THE GREEK TRIREME

DESIGN AND PROPULSION

BY

J. F. COATES, O.B.E., M.A., C.ENG., F.R.I.N.A., R.C.N.C.

Introduction

The trireme (Greek, *trieres*—three-oared) reached the peak of its evolution in the Mediterranean of the 5th century B.C. That was the time when Xerxes, Emperor of the vast Persian Empire, attacked the small city states of mainland Greece. The crucial battle turned out to be between not the armies but the fleets, at Salamis just west of Athens, in 480 B.C. Salamis is one of the great turning points of history between the emerging Greek democracies of the West and a monolithic Eastern autocracy. The Greeks won. How did they do it?

The answer centres around the capabilities and limitations of the trireme which was the principal warship of the time, and the superior seamanship and tactics of the Greeks. Unfortunately information about these topics in the 5th century is sparse. The ships have been puzzling classicists and archaeologists for a century or more, which is quite understandable because the development of the whole Classical world hinged upon the exercise of sea power as much as anything else.

Three fairly recent events have come together to make it possible to reconstruct a Greek trireme for the first time and fill this gap in history. First, a classicist, John Morrison, has assembled over a working lifetime all known source data about Greek oared ships[1]. Second, a naval constructor, the author, has taken that information as the 'Naval Staff Requirements' for a ship, and developed a design to meet them. Third, a merchant banker, Frank Welsh, resolved to get a trireme built. The three have formed the Greek Trireme Trust and the author is now preparing the design for building with the help of some other retired constructors and Commander Eric McKee R.N. (retired) who is a leading British authority on wooden boat construction.

The design and propulsion of this ancient warship may be of interest to modern naval engineers because, in developing its design to meet the historical 'requirements', it has emerged as a vessel whose performance was as sensitive to space and weight as any modern frigate. Its structure was evidently pared to the bone. Its great length relative to depth of hull demanded the utmost of its longitudinal strength. Its 'engine room' occupied virtually the whole hull and its oarsmen were practiced and skilled freemen, citizens not slaves. Its performance was impressive: with picked crews for urgent missions these vessels maintained 8 knots or more under oars alone for as long as 24 hours. A modern racing shell would do little better—and that only in calm water.

Speed, of itself, was probably no more than a by-product of the agility in manoeuvre essential to success in a fleet ramming contest. The ram was the trireme's main weapon and its purpose was to render enemy ships *hors de combat* by holing them below the water line. Being in all probability unballasted, they did not then sink but became merely waterlogged and useless. Only a few soldiers and archers were carried as secondary armament by the Greeks. It was the Romans who, taking to sea warfare later, and reluctantly, to deal with the Carthaginians, converted sea battles into more of a sword fight after boarding. Their ships, quadriremes, quinqueremes etc., carried large numbers of legionaries and were larger, slower and less interesting. The Greek trireme was therefore at the zenith of the whole evolution of oared warships, from earliest times to their disappearance in the 18th century A.D.

Evolution of the Trireme

That evolution started with 20- and 30-oared ships with oarsmen in a single file on each side of the vessel. Those were the ships of Homeric times, of the Iliad and the Odyssey in the 2nd millenium B.C. They all carried rams. Later, the 50-oared ship, the pentekontor (FIG. 1), appeared with oarsmen in 2 files on each side, to become the principal warship of the Mediterranean for many centuries. Simple dimensional analysis of its performance compared with single file vessels shows what an advance it was, largely through packing more oarsmen into the same length of hull. Its acceleration would have been 10% better and its rate of turning with oars 40% better than the triakontor: it was probably no faster on a straight course and would have been about 50% more expensive. In a ramming battle, however, it is easy to believe that pentekontors gave value for money.

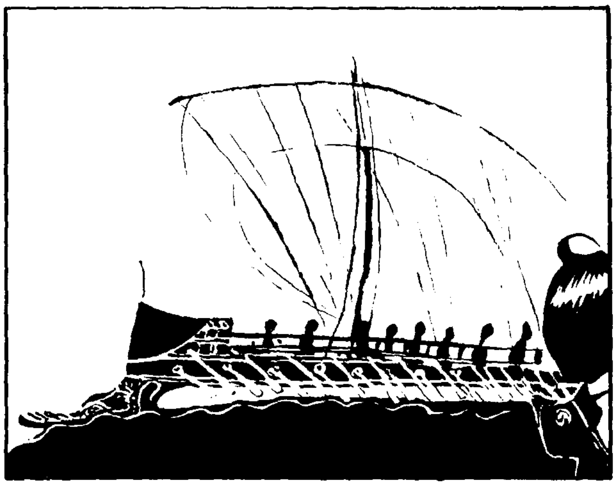


FIG. 1—A PENTEKONTOR, PAINTED ON A BOWL OF THE 6TH CENTURY B.C.
British Museum

The first appearance of the trireme is historically obscure, but it represents the next step in increasing oar thrust per unit length of hull. The pentekontor seems to have been transformed into the trireme by seating an additional file of oarsmen outboard and slightly above the upper file of the pentekontor. The additional files pulled oars pivoting on tholepins mounted on outriggers and the gunwale was raised to that level. Increase in weight of hull and men, as well as a rise in the ship's centre of gravity, would have necessitated more beam on the water line to retain adequate stability. The increase in depth of hull structure by about 50% allowed a proportionate increase in hull length which seems, as in the previous types, to have been exploited to the full. Thus the number of oarsmen rose from 50 in the pentekontor to no less than 170 in the trireme. The result was a large slender vessel (FIG. 2)

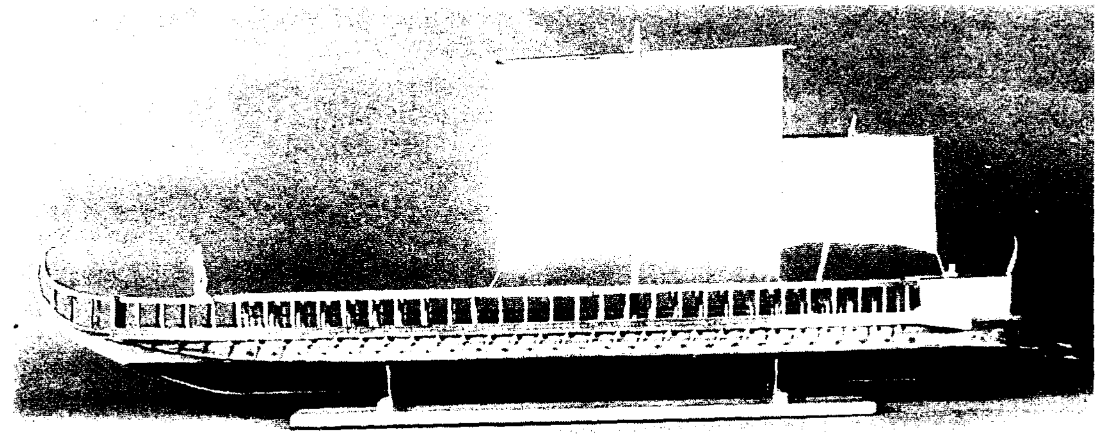


FIG. 2—MODEL OF PROPOSED RECONSTRUCTION OF TRIREME
Photograph by courtesy of Mr. Sam Farr

about 38 m long overall (33 m on WL) and 5·5 metres wide overall (3·8 m on WL), with a draft of about 1·0 metre at a battle displacement of 48 tonnes or so.

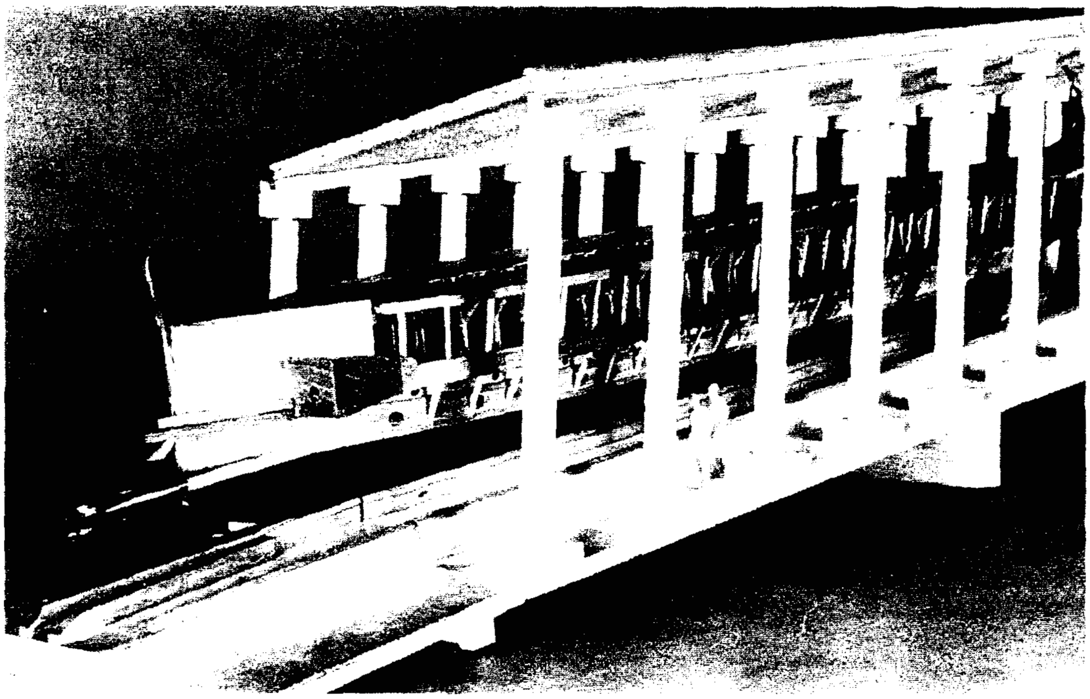


FIG. 3—MODEL OF TRIREME, WITH SHIP SHED

Photograph by courtesy of Mr. Sam Farr

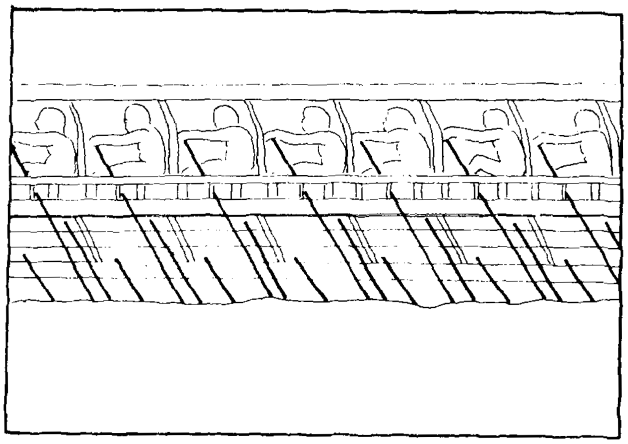
The overall dimensions of the trireme were limited by the internal dimensions of the ship sheds, built in large numbers to keep the majority of the ships of the fleet out of sea and sun (FIG. 3). These sheds have been excavated so their size is certain.

Arrangement of the oars

The profile of the trireme is shown in a fragment of a relief stone carving found in the Acropolis of Athens (FIG. 4). The number of oars in each file is stated in lists of naval stores, which also specify lengths of oars as 9 and 9½ cubits (4·0 and 4·4 m). It is also known that each oar was pulled by only one man and that the fore-and-aft distance between successive tholepins was 2 cubits (0·888 metres). Passages in Aristotle and Galen indicate that the shorter oars were not used in the lowest files as one might suppose, but at the ends of the vessel where its breadth diminished.

FIG. 4—TRIREME OARSMEN, FROM AN ACROPOLIS RELIEF CARVED IN STONE C.400 B.C.

Acropolis Museum, Athens



It follows that an arrangement of oarsmen has to be found in which oars of equal length may be worked from 3 levels. That adopted for the reconstruction, after taking many factors into account, is shown in Figs. 5 and 6. It is necessary that oarsmen be packed densely. Their longitudinal spacing of 0·888 m is small enough, but they must also be placed absolutely no higher than necessary, for stability. Thus each file must sit immediately outboard of the file below, to overlap them in height as much as possible. To achieve that, the tholepins of successive files as one goes up must be outboard of those of the file below. Placing the top tholes on the outrigger at the maximum beam that would allow the vessel to go into the sheds (5·5 metres) and making oar loom (the inboard part of the shaft) one quarter of their total length—about right for seaboats—one finds that the tholes of the bottom files have to be about 3·8 metres apart athwartships. That happens to be the beam of hull on the waterline necessary to obtain sufficient stability to provide a reasonable capacity to carry sail. The lower oars have therefore to be pivoted and emerge from the hull in some way that satisfies that condition. It is known that the oarsmen sat on leather cushions which are believed to have been greased with mutton fat—an early equivalent of a sliding seat.

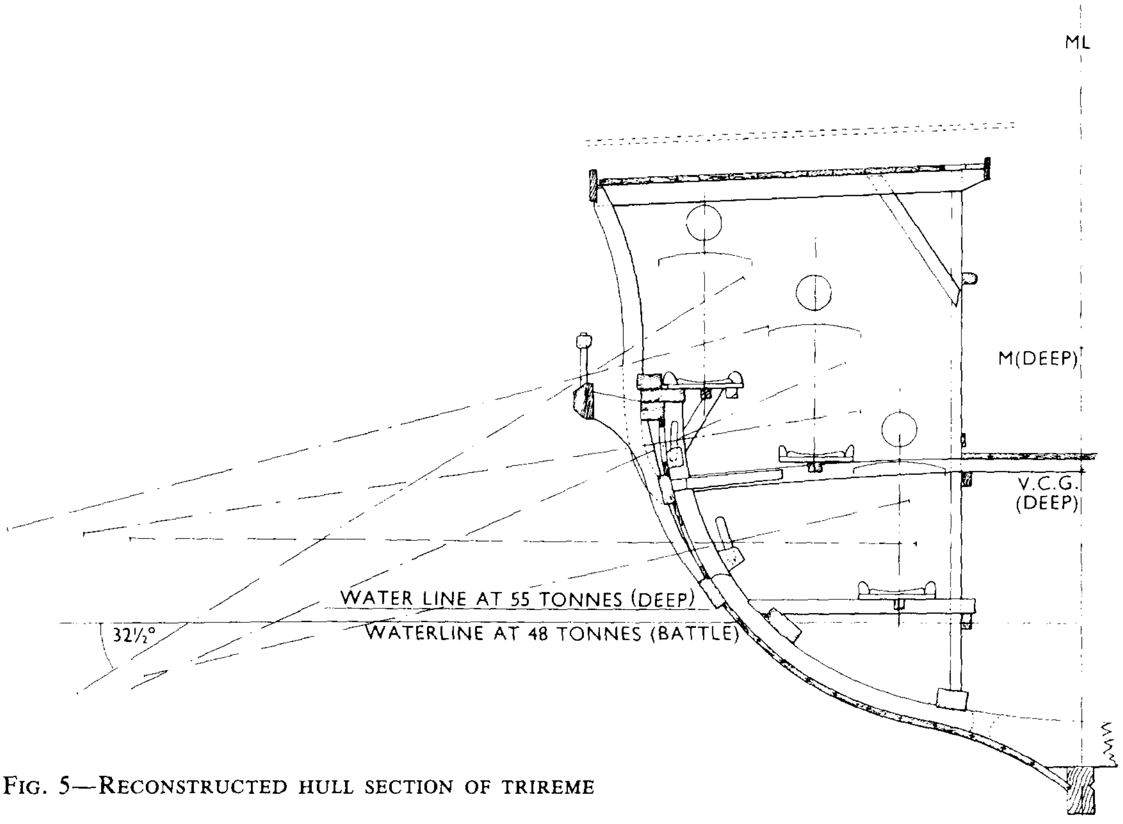


Fig. 5—Reconstructed hull section of trireme

Hull Construction and Design

All Classical ships were built with flush planking erected before insertion of frames and joined edge to edge by loose tenons of hardwood, set in mortices cut in the plank edges and pegged in place. Transverse hull sections were formed of easy arcs, starting at the garboard, rising at quite a steep angle to give access to bore and drive pegs securing garboard tenons into the keel. Fig. 5 shows the resulting hull section. Merchant ship sections were formed in the same way, with the addition of a flat inserted at the point of inflexion. Such sections entail considerable flare at the water line, an almost

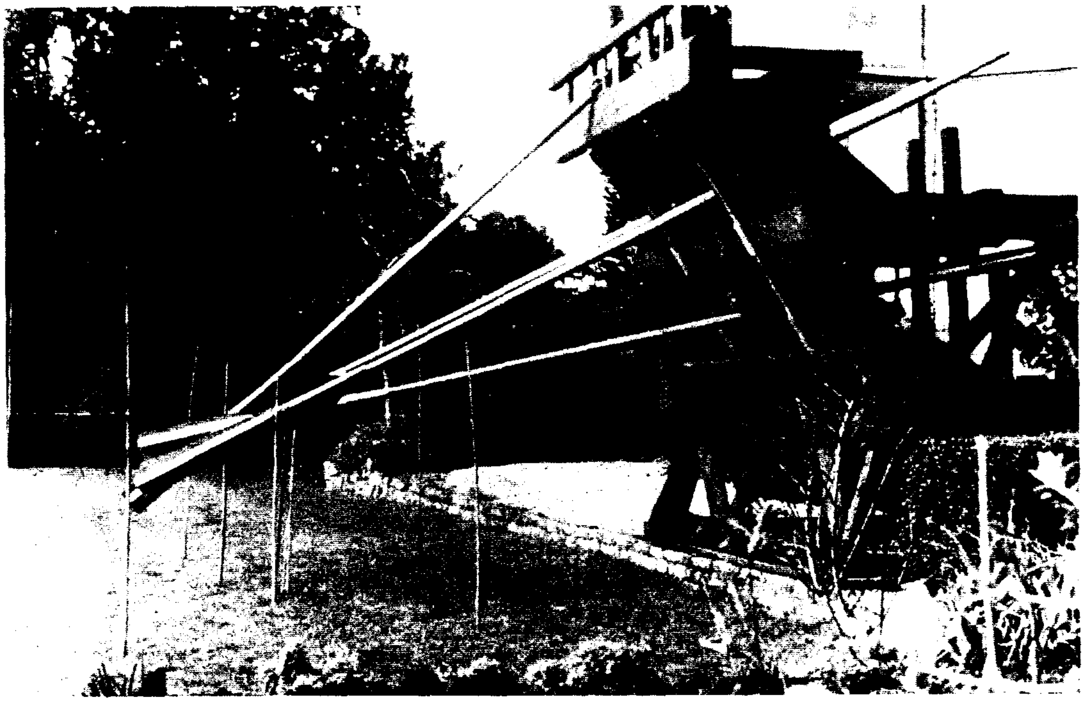


FIG. 6—FULL SCALE MOCK-UP OF TRIREME
The string on the lawn represents the water level.
The short river oars have been extended to simulate sea oars of the correct length.
Photograph by the author

invariable feature of Mediterranean craft to this day. They also demand, following the point in the previous paragraph, that the lowest tholes be well inside the planking. That in turn requires that the lowest oarports be large enough to allow the oars their proper motion. Such a feature would seem both undesirable and unlikely so near the waterline, but a vase painting shows just such large ports for the lowest file, and a passage in Herodotus is quite clear that they were large enough for a man's head to be put through them. They were also known to be fitted with leather sleeves able to pass an oar but exclude water. Thus the proposed arrangment accords well with historical evidence, and the necessity for a curious feature is explained.

Having obtained a dense but apparently workable arrangement of oarsmen, the next step was to look more closely at the shape and structure of hull to contain and support the whole array. First estimates suggested that the hull structure would weigh just over 20 tonnes, taking scantlings from the wreck of the Punic oared ship recently recovered off Marsala, and making the gunwales heavy enough to provide sufficient longitudinal strength. It seemed likely that the total displacement would be made up of:—

Hull	23 tonnes
200 men and effects	17 tonnes
Equipment	3 tonnes
Stores	5 tonnes
Displacement	48 tonnes

Observing the numerous references in Classical Greek literature to the importance of lightness in oared warships, the use of ballast as part of the design was dismissed as unlikely. Thus the hull shape had to very slender indeed. Displacement volume was less than one third of the block volume (Length on WL × Beam on WL × Draft). However the section in FIG. 5 has an area below the waterline of little more than half Beam × Draft, allowing the hull prismatic coefficient to be high—a long parallel middle body with relatively bluff ends for such a generally slender form, but not so bluff as to generate undue wave-making resistance at sprint speeds.

Resistance, Power, and Speed

The resistance of such a hull is shown in Fig. 7 against a base of speed. Frictional resistance is dominant, though above 8 knots wave-making does become significant. While speed was probably not, as already mentioned, the most important aspect of performance of oared warships, the fact is that triremes are reported to have occasionally and in special circumstances of need covered long distances at continuous speeds of 8 knots or more. To achieve complete historical respectability a reconstruction must one day do the same. So the resistance and propulsion at the maximum sustainable speed has to be taken into account in its design.

The resistance and effective power in Fig. 7 are probably fairly reliable estimates. In due course it is planned to have a model towed to check them. Difficulties arise however in estimating the efficiency of oar propulsion, the unproductive mechanical work done in manipulating oars, and the maximum power oarsmen can generate for various lengths of time. I have been able to find little reliable information on these matters, analogous in a modern ship to the efficiency of the propulsor, the losses in transmission, and the power ratings of the prime mover, for various lengths of time. The values entered in Fig. 7 for η (0·3 at high, 0·4 at middle and 0·6 at lower powers) are

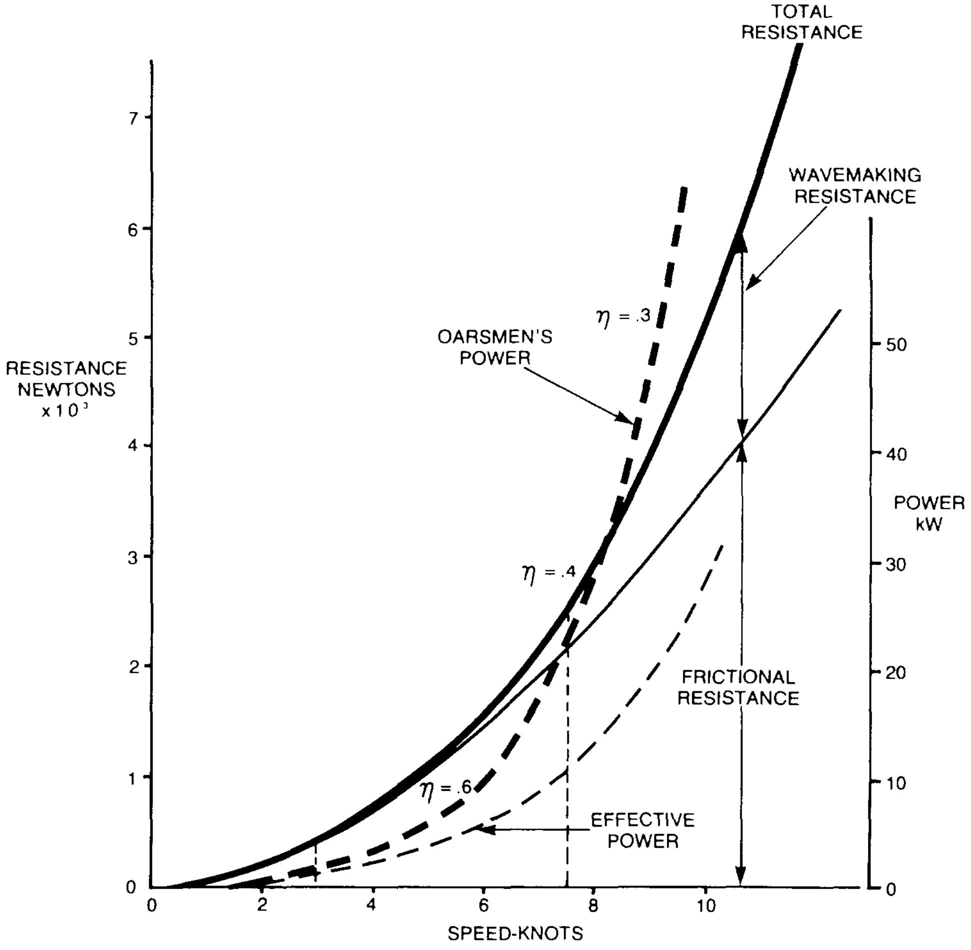


Fig. 7—Speed, resistance, and power

intended to be conservative guesses after studying data about pulling races at Annapolis and papers by Alexander[2] and Wellicombe[3]. η embraces the efficiency of the oar propulsion and the unproductive work. I may have underestimated the efficiency of oars, for their combined blade area is indeed large and their mean slip low. I have understood from Dr. Wellicombe that oar efficiency in modern river shells can be as high at 75% so it is just possible that even in the cruder conditions in a trireme, η could be as high as 0·5 at high powers and 0·6 at medium levels.

FIG. 8 shows the maximum steady power produced by a modern man, normal or trained, against the period of time for which it can be produced[4]. Quite high power can be generated for short periods, but it falls sharply as the period considered lengthens, towards a relatively low power sustainable for a long time. From the curves of FIGS. 7 and 8 the speeds that can be sustained for various periods can be derived, assuming that all oarsmen in the vessel are pulling continuously. Those speeds are given in FIG. 9.

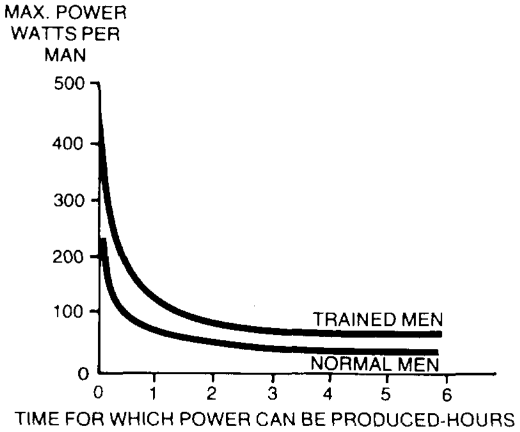


FIG. 8—SUSTAINABLE POWER

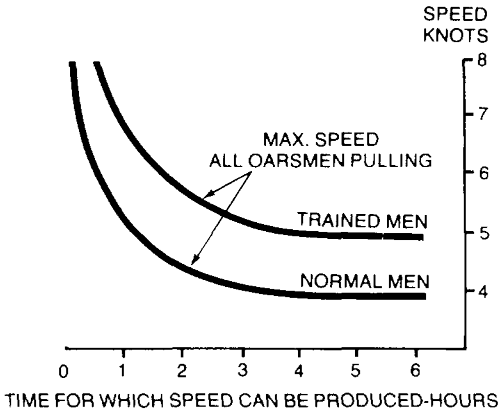


FIG. 9—SUSTAINABLE SPEED

Higher sustained speeds are possible if half crews pull 100 to 200 strokes in turns

It will be seen that the maximum continuous speed with all men pulling is well short of the 8 knots or more required. It will however also be noted that oarsmen's maximum power can be more than doubled if the period over which it has to be produced is much reduced. Thucydides mentions that a trireme on an urgent mission from Athens to Mytilene in the north-east Aegean made its maximum speed with the crew pulling and sleeping in turns. Such turns could scarcely have been less than 1 hour, for which FIG. 9 gives a maximum speed of only 7 knots with all oarsmen pulling; half pulling at a time would on the same basis achieve only about 5½ knots. If turns were ½ hour, half the crew could just manage 7 knots, and the shorter the turns the easier it would be to exceed that speed. However if η could be greater, as suggested above, historical requirements may be met! Astrand and Rodahl[4], while pointing out that the physiological literature of intermittent work is sparse, indicate that the power achievable over short repeated period of work separated by equal periods of rest is not very different from that achievable over a single isolated period of the same length. They also state the curious finding that achievable intermittent power is actually reduced if rest periods are lengthened. This suggests that, whatever the maximum speed of triremes over long periods turns out to be, it will be achieved by half the oarsmen pulling and resting in turns which are as short as practicable.

The Aim of the Reconstruction

It is hoped to test the reconstruction of the Greek trireme to establish its performance and manoeuvring capabilities numerically, and to find out its operational limits. It should then be possible to simulate its motion and feasible tactics to explore fleet tactics of Classical times. The aim of the reconstruction is not so much in its building and subsequent exhibition (though that will be necessary) as to increase our understanding of naval warfare during an important period of history.

References

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