Details of the British bronze piece of gunnery from the 16th century, with the inscription "DA COMPANHIA GL DO BRAZIL". On the bottom, the armillary sphere with the phrase "SPERO IN DEO". A little more under it the number 2640A, the weight of the piece in "arretéis" (a former Portuguese unit of weight, corresponding each to about 16 ounces).

THE GUNS OF THE *SANTÍSSIMO SACRAMENTO* *

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This study is an application of technological analysis to marine archaeology by a military historian, specifically to the cannon of the Portuguese galleon *Sacramento*, lost off the coast of Brazil in May of 1668 and recovered by divers of the Brazilian Navy between 1976 and 1978. It has three main purposes: the first is to demonstrate the contribution which technical analysis of early modern ordnance can make to marine archaeology and the history of warfare at sea. The second is to extract the maximum benefit from archaeological investigation of the wreck. The third, and the most important, is to place the early modern cannon founder, his understanding of his art, his control of his medium and his relation-

* Prepared for the Serviço de Documentação Geral da Marinha.

ship with the seaman and shipwright, in an appropriate historical and technological context.

The interplay between marine archaeology and other disciplines is hardly new. As a high technology discipline habitually open to innovation, marine archaeology has been willing from the first to seek out and exploit specialist expertise across a wide range of fields. Indicative of this openness of approach, this study began with an invitation to the author from the Historical Service of the Brazilian Navy, the *Serviço de Documentação Geral da Marinha,* to visit Brazil to examine and analyze the recovered ordnance.

The use of advanced technology and novel techniques in marine archaeology is an established fact. The use of exotic preservatives to stabilize timber recovered after millenia of immersion is a case in point; the exploitation of radio carbon techniques to date organic material is another; so is the application of the expertise of the numismatist, and experts in early pottery and galssware have made substantial contributions. [1]

But despite the recognized importance of guns and gunnery to early modern naval history and despite recognition of the importance of cannon recovered from wrecks of the sixteenth and seventeeth centuries, little effort has been made to apply the specialized study of ordnance to marine archaeology. Significantly, most of the analytical work done on cannon recovered from beneath the sea has been done by technologically oriented diver--archaeologists rather than by academic scholars. [2] As a result, guns recovered from early modern wrecks have been effectively exploited in only a handful of cases. [3] The cause and the consequence of this situation is a general lack of understanding of early artillery, particularly naval artillery.

It is safe to say that the systematic study of early modern ordnance has hardly begun. It is equally safe to say that what is known has not been effectively applied to marine archaeology. The reasons for this are pervasive. Marine archaeology draws on and feeds a general fascination with the development of ships, a fascination which increases in intensity as we go further back into history and into areas for which written records are scarce. Cannon, however, appear relatively late in the development of ships: the oldest wrecks having cannon associated with them date from the mid-sixteenth century, by which time written records were relatively abundant. The *Mary Rose,* sunk in 1545 is the earliest such wreck which comes readily to mind. [4]

Much of the specialist knowledge applied to marine archaeology has been devoted to the dating and identification of wrecks. The wrecks of cannon-armed vessels, however, are usually recent enough to be identified by archival research, an area into which marine archaeologists and treasure hunters alike have moved with alacrity. As a rule, the mass of evidence associated with such wrecks is so great that there is no need to resort to an analysis of recovered cannon for dating or for identification. Where cannon are used, bronze cannon in good condition, with legible royal *crests,* dates, and founders' marks, are normally involved. In neither case is there likely to be a demand for in-depth analysis of the recovered ordnance. Since the information to be gained from cannon is apparently unnecessary, easily obtained by other means, or both, there has been little pressure to expand our knowledge.

The lack of curiosity about early naval ordnance is underwritten by a tendency to assume that since artillery and the *broadside sailing ship* are comparatively recent developments, our knowledge of them is accurate and complete. Cannon went to sea in significant numbers only in the sixteenth century; by the middle of the eighteenth century, the manufacture and employment of naval artillery was rationalized, standardized and organized along lines which seem familiar to us today. As a result, we tend to read back into our analysis of ships and guns of the sixteenth and seventeenth centuries the technology, tactics, organization and attitudes of the eighteenth and nineteenth. Even the cannon work against themselves: as early as the 1520s bronze cannon were cast which were similar in overall appearance to cannon cast for the next three centuries. [5] Since there was little change in appearance, we assume that there was little change in substance. This implicit assumption is false.

Two examples of the tendency to read back the characteristics of later technology into sixteenth and seventeenth century naval history make the point and introduce our analysis: In his study of naval warfare under sail, the prophet of seapower, Alfred Thayer Mahan, persistently endowed the ships and fleets of the mid-1600s with the structural characteristics, firepower, *seakeeping capabilities* and *cruising endurance* of those of the Napoleonic era. [6] The profound influence of Mahan's erronius assumption of technological stasis on his work and on that of his sucessors is only now being recognized and corrected. [7] This is directly relevant to our study, for the Portuguese galleon which is its object was intended for purposes which were different than those which and orthodox Mahanian analysis would suppose.

The second example of reading back is even more to the point: Generations of naval historians have assumed that long guns meant long range, that cannon with long barrels fired their projectiles further than those with short barrels. [8] This is true for modern rifled artillery using nitratebased propellants; it is not true for *black* powder cannon. The burning rates of nitrate-based propellants increase as a function of pressure and temperature; with proper propellant *grain* design, this means that the potential velocity increase to be gained from increasing barrel length is effectively limited only by the ability of the chamber to withstand heat and pressure. [9] The burning rate of black powder, the classic mixture of approximately 75% Potassium Nitrate, 15% charcoal and 10% Sulphur by weight, is essentially constant. [10] Once the decomposition reaction is initiated, increasing pressure and temperature have no effect on the burning rate. This basic fact has profound ballistic significance. As a practical matter, it means that a cast iron cannonball attains some 80% of its final velocity at a point only 12 calibers (that is 12 times the bore diameter) down the barrel. At a point 18 calibers down the barrel, the cannonball has attained essentially all the velocity which a change of black powder is capable of giving it. [11] Any additional length of barrel — and most sixteenth and seventeenth century cannon barrels were a good deal longer than 18 calibers — had no practical effect on muzzle velocity whatever and thus no effect on range.

The tendency to attach importance to the supposed range advantage of long guns represents a further ramification of the tendency to read back, for range, as the term is used today, had little relevence in early modern warfare at sea. Smoothbore cannon firing a spherical projectile were inherently inaccurate, and attempts to hit anything beyond 500 yards or so were normally a waste of powder and shot — and long barrels had no more beneficial effect on accuracy than on range. [12] Not only was it impossible to hit a target with precision at long range, particularly from the rolling deck of a ship, an inert iron cannonball had very limited destructive powers at the end of its trajectory.

There were occasional exceptions to the rule: a "*long shot*" might smash a spar or cut a crucial piece of rigging to permit escape or to allow a prize to be captured. By and large, however, fascination with maximum range is a modern preoccupation based implicity on the characteristics of post-1850 rifled artillery firing explosive projectiles which *are* effective at maximum range.

Differences in barrel length *were* significant in bronze cannon — and good ordnance of cast bronze set the standard for first class artillery until well into the nineteenth century — but the reasons had nothing to do with muzzle velocity, range or accuracy. In Western European practice, cannon were cast breech down in a *sunken* pit, the molten bronze being poured into the mold through a so-called *casting bell* at the muzzle. [13] The pressure developed by a column of molten bronze, like that developed by any liquid, is proportional to the height of the column. The pressure under which the bronze was cast, therefore, was greatest at the breech of the mold and was greater as the height — the length of the barrel — increased. Bronze gunmetal has a tendency toward porosity and sponginess (any doubt as to the aptness of this categorization can be overcome by examining the remains of a *burst* bronze cannon; the torn metal looks like a ripped sponge), a tendency which was exacerbated by the early gun founder's lack of control over his metal.

The negative effects of porosity, sponginess and the presence of impurities on the strength of the metal could be minimized by casting the bronze under greater pressure. Greater casting pressure could be achieved by increasing the length of the barrel, thus placing the breech at the bottom of a taller column of molten metal. Whether the cannon founders of the sixteenth and seventeeth centuries were explicity aware of this relationship, we do not know. It is apparent, however, that they were implicitly aware of it, for they exploited it in a systematic and controlled manner, along with the other critical variables of cannon design.

We know that the better founders cast their cannon within very close tolerances to a standard model which changed very slowly with time; the cannon of the *Sacramento* provide clear evidence of this practice. We know that there *was* explicit awareness of a positive relationship between barrel thickness and strength, though the nature of the relationship was not clearly understood — nor is it clearly understood today. [14] We know, further, that cannon tended to get shorter and thinner as founders developed better control over the quality of their metal and that better founders consistently cast shorter, thinner cannon.

It may appear that we are using a circular argument, that shorter, thinner cannon were better because they were shorter and thinner. In fact, this is not so; better cannon were cast by better founders, men who are clearly identifiable by their work if not always by name.[15] Better founders used their skill to minimize the amount of expensive bronze in their cannon; this had the side benefit of producing a lighter, handier piece for the same weight of ball. The advantages were obvious and were appreciated. Similarly, the penalties of casting cannon of insufficient strength were severe and minimum thickness and lengths were as closely observed as maximums. The damage which a burst cannon could do to a crowded *gundeck* — or to a founder's reputation — was horrendous and the cost of recasting the metal from a cannon which burst under proof (the molds were constructed of fired clay and could be used only once) was sufficient to deter random experiments. There should, therefore, be no doubt about the reality of the relationships — both perceived and actual — between barrel wall thickness and strength.

About the reality of the relationship between length and strength there is no doubt either. Tests conducted in the 1850s by Thomas Jefferson Radman on cannon which were cast in the manner described above, but which were considerably shorter than those with which we are concerned, revealed that the metal at the breech was 5% denser than that at the muzzle. This modest increase in density increased the tenacity of the metal, the ability to resist shearing stress, by a factor of two. [16] Knowledge of this relationship enables us to evaluate the quality of early bronze ordnance.

The length and thickness of a cannon are only two of a number of factors which must be considered; they tell us little about a cannon if we do not know its notionality and date of manufacture, for example. But taken in context, the length of the bore and the barrel wall thickness provide a useful and unequivocal, *if non--dimensional*, indication of the cannon's quality and the founder's competence.

A final technical note is necessary before we turn to the analysis of the *Sacramento* and her guns. This involves the relationship between bronze cannon and cannon of cast iron. While there is no doubt that the development of a method for casting reasonably safe cast iron cannon, first mastered by the English and then by the Dutch, Germans and Swedes, was an achievement of immense importance, this was not because of any improvement in the quality of cannon. Cannon of cast iron were larger and heavier than cannon of bronze designed to fire a ball of the same weight. Worse, they were subject to internal corrosion and, partly as a result, were much less safe. When they burst they did not remain essentially intact as bronze guns usually did, spewing hot gasses through a split barrel (which was bad enough); rather they blew apart in jagged fragments like a bomb. Iron cannon were used, and they were used in considerable numbers, for they cost only a third as much as equivalent bronze guns. [17] But they were not the weapon of choice. Their use on a first class warship of the seventeenth century suggests a serious shortage of cannon.

Comparatively little documentary evidence has survived concerning the *Sacramento*. Chronicles and contemporary correspondence give the time and circumstances of her loss and little more. [18] When she went down on the fifth of May, 1668, she was the *capitânia*, the flagship, of the escort provided by the *Companhia Geral do Comércio do Brasil* for the company's annual Brazil convoy from Lisbon to Bahia and return. The annual convoy was of considerable economic importance to Portugal — it consisted of fifty ships in 1668 — and the possibility of armed interference with it was large. There is thus no reason to doubt the word of the chronicler Sebastião de Rocha Pita when he states that *Sacramento* was "...one of the best ships in Portugal at that time." [19] *Santíssimo Sacramento*'s place as *capitânia* would have gone to just such a ship.

War between Holland and Portugal had gone on for decades along the Brazilian coast in the East Indies and along the sea lanes between. Both sides had ample opportunity to test their mettle. We know from the frequent and well documented results of Dutch encounters with the Spanish, English and French, that the Dutch were not lacking in courage, material nor skill; when it came to sailling and fighting broadside warships, they knew their business. We know also that the Portuguese ultimately prevailed along the coasts of Brazil and, though our knowledge of the tactical details is scant, that victory owed much to the quality of Portuguese warships and the way they were handled. Beyond reasonable doubt, therefore, *Sacramento* was a first class warship for her time and place.

Concerning the identity of her wreck, there is no doubt. Documentary evidence relating the circumstances of *Sacramento*'s loss coincides perfectly with the location of the wreck, *at Latitude 13° 02' 18" South, Longitude 30° 30' 04" West*, off the mouth of the Rio Vermelho, south of Salvador, Bahia. [20] Artifacts recovered correspond exactly to what we would expect from the wreck of a major Portuguese warship of the mid-1600s. More specifically, dates and founder's marks on the nineteen bronze cannon recovered from the wreck by Brazilian Navy divers under the supervision of marine archaeologist Ulysses Pernambucano de Mello Neto (seven cannon were raised earlier by private divers under uncontrolled conditions) point clearly to a ship laid down around 1649 and launched no earlier than 1650, probably in 1653 (Fig. 1). All of this evidence meshes exactly with records of known Portuguese ship losses and points clearly to the *Santíssimo Sacramento*, lost in 1668. [21]

Significantly, it was the dates and founders' marks of the cannon which gave the first real confirmation of the ship's identity. [22] The clincher was in the recovery of artifacts bearing the personal monograms of the ship's captain, João Correia da Silva, and the Captain General of Brazil, Francisco Correia da Silva, also lost in the wreck. [23]

Having identified the ship, what can we say about her? Without reference to marine archaeology, not much; we are therefore in debt to Professor Pernambucano de Mello Neto, to the divers of the Brazilian Submarine Force, and to the officers and men of the submarine rescue vessel *Gastão Moutinho* from which exploration and recovery operations were conducted. Contemporary sources are consistent in referring to *Sacramento* as a *galeão*, a galleon; one source states that she had sixty guns. [24] From this, we can deduce with certainty only that she was a purpose-built warship. While the term *galeão* can be associated with a particular type of warship in the sixteenth century (unlike the Spanish equivalent *galeón*, the term *galeão* was never applied to merchant vessels [25]), the middle of the seventeenth century was a period of flux

Figura 1

Ball weight in lbs.	Date and founder's marks	Author's identification number	Weight marks	Weight expressed in lbs.	Pounds weight per pound of ball	Bore length in calibers	Maximum barrell wall thickness as function of bore diameter
26	1649 Lucas Matias Escartim*	10	+ 36 — 2 — 10 +	3758	144.6	18.22	.97
26	1649 Lucas Matias Escartim*	11	+ 36 — 1 — 16 +	3739	143.8	18.16	.96
26	1649 Lucas Matias Escartim*	12	+ 36 — 3 — 08 +	3782	145.5	18.17	.96
26**	1649 Lucas Matias Escartim*	14	+ 36 — 1 — 00 +	3723	143.2	18.17	.96*
26	1649 Lucas Matias Escartim*	15	+ 35 — 1 — 00 +	3620	139.2	18.13	.95
26**	1653 Lucas Matias Escartim*	16	+ 36 — 2 — 04 +	3752	144.3	18.19	.96*
28	Mid 1600s A. G. F.*	9	39 — 1 — 16	4047	144.5	18.42	.95
24	Mid 1600s *	17	— 37 — 0 — 8 —	3808	158.7	19.46	.96
11**	Reign of João III, *	18	+ 25 — 1 — 08 +	2601	236.5	24.28	1.06
11	Reign of João III, *	19	+ 25 — 3 — 08 +	2583	234.8	25.25	1.07
11	Early 1600s, A. G. F. *	3	23 — 2 — 16	2430	220.9	24.80	1.06
11	Early 1600s, *	4	25 — 2 — 0	2619	238.1	25.51	1.20
11	Mid 1600s, *	5	+ 26 — 0 — 1 +	2671	242.8	25.17	1.04
11	Mid 1600s, *	23	+ 25 — 3 — 1 +	2645	240.5	25.51	1.11
14	Mid 1600s, * PDB	6	31 — 2 — 12	3247	231.9	23.92	1.11
20	1590 John and Richard Philips	13	3640 A A VIII X 3600 — 1 — 6	3728	186.4	18.25	1.11
20	1596 John and Richard Philips	8	3610 A 3500 — 1 — 1 — VIIIA	3620	181.0	18.42	1.14
11	1597 George Elkine	20	2700 A 2600 — 1 — 5	2702	245.6	20.84	1.14
11	1597 George Elkine	2	2650 A 2500 — 3 — 9 VI	2654	241.2	21.87	1.16
11	Mid 1500s *	1	2630 A 2500 — 2 — 18	2619	238.1	26.52	.95
8	Mid 1500s *	21	2640 A 2500 — 1 — 25 II	2637	329.6	29.37	1.12
20	1649 Conrad Wagwaert	7	37A119	3834	191.7	19.2	1.07
14	1622 Henricus Meus	22				23.27	1.09
20	1634 Assuerus Koster	24	38 FO	3902	195.1	21.00	.96
4½	Mid 1600s Assuerus Koster	34				13.9	.79
4½	1646 Henricus Vesterinck	35				12.55	.62

* Indicates Portuguese Royal Crest Cast on Barrel.

** The Bores of Those Cannon Were Slightly Larger Than Others in Their Ball Weight Class; It is Conceivable, Therefore, That the 26 Pounders are 27 Pounders and the 11 Pounder is a 12 Pounder.

and rapid change in naval architecture and we cannot say with precision what the term meant when *Sacramento* was launched. Very little is known about the design, construction and armament of Portuguese warships in this period. The sixty gun figure may have been an artificial "rating" rather than an actual count; it probably included numbers of *swivel pieces, boat guns*, and so on which would not count as broadside cannon according to our modern sensibilities.

While a good deal is known about the design and armament of English, French and Dutch warships of *Sacramento*'s period, we cannot extrapolate our knowledge of them across to Portuguese practice with confidence. This is in large part because much of the attention given to the development, of warship design of the early to mid-1600s has focussed on major *ships-of-the-line*, particularly massive 100 gun behemoths such as *Sovereign of the Seas, Prince, Soleil Royal* and *Zeven Provinzien*. These ships, like *Santíssimo Sacramento*, were considered the "best ships" of their time in their respective nations, but they were very different in concept and construction. They were also quite different from *Sacramento*'s English, Dutch and French opposite numbers, the ships which contended with her and her sisters for the commerce and security of the Brazilian coast.

The *Sacramento*, a smaller and less powerful warship, might seen un impressive in comparison with the huge battleships noted above, but we must consider the strategic and technological context. The massive 100 gun ships of the mid--1600s mustered great combat power, but they were not true transoceanic warships. Unlike their equivalents of a century and a half later — *Victory* and the *Ville de Paris* are among the better known examples — they rarely strayed far from home port and usually campaigned only briefly and during the relatively calm months of late spring and summer. [26] Enormously expensive to build and operate, they must be understood as the highly specialized craft they were; we must not read back into them the characteristics of the first class ships of the line of a later era.

The *Sacramento* was not a *line-of--battle-ship*, but a genuine transoceanic warship; in her day the two were not one and the same. Ultimately, advances in naval architecture allowed the two functions to be performed by the same ship; the 74 gun *ships of the line* of the late eighteenth and early nineteenth centuries are the most notable and perhaps the most important examples of this. In *Sacramento*'s day, however, this was not possible.

It is therefore tempting to view *Sacramento* as *proto-frigate*, a transoceanic cruiser which could outflight anything which it could not outrun and which it was likely to come up against as far away from home as the Brazilian coast. This is an intriguing hypothesis and one which bears further exploration; it is supported to a degree by the probable size of the galleon's gundeck and the weight of her ordnance. Was *Sacramento* a large, swift, and heavily gunned Portuguese equivalent of a third rate ship of the line? All we can say with certainty is that *Sacramento*'s design was worked out according to the dictates of the peculiar tactical and strategic demands of the *Companhia Geral do Comércio do Brasil* and within the bounds imposed by economic factors and the capabilities and limitations of the human resources available. [27]

Speculation concerning *Sacramento*'s design and constructional features is beyond the scope of our effort for now; we will concentrate our efforts on her ordnance. Thirty-four cannon of bronze and eight of cast iron were made available to the author for examination; these are listed along with their salient features in Figure 1. The bronze guns are particularly important, both because they are representative of the best naval ordnance available to Portugal and because they have survived in remarkably good condition. We have limited knowledge of an additional eight cannon of cast iron which were left on the bottom pending development of a method of preserving them from the severe corrosion which attacks cast iron upon exposure to the atmosphere after long immersion. We know the distribution on the bottom of most of the major items recovered, including 35 of the 42 cannon accounted for. Though incomplete, for the location of the seven cannon recovered before archaeological controls were imposed is not known, the evidence provided by the plan giving this information is critical (Figure 2).

The distribution of wreckage which the plan shows suggests that the ship came to rest on the bottom rightside up on a relatively even keel. This disposition is plain from the arrangement of anchors and guns. The cannon were found in two ragged parallel lines flanked by four of the five anchors at what, given the regularity of the lines of guns, we can safely assume was the forward end of the ship since a ship's main anchors were normally carried outboard in the bows. This arrangement corresponds exactly to the plan. Deviations from this overall scheme are minor and reinforce the conclusion that the locations from which the cannon were recovered corresponded closely to their locations on a horizontal plan of the ship before she went down.

The lines of cannon curve inward at the extreme stern just enough to suggest that the two cannon in the opposing lines closest to one another were stern chasers, mounted side by side to fire rearward on either side of the rudder. The lines of cannon are least regular at the stern where the hull and superstructure would have been deeper, leaving a greater mass of rotting timber to disorder the tows of cannon in their slow trip to the bottom as the wreck decayed.

The length of the lines of cannon suggests a gundeck about 158 feet (40m) long. Such a gundeck length suggests an overall hull length of about 200 feet (51m) from stem to stern. A contemporary equivalent English or Dutch warship of the *Sacramento*'s *vintage* — and we are on slyppery ground here — would most probably have been a third rate ship mounting about 40 cannon on her two main gundecks. The biggest of these cannon would have been no bigger than 32 pounders (that is designed to fire a 32 pound cannonball of cast iron) and no smaller than 24 pounders; the picture which emerges is remarkably similar to the model of a 70 gun English ship of 1692 mentioned by the late R. C. Anderson in his *Seventeenth Century Rigging.* [28] The guns of the lower gundeck, about half of the total, would have been larger than those of the upper gundeck. If, for example, the cannon of the lower deck had been 32 pounders, we would expect 24 pounders on the upper deck; if the cannon of the lower deck had been 24 pounders, we would expect 12 or 18 pounders above.

This tallies closely with *Sacramento*'s ordnance. Of the twenty-six bronze cannon recovered, two are very small pieces, 4 1/2 pounders which would have been mounted on the upper decks and are thus excluded from our analysis for now. The rest are split almost evenly between 20 pounders or larger (12) and 12 pounders or smaller (10). This and the close spacing of the guns in their two rows (Figure 2) erases whatever doubt we may have that the ship's main battery was mounted on two decks. Two additional pieces, an archaic Portuguese 14 1/2 pounder and a long and unwieldy Dutch 15 pounder, might have been part of the lower gundeck battery because of their size and bulk; they might have been assigned to the upper gundeck because of their relatively light shot.

The solution to this puzzle lies with the eight iron cannon still on the bottom. Of the eight iron guns recovered, four, judging by their gross external dimensions, fall into the 20 pounder or larger category and four fall into the 12 pounder or smaller category (this further confirms the two gundeck hypothesis since the plan indicates that at least seven of the eight were found adjacent to one another in an area corresponding to the starbord side rear; that is the smaller guns of the upper gundeck fell through the rotting hull onto a like number of larger guns directly below them). The recollection of *Gastão Moutinho*'s captain, based on divers' reports, is that most, if not all of the eight cannon remaining below, were in the larger category. [29]

This, combined with analysis of the guns recovered, suggests that the *Sacramento*'s intended main gundeck battery was of bronze 26 pounders, but that a severe shortage of good ordnance had forced the inclusion of numbers of cast iron cannon — this is certain — of bronze cannon as small as 20 pounders, or both. The *Sacramento* thus provides unequivocal physical evidence of a general shortage of good cannon in Portugal in the decades following reassertion of independence from Spain in 1640. This confirms and places in perspective literary evidence to this effect.[30] The heterogeneous nature of the galleon's main battery is only the most obvious indication of the shortage and by no means the most conclusive, as we shall indicate.

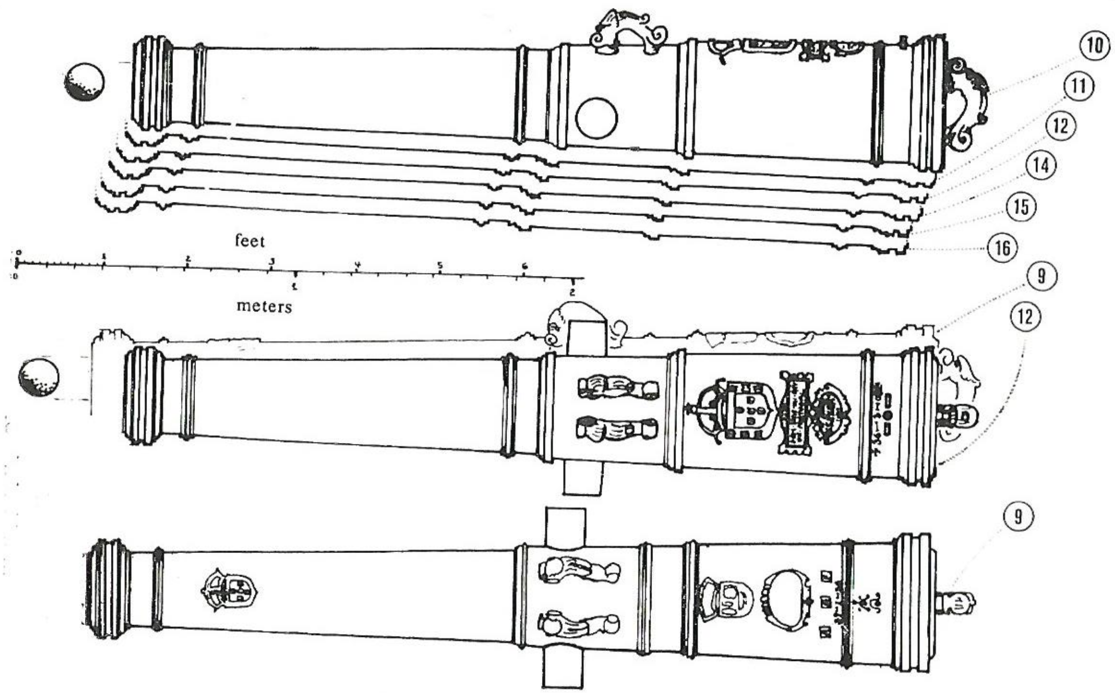
That *Sacramento*'s builders would have preferred a main battery of good Portuguese bronze ordnance, there can be no doubt. This is confirmed by examination of the Portuguese cannon which we can assign unequivocally to the lower gundeck on the basis of size. There are eight of these: a 28 pounder by the founder A.G.F., probably António Gomes Feio,[31] the largest cannon recovered; a 24 pounder by an unknown founder (though unsigned, the gun is plainly Portuguese in design, proportions and the Royal crest on the muzzle); and six 26 pounders by the founder Rui Correa Lucas Matias Escartim, five of them cast in Lisbon in 1649 and the remaining one in 1653, the latest date on any cannon recovered. These last six guns in particular are remarkable cannon. There is a consistency of line and proportion which shows clearly that Portuguese founders followed an established model; comparison with the *Sacramento*'s captured Dutch cannon (of which there are two in addition to the two 4 1/2 pounders and the 15 pounder mentioned earlier) suggests that it was a superior model. Though the three larger of the Dutch guns all fired a smaller ball — 20, 20 and 15 pounds respectively — they are heavier, longer, or both, than the Portuguese 26 pounders just mentioned.

The question of length and weight raises a number of basic issues, for the weight and size of a cannon as a function of projectile weight are, as we have suggested, unequivocal indications of quality. The way in which weight and size are measured is clearly central to our analysis. The external dimensions of the cannon were measured with a steel tape and lengths and circumferences recorded by the author. While there are certain inherent inaccuracies in this method, parallax and the sag in a stretched tape to name two, the author considered these to be sufficiently small as to be practically irrelevent. It was further felt that consistency in technique would make the results valid for comparative purposes. This proved to be true only to a degree. The results are undoubtedly sufficiently accurate for gross comparative purposes, but what was not anticipated was the dimensional precision with which at least some of the cannon were made. This precision, *ex post facto*, demands a more precise method of measurement for future exploitation. No direct measurement of weight was possible, however, all the Portuguese and English guns have markings stamped on their breeches which clearly represent their barrel weights. We will say more about the probably accuracy and precision of these markings further on. Here it will suffice to say that preoccupation with cannon weights was a traditional concern, at least in some areas, and that such markings as are found on bronze cannon barrels are in line with rough computations of their expected weight based on their estimated volumes and the density of their bronze.[32]

Measurement of the six pieces by Lucas Matias Escartim, revealed remarkable dimensional uniformity (Figure 3). In spite of the fact that each cannon was cast in an individual mold which was destroyed to remove the finished gun, and in spite of the fact that one of the six was cast four years after the others, in essential dimensions they are extremely close copies of the same model. Given the limited precision of the method of measurement, it is impossible to say how close. The maximum measured variation in length between any of the six — and most of this is probably due to the limitations of the author's method — was some two-thirds of an inch (1.5cm) from the muzzle to the base of the breech reinforce a distance of nine and a half feet (2.90m). For bronze castings of over

Figure 3

The Dimensional Uniformity of Six 26 Pound Cannon by Rui Correa Lucas Matias Escartim



Outlines of Lucas Matias Escartim pieces compared in lateral aspect.

Lucas Matias Escartim piece *12 in vertical aspect compared with A.G.F. 28 pounder, *9.

3,500 pounds (1,600 kg), this is not bad, even by modern standards. Barrel wall thickness, though impossible to compute accurately until the bores can be cleaned of marine growth and measured precisely, shows evidence of similar precision.

Based on measurement of bore diameters at the muzzle, a process requiring estimation since wear has rounded the inside corners, there is a maximum variation in the thickness of the barrel wall immediately behind the touchhole — probably the most critical single dimension — of only 3%. If we assume that two of the cannon with particularly worn muzzles whose bores were measured as being larger by about .04" (2mm) were, in fact, 26 pounders with the same bore diameters as the others, the difference drops to 2%.

The supposition that all six Lucas Matias Escartim cannon were at least intended to have the same bore diameter is reinformed by analysis of the correlation between barrel wall thickness and weight markings on the cannon. The correlation produced by a *least-squares regression* analysis is .43 if we assume the bore measurements of the two "off" cannon to have been made accurately; the correlation is .88 if we assume all six to have had bores of 5.98" (15.2cm).[33] Since sixteenth and seventeenth century founders cast their cannon hollow, then "trued up" the bores by reaming them smooth, a process which sometimes produced variations in bore diameter, this is more suggestive than conclusive. But even as a measurement of the founder's ability to control weight as a function of *intended* bore diameter, this is respectable. This is underlined by the variation in weight between the six: the heaviest cannon weighs only 1.42% more than the mean, the lightest only 2.93% less, despite the documented and considerable difficulty in standardizing barrel weights, a problem which was never solved as long as bronze cannon were cast.[34]

That control of a cannon's weight and critical dimensions was not an easy thing is shown by evidence that the non-critical dimensions were *not* so closely controlled. The trunnions on two of the six Lucas Matias Escartim pieces are noticeably skewed in the horizontal plane, an inconsistency also present on one of the six Portuguese 11 pounders. (Figure 3 and 4).

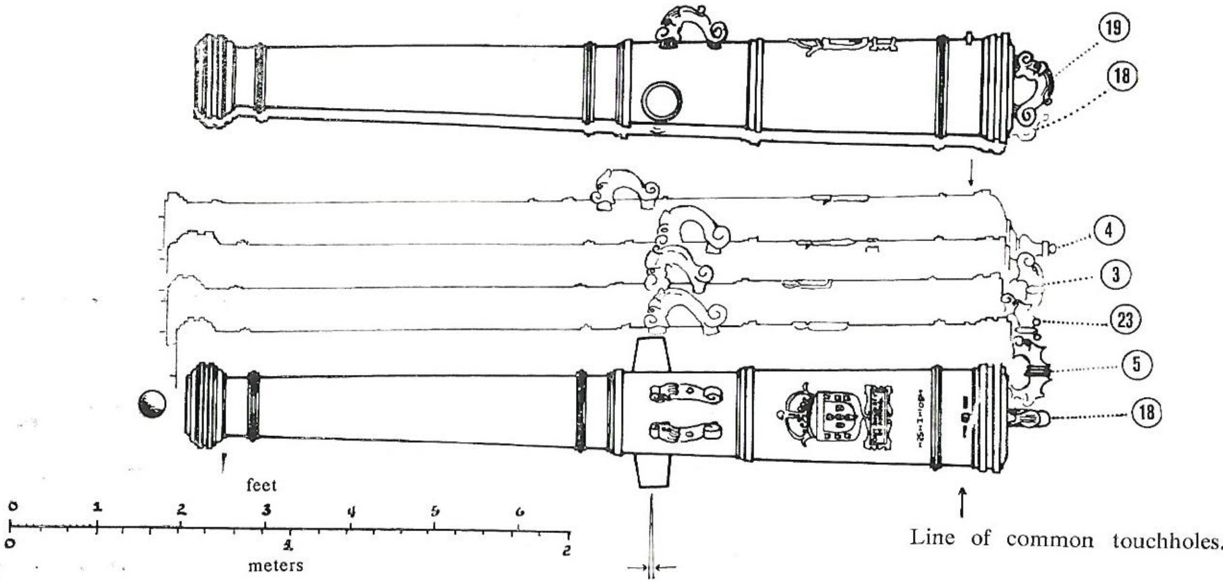
To form a definitive opinion of the quality of these pieces we will have to determine the degree to which their bores approximated perfect cylinders and the precision with which they were centered. Nevertheless, the relative shortness and lightness of these six pieces — their bores are just a shade over the 18 calibre length which represents *the point of diminishing internal* ballistic returns — leaves little doubt as to their quality.

Their quality is echoed in that of the Portuguese 11 pounders of the upper gundeck, though with intriguing differences. There are six 11 pounders of Portuguese origins among *Sacramento*'s guns, but of the six only two are of a vintage and apparent quality comparable to that of the six Lucas Matias Escartim 26 pounders. Though they bear no founder's mark, these two 11 pounders are clearly closely related to their big brothers. The arrangement, spacing and contours of the reinforces and *breech caps* are virtually identical to those of the Lucas Matias pieces; the Royal crest and monogram of *Don João IIII* are rendered identically and the design of the dolphins atop the barrels and on the breeches are virtually identical as well.

Given the necessary difference in proportions between an 11 pounder and a 26 pounder, it is apparent that the two 11 pounders in question and the six Lucas Matias pieces were made within the same manufacturing tradition and probably in the same foundry. Why do the smaller pieces bear no founder's mark? The most probable reason is that the casting of larger cannon was considered more important and prestigious and was supervised by the master founder himself, while the casting of smaller pieces was entrusted to understudies or apprentices. This hypothesis is reinforced by the fact that the only one of the *Sacramento*'s Portuguese 11 pounders to bear a founder's mark, that of the founder A.G.F., is the lightest of the six by some 150 pounds (68 kg) despite its being a probable decade or

Figure 4

Dimensional Comparison of Portuguese 11 Pounders



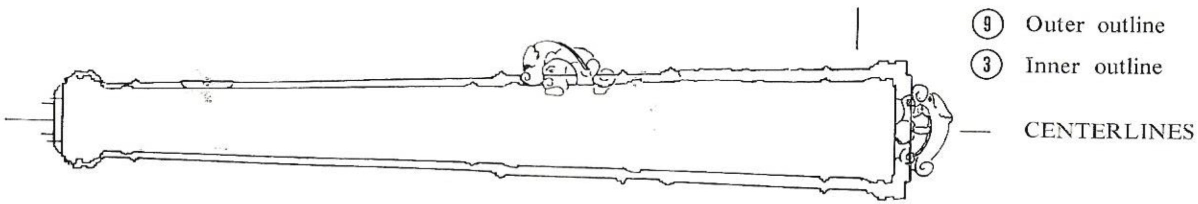
Trunnions of 18 sloewed 1,27° in horizontal plane.

Cannon *18 and *19 were cast with the monogram of King João IIII (n. 1640-56) and are virtually identical. Pieces 4, 3, 23 and 5 bear the Portuguese royal arms but are undated.

Figure 4a

Dimensional Comparison of a 28 Pounder and an 11 Pounder by the Founder A. G. F.

The outlines are drawn with superimposed centerlines and touchholes, so as to depict the bases of the bores in the same transverse plane. Note that the muzzle of the 11 pounder projects beyond that of the 28 pounder.



COMPARATIVE DATA

	Weight of barrel* per pound of ball	Relative length of barrel	Thickness of barrel wall at base of bore
28 pounder, 9	137 lbs.	18.4 calibers	.95 bore diameter
11 pounder, 3	209 lbs.	24.8 calibers	1.06 bore diameter

* For purposes of computation ball weights were converted to *arratels* of 465.8 grams.

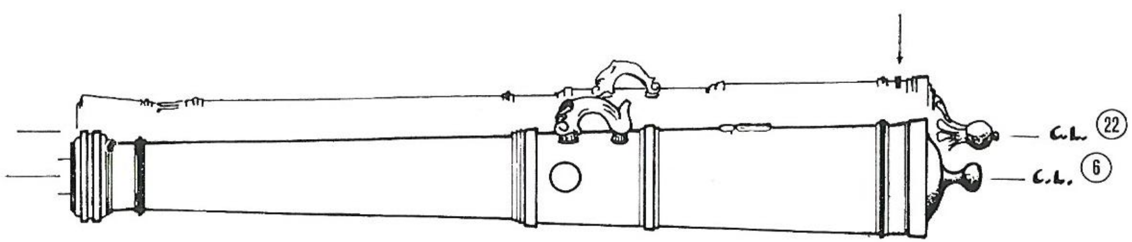
Figure 4b

Comparison of Santíssimo Sacramento's Two 14 Pound Cannon by the Portuguese Founder P. D. B. and by the Dutch Founder Henricus Meus

These two cannon are of interest for reasons beyond their strong resemblance to one another in appearance and dimensions:

— They are the only bronze cannon of the 26 recovered in their shot weight category, a circumstance suggesting archaic design, a general shortage, or both.

— This is reinforced by the fact that the Meus piece is the oldest of the Sacramento's five Dutch guns. Similarly, the appearance and proportions of the P. D. B. piece point to it as probably the oldest of the *Sacramento*'s Portuguese guns.



COMPARATIVE DATA

	Date cast	Weight markings	Presumed or calculated weight	Barrel wall thickness At base of bore. At muzzle throat	Weight of barrel per pound of ball
Henricus Meus 14 pounder, 22	1622	none	3548 lbs.*	1.09 bore .40 bore	246.8 †
P.D.B. 14 pounder, 6	unk.	31-2-12	3162 arratels/3247 lbs.	1.11 bore .48 bore	225.9 †

* Calculated based on the volume of the cannon and the assumption that it's metal density is some 516 lbs/ft^3, about the same as that of the 1634 Assuerus Koster 20 pounder, and slightly less than the calculated 520 lb/ft^3 of the 1649 Wagwaert 20 pounder.

† This computation assumes a ball weight of 14 *arratels* of 465.8 grams of 14.38 pounds.

more older than the two similar pieces just mentioned.

A direct comparison between the foundry practice of A.G.F. and Lucas Matias Escartim, based on the A.G.F. 28 pounder, suggests that the two founders were of comparable ability. The weight markings on the breech indicate that the large A.G.F. piece contains just over 140 pounds of bronze for each pound of cannonball thrown, while the six Lucas Matias pieces contain from about 140 pounds to just under 142 pounds. Like the Lucas Matias 26 pounders, the two similar 11 pounders show a strong dimensional uniformity; they vary in length by only ½" (1.3cm) in 9 1/2" (2.9m) and in weight by less than 60 pounds in over 2.500 (1134 kg). One of the two, like two of the six larger pieces, has its trunnions skewed in the horizontal plane by about a degree and a half.

The remaining three of *Sacramento*'s Portuguese 11 pounders are a mixed bag (Figure 4). They appear to be older than the other three. They do not, however, differ dramatically from them in proportions or weight. The Portuguese had apparently found cannon of this size and ball weight to be useful well before the mid 1600s and had standardized on them to the degree possible. If our galleon's gundecks are an accurate indication — and it should not be forgotten that *Sacramento*'s cannon are fixed archaeologically in time and context — the English may have standardized along similar lines, for three of *Sacramento*'s total of nine bronze 11 pounders are English.

Significantly, if we assume an equivalent level of technology, smaller cannon tend to be heavier in terms of projectile weight than larger ones. The difference in relative weight was not trivial. The six 11 pounders range from some 237 pounds of barrel per pound of ball (the A.G.F. piece) to over 257 pounds, all containing almost 100 pounds of bronze per pound of ball more than the 26 pounders. The most likely technical reason for this relative inefficiency is suggested by the relatively greater lengths of the smaller pieces. Though designed to throw a ball weighing less than half as much, the 11 pounders are only marginally shorter in absolute terms than *Sacramento*'s 24, 26 and 28 pounders. This was probably due to an implicit recognition that a column of molten bronze had to be of a certain minimum height in order to produce metal of the density and strength needed for a cannon's breech.

The question is, Why were relatively inefficient smaller guns cast at all? In land use, the rationale for greater numbers of smaller guns, as opposed to a few larger ones however ballistically efficient, is clear. The inflexible restrictions of horse traction placed obvious limits on the mobility of large cannon, and several small projectiles were tactically more effective than a single large one of the same weight when engaging dispersed human and animal targets. But at sea, where destruction of the structure of a ship was the main objective, the advantages of larger guns in terms of ballistic efficiency and relative cheapness would seen to have been compelling. Whatever advantage smaller cannon might have had in rapidity of fire would have been more than offset in their relative lack of destructive impact.

On reflection, it is apparent that the issue was more complex, revolving around sophisticated questions of the strength and weight of bulwarks and gundecks, center of gravity considerations, moments of inertia — though these were not explicitly understood for many decades — and a host of additional issues that we can only guess at. Although we cannot say with precision what the questions and their solutions were, it seems obvious that the naval architects who designed *Santíssimo Sacramento* and supervised her construction had clear ideas concerning the preferred size, composition and arrangement of her main and upper gundeck batteries. The resultant logic pointed clearly to 26 pounders below and 11 pounders above. There is indirect evidence, which we shall discuss later, that the *Sacramento*'s center of gravity was carefully calculated by the crew, much as that of a modern transport aircraft.

It is likely, therefore, that 26 pounders below and 11 pounders above represented a ballistic and structural ideal, the optimum combination of useable firepower which could be built into a truly transoceanic warship in Lisbon — or anywhere else — in the late 1640s. Does *Sacramento*'s varied assortment of 15 and 20 pounders (of which there were no less than six, all of them but a single long and heavy Portuguese 15 pounder either Dutch or English) represent convergence toward the ideal, or the acceptance of limited supply? The absence of Portuguese 20 pounders suggests the latter, but we simply do not know. Though it is clear that the shortage of ordnance was real, Portuguese shipbuilders may have designed around it. Careful comparison with the design criteria observed in other countries should be instructive.

At this point a more detailed explanation is in order concerning our use of weights. This is basic to the process of evaluation and comparison, for our only positive evidence of the weights of the cannon is in the markings stamped on their breeches.

We have treated the incised weight markings in the form + 36 – 1 – 16 + as indicative of the weight of the barrel in *quintaes* (hundredweights), *arrobas* (fourths of a hundredweight) and *arrataes* (Portuguese pounds). The validity of this assumption is open to challenge. The cannon have not been weighed following their recovery, scales capable of accurately weighing objects of 3,500 pounds (1,600 kg) not being commonplace. The results of a modern weighing will be only generally indicative in any case since certain of the cannon have been corroded at the surface by prolonged contact with seawater and since the wrought iron *cruzetas* imbedded in the cannonmetal to center the mold cores on casting have all corroded to one degree or another.

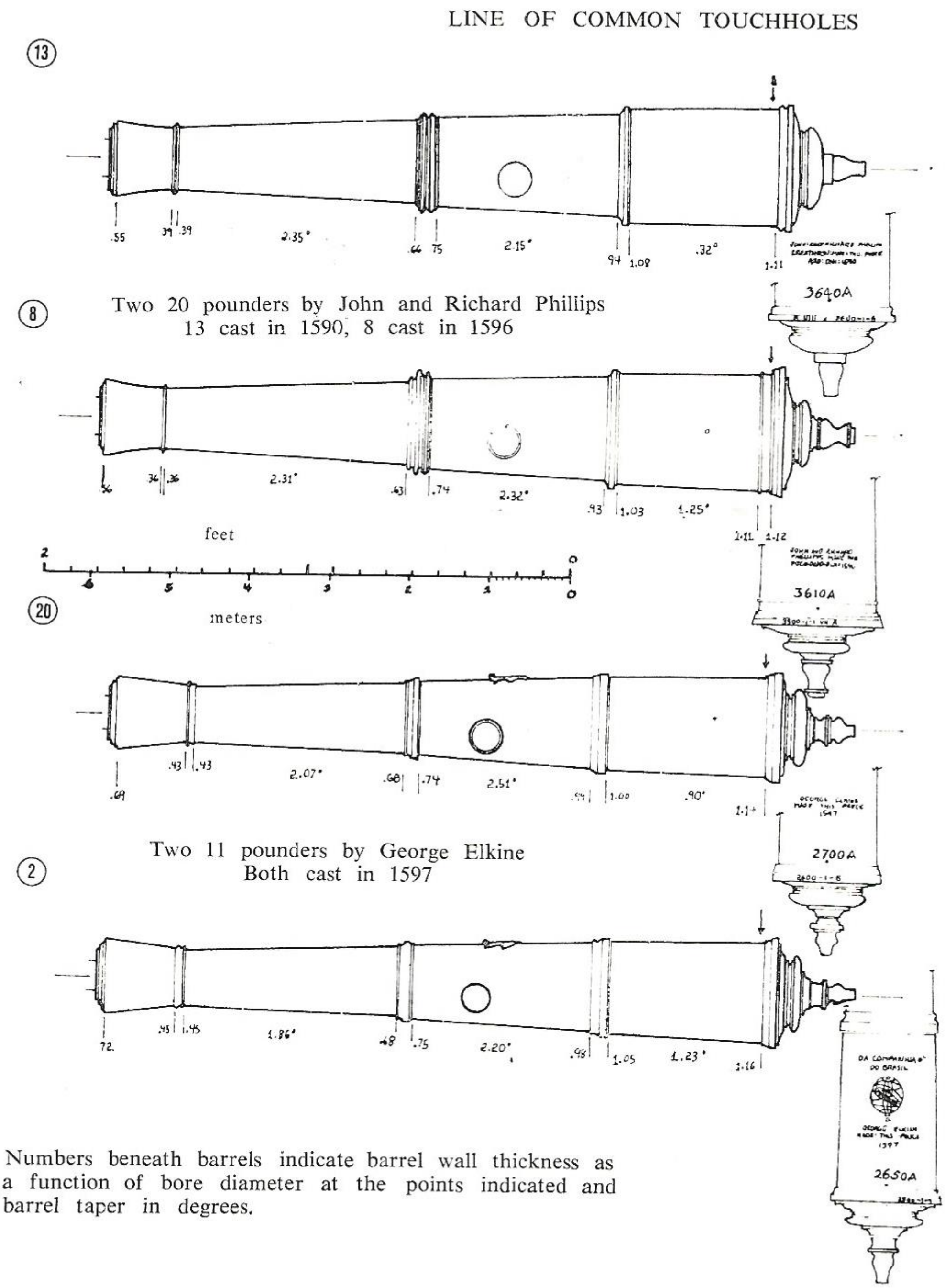
Assistance came from an unexpected source in the form of *Sacramento*'s six English cannon. In addition to Portuguese weight markings in the form indicated above, these bear English markings in the form 2630A (Figures 5 and 6). Markings in this form plainly represent barrel weight in pounds avoirdupois, so we are on firm ground here.[35] Four of the six cannon in question were cast by founders know to have worked in England at times corresponding to the dates cast into their breeches alongside their names, the dates ranging from 1590 to 1597.[36] The other two are English in form and markings. Though neither is signed nor dated, they appear to be much older, corresponding in size and shape to demi-culverins from the wreck of the *Mary Rose*; the Portuguese royal crest is cast into their muzzles, apparently dating them before the incorporation of Portugal into the Habsburg Empire in 1580-81, but their overall appearance is older still.[37] They were thus probably over a century old when *Sacramento* was launched, a consideration with implications on which we shall touch shortly.

Since the English avoirdupois pound had a constant value of 7000 grains, or 453.6 modern grams, for the entire period in contention,[38] we can use the double markings on the six English cannon to test the validity of our assumption concerning the nature of the Portuguese weight markings. We can also establish the Portuguese unit of weight and gain some idea of the prevailing standards of precision and accuracy.

A least squares regression analysis shows that the two sets of markings are parallel expressions of the same quantities in different, but consistent, units of measure with a correlation of .9989 (Figure 7). Confirming beyond any reasonable doubt that the three part markings on the breeches of *Sacramento*'s cannon are indeed weight markings, this also suggests that unexpectedly high standards of accuracy and precision were observed by English founders and Portuguese arsenal workers. When we consider that the correlation was adversely and cumulatively affected by the inaccuracies in each of two weighings, this is particulary impressive, raising several intriguing questions: Why was precision important? The expense and trouble involved in weighing large objects so precisely was considerable then as it is now; there was therefore clearly good reason to do so. Were cannon sold by the pound and the weights recorded and marked on the gun before sale? Perhaps, but if so, why are such markings comparatively uncommon on English and Portuguese cannon of similar vintage in museum collections, most of them pro-

Figure 5

Sacramento's **Dated English Cannon**



Numbers beneath barrels indicate barrel wall thickness as a function of bore diameter at the points indicated and barrel taper in degrees.

Figure 6

Archaic English Cannon Recovered from the Santíssimo Sacramento

Cannon 1 an 11 pounder, and 21, an 8 pounder, are remarkably similar in overall dimensions. Both bear the Portuguese Royal Crest and an indistinct globe device atop their muzzles; both show indications of iron within their trunnions, the lugs atop the barrels, and their breech caps.

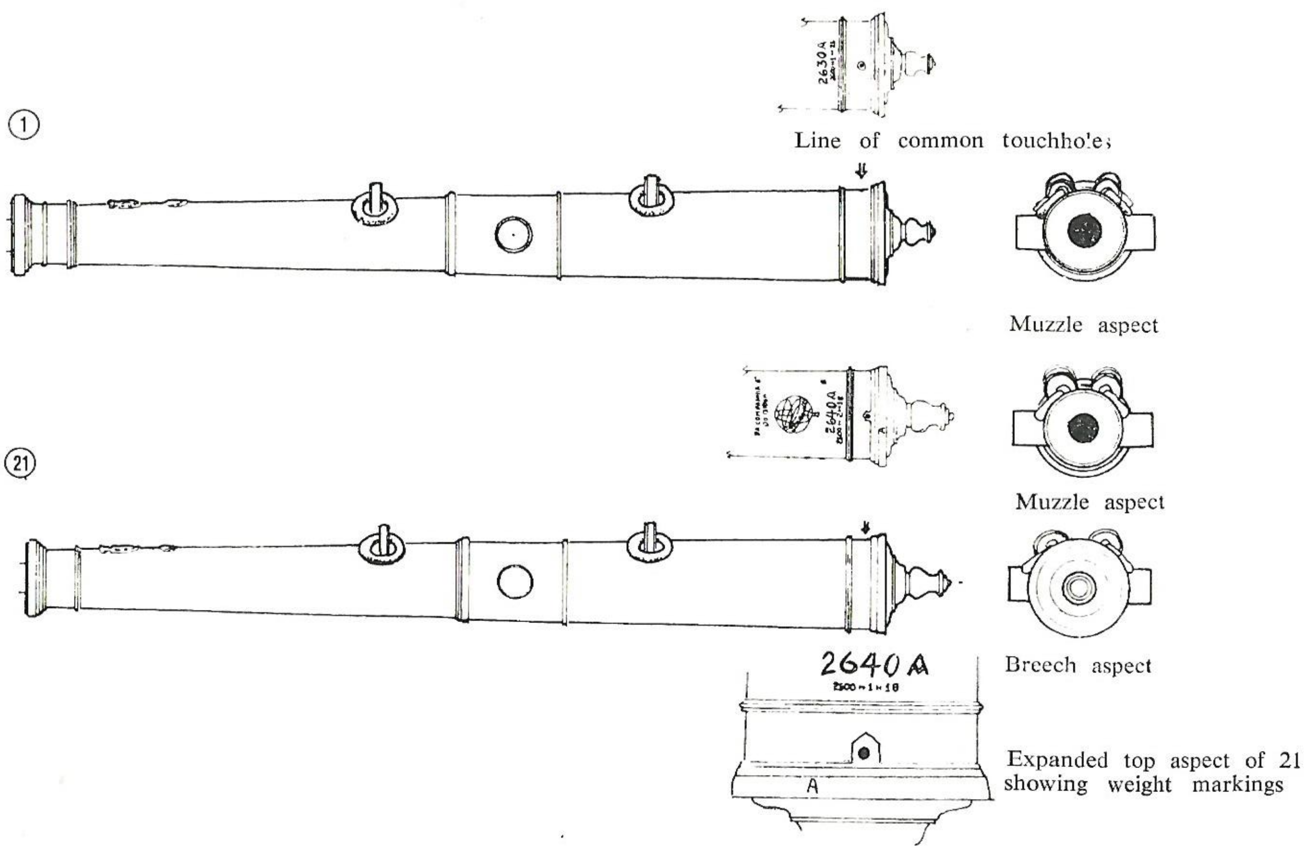


Figure 7

Linear Regression Analysis of Double Weight Markings on Santíssimo Sacramento's Six English Cannon

Author's Identification Number	*Description*	*English Weight*	*Portuguese Weight Markings and Weight*	*Computed grams per "arratel"*
1	Archaic 11 pdr.	2630	2500-1-25/2550	467,83
21	Archaic 8 pdr.	2640	2500-2-18/2568	466,32
13	1590 20 pdr.	3640	3600-1- 6/3631	454,72
8	1596 20 pdr.	3610	3500-1- 1/3526	464,41
2	1597 11 pdr.	2650	2500-3- 9/2584	465,19
20	1597 11 pdr.	2700	2600-1- 5/2630	465,67

Counting all Six Cannon

Average uniformity = .97867 pounds/*arratel*, yielding a 463.5. gram *arratel*. Correlation coefficient — .99893.

Discarding # 13

Average uniformity = .97385 pounds/*arratel*, yielding a 465.8 gram *arratel*. Correlation coefficient = .99992.

The correlation coefficient is a measure of the degree of consistency in the values of the weights of the individual cannon in one unit of measure expressed in terms of the other. Put another way, if the correlation coefficient were 1.0000, dividing the English weight of each of the six cannon by its Portuguese weight would yield exactly the same value in each case and the computed grams per arratel figures would be identical.

Mathematically, the correlation coefficient, r, is expressed by the equation. *

$$r = \frac{m\,\sigma x}{\sigma y}$$

where m is the slope of the curve of the weights of the cannon in pounds, x, plotted against their weights in *arrateis*, y, on a two dimensional scatter diagram, and where σ represents the square root of the variance of the weights in pounds, σx, or *arrateis*, σy according to the expression

σx^2 = variance of the weights in pounds.

$$= \frac{\sum_{i=1}^{n} y^2}{N} - y^{-2}$$

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* Texas Instruments TI-55 Owners Manual (1977), pp. 39ff.

bably intended for use on land?[39] Were the weights determined and marked on the gun, in English and Portuguese practice, to assist in balancing ship? Support for this theory is offered by the fact that Dutch cannon were not marked with their weights at the foundry, yet the two largest of *Sacramento*'s Dutch guns have what appear to be Portuguese weight markings crudely scratched onto them (the third element, that denoting *arrataes*, is omitted on one). Were guns captured by the Portuguese weighed on the spot with field scales incapable of fine precision? This theory, plausible on balance, implies a high Portuguese standard of competence in arming and preparing ships for war.

The double weight markings on the English guns raise a final question. If we discard one pair of markings which is slightly "*out*" — the correlation now goes up to .9999 — we derive a value of 465.8 grams for the *arratel*, a value which corresponds to no known value of which the author is aware, 459 grams usually being given.[40] Was there a special naval *arratel* or perhaps a secret ordnance *arratel*? Conceivably, for the Portuguese were notoriously close-mouthed in such matters. In any event, the picture which emerges is one of great care and systematic precision. Is it more than accident that similarly high standards were similarly applied in Portugal and in England? Did the centuries-long alliance between England and Portugal which ended with Phillip's assumption of the Portuguese throne involve close technical collaboration? Only further investigation will tell.

Before proceeding, a point concerning consistency — or the lack thereof — in units of weight: For convenience, we have given the weights of cannon in the original Portuguese units. Our purpose is comparative, so as long as we are consistent Portuguese *arrataes* will serve as well as any other unit. But we have given the "ratings" of the cannon, that is the weight of ball they were intended to fire, in pounds avoirdupois. This facilitates comparison with the armament of contemporary ships of other countries. Since virtually all published references to early modern naval armament categorize cannon in terms of ball weight in pounds avoirdupois, and since the difference is small in any case, there is no good reason to do otherwise.

It is just possible that the *Sacramento*'s 26 pounders discussed above were intended to fire a ball of 25 rather than 26 *arrataes*. The reasoning behind this speculation is based on the value of the *arratel* calculated above, on the bore diameter measurements, and on the best available evidence concerning the difference between ball diameter and bore diameter. The most reliable value for this difference, called "windage", is from the late sixteenth century Spanish author Luis Collado, virtually the only practical gunner to have written on the subject in the early modern period.[41] Collado states that the ball should weigh 10% less than the bore; in other words the ball should be 90% of the weight of a ball which would fill the bore completely, a value which is generally confirmed by at least one English source of a later date.[42] There can be little doubt that Collado's rules for computing windage accurately reflected the accumulated wisdom of the best and most experienced gunners of his day, that is of the 1570s and 80s. Better gunners and cannon founders undoubtedly appreciated the theoretical advantages of reduced windage — more muzzle velocity for less gunpowder was seen as the main benefit.[43] It is probable, too, that the bores of the *Sacramento*'s better cannon were straighter and truer than those of the general run of cannon in Collado's day and that mid-seventeenth century cannonballs more closely approximated perfect spheres than those of a century earlier. But while these factors might have permitted a slight reduction in windage from Collado's day (as they undoubtedly did over the long haul[44]) they were of less consequence than the need to provide adequate clearance for the buildup of powder residue in the bore. If our assumptions concerning the level of competence of early modern cannon founders are correct, then these two factors were carefully considered and weighed against one another.

If we assume that the intended bore diameter of the six pieces by Lucas Matias

Escartim was 5.98" (15.2 cm), then a cannonball of 25 *arrataes* would have weighed 88% of the bore "weight" and a 26 *arratel* ball would have weighed 92% of the bore. On balance, the larger value seems the more probable; it is just marginally tighter than Collado's value of three quarters of a century earlier, which is what we would expect, so our 26 pounders are 26 pounders in either system. The difference is a fine one: We are talking about a total difference in windage and ball diameter of only about .04" (1 mm). Still, we have every reason to believe that the seventeenth century founder strived for, and frequently attained, the standards of precision which this implies.

To return to the main thread of our argument, the age of the *Sacramento*'s English cannon is undoubtedly indicative of a general shortage of good ordnance. The efficient proportions and apparent high quality of the new Portuguese 26 pounders and 11 pounders makes it clear, *prima facie*, that more of them were not used only because no more of them were available. But we should not make too much of this, for the most persuasive evidence of shortage which the English guns provide is not their age, but the fact that three of the six deviate from the presumed standard of 26 pounders for the lower gundeck and 11 pounders for the upper.

If their condition after three centuries of salt water immersion is any indication of quality, the *Sacramento*'s English guns were every bit as well made as the rest of the ship's ordnance and a good deal better than some of it. Despite their advanced age when the ship went down, they are in better condition today than all but the Lucas Matias Escartim pieces and two of the Dutch guns. More significantly, the four dated English pieces are comparatively light in terms of projectile weight.

The two 20 pounders by John and Richard Phillips compare favorably with the only other 20 pounders aboard; these are two Dutch cannon, one cast by Assuerus Koster in 1634 and the other by Conrad Wagwaert in 1649. If we assume that the crudely scribed inscriptions on the Dutch guns referred to earlier represent their weights (an assumption confirmed by rough volume/density computations, comparing indicated weight per unit of volume with that of contemporary Portuguese guns: all fall in the range of .23 lb/in^3 to .25 lb/in^3 [45]) we get a value of approximately 190 pounds of gun per pound of ball for the Dutch cannon and 180 pounds per pound for the English. When we consider that 38 years of development separated the newest of the English cannon from the oldest of the Dutch and that the whole thrust of cannon development was toward shorter, lighter guns (a point thoroughly documented for English cannon by Michael Lewis [46]) the quality of the English guns is apparent. This point, and the impression of quality, is further underlined by comparing the two English 20 pounders with each other. The newer of the two, though clearly made to the same model (Figure 5), is significantly thinner toward the muzzle and thirty pounds lighter. Did the Philips brothers slowly and steadily refine their model as they mastered their medium? Though a sample of two and a difference of thirty pounds is too thin a statistical basis for sweeping generalizations, it is hard to escape the suspicion that we can see, in these two guns, a process of incremental modification under extremely close quality control, directed toward the ideal of lightness and shortness. The virtually identical proportions of the two 1597 11 pounders by George Elkine strengthens the suspicion.

The presence in *Sacramento*'s battery of five Dutch cannon, like that of six English cannon, implies a shortage of good ordnance. The reasons, however, are different. Unlike the English guns, the Dutch cannon are not particularly old. The oldest was cast in 1622 (the undated 4 ½ pounder by Assuerus Koster was probably cast in the 1630s or 40s). They are, however, utterly unstandardized in bore diameter and ball weight. Since they were probably acquired through capture, this is understandable; but the need to use a polyglot mixture of captured cannon on a first class warship speaks for itself, unless the ordnance in question was of superior quality, and there is nothing to suggest that it was.

Leaving the two small *deck pieces* out of the discussion, for we have nothing against which to compare them, the two Dutch 20 pounders match only the two pieces by the Philips brothers. The 15 pounder finds a counterpart in the Portuguese piece by the founder P.D.B. The proportions of these two cannon are very close to one another but this apparently favorable comparison must be qualified for the P.D.B. cannon, though undated, is probably the oldest of *Sacramento*'s Portuguese guns. It is longer and thicker in its proportions than the other Portuguese cannon and differs markedly from them in both the design of the breech cap and in the color and condition of its metal, which is badly pitted and has a distinct greenish hue. The simple and relatively small Portuguese royal crest on the breech of this piece is nearly identical in design to the crests on the two oldest English cannon. Is this evidence that the P.D.B. gun was cast before 1580? Perhaps; the implication in both cases is that Dutch founders followed a model which had already been abandoned as obsolescent in England and Portugal. The considerable variation in color among the Dutch pieces — the Conrad Wagwaert 20 pounder has a blackish, almost ebony-like sheen, and the Henricus Meurs 15 pounder has oxidized to a light pastel green — suggests that their Dutch founders had not yet established the degree of control over the composition of their alloy that English and Portuguese founders had.

What *is* plain, is that the Dutch cannon differ markedly in design and construction from their Portuguese equivalents. There is reason to believe that Dutch methods, whatever their technical merits, produced a gun which was more expensive than its Portuguese equivalent. (Figure 9)

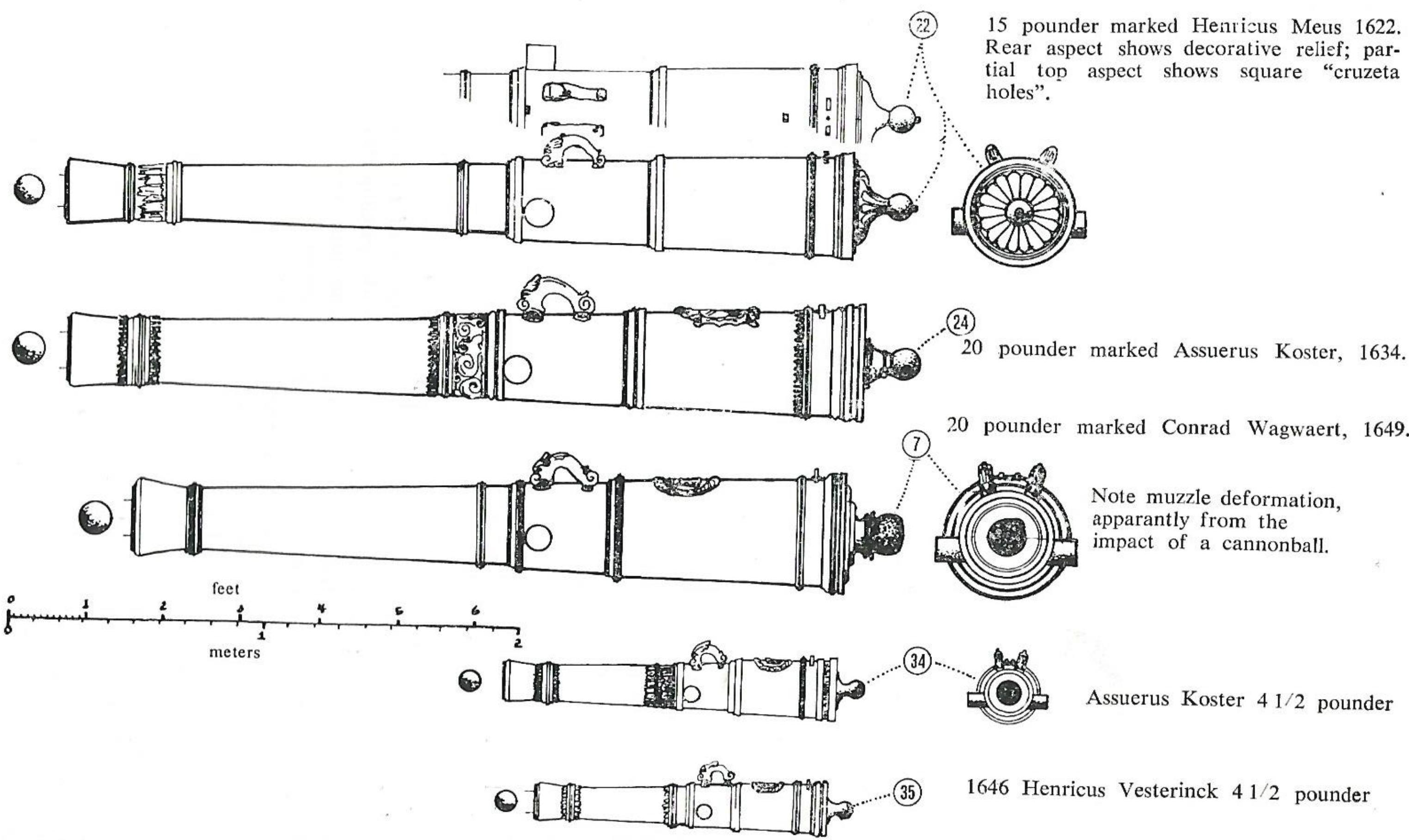
This is perhaps unfair to the Dutch founders. With the exception of the Conrad Wagwaert 20 pounder cast in 1649, the *Sacramento*'s Dutch cannon are older than all but the oldest one or two of the Portuguese guns and the Wagwaert piece is only marginally longer and thicker than we would expect a contemporary Portuguese 20 pounder to be. It is worth noting in this context that while the *Sacramento*'s 1634 20 pounder by Assuerus Koster is relatively long, thick (and heavy if the scratched-on weight markings are believed) by Portuguese standards, a 1649 28 pounder by the same founder in the *Naval Shipyard* in Rio de Janeiro is close in proportions to the best of *Sacramento*'s 26 pounders. This suggests that Dutch founders had caught up by mid-century. The fact remains, however, that *Sacramento*'s Dutch guns are longer and thicker than Portuguese and English equivalents locked in the same archaeological context, this despite the fact that the English cannon are from a quarter to a half century older. Were the metal workers who cast *Sacramento*'s Dutch guns relatively new to the business of cannon founding and just beginning to catch up to Portuguese and English practice? The question is an intriguing one which deserves exploration.

In one area evidence of Dutch economic inefficiency is unequivocal. Even assuming a rough parity in ball weight to barrel weight ratios, Dutch cannon must have been significantly more expensive than their Portuguese and English equivalents in terms of hours of skilled manpower expended per pound of ball thrown. The Dutch cannon are, to a gun, encrusted with elaborate raised floral ornamentation, inscriptions, and nautical motifs. The presence of elaborately decorated guns as functional booty on the gundecks of an enemy warship suggests convincingly that such ornamentation was not confined to a handful of select presentation pieces. It is the author's impression, formed in museum collections and solidly backed by *Sacramento*'s gundeck, that ordinary operational Dutch cannon were showcases for the low relief sculptor's art. Each of the *Sacramento*'s five Dutch cannon is covered with a jungle of entwined foliage, fouled anchors, Admiralty crests and mythological beasts. The beauty of the results speaks for itself; but ornamentation added weight, absorbed labor and did nothing whatever for ballistic efficiency.

Why did the Dutch expend such effort on ornamentation? How does the care devoted to decoration square with appa-

Figure 9

Dutch Cannon Recovered from Santíssimo Sacramento



rent failure to weigh the product? The obvious explanitory hypothesis is that labor was cheaper in Amsterdam than in London or Lisbon.

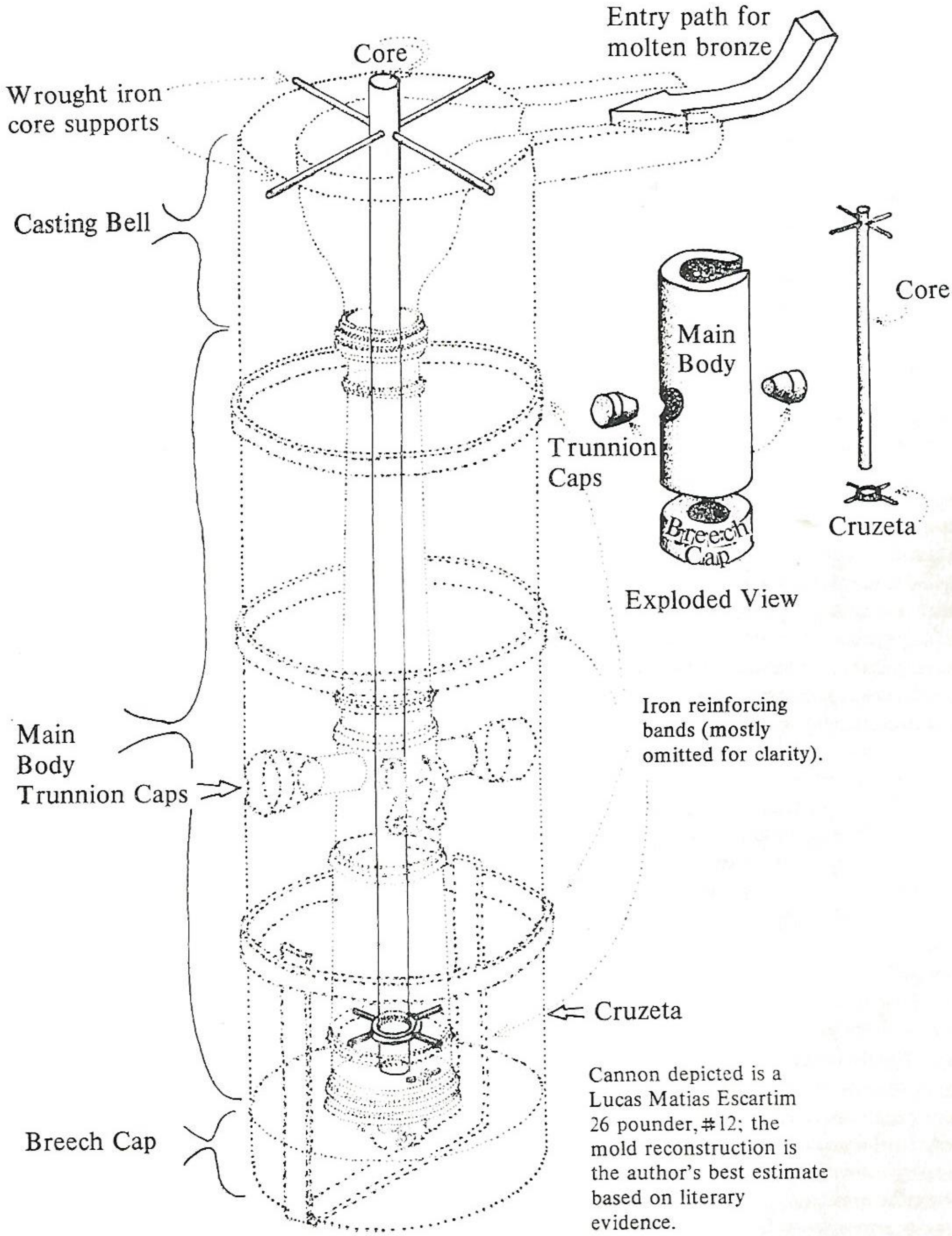
This hypothesis, however, is questionable on both technological and economic grounds. Northern European founders were among the first to abandon cannon designed to fire cannonballs of *cut stone*, the Dutch presumably among them — if they ever embraced cannon firing stone cannonballs, a suggestive area of doubt. The main driving force behind the abandonment of stone cannonballs and cannon designed to fire them was economic, the rising cost of labor. Stone cannonballs were more effective tactically than those of cast iron, particularly at sea. Cannon designed to fire them used a third less bronze for the same projectile weight, a significant economic advantage since bronze was expensive. But the labor of a skilled stonecutter — and it required immense skill to cut a perfect sphere of stone to exact dimensions — was expensive too, and wage rates rose precipitously beginning early in the sixteenth century and continuing through the seventeenth. [47] Significantly, the stone--throwing cannon fell from favor earliest in areas where the wage price spiral advanced earliest. Northwestern Europe was the first such region. That the technical and tactical advantages of stone--throwing cannon were exploited where economic conditions permitted provides strong, if indirect, proof of the hypothesis of economic causation. The Portuguese continued to cast cannon designed to shoot stone cannonballs in India, long after they had abandoned them in the West: The most recent Portuguese stone-thrower of European manufacture in the collection of the Museu Militar in Lisbon was cast in 1578 while such cannon cast in India through the middle of the seventeenth century are common. [48] Stone-throwing cannon continued to be cast in the Ottoman Empire, where the advance of the wage price spiral was much slower than in northwest Europe, into the eighteenth century. [49] In sum, there is compelling evidence that labor, both in general and as it affected cannon founding, was relatively expensive in northwestern Europe in the middle 1600s, yet Dutch cannon founders persisted in the obviously labor intensive practice of elaborately decorating their product. Why?

Are we dealing with an entirely distinct technological ethos, involving an independent and separate tradition of cannon founding? Were Dutch founders — to overstate the point — romantic exponents of an obsolete tradition while their English and Portuguese brothers were hardheaded realists, held firmly in touch with technological efficiency by fiscal reality?

While the question is speculative, it is certain that Dutch constructional techniques represented in *Sacramento*'s cannon differ sharply from contemporary English and Portuguese practice in at least one important particular. Following a tradition which can be traced back to Biringuccio's *de Re Pirotechnia* of the 1530s, *Sacramento*'s English and Portuguese cannon were cast with a wrought iron centering device for the core of the mold imbedded in their breeches. The centering device, called a *cruzeta*, was of wrought iron. It consisted of a thin ring with an inside diameter equal to that of the bore, held in the center of the mold by evenly spaced rods, usually four, projecting outward from it in the same plane. [50] (Figure 8).

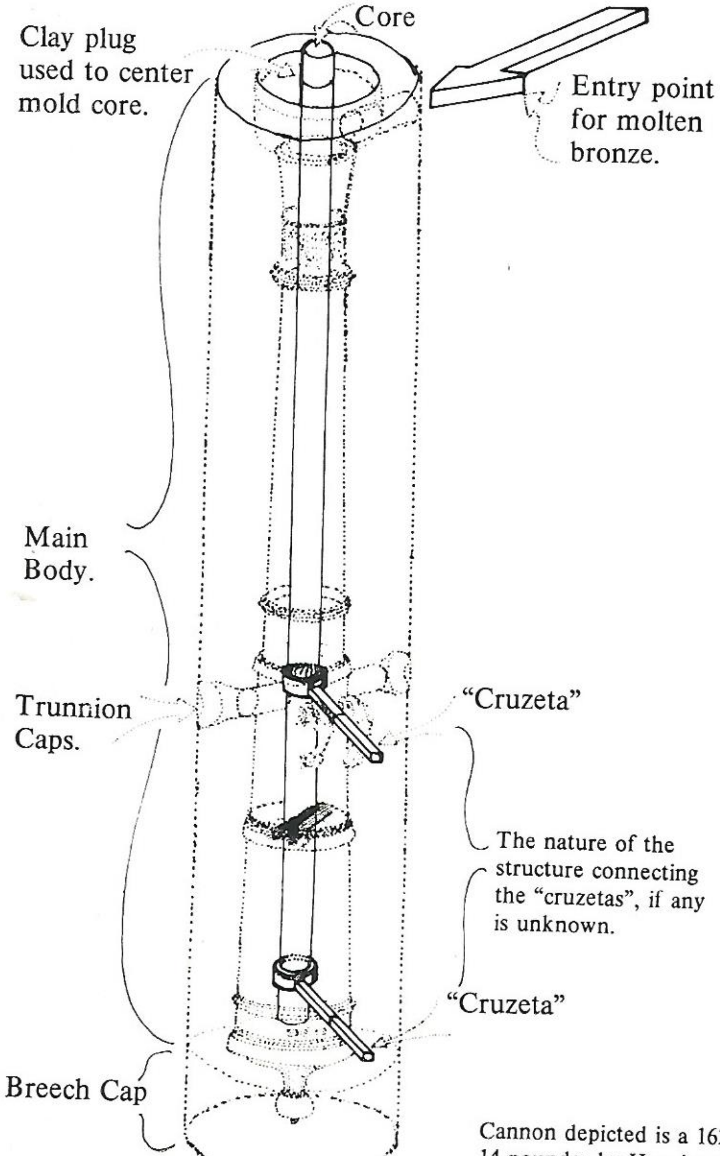
In preparation for the casting process, the body of the mold was lowered into the casting pit muzzle upward. The core was then lowered into the main mold supported and centered at the muzzle by means of external supports, probably iron rods passing through the extended core and into the walls of the mold *for the casting bell.* [51] The trunnion caps were then placed on the main mold (which was made in the form of a sleeve, open at the breech, the muzzle and the ends of the trunnions). Next, the *cruzeta* was slipped over the bottom of the core and into the mold from below and clearances checked to insure that the projecting rods held the core exactly centered. After insuring that the mold was dry, clear and free of foreign matter which might have fallen in, the breech cap was fastened to the bottom, and the final layers of reinforcing material placed around the assembled mold and baked dry.

Figure 8
Portuguese Cannon Mold Schematic



Cannon depicted is a Lucas Matias Escartim 26 pounder, #12; the mold reconstruction is the author's best estimate based on literary evidence.

Figure 8a
Dutch Cannon Mold Schematic



Cannon depicted is a 1622 14 pounder by Henricus Meus, # 22. Placement of the twin "cruzetas" is based on examination of the cannon; their external dimensions are hypothetical.

When the cannon was cast, the *cruzeta* remained imbedded in the cannon metal. Because time was limited and because the author did not fully appreciate the significance of *cruzeta* design and placement at the time, investigation of the *cruzetas* was limited to efforts to locate the external tips of *cruzeta* rods. This was accomplished visually where the rods had corroded away, leaving holes (these are typically round and ¾" (1.5 cm) in diameter), and by the use of a magnetic detector (an ordinary stud finder was used) where they had not.

This approach presented problems. Remarkably few of the *cruzetas* have corroded away; those which have not are hard to see — in some cases, impossible. Their magnetic attraction is slight (the author's assistant, Brazilian Navy Corporal Ideraldo Barbosa de Souza, was far more successful, both visually and magnetically, than the author). This presented few problems with the modern Portuguese 26 pounders and 11 pounders. On these pieces, *cruzeta* placement was regular and the area of magnetic search could be narrowed down. On all of these cannon the location of the *cruzeta* tips along the fore and aft axis of the barrel was consistent; on all of these cannon the angular placement of the four *cruzeta* tips in a transverse plane corresponded closely to 1:30, 4:30, 7:30 and 10:30 o'clock, viewing the cannon from the rear and visualizing the breech as a clock face. Variations in the radial placement of the tips from this ideal scheme were typically less than thirty minutes on the imaginary clock face, but in a few cases were as much as an hour. This incidence of variation suggests that *cruzetas* were individually fitted after the moulds had been set up, implying that considerable effort was expended to insure that the cores were precisely centered. This makes perfect sense, since barrell wall thickness at the breech was the most critical single dimension in a cannon.[52]

With the older Portuguese cannon *cruzeta* placement was less standardized. In several cases it appears that the *cruzetas* had only three legs, though it is probable that at least some of the missing "fourth legs" could not be located because they were at the bottoms of breeches of cannon which could not be lifted to check. The *cruzeta* tips on the English cannon were particularly difficult to locate; as a result, there is a possibility that the Phillips brothers used a design with only two horizontally opposed supporting rods.

It is nevertheless clear that the founders who produced *Sacramento*'s Portuguese and at least her four newest English cannon worked within the same tradition of *cruzeta* design and placement. The Dutch cannon are another story. The two small 4 ½ pounders appear to have *cruzetas* much like those of *Sacramento*'s English and Portuguese pieces; it is possible that the 1649 20 pounder by Conrad Wagwaert does too (magnetic indications of iron were found in only one spot, but that spot was consistent with Anglo--Portuguese practice). The other two Dutch guns, however, were cast with some sort of internal iron structure within the cannon metal about halfway down the barrel. This is most clearly apparent on the 1622 piece by Henricus Meus which has two square holes measuring about 1" X ¾" (2.5 cm X 2.0 cm) on top of the barrel, one forward of the touchhole and the other between the lifting *dolphins*. The 1634 20 pounder by Assuerus Koster has two conventionally placed *cruzeta* tips at 10:30 and 1:30, but there is magnetic evidence of a large mass of ferro-magnetic material atop the barrel between the dolphins. This last indication is particularly puzzling: the cannon in question has been well cleaned and polished (it is kept under cover at the 2nd Naval District Headquarters in Salvador), so there can be no question about the quality and appearance of the surface of the gun, yet there is no visual or tactile evidence whatever of anything but bronze in the area of strong magnetic indications.

Was the 1634 Assuerus Koster piece cast with a free-floating structure of iron within the barrel? Was it cast with an iron structure protruding into the mold which was cut away after casting and filed down into a depression which was subsequently filled with molten bronze? The first hypothesis seems unlikely on structural grounds; what good would an assymmetrical iron structure within the barrel (the only magnetic indications are at the 12:00 o'clock position) have done? The second seems improbable in light of the labor required. All we can say with certainty is that some Dutch founders used a second *cruzeta*-like structure imbedded in the cannon metal approximately halfway down the barrel and that in some cases it approached the surface of the cannon, if it did not reach the surface, at the 12:00 o'clock position between the cannon's dolphins.

Clearly, the Dutch founders represented on *Sacramento*'s gundeck imbedded more iron beneath the surface of their cannon than their Anglo-Portuguese contemporaries. Why? Did they use a second *cruzeta* to avoid the use of external supports for the mold core? Did a second "*cruzeta*" allow them to dispense with the use of a *casting bell*, yielding savings in bronze and fuel required for casting? This hypothesis squares with the relatively greater length of the Dutch pieces, for a longer barrel served the same purpose as the casting bell: a taller column of molten metal and, therefore, denser, stronger metal at the breech. But such a practice would ultimately have been inefficient in terms of bronze consumption, for the height of the *casting bell* could be varied independently without affecting barrel proportions, and the bronze in the bell could be remelted and reused after it was cut away. The only plausible economic advantage in such a casting method would have been in fuel consumption, a smaller amount of bronze having to be melted for each cannon. It is difficult to imagine this advantage being important except in a very small scale operation or where charcoal was very expensive. This may be a useful clue. There was a relatively unified world market in bronze, and in its constituient metals, copper and tin; all were high value, low bulk commodities which could be economically traded over long distances. [53]

Since the Netherlands were presumably no better off in charcoal resources than England, and since we know that England effectively exhausted her industrial charcoal resources before 1600 (one of the most important effects of this development was the elimination of England as a factor in the international export trade in artillery [54]), this makes a certain amount of sense. Though the Dutch could presumably have imported fuel from Germany and elsewhere, the impact of freight costs on the cost of charcoal, a low bulk, relatively low value commodity, would have been considerable.

Still the fact of the matter is that the Dutch continued to cast cannon which could compete effectively with those of their enemies, however expensive they may have been. It should also be remembered that the Dutch were specialists in high bulk, low value maritime trade and that they were able to sustain a generally favorable trade balance, year in and year out, in spite of everything. If *anyone* could have afforded to use expensive imported charcoal in the seventeenth century, it would have been the Dutch. The facts most relevant to our analysis, therefore, are the relatively inefficient proportions and the apparently inefficient design of Dutch artillery.

Were the Dutch relative latecomers to cannon founding, using technically effective but economically inefficient technology as they caught up? There is additional evidence to support this hypothesis in the two oldest of the *Sacramento*'s English cannon. Both of these cannon show, like the Dutch guns, evidence of large amounts of ferro-magnetic material imbedded in their bronze, in this case in the breech caps, the trunnions, and the lifting rings atop their barrels. Our relatively primitive means of investigation preclude saying more; a stud finder will not react to iron more than about an inch (2.5 cm) away, regardless of the amount involved. We can therefore only be sure that there is ferro-magnetic material beneath much of the surface of these two cannon, most of it in areas where high strength was desirable.

Were these cannon made of a composite structure, with a wrought iron reinforcing structure interlacing the bronze? Were the Dutch guns with indications of an internal iron structure similary made? Though there is no written record of such composite construction, the idea is an intriguing one. The long persistance of non-functional "reinforcing rings" on bronze cannon barrels suggests a continuity of design tradition extending back to the wrought iron bombards of the fifteenth and fourteenth centuries with their thoroughly functional shrunk-on hoops. The composite iron and bronze construction of *Sacramento*'s oldest English cannon may well represent a missing link in the chain of design and manufacturing tradition which we have posited. A careful re-examination of contemporary ordnance in collections throughout the world in light of what we have found here should test out this hypothesis.

We know that the tradition of cannon founding which we have described here and traced back to Biringuccio was not the only one. Though we know that it ultimately became the dominant tradition, at least in Europe, we cannot say when or how it prevailed. In short, we do not know the relationships between this central tradition of cannon founding and the other traditions of which we are aware.

Perhaps the best documented of these competing traditions was that used by the Ottomans in casting large stone-throwing cannon. These guns were cast with their breeches uppermost in the casting pit, an arrangement which permitted relatively thin barrel walls forward of the powder chamber, resulting in significant economies in the amount of bronze required for the weight of ball thrown. [55] This method remained viable as long as labor was cheap and bronze expensive and continued to be employed in the Ottoman Empire well into the 1700s.[56] There are whispers of evidence that suggest the existance of other traditions: Ottoman *cruzeta* placement on iron-throwing cannon seems to have varied, at least in some cases, from the practice which we have described here, no less than five *cruzeta* legs being observed on the surface of the breech of one example. [57] At least some Ottoman stone-throwers were cast breech down, or so the existance of *cruzetas* in their breeches would seem to indicate. [58] The evidence of an independent Dutch tradition of *cruzeta* placement which we have cited here is unequivocal and may be indicative of differences in other areas such as alloy composition.

It is a safe bet that there were other traditions of bronze cannon design and founding which remain undiscovered, perhaps including an ancestral tradition which was superseded for economic reasons. This is enough to suggest that a searching look be given to early bronze cannon throughout the world as a first step toward developing hypotheses concerning the origins of cannon and gunpowder, an area which, despite its historical importance, has been the subject of far more uninformed speculation than serious scholarly investigation.

We thus end our analysis where we began, with the importance of early ordnance in general and early modern naval cannon in particular. Through analysis of the guns of *Santíssimo Sacramento*'s gundecks we have validated some old hypotheses and developed some new ones to apply to the analysis of early guns and gunnery. These lead to a number of general conclusions:

We now know that at least the very best early modern bronze ordnance could remain in active service for much longer than we might have supposed, perhaps for well over a century. We suspected this previously, but lacked unequivocal supporting evidence. How exceptional were *Sacramento*'s two archaic English cannon? We cannot say, but their presence aboard an operational warship over a century after their manufacture, positively confirmed by the archaeological context, tells us a great deal more than we would have suspected otherwise.

This suggests in turn that the very finest bronze cannon of the sixteenth century were barely inferior — if at all — to the best cannon of the seventeenth, and were centainly better than the run of the mill average. This contradicts the usual mental construct which views technology as advancing by qualitative improvements in the technical capabilities and characteristics of individual examples of the item of technology in question. The implication in this case is that evidence of advances in cannon technology should be sought in increases in range, accuracy or destructive capabilities or relative reductions in size or weight. Economic factors and quantitative considerations normally receive short shrift. Evidence from the *Sacramen-*

to's gundecks contradicts this. The suggestion that earlier foundry practice may have produced technically superior ordnance by labor-intensive methods which could not be retained in the face of the wage and price spiral of the late sixteenth and seventeenth centuries is supported by the long survival in operational service of cannon with archaic constructional features as noted above. Long survival in demanding service at sea is eloquent testimony of technical quality; the disappearance of the constructional methods used in their manufacture was therefore almost certainly unrelated to technical excellence or tactical effectiveness. The most reasonable hypothesis is cost and the most likely casual mechanism the rising price of labor, a factor which was offset, in part if not wholly, by economies of scale as capital investment increased and cannon founding transitioned from a craft to an industry.

The degree of control which at least the best of the Portuguese and English founders represented on *Sacramento*'s gundeck exercised over the physical characteristics of their product suggests that historians of technology and science have badly underestimated the early modern cannon founder. The evident care and precision with which the English and Portuguese weighed at least their naval ordnance suggests that the early modern sailor, shipwright and gunner have been similarly underestimated as well. Though their efforts were not driven — at least so far as we know — by elegant theories of internal ballistics, metallurgy, or the relationship between *stress and strain* in thick-walled tubing, their application of incremental development based on trial and error supported by close quality control was highly successful. The fact that we cannot, to this day, articulate a coherent theory capable of explaining the explosive decomposition of black powder [59] or predicting the safe limits of chamber pressure in a cast bronze cannon [60] suggests that this is an area worthy of serious scholarly attention. The historical importance of cast bronze cannon combines with the inability of traditional historiography to explain how and why early bronze ordnance was made as it was to suggest the possibility of a major breakthrough in methodology might result from the effort.

It is apparent that the development of cannon founding did not proceed evenly throughout Europe or the rest of the World. Rather, there is clear and unequivocal evidence of several independent traditions of cannon foundry. Of the examples at hand, the English tradition seems to have advanced furthest during the sixteenth century, perhaps in concert with the Portuguese. The Dutch, by contrast, seem to have lagged behind the Portuguese during at least the first half of the seventeenth century, preserving an independent foundry tradition and producing cannon which were longer and bulkier than their Portuguese equivalents and probably more costly to produce in terms of man hours of labor required as well.

The belief that Portugal was desperately short of ordnance following her reassertion of independence in 1640 is strongly confirmed by the evidence of *Sacramento*'s gundeck. Despite evidence that Portugal's founders and shipwrights were well aware of the value of artillery standardization and were technically capable of achieving it, the *Sacramento* carried an amazing diversity of armament. Nearly half of her gundeck ordnance was of cast iron and much of her bronze ordnance clearly represents what was available rather than what was preferred. The unequivocal evidence of Portuguese technical competence which emerges from the examination of *Sacramento*'s cannon makes the evidence of shortage even more persuasive.

The above points lead to another conclusion, perhaps the most basic of all. Virtually everything that we have learned from the *Sacramento*'s gundeck is heavily colored, if not exclusively driven, by the archaeological context. Had our cannon been preserved independently and studied individually, out of the context provided by marine archaeology, the conclusions would have been quite different and far more limited. It is no exaggeration to assert that the application of marine archaeology broadens the study of early modern ordnance from a technical exercise of limited value to a potentially powerful source of evidence for the economic and social historian as well as for the student of naval architecture and weaponry.

Much still remains to be learned from the cannon which went to the bottom off the mouth of the Rio Vermelho on that ill-fated night in May of 1668. Measurement and careful examination of the insides of the bores is an easy and obvious next step. This would significantly expand our knowledge of *cruzeta* design, a matter of interest for the Dutch cannon in particular. It would also permit examination of touchhole placement within the bore, probably the second most critical dimensional characteristic next to barrel wall thickness at the breech. [61] This would also shed light on the shape of the inside chamber, a critical area of cannon design about which next to nothing is presently known. The amount of work required to clean the bores should not be great and the problem of devising special tools to permit visual examination and measurement of the insides of the bores should not be difficult.

Weighing the cannon and measuring their volumes through determination of the amount of water which they displace is another step which can be undertaken without the commitment of extensive technical resources. An industrial scale and a calibrated water tank would suffice. Knowledge of the weights and densities of the cannon would sharpen our comparative dimensional analysis permitting, for example, close estimates of the proportion of non-structural bronze used in decorative appendages and ornamentation.

More sophisticated methods for determining the placement and amount of iron within the bronze barrels should be possible, beginning with specific density calculations based on weight and volume determinations as suggested above and extending to experimental determinations of centers of gravity.

Finally, the removal of small metal samples from carefully selected locations on the cannon for spectroscopic, chemical and photo micrographic analysis should lead to enormously expanded understanding of the metallurgy of bronze cannon and, from that, to an enhanced understanding of the founders and their art. Samples consisting of as little as 20 miligrams of drill cuttings, containing a quantity of metal about the size of the tip of a pencil lead, are sufficient for spectroscopic analysis. Slightly larger samples are sufficient for quantitative and qualitative chemical analysis. While the removal of metal from the guns should be undertaken only as a final step and in light of all other evidence, the author's experience suggests that a great deal can be learned from in this way. [62] What trace elements were present in the cannon metal? How closely could a given founder control the composition of his alloy? How much did the composition of the alloy vary from one part of the cannon to another? Finally, and perhaps most basic, how did variations in the composition of the metal from one part of the cannon to another affect the strength of the barrel? The answers to this last question, which may well have implications in metallurgy and experimental stress analysis, will not be easily gained; the destructive testing of small billets of bronze, specially alloyed and cast to duplicate the composition of the cannon metal at given locations in given guns, would be required to develop a comprehensive structural picture of the cannon. While neither cheap nor easy, the process would surely add to our understanding in a number of areas.

Our final question is impressionistic and romantic rather than quantitative and calculating. What kind of a ship was the *Santíssimo Sacramento*? What did she look like? How did she operate? What was service on her gundeck like?

We can offer a few suggestions based on the limited evidence at our disposal. We must begin with a presumption of competence. However ill-advised *Sacramento*'s direction was on the night of the wreck, such ineptitude must have been exceptional. The Dutch, after all, were no slouches; in warfare afloat, they gave as good as they got against some very competent opposition. There is no reason whatever to suppose that they sent their second team South while their best ships and seamen had at it with the hard bone of the English fleet in the Channel 1. Not only does the chronology militate against the supposition, the Dutch simply didn't operate like that. The Portuguese caught it from the best that Holland had to offer — at least the best that was capable of operating with effect so far from Zeeland and the Scheldt — and the Portuguese, dealing from a very weak deck, beat them at their own game. The grueling and sustained war along the Brazilian coast and along the sealanes connecting Brazil with Portugal did not go to the Portuguese by default.

Sacramento's gunners, therefore, were competently led: They were men who knew how to use their cannon with telling tactical effect. They had to be good, for any likely arrangement which we may posit for her gundeck ordnance—and any such arrangement is highly tentative in light of our relative ignorance concerning the galleon's cast iron guns — suggests serious operational problems. The close proximity to one another of cannon firing different sizes of ball and requiring different quantities of powder and sizes of ladle would have presented difficulties under the best of conditions. How was ball and charge matched to bore in mid--battle in the earsplitting chaos of a smoke-filled gundeck? Who supervised the issue of shot from the shotlocker? Did the gunners have shot gauges to guard against possible error? None have been found in the wreck, but this is not necessarily conclusive since they may have been of wood. It does not appear that the *Sacramento*'s gunners made use of the gunner's quadrant, though this statement must be similarly qualified. They did, in at least some cases, make use of *gunner's picks*, calibrated measuring "daggers" and copper knives for cutting cartridges open.

More basically, who decided which cannon went where based on what criteria? The carefully incised weight inscriptions on the Portuguese and English cannon hint at a strong central direction of considerable sophistication and competence; the more crudely scratched weights on the captured Dutch pieces suggest that a great deal of that competence and sophistication went to sea.

What was the opinion of the gundeck concerning the relative merits of Portuguese, Dutch and English ordnance? Did it match our own? How conscious were *Sacramento*'s officers and men of the shortage of cannon which afflicted their nation and their ship?

The answers to these questions are ultimately lost in the mists of time, but they are well worth asking for, we who write and study have an obligation to those from whom our evidence has been taken. We can learn from knowledge of the consequences of their actions. In this sense, *Sacramento*'s gundeck crew and the men who cast her cannon live on.

NOTES

1. For instance BASS, George F. and NICKIN, Jr., Charles R., "New Tools for Undersea Archaeology", *National Geographic*, v. 134, n. 3 (sept. 1968) and FROST, Honor, "The Punic Warship Re-erected in Marsala", *The Mariner's Mirror*, Vol. 56, No. 1 (February 1979), p. 37.

2. Notably the work of Colin Martin, *Full Fathom Five: Wrecks of the Spanish Armada* (London, 1975) and that of Robert Sténuit published in *National Geographic*, most recently "The Sunken Treasure of St. Helena", Vol. 154, No. 4 (Oct. 1979).

3. ALLEN, Geoffrey and David, *The Guns of Sacramento* (London, 1978) is unique in describing a marine archaeological effort focussed on the recovery and analysis of ordnance. Through the Allens' identification of their wreck as the Portuguese India galleon *Santissimo Sacramento*, lost off the southeast coast of Africa near 34° South Latitude on 29 June 1647, has been questioned, I find their arguments convincing. There are strong parallels between the Allens' *Sacramento* and the subject of our analysis (the names are identical by coincidence; *Santissimo Sacramento* was a popular name for Portuguese warships; no less than six India galleons alone received that name or minor variations on it between 1629 and 1692, information in a letter to the author from Professor T. Bentley Duncan, Department of History, University of Chicago, cited in full in note 21 below) and the wrecks were separated from one another in time by only two decades. The opportunity for a parallel study of Portuguese cannon founding practice in the East and in Portugal is a compelling one and a joint study has been proposed to Mr. David Allen by the author.

4. Practical broadside shipboard artillery predated the *Mary Rose* by only a decade or so, if at all. Evidence for the watertight gunport, an inextricably connected development, is scanty and equivocal before the *Mary Rose*'s day, yet there is no doubt that *Mary Rose* had lidded gunports. See RULE, Margaret. "An Early Gun-Port Lid", *The Mariner's Mirror*, Vol. 62, No. 2 (May, 1976) pp. 184-5.

5. BIRINGUCCIO, Vannoccio. *The Pirotechnia*, Cyril S. Smith and Martha T. Gnudi trans. (New York, 1942), based on the 1540 Venice edition. For the technical development of bronze artillery before design crystallized along the lines described here, see MULLER, Heinrich. *Deutsche Bronzegeschützrohre* 1400-1750 (Leipzig, 1969).

6. MAHAN, Alfred Thayer. *The Influence of Seapower Upon History*, 1660-1783 (Boston, 1890), for example p. 10 and pp. 21-22 where Jominis is quoted to the effect that changes in firepower have little effect on "...great strategic operations and the grand combinations of battles."

7. For an incisive critique of Mahan's method, see SYMCOX, Geoffrey. *The Crisis of French Seapower 1688-1697, From the Guerre d'Escadre to the Guerre de Course* (The Hague, 1974), p. 228: "Mahan's conservative cast of mind, and his lack of interest in technological matters, blinded him to the continual changes that had taken place in the way war was conducted at sea. *The Influence*... contains no discussion of guns and sails, of rigging and provisions... Seventeenth century fleets could not win and hold control of the sea as his doctrine required: Beachy Head and La Hogue are clear proof of this."

8. LEWIS, Michael. *Armada Guns, A Comparative Study of English and Spanish Armaments* (London, 1961), for example, p. 167, though the assumption that long barrels meant long maximum range is implicit throughout the entire work. For the belief that length and range are positively related pushed to the logical extreme, see MUÑIDO, Olesa. *La Galera en la Navegación y el Combate* (1971, Barcelona), Vol. I, pp. 102-3, where he concludes, a *priori*, that Spanish culverins had a range advantage over Venetian culverins because they were heavier. In fact, Luis Collado, a contemporary, a Spaniard and an artillerist, considered the greater weight and length of Spanish guns an encumbrance and nothing more, *Platica Manual de Artilleria* (Milan, 1592), *Tractado* II, *Capitulo* II, folio 8, and explicitly ranks them behind Venetian cannon in quality. Much scholarly discussion of ranges has been based on the maximum values in the "range tables" contained in many sixteenth and seventeenth century works on ballistics and gunnery. With the occasional exception of values for point blank ranges, these tables are almost entirely fanciful, containing maximum ranges which could have been obtained only by muzzle velocities in the neighborhood of 6,000 feet per second (2,360 meters per second), nearly six times the speed of sound. This was determined for the author by Mr. J. W. Kochenderfer and his co-workers in Firing Tables Branch, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, in the spring of 1970, using orthodox ballistic theory as stated in LIESKE, Robert F. and REITER, Marly L. Ballistic Research Laboratory Report No. 1314, *Equations of Motion for a Modified Point Mass Trajectory* (Aberdeen, March, 1966) and accepted drag coefficients for spherical projectiles. In fact, muzzle velocities in excess of 1,500 feet per second (590 meters per second) were probably rare and anything above 2,000 feet per second (780 meters per second) must be considered suspect. See RODMAN, Thomas Jefferson, *Reports of Experiments on the Properties of Metals for Cannon and the Qualities of Cannon Powder...* (Boston, 1861), pp. 106-109, for the results of calibrated test firings with black powder and spherical projectiles. Rodman's tests produced no velocities in excess of. 1,400 feet per second (551 meters per second).

9. ARMY Material Command Pamphlet AMCP 706-150 Engineering Design Handbook, Ballistic Series, *Interior Ballistics of Guns* (February, 1965) contains a useful discussion of burning characteristics of artificially compounded propellants.

10. The best treatment of this complex and ill-understood subject of which I am aware is HARRIS, L. E., LANNON, J. A., FIELD, R. and HUSTED, D. "Spectrographic Investigation of the Combustion of Black Powder", *Journal of Ballistics*, Vol. II (1978), pp. 353-91; since this study is concerned primarily with the initiation and chemistry of combustion, its discussion of the effect of pressure on the combustion rate of black powder must be qualified. See GUILMARTIN, JR., John F. *Gunpowder and Galleys* (Cambridge, 1974), pp. 277-83, for a general discussion of the factors involved, particularly p. 282 for experimental results indicating that above a low threshold pressure of approximately 200 lb/in^2 ($14.06\ kg/cm^2$) pressure ceases to have an effect on the burning rate of black powder. Though over a quarter of a century old, BLACKWOOD J. D. and BOWDEN, F. P. "The Initiation, Burning and Thermal Decomposition of Gunpowder", *Proceedings of the Royal Society*, Series A, Mathematical and Physical Sciences, No. 1114, Vol. CCXIII (8 July, 1952) remains a basic text on the subject.

11. This was well known to ballisticians and ordnance experts in the latter half of the nineteenth century. See, for example, BENTON, J. G., *A Course of Instruction in Ordnance and Gunnery...* (New York, 1862), pp. 29, 126-29 and 153 and RODMAN, ...*Cannon Powder*, pp. 195ff.

12. The main cause of inaccuracy was the aerodynamic instability of a spherical projectile. A ball departing the muzzle with little or no spin will "float" erratically and unpredictably like a baseball pitcher's knuckleball (the knuckleball, delivered with a minimum of spin, is an effective pitch precisely because its path is

unpredictable — even to the pitcher!). Whatever spin the ball acquired through contact with the barrel walls was about an axis perpendicular to the direction of travel, causing the ball to "hook" or "slice" like a golfball, again unpredictably. Another cause of inaccuracy was "*balloting*", the ball's bouncing from one side of the bore to the other, an unavoidable problem since the ball had to be undersized to avoid jamming the barrel. The problem of balloting was explicitly recognized though no cure was available; see COLLADO, Luis, *Platica Manual de Artilleria* (Milan, 1592), Tractado II, Capitulo IIII, folio 38. None of these causes of inaccuracy was affected by barrel length.

13. BIRINGUCCIO. *The Pirotechnia*, p. 235, and GUILMARTIN, *Gunpowder and Galleys*, pp. 284-91.

14. We know that founders were explicitly aware of the relationship because the wall thicknesses of their products were remarkably consistent. All physical evidence which the author has examined, including examination and measurement of some 100 cannon in the collections of the Museo del Ejercito, Madrid, the Museu Militar, Lisbon, and the Askeri Musesi, Istanbul, supports the idea that each founder had an established "model" which he followed closely, that one of the most important characteristics of the model was barrel wall thickness at the breech and that founders tried to make their cannon as thin as they safely could. The ultimate confirmation of the validity of their calculations and the quality of their metal was established by "proof" firing, firing the cannon with an established overcharge, usually a double charge, of powder and ball. For routine dependence upon proof firing — "reasonable testing" — to verify the soundness of cannon, see CIPOLLA, Carlo, *Guns, Sails and Empires* (New York, 1965), p. 61. Though Cipolla's example relates to cast iron cannon, the principles applied throughout. Modern theory of stress and strain in thick walled tubing suggests that any increase in barrel wall thickness beyond about one half the bore diameter is wasted metal. The relationships are indicated, in simplified form, by the formula $S = P \dfrac{D^2 + d^2}{D^2 - d^2}$ where S is the maximum stress in lb/in^2 which the material in question can withstand, P is internal pressure in pounds, D is the outside diameter of the tube and d is the inside diameter in inches. This assumes that the tube is made of a homogeneous material; we know that cast bronze cannon were *not* homogeneous. This is the most likely reason for the inapplicability of orthodox theory. Modern stress theory cannot relate stress to strain in a non-homogeneous thickwalled tube in any straightforward, simple fashion.

15. The evidence is inferential, but persuasive. COLLADO Luis, *Platica Manual*, gives elaborate and precise rules for determining the safety of cannon by measuring them and calculating their thickness. Collado's thoroughness and care make it apparent that there were significant differences in quality between cannon founders. Collado's ideas concerning the relative merits of the various national traditions of cannon founding are confirmed by the historical record of tactical effect in battle and by the appearance and dimensions of surviving cannon. Those cannon which he says *should* have been superior, notably Venetian and German guns of which he speaks highly, are generally shorter, thinner and lighter than those which he disparages (unfortunately Collado's orientation is primarily Mediterranean, and he says nothing about Portuguese or Dutch ordnance). Finally, surviving guns with founders' marks and monograms cast into their metal are almost invariably superior in lines and dimensions to unsigned contemporaries within the same national tradition. Where two or more similar cannon signed by the same founder have survived, they invariably display remarkable consistency in dimensions, weight and the composition of their metal. *Sacramento*'s six pieces by Rui Correa Lucas Matias Escartim are unique in this regard only in their number and that they were plainly operational cannon. Examples of this kind of consistency by an exceptional founder include four magnificent 44 pound cannon of battery by the German founder Gregory Leoffler in the Museo del Ejercito, Madrid (*Grupo* 45, Nos. 2826, 2827, 2828 and 3430, cast in 1542, 1546, 1546 and 1543); despite having been cast at different times, these differ hardly at all in external dimensions and, if the markings are to be believed, by only 200 pounds in weight. Chemical and spectroscopic analysis of metal samples extracted from within the muzzles of two 12 ½ pound *medios culebrinas* by Leoffler, Nos. 3429 and 3348 in the Museo del Ejercito, cast in 1513 and 1545 respectively, yielded the following results (all figures are percentages; <means "less than", ranges of possible results are indicated by a / separating the extremes):

By Chemical Analysis

By Spectrographic Analysis

	Cu	Sn	Pb	Fe	Ni	Sb	As	Ag	Mg	Bi
n 3429	87.02	7.12	0.3/0.6	<0.01	<0.05	0.1/0.3	0.1/0.3	0.05/0.15	<0.0005	<0.01
n 3348	86.94	7.05	0.2/0.5	<0.01	<0.05	0.1/0.3	0.1/0.3	0.05/0.15	<0.0005	<0.01

Spectrographic analysis revealed no traces of An, Si, Al, or Mn. Similarly spectroscopic and chemical analysis of two 5 pound *sacres* cast in 1546 by the founder Wolpedacht, Nos. 3928 and 3929 in the Museo del Ejercito, yielded the following:

By Chemical Analysis — By Spectrographic Analysis

n 3928	Cu 87.91	Sn 6.05	Pb 0.1/0.3	Fe 0.01	Ni 0.2/0.4	Sb 0.05/0.15	As 0.1/0.3	Ag 0.05/0.15	Mg&Bi 0.01	Si 0.03
n 3929	87.89	6.81	0.1/0.3	0.01	0.15/0.35	0.05/0.15	0.1/0.3	0.05/0.15	0.01	0.01

No indications of Zn, Al or Mn were found. The author is indebted to *Col* Gonzalo Garcia Garcia, *Subdirector* of the Museo del Ejercito, for having granted permission for the extraction of the metal samples in the fall of 1969, to Captains David Olson and Joseph Delfino of the Department of Chemistry, USAF Academy, for quantitative chemical analysis of the samples and to Mr. Harold George and Mr. Samuel Seitelman of the Quality Assurance Directorate, U. S. Army Frankford Arsenal, Philadelphia, for having conducted the spectroscopic analysis

16. RODMAN. *Reports of Experiments on the Strength and other Properties of Metals for Cannon...* (Philadelphia, 1856), pp. 153ff. Rodman tested samples of metal cut from the "breech square" and "gun head" of a 6 pound howitzer, a relatively short piece.

17. CIPOLLA. *Guns, Sails and Empires*, p. 45, n. 3.

18. Summarized by MELLO NETO, Ulysses Pernambucano de. "O Galeão Sacramento", *Navigator* (the journal of the Brazilian Naval Historical Service), No. 13 (June 1976 to December 1977), pp. 10-11. The primary published source is ROCHA PITA, Sebastião de, *História da América Portuguesa* (Lisbon, 1730).

19. PERNAMBUCANO. "O Galeão Sacramento", p. 10, from ROCHA PITA, pp. 376-80.

20. PERNAMBUCANO. "O Galeão Sacramento", p. 9, fig 1.

21. Letter to the author from Professor T. Bentley Duncan, Department of History, University of Chicago, dated 10 May 1979. Professor Duncan cites correspondence in the Biblioteca Nacional de Rio de Janeiro, *Documentos Históricos*, vol. 9, pp. 294-97, ROCHA PITA (1950 Bahia edition), pp. 238-40, and MAURO, Frédèrich, *Le Portugal et l'Atlantique au XVII^e Siècle* (Paris, 1960), p. 86. Duncan's analysis suggests that *Sacramento* was not launched before 1651.

22. Information obtained from *Capitão-de--Mar-e-Guerra* (RRm) Max Justo Guedes, Director of the Brazilian Naval Historical Service, and *Vice Almirante* Fernando Ernesto Carneiro Ribeiro, Commander of the Second Naval District, encompassing the coastal waters of Bahia, at the time of the wreck's discovery and during salvage operations. Positive identification of the galleon was achieved by careful correlation of the dates on her cannon with what was known about vessels involved in major wrecks in Bahian waters. These two men, highly informed students of early modern naval history and technology, were instrumental in the process of identification, a fascinating story in itself. The saga began with Admiral Carneiro's identification of the seven privately recovered cannon in a Salvador salvage yard. Recognizing them as something more than ordinary cannon of Napoleonic vintage, he had them seized as national treasures and set the machinery in motion which ultimately recovered the rest.

23. Information received from *Capitão-de--Mar-e-Guerra* Guedes and *Vice-Almirante* Carneiro Ribeiro.

24. ESPARTEIRO, António Marques. Três Séculos no Mar. (1640-1910), Caravelas e Galeões/I Parte. Ministério da Marinha, Lisboa, 1974, p. 98.

25. BARATA, João da Gama Pimentel. "Os Navios", *História Naval Brasileira*, vol. I, Tomo I (*Serviço de Documentação Geral da Marinha*, Rio de Janeiro, 1975), pp. 80-81.

26. SYMCOX, Geoffrey. *The Crisis of French Seapower* 1688-1698, *From the Guerre d'Escadre to the Guerre de Course* (the Hague, 1974), p. 57: "One of the underlying causes of the tactical stalemate (of the late 1600s)... was the seasonal nature of main fleet operations. The limited endurance of the crews and the unseaworthiness of the great ships that formed the blackbone of a battle fleet effectively restricted large-scale operations to the summer campaigning season." and p. 59 "...whereas ships of the lower rates were often seaworthy enough to keep the sea throughout the year, the clumsy three deckers of the first and second rates were dangerously unseaworthy... over--gunned and under canvassed..."

27. For the impact of strategic and tactical considerations on ship design in a parallel context, see the excellent comparative analysis of French and English design practice by GARDINER, Robert, "The First English Frigates", *The Mariner's Mirror*, Vol. 61, No. 2 (May, 1975). Quoting Gardiner, "... [analysis of] Ship design is too often divorced from strategy, tactics and economics, which often leads to distortion and lack of understandings". See GUILMARTIN, *Gunpowder and Galleys*, pp. 204-212, for the effect of social factors on the design of warships.

28. London (1955), Plate 2 facing p. 68. *Sacramento* would have been of about the same size as the prototype for Anderson's contemporary model (sadly, but typically, Anderson says nothing about scale or ordnance), but more lightly armed. The obvious point of similarity is the gun arrangement of Anderson's vessel: if we assume the presence of two stern chasers on the lower gundeck and two bow chasers on the upper, it had 28 cannon on each; the remaining 14 cannon are visible in the photograph of the model, all obviously very much smaller than the guns of the two main gundecks. *Sacramento*, built nearly a half century earlier, would reasonably have had a higher proportion of smaller cannon. In addition, some of her lower gunports might have gone unfilled as a

result of the shortage of ordnance. See ROBISON, S. S., Rear Admiral, *A History of Naval Tactics from 1530 to 1930* (Annapolis, 1942), pp. 121, 214, for the categorization of the English "rates" ca. 1650 and at century's end. SYMCOX, *French Seapower*, p. 36, gives the equivalent French *réglements* of 1674 and 1689. Robison's data gives English third rates main and upper gundecks armed with 26x32 pounders and 28x12 pounders respectively at century's end. Symcox' 1674 table, probably a better indicator, shows French third rates as mounting nothing larger than a 12 pounder. Similarly, Robison, p. 121, suggests that English third rates ca. 1650 had only "a few" 32 pounders as their heaviest cannon and that contemporary Dutch warships carried nothing heavier than a 24 pounder.

29. Information received from *Capitão-de-Fragata* Oscar Moreira da Silva, captain of the *Gastão Moutinho*.

30. CIPOLLA. *Guns, Sails and Empires*, p. 56, n. 1, shows Portugal initiating large scale importation of Swedish cast iron ordnance following the resumption of independence. In 1694 Cipolla shows Portugal importing more Swedish iron cannon than any other customer.

31. PERNAMBUCANO. *O Galeão Sacramento*, p. 37 and p. 35, photo 52.

32. These computations are necessarily aproximate and provide only a rough check. They do, however, provide consistent results. The Lucas Matias Escartim pieces were treated, for purposes of computation, as five frustrums of cones (most of the barrel) and seven cylinders (the muzzle, the trunnions, approximations of the "dolphins" and the bore, the volume of which was subtracted from the total). Dividing the volumes into the weights, as marked on the breeches, yielded densities of some .22 lb/in^3 (.0061 kg/cm^3). The Conrad Wagwaert 1649 peice and the 1634 Assuerus Koster piece yielded densities of about .24 lb/in^3 (.0066 kg/cm^3). The two archaic English pieces yielded .24 lb/in^3 and .25 lb/in^3 (.0066 kg/cm^3 and .0069 kg/cm^3) respectively, though the values may have been driven up slightly by their internal iron structures, wrought iron having a density of as much as .28 lb/in^3 (.0079 kg/cm^3). These values compare with that given by RODMAN, *Metals for Cannon*, p. 153, of .31 lb/in^3 (.0087 kg/cm^3), the greater density being presumably attributable to two centuries of improvement in foundry practice. Interestingly, preliminary computations on the English pieces by George Elkine and the Phillips brothers yield values similar to Rodman's. The potential of this line of investigation is considerable, but it can only be carried through to completion by means of precise measurements of the volumes, dimensions and densities of the cannon in question.

33. The degree of correlation indicates how well two variables, weight and barrel wall thickness, fit a straight line curve when plotted on a two dimensional scatter diagram. Perfect correlation would be indicated by a value of 1, showing that a change in one of the two variables yields an exactly proportionate change in the other.

34. RODMAN, *Metals for Cannon*, p. 152, describes a test conducted on two 12 pound howitzers cast 8-10 minutes apart from the same melt. They varied in the density of their metal by 3 ½%.

35. Both English and Spanish documents from the mid-1500s, if not earlier, almost invariably list cannon by weight. For English cannon, for which the record is clearest, the pound avoirdupois was certainly used from the reign of Elizabeth I, if not earlier. ZUPKO, Ronald E., *British Weights and Measure, A History from Antiquity to the Seventeenth Century* (Madison, 1977), p. 25, traces the pound avoirdupois to the Statute of Westminster in 1357, though the value was adjusted from 6992 grains to 7000 grains early in the reign of Elizabeth I; he affirms, pp. 116, 133, and 135, that the pound avoirdupois was the traditional unit of measure for trade in gunpowder and bell metal, a close relative of cannon metal (cannon metal, significantly, is not listed). For general analysis of units of weight and measure applied to ordnance in the sixteenth and seventeenth centuries, see MUÑIDO, Franciso-Felipe Olesa, *La Organización Naval de los Estados Mediterraneos y en Especial de España Durante los Siglos XVI y XVII*, Vol. I, pp. 285-88. Though the author has found no explicit documentary evidence to confirm the supposition that the symbol means "pounds avoirdupois", the hypothesis is supported by the computations described in note 32, above, and by linear regression analysis of the double weight markings on *Sacramento*'s English cannon; these demonstrate conclusively that *whatever* units of weight were used, the weights were determined with great precision and consistency.

36. The activities of George Elkine and the Phillips brothers are verified by contemporary English records, letter from Admiral Sir Terrance Lewin, GCB, MVO, DSC, ADC, to *Capitão-de-Mar-e-Guerra* (RRm) Guedes dated 14 June 1977. John and Richard Phillips are mentioned in the Calendar of State Papers of 16 August 1588 as purveyors of cannon; George Elkine, who apparently died in 1604, is mentioned first in 1595.

37. Based on the appearance of cannon from the *Mary Rose*, viewed by the author in the Museum of the Royal Artillery Institution, in the Rotunda at Woolwich, England; the earliest date on these cannon is 1529, *Catalogue of the Museum of Artillery*, Part I, Ordnance (London, 1963), p. 7. This impression is sustained by the appearance of dated cannon in the collections of the Museu Militar, Lisbon, the Museo del Ejercito, Madrid, and the Askeri Musesi, Istanbul.

38. ZUPKO, *British Weights*, pp. 78-86.

39. Based on notes and photographs taken in examination of the collections in Lisbon, Madrid and Istanbul cited in note 37, above, in the Fall of 1969 and at the Museum of the Royal Artillery Institution in August of 1975.

40. LEWIS, *Armada Guns*, p. 129, and MUÑIDO, Olesa, *La Organización*, p. 287, for equivalent Castillian units.

41. COLLADO, *Platica Manual*, Tr. III, Cap. XV.

42. For example, the tables from the 1627 and 1692 editions of John Smith, *A Sea-man's Grammar*, reproduced in ARCHIBALD, E.H.H., *The Wooden Fighting Ship in the Royal Navy AD 897-1860* (London, 1968). Collado's rule consistently yields a ball diameter 3% smaller than the bore. LEWIS, *Armada Guns*, p. 39, indicates that the English rule for cannon was 1% smaller than the bore and the rule for culverins 5% smaller.

43. COLLADO, *Platica Manual*, Tr. III, Cap. XXX, fol. 51-2, in discussing the use of a closely fitting wad to hold the ball in the barrel when shooting downward, cautions that a reduced powder charge should be used to avoid blowing the gun up; his understanding of the relationship between reduced windage, in this case zero, and internal pressure is clear. In fact, the difference in muzzle velocity to be gained from reductions in windage was negligable; see RODMAN, *Metals for Cannon*, pp. 109ff, for experiments with a 42 pound cannon demonstrating this. The actual benefit was, as Collado indirectly suggests, in the reduction of powder charges. This was realized slowly as manufacturing standards tightened with time. Collado gives the standard charge for a cannon of battery in his day, *Tr.* II, *Cap.* XXXIII, fol. 29 and *Cap.* XXXVI, fol. 31, as two-thirds the weight of the ball, though a reduction to one--half the ball weight was recommended for old, unsafe or worn out guns. A century later, it was calculated at only one-half the ball weight in French practice as given in Sebastien Le Prestre de Vauban, *A Manual of Siegecraft and Fortification*, George A. Rothrock trans. (Ann Arbor, 1968) and was probably a bit less in practice since Vauban's figures represent logistical planning calculations and do not account for the inevitable wastage.

44. For example, RODMAN, *Metals for Cannon*, pp. 109ff; in 1856, the standard windage for an American 42 pound cannon with a 7 inch (17.8 cm) bore was .18 inches (.45 cm). Application of Collado's formula for the same bore yields a windage of .24 inches (.61 cm), or half again as large.

45. See note 32 above.

46. LEWIS, *Armada Guns*, p. 201.

47. See VAN BATH, B. H. Slicher, *The Agrarian History of Western Europe AD* 500--1850 (London, 1963), particulary pp. 113-115 for a concise explanation of the wage and price movements of the sixteenth and seventeenth centuries, BRACKENBURY, Henry, Sir, "Ancient Cannon in Europe, Part II", *The Journal of the Royal Artillery Institution*, V (1865-66), pp. 8-9, cites a French document of 1375 comparing the cost of a cut stone cannonball with that of the cannon for which it was cut. The ball cost two shillings and sixpence while the iron needed to construct the cannon cost only sixpence a pound. Since the cannon weighed only 500 pounds, the ball was a small one, probably no larger than 6 inches (15.2 cm) in diameter. Since stone was cheap, the difference is attributable to labor. COLLADO, *Platica Manual*, Tr. III, Cap. XXXII, fol. 53, is explicit on the relative lightness of stone-throwing cannon.

48. This is an exquisitely cast 32 pounder some six feet (1.82m) long, marked CUDEBAT, PETRUS.GEORGIUS.FIGUIEIRA. M.D.C. LXXVIII.

49. GUILMARTIN, *Gunpowder and Galleys*, pp. 109-11, for a summation of the evidence in a naval context.

50. BIRINGUCCIO, *Pirotechnia*, pp. 246-48, Biringuccio offers several alternate *cruzeta* designs, including four part *cruzetas* and an elaborate structure called a "castle" which vaguely resembles a wrought iron flowerpot stand which was intended to support the weight of the core as well as centering it. His preference is for a wrought iron ring with four equally spaced centering rods as described here.

51. Although, BIRINGUCCIO, *Pirotechnia*, pp. 246-7, express a preference for a clay disk as the external support for the core.

52. TARTAGLIA, Niccolo, *Three Bookes of Colloquies Concerning the Arte of Shooting in great and small pieces of Artillerie*... Cyprian Lucar, trans. (London, 1588), Colloquie 22, p. 41, "...a peece which breakes doth most commonlie breake at the breeche or neere unto the mouth and seldom tymes in the middle..." Tartaglia, a theoretical mathematician and not a gunner, is occasionally vague or inaccurate on points of operational practice, but he is reliable in his reporting of foundry problems and procedures. His opinion is confirmed by surviving examples of burst cannon, notably in the collections of the Museu Militar, Lisbon, and the Deniz Musesi, Istanbul.

53. BRAUDEL, Fernand, *La Méditerranée* (Paris, 1966), p. 406.

54. CIPOLLA, *Guns, Sails and Empires*, p. 55, n. 5, cites a Swedish source to the effect that by 1626 iron cannon were no longer exported from England and states, p. 63, that "...according to available figures the [English] fuel [charcoal] crisis seems to have exploded in all its gravity durnig the 1630s." Cipolla's data is remarkably comprehensive and his analysis convincing.

55. KRITOVOLOUS, *History of Mehmed the Conqueror*, Charles T. Riggs, trans. (Pinceton, 1954), pp. 43-6, for an eyewitness account. COLLADO, *Platica Manual*, Tr. II, Cap. VII, fol. 11, and Cap. XXXII, fol. 34, states, ca. 1570, that a stone-throwing cannon needed only one-half to one-third the amount of bronze for a ball of the same weigth, thus such a cannon would have had only 88 to 136 pounds of bronze for each pound of ball. In addition, stone-throwing cannon required a smaller powder charge, only one-half the ball weight as opposed to two-thirds for cannon of battery.

56. Two of these, cast in 1714 and 1804, were on display in the park of the Deniz Musesi when the author visited Istanbul in 1969. The larger of the two, the 1714 piece, fired a 380 pound (172 k) projectile.

57. Noted by Professor Joel Shinder, formerly of Fredonia State College, New York, on an Ottoman cannon in the park of the Arkeri Musesi, Istanbul, in the spring of 1970.

58. Observed by Professor Shinder, note 57 above.

59. U. S. Army Special Text, ST 9-153, *Fundamentals of Ballistics* (Aberdeen Proving Ground, April 1964), pp. 14-16. A *stoiochiometric* equation cannot be written for the chemical decomposition of black powder; this is because of the key role played in the decomposition reaction by the alkyhydrocarbon "impurities" in charcoal. To further illustrate our limited understanding, consider that there is no consensus concerning the nature of the role played in the reaction by sulphur which composes some 10% of black powder by weight. It is no exaggeration to say that if the composition of black powder were not known empirically, it could not be discovered by theoretical means.

60. Not only is the theory of stress and strain in thick walled tubes inadequate to the task of predicting the ability of a non-homogenious bronze tube to resist internal pressure, knowledge of the physical properties of bronze alloys with the general composition of early modern cannon metal is scant at best. BIRINGUCCIO, *Pirotechnia*, p. 210; COLLADO, *Platica Manual*, Tr. II, Cap. III, fol. 10 and TARTAGLIA, *Three Bookes*, as quoted in LEWIS, *Armada Guns*, p. 18, give compatible values for the proportion of tin in gunmetal, ranging from 7% to almost 15%. Modern engineering handbooks have little to say about copper/tin alloys in this range, for example *Metals Handbook* (8th Ed.) Vol. I, *Properties and Selection of Metals* (Novelty, Ohio, 1961), pp. 975-6. The problem is further complicated by the presence of other metals and non-metallic impurities in cannon metal. As noted above, small samples of metal extracted by the author from sixteenth and seventeenth century cannon of Spanish, German and Venetian origins and tested spectroscopically at the U. S. Army Frankford Arsenal in the summer of 1970 revealed detectable quantities of Iron, Antimony, Arsenic, Nickle, Silver, Magnesium, Silicon and in some cases Manganese, Aluminum, and Bismuth. Though most of these impurities — if that is what they were — were present in quantities of ½% or less, several cannon showed appreciable amounts of Zinc and Lead.

61. COLLADO, *Platica Manual*, Tr. I, Cap. III, fol. 10, states that the touchhole should enter the chamber at the extreme upper rear corner (he assumes a square-shouldered chamber) if violent recoil characteristics are to be avoided. His description of adverse recoil characteristcs and his statement that he observed a large battery piece with a misplaced touchhole lifted completely out of its carriage on recoil is supported by a fascinating discussion which suggests an empirical understanding of the propigation of pressure waves within the chamber. Though the skeptic might be inclined to lump Collado's descriptions with the gunners' tall tales repeated by the gullible Tartaglia (eg. *Three Bookes*, pp. 39-40, where he describes cannon ingesting small dogs after firing!), Collado's theorizing is sustained by modern scholarship. See for example, MAY, J. W., NELSON, C. W., ROCCHIO, J. J. and WHITE, K. J., "The Role of Ignition in Artillery Propulsion" (Aberdeen, 1977) and MAY, I. W. and CLARK, E. V., "The reverse Pressure Gradient, a Tool for Assessing the Effects of Wave Dynamics on the Ballistic Performance of Guns", *Proceedings of the Second International Symposium on Ballistics* (March, 1976).

62. GUILMARTIN, *Gunpower and Galleys*, p. 287, citing the extremely small variation in the percentages of trace elements in samples of bronze extracted from the same location on the matched pair of *sacres* by the founder Wolpedacht in the Museo del Ejercito, Madrid, as discussed in note 15 above.