of the water from above the body will be lost; an upward movement of the parts of the fluid will take place; this upward movement will result in the formation of waves; gravitation will begin to level these waves as soon as they are created; and energy will consequently be lost. Hence, even were water a perfect fluid, energy would have to be expended upon a floating body to keep it moving at a uniform speed, and this energy would of course be the exact equivalent of the energy expended by what would be called the fluid resistance. Here we have, therefore, in the production of waves at the surface, a primary element of resistance, which clearly will not be diminished by the substitution of water for a perfect fluid. With this substitution, on the contrary, there will enter a second element of resistance, viz., that due to the friction and viscosity of the water, which oppose every movement of the particles, whether that movement be among the particles themselves or past the surface of the moving body. And there is a third element of resistance which will enter at the same time, viz., that due to the energy expended upon the production of eddies by abrupt interferences with the general movements of the body and of the water, should such exist. These eddies would obviously not exist in a perfect fluid of indefinite extent in all directions, for there no such loss of energy could take place. I need hardly say that in the foregoing brief account of the now-received doctrine of the elements of resistance, I have merely summarised the views arrived at by the combined labours of Stokes, Rankine, Froude, and others.

In dealing with actual ships, not only have the foregoing elements of resistance to be considered, but account has also to be taken of other interferences with the performances of ships, some of which have the effect of virtually adding to the resistance experienced, while others may be more properly regarded as affecting the efficiency of the forces which propel the ship.

Of the former class I will select for mention that effect of a steam-propeller which retards or prevents the stream-lines of the

fluid from duly closing in upon the run or after body of the ship, and contributing as much as they would otherwise contribute to the advance of the ship. In a perfect fluid of indefinite extent, and in the case of a ship moving with uniform velocity, the energy expended on the bow or fore-body of the ship would be fully restored by the closing in of the fluid (moving in stream lines) upon the stern or after body. But this closing in of the fluid upon the after part is interfered with in the case of a ship propelled by the paddle or screw, not only by the viscosity and friction of the fluid, &c., but also by the fact that the propeller more especially if it be a screw, takes direct effect in driving astern the water which is seeking to follow and to close upon the ship. If the propeller, even where it is a screw-propeller, were placed sufficiently astern of the ship to allow the stream lines—such as they are in the case of a viscous and imperfect fluid like water—to complete their return to parallelism, so to speak, the propeller would be responsible for those losses only which were due to its own imperfections. But placed where it usually is, it is responsible likewise for breaking in upon the stream-line action of the water, thus diverting it more or less from its natural embrace of the ship, and adding much more largely than many might suppose to the balance of resistance imposed upon her. In cases, not a few, the screw propeller has been placed so near to the stern-post, or close to so broad a stern-post in wood ships, or behind so full a run in ships badly formed for their speed, that the usual excess of resistance due to the cause under consideration has been still further aggravated to the great injury of the steam performance. This injurious effect of the screw in augmenting the resistance by reducing the pressure on the stern was subjected to experimental investigation by the late Mr. Froude, who adopted the device of running a screw just astern of a model by independent means, and measuring the augmentation of resistance thus occasioned. His experiments showed that “with ships of ordinary form, the augment is from 40 to 50 per cent. of the ship’s net resistance.”¹ “I think,” said Mr. Froude, “if the screw were placed something like a quarter of the ship’s beam astern of the ship, it would be a great advantage, and probably would reduce the loss to 8 or 10 per cent.” He also said, “It is a most remarkable thing to find at how great a distance it produces a sensible increase of resistance.” . . . “I found that when the screw was removed to about one-third of the ship’s

¹ Trans. Inst. Naval Architects, vol. xvii., pp. 174, 180.

breadth from the stern the maximum effect of advantage was produced, but even then there was some little augmentation of resistance." So far as I am aware, there have been no experiments serving to show to what extent this cause of augmentation of the effective resistance is relieved by increased fineness in the ship's run; but the very nature of it is such as to suggest that every approach to fulness in the after water-lines must be objectionable, and should be avoided throughout the whole immersed depths of the stern—a point well worthy of the naval designer's attention in these days of high speeds.

Another point of considerable importance to the steaming capabilities of a ship, as affecting the effective resistance which she experiences, is the relation of her form to the wave-system which she sets up when driven at a uniform speed in comparatively smooth water. This is a subject of great importance, but one which is as yet so imperfectly developed that it can hardly be regarded as playing any active part in the determination of the forms of ships, although there are some constructors who are doubtless giving it attention. It is well known to most persons connected or acquainted with the mercantile marine, that very diverse results have been experienced by those who have lengthened steamships. In some cases a considerable addition to the length of a ship's middle or parallel body has been made with great advantage to her steaming performances; in other cases, the results have been disappointing. No formula known at the time, and I believe no formula known at present, offers any explanation of these discrepancies. But here again the late Mr. Froude stepped in, and, although he did not furnish, and could not have furnished quantitative solutions of the problem, or devise formulas for such solutions, he certainly opened up a path which we may hope will one day lead to them, especially as his mantle has fallen upon a son, Mr. R. E. Froude, who is following up his father's labours with surprising ability and success. And as it is impossible to do any sort of justice to this subject without frequent references to the experimental labours of the Froudes at Torquay, it may, perhaps, be permitted me to claim a vital, although but a remote interest in those labours, by quoting a sentence from a biographical notice of my deceased friend Froude, the writer of which says:—"Mr. E. J. Reed, then Chief Constructor of the Navy, saw the importance of encouraging a method of thus economically ascertaining the resistance of ships; and having visited Mr. Froude, and seen the experimental results, he requested Mr. Froude to put into a definite proposal his

willingness to conduct a series of experiments for the Admiralty.”¹ Having thus initiated, as it were, that long course of Admiralty experiments, by means of which the Froudes have endowed the civil engineer and naval constructor with such priceless scientific results, I trust you will permit me to make such frequent reference thereto as I may find necessary.

The further element of resistance now to be mentioned lies beyond the wave-making element of resistance already explained, and depends upon the waves produced by the bow coming into such relations with the stern and with the stern-wave, as to cause either an additional resistance, or a forward force which partly counterbalances the resistance originally due to their creation. Whether an augmentation or a diminution of resistance is thus brought about depends, with given entrances and runs, upon the distance at which these are kept apart by various lengths of parallel, or nearly parallel, middle body. If the ship is so formed that the wave produced at the bow remains large enough on reaching the stern to produce the effect here spoken of, then if the crest of the wave happens to fall at a certain distance forward of the stern-post, the effect will be to assist in the propulsion of the ship; if the hollow fall at that place, the opposite effect will occur, and the resistance will be augmented. The first idea was that these results were due to increases or decreases of hydrostatical pressure upon the after body of the ship; but the stream-line theory, indeed, the theory of waves itself, is scarcely consistent with this conception of the matter; nor is it any more consistent with either theory to suppose that the bow-created wave can at one and the same time exert its energy upon the stern in forward effect, and leave the stern-wave unaffected. The very existence of the stern-wave implies the absence of the bow-wave energy, and if the latter were fully restored, the reason for the former would be gone. Mr. R. E. Froude has seen this quite clearly. He has said,² “The bow-wave in being absorbed must do something to the stern-wave;” and his most reasonable suggestion is, that the action of the bow-wave at the stern is that of arresting the formation of the stern-wave—“That, in fact, the function of the afterbody, when advancing into water already in a certain state of wave-motion, is to “swallow up that wave instead of making any of its own.” And he adds, “If so, the placing of the afterbody in the most favour-

¹ Trans. Inst. Naval Architects, vol. xx., p. 266.

² Ibid., vol. xxii., p. 229.

able position in reference to the bow-wave series, has a double benefit: (1) The bow-waves restore their energy, and are absorbed; and (2) in doing so, they prevent the expenditure of energy in making stern-waves."

But whatever may be the correct theory of the matter, the Torquay experiments established in a satisfactory manner that it is highly desirable so to form the ship as to bring the crest of the bow-formed wave into a suitable relation to her stern, a very considerable reduction of net resistance being thus secured. All this presumes, of course, that the *speed* of your ship is defined; for it need hardly be said, that the train of waves set up by a given ship in uniform motion varies with every variation in the speed at which the uniform motion is to take place.

The element of resistance due to eddy-making, which I have mentioned in passing, is of very considerable importance, and its existence has suggested the great desirability of avoiding, as far as possible, everything which can give rise to it. This is especially important in twin-screw ships of high speed, because of the drag of the shaft brackets—sometimes four in number—through the water. All such things should be tapered fore and aft, the fineness of the taper towards the stern being of much importance.

Of the three contributing elements of resistance, that of friction is nearly always the largest in amount. It is regarded as being regulated by the extent of the immersed surface of the ship, the roughness of that surface, and the speed, varying approximately with the square of the speed. Ordinarily it is not dependent upon the form of the immersed body of the ship, although there are doubtless some exceptions to be made to this. For low speeds it usually occasions about $\frac{9}{10}$ of the total resistance, and even at very high speeds exceeds one-half of it. The resistance due to eddy-making is small in ordinary ships, not exceeding one-tenth of the resistance due to friction. The resistance to wave-creating is of much more serious amount, approaching at high speeds to the frictional resistance.

Speaking to professional men I feel that I should be wanting both to you and to myself if, before concluding, I did not express some opinion upon that most important outcome of all ship-questions, viz., their relation to the naval eminence of this country. I have adduced to you several illustrations of the fact that the construction of ships with thick sides—of armoured ships—while imposing upon us great changes of form and proportions, is not by any means necessarily attended by those enormous increases of

dimensions which those might suppose who are familiar only with commercial ships. On the contrary, we have seen, that while long fine-lined ships built of thick armour would require to be of enormous size and power even to float, ships of shorter and fuller forms are vastly more economical, and can be driven at high speeds with much less power. Into the methods and devices by which the extent of armoured surface can be reduced, while remaining ample (while it remains intact) to preserve the buoyancy and stability of the ship, there has not been time to enter. But you will perhaps accept from me the assurance that the resources of science in this respect have not by any means been exhausted, or even seriously drawn upon, as yet. Great impediments to their employment exist, among which I may mention the restrictive influences of our stone docks, and the absence of floating iron docks capable of receiving ships of any required size or form. But all such impediments can be overcome, by the engineer at least, and, so far as we are concerned, there is no difficulty in producing armoured ships of great breadth. We require such ships not only for the purpose of economizing the amount of the armour employed in proportion to the stability and buoyancy protected, but also for the purpose of keeping the ram and the torpedo at an ample distance from the boilers and magazines, which should in fact be protected by an inner citadel, so to speak, well removed from the outer one. All these possibilities of naval development have, however, been abandoned, and for many years past the construction of armoured ships has itself been given up in this country—armoured ships being those which have a sufficient volume protected above water to keep them afloat and from capsizing all the time the armour is unpenetrated. The production of such ships has been left to those foreigners who may care more than we do for power and endurance in battle. But I wish to say that neither true science nor sound engineering has made necessary or sanctioned this surrender. So far is that from being the case, the recent developments of science, as Froude and others have shown, have facilitated, and even invited as sound and beneficial, that very resort to increase of breadth, &c., which the development of the war-ship needed. They have shown us clearly that a combination of practical invulnerability and high speed is perfectly possible. Of course an invulnerable high-speed ship must in these days be a large ship, and size and cost are the bugbears of our politico-naval administration. By the true engineer they are, however, justly regarded as secondary to great and noble objects, among which surely ought to be comprised the naval pre-eminence of our country. At any

rate I maintain that there is no engineering obstacle whatever to England constructing and sending to sea not merely those great and fast but delicate and fragile Atlantic hotels in which the British Navy is now to embark and fight, for the want of anything better, but war-ships, real war-ships, almost as invulnerable as these islands themselves, and capable of bearing the once-proud flag of England boldly into the waters of any enemy whatever.

Sir F. BRAMWELL, President: Gentlemen, your acclamations have forestalled the proposition I was about to make, namely, that we should give our best thanks to the lecturer of this evening. I am sure you will agree with me that the Institution is fortunate in having among its members a gentleman like Sir Edward Reed, competent to deal in the manner in which he has dealt to-night with so important a subject, and done so with a weight of authority which few can equally possess, and none claim to have in greater measure. Notwithstanding the clear manifestation of approval which you have already given, it is Sir Edward Reed's due that there should be on record a formal vote of thanks. I therefore beg leave to propose that the very best thanks of the members are due to Sir Edward Reed for the able and instructive lecture on "Forms of Ships," which he has given us this evening.

Mr. ABERNETHY, Past-President: I have pleasure in seconding the vote of thanks proposed by our President for the very able lecture that we have heard to-night upon a most important part of engineering science—one of the most important perhaps of the present day. I think also it is due to the gentlemen who have delivered the previous lectures that we should return our sincere thanks to them for the very valuable additions they have made to our scientific knowledge.

Sir F. BRAMWELL, President: It is now my duty to ask you, on this the concluding evening, to return your thanks to Mr. Evans, Dr. Pole, Professor Unwin, Sir Charles Hartley, Mr. Stevenson, and the lecturer of this evening, Sir Edward Reed, for having so ably and clearly brought before us the various branches of this session's course of lectures—Hydro-Mechanics—a subject of vast importance to the engineer, and one that has been fortunate in being represented by gentlemen of the rare ability and distinguished position possessed by each of the lecturers, to whom I now ask you to return the sincere and hearty thanks which they so richly merit.

The resolution was unanimously agreed to.

Sir EDWARD REED: Mr. President and Gentlemen—It is my duty

to thank you on behalf of those gentlemen who have lectured on former occasions during the session. I am quite sure that all the members of this Institution, and pre-eminently the members of the Council who are entrusted by your suffrages with the responsibility of managing it, are most anxious to serve you in any way they can, and are very proud to have had the opportunity of delivering their respective lectures. For my part I confess I feel some compunction in having detained you so long a time with a lecture which was necessarily more or less imperfect. I thank you sincerely, however, for the patience and careful attention with which you have listened to me. Although I for one feel that it must be a great tax upon members of the Institution to be required to attend here twice a week, it is on the other hand no tax to those gentlemen who have the honour of being invited by the Council to deliver lectures, but it is a very great privilege, while you are willing to come and listen, for them to do their best to interest you, and to suggest matters for your consideration which they hope will not be without some advantage.