THE INTRODUCTION AND USE OF COPPER SHEATHING - A HISTORY

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For over two thousand years seafarers have tried a variety of methods to protect ships' hulls from attack and fouling by marine organisms. Organisms such as *Teredo navalis*; commonly called the shipworm or teredo (a boring bivalve molusc) and *Limnoria* sp; commonly known as gribble (a wood-boring isopod crustacean) which attack the submerged section of a wooden ship's hull eventually causing major structural damage to the timber. The teredo, which may reach 3 cm in diameter and 20 cm in length, eats into the timber leaving burrows and as it does so secretes a shelly tube of calcium carbonate. A severe teredo infestation can reduce a new wooden vessel to a leaky, sinking hulk in a few years if no protective measures are taken to prevent, or at least slow, teredo attack. While teredo attack may cause serious damage to a ship's hull the growth of marine organisms on the hull will reduce the vessel's speed and ease of handling at sea. Seaweed, coralline algae and barnacles fouling the hull can halve a vessel's speed and the build up of these organisms can be very rapid.

The use of sheathing to protect a ship's hull from teredo attack (by placing a layer of material over the outer planking which either prevents or slows down the teredo's access) has been known since at least the 4th century BC. A Greek merchant vessel excavated near Kyrenia in Cyprus proved to have sheets of lead up to 1/8th inch (3 mm) thick attached by copper tacks to the hull below the water line (Katzev, 1970:841-57). A vessel found in Lake Hemorese, Naples, in the 15th century and believed to date from around 100 AD had a sheathing of lead with nails of brass and copper. The Roman vessels found in Lake Nemi in the 19th century proved to have bitumen applied to the outside, over which a sheathing of lead was fastened by "gilt" (brass?) nails (Wilkinson, 1842:400). Further excavation work in the Mediterranean region has demonstrated that both Roman and Greek ships used lead sheathing as protection against teredo attack (Frost, 1973:33). During the 15th century lead sheathing was used by the Spanish, though the present lack of archaeological remains from shipwrecks of the intermediate period may explain the absence of data on sheathing methods. Sebastian Cabot, who entered the service of the King of Spain in 1512, saw lead sheathing in use in 1514. Upon his return to England he was responsible for the lead sheathing of one of the vessels in which Sir Hugh Willoughby made his famous attempt to find a North East Passage (Wilkinson, 1842:400).

At the beginning of the 16th century, the teredo was restricted to its natural range in the warm seas from southern Florida to Brazil, across the Atlantic Ocean to Morocco and South-West Africa, some areas of the Mediterranean and other tropical seas. The expansion of European shipping into these areas on voyages of exploration, piracy and trade, brought them into contact with the teredo and the massive damage which it could inflict on an unprotected vessel. Prior to this time the effects of *limnoria* attack and fouling had been controlled by periodically 'careening' the ship; beaching the vessel, scraping off the barnacles, seaweed and dry rot and then "graving" the hull. "Graving" was the process of smearing the hull with "graves", the residue of melted tallow left after a mixture of tallow and resin was boiled together (Abell, 1948:91). This was of little effect against the teredo leading ship owners to experiment with sheathing methods to protect their vessels.

The most effective method of sheathing was found to be the use of pitch, hair and thin boards introduced by a British merchant ship owner, John Hawkins, in the late 16th century. Hawkins wrote of his new method of sheathing:

> ".....Before the sheathing board is nailed on, upon the inner side of it they smear it over with tar, another half finger thick of hair.... and so nail it on, the nails not being above a span distance one from another; the thicker they are driven the better...." (Glasgow, 1967:177-184).

For almost two centuries this type of wooden sheathing, with minor variations, was to remain the most widely used method of protection against teredo attack employed by most European countries.

The first serious attempt to improve upon the wooden sheathing method came in the mid 17th century when Sir Phillip Howard and Major Francis Watson experimented with lead sheathing following the early Spanish example. By 1670, Howard and Watson had patented a method of sheathing ships with milled lead (Patent 158. 1670). The right to manufacture milled lead for sheathing, was granted to the two inventors for 25 years by Act of Parliament, thus ensuring a monopoly. One of the earliest Royal Navy vessels sheathed with lead was the fourth rate *Phoenix* which made two voyages to the Straits of Magellen apparently for the sole purpose of testing the invention. On her return in 1673 she was careened at Deptford and personally inspected by King Charles II who issued an order that his Majesty's ships should in future only be sheathed with lead (Wilkinson, 1842:400-404). During his reign, 20 vessels of the Royal Navy were sheathed with lead and fastened with copper nails. Unfortunately, the Navy Board was far less enthusiastic than the King about the new sheathing method, reporting that:

> '...every ship of His Majesty's which has been so sheathed they have had complaints of the extraordinary eating and corroding of their rudder and bolts, beyond whatever was found upon any ship not so sheathed....." (Knight, 1976:299-309).

Although the Navy rejected the new sheathing method it was tried on a 600 ton merchantman, the *Antelope*, two ships owned by Shephard of London and the *Fortune* in the 1690s (Harris, 1966:550-568). In fact the process was not wholly discontinued by the Navy until 1770 when the *Marlborough* was examined at Sheerness, and later at Clapham, and found to have lost all her lead sheathing except for a small portion at the bow and on the rudder (Fincham, 1851:92-101). Galvanic corrosion, caused by two different metals in contact in seawater, was a process which was not understood until the nineteenth century. Consequently, lead sheathing in association with iron nails and bolts, caused the iron to corrode, eventually making it necessary to drive out and replace the iron fastenings. No further experiments with lead sheathing appear to have been made after the middle of the eighteenth century.

Apart from the lead sheathing experiments the main thrust of experimentation during the 17th and 18th century was to find an improved "graving" compound which would resist teredo attack and so improve the established method of wooden sheathing. A wide variety of compounds, which varied in effectiveness, were patented, including:

> Emerton's "....compounded poisons, powdered glass, stone, dust, sand, cemented with the strongest compound of several sorts of painting colours and dyes...." (Patent 557. 1737).
>
> Feyn's "....Worm Pitch.... a composition of spiritual and corporeal ingredients...." (Patent 559. 1737).
>
> Lewis' "....Plantation tar.... distilled and mixed with clarification turpentine...." (Patent 690. 1757).
>
> Smith's "....crushed glass mixed with pitch, tar, turpentine and white lead...." (Patent 887. 1767).

In 1737 the Navy tested four different "graving" compounds and it was found that the best of these was a mixture of pitch, tar and brimstone prepared by Mr Lee, the master caulker of Portsmouth dockyard. *Teredo* had not penetrated Mr Lee's compound after two years of exposure in teredo infested waters.

As early as 1708 Charles Parry approached the Navy with a method for sheathing ships with copper. It was to be tested on a merchant ship and should the Navy wish to take up the system, he planned to ask for a period of monopoly. The Navy Board surveyors opposed the scheme on the grounds that it was not economical, would increase the time taken to put the sheathing on, and would make it difficult to examine the caulking beneath the sheathing (Knight, 1976:292-4). In 1728 Benjamin Robinson and Francis Hauksbee patented a system of sheathing with "....rolled copper, brass, tin, iron or tinned plates...." (Patent 497. 1728). However this sytem seems never to have been put into use.

In 1740 Nehemiah Champion of the Brass Company of Bristol proposed the use of a "Brass Lateen" sheathing which he claimed:

> " is not so liable to be eat with saltwater as iron, copper and other metals..."

Although a limited trial was carried out using this material the Navy Board yet again rejected the system (Harris, 1966:550-68).

Although none of the above sheathing methods were put into use they demonstrated a willingness on the part of the Navy Board to experiment with metals in an attempt to find an improved method of sheathing. This was later to provide the Navy Board with valuable data with which to compare the copper sheathing trials of the 1760s.

In its continuing series of experiments to find a better method of sheathing a ship's hull, the Navy Board ordered the 32 gun frigate *Alarm* sheathed with thin copper (12 ounces per square foot) in October 1761. On her return from two years service in the West Indies the *Alarm*'s hull was closely examined and the results of that survey were communicated in a letter from the Navy Board to the Admiralty dated 31 August 1763. This letter detailed the way in which the copper sheathing had worn, the absence of barnacles and teredo attack in the areas where the copper remained intact and the way in which the iron rudder and false keel fastenings had corroded. Of greatest importance in the letter are the concise, accurate observations of the advantages and disadvantages of copper sheathing:

"...1st - that so long as copper plates can be kept upon the bottom, the planks will be thereby entirely secured from the effects of the worm.

2nd - that neither plank or caulking received the least injury with respect to its duration by being covered herewith.

3rd - that copper bottoms are not incident to foul by weeds or any other cause..... the difficulties... the greatest of which is, the bad effect that copper has upon iron.... whence we presume if the head of the bolts and other surfaces of iron were covered with flannel and a very thin leaf of lead, they would be better secured from the corrosion". (Bugler, 1966:164-8).

The Navy Board's suggested solution to the problem of corrosion of iron fastenings below the water line clearly demonstrates their failure to understand the cause of the problem. The letter was favourable enough to encourage the Royal Navy to continue with the copper sheathing of a number of smaller vessels. By 1770 a total of eight 5th and 6th rate ships had been coppered. (These ships were the *Alarm*, *Tartar*, *Dolphin*, *Tamar*, *Swallow*, *Aurora*, *Stag* and *Hawke*).

In some of these ships, copper bolts and fastenings were tried but it was found that the copper was too soft and did not have the holding power of iron fastenings. When the iron rudder fastening of the *Tartar* in 1765 and the *Dolphin* in 1768 were examined it was found that the copper sheathing had:

".... very pernicious effects upon all the iron work under water...." (Harris, 1966:550-68).

The corrosion of the iron fastenings proved to be a major problem which necessitated driving out the iron bolts and regularly replacing them - a time consuming and difficult task. For this reason there was no immediate attempt to expand copper sheathing to all of the Navy's ships or to sheath the larger 1st, 2nd and 3rd rate ships. Although the Navy Board recognised the very real advantages of copper sheathing, very sensibly, they were unwilling to commit the Navy to copper sheathing until a solution to the iron corrosion problem had been found.

By 1775 the Navy was beginning to show renewed interest in copper sheathing, possibly as a result of the return of the sloop *Hawke* after five years in the Far East. Lord Sandwich, the First Lord of the Admiralty, personally examined the soundness of this vessel at Sheerness. This renewed interest led to the coppering of more small vessels but the Navy was still reluctant to attempt its use on capital ships. In an attempt to finally solve the problem the Navy commissioned James Keir and Matthew Boulton to develop a bolt made from copper with zinc and iron added. Trials were carried out with bolts made from 'Keir's metal' (100 parts copper: 75 parts zinc: 10 parts iron) but by 1781 it was concluded that other copper alloy bolts held more promise for ships' fastenings.

The real impetus to introduce copper sheathing throughout the British Fleet came during the late 1770s when Britain became involved in wars with France, Spain and the rebellious colonists in America. In order to keep the Fleet at sea for long periods it became necessary to use copper sheathing on even the largest ships of the Royal Navy. Unfortunately for the Navy, the decision to copper the Fleet was made before a really effective solution to the problem of iron corrosion had been found. In 1780 a total of 46 ships of the line had been sheathed with copper, most of which were still using iron bolts and fastenings below the waterline. By early 1782 eighty two capital ships had been copper sheathed and Lord Sandwich, enthusiastic about the results, wrote to Admiral Hood:

> "....Copper bottoms need fear nothing..." (Knight, 1973:299-309).

The decision to copper the Fleet was bitterly regretted after the foundering of the *Ramillies* (97 guns) and *Centeur* (74 guns) off Newfoundland in September 1782 as a result of corroded bolts. The controversy over this disaster raged throughout 1783 with the Admiralty in favour of abandoning copper sheathing while the Navy Board, having strongly backed the system, finding it difficult to back down. Fortunately for the Navy Board the development of a new type of copper/zinc bolt mechanically strengthened by being drawn through grooved rollers had been made by the naval copper contractor William Forbes. This allowed the Navy Board to finally reject Keir's metal bolts in December 1783, and begin using the new bolts on naval vessels. The decision to change all naval ships to the new bolts was made in 1786, finally bringing an end to the controversy.

By the middle of 1784 the new copper bolts were being supplied to the Navy by a number of copper contractors; Raby, Forbes, Collins, and Roe & Co being the largest suppliers. These contractors were instructed to mark the copper fastenings and fittings which they supplied to the Navy with their names in order that the Navy could maintain checks on their quality. The importance of the Navy's use of copper sheathing and fastening to the capitalists of the copper industry can be gauged in terms of the tonnage of copper required to sheath a ship and its cost. The *Victory*, for example, which was first copper sheathed in 1780, required 13 tons of copper to do the job. When one considers the number of ships in the British Fleet (a minimum of 300 ships) the tonnage of copper necessary to copper then was considerable. The increased cost of using copper fastenings over that of the old iron fastenings varied from 440 pounds for a 5th rate frigate, to 2,200 pounds for a 1st rate capital ship. Therefore, the Navy's continued use of copper sheathing and fastenings was of great economic importance to the copper mining industry in Britain, and to those associated with the manufacture and fitting of copper sheathing and fastenings. In fact, if the system could be proved to be successful on the Navy's ships, the extension of its use to the merchant fleet could be assured, guaranteeing large profits for the magnets of the copper industry.

While the Royal Navy, in time of war, could afford to ignore the economic considerations of introducing coppering, the British merchant fleet could not. Thus, while the entire naval fleet underwent the transition to copper sheathing and fastening during the 1780s, only a small percentage of the merchant fleet did likewise.

The first merchant vessel was copper sheathed in 1777, some 16 years after the *Alarm* trials were initiated, and by 1786 only 275 merchant ships had been so sheathed, representing about 3% of the total number of ships registered with Lloyds that year. In fact the expansion of copper sheathing and fastening within the British merchant fleet was to prove steady, but disappointingly slow for the next thirty years. By the end of the Napoleonic wars only about 18% of the vessels registered with Lloyds were copper sheathed (Rees, 1971:85-94). The main factor which mitigated against the use of copper by merchant vessels was simply one of cost. The initial cash outlay to copper a ship could add 100 pounds to the cost of a sixteenth share in the vessel. Such a cost could not be justified in many cases particularly if the ship was not spending long periods in teredo infested waters. Even where the savings in terms of reduced cost of maintenance, faster passage times and increased working life of the vessel would have justified the initial outlay, the conservative British ship owners were more inclined to regularly pay small amounts for maintenance rather than a large cost all at once. So the majority of merchant vessels continued to use wooden sheathing, requiring regular replacement, even in voyages to the West Indies, Africa and America.

Those ships which were copper sheathed during the closing decades of the 18th century were almost exclusively involved in the East and West Indies trade, the African trade (usually meaning the slave trade) and voyages to the Americas. In 1786 these destinations were listed for over 80% of the copper sheathed vessels in Lloyds register with the African trade being the most common (45.1%) (Rees, 1971:85-94). While the expansion of copper sheathing over the next 30 years made it possible to find some coppered ships in all trades the most common area of employment were still in the teredo-infested tropical seas.

During the 1780s the British copper contractors began to sell copper fastenings and fittings, particularly the new copper bolts, to all the naval powers in Europe. The lead which Britain had in introducing the new technology necessary to produce copper sheathing and fastenings, allowed the British copper contractors to make large profits from their dealings with the continental Navies. By 1792 the French had found it necessary to import a small colony of British workers to build and operate a copper sheathing factory, to supply the copper sheathing for the King's ships. Liverpool became a major centre for copper sheathing during the 1790s not only supplying the British merchant fleet, but also European merchant ships, and increasingly vessels from the newly independent United States of America.

The New England ship builders and owners were intent on expanding their trade into areas which had been denied them under British sovereignty. Many of the ships built during the last decade of the 18th century were intended for voyages into tropical seas, and consequently required copper sheathing. As the techniques and knowledge of coppering were still concentrated in Britain, it was there that a large number of American ships went to be sheathed. The importance of Britain as the centre of copper sheathing technology declined somewhat after about 1800, partly as a result of the Napoleonic wars which prevented the British from selling to the European Navies and partly due to other nations developing independent sources of copper, and the technology to make copper sheathing and fastenings. After 1815 the Americans began to use copper from mines in Pennsylvannia and the technology acquired from the British. They began to produce their own copper sheathing and fastenings for vessels built in the New England dockyards during the first half of the 19th century, though as late as 1850 sufficient copper plate to sheath nearly 600 vessels was being imported from Britain by the United States of America (Ronnberg, 1980:125-48).

The next major development in sheathing methods did not occur until the 1830s when G.F. Muntz developed an alloy of copper and zinc known later as "Muntz metal" or "patent yellow metal". Muntz metal (60% copper, 40% zinc) proved to be ideal for sheathing the bottoms of ships. It released just enough copper to prevent marine growth on its surface and because it had a slower corrosion rate than copper it lasted longer. It proved lighter and stronger than copper and because it had a large percentage of the relatively cheap metal zinc it was less expensive to manufacture (Flick, 1975:70-88).

Muntz secured a 14 year patent in 1832 for the right to manufacture and sell yellow metal as sheathing and fastenings for ships. Unfortunately, breaking into the sheathing market proved a difficult procedure though not as time consuming as the introduction of copper sheathing. Muntz attempted to interest shipowners in his sheathing metal by allowing them to nail a few plates over their copper sheathing to see what would happen during a voyage. However, there were no buyers for the new sheathing and attempts to interest the Royal Navy proved equally unsuccessful. Indeed the Navy declined to use the alloy and continued their refusal long after most private shipowners had turned to it.

Finally, in a desperate attempt to exploit his new sheathing method, Muntz resorted to selling it sometimes below costprice and guaranteeing private shipowners against any loss occasioned by the failure of the alloy. Gradually some shipowners began to utilise the new sheathing metal. In 1834, 20 vessels in London were wholly or partly sheathed with Muntz metal and this increased to 27 in 1835 (Flick, 1975:70-88). At the same time, a few vessels in Liverpool tried the metal though the venture continued to be in doubt until 1837 when 50 ships were sheathed in London. This increased to over 100 in 1838, over 200 in 1840 and 400 in 1844 in London alone with many other ports following suit. Thus, by the 1840s Muntz metal had begun to supplant copper as the major metal sheathing method utilised in Britain. When Muntz's original patents ran out in 1846 his company had established its dominance in the market for sheathing metal. Yellow metal became the most widely used metal sheathing method and its use expanded to foreign and colonial built vessels during the 1840s and 1850s.

Zinc sheathing was used by some countries during the first half of the 19th century though historical research at least in the English language, into zinc sheathing is very limited. Its introduction preceded Muntz metal though records indicate that it was only occasionally used in British or American built vessels (Ronnberg, 1980:125-48). The centre for zinc sheathing methods and technology was France, probably because she was the largest zinc producer in Europe at the time. Other European nations used zinc sheathing but it never made substantial inroads into the sheathing of ships from Britain, her colonies or the U.S.A. Zinc sheathing plates were 140 cm long by 35 cm wide by 0.67 mm thick, required 105 nails and 7.8 kg/m^2 (approximately 26 ounces per square foot).

The Techniques of Metal Sheathing

The copper sheathing used on the *Alarm* in the 1761-3 trials consisted of sheets made of 12 ounces to the square foot of copper. These sheets proved to be much too thin and consequently were subject to being washed off the hull due to the mechanical effect of the sea rushing past them. The Navy replaced these sheets with a much heavier gauge of copper sheet after the first trial. The new sheets were 28 ounces per square foot (8.5 kg/m^2) which became the standard guage for copper sheathing used by the Navy. The gauge of copper used was not standard outside the Royal Navy, and varied according to the country of origin, type of ship and location on the hull. In general the copper used was between 20 and 32 ounces to the square foot, (the most common gauges were 22, 24, 26 and 28 ounce per square foot).

By the 1850s the methods and gauges of copper sheathing were well established. Ronnberg (1980:125-48) reproduces as an appendix, details of sheathing from I.R. Butts *The Merchant's and Mechanic's Assistant* (1856). This includes a complete description of the methods of sheathing employed including a detailed breakdown of the gauges of copper which were used on different sections of the hull.

The size of each sheet was also variable. The *Victory* for example, was fitted with sheets which were 4ft long and 14 inches wide (1.22 m x 0.36 m), and weighed about 8lbs (3.6 kg). The French on the other hand used sheets which varied between 112 cm and 162 cm in length and 23 cm and 49 cm in width (Lucas, 1978:32-47). There were a number of factors which caused variations in the size of the copper sheets. One of these was the width of each plank in the outer surface of the hull. The British copper sheets were designed to join midway between the horizontal joins of the outer planking, with each plank being 12 inches (0.31 m) wide, the necessary width of the copper sheet was 14 inches (0.36 m) to allow a 1 inch (0.025 m) overlap at the top and bottom of each sheet. If the width of the plank was larger or smaller, the copper sheets had to be correspondingly larger or smaller, to prevent the problem of the joint betwen the copper sheets falling directly over the joints between planks.

Before each sheet was attached to the hull, a layer of pitch or tar was spread across the outer planking. Before copper fastenings were introduced the iron bolt heads were painted with a mixture of white lead and linseed oil and in some cases a thin leaf of lead was placed over them to 'insulate' against the effects of the copper. The next step was to stick a layer of paper, canvas or felt onto the layer of tar or pitch. In order to copper the 120 gun *Calendonia* over 30 hundredweight of copper was used, and 21 reams of paper were stuck onto the hull (Falconer, 1780:451-2).

Each copper sheet had the holes for the nails punched by a small hand punch with a collar which ensured that the hole would not be larger than was necessary to take the nail. The handpunch was used with a specially shaped coppering hammer which had a fairly large rounded face and a claw opposite which was used to remove the nails and sheets. The coppering hammer was also used to beat the copper sheets to fit the curves of the hull and to drive home the nails which held the sheets to it (see Fig. 1).

When coppering a vessel one accepted procedure was to begin where the stern post met the keel and work forwards and upwards on the hull from there. In this way all vertical joints between sheets faced aft to reduce the possibility of the water moving past lifting the sheets from the hull, and all horizontal joints faced down (Underhill, 1958:129-131). This system however only applied to British merchant vessels, the Royal Navy used a different method where the horizontal joints faced upwards. This was the same method adopted for use by the French and is illustrated in Fig 2.

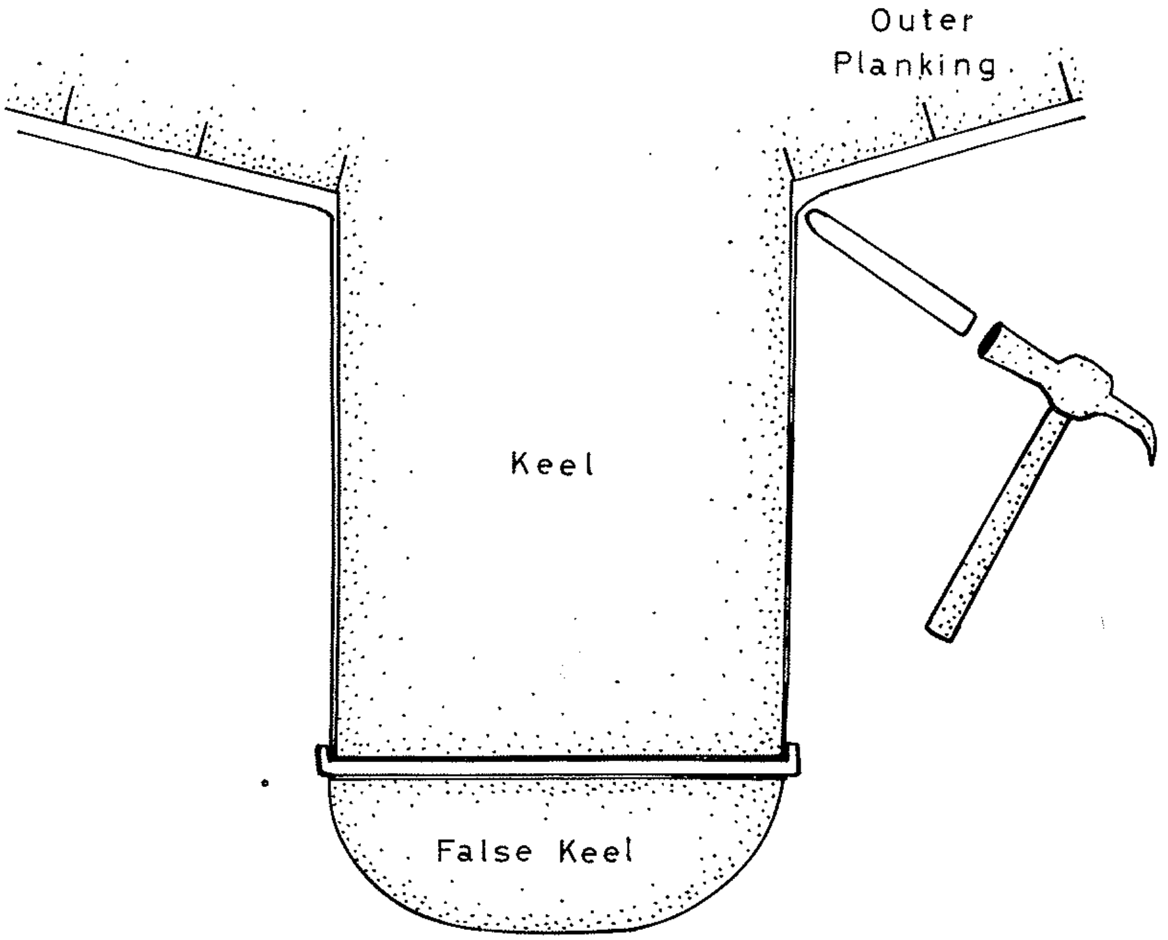


Fig. 1 The use of a coppering hammer and a flat faced rod to hammer the copper sheets flat against the hull.

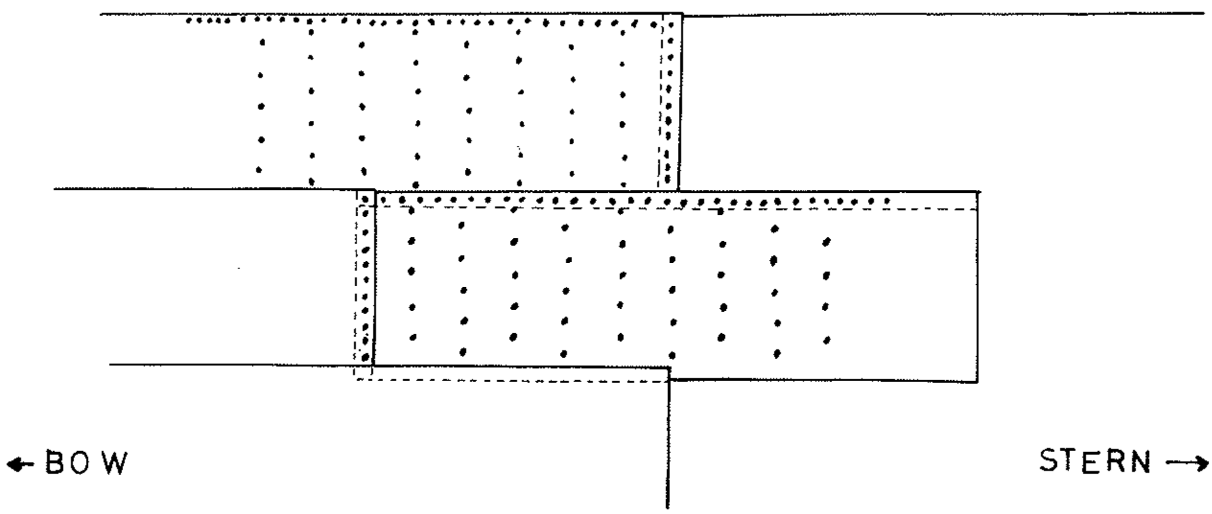


Fig. 2 Copper sheathing showing the methods of joining the sheets by overlapping and nailing.

The two methods of coppering appear to have been utilised during the late 18th and early 19th centuries. The "no-belt" copper pattern resulted from the greater distance from the keel to the waterline amidships than at either bow or stern. This resulted in a "bowed" pattern where there were more rows of copper sheathing amidships and the rows curved sharply upwards at the bow and stern.

Three methods were used to finish off the coppering pattern about 1 foot above the waterline. One method was to have a row of copper plates which ran parallel to the waterline which overlapped the ends of curved rows of copper plates. The alternative methods were to replace the row of copper plates with a wooden batten 9-12" (23-30 cm) wide and a 1 1/2" (4 cm) thick or a roll of canvas nailed onto the hull (Zimmerman, 1978:95-9).

The alternative "Goring Belt" copper pattern was developed in order to overcome the problems which the shape of the hull caused. Certain sheets of copper were cut to fit into triangular sections at both bow and stern where the rows of copper sheets were not parallel to each other. The methods achieving well-fitting copper sheets at bow and stern varied from one shipyard to another. Zimmerman (1978) suggests that the use of belts was a later development and perhaps was restricted to larger vessels. Certainly the *Victory* was coppered using two belts though whether this was done during her original coppering in 1780 or later cannot be determined. The two methods are illustrated in Fig. 3.

At first the nails used to attach the copper sheets to the hull were hand made, but cut nails were introduced during the 1790s though the heads were still shaped individually by hammering. It was not until 1815 that the heads were also machine made (Hume, 1968). The copper tacks used to attach the copper sheets on the *Victory* were 5/32 inches in diameter, about 1 1/2 inches long with a counter sunk head, and weighed about 92 to the pound (Bugler, 1966:164-8). The French are known to have used tacks about 30-34 mm long, 5 mm in diameter with either a counter-sunk or flat head (Le Bot. 1977:41-48).

The spacing of the tacks on the sheet varied considerably both from one dockyard to another and with the passing of time. Again, the *Victory* provides the best example of the early British nailing pattern. The copper tacks were spaced at 1 1/4 to 1 1/2 inch (3-4 cm) intervals where the sheets overlapped and about 4 inches (10 cm) apart on the main part of the sheet. This meant that there were 3 or 4 tacks in a vertical row and 12 or 13 rows across each sheet. On the other hand the French used a system of drawing-in the diagonals across the sheet with chalk and then drawing parallel lines to the diagonals at about 8 cm intervals, where each line crossed another a tack hole was punched. As the French copper sheets were larger (162 cm x 48 cm) than the British sheets, there were 6 tacks in a vertical row and 11 rows across the sheet (Boundroit, 1975:241-5).

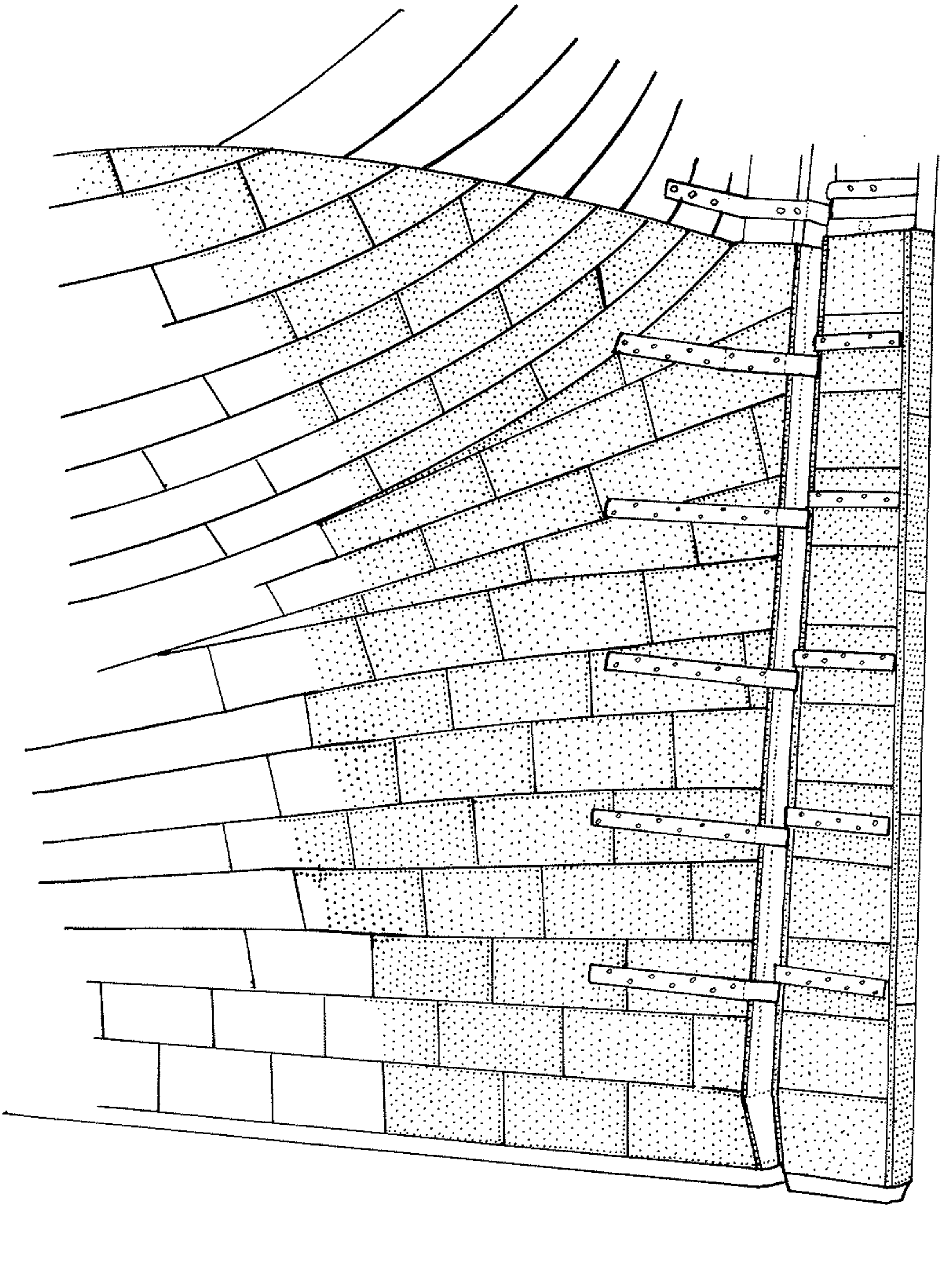


Fig. 3 Copper sheathing at the stern of a vessel showing the 'Goring Belts' and the method of sheathing the rudder.

Copper sheathing proved to be highly successful in resisting the attack of the teredo. The coppered hull remained free of fouling marine organisms for the greater length of time thus increasing the ease of handling and the speed of the vessel. The system was used occasionally well into the 20th century. However, the introduction of yellow Muntz metal in the 1830s led to the gradual decline in the use of pure copper for sheathing purposes.

The copper sheathing and fastenings of the American China trader *Rapid* (1812)

Introduction

An investigation of the copper sheathing and fastenings of the American China trader *Rapid* was made during the 1982 excavation of the wrecksite at Point Cloates, WA. Despite three seasons of excavation on the inside of the hull, little information had been forthcoming about the sheathing methods used on the vessel. Indeed, the large quantities of flat leather found near and under the edges of the hull had resulted in a hypothesis that the *Rapid* was at least partly clad with leather.

Although the first trials with copper sheathing had been made 50 years before the *Rapid* sank in 1812, the use of copper sheathing and fastening by merchant vessels only dated from the 1780s. By 1810 copper sheathing was still restricted to vessels working in the Slave trade, the East Indies trade and other voyages into tropical seas. Fewer than 18% of vessels registered with Lloyds in 1810 were listed as being copper sheathed (Rees, 1971:85-94).

The late 18th and early 19th centuries were a period of rapid expansion in the ship building industry of the newly independent nation of the United States of America. Despite the available archival information about the ship building industry very little is documented about the introduction and use of copper sheathing by American merchant vessels of the period. Although a large part of the increase in speed and manouverability in vessels of the period can be attributed to changes in sail rig and hull shape, some recognition of the important part which the new copper sheathing played must be made. Copper sheathing reduced maintenance costs by reducing or eliminting teredo attack, it prevented the build-up of fouling organisms on the hull and so increased the speed and ease of handling of the vessel. The *Rapid* site provided an early, essentially complete opportunity, to evaluate the use of sheathing in early 19th century vessels.

Objectives

The investigation of the sheathing used on the *Rapid* had three main objectives:

1. To establish the method of sheathing used on the *Rapid*;
2. to develop an accurate method of recording the sheathing used on the *Rapid*;
3. to analyse the sheathing techniques used on the *Rapid* and compare them to sheathing techniques known from the historical record.

Recording and measuring techniques

The nature of the wrecksite and the excavation work being carried out as part of the overall excavation predetermined that the study of the copper sheathing and fastenings should be concentrated in two main areas. Firstly, in order to examine in detail the features of the keel and false keel the entire length of the vessel on the starboard side, where only about 1 m of the hull timbers remained above the keel, was excavated down to the false keel. This investigation immediately showed that the *Rapid* was sheathed with copper or a copper based alloy; for ease of description the sheathing will be referred to as copper sheathing throughout this paper. The copper sheathing and fastenings in this area were closely examined, measured, photographed and recorded. The second area studied was on the port side where the bow section was missing. Here the sheathing and fastenings could be examined from the keel up as far as the wooden sheathing used above the water line (see Fig. 4).

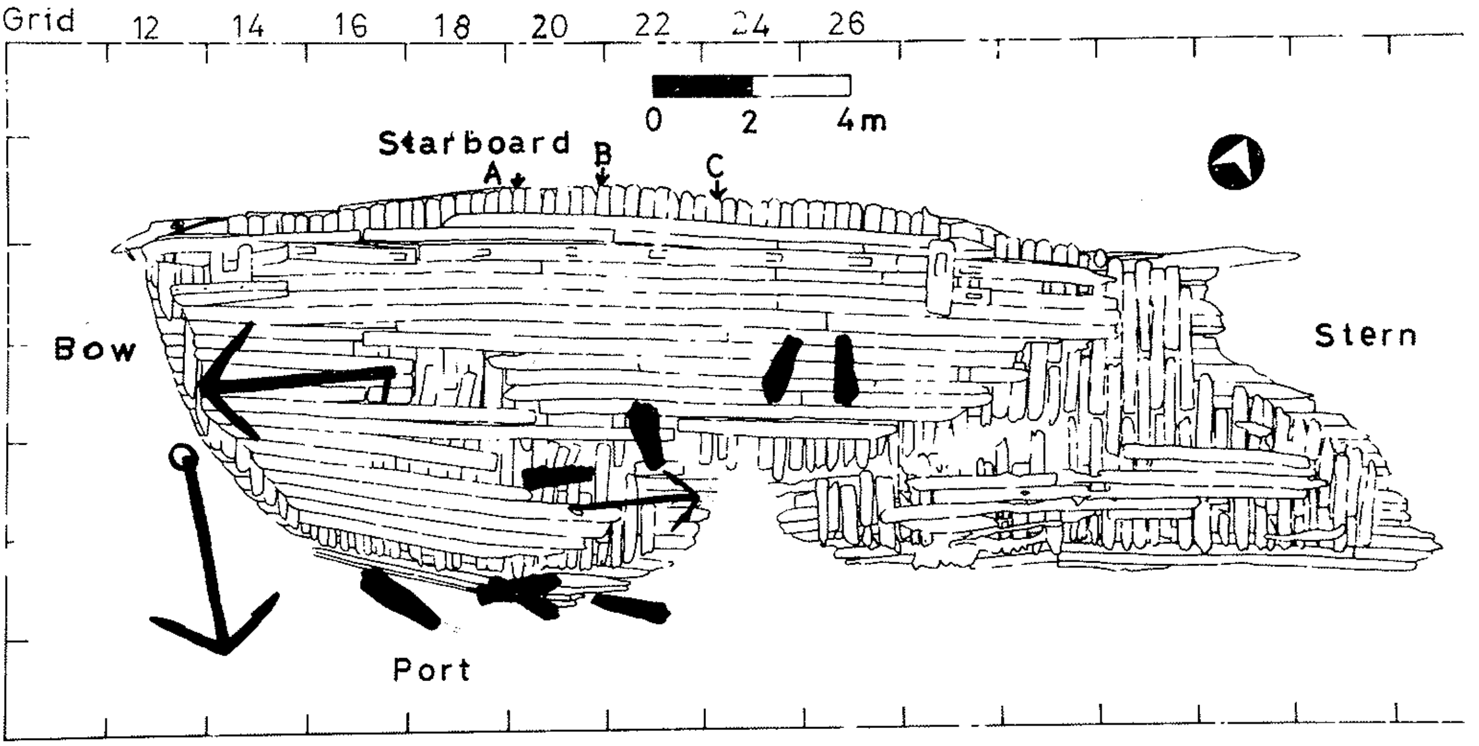


Fig. 4 Plan of the site of the *Rapid*.

(i) Starboard side

After the length of the starboard side down to the keel had been excavated using an airlift, the corroded copper sheathing and copper tacks were visible. Once revealed, a suitable method of measuring and recording the copper sheathing and the tack pattern had to be devised. Two main methods were tried: 1:1 tracing and a three tape method.

The 1:1 tracing method was first tried using a 1 m x 1 m square of waterproof plastic drawing film which was cut to size before the dive. The plastic film was taken to the area to be examined on the hull and was pinned into position with drawing pins. Using a black felt tip pen (Sashihta Artline 70) the remaining tack heads and nail holes were then traced from the hull onto the film. Several problems were found with this system so it was modified by using clear polythene sheet rather than the drawing film in later tests. This allowed the nail holes to be seen much more easily.

Position A is 6.50 m from the bow and represents the area illustrated in Fig. 6.

Position B is 9.00 m from the bow and represents the area illustrated in Fig. 7.

Position 4 is 11.25 m from the bow and represents the area illustrated in Fig. 8.

At this stage the measurement of the position of each remaining nail head, or where the nail was missing the nail hole, could be commenced. The third tape was stretched across between the 0 marks on the two tapes, and any nail position was recorded in terms of a two-dimentional coordinate system. Coordinate A was the distance up the double tapes (in this case 0) and coordinate B was the distance across the third tape, the beginning of the tape closest to the stern being arbitrarily called position A=0, B=0. The third tape was then moved up the double tapes until it reached the next nail position; always ensuring that the tape was fully stretched betwen the same values on the two vertical tapes. Thus, a series of A and B coordinates representing the positions of the nails was recorded with a pencil onto a perspex board covered with waterproof drawing film. The method was continued until reaching the 1 m mark on the two tapes or where the outer planking was broken away and missing, whichever came first.

The system required two divers to operate it, one holding one end of the horizontal tape and the other diver holding the other end of the tape and recording. The system is relatively time consuming and consequently is more suitable for sheltered shallow water sites where diver bottom time is of minimal importance. Each area of 1 m x 1 m took approximately 45 minutes to set up, measure and record. However, the ease and accuracy with which the results could later be plotted up made it preferable to the other method attempted.

Measurements were also made of the outer planking, the keel and the false keel on the starboard side, including details of the bolts and treenails (wooden dowels) used as fastenings in that area of the hull. A total of three diving shifts for two divers were needed to complete the work done on the starboard side, approximately 18 diving hours.

(ii) Port side

The bow section of the *Rapid* has broken away on the port side in the area of the two large anchors (see Fig. 4). Previous excavation in this area combined with the curve of the hull has left a hollow in the sand beneath the timbers. In order to examine the copper sheathing in this area it was necessary to use the large airlift to enlarge the hollow in the sand so that the sheathing all the way up the port side could be examined. After the airlifting was completed it was possible to measure and record the copper sheathing between the keel and the pine boards used as wooden sheathing or sacrificial planking above the waterline.

First the corroded copper sheathing was removed with a geo-pick. Measurements were then taken of the distance between the keel and the pine boards; the number of rows of copper sheets; and the width of each row of copper sheets. The airlifting was then resumed in the area of the pine boards in order that these could be measured and the method of fastening them to the hull could be recorded.

After the *Beagle* (the Museum's workboat) had left the site to return to Carnarvon, an attempt to use the small hookah powered airlift to excavate further in the area of the pine boards and in other areas on the port side proved unsuccessful. Overall, the work on the port side occupied a single diver for three diving shifts, approximately 9 diving hours.

Results

The first time that the three tape method was used to measure and record the nail pattern used to attach the copper sheathing to the outer planking, the corroded copper sheathing was still in place on the hull. It was found that this obscured the heads of the copper tacks and many which were covered by corrosion products went unrecorded. The horizontal joints between the sheets of copper appear clearly in the Nail Pattern Diagram (Fig. 6). However, the vertical joints could not be discerned. The position of copper bolts and treenails in the outer planking were recorded when they were visible.

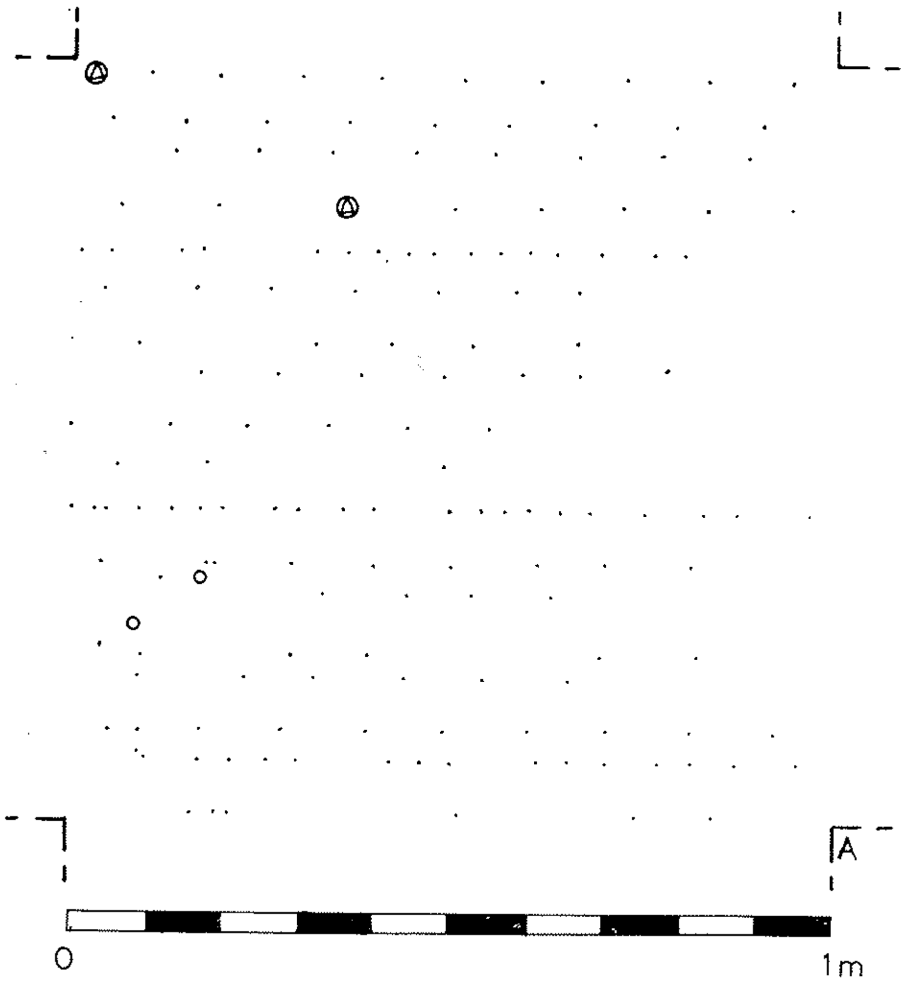


Fig. 6 Nail pattern diagram

As part of the overall excavtion strategy it was decided to remove the corroded copper sheathing in order to examine the outer planking beneath it. This was carried out by tapping the corroded sheathing with a geo-pick or dumpy hammer which would break it away from the hull. Therefore, when the three tape method was used a second time to measure and record the nail pattern, the corroded copper sheathing was no longer in place which allowed an unobstructed view of the nail holes, copper bolts and treenails in the outer planking. This proved to be far more successful in that almost every copper tack head or the hole left where the tack had corroded or been knocked out, was recorded. The horizontal joints between the sheets showed very clearly though the vertical joints are still indistinct.

Fig. 7 Nail pattern diagram showing vertical joints between sheets.

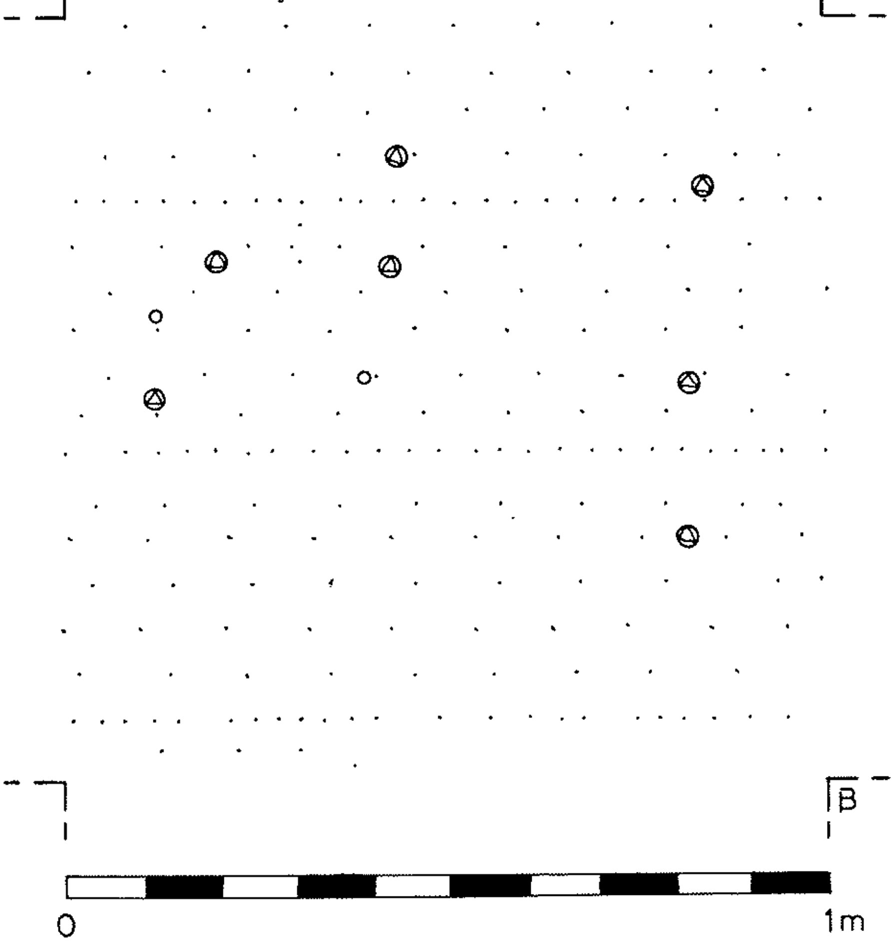
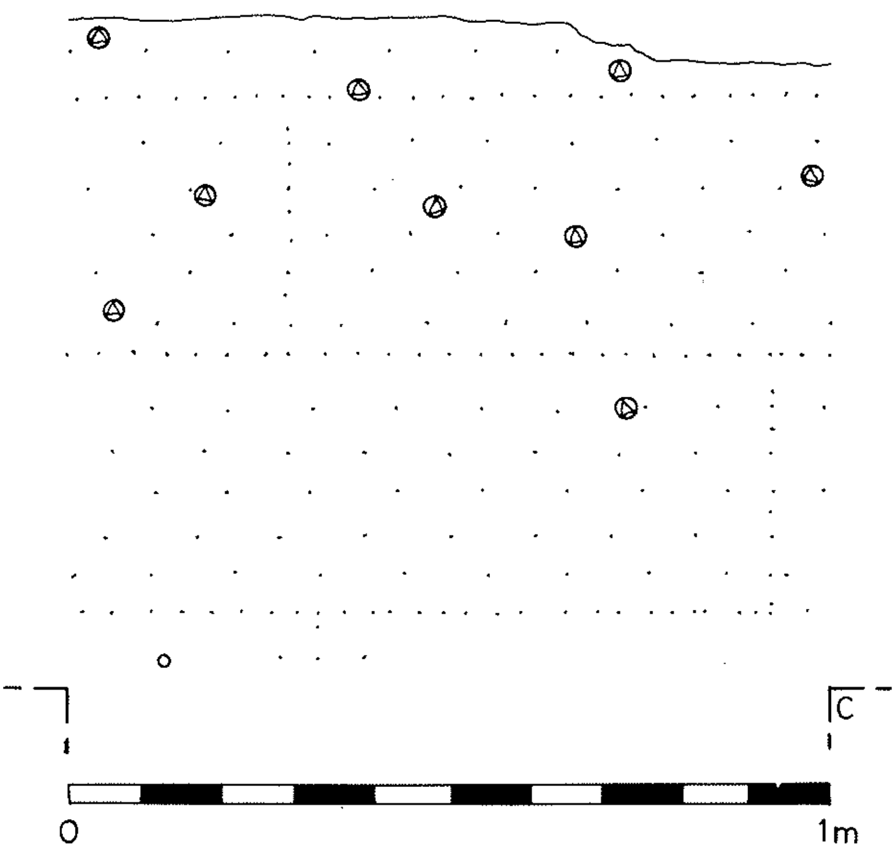


Fig. 8 Nail pattern diagram showing vertical and horizontal joints.



In order to accurately determine the position of the vertical joins between the copper sheets it was necessary to measure a third area of the copper sheathing. This proved most successful, with the horizontal and vertical joints being clearly visible. The area chosen for these measurements was less than 1 m in height because the planking above the 85 cm mark on the vertical tapes was broken and showed signs of severe teredo attack (Fig. 8).

Figure 9 shows part of the area of hull used to obtain the above results.

Fig. 9 Photograph showing outer planking with rows of copper sheathing tacks clearly visible.

A single copper sheet was examined in detail and when combined with the information from the three areas measured by the three tape method the following diagram, an 'average' copper sheet on the hull of the *Rapid*, was made (Fig. 10).

Fig. 10 Diagram of an 'average' copper sheet on the hull of the *Rapid*.

Length of the copper sheet	= 1.21 metres
Width of copper sheet	= 0.35 metres
Top horizontal overlap	= 34 tacks average separation = 4 cm
Bottom horizontal overlap	= 32 tacks
Left vertical overlap	= 10 tacks
Right vertical overlap	= 9 tacks average separation = 4 cm
Total number of tacks	= 124 tacks

The copper tacks in the centre of the sheet were arranged in alternate vertical rows of three and two tacks (11 rows of three tacks and 10 rows of two tacks). The average separation distance between the tacks in each vertical row was 11 cm and the distance between rows was 5.5 cm.

Figure 11 shows the joint between the keel and the outer planking and illustrates both the horizontal and vertical overlap joints between the copper sheets. (The vertical overlap joint is on the extreme right of the photograph).

The perspective distortion caused by the tilt of the photograph does not allow a scale to be used with this photograph. The conditions for photography in this section of the wrecksite were extremely difficult with suspended sediment in the water reducing visibility. Consequently this is one of the few clear close-up photographs of the area.

Fig. 11 Photograph showing the horizontal and vertical overlap joints between copper sheets.

Outer planking, keel and false keel

In association with the data obtained on the copper sheathing on the starboard side of the *Rapid* site measurements of the dimensions, type and number of fastenings of the outer planking, keel and false keel were made.

One of the outer planks was found to be 7.95 m in length, 29 cm in width and 5 cm thick and was held to the frames by 26 treenails (3 cm in diameter) and 12 copper bolts. It was not possible to measure the length of all of these fastenings because they did not go right through to the inner surface of the frames. However, where they could be measured both the copper bolts and the treenails were found to be betwen 30 and 35 cm in length; others went through the ceiling planking as well and were between 38 and 40 cm in length.

The Butt joint between the ends of two planks was examined in detail and a diagram of the positions of the 4 copper bolts and 2 treenails which made up the fastenings in this joint is shown below (Fig. 9).

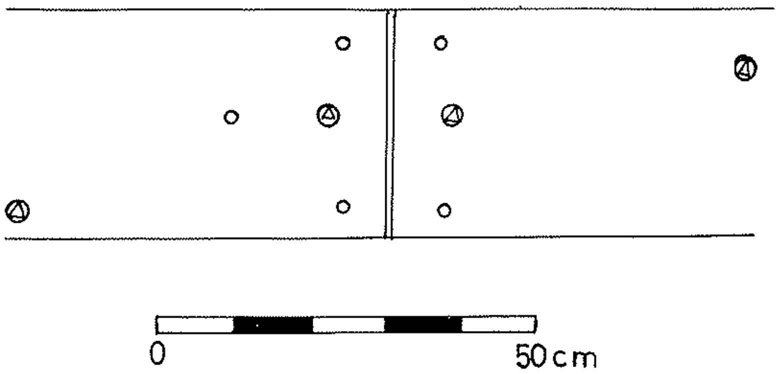


Fig. 12 Planking butt joints showing fastenings.

The keel was 45 cm deep and made up of timber of two heights: the upper section was 22 cm high and the lower section 12 cm high. The keel with the outer planking above and the false keel visible below, can be seen in Figure 13. The joint in the lower timbers can be clearly seen together with the horizontal row of copper tacks attached to the copper sheathing which sent under the keel.

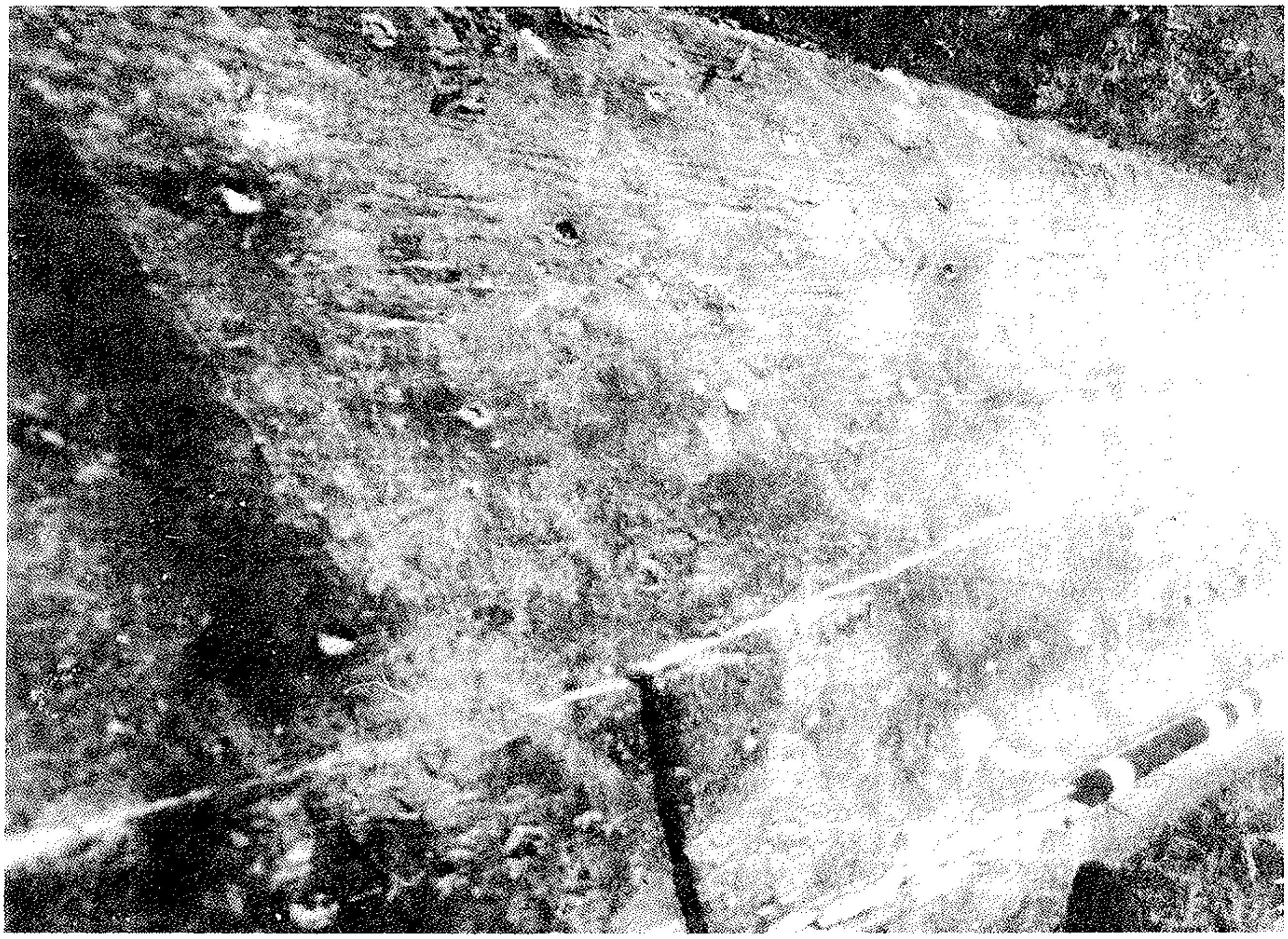


Fig. 13 Photograph of the keel, outer planking and false keel showing the keel joint.

The keel bolts varied in size from 0.5 m in length to 1.5 m in length and from 3 to 5 cm in diameter and were hammered at both ends to spread the head, the head being up to 8 cm in diameter. The larger keel bolts went right through the keel, frames and keelson.

The row of copper sheets over the base of the keel were placed over a thick layer of felt to cushion the false keel against the keel. The false keel was made from a roughly cut half of a tree trunk and was secured to the keel by means of 3 cm diameter copper bolts. Figure 14 shows the false keel with the scale in the join between the keel and the false keel and one of the false keel bolts appearing in the bottom right of the photograph.

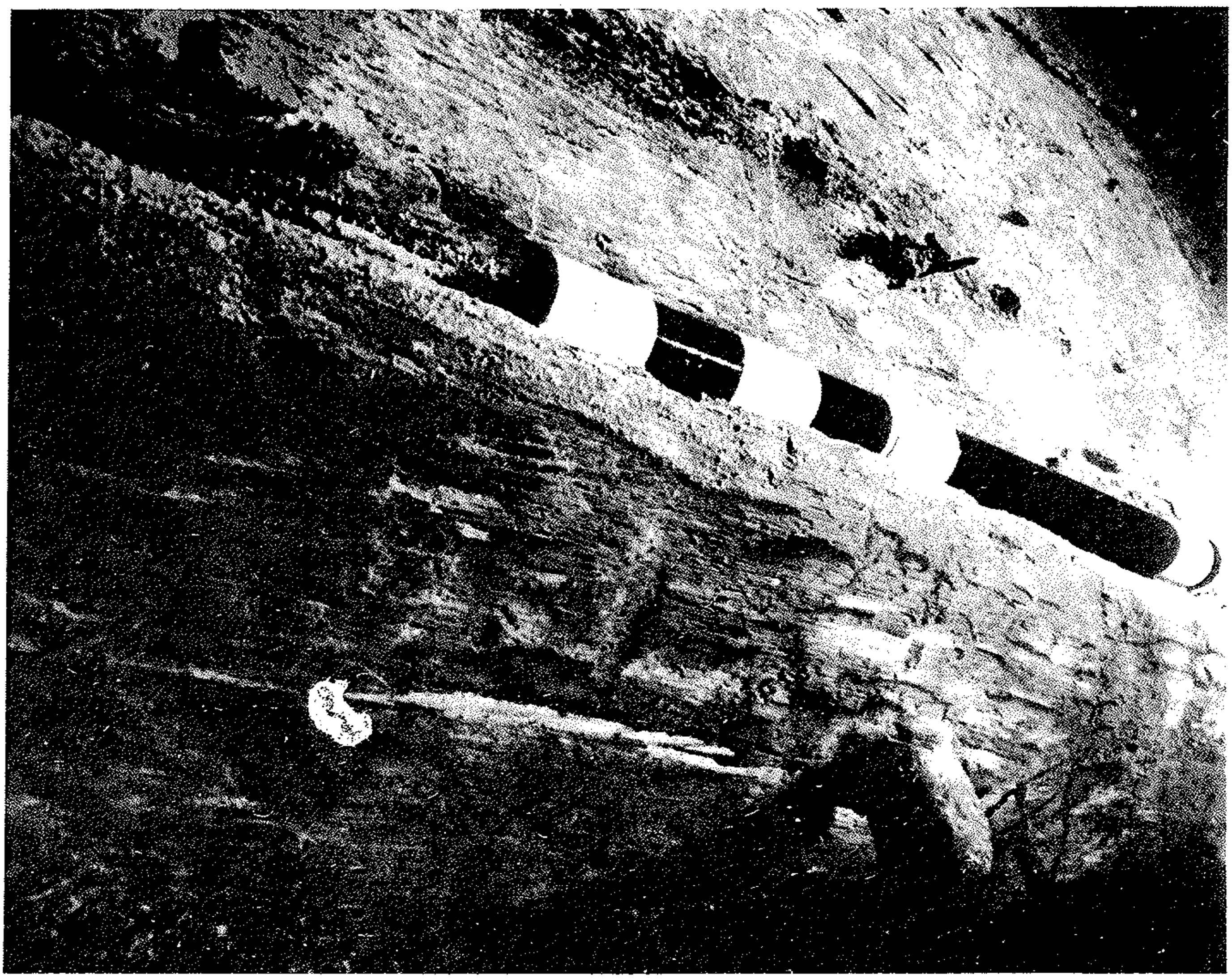


Fig. 14 Photograph of the false keel showing false keel fastenings.

Copper sheathing tacks

Many hundreds of the copper sheathing tacks from the *Rapid* have been recovered during the four seasons of excavation. Originally each tack would have been 3 cm in length, with an irregularly circular head and a tapering square or round shank. The diameter of the head is approximately 1 - 1.25 cm and the shaft less than 0.5 cm in diameter at the head tapering to a square faceted point. Many of the copper sheathing tacks were broken at the juntion between the head and the shank of the tack. This is caused by differential corrosion rates; the corrosion of the tack in the area between the copper sheet and the timber being a more rapid form of corrosion (Ian MacLeod, pers comm). Figure 15 shows copper sheathing tacks with the top row of tacks being close to original size while the bottom row shows signs or corrosion, in some cases severe.

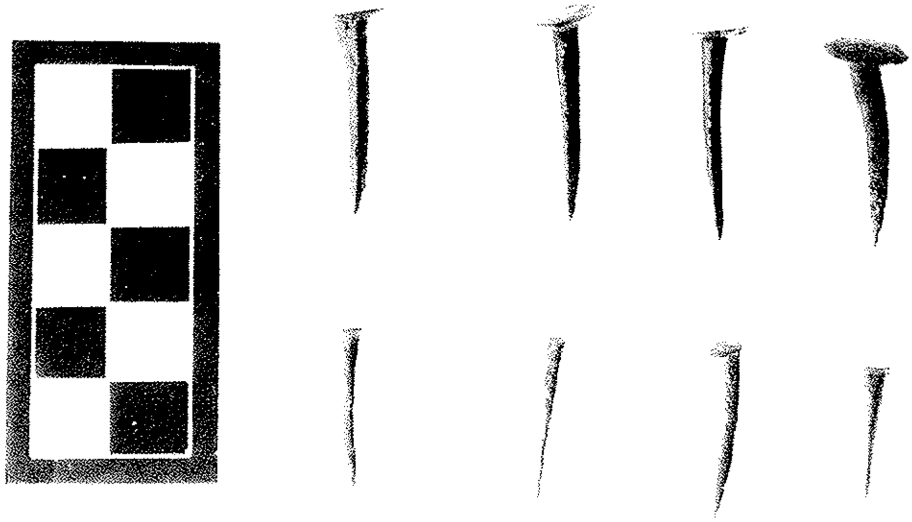


Fig. 15 Photograph of copper sheathing tacks.

Copper nails

Although the copper sheathing tacks were designed for and indeed used in only one area of the vessel, copper nails would have been used in a number of areas. The copper nails were around 7 cm in length with an irregularly circular head of 1.5 cm diameter. The shank was square in cross section below the head and tapered to a wedge shaped point of width 0.5 cm.

Figure 16 shows copper nails which held the pine boards (sacrificial planking) used above the waterline in place of copper sheathing.

Fig. 16 Copper nails used to fasten sacrificial planking to outer hull planking of the hull.

Copper bolts and spikes

A single sized copper spike predominated the finds from the *Rapid*'s hull and her stores, including a large number of beautifully preserved and unused spikes which were probably from the ship's stores or carried as cargo. These spikes were around 16 cm in length with a 1 cm square shank. The head of the spikes was square with each corner of the square sliced off causing the opposite diagonal corners to be burred in opposite directions. The shank tapered into a wedge shaped end which was then hammered flat to form a spatula or expanded point.

Figure 17 shows a number of copper spikes from the *Rapid* with the one on the extreme left being from the stores and is in an unused and uncorroded condition while the others show signs of severe corrosion.

Fig. 17 Photograph of copper spikes, some showing severe corrosion.

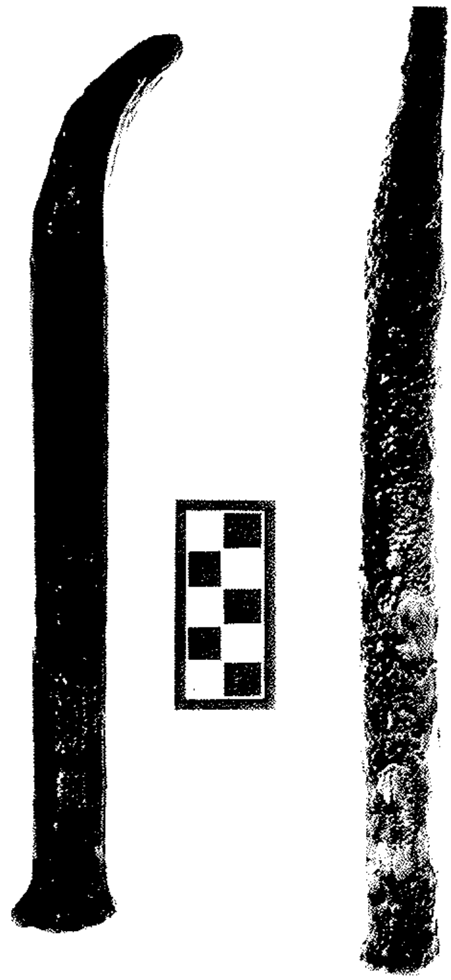


Fig. 18 Photograph of two short bolts used to fasten the outer plankir to the frames.

Copper spikes were used to secure the ceiling planking to the frames, on the internal fittings of the vessel and to secure the outer planking to the hull.

The copper bolts used on the *Rapid* varied greatly in size depending on the location and function. The shortest bolts appear to be used to hold the outer planking to the frames. These may be only 25 cm in length and 2 cm in diameter while the largest bolts were used through the keel, frames and keelson at the bow and stern and could be 1.5 m long and up to 5 cm in diameter. Figure 18 shows two of the shorter bolts used to secure the outer planking.

Port side

The distance between the joint between the keel and the outer planking and the start of the pine board sheathing was measured and found to be 3.60 m. Ten rows of copper sheets were measured in this distance and found to average 35 cm in width. There was no evidence of the narrowing of the copper sheets which could be associated with the Goring Belts at the bow. Each plate was measured and averaged 1.12 m in length.

Measurements of the pine board planking were made and found to average 28 cm in width and just over 2 cm in thickness; one plank was an exception in that it was only 22 cm in width. Two interesting features were found in this area, the first being a triangular shaped piece of the pine boards which showed evidence of being planed to a curved face; possibly the wooden equivalent of a Goring Belt. The second was a double thickness of the pine planking at the level of the sixth plank which may have been a wale. Unfortunately, it was not possible to measure the length of the pine boards or to measure beyond the sixth pine board because of pressure of time during the excavation.

Discussion

The two methods experimented with during this study showed suitability for use in other wrecksites where a large section of the hull is well preserved as it was in the case of the *Rapid*. The 1:1 tracing method, because it is quicker in terms of diver time, would be better suited to deep water sites where diver time is at a premium. This method is slow in terms of overall time taken to produce a drawing of the nail pattern on the copper sheets because it necessitates a 'doubling' up of the recording time. Basically the 1:1 tracing must be laid out and measured back at the expedition headquarters before the measurements are in the same form as those produced directly by the three tape method. The three tape method was preferred on the *Rapid* site because being a shallow water site, diver time was not as important and the results obtained using this method could be directly plotted onto graph paper at a suitable scale reduction in a very short time on the same day that the measurements were made.

The results obtained using the three tape method illustrate that accurate diagrams of the nailing pattern used to attach the copper sheets could be produced and that with a little practical experience using the method the time taken to produce the measurements could be reduced considerably.

Overall the results obtained on the starboard side of the hull of the *Rapid* showed great similarity to those recorded sources on the sheathing of HMS *Victory*. Firstly, the size of the copper plates were identical in dimensions: 4 feet long on the *Victory* and 1.21 m on the *Rapid* (3ft 11.6 in), 14 in. wide on the *Victory* and 35 cm on the *Rapid* (13.8 in). The *Victory*'s plates were made from 28 ounce to the square foot (40 gauge) copper while the 24 stamped in a circle found on one of the *Rapid*'s copper plates would seem to indicate that they were made from 24 ounce to the square foot copper, making the *Rapid*'s copper plates weigh about 7 lb., one pound lighter than the *Victory*'s plates. The copper tacks also are remarkably similar in size to those found on the *Victory*: 1 1/2 inch x 5.32 inch in diameter on the *Victory* and 3 cm x less than 0.5 cm in diameter on the *Rapid*. So too the nailing pattern of the copper sheathing tacks are almost identical on these two vessels: 1.25 - 1.5 inches on the overlaps and 4 inch spacings across the sheet on the *Victory* and then 3-4 cm and 11cm respectively on the *Rapid*. That the similarities between the copper sheathing of these two ships should be so close is not surprising. *Victory* was first copper sheathed in 1780 and while she was probably resheathed a number of times in her long career. However, the sheathing techniques are likely to have been similar throughout her career. Many American shipbuilders used Liverpool during the 1790s to have their vessels sheathed with copper. The techniques developed and used in Britain would have been closely followed by the New England shipbuilders. Consequently, whether the *Rapid* was copper sheathed in Liverpool or America, the techniques used would have been extremely similar.

From the information obtained in this study we can gain a clear picture of the copper sheathing of the *Rapid*, a picture which would undoubtedly be very similar in many aspects to that of a large number of British and American vessels of the late 18th and early 19th centuries. Once the outer planking had been secured, the *Rapid* was caulked with oakum along all of the joints between the planks and a layer of yellow/orange coloured pitch, which was smeared right cross the hull below the waterline. Then a layer of tarred brown paper was laid on top of the pitch; with a special thick layer of felt under the keel. Each copper sheet would be marked and the holes for the copper tacks punched with a hand punch. Then starting on the keel at the stern, the plates were attached with around 125 copper sheathing tacks. In this way all overlaps faced down or aft. At the waterline the copper sheathing stopped and was replaced by pine planks used as sacrificial planking which extended at least 1.5 - 2 m further up the hull. The purpose of the sacrificial planking being to protect the outer planking from the teredo when the ship was heeled over with the wind; this part of the hull could remain submerged for days and even weeks with the ship sailing with a constant wind.

One interesting point which the use of sacrificial planking seems to indicate is just how far up the hull of the *Rapid* the copper sheathing went. It appears likely that the 3.6 m distance between the keel and the top of the copper sheathing near the bow represents the highest point to which the copper sheathing extended on the hull. Certainly there would have been more than 10 rows of copper sheets at midships though how many more could only be determined from the lines of the vessel. It is possible that the builders of the *Rapid* decided to cut down on the amount and consequent cost of copper sheathing by only sheathing the vessel up to the lowest waterline and using pine boards above this level on the basis that after each voyage the boards could, if necessary, be stripped off and replaced. If this was in fact done the saving of perhaps 4 rows of copper sheets and the necessary fastenings would have saved the owners the cost of around 700 copper sheets, 70 000 copper tacks and a total weight of copper in the region of 2 tons.

Estimates of the number of sheets of copper, the number of copper tacks and consequently the total weight of copper used in the sheathing cannot make any claims to absolute accuracy. Based on the size of the *Rapid*, the size of the copper sheets and the number of copper sheets it is likely that the *Rapid* required 2 000 copper sheets, nearly 200 000 copper sheathing tacks and a total weight of copper of nearly 8 tons. This is substantially less than the 13 tons required to copper the *Victory*.

Though machinery was being introduced, at the time the *Rapid* was built, to produce nails and bolts its use was not demonstrated in the fastenings from the *Rapid*. The copper sheathing tacks were hand made, probably from lengths of wire produced by machines but the heads and points of each tack having to be hammered into shape. The copper spikes clearly showed evidence of the heads being hand cut and hammered as did the bolts. The copper bolts would have been made using the grooved rollers introduced in the 1780s with the heads and points having to be hammered.

The results of this study have clearly shown the original hypothesis that the *Rapid* may have been at least partly leather sheathed to be incorrect. On several occasions the author found large sheets of leather close to and indeed under the hull. However, on no occasion was he able to find any evidence that this leather was at any stage attached to the hull to form sheathing. Clearly an extremely mobile material such as leather, where it survives, can be moved considerable distances around a wrecksite and its occurrence under the hull can only be deemed fortuitous. The *Rapid* is an early example of copper sheathing on an American merchant vessel demonstrating the techniques of copper sheathing in use at the time. The sheathing techniques used on the *Rapid* were extremely similar to those used on the *Victory*; though the gauges of copper used were different. The techniques used on the *Rapid* were in the British tradition utilising copper and sacrificial planking to save on some of the costs involved.

Conclusions

The copper sheathing and fastening of the *Rapid* clearly demonstrated substantial similarities to the recorded archival information from British sources. The British origins of the techniques used in the copper sheathing of the *Rapid* were shown. The hypothesis that leather sheathing had been used on the *Rapid* was shown to be incorrect while the use of sacrificial planking in the region above the copper sheathing on the hull was proved.

The technique developed in the field to examine the copper sheathing proved to be extremely successful and depending on circumstances could be applied to other wrecksites using a minimum of equipment to produce detailed results.

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References

Archibald, E.H.H., (1973)
The Wooden Fighting Ship in the Royal Navy AD. 897-1860.
London. Blandford Press:59.

Boudriot, J., (1975)
Le Vaisseau de 74 canons. Vol.1:241-245.
Boudriot, Paris.

Bugler, A., (1966)
HMS Victory. *Building, restoration and repair.*
Her Majesty's Stationary Office:164-8. London.
Desmond, C., (1919)
Wooden shipbuilding.
Rudder:213. New York.
Falconer, W., (1780)
A universal dictionary of the marine.
London. Cadell:451-2.
Fincham, J., (1851)
A history of naval architecture.
Scolar Press, London:92-101.
Flick, C. (1975)
Muntz metal and ship's bottoms.
The Trans. Birmingham & Warwickshire Archaeological Soc., 87:70-88.
Frost, H., (1973)
First season of excavation of the Punic Wreck in Sicily.
International Journal of Nautical Archaeology, 2(1):33-49.
Glasgow, T., (1967)
Sixteenth century English seamen meet a new enemy - the shipworm.
American Neptune, 27(3):177-184.
Harland, J.H., (1976)
Piet Heyn and the early use of copper sheathing.
Mariner's Mirror, 62(1):1-2.
Harris, J.R., (1966)
Copper and shipping in the eighteenth century.
Economic History Review 19:550-568.
Katsev, M.L., (1970)
Resurrecting the oldest known Greek ship.
National Geographic, 137(6):841-857.
Knight, R.J.B., (1973)
The introduction of copper sheathing into the Royal Navy.
Mariner's Mirror, 59(3):299-309.
Knight, R.J.B., (1976)
Early attempts at lead and copper sheathing.
Mariner's Mirror, 62(3):292-4.
Le Bot, J., (1977)
Le doublage en cuivre des terre-neuvas.
Le Petit Perroquet, 21:41-48.
Lucas, P., (1978)
Cuivres et feutres a doublage 1815-1977.
Le Petit Perriquet, 23:32-47.
Patents for Inventions, (1862)
Abridgements of the specifications relating to ship building, repairing, sheathing, launching, &c.
London. George E. Eyre & William Spottiswoode.
Rees, G., (1971)
Copper sheathing - an example of Technological diffusion in the English merchant fleet.
J. Transport History, 1(2):85-94.
Ronnberg, E.A.R., (1980)
The coppering of 19th century American merchant sailing ships. *Nautical Research J.*, 26(3):125-148.
Underhill, H.A., (1958)
Plank-on-Frame Models.
Glasgow, Brown, Son and Ferguson.
Wilkinson, J.J., (1842)
On wood, lead and copper sheathing.
Nautical Magazine and Naval Chronicle, 11:400-404.

Willcox, Mr., (1832)
On the defects in ships bottoms by marine animals.
Nautical Magazine and Naval Chronicle, Simkins Marshal & Co. London. 1:566-570.
Zimmerman, W.J., (1978)
A method for coppering models.
Nautical Research J., 24(2):95-99.