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RĀJAGOPĀLA - THE MASSIVE IRON CANNON AT THANJAVUR IN TAMIL NADU

R. Balasubramaniam*, A. Saxena* and T.R. Anantharaman**

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This paper is based on a scientific and historical study of Rajagopala, the large forge-welded iron cannon at Thanjavur in Tamil Nadu. Available records indicate that the seven-and-half meter long cannon weighing over 20 tons belongs to the time of the Nayak kings and was constructed in the first of the 17th century. The dimensions of the cannon are set forth and the manufacturing methodology of the cannon is addressed on the basis of careful observation of its constructional details. The barrel of the cannon is shown to have been manufactured by forge welding of three layers of pre-forged iron rings around longitudinal iron strips utilizing a central mandrel. The longitudinal iron strips served as the inner surface of the cannon barrel. The rear portion of the cannon is solid and has been constructed by shrink fitting iron rings over a central cylindrical shaft. The intricate forge welding operation that required correct positioning and alignment reflects engineering skill of a high order on the part of the medieval Indian blacksmiths. Microstructural examination of the iron from the cannon reveals that the iron was extracted from the ore by the direct process. Thus, the cannon has been fabricated by forge welding and not by casting. Electrochemical polarization studies indicate that the corrosion rate of the cannon iron can be compared to that of 0.05% C mild steel under complete immersion conditions. However, the atmospheric corrosion resistance of the cannon is far superior to that of modern steel and can be attributed to the formation of an adherent protective surface film. Some information on the nature of atmospheric rust has been obtained by X-ray diffraction and infrared spectroscopy studies. It is concluded that this cannon constitutes a marvel of medieval Indian metallurgical skill.

Keywords: Electrochemical behavior, Forge welding, Iron cannon, Microstructure, Protective surface film, Wrought iron.

Introduction

The high status of iron and steel technology in ancient and medieval India is amply reflected in the manufacture and use of numerous large iron

*Department of Materials and Metallurgical Engineering, Indian Institute of Technology, Kanpur 208016, INDIA; author for correspondence: bala@iitk.ac.in.
**Ashram Atmadeep, P.O. Box. 3, DLF City, Gurgaon 122002, INDIA.

objects. One of the significant large iron objects manufactured in medieval India was forge-welded cannon[1,2]. There are scattered reports on the many large cannons present in different parts of India[1-5]. Some notable medieval iron cannons manufactured by the forge welding technology are to be found at Nurwar, Murshidabad, Dacca (in Bangladesh), Bishnupur, Bijapur, Gulbarga and Thanjavur. These are shining examples of the medieval Indian blacksmith's skill in the design, engineering and construction of large forge-welded iron objects. These large iron objects rightly attest to the high level of skill of the ancient and medieval ironsmiths of India in the extraction and forging of wrought iron.

The wrought iron cannons found in different parts of medieval India[1] were basically manufactured from individual iron rings, which were forge welded together. The medieval blacksmiths continued the rich tradition of manufacturing iron objects by the forge welding technique, which was the method used to fabricate small and large iron objects like the Delhi[6,7] and Dhar[8] iron pillars. The medieval forge-welded iron cannons of India have not been properly catalogued, unlike their European counterparts [9-11]. Several varieties and a large number of forge welded iron cannons have actually been located in forts across India. Some of these cannons are preserved in well-known museums. The publications available on these cannons provide only meagre details like their present location and the probable time period of their construction[12]. The massive cannon at Thanjavur in Tamil Nadu will be addressed in the present communication.

History

Based on its weight and size, the forge-welded iron cannon (Fig. 1) at Thanjavur, earlier known as Thanjai or Tanjore, must be regarded as one of the largest forge-welded iron cannons in the world. According to a recent authoritative history of Thanjavur[13], the cannon was manufactured in Thanjavur during the regime of Raghunatha Nayak (1600-1645 AD). Thanjavur was by this time a very important centre of Hindu architecture (as exemplified by the world-heritage Bṛhādiśvara Śiva Temple), literature (with thousands of palm leaf manuscripts still preserved at the library of the Sarasvati Mahal Museum at Thanjavur) and metallurgical skill (as enumerated by the numerous excellent

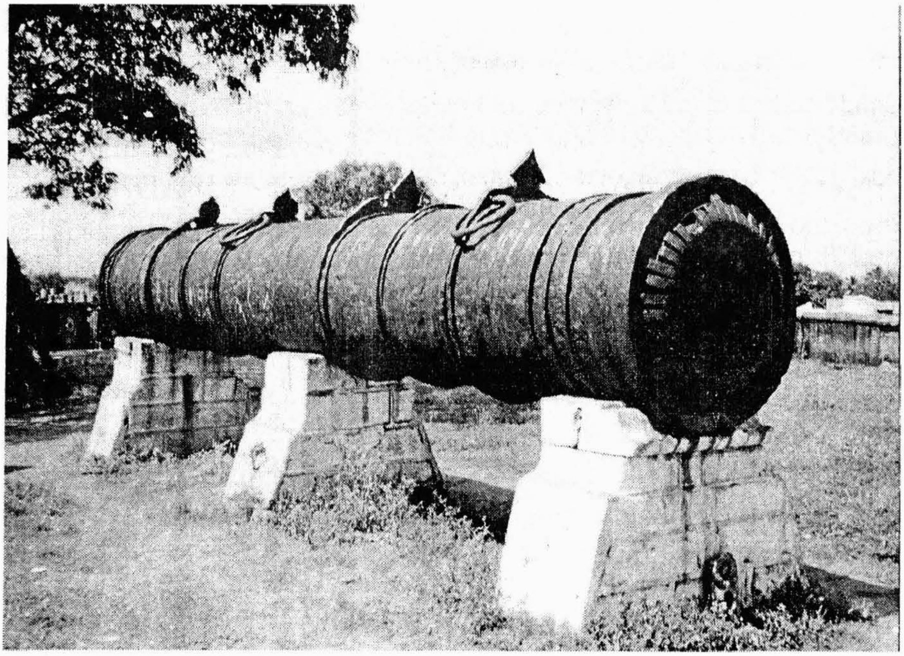

Fig. 1: *Rājagopāla,* the historical forge-welded iron cannon at Thanjavur.

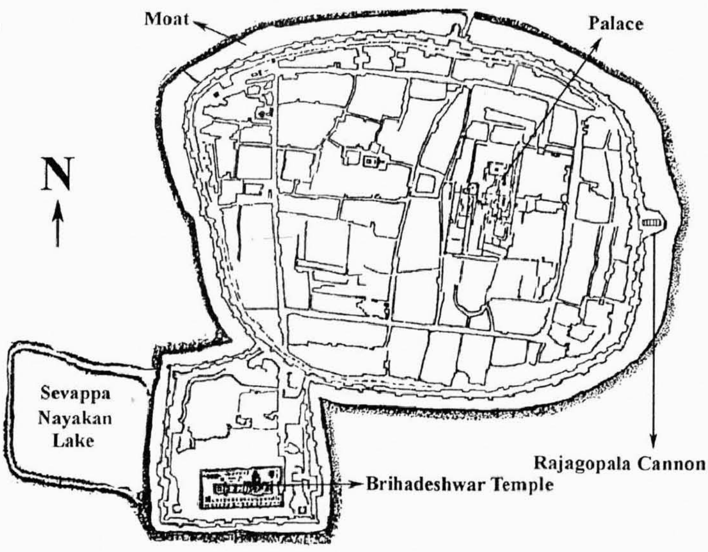

Fig. 2: Copy of an old map of fortified city of Thanjavur during medieval period, showing the location of the *Rājagopāla* cannon.

bronze sculptures executed by the lost-wax process). It is to be noted here that the art and science of metal casting and forging received since ancient times the patronage of the royal dynasties that ruled over Tamil Nadu, viz., the Pallavas (300-900 AD), the Colas (900-1300 AD) and the Pandyas (1300-1500 AD). The Nayaks (1500-1700 AD) and the Marathas (1700-1850 AD) continued this tradition and also paid special attention to the fortification of the ancient city of Thanjavur. For example, the defense barricade of the Bṛhādiśvara temple, then already a few centuries old, was reinforced because of constant threat of its desecration. The Thanjavur cannon formed an important component of this fortification scheme and it was located at the eastern entrance of the ancient fortified city, which was called '*periakoṭṭai*' (large fort)[13]. An old map of Thanjavur city (Fig. 2) shows the ancient fortification scheme of the city and the location of the Thanjavur cannon[13]. The cannon is referred to as *Rājagopāla*, according to local traditions.

There is no specific recorded history of the cannon. However, based on literary sources, it can be established that the cannon was manufactured during the Nayak period[13]. A Thanjavur palace novel by Yajñanayarana called *Sāhitya Ratnākara*, which describes the rule of Raghunatha Nayak (1600-1645 AD), mentions the presence in the Thanjavur fort of an object referred to as *analavarthiurthayar nalikā āyudham,* meaning 'fire-breathing barrel shaped weapon.' Raghunatha Nayak was the greatest of the Nayak rulers of Thanjavur. Danish and English traders sought trade with his prosperous kingdom. During the reign of the Maratha king Serfoji I (1711-1729 AD) was written a literary work based on Thanjavur called *Sarabharājā Vilāsam* mentions the presence of a *agniyantra* (fire weapon) on the eastern rampart of the fort. The mound on which the cannon is currently located was called as '*kizhaku kothalam*' ("Eastern Rampart") during the Nayak period. This was later known as '*dasmeḍu*' during the Maratha period and the mound also served as a time-announcing stage. The cannon is supposed to have been constructed in the Manojipatti area of Thanjavur. Historical records mention that a locality in this area known as *kollimeḍu* was very famous for iron working[13]. The Nayaks allowed the Danish to set up a settlement at Danesborg at Tharagambadi (Tranquebar) along the Coramandel coast in 1620 AD. The interaction of the local ironsmiths with the Dutch has been speculated to be one of the reasons for construction of this cannon [13]. However, the manufacture and use of large cannons was well known in India even in times prior to interaction with the Europeans [14]. Interestingly, during the initial period of European trade with India, historical records reveal that intellectual property was extracted and transferred from India to Europe rather than the other way around. Moreover, there are no records of wrought iron cannons of the size of *Rājagopāla* anywhere in medieval Europe [9]. The gun is still standing at the same location in Thanjavur, facing the east direction, with the present city having outgrown the ancient fortified town limits. Its location within Thanjavur city is now known as '*beīrangī-meḍu*' in Tamil, literally meaning the 'cannon-mound'. It is located on the same mound on which it was originally erected and it can be reached by climbing a flight of steps from the road level. It is a protected monument of the Archaeological Survey of India.

Design

The Thanjavur iron cannon rests on three concrete supports, about 60 cm thick and 120 cm high and separated by 2.25 m from each other. The concrete supports rest on the ground. The cannon is a muzzle-loading type cannon, wherein the gunpowder and the projectile object are loaded from the muzzle (i.e. front end) of the cannon. The various sections of the iron cannon were analyzed and precise dimensions recorded. The overall dimensions of the iron cannon are provided in the engineering drawing of Fig. 3. The iron cannon is totally 751.5 cm in length from end to mouth, including the 31.5 cm projection at the end of the barrel. The outside and inner diameters of the gun barrel are 93 and 63 cms, respectively. All the dimensions in this communication, including the figures, are in centimeters. This has been provided because of the metric unit system is currently followed in India. However, it must be realized that the cannon's dimensions are closely related to the inch system of measurement. It has been shown elsewhere that the inch system of measurement was the unit of measure in ancient India [7]. In this context, the entire length of the cannon is 25 feet and the rear portion is 1 foot long. The inner and outer diameters of the cannon barrel are 25 and 37 inches, respectively, with each ring being of approximately 2 inches in thickness. The reader can convert the dimensions mentioned in this paper to the inch system in order to obtain a better understanding of the dimensional proportionality of the cannon.

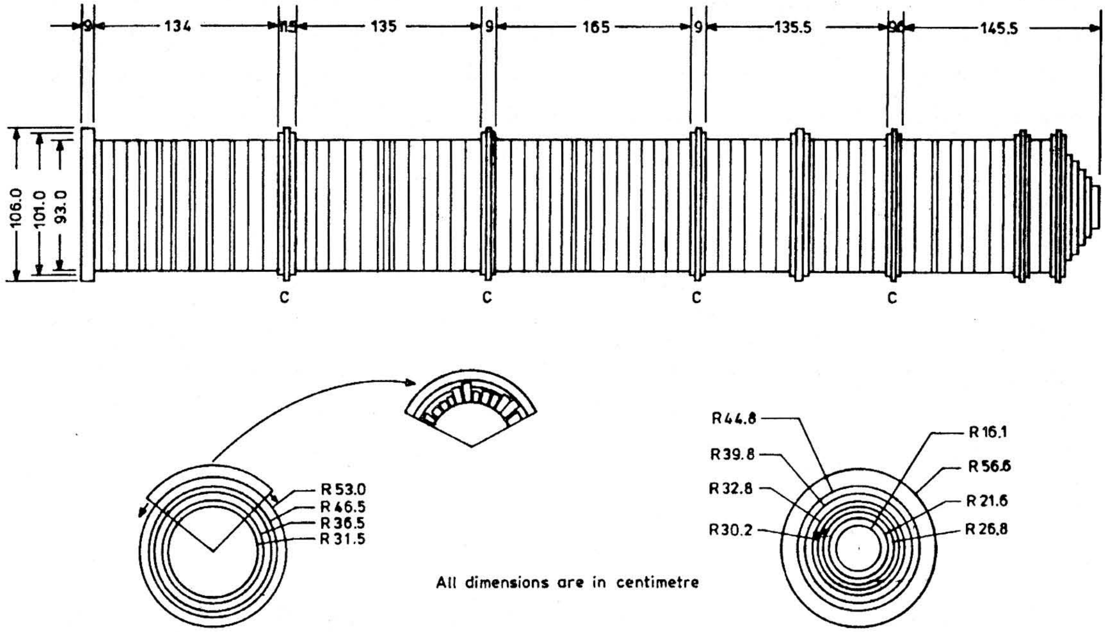

Fig. 3: Dimensions of the cannon. The handling clamps are located at the locations marked C.

Assuming the hollow cylinder of the cannon barrel extending to the complete end of the cylindrical barrel (length of 720 cm), the minimum weight of the cannon estimated from the known thickness of the barrel (i.e. 15 cm) is 20.6 tons. The solid portion in the rear end of the cannon is not known with certainty and therefore, the estimate provided above is a lower bound value because the solid portion in the rear end will add additional weight to the cannon. The distance from the fuse hole to the end of the barrel is 36 cm. It is reasonable to assume that the fuse hole represents the rear end of the hollow section of the cylindrical barrel, as is usually the case with medieval wrought iron cannon designs [9]. Therefore, the rear solid portion of the cannon will add approximately another ton to the weight estimated above. Counting the weight of additional supporting external rings, the minimum weight of the cannon adds to the staggering figure of over 22 tons.

The front end of the iron cannon (Fig. 4) indicates that there are a total of 39 iron strips, which have been folded out from inside the cannon. Each iron strip is about 1.5 cm thick and 5 cm in width. These iron staves continue longitudinally through the length of the inner bore of the cannon barrel. Their purpose appears to have been to provide a smooth inner surface to the cannon barrel. The front end also reveals that concentric layers of iron rings have been used to construct the barrel of the cannon. Four concentric rings are clearly visible in the front plane of the cannon barrel (Fig. 4). The iron strips and iron rings will be addressed later during the discussion on construction methodology of the cannon. The complete cannon barrel is made up of three rings, hooped over the iron staves.

Fig 4: Front end of the cannon

Fig. 5: Close-up view of one of the forge welded joint regions on the outer surface showing that a smaller ring has been used to join the gaps between larger rings. The provision of a handling hole on the smaller ring should also be noted.

Based on the detailed dimensional analysis, it is noted that width of the individual rings that are seen along the length of the cannon was not constant. Generally, rings of smaller widths were also located along the length of the cannon. This can be noted in Fig. 5. It has been suggested that that the smaller rings might have been placed for filling the gaps or for sealing the cannon barrel [3]. This may be true in case of only some of the smaller rings. In this regard, it is also important to note the systematic placing of smaller rings between larger rings at two specific locations, just behind the muzzle of the barrel

(Fig. 6) and also in the middle of the cannon. In these locations, the smaller rings seem to have been placed in a very calculated manner. Therefore, the design of the cannon required the use of smaller width rings in the construction of the cannon and not necessarily for only closing the gaps between the larger width rings. The special design of smaller-width rings in between the larger-width ones must have ensured greater toughness for the barrel.

At periodic intervals along the length of the cannon, additional external rings have been provided on the external surface of the cannon. These raised locations can be noticed in Fig. 1. Seven such locations can be identified along the length of the barrel. These additional rings usually are present as three-ring assemblies (see Fig. 7). At four locations along the length of the cannon (i.e. the first, third, fourth and sixth three-ring assemblies assuming the first one to be closest to the muzzle), the outer forged central ring, of larger diameter, ends in a plate of thickness 2.5 cm (Fig. 8a). Each of these four plates is

Fig. 6: Systematic placing of smaller width rings in between larger width rings indicating that small rings were not only used to close the gaps between the rings, but had an engineering purpose.

Fig. 7: Rear portion of the barrel showing the additional outer rings provided as three-ring assemblies. These additional ring-assemblies would have provided further strengthening to the cannon.

provided with arrangements for holding two handling rings each. All holding clamp rings, but for two, are currently missing. The rings measure 40 cm in diameter and the diameter of the cross section of the ring is 4 cm (Fig. 8b). These rings were provided for manipulating the cannon's direction and also for possibly aiding its movement and transportation. Only two of the original eight rings still remain. Similar iron rings can be noted on the large forge-welded cannons at Murshidabad and Gulbarga [1]. Long iron rods or wooden beams, inserted through these clamp rings, would have aided positioning of the cannon during its use. The method by which the gun was moved using these clamping rings is not known, but it must have involved lifting by means of either a chain-and-pulley arrangement, or manual methods. The former method appears likely given the enormous weight of the cannon. It is worth noting that trunnions (i.e. supporting cylindrical projections on the sides of the cannon), like those usually found on smaller sized cannons, are not provided. These trunnions were used to house the cannon on wheels, thereby aiding its easy transportation. Therefore, the absence of such a device on the Thanjavur cannon

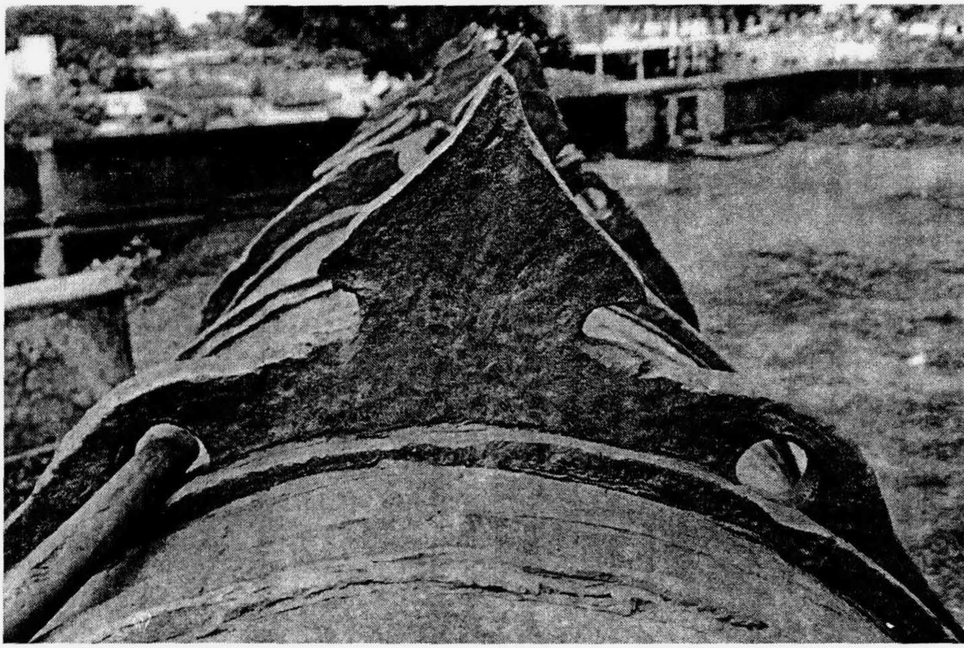

Fig. 8: (a) Details of one of the handling clamps

Fig. 8: (b) Iron ring located in one of the handling clamp

indicates that the large cannon was not meant for mobile use and its function was to be a stationary cannon to protect the eastern gate of Thanjavur city during the medieval times.

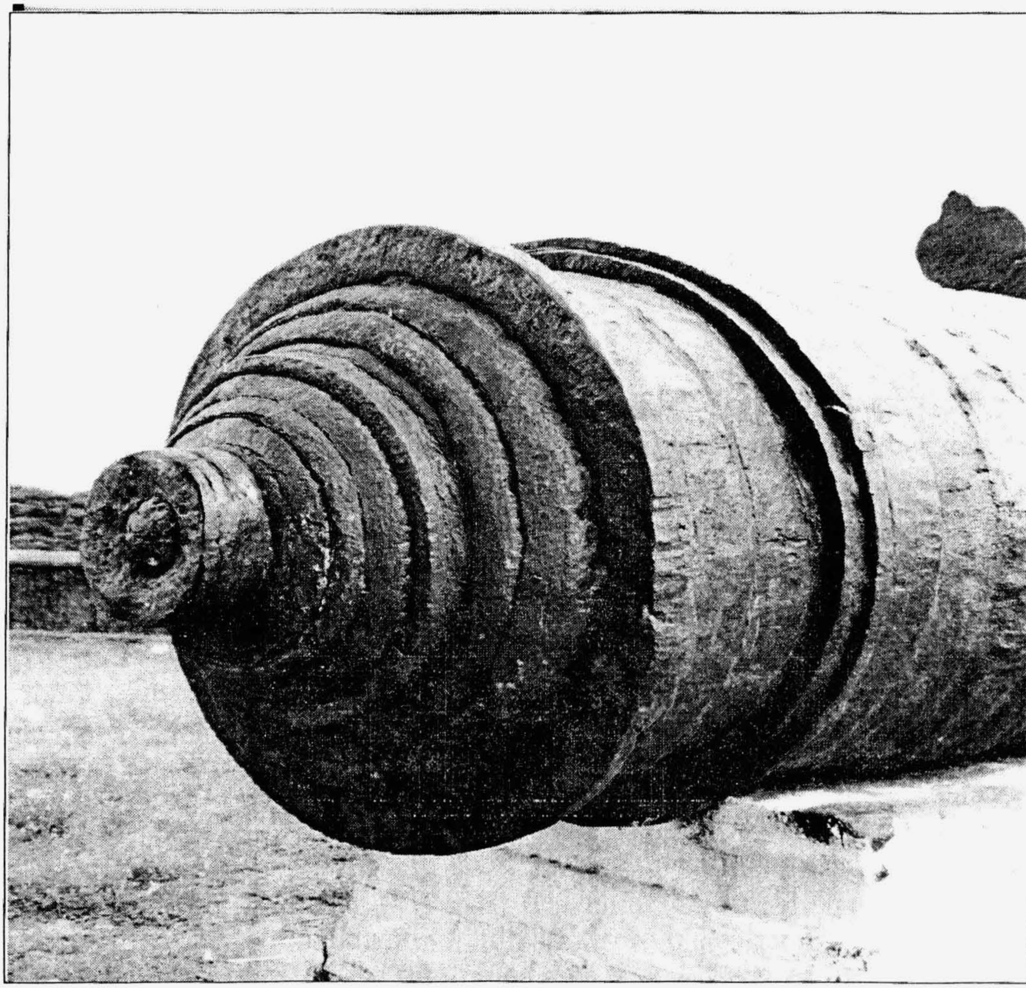

Fig. 9: Rear end of the cannon

The rear end (Fig. 9) is not flat but consists of successively smaller diameter circular iron rings, presumably to provide impact resistance to the rear section of the cannon. A fuse hole, of 10 cm diameter, is located on top surface of cannon near the rear end and this was used for ignition of gunpowder. Based on the location of this fuse hole and the measured dimensions of the cannon (i.e. cross sectional area of 630 square mm and length of 500 mm), Roessler estimated that the volume of gunpowder that must have been utilized to fire the cannon was at least 155 litres [3]. However, this estimate is not reliable because Roessler assumed the rear portion of the cannon barrel to be hollow, whereas it is known that the rear end of the cannon up to the location of the fuse hole is solid. The amount of gunpowder that was packed to create the explosion must have depended on the type, number, size and nature of the projectile material. Therefore, it would be not possible to speculate on the gunpowder volume used to fire this cannon. It is obvious, however, that this must have been quite a significant amount based on the dimensions of the cannon. It is interesting to note that an additional three-ring assembly has been provided just behind the fuse hole location (see Fig. 7) for strengthening and providing additional impact resistance to the cannon barrel at this location.

The actual size of the cannon ball used for firing from this cannon is not known with certainty. Assuming the diameter of the spherical cannon ball to be slightly smaller than the inner diameter of the cannon barrel, the weight of the ball can be estimated as 1000 kg. if made of iron or 300 kg, if made of stone[3]. The type of cannon balls used in the cannon, however, is not known. Cannon balls were usually made of iron and not of stone, as recent discoveries of cannon balls in Thanjavur testify. The amount of gunpowder that must have been required to force this heavy one-ton iron cannonball must have been enormous and moreover, the impact from the explosion of such a large amount of gunpowder must have been very severe. Therefore, the cannon ball must have been much smaller than the actual inner diameter of the cannon barrel.

Construction

The engineering skill involved in the construction of this large cannon deserves high appreciation. Some insights on its possible method of manufacture can be obtained from the detailed study of its structural condition, described above. Ultrasonic measurements, conducted by Roessler[3] on the wall of the cannon indicated that there were a total of three layers of rings, each of them about 5 cm in thickness, which have been skillfully shrunk fitted around each other. The iron rings appear to have been joined together by hooping and later by forge welding. There are only three ring layers used for constructing the length of the cannon barrel, as evident from the measured diameter of the cannon at the front face and along the gun barrel. The thickness of the middle ring and the external ring, along the wall of the cannon, is 5 cm each. This is evident from the front face where the three inner iron rings can be made out. The front face also shows the presence of an additional outer ring that has been provided for further strengthening the front face (see Figs. 4 and 6). Additional outer rings have also been provided at the clamping locations (Fig. 7). The front view of the cannon (Fig. 4) further indicates that there is an additional layer of 1.5 cm thick iron strips, which have been tightly placed in the inner pipe along the innermost ring. These long iron strips progress all the way across the whole length of the cannon. They have been bent on the front side of the gun, and have been tightly placed in order to hold the whole structure together (Fig. 4).

It has been commented that the medieval Indian blacksmiths were sluggish to adopt casting techniques when it came to iron although this method was successfully used in the manufacture of very intricate bronze objects. Available evidences indicate that the medieval Indian blacksmiths did not seriously explore iron-casting techniques [14], which required high temperatures. Their lack of interest in casting technique was also due to their mastery over the forge welding technique to produce large iron objects. It is certain that the iron cannon was not cast, implying that the material of construction of the cannon is wrought iron. The cannon was fabricated by forge welding, i.e., it has been manufactured by forging together rings of forge-welded iron. Forge welding has also been employed to join the layers of secondary and tertiary rings that further strengthened the entire structure. The manufacturing technology of the Thanjavur cannon can therefore be classified under forge welding of pre-forged iron rings, hooped over longitudinally placed iron staves, with correct positioning and alignment. Available evidence and examples from medieval European wrought iron cannons [9] indicate that the cannons were divided into two distinct parts – the chamber and the barrel. The function of these parts and hence, the material and design requirements are also different. For example, the barrel's main function was to contain the lateral exhaust of the gas (from the explosion of the gunpowder) and in this process, the projectile was pushed out. The barrel needed to be tough and not deformable. It also needed to possess a smooth inner surface for ejecting the projectile. On the other hand, the chamber was prone to much higher gas pressures than the barrel due to the exploding gunpowder at the point of ignition. The rear side had to be tightly closed on the backside in order to withstand the gunpowder explosion. Therefore, this part had to be impact resistant.

External observations of the cannon surface indicate that the same type of material (i.e. wrought iron) and manufacturing methodology (i.e. forge welding) has been used for the chamber and the barrel of the Thanjavur cannon. Interestingly, while the wrought iron cannons were manufactured by separately fabricating the chamber and the barrel and later joining them together, the cast guns were fabricated as one piece. It is with this perspective that that manufacture of the Thanjavur cannon must be viewed. The cannon is made of two distinct parts that were skillfully joined together. The methodology by which the cannon was manufactured can only be hypothesized today. The manufacturing methodology of the barrel can be deduced from the appearance of the barrel. However, the manufacturing method for the chamber is not known with certainty and the proposals presented here are based only on the features clearly evident on the cannon surface.

It is known that the cannon is solid up to the fuse hole from the extreme rear end of the cannon. Therefore, this solid part could have been built using forged iron plates or rings over a cylindrical central solid iron shaft. Some details of the methodology can be gleaned from the appearance of the rear portion of the cannon (Fig. 9). It appears that iron rings were forge welded over a solid cylindrical shaft that made the rear portion. The solid cylinder's outline can be seen in the extreme rear section of the cannon. Notice how iron rings have been successively forged in order to close the gaps between the iron rings in the rear section of the cannon. The depth of the hollow slot of the cannon could not be determined for want of a sufficiently long pole. However, based on the design of the forge welded-iron cannon at Bishnupur [15] and also based on the design of cannons in general, the solid portion of the rear of the cannon should extend up to the fuse hole location. This solid portion appears to have been constructed of rings, which have been successively forged over each other (see Fig. 10). It appears that the medieval engineers were familiar with the idea of structural design for improved fracture toughness because the solid structure created with successively larger diameter rings would have possessed a better impact resistance compared to a single solid piece of wrought iron. Therefore, there were additional benefits to be obtained by constructing the rear solid portion of the cannon using iron rings rather than construct it out of a solid piece of material. The solid rear portion of the cannon was constructed by forge welding iron rings of different diameters over a central solid cylindrical shaft.

The barrel must have been fabricated separately of the chamber. Initially, the long iron strips were placed on a mandrel in order to provide it support and to aid manufacturing operations that followed. Pre-fabricated iron rings were expanded and then shrunk fit over the long iron strips. The rings of the first layer were brought from the front end. After the first layer was forge welded, the other two layers were subsequently built up. Roessler suggested that after the rings of the first layer were forged welded, the rings in the second layer were positioned in such a manner that the middle of each ring closed the gap between the rings of the first layer. Similarly, the rings of the outermost layer were proposed to close the gaps in the second layer. This hypothesis has to be verified by careful non-destructive studies. Once the barrel had been fabricated, the protruding iron strips on the front face have been folded up (see Fig. 4). The protruding iron strips at the rear end must have been connected at appropriate locations to the solid cannon rear section, and the complete cannon realized. The chamber and the barrel must have been joined using the protruding longitudinal staves of the barrel and by strengthening this joint area externally by additional rings. This is schematically shown in Fig. 10.

The total number of rings counted on the cylinder barrel surface is 95 and the number of rings visible in the rear end of cannon is 6. The number of rings across the thickness of the barrel is known (three), while the number in the solid rear portion is not known. Therefore, there is a minimum number of 291 iron rings used in the construction of the cannon. It is important to realize that the iron rings, which constituted the different layers, had to be engineered precisely to exact dimensions, considering the large expansion and shrinkage on heating and cooling while the rings were laid on each other to form the final three-layer structure over the strips. This provides a glimpse of the engineering skills of the medieval Indian ironsmiths. The method by which the entire cannon was handled during its manufacture is not known. Needless to state, the method must have been ingenious because of the additional complications due to the high temperatures involved in the forge welding operation. The handling of the cannon must have involved an arrangement similar to that utilizing the iron handling rings. A careful non-destructive study will throw further insights on the manufacturing methodology, especially in the rear solid portion of the

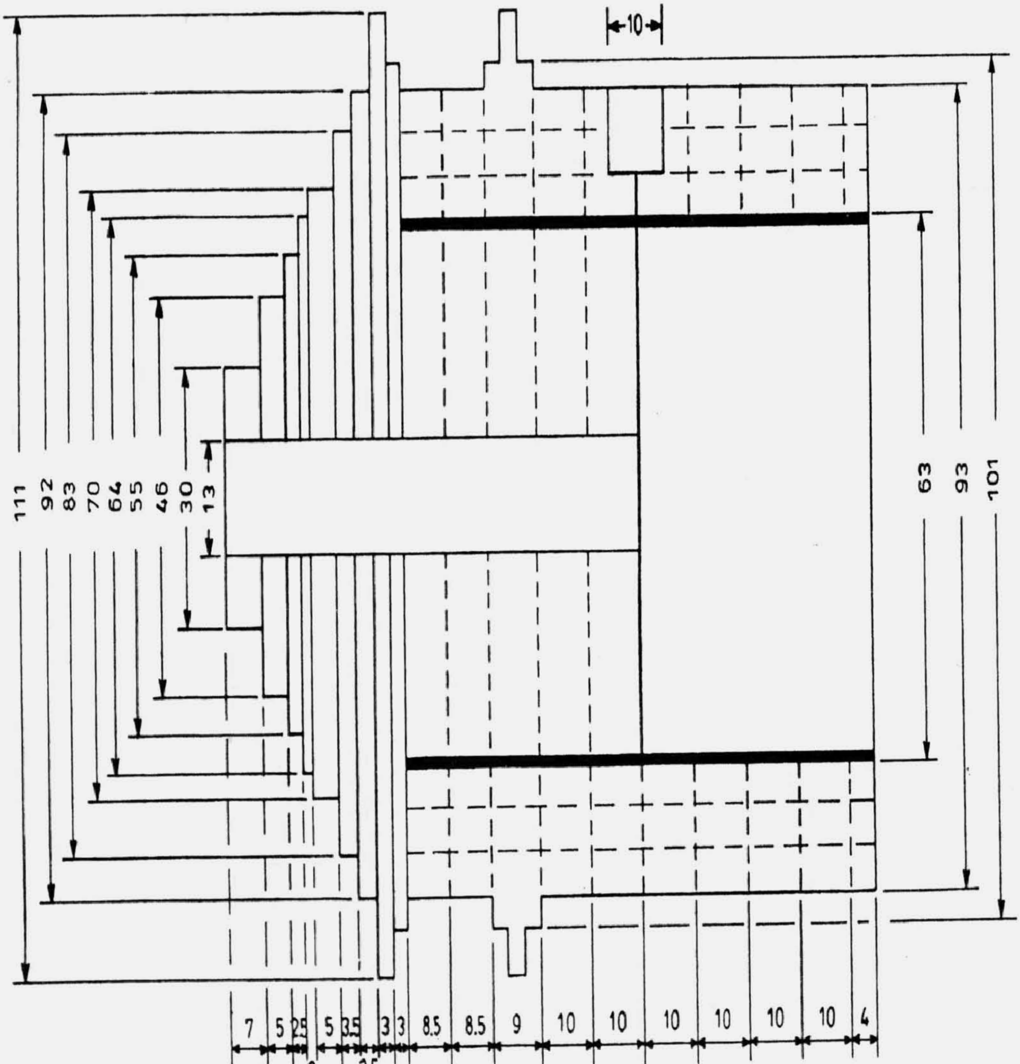

Fig. 10: Schematic showing a conjectural construction of the rear end of the cannon.

cannon. It may be interesting for the reader to note that iron cannons were also manufactured by forging together round-shaped solid pancakes of iron and later punching out holes in the center using chisels [14]. There is mention of iron cannons fabricated in this manner in North India during the reign of Akbar (1556-1605 AD) [14].

Material Characterization

An extremely small iron sample was extracted from the plate, at the first clamping location, for analysis. It was used for all the scientific studies reported in this communication. The chemical composition of the iron was determined by a Jobin Yvon JY-385 inductively coupled plasma atomic emission spectrometer and it provided the composition as 93.4% Fe, 0.01% Cr, 0.003% Al, 0.026% Ni, 0.003% Mo, 0.042% P, and 0.411% carbon. A separate analysis for the carbon content provided 0.419%, while a separate analysis for S content revealed that it was less than 500 ppm. The low amount of P at this location must be noted and this is generally not the case with ancient and medieval irons[6-8]. They contain a significant amount of P because limestone was not added in the charge of the bloomery furnaces and therefore, a higher amount of P was retained in the metal[16]. The unusually low P content could be due to a lower amount of P in the particular sample that was analyzed. Metallographic investigations revealed that the iron sample extracted contained a relatively high slag volume fraction and this could be one reason for the lower amount of P determined in the metal. The microsegregation of P in archaeological iron is quite different from macrosegregation that is observed in modern iron and steel making practices. The microsegregation is strongly influenced by the presence of entrapped slag inclusions and also by high temperature metallurgical phase transformations[17]. Another reason for the low P (and the relatively high C) detected here could be due to the deliberate heat treatment (by carburization) of the iron used in the location from where the sample was obtained. Metallographic investigations, to be discussed below, did not reveal any deliberate carburized structure. Therefore, some of the carbon in this analysis may have arisen from entrapped cinder in the iron sample.

The total elemental composition added up to 93.895 wt. %, thereby indicating that the remainder of the material used for the chemical analysis

Fig. 11: (a) Optical micrographs

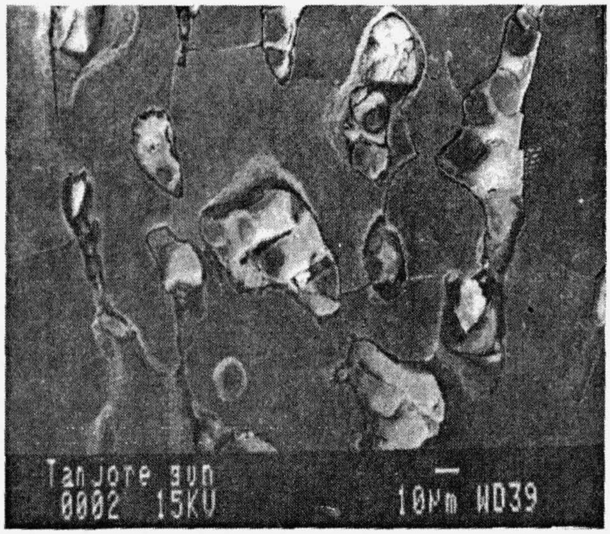

Fig. 11: (b) SEM micrographs showing slag inclusions in ferrite matrix

must have been the entrapped slag inclusions. The presence of entrapped slag inclusions was verified by volume fraction analysis in an optical microscope (Fig. 11). These inclusions were not uniformly distributed. At some locations, there was a much larger fraction of these inclusions compared to other locations. In addition to their distribution inside the ferrite grains, slag inclusions were also observed to coat some of the grain boundaries. The grain size of the sample was not uniform. These observations are in tune with the general characteristics of ancient Indian irons [4,5]. The volume fraction of the entrapped inclusions was determined by the grid intercept method, based on a large number of fields of view. The volume fraction of entrapped slag was found to be 6.07%. This is slightly greater than the usual volume fraction of about 2 to 4 volume percent slag inclusions generally observed in ancient Indian irons. Microstructural analysis revealed that the material of construction was not a cast structure, thereby firmly verifying that the cannon was manufactured by forge welding of wrought iron and not by casting.

In order to conduct electrochemical studies, the iron sample from the Thanjavur cannon was mounted after providing electrical connection on the backside. The surface area exposed for electrochemical studies was precisely maintained by providing a protective layer coating at the edges. Microstructural analysis of the area exposed for electrochemical studies indicated that the volume fraction of slag inclusions at this location was low. The same sample was used for all electrochemical experiments, with the surface prepared to 4/0 emery paper finish before every experiment. The sample surfaces were also thoroughly cleaned and degreased before each electrochemical experiment. Electrochemical polarization studies were conducted in double distilled water containing 0.005 M Na_2SO_4 (to aid solution conductivity) of pH 7.00 and a borate buffered solution (0.01 M KNO_3, 0.5 M H_3BO_3 and 0.05 M $Na_2B_4O_7.10H_2O$) of pH 7.62. For comparison purposes, a 0.05% C mild steel (composition determined by wet chemical analysis provided 0.062 C, 0.005 Si, 0.006 P, 0.02 Ni, 0.004 Co, 0.185Mn, 0.042 Cr, 0.005 Mo, 0.024Cu, 0.0007 Ti, 0.032 Al and 0.012 S) was also investigated. The electrochemical studies were conducted on a Model 263A EG&G Princeton Applied Research potentiostat. A round-bottom electrochemical cell was used for the studies, with a saturated calomel electrode (+0.242 volts versus standard hydrogen electrode) as the reference electrode and graphite as the auxiliary electrode. All the polarization experiments were performed after stabilization of free corrosion potential.

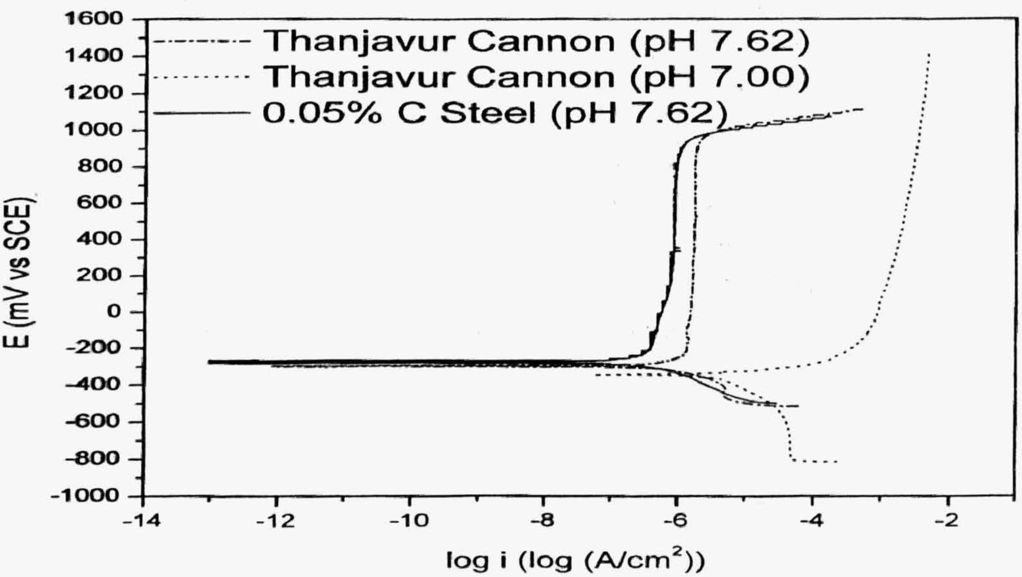

Fig 12: Potentiodynamic polarization curves for Thanjavur cannon iron in borate buffered solution and double distilled water compared with that of 0.05%C steel in borate buffered solution.

The potentiodynamic polarization behavior of the Thanjavur cannon iron has been compared with that of mild steel in Fig. 12. Both the irons exhibited active behavior in pH 7.00 solution and stable passive behavior in the pH 7.62 solution. The polarization behavior of the irons was comparable. The breakdown potential for both the samples in the borate buffered solution was similar thereby indicating that the slag inclusions did not affect passive film breakdown. The corrosion rates were determined by the Tafel extrapolation method as per ASTM standards. The results are tabulated in Table 1. The corrosion rates of the ancient and modern irons were comparable and of the same order of magnitude.

Table 1: Parameters measured from Tafel extrapolation studies. DDW means double distilled water.

Material	β_a (V/dec)	β_c (V/dec)	i_{corr} ($\mu A/cm^2$)	µm/yr
Thanjavur Iron pH 7.62	0.110	0.146	0.129	1.499
Thanjavur Iron DDW pH 7.00	0.223	0.210	0.244	2.827
0.05%C Steel pH 7.62	0.237	0.075	0.346	4.010

Rust thickness can be predicted from known atmospheric corrosion rates of iron in several environments [18]: 4-45 µm/y rural environments, 26-104 µm/y marine, 23-71 µm/y urban and 26-175 µm/y industrial. Assuming the Thanjavur weather to be rural, the estimated corrosion product layer over a period of 350 years should be between 2800 µm to 31500 µm. Utilizing the corrosion rate measured in the polarization testing of immersed sample, the total approximate corrosion suffered by the Thanjavur cannon iron must be 350 y × 2 µm/yr = 700 µm. When converted to rust, it should have resulted in a rust of thickness 1400 µm. This has certainly not been the case because the Thanjavur cannon does not show any evidence for significant rusting (Fig.1). Measurement of the rust thickness at one location by cross sectional microscopy indicated a maximum thickness of about 140 µm [19]. As the surface was not significantly corroded, it indicated that the surface was protected against atmospheric corrosion by the surface layer. Further ideas about the atmospheric rust nature were, therefore, obtained by rust characterization studies.

Samples of atmospheric rust were scraped out from the atmosphere side of the Thanjavur cannon. This rust was used for identifying the constituents of the atmospheric rust by X-ray diffraction and Fourier transform infrared spectroscopy (FTIR). FTIR spectroscopy is a very powerful technique to identify the iron oxides and oxyhydroxides, even if they are present in the amorphous form. Therefore, analysis of any rust in general by XRD would provide information about the crystalline phases, while the FTIR spectroscopy, in addition to confirming the results of the XRD analysis, would also provide information about the amorphous phases. The FTIR spectrum from Thanjavur cannon rust is shown in Fig.13. The broad band seen in the region 3000–3500 cm^{-1} was due to hydration of the rust. It is known that O–H stretching leads to a strong peak

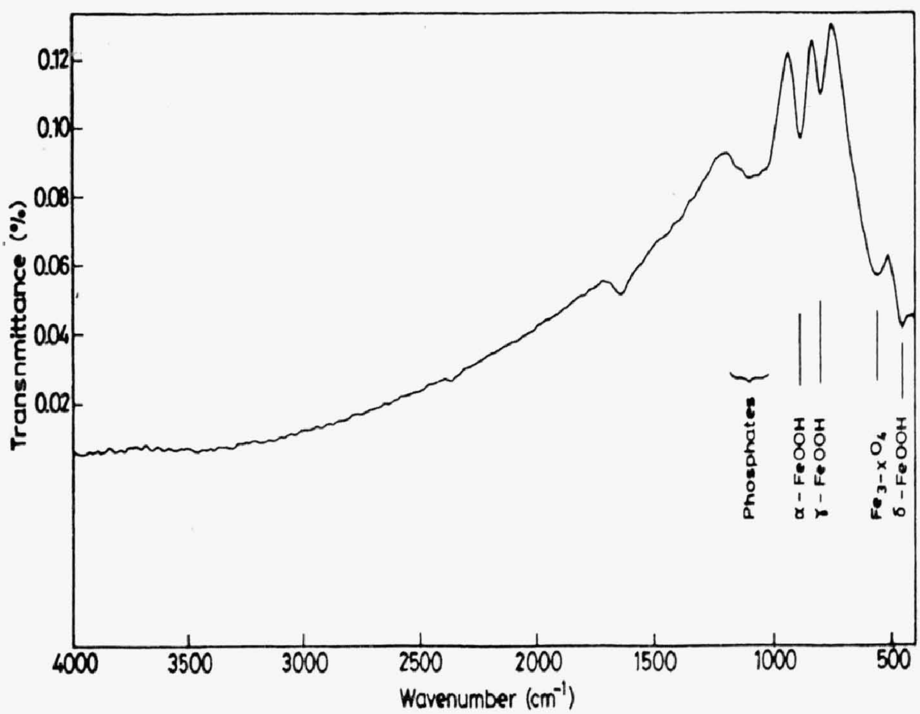

Fig. 13 Fourier transform infrared spectrum from Thanjavur cannon iron rust.

between 3000 and 3700 cm^{-1}, while O–H bending to a medium band between 1200 and 1500 cm^{-1}. Therefore, hydration of corrosion product(s) in the rust was implied. The presence of lepidocrocite (γ-FeOOH), goethite (α-FeOOH), magnetite ($Fe_{3-x}O_4$) and δ-FeOOH is confirmed by peaks at 1104.10 cm^{-1} and 797.38 cm^{-1} (γ-FeOOH), 887.72 cm^{-1} (α-FeOOH), 559.05 cm^{-1} (magnetite) and 455.01 cm^{-1} (δ-FeOOH) [20]. The spectrum shows a shoulder broadening at 1000-1200 cm^{-1}, which may be attributable to presence of ionic phosphates [20,21].

The XRD pattern obtained from the Thanjavur cannon rust has been shown in Fig. 14. The spectrum was compared with the JCPDF database using the Diffrac+ program. Sharp diffraction peaks were not observed from iron oxyhydroxide and oxide phases. Some phases identified were lepidocrocite, goethite and magnetite. This was also confirmed by µXRD studies conducted

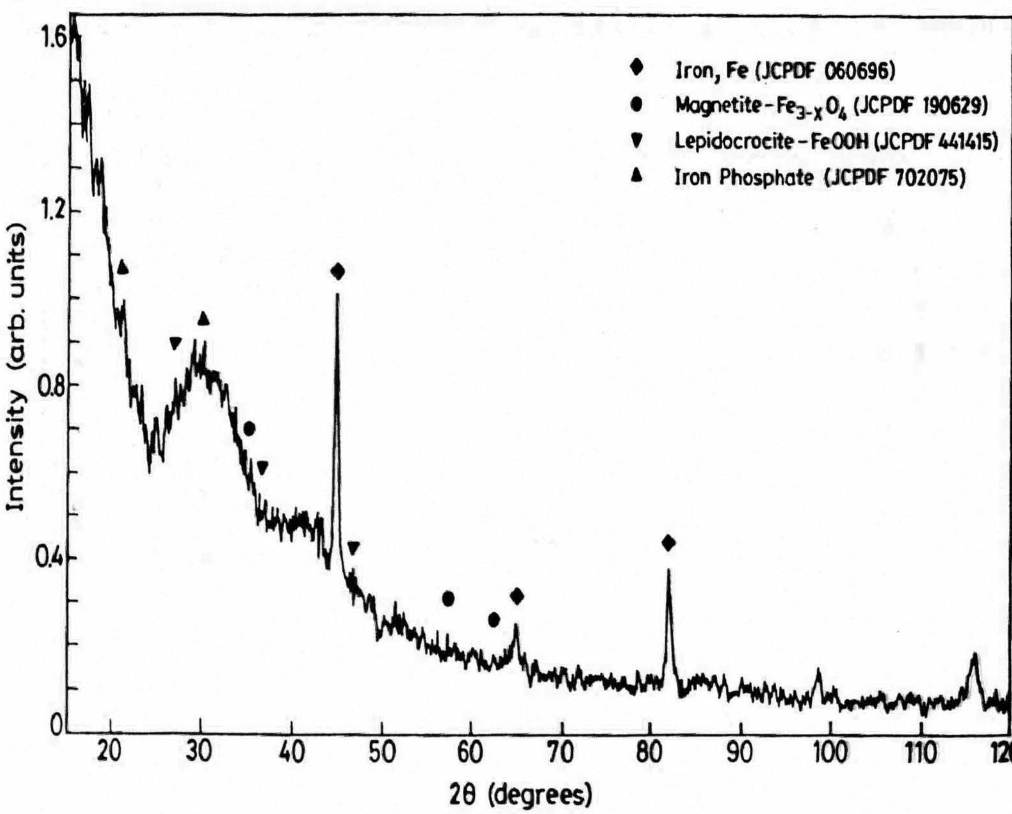

Fig. 14: X-ray diffraction pattern from rust confirming presence of lepidocrocite, goethite, magnetite and phosphate.

at several locations the rust cross section of the Thanjavur iron cannon rust using synchrotron radiation[19]. Therefore, the XRD results complimented the FTIR spectroscopy results. Phosphates were not identified in the rust location studied by μXRD and this must be related to the low P content in the iron matrix underneath, as revealed by the compositional analysis. However, the color of the surface of the cannon is quite indicative of the enrichment of P in the atmospheric rust of the cannon. The phosphorous content in rusts on ancient Indian iron generally follows the mesoscopic variation of P contents in the iron matrix[22].

Conclusions

The seven-and-half meter long forge-welded medieval iron cannon located at Thanjavur in Tamil Nadu has been studied. The cannon was locally fabricated between 1600 and 1645 AD. Its dimensions have been measured. Its construction methodology has been illustrated based on a detailed analysis of its structural design. The chamber and barrel of the cannon have been separately manufactured and later joined together. The material of construction was wrought iron and the method used to join the iron lumps and rings used in the fabrication of the cannon was forge welding. The material and electrochemical characterization of the material of construction of the iron gun has been discussed in detail. Its microstructure of the wrought iron consisted of ferritic grains with entrapped slag inclusions. Its electrochemical behavior was similar to that of mild steel under normal immersion conditions. The presence of lepidocrocite, goethite, magnetite, δ-FeOOH and phosphates was indicated by rust analysis. The Thanjavur cannon is one of the marvels of medieval Indian metallurgical skill.

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