Special Issue on Nonferrous Materials Heritage of India

Guest Editors

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in association with
The Indian National Academy of Engineering

PREFACE

The materials heritage of India is indeed spectacular. Of the eight metals-gold, copper, silver, iron, zinc, lead, tin and mercury- known since antiquity, Indian contributions are striking for at least three of them. Indian heritage in ferrous metallurgy is a celebrated one. The Delhi Iron Pillar stands as eloquent testimony to the skills of iron production and manufacturing in ancient India. Standing 7.16 meters high and weighing 6.5 tons, it has defied the vagaries of the environment since AD 400. Wootz steel, an anglicized version of the Kannada term 'ukku' for steels, was produced in India as early as 300 BC and was prized as the most advanced material for making swords for nearly two millennia and in several nations. The Indian Institute of Metals, together with the Indian National Academy of Engineering organized a special session on Iron and Steel Heritage of India in 1997 and brought out the proceedings as a special publication with assistance from Tata Steel. A similar session on Nonferrous Materials Heritage of India was organized in 1998.

This Special Issue of the Transactions of the Indian Institute of Metals contains an updated version of the papers presented as well as additional contributions. The overview on Nonferrous Metals Heritage of mankind by Sharada Srinivasan and S. Ranganthan sets the scene. It covers all the seven metals known in antiquity and in addition considers zinc. This paper is helpful in seeing Indian achievements in the backdrop of achievements by other civilizations such as Egyptian, Mesopotamian, Chinese and Meso-American cultures. In the field of nonferrous metals, India is renowned for its intense affinity for gold. R.K. Dube explores several aspects of the history and metallurgy of gold in India in early times on the basis of literary evidence starting from *Ṛgveda*. A reference to Pipilaka or Ants' Gold in the epic Mahabharatha throws new light. The trade connection with South-East Asia is also emphasized. Though India was not the first to produce copper it played an important role in copper metallurgy. R. Balasubrmaniam discusses the archaeometallurgy of ancient Indian copper. An analysis of two samples is presented. The long term corrosion mechanism of ancient copper samples point to potential benefits for long term storage of nuclear wastes. The extraction of zinc was done first in India. For a long time it was thought that William Champion process in 1840 was the first production of zinc. His process was anticipated by several centuries, as the retorts in Zawar show zinc production on a large scale at least since AD 1200. K.T.M Hegde, Arun Kumar Biswas, P.C. Craddock and Lynn Willies have contributed in a significant fashion in unraveling this development. The paper by Biswas on zinc and related alloys the pioneering traditions in ancient and medieval India. narrates this and includes a brief account of the Bidri alloy.

Bronze, as an alloy of copper and tin was one of the earliest alloys to be used by mankind. Indian contributions to bronze technology are rich. R.M. Pillai, A.D Damodaran and S.G.K. Pillai discuss in detail the shaping of bronze in ancient India and provide several case studies from South India. They report on the case histories of Aranmula mirror making, Kadavaloor high tin bronze eating bowl, and gong making. A description of the lost wax process for making icons, utensils and bells in Swamimalai and Mannar enriches our understanding. Baldev Raj, B. Venkataraman, R. Balalsubramaniam and V. Jeyaraj have shed further light on bronze icons. The use of nondestructive testing for the authentication of art objects is highlighted.

Six papers have been collected together in this Special issue on Nonferrous Materials Heritage of India. In addition to providing overviews they also contain new research findings. It is hoped that this publication will lead to further accelerated research so that we may gain a full and comprehensive knowledge of the accomplishments of ancient Indian metallurgy. The transition from one material to another in India can then be mapped out with greater precision. Also, how the ancient materials and process technologies anticipated many advances in science in recent times can be documented. The editors express their gratitude to all the authors for their contributions. Thanks are due to K. Bhanu Sankara Rao, Chief Editor and R. Sandhya, Editor for their assistance. The Metal Sciences Division of the Indian Institute of Metals and the Study Group on Metallurgical Heritage of the Indian National Academy of Engineering are thanked for their support.

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NONFERROUS MATERIALS HERITAGE OF MANKIND

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ABSTRACT

The symbiotic relationship between materials and civilization has been receiving increasing attention in recent years. In this article a brief history of the nonferrous metals in antiquity is narrated. The metals include gold, copper, silver, lead, tin, mercury and tin. A few alloys of antiquity, in particular electrum, tumbaga, arsenical and tin bronzes, are also described. Further silk and diamond have been added in view of the prominence they have enjoyed since antiquity. The historical development of these materials is viewed against the geographic landscape of continental Africa, Asia, Europe and America. The transition from the predominant use of one material to that of another material is discussed from technical and socio-cultural perspectives. The anticipation of modern science in ancient metallurgical practice is a recurrent theme.

1. INTRODUCTION

Materials are synonymous with human civilization. Artifacts made of materials for both artistic and utilitarian purposes dominate every day life. With the passage of time they have become increasingly sophisticated. It is intriguing to observe that just as man has evolved through the Darwinian process of biological evolution with the survival of the fittest, materials have also gone through a process of evolution, inanimate though they are. Thus, at different periods of history one set of materials was in predominant use only to give place at a later time to a more advanced material. Different stages in this evolution have been christened as the Stone Age, the Bronze Age and the Iron Age. This classification system is relatively recent and was devised by the Danish curator of museums, C. J. Thomsen in 1836 for the sequence of technological periods (stone, bronze, and iron) in Old World prehistory [1]. It established the principle that by classifying artifacts, one could produce a chronological ordering. In reality, the technology of iron smelting was developed at different times throughout the Old World, and in some cases, as in parts of the African continent, the Bronze Age was entirely skipped. In the Americas the age of gold and even platinum flourished until this development was abruptly shattered by the invading Spaniards with iron and steel.

The time line of material evolution captures some key events in the evolution of materials (Table 1). This must be considered as illustrative, as new knowledge derived from archaeometallurgy continually refreshes our knowledge in this area and alters the dates. Silk has been added to this list as it is another material from antiquity which linked religions, nations and historical periods in an extraordinary way through its trade on the Silk Road. Diamond has also been added, as it has a dazzling Indian connection. The table ends with 1856, when the advent of tonnage steel by the Bessemer converter brought about a tectonic change in the use of materials.

From the discovery of naturally occurring metals and materials there was a passage to deliberately engineered materials with an astounding combination of properties. Indeed, the ever-accelerating pace of development of engineered materials also leads to new machines and devices marking quick social changes and upheavals. Figure 1 is a pictorial representation of the materials civilization timeline, adapted from the excellent book on Understanding Materials Science' by L.E. Hummel of University of

Table 1

TIMELINE OF THE EVOLUTION OF MATERIALS

	1,000,000 BC	Man on Earth
Stone Age		
Chalcolithic Age	8000 BC	Native Copper, Native Gold,
	6500 BC	Smelting of copper from malachite,
		Arsenical bronze-an accidental alloy
	4000 BC	Silver
Bronze Age	3000 BC	Tin bronze
2900 BC	First man-made iron object in the great pyramid of Giza	
2700 BC	Meteoritic iron in Egypt	
2500 BC	Lead in Indus Valley, India/Pakistan	
	1750 BC	Tin
	1500 BC	Bronze by Shang dynasty in China
		Chinese princess discovers silk
Iron Age		
	1200 BC	Smelting of iron by Hittites
		Bronze bells in China
	1000-500 BC	Wrought and quenched high-tin beta bronze vessels in South Indian megalithic and iron age sites
	1000 700 BC	Greeks and Indians quench and temper iron to improve the cutting characteristics
	750 BC	Mercury
	500 BC	Deepest old gold mine at Maski, India
	500 BC	Gold, Copper-gold, Gold–platinum alloys: Mayans, Aztecs, Incas in the Americas
	500 BC	Reference to diamond in Indian Sanskrit texts
	300 BC	Crucible steel in South India, later known as wootz
	200 BC	Cast iron in China
	100 BC	Development of the Silk Road
	AD 400-420	Delhi Iron Pillar
	AD 1200	Zinc smelting at Zawar, India
	AD 1400	Blast furnace for iron making
	AD 1856	Bessemer Steel

Florida, USA. His book weaves together history, properties and applications in a vivid fashion [2]. The Fertile Crescent encompasses Sumerian, Egyptian, Mesopotomian, Babylonian and Hebrew civilizations. This covers an area, where some of the earliest use of metals occurred. Another map (Fig. 2) drawn by Michael Ashby of Cambridge University, UK gives a panoramic view of the development in the use of materials over ten millennia [3]. A graphic depiction of the different classes of materials from ceramics to metallics, polymerics and more recently to composites is vividly brought out. The passage from discovery through development to design of materials can be noted. The diagram is beguiling in its chronological

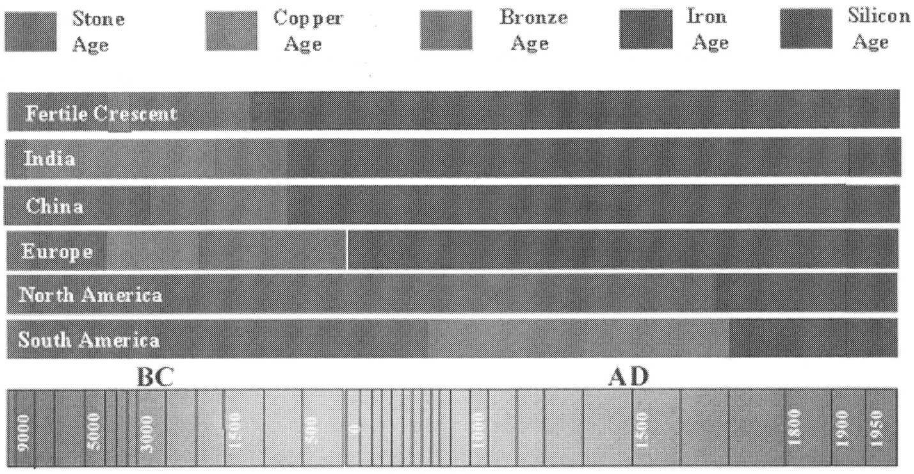

Fig. 1 : Time Evolution of Metals from a geographical perspective (adapted from reference 2)

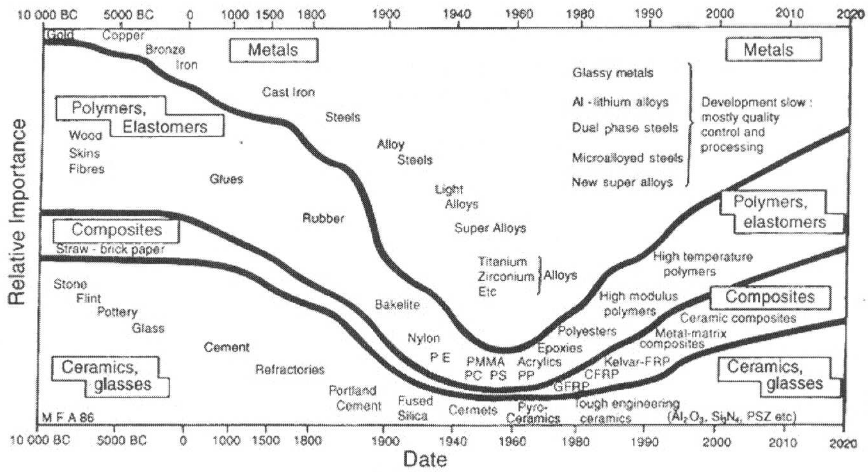

Fig. 2 : Ashby Map indicating the waxing and waning of different classes of materials over ten millennia [3]

scale. In time scale the past fifty years occupy the same space as the preceding ten millennia!

In some sense metallurgy and human civilizations enjoy a symbiotic relationship. This article surveys the metallurgical heritage of mankind with an emphasis on six of the seven metals (Gold, Copper, Silver, Lead, Iron, Tin and Mercury) found in antiquity. The eighth metal, Zinc, is added not only because of the unique Indian context but also because the discovery of other metals had to await a few centuries and the advent of the scientific revolution.

The variables in linking metals and mankind are many. History is a time variable and geography is a space variable. Within each region, such as the Pharaonic and Chinese dynasties in Egypt and China, cultural changes introduce yet another variable. The initial use of metals and alloys was, as Smith has pointed out, in ornaments and weapons to conquer other women and men [4]. To this we may add a third motivation of religion and ritual. These sensuous, strategic and sacred applications give one more degree of freedom. Thus our survey will have the difficulties that one encounters in depicting a multi-component phase diagram with temperature, pressure and composition as variables requiring a hyper-dimensional representation from ternaries onwards. We have adopted therefore a linear progression based on metals in the order of their coming into use: Gold, Copper, Silver, Lead. Tin, Mercury and Zinc. In each metal the regional and cultural parameter – Egypt, Mesopotomia, India, China and Mesoamerica- is followed. Within each region the applications-sensuous, strategic and sacred - are used in a sequential form. A short description of the alloys in antiquity with a coverage of brass and bronze follows. This does not do justice to the vast panorama of the intertwining of history, civilization and metallurgy. The recent books by Trivedi [5], Sass [6] and Howell [7] provide fascinating accounts of this remarkable story. The interplay of spiritual beliefs, artistic impulses, sociopolitical factors and cultural developments is indeed a complex web. Perhaps the modern world - wide web provides a better medium with its hyperlinks [8].

Genetic studies are beginning to throw new light on the evolution of mankind. It appears that the original Homo Sapiens may have first existed in Africa. Between 50,000 and 200,000 years ago successive migrations took place outward to Asia and Europe. The early habitats were near rivers. Thus we see the flowering of great civilizations around the Nile, the Euphrates and the Tigris (the region between the two rivers acquiring the name Mesopotomia as mesos and potomas mean middle and rivers in Greek), the Indus and the Yellow-Yangtse river valleys. For all practical purposes the evolution of civilization was synonymous with the mastery over materials. Thus the earliest periods have become known as the Stone Age (Neolithic Age), the Copper Age (some times called the Chalcolithic Age, Chalco and Lithos mean Copper and stone in Greek and indicating an overlap of the Stone and Copper ages), the Bronze Age and the Iron Age. If civilizations flourished in Asia and in particular in the huge land masses of India and China, it is not surprising that many of the innovations in the development of metals are of Indian and Chinese origin. What is surprising is that this fact is not as well appreciated, as it ought to be. The flowering of civilization in Mesoamerica as an almost independent development poses rich cultural and scientific puzzles.

2. THE STONE AGE

The Stone Age marks the time, early in the development of human cultures, before the use of metals, when tools and weapons were made of stone. The Stone Age occurred at different times in different parts of the world. In Europe, Asia, and Africa it began about two million years ago. In the most advanced parts of the Middle East and Southeast Asia it ended about 6000 BC, but it lingered until 4000 BC or later in Europe, the rest of Asia, and Africa. The Stone Age in the Americas began 30,000 years ago when human beings first arrived in the New World, and lasted in some areas till about 2500 BC. Throughout the immense time span of the Stone Age, vast changes occurred in climate and in other conditions affecting human culture. Humans themselves evolved into their modern form during the latter part of it. The Stone Age has been divided accordingly into three periods: the Paleolithic (> 10,000 BC), Mesolithic (10,000-8000 BC) and Neolithic (8000-6000 BC) eras. The Chalcolithic Age, when copper emerged as a new material and was used alongside stone, lasted from 6000 to 3000 BC, eventually giving way to the Bronze Age.

3. LITERARY SOURCES

Table 2 lists the metals of antiquity. As iron was first found in meteorites, there was a natural impression that metals had a connection with stars. In many languages the name for metallurgy is siderurgy. Thus it is not surprising that each metal was associated with a celestial body – the sun, the moon and the known planets of that era. This association is also indicated in the table. Metals were also the spring - board for alchemy. Thus we find in the mists of antiquity metallurgy, alchemy and astrology were tied together. Many old literary sources connect these disparate subjects. In the light of modern knowledge their value is an indication of which metals were in use.

We can press the analogy with phase diagrams a little further. As the number of components increases, the number of diagrams to be established by experiments increases in a dramatic fashion. Hence attempts are made to calculate from first principles the phase diagrams given only the atomic number of the constituent elements. A natural question is whether the sequential discovery of metals and their regional destiny can be similarly arrived at from first principles. More complex factors are at work, as unlike the inanimate phase diagram this question involves man and his cultural attributes. However, some simplifications can be attempted. The cosmic abundance of elements is controlled by the stability

Table 2

SEVEN METALS OF ANTIQUITY AND TWO METALS OF THE FIRST HALF OF THE SECOND MILLENNIUM AD

Metal	Discovery	Planet	Latin name	Symbol
Gold	ca. 6000 BC	Sun	Aurum	Au
Copper	ca 4200 BC	Venus	Cuprum	Cu
Silver	ca 4000 BC	Moon	Argentum	Ag
Lead	ca 3500 BC	Saturn	Plumbum	Pb
Tin	ca 1750 BC	Jupiter	Stannum	Sn
Iron (Smelted)	ca 1500 BC	Mars	Ferrum	Fe
Mercury	ca 750 BC	Mercury	Hydrargyrum(Greek)	Hg
Zinc	1200 AD	None	Zince(German)	Zn
Platinum	1500 AD	None		Pt

of the nucleus. Thus iron is abundant in the Universe. The crustal abundance depends on the formation of planet earth and the subsequent geological processes. The electronegativity of the metals leads to reactivity and the occurrence of metals in the native state and as combined oxides, sulphides etc. The ease of separation depends upon the stability. Thus Au, Ag and Cu can be shown to appear in native form. The melting points of metals have a bearing as well. Thus mercury is found in the native state. On the other hand aluminum is abundant on earth's crust, yet its oxide is tenacious and it was separated only in modern times. Table 3 gives the crustal abundance of metals, their melting point as well as significant ores of earlier times.

Minerals attracted attention from the beginning. The colour of the pigments was a magnet for mankind. Theophrastus was a student of Aristotle and succeeded him as head of the Lyceum in Athens. His book on "De Lapidibus" (On Stones) was composed around 315 BC and is one of the earliest surviving texts on minerals [9]. Another important book is the Natural History by Pliny (23-79 AD) [10]. The publication of "De la Pirotechnica" by the Italian Vannoccio Biringuccio is a milestone [11]. The author was a metal worker and his book is a masterpiece on the foundry practices prevalent at that time. The publication of "De Re Metallica" by Georgius Agricola in 1556 AD is another major landmark, as it represents the first acknowledged treatise of metal extraction and processing [12]. Indeed it is held to mark the transition from the prehistorical period of metallurgy to modern metallurgy. Agricola wrote it in Jachimov near the Czech-German border. Most of the 16th century mining activities he wrote about were based on local activities.

The existence of texts in India and China, predating these monumental publications, is only now winning grudging recognition. India has had a hoary tradition in mining, as evidenced by the writings of Kautilya [13] in Arthashastra (ca 330 BC). It required the gargantuan efforts of Joseph Needham, whose magnum opus, "Science and Civilization in China" shed brilliant light on the numerous accomplishments of Chinese science and technology [14]. Indeed the fifteenth century superpower was China. India still awaits a similar scholarly and comprehensive treatment as that of Needham on China. Of course, one must remember when comparing Indian or Chinese texts predating it that Metallica differs in being based for the first time on a great deal of factual information and recording and drawings, whereas the Indian texts are more like ritual prescriptions and the Chinese kept historical records.

In modern times archaeometallurgy has evolved as a discipline in its own right. Thus we have many studies across the globe. Special mention may be made of

Table 3
SOME IMPORTANT PARAMETERS OF METALS OF ANTIQUITY

Metal	Crustal abundance	Primary oresin antiquity	Melting Point Degrees Celsius	Dominant Regions
Gold	0.004 ppm	Native, Tellurides	1063	Mesopotamia, Egypt, India, Meso-Americas
Copper	68 ppm	Native, Malachite, Chalcopyrite	1084	Sumeria Egypt Mohenjadaro, North America
Silver	0.08 ppm	Native,Argentite	961	Greece
Lead	13 ppm	Galena	327	Rome
Tin	2 ppm	Cassiterite	232	Cornwall,Indo-China
Iron		Native meteorite,	1535	Hittites, India, China
Mercury	0.08 ppm	Native, Cinnabar	- 38.87	Egypt, Greece, India, China
Zinc	70 ppm	Sphalerite	419	India, China
Platinum	0.003 ppm	Native	1773	Meso-Americas

the contributions by Cyril Stanley Smith [4], Robert Maddin [15], Tsun Ko [16], Fathi Habashi [17], A.K. Biswas [18, 19] and R.F. Tylecote [20, 21]. It is surprising to note that while many books and treatises exist covering the whole gamut of metals in antiquity, none of them is entirely satisfactory (Tylecote [21], Craddock [22]). It is interesting to point out that a modern chronicle of "The Coming of Materials Science" by R. W. Cahn will attract similar attention from future historians [23].

4. GOLD

Gold is found in the native state and is used to make jewelry and sheet metal due to the great ductility and lustre of the pure metals. Gold is invariably associated with quartz or pyrite, both in veins and in alluvial or placer deposits laid down after the weathering of gold-bearing rocks. It was usually collected by panning alluvial sands from placer deposits.

Some of the early rich finds of gold artifacts were from the cemeteries in Bulgaria in Europe (5th millennium BC) with accouterments of hammered and sheet gold. Some of the most elegant gold vessels made by the repousse technique come from the Mesopotamia (ca 2500 BC). Spectacular gold castings are known from ancient Pharaonic Egypt, such as the enigmatic face of the young Pharaoh Tutenkhamen (ca 1300 BC). Detail from a panel on the gold plated shrine from the tomb of Tutankhamun in the Cairo Museum is depicted in Fig. 3. The tomb itself contained more than 112 kg of gold. Gold came to be used as coins in Egypt around 3400 BC. The interesting technique of granulation of gold in making jewelry was developed in Egypt and was used extensively by the ancient Greeks (ca 600 BC). Surface tension was used to turn melted gold filings into spheres. It has been said that the world conquest of Alexander was spurred by the occurrence of gold mines on the route that his conquest took him. The Greek epics are full of references to golden objects.

The significance of gold in Indian antiquity is abundantly borne out by many references in Rig Veda Samhita, the Arthasasthra and the Tamil classic, Silappadikaram. The tradition of mining gold started at least as early as the first millennium BC which has the distinction that the deepest ancient mines in the world for gold come from the Maski region of Karnataka with carbon dates from the mid 1st millennium BC [24]. The admixture of gold with silver in artifacts of the Indus Valley civilization also suggests that this gold might perhaps have originated

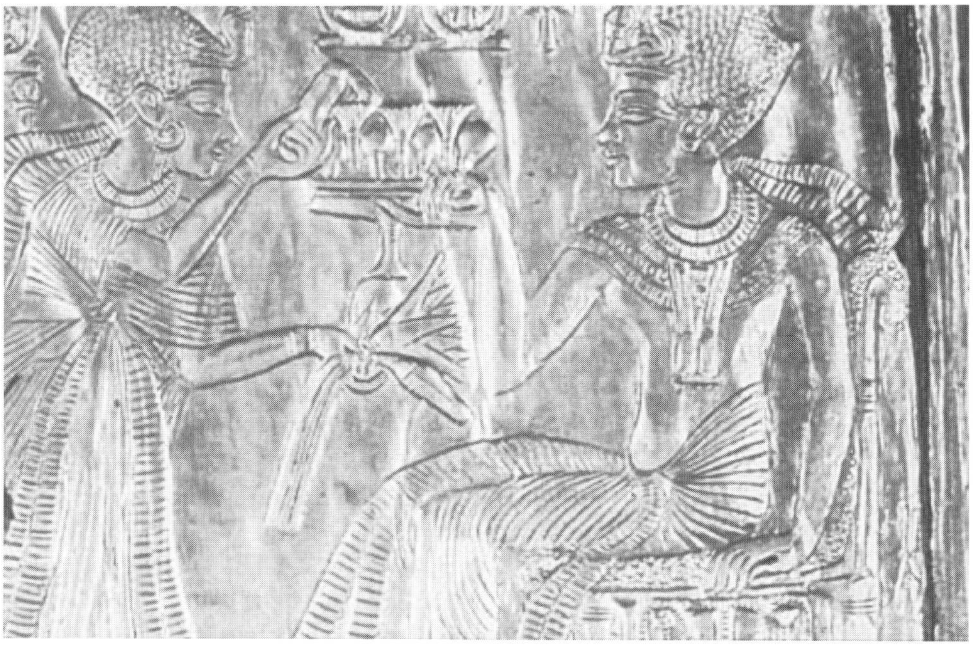

Fig. 3 : Detail from a panel on the gold plated shrine from the tomb of Tutankhamun in the Cairo Museum (Courtesy: World Gold Council - www.gold.org)

in Kolar in Karnataka. The Champion reef at the Kolar gold fields was mined to a depth of 50 m during the Gupta period in the fifth century AD. The metal was continued to be mined by the eleventh century kings of South India, the Vijayanagar empire from A.D. 1336 to 1560 and later by Tipu Sultan. It has been stated that the Indian influence and conquest of the Southeast Asian regions in the distant past was driven by the desire for gold. The granulation technique was also used to make gold jewelry in India in the late 1st millennium BC to early Christian era, with some examples found from Afghanistan to the south of India.

Ancient Chinese metallurgical choices are in stark contrast to those of Egypt, Mespopotamia, India and South Asia, where gold and silver were preferred for both jewelry and rituals. In China jade was prized from the neolithic period as the most beautiful stone and became a status symbol for the elite. Bronze joined the position accorded to jade and denied to gold!

Thanks to the perfect record keeping in Japan it is known when exactly gold was found. In AD 749 the discovery of gold in the Province of Mutsu in the Iwate prefecture was reported. The Konjikido of Chusonji Temple, built by the Fujiwaras, is decorated inside and out with lacquer containing gold foil and studded with gold and silver, a symbol of the gold culture of Hiraizumi (Fig. 4). It is commonly assumed that when Marco Polo wrote in Tales of the Orient of his travels to extravagant places in "Zipangu," as he called Japan, where even the roofs were covered with gold bars, that he was referring to the Golden

Fig. 4 : Japan Konkikodo

Hall. In fact the Oshu-Fujiwara family was engaged in trade with Sung dynasty of China between AD 960-1279, so it is not surprising that news of the Golden Hall would have reached the ears of Marco Polo.

One of the most remarkable episodes in metallurgy is the independent development of gold metallurgy in Peru and Mexico. The Incas and the Aztecs were master goldsmiths. The occurrence of gold was so plentiful that the bronze age was not traversed by them. Their ability to use the lost wax method was so exquisite that they truly wrought fantasies in gold. The South American empires of the Incas and Aztecs also cast stunning gold masks, some of which have survived being melted down by the Spanish conquerors. Figure 5 shows an example of a golden mask from the Chimu civilization in Peru before 15th century. In that bygone era every day items such as dolls, vessels, and furniture were all made of gold.

Fig. 5 : This mask from the Chimu civilization in Peru (before 15th century) is a rare objects in gold to have survived the invasion of the Spanish Conquistadors (Courtesy: World Gold Council- www.gold.org)

Europe entered the picture in a dramatic way towards the end of the fifteenth century. Spain and Portugal were the pioneers in navigation. From the city of Seville set forth the major expeditions of Amerigo Vespucci and Magellan. The conquest of the nations of South America followed. Cortes and Pizarro brought back the gold from the New World to the Old World to enable them to undertake development. A new metal, iron, conquered an old metal- gold! Tragically many of the artistic masterpieces were melted down. In 1520 when Albert Durer saw the golden treasure sent by Cortes to Charles V Holy Roman Emperor, he remarked that ' Never in all my life have I seen any thing that warmed my heart as much as these things'. A twelve sided tower, known as Torre del Oro (tower of gold) stands as testimony to that era.

5. COPPER

Native copper, i.e. copper metal, is thought to have been the first metal used by man and may have been used in ancient Turkey and Mesopotamia by about the seventh millennium BC. Its name is derived from Cyprus. Native copper is abundantly available in large masses in the Great Lakes region of North America and was used fairly extensively by the North American Indians to make weapons and implements solely by hammering and annealing so that casting and smelting was not attempted. Later discoveries at Rudna Glava in Yugoslavia have shown that copper was in use there in 4000 BC, although bronze was not made at that time.

Copper is mainly found as sulphide, oxide or carbonate. Its major ores are Chalcopyrite $CuFeS_2$, chalcocite Cu_2S, Cuprite Cu_2O and malachite $Cu_2CO_3(OH)_2$. Malachite may have been the major source in the beginning. Clear early evidence for smelting copper comes from the Middle East from about the fourth to third millennium BC onwards, from parts of Israel, Jordan and Egypt where copper oxide ores such as green malachite were smelted at temperatures of around 1200 ^{O}C. While there are possibilities that copper was smelted accidentally in camp fires, there is every indication that copper smelting was a deliberate act as it requires much higher temperatures than that attained in cave fires. Earlier experiences with pottery kilns must have helped the metallurgists to smelt copper.

Early copper artifacts of about the sixth millennium BC are also reported from the pre-Indus Valley sites of Baluchistan in the northwestern part of the Indian subcontinent close to the Iranian border. There is also some evidence for smelting furnaces from the Harappan civilizations of the northwestern part of the Indian subcontinent. There is fairly extensive evidence for the ancient mining of copper ores from the Khetri region of Rajasthan in northwestern India dating to about the third -second millennium BC [25].

6. SILVER

Silver is valued next only to gold for ornamentation. It occurs in the native state and is also widely distributed in a sulphide ore (argentite, Ag_2S). In addition as silver ores often occur in conjunction with lead ores, a process known as cupellation came into vogue and was the prevalent practice from 2500 BC. It consisted of the production of a silver-lead alloy from the sulphide ore, whenh lead was removed by oxidation. The alloy was melted in a shallow porous clay basin called cupel.

Silver began to be used ca 4000 BC. The Royal Cemetry at Ur, in Mesapotamia, *ca.* 3500-3000 BC contained an exceptional amount of early silver [26]. Interestingly, as far as silver production goes, the Aravalli region in north-west India along with Laurion in Greece and the Roman mines of Rio Tinto in Spain ranks amongst the few major ancient silver producing sites from about the mid 1st millennium BC onwards. The life-size silver urns in the Palace and Museum of the Maharaja of Jaipur, Rajasthan are the largest silver objects in the world. The art of fine filigree work in silver is still practised in places such as Orissa in eastern India.

7. LEAD

The principal ore is galena (PbS), though Craddock [22] has suggested that cerussite (lead carbonate) may have been an important source. It was used for both artistic (sculpture) and architectural purpose (roof covers, pipes, cisterns). Its resistance to climatic variations and low and melting point, led to its substitution for precious metals or bronze in some applications.

The first known lead containing statue was found in Turkey and is dated to 6500 BC. The Osiris temple in Egypt, 3500 BC has a carved lead statue. In ancient predynastic Egypt (ca 4000-3000 BC) galena was used in the manufacture of kohl or eyeliner and indeed a striking feature of Egyptian art is the beautiful and exaggerated lining of the eyes. Stone palettes for grinding kohl are found in ancient Egypt along with artifacts of lead, indicating that lead was one of the earliest metals to be smelted since lead ore is easily reduced and does not require very high temperatures. Lead was commonly alloyed with copper and bronze for making castings. In De Re Metallica, the Renaissance period text authored by Agricola more than five centuries ago, the Westphalian process of smelting lead ore is described where lead ore is smelted in an open hearth [12]. The mineral-rich Aravalli region of Rajasthan was one of the important early lead mining regions in antiquity. The use of low melting lead-tin eutectic as a solder became common in Europe by the late medieval period. Lead is toxic and some historians have advanced a theory that the fall of the Roman empire may have been caused by slow lead poisoning of the ruling elite.

8. TIN

From Pliny's writings [10] it is evident that in his time the distinction between lead and tin was not grasped, as they were called black and white lead. Tin ore occurs as alluvial deposits as well as ore bodies. The most important ore of tin is cassiterite (tin oxide, SnO_2). Tin mines are known from ancient Turkey dating to the third millennium BC. In an exceptional finding, Srinivasan [27] found evidence for the manufacture of bronze by co-smelting copper and tin ores from a site in Karnataka in southern India. One of the most extensive tin mining regions in the past was Cornwall in Britain, which is thought to have been mined at least by Roman times, while Southeast Asia has some of the largest alluvial tin deposits. Lead, copper and silver have relatively unstable oxides, which can be converted to metal by very low concentration of reducing gas. Tin oxides are reduced under more stringent conditions. Hence tin as a metal was a later addition, though as an alloying element with copper to make bronze, it appeared earlier. Tin was alloyed to copper to get harder bronze for making weapons, prior to the use of iron, in the Bronze Age cultures of the world. In addition it was also used for making bronze bells and bronze mirrors. It was used for coinage from the 7th century BC.

9. MERCURY

Mercury is a metal that has been of great alchemical importance in ancient times as a possible key ingredient for the transmutation of base metals to gold. Its association with silver led to its being called Hydrargyrum (Liquid silver) and led to the chemical symbol "Hg". Though transmutation was not possible, these efforts led to metallurgical developments of great consequence. This metal was associated with the planet mercury.

Mercury has been found in Egyptian graves dated around 1500 BC. In ancient China there is evidence that mercury was used by the latter half of the first millennium BC mercury, while mercury metal is reported from Hellenistic Greece. It was known in antiquity in India.

The ore is cinnabar (HgS). Mercury is a volatile metal, which is easily produced by heating cinnabar followed by downward distillation of the mercury vapour. Some of the earliest literary references to the use of mercury distillation comes from Indian treatises such as the Arthashastra of Kautilya dating from the late first millennium BC onwards [13]. Some evidence for mercury distillation is reported from the ancient Roman world.

There is an interesting variant of the production of mercury by a technique now known as mechano-chemical synthesis. In this process mercury is produced by pounding cinnabar with vinegar in a copper mortar. The processes of mechanical milling have become quite common in recent decades but this production of mercury is a historically significant event. It is described in De Lapidibus by Theophrastus [9] written in 315 BC. A detailed account has been given by Lazco Takacs [28].

In India, vermilion or cinnabar i.e. mercuric sulphide has had great ritual significance, typically having been used to make the red bindi or dot on the forehead of Hindu women. Ingeniously in ancient Chinese tombs cinnabar was used successfully as a preservative to keep fine silks intact.

10. ZINC

Three milestones in the production of zinc are the first preparation of elemental zinc in India in the 13th century AD, its transfer to China in the 16th century and the final wending of these technologies to England in the 18th century, paving the way for modern zinc technology. Biswas has covered this theme in an authoritative fashion [18].

The earliest firm evidence for the production of metallic zinc comes from India. Of the metals used in antiquity zinc is one of the most difficult to smelt since zinc volatalises at about the same temperature of around 1000 degrees centrigrade that is needed to smelt zinc ore. As a result it would form as a vapour in the furnace which would immediately get re-oxidized and hence lost. Hence metallic zinc is seldom reported in antiquity. However in India there is unique evidence for the extensive and semi-industrial production of metallic zinc at the Zawar area of Rajasthan as reported in Craddock [22]. An ingenious method was devised of downward distillation of the zinc vapour formed after smelting zinc ore using specifically designed retorts with condensers and furnaces, so that the smelted zinc vapour could be drastically cooled down to get a melt that could solidify to zinc metal. The aubergine-shaped retorts were stuck vertically through the perforations such that the top parts were filled with charge while the stem forming the condenser led into the bottom cooler chamber so that the vapour could condense through the stem and drip and be collected in vessels placed at the bottom. Indeed the remains suggest that the sophistication of zinc production at Zawar was almost on an industrial scale in an era preceding the Industrial Revolution, with each furnace having held about 36 retorts with no less than 252 furnaces being simultaneously fired. Zinc mining at Zawar continued on a large scale during the Moghul era although this activity seems to have died out by the 17th century. Extensive zinc mines are found at Zawar with huge mining galleries, some of which have been carbon dated back to about 2000 years i.e. the Christian era.

The Rasaratnakara, a Sanskrit text ascribed to the great Indian scientist Nagarjuna, of the early Christian era describes the Indian method of production of zinc, i.e. tiryakpatana or downward distillation, while other early Hindu and Buddhist alchemical texts also describe similar processes such as the Rasaratnasamuchhaya. A description of the cementation process is also given in the Sanskrit text of the Rasaratnakara. Although the organic prescriptions in the Rasaratnasamuchhaya may sound scientifically improbable they have been found to remarkably correlate with the finds at Zawar down to the description of the retort as being aubergine-shaped.

There is evidence from China that metallic zinc was produced by the 16th century from excavation in the Yunnan during the period of the Ming dynasty. Although the process used was essentially of condensing of zinc vapour, as in the Zawar process, the design of the retorts were different with the condensation of zinc metals taking place in collectors below the lids of the retorts. By the mid 17th century zinc was being exported from China to Europe, referred to in a Chinese text as a word of foreign origin, 'tutenag', which may derive from 'tutthanaga' an old name for zinc in south Indian languages. This suggests that ideas about zinc smelting were transmitted to China from India.

In Europe, the production of metallic zinc was virtually unknown until William Champion first established commercial zinc smelting operations in Bristol in the 1740's following which it was industrially produced. Interestingly the method of production adopted by downward distillation bears a strong resemblance to the Zawar process and it has been pointed out that Champion's process was very likely inspired by the Zawar process which would have been made known to the British during the forays of the East India Company.

11. ALLOYS IN ANTIQUITY

Pure metals are soft. While they can be used for ornamental and coinage purposes, they do not serve useful engineering applications for making tools and weapons. Alloying leads to an improvement of properties. Two alloys dominate the ancient landscape. They are bronze, made by alloying of copper with tin and wootz steel, made by adding carbon to iron. We have narrated in detail the developments surrounding the wootz steel - an advanced material of the ancient world [29]. The fact of alloying with carbon was not known until the last century. But in the case of copper many alloys had been prepared either accidentally or by intention leading to bronzes with profound consequences for the evolution of civilization. The lowering of the melting point led to better castings. Thus Cu-10% Sn melted at 950^0 C, nearly 100 degrees lower than pure copper. A few other alloys were known in antiquity but were not significant in their impact and are briefly considered in a later section.

11.1 Brass

In Roman times brass was made by not by direct alloying of metallic zinc to copper but by directly reducing vapours of zinc oxide into copper metal in the cementation process, which produced low-zinc brass of up to 28% zinc. Pliny's Natural History [10] mentions Campania as the centre of the Roman brass industry in Italy. The medieval Islamic world (Persia, Turkey and Syria) excelled in decorative metalwork with the art of 'damascening' or inlaying of brass and metal with silver with some of the finest examples of decorative metalwork, which are also found from late medieval Mughal India. The earliest known examples of high-zinc brasses with around 30% are from the Indian subcontinent suggesting they were made by alloying metallic zinc, from the Bhir mound of Taxila of the late first millennium BC.

11.2 Bronze

The Bronze Age refers to the time in the development of any region, before the introduction of iron, when most tools and weapons were made of bronze. Chronologically, the term is of strictly local value, for bronze came into use, and was again replaced by iron, at different times in different parts of the world. It generally succeeded a culture's Copper Age. To some extent archaeological discoveries since 1960 have upset traditional theories concerning the origins of copper and bronze technologies. It had generally been thought that the use of bronze had originated in the Middle East. However, intriguing discoveries from Ban Chiang, Thailand, suggest that bronze technology was probably known there as early as 3600 BC.

The first bronze to be made by man was an alloy of copper and arsenic, which was a totally accidental outcome of unintentional smelting of arsenic containing copper ores. It was in use in ancient Mesopotamia prior to the use of tin bronzes. The most famous and extraordinary examples of arsenical bronzes are the bronze bulls of the third millennium BC from Mesopotamia, where the enrichment of arsenic at the surface resulted in a shiny coating. An interesting question is whether arsenic bronze was just dirty copper or an intentionally prepared alloy. Archaeologists and historians of metallurgy have attempted to explain the gradual abandonment of arsenic bronze in favour of tin bronze in the ancient Old World by making comparisons between the mechanical properties of the two bronzes. These comparisons purported to show the superiority of copper-tin alloys over alloys of copper and arsenic, although recent studies throw fresh light. Whereas tin bronzes can be work hardened more extensively than arsenic bronzes, the far greater ductility of arsenical bronze makes it a desirable alloy for the manufacture of thin metal sheet. The widespread use of low-arsenic copper-arsenic alloys in the Americas, especially in the Andean culture area, is attributable in part to the tradition there of sheet metal production in the elaboration of three-dimensional forms. Indeed, there are indications that arsenical bronze was the first superplastic alloy ever made. Arsenical fumes were of course toxic and often led to lameness. Thus, in many cultures the metallurgist is featured as a lame person. With the discovery of tin bronze the arsenical bronze faded away - yet another example of Darwinism in materials.

The use of tin bronze to cast metal figurines goes back to the great civilisations of the Old World with one of the most celebrated early bronze casting being the famous Egyptian cat which is a hollow image. Bronze began to be used in Greece by about 3000 BC. The Bronze Age in the Middle East and the Eastern Mediterranean has been divided into three phases early, middle, and late. The early phase is characterized by increased use of the metal, from the sporadic to the common. It was the time of the Sumerian civilisation and the rise of Akkad to prominence in Mesopotamia. It also generated the spectacular treasures of Troy. Babylon reached its height of glory during the middle Bronze Age. Minoan Crete and Mycenaean Greece were major Late Bronze Age civilizations. The finely crafted Greek figurines of the first millennium BC representing the numerous gods of the Greek pantheon including Venus are well known. The Bronze Age ended there about 1200 BC, after which iron technology became common. The superb naturalistic Greek bronze figurines of the first millennium BC and other Hellenistic and Roman bronzes are well known, which included gods and goddesses such as the bust of Athena, goddess of wisdom. A resurgence of bronze casting inspired by the Hellenistic period was seen in the Renaissance period in Europe.

Amongst the earliest bronze castings in the world is the well executed miniature statue of a dancing girl from Mohenjodaro from the Indus Valley ca 2500 BC. Some of the most beautiful bronze castings in the world are the icons from the Chola period in the Thanjavur area of south India of the 10th century AD, such as the Ardhanarishvara in Government Museum, Chennai, representing godhood as the union between the male counterpart Siva and the female counterpart Parvati. A point of interest is the contributions of the pious queen Sembiyan Mahadevi. As a patron of the arts, she encouraged bronze and stone sculpture. Indeed the sculptors of the Chola era were true materials scientists, as they worked with equal ease on such disparate materials as stone and bronze. Baldev Raj et al. [30] have provided an interesting account of the bronze icons of South India. South Indian bronzes were mostly solid cast whereas images from Southeast Asia are mostly hollow cast. Srinivasan [30] analysed nearly 150 south Indian and Chola icons by inductively coupled plasma atomic emission spectroscopy and found them to be leaded bronzes although a significant proportion were also brasses. In the Indian subcontinent, from the early historic period onwards copper alloys were used to make metal icons of Hindu, Buddhist and Jaina affiliations. Bronzes including the image of Nataraja, famously described as the 'Cosmic Dance of Siva' (Fig. 6) by the celebrated art historian and philosopher Ananda Coomaraswamy rank amongst the most beautiful statuary in the world. Religion, metallurgy and a sensuous celebration of life flourished together. The very fine Buddhist bronzes of the fabled Golden Age of the Guptas of the North Central India (3rd-5th century. AD) and the Amaravati Buddhas of South Western India (ca 1st century BC-2nd century AD) were to have a far-reaching influence on the transmission of Buddhist art to Southeast.

Mirrors were made of bronze in different parts of the Old World including India. Interestingly, archaeometallurgical investigations by Sharada Srinivasan [31] on vessels from South Indian megaliths of the Nilgiris and Adichanallur (ca 1000-500 BC) showed that they were of wrought and quenched high-tin beta bronze, ranking amongst the earliest known such artifacts. Srinivasan [32] found that mirrors in Aranmula, Kerala are made of an alloy of 33% tin-bronze, close to the delta phase composition with ideal specular properties for making mirrors. The investigations by Pillai et al. [33] are also significant.

There is an interesting aside from Thailand. At Ban Chiang Bronze metallurgy developed around 3500 BC. It appears that the Thai people went straight from the Neolithic age into the Bronze Age by leap frogging.

Fig. 6 : India - Chola Icon

The use of copper, bronze and other alloys in China, including primitive brass and arsenic copper first began in the early 5 th and 4 th millennium BC, nearly all in the form of small tools and ornaments. The bronze age began around 2100 BC when small wine vessels, following their pottery predecessors, appeared, and by 1600 BC had developed into heavy ritual articles. The form, shape and structure of bronzes changed to more vivacious, liberal style after 900 or 800 BC, as the social structure had moved from slave system to feudal system with private ownership of land and crafts, which resulted in the introduction of coinage in 514 BC to facilitate commercial transactions. This usage of bronze, and later on brass, had lasted for 2500 years until mid-thirties of the 20th century. Fine ceremonial vessels were made in China as reported by Zhu Shoukang [34] and Gettens [35]. These ritual vessels rank among the finest objects ever made by man and constitute the most outstanding accomplishment in metal craft until modern times (Fig. 7). The use of bronzes in farming implements, tools, weapons and household articles were replaced by iron after 4 th or 3 rd century BC, except in the nobles' houses. The smelting of copper, first with oxide ore, was extended to sulphide ore in certain regions in the period between 4 th and 3 rd century BC.

A remarkable discovery relates to a set of huge and artistically decorated bronze bells each weighing about 2500 kg. Dated to 433 BC these belonged to Marqui Yi. The bells produced a two tone music. Figure 8 shows this magnificent ensemble of bronze bells. The Chinese have been able to reproduce the ancient music that must have been played with these sonorous bells.

A large number of well decorated cast mirrors have been found from China, some of which were found to be of leaded bronze, and mirrors even had magical significance in China.

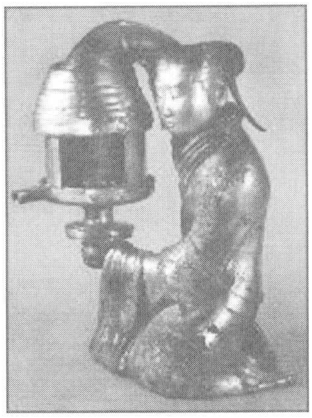

Fig. 7 : China - Bronze Vessel

The statue of the Great Buddha in Toda-ji Temple at Nara marks in many ways the entry of Japan into metallurgy (Fig. 9). The Buddha's face measured 5 metres across, the length of the palm was 3.7 metres and that of the middle finger was two metres. The lotus pedestal alone weighed one hundred and thirty tons. According to the archives of Todaiji, materials used to cast the Great Buddha were about 443 kg of copper, 7,560 kg of refined wax (for soldering), 392 kg of tempered gold, and 198 kg of mercury. Japan had intended to import gold from China and Korea. In 749 the discovery of gold in the Province of Mutsu in the Iwate prefecture was reported. It was taken as a blessing by the Buddha. The statue itself was 14.9 m high and the total height including the pedestal was 17 m. Workers mobilized for the construction of the temple numbered as many as 1,665,000 man-days. These figures show that at that time this construction was the nation's single greatest undertaking. The eye-opening ceremony for the Daibutsu was done in 752. The Indian monk, Bodaisenna, the first Indian to set foot in Japan, painted the eyes of the Great Buddha, a symbolic

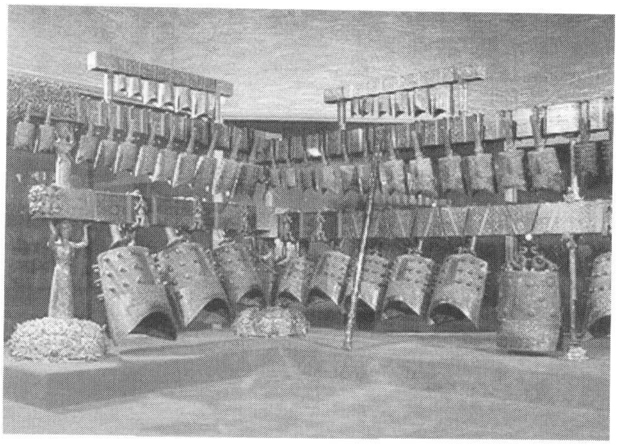

Fig. 8 : China - Bronze Bell

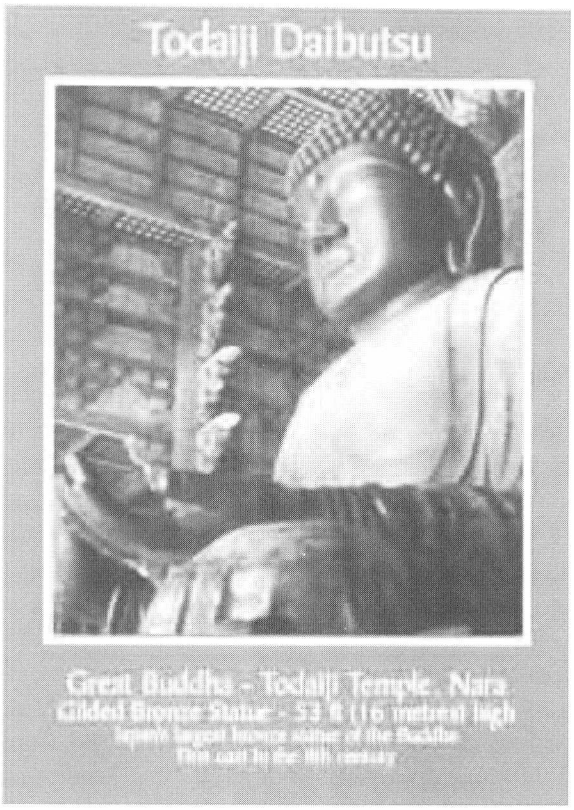

Fig. 9 : Japan - Nara - Bronze Buddha

awakening of the statue into life. He was assisted by Japanese and Chinese monks.

The pre-Columbian civilizations of the Americas had no bronze technology until about 1000 AD.

The mastery of bronze in antiquity is a remarkable chapter in human history. The phase diagram of Cu-Sn system was first established by Heycock and Neville [36] in 1903. It was the second phase diagram of importance to be determined in metallurgy and followed that of Fe-C system by Roberts-Austen [35] earlier in 1898. The Gibbs phase rule that governs phase equilibria was just beginning to be understood. It is an accomplishment that the first determinations were substantially correct. Figure 10 shows this classic diagram [36]. It will be seen that the diagram features several phases designated by the Greeek letters a, b,c and d. The a phase is a solid solution of Sn in Cu and enhances strength. It has a pleasing golden colour as well. It is seen that the addition of Sn lowers the melting point and improves castability. This is ideally suited for making statues and icons.. The b phase is an intermetallic with a body centerd structure and is stable at high temperatures. It is ductile and can be worked. However slow cooling will lead to an eutectoid decomposition and result in brittleness. Rapid quenching from high temperature results in a martensitic phase with retained strength and ductility. Sheer empirical experience led the ancient craftsmen to devising suitable thermomechanical treatment. This composition -15 to 125 % Sn- also leads to alloys for making bells due to the sonorous quality. Such alloys rae called Bell Metal. Additional tin leads to Speculum Metal used for making reflectors and mirrors. Even more astounding is the use of the d phase. This an intermetallic with about 33% Sn. It has a high reflectivity but alas is brittle. By casting narrow compositions in thin blocks an ingenious way was found to make the bronze mirrors. The structure of the phase is that of gamma brass and contains icosahedral clusters. The icosahedron is the most symmetric of all objects. Is it possible that the beautiful lady gazing in the mirror sees not only her reflection but the inner beauty of the intermetallic mirror?

12. AN ALLOY MISCELLANY

In addition to brass and bronze- the two major alloys of copper- discussed above, a few other alloys were known in antiquity. But their significance pales in the face of the brilliant changes brought about by bronze. These alloys are Electrum, Cupro-nickel, Paktong, Pewter and Bidri.

Early gold artifacts are often alloys containing significant amounts of silver. This led to the mistaken thinking that electrum was another metal. Electrum

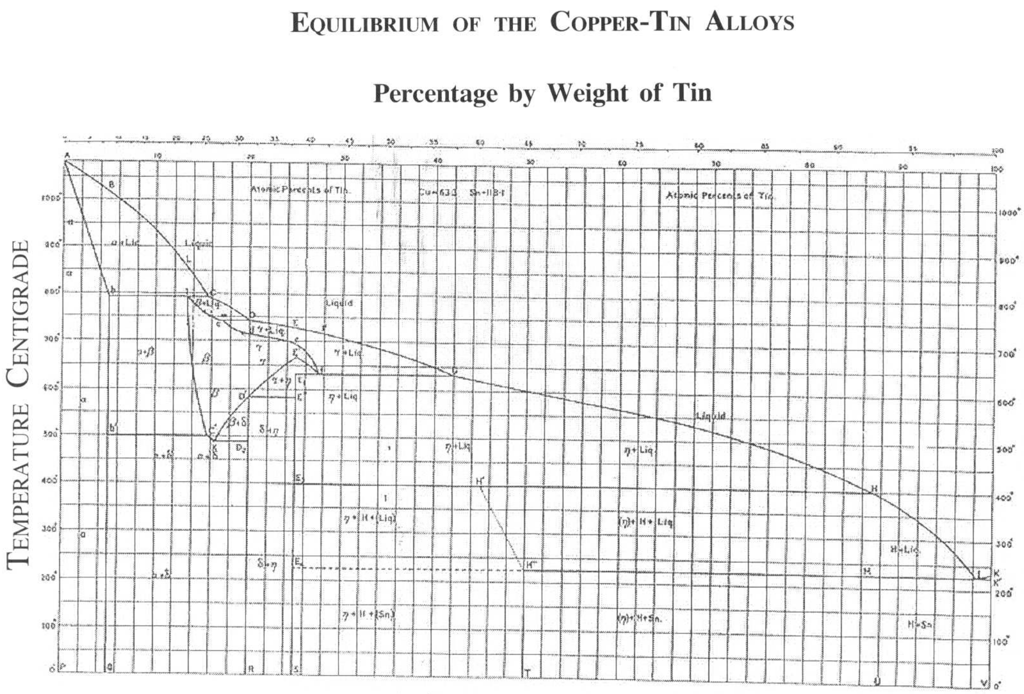

Fig. 10 : The first evaluation of the Copper-Tin Phase Diagram (from the Royal Society 1903 Bakerian Lecture of Heycock and Neville reference)

was pale yellow and similar in color to amber and often found along with gold. The first coins were introduced by the Lydians of Anatolia using electrum. As they could contain varying amounts of silver, they were eventually supplanted by pure gold. The discovery of depletion gilding by pre-Columbian civilisation is an astonishing development.

When the sulphide ores s of copper and nickel were smelted together, it led to copper-nickel alloy in the 4 th century China. Zinc was added in the 12 th century to form silvery, rust resisting alloy known as Paktong, or white copper, which was widely used in Europe before stainless steel was invented.

Another remarkable artistic innovation by Indian metalworkers of the past was the use of zinc in making highly elegant bidri ware, an inlayed alloy with over 90% zinc, which is the earliest known example of decorative metalwork in predominantly zinc metal. Bidri came into vogue under the Muslim rulers of the Bidar province of north Karnataka and in the Andhra region from about the 14th century AD. Several impressive vessels, ewers, pitchers, vessels, huqqa bases etc. were made of bidri ware with patterns. These were influenced by the fine geometric and floral patterns and inlayed metal work of the Islamic world where decorative metalwork reached some its most exquisite heights, for instance in the metalwork of the medieval Ottoman empire.

13. THE SILK ROUTE

The development of silk by the Chinese is a fascinating story, which has an indirect bearing on the history of materials. It was traded across two continents along the Silk Road/Route, spanning China, Central Asia, Northern India going back to the Parthian and Roman Empires. The Silk Road connected the Yellow River Valley to the Mediterranean Sea and linked the Chinese cities of Kansu, Sinkiang and Iran, Iraq and Syria. In an eastern move it linked Nara, the first capital of Japan to China. Silk also wended its way into India eventually reaching places like Varanasi in the Gangetic plain and Kanchipuram in southernmost India. These places became major centres for silk as seen in the present day repute of its silk sarees. This silken bond along the Silk Route brought about increased contact among diverse nations resulting in the crucial diffusion of materials and technology. Buddhism travelled along the Silk Road from India to China, Korea and Japan altering their cultures and destinies in an irreversible fashion. The tale of silk also has a bearing on that of crucible steel, as the oasis of Merv on the Silk Road in Central Asia became a significant production centre by the end of the first millennium AD.

14. DIAMOND FROM INDIA

If silk is synonymous with China, diamond has a similar association with India. The word 'diamond' is derived from the Greek word 'adamas' meaning invincible. Sanskrit texts from India dating to 500 BC refer to diamond, indicating a clear knowledge of this material. In fact the famous Diamond Sutra of Gautama Buddha uses this term in an allegorical sense to indicate that these chants can cut through illusions, just as diamond cuts through other substances. Up to the eighteenth century India was the only known source for diamond. The diamond mining and trade had the patronage of the Vijayanagar, Bijapur and Golconda kingdoms. The Golconda mines, near Hyderabad, were the most famous. Marco Polo mentions the fame of diamonds under a south Indian queen, Rudramma. Jean-Baptiste Tavernier, a French merchant, travelled in South India around 1776 and in his travelogue [36] has recorded the extraordinary commerce in diamonds. It is an astonishing coincidence that he also referred to wootz steel from the same region.

A number of individual diamonds found in India have become famous. They are noted not only their size but also for their colour, cut and history. Tavernier had described the Great Mogul diamond weighing 240 carats. It has mysteriously disappeared since. The Koh-i-Noor Diamond weighs 101.6 carats and is now part of the British crown jewels and may have been actually cut from the Great Mogul diamond. The history of diamonds is full of several such remarkable stones including the Pitt, the Orloff, the Nizam and the Hope.

Eventually diamond was found in Brazil in 1723 and in South Africa in 1867. The earliest evidence of cutting diamonds is from Venice in 1330. In the past decade Antwerp has emerged as a major centre. India has long since ceased to mine diamonds. In a remarkable comeback, Indians have emerged as major entrepreneurs in diamond cutting.

Diamond is elemental carbon, which has another form as graphite. Carbon is the fourth most abundant element in the solar system after hydrogen, helium and oxygen. Just like iron, carbon was also born out of cosmic alchemy by nucleosynthesis in the early life of our universe. While some diamonds are presolar and others have occurred during the formation of the solar system, the geodynamic evolution of the earth led to high pressures and high temperatures leading to the conversion of graphite to diamond. This extraordinary occurrence has now been duplicated in industrial laboratories to synthesise artificial diamonds.

15. MATERIALS TRANSITIONS IN HISTORY

The civilisational transition from the predominant use of one type of material to another raises several questions concerning the causes and factors influencing such transitions. Evidently the availability of the raw material and cost of production are primary factors. Equally important are the achievable properties. Table 4 gives the yield strength of several materials. It is only one of the parameters and one must consider the combination of properties. Nevertheless some first order conclusions are possible. The superiority of alloyed bronze over metallic copper is evident. In addition, bronze has a lower melting range of 830-1100 °C. This is less than the melting point of copper and lends itself to the production of exquisite castings.

Table 4

MATERIAL PROPERTIES AS A DISCRIMINATOR: YIELD STRENGTH

Pure copper	200 MPa
Bloomery iron	260 MPa
Bronze (11 wt % tin)	400 MPa
Fe-0.2% carbon	400 MPa
Work hardened iron	660 MPa
Work hardened bronze	800 MPa
Fe-1.2 % carbon	860 MPa
Work hardened steel	1600 MPa

The contest between bronze and iron in terms of relative strength is interesting. While bronze has a higher strength than bloomery iron, work hardened iron has a higher value. However, it is possible to work harden bronze to reach higher values. Steel with a high percentage of carbon scores over bronze. On the other hand, iron and bronze are quite comparable in strength. Nevertheless there was a sharp transition from the bronze to the iron age. There has been speculation that this may have been due to factors of relative scarcity or decline in the supply of tin, whereas iron ores are far more abundant in the world.

In addition to purely technical reasons, such transitions are also mediated by cultural and religious traditions. Robert Ehrenreich [37] has argued that societal beliefs led to the introduction of bronze in China. China was initially obsessed with the precious material, jade. Around 1900 BC there was a sudden explosion in the quantity and sophistication of bronze objects and in particular ritual vessels. The Chinese rulers believed that ancestral guidance was a crucial element and offerings of wine and food in large cauldrons was a part of the ritual. Bronze was needed to make these vessels. From a purely religious use, bronze then spread to making of tools and other appliances. While a belief system helped usher in a new material in China, just the opposite happened in the Andean society in South America. The Incas placed enormous emphasis on human breath and invested it with life forces. During smelting they believed that it is this life force that transmuted ore into copper metal. They did not believe that artificial aids like bellows would have the same effect. Thus they did not traverse the smelting route of other cultures and missed discovering iron.

It may also be pointed out that the reasons as to why the scientific revolution and the industrial revolutions were staged in Europe rather than in India and China, which had a dominance in these fields till 1492, are being explored by many scholars. In an intriguing essay Alan McFarlane [38] has argued that the improvements in glass production contributed to the sweeping changes that engulfed Europe from 1200 to 1850. It led to remarkable developments in optics including the invention of telescopes and microscopes. The Islamic, Indian and Chinese civilizations did not evince the same interest in glass production and thus were left behind. This was despite the fact that Islamic glass was among the most exquisite products in medieval period.

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OVERVIEW

SHAPING OF BRONZE IN ANCIENT INDIA - SOME CASE STUDIES FROM SOUTH INDIA

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ABSTRACT

The history of metals and their shaping is as ancient as the history of civilization. Many of the artifacts excavated and preserved as well as some of the metallurgical arts still being practiced are standing examples depicting the excellent metallurgical skill possessed by mankind. The Indian subcontinent too stood at par with the rest of the world in ancient metallurgical skills and expertise. Indian artisans and craftsmen had been great masters in extracting and shaping metals and alloys. Indian craftsmen's knowledge of metallurgy predates technologies of many other civilizations. Archaeological finds from the 2nd and3rd millennium BC testify to the antiquity of the Indian metallurgical knowledge. Further, these metallurgical arts revealed the presence of a high degree of technical excellence in shaping metals and alloys in general and bronze in particular as a single system. This presentation brings out the case histories of the study carried out by the authors on a few ancient metallurgical arts of shaping bronze, which are still being practiced namely, Aranmula metal mirror making, Kadavaloor high tin bronze eating bowl and gong making and lost wax process utilised for making icons, utensils and bells in Swamimalai and Mannar.

1. BACKGROUND

Mastery over-mining, extraction and working of metals were instrumental for the growth of the material culture. Indian artisans and craftsmen have been great masters of extracting and shaping of metals. Archaeological finds from the 2nd and 3rd millenium BC testify the antiquity of Indian metallurgical knowledge. The tradition of shaping ferrous and nonferrous metals and alloys achieved a high degree of excellence as is evident from the following important ancient metallurgical arts / artifacts. These include the dancing girl, the earliest known Indian lost wax process cast bronze figure (3rd millennium BC); the bronze icon of Lord Nataraja (8-15th century AD) and 3000 years old figure of Mother Goddess in bronze discovered at Adichanallur, again cast by lost wax process; Dhokra ware of central and eastern India, the brass and bell metal craft using lost wax process; the iron pillar, Qutab Minar, New Delhi (310 AD), forge welded excellent quality wrought iron; Aranmula metal mirror, an example wherein a very slow cooling rate is utilized to precipitate a hard and brittle intermetallics in high tin bronze (16th century) ; high tin bronze eating bowl and gong, an excellent example for thermo- mechanical processing of difficult to shape high tin bronze (16th century) ; Wootz or 'Damascus' steel (2nd century AD), an example for perfecting melting, shaping and treating of steel ; guns and cannons (an example of forging technology in the absence of iron casting technology) and iron craft of Bastar, making icons and votive (dedicated in fulfillment of a vow) animals from pure iron. During the reign of Alexander the great, swords manufactured in Middle East / Europe were from steel imported from India.

Vedic literature do mention about different metals viz., gold, tin, silver, lead, copper and bronze. Despite borrowing of a few techniques from other countries for extraction and shaping of metals, many seemed to have been developed indigenously. The traditional metal worker knew his job so well that he could make alloys to suit his intended function. The Chola bronzes reveal the existence of high degree of excellence in making nonferrous metal castings by lost wax process, which is even now prevalent in different parts of India. The art of making metal mirrors which survives even today in Kerala bears testimony to the sophisticated metal shaping techniques developed in the country. The recovery of valuable metal from modern industrial waste is being done by the Mirzapur brass workers utilizing their traditional knowledge.

The first quarter of the first millennium BC witnessed development of the technology of iron smelting, while steel making was practiced since the 4th century BC. Further, Indian iron and steel were well known for their quality and exported to many countries including Britain till early nineteenth century. The iron pillars at Delhi and Dhar and the famous Damascus swords are examples depicting the order of skill and knowledge of Indian smelters and black smiths. The iron was extracted in the solid state as sponge iron and forged into desired implements. The highly valued 'wootz steel' containing 1.3-1.6%C, the material of 'Damascus sword' [1] obtained after proper thermomechanical treatment, was produced by packing the sponge iron with wooden chips and leaves of certain plants in a crucible and heating in a furnace. The enigma of the corrosion resistance of the iron pillar and the structure of the Damascus swords has still not been satisfactorily explained in spite of international attempts using the latest sophisticated techniques. Smelting of copper was well established in India by the third millennium. The alloying of copper with tin to obtain bronze was also known. In addition, the copper smiths were well versed with the casting and forging of copper and bronze. The distillation of zinc oxide to obtain zinc was developed in India in the last quarter of the first millennium BC. However, W. Champion of Britain has been credited for its invention in 1748. Indians also excelled in shaping brass for more than 2000 years. These indigenous technologies suffered a set back during British rule and deteriorated after independence due to resource and market constrains leaving only a few practitioners. It is to be noted that these knowledge and experience are still being used even now by traditional artisans in select parts of the country.

Bronzes are copper-tin alloys and those containing more than 11% tin do not find any engineering applications because of their increasing brittleness and hence decreasing ductility [2,3]. However, high-tin bronzes, also known as β bronze or speculum or bell metal, containing 20-30% tin have long been shaped and utilized as consumer articles such as metal mirrors, kitchen wares, musical instruments, bells and ornaments in many parts of the world including India [4-14]. The peculiar properties of high tin bronze, namely, (i) Hard and brittle on slow cooling, (ii) Ductile and malleable when worked at a particular temperature range, (iii) Inertness to the food eaten in Kerala and (iv) Sonority (having the character of a loud deep sound or reverberance) after hot working and quenching had been identified and exploited by Kerala artisans for shaping this material into metal mirror (Aranmula Kannadi), eating bowl (Kadavaloor ottu kinnam) and gong (Kathakali Chengala). Moreover, lost wax process, used over the ages for making icons, lamps, bells, utensils, etc is also being still used in various parts of India. These techniques and processes used by the traditional metal workers of the country need to be studied more seriously to gain insight into the science behind some of these still existing metallurgical arts. This paper aims at describing the following case studies conducted by the authors relating to shaping bronze and other suitable copper base alloys into metal mirrors, kathakali gong, eating bowl, icons, bells, lamps, etc in Kerala and Tamilnadu .

1. Making of Aranmula Mirror by casting [8] .
2. Shaping of Kadavaloor eating bowl and Kathakali gong by casting cum thermomechanical processing [9,10] .
3. Making of icons, bells, lamps, utensils, etc. by lost wax technique in Swamimalai (Tamilnadu) and Mannar (Kerala) [15] .

2. MAKING OF ARANMULA METAL MIRROR (KANNADI)

The discovery of Aranmula metal mirror is closely associated with the Aranmula Parthasarathy temple, the nerve center of the then Pampa valley civilization. Centuries ago, eight families of artisans well versed in temple arts and crafts had been brought from Sankarankoil, near Thirunelveli, Tamilnadu by the local king. With the passing away of time, the decendants of these artisans became lazy and nuisance to the public, which made the king order their eviction from Aranmula. The worried artisans prayed to the residing deity Lord Krishna to rescue them. The divine vision the artisans had that night prescribed the composition of the metal giving distortion free images. The artisans made a magnificent crown with the divine composition and presented it to the king, who was overwhelmed and honoured them with land and jewels. Since then, the artisans had chosen metal mirror making as their profession through generations.

The art of making Aranmula mirror essentially consists of casting a thin disk (2-3 mm thickness) of suitable dimension depending on the size requirement of the final mirror at a very slow cooling rate and polishing the resulting cast disk to mirror finish followed by fixing in a suitable frame.

Cu-Sn alloy is made by melting measured quantities of Cu (10 parts) and Sn (5.5 parts) in a clay crucible using a furnace fired with coconut shell or wood charcoal. Once the alloy is molten and homogenised by stirring, a small quantity is poured out and allowed to solidify on the ground. The cooled sample is broken with a hammer and the fractured surfaces of the sample are inspected for its colour with naked eye by the chief artisan to assess the composition of the alloy. More copper or tin is added to the melt, if required, depending on the above assessment and the melt after attaining the required temperature is cast into disks in open sand moulds prepared on the ground. These disks are again broken into smaller pieces, which form the alloy charge material for the Aranmula mirror.

The steps involved in making the mould cum crucible assembly for 2-3 mm thick disk or unpolished raw mirror casting are illustrated in Fig. 1. Interestingly, instead of attaching a riser or feeder and gating system to the mould cavity to accommodate pouring, the crucible itself is attached. The mould-crucible assembly with the required quantity of charge in place is positioned with crucible down in a pit furnace fitted with a manual blower. This placement of mould-crucible assembly enables faster melting of the charge as well as preheating of mould. When the artisan decides that the charge is completely molten and superheated, the assembly is removed from the furnace and shaken gently to enable thorough mixing of the melt. Slow tilting of the assembly as shown in Fig. 2 results in gentle filling of the mould by the molten metal from the crucible. The crucible is broken once mould filling is completed and the mould is gently tapped during solidification.

The second investment layer and clamps (Fig. 1) are removed, immediately after the completion of casting solidification. The casting is completely separated from the mould by scrapping away the first investment layer. Ingate and fins, if any, are removed and the outer contour of the raw mirror casting is filed so that it is ready for polishing. To facilitate easy handling of this highly brittle raw mirror casting during polishing, it is mounted with wax on a wooden blank. Polishing is carried out initially with well ground burnt clay powder made from the broken burnt mould followed by caster oil, which results in easy and faster polishing, on a jute cloth. The polishing can go on from one to two days to arrive at a highly reflective mirror surface. It is critical to note that great care needs to be taken during polishing and handling stage since the disk is very brittle. From this perspective, making of larger mirror can be very challenging. When a satisfactory finish is achieved, the polished mirror disk is separated from the wooden blank by heating the former and is mounted on a brass frame as shown in Fig. 3. The known largest Aranmula metal mirrors are preserved at the British Museum in London (450 mm tall) and the Padmanabhapuram Palace in Padmanabhapuram, Kanyakumari district, Tamilnadu.

3. MAKING OF KADAVALOOR EATING BOWL (OTTU KINNAM)

The charge material for making the Kadavaloor eating bowl consists of pure copper and tin in the ratio 10:3 by weight. This ratio has been handed down through

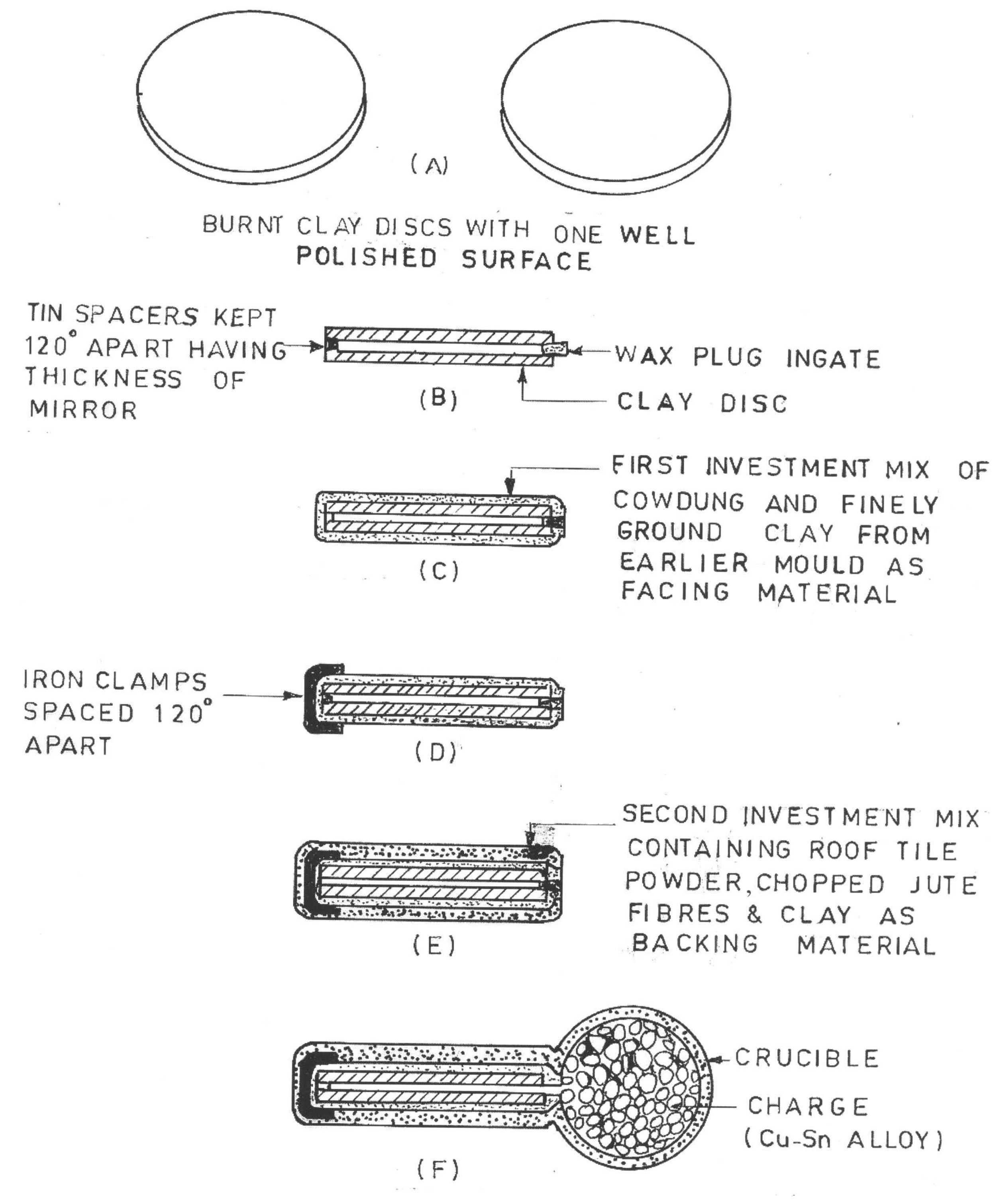


Fig. 1 : Various steps in the preparation of the mould-crucible assembly for casting an Aranmula Metal Mirror disk.

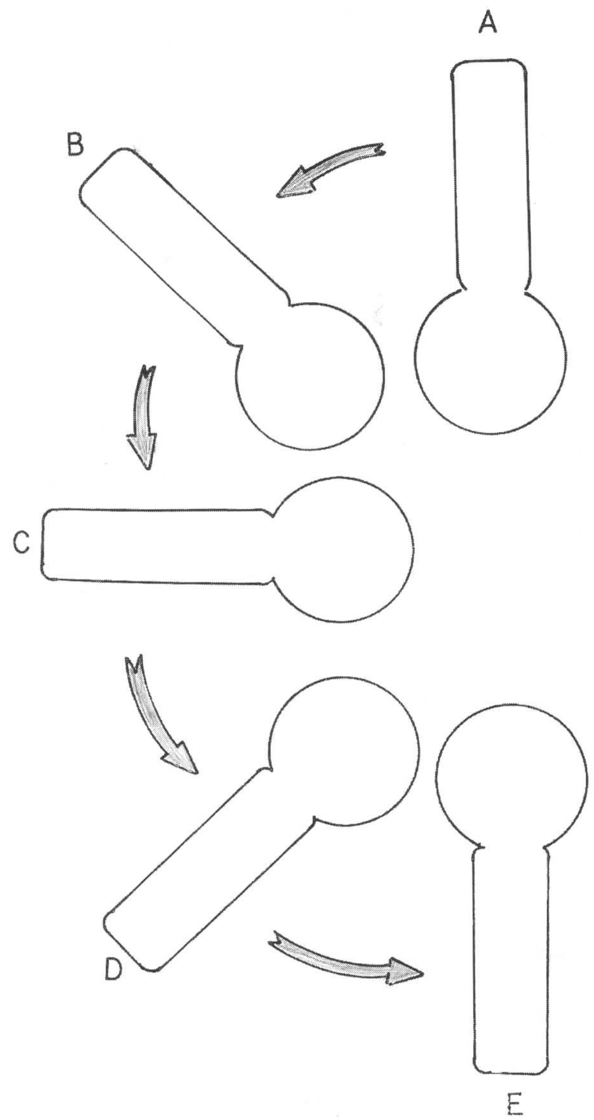


Fig. 2 : Positions of the mould-crucible assembly as the crucible is heated in the furnace (A), and the mould cavity is slowly poured (B-E).

generations of craftsmen, and it works out to slightly more than 23 wt% tin. Because of melting losses during processing, however, the actual tin content of the finished bowl will be slightly less.

Traditionally, the crucible used for melting of the alloy is made from a well-ground mixture of local clay and jute fibers; the raw material is shaped to the desired crucible size, dried in the sun, and then fired in a charcoal fuel furnace. Today, readily available clay graphite crucibles are also used by the artisans. The furnace is constructed in the ground prior to hot working, and hand operated bellows provide the

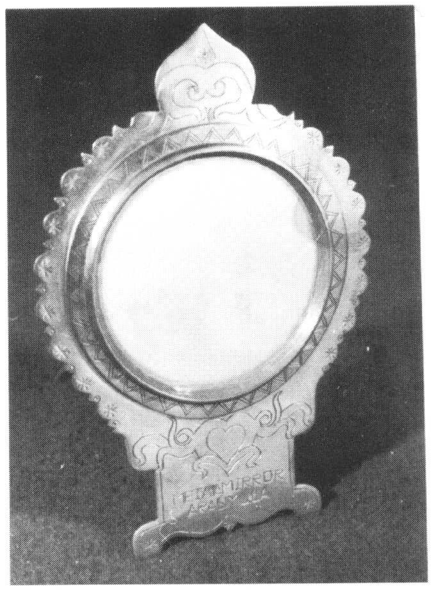


Fig. 3 : Photograph of finished Aranmula metal mirror .

required air. Wood or coconut shell charcoal is used as fuel as well to cover the melt surface. In the well-heated crucible, melting is carried out under a reducing atmosphere, obviating the usual oxidation-reduction technique recommended for melting copper-base alloys. The resulting gas porosity in the alloy is not a problem, as the alloy will be hot worked. Simulating the hot-working operation by casting a small disk and subjecting it to prolonged high-temperature hammering tests the quality of the alloy.

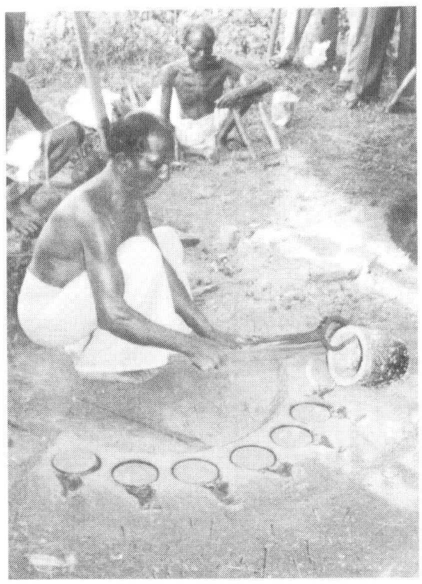


Fig. 4 : Casting of high tin bronze disks in open sand moulds.

The alloy is considered fit if it does not crack during hammering.

If the sample passes the test, the remaining metal is cast into disks (100 mm diameter, 8 mm thick) in open sand molds (Fig. 4). The mould for these disks is prepared by ramming a pattern into moistened silica sand and sprinkling bran from parboiled rice onto the surface. The gas generated by burning the bran results in reducing atmosphere. The bran seems to fulfill the same function as that of coal dust used with the molding sand in an iron foundry. Essentially, it creates a cushioning effect between the melt and the mold, preventing a metal-mold reaction and ensuring a clean and smooth metal surface.

Fig. 5 : Rhythmic hammering of the disks into a bowl shape by three men as the chief craftsman controls the progress.

The cast disks are reheated in open charcoal fire to a temperature judged suitable by the chief craftsman, who controls the hot-working operation. The heated disks are placed on a granite anvil and repeatedly worked with specially constructed hammers wielded by two or three workers in a regular and rhythmic sequence (Fig. 5). A granite anvil is preferred to a metal one since the former extracts heat more slowly from the disk. Holding the disks with tongs, the chief craftsman positions the disks during the forming operation, synchronizes the hot working, and stops the operation when he judges that the disks have cooled to a temperature that risks damage from brittleness. The partially worked disk is then reheated and reworked (Fig. 6). The chief craftsman judges the temperature of the disk by observing its color. To see the disk in the appropriate light, the craftsman puts up and adjusts screens in the work area. The process of reheating and hot working is continued until the desired diameter of the bowl is achieved at a thickness of 2-3 mm. During the latter stages of hot working, the bowl's rim shape is obtained by adjusting the hammer blows. The last phase of the hot-working operations is conducted on a wooden log with a wooden mallet (Fig. 7). Once the desired shape is achieved, the bowl is reheated once more and then quenched in room-temperature water. The

Fig. 6 : Continuation of working after reheating, which are continued until the desired shape is achieved

Fig. 7 : Conducting the last phase of the hot working operation with a wooden log and a wooden mallet prior to heating again and quenching in water.

Fig. 8 : Photograph of finished Kadavaloor eating bowl.

shape of the quenched bowl is corrected with a wooden mallet, and irregular edges are removed with a sharp cutting tool fashioned from worn-out files. A similar tool is used to scrape the inside and outside surfaces of the bowl. Figure 8 shows a finished Kadavaloor eating bowl (ottu kinnam).

4. KATHAKALI GONG MAKING

The procedure for making gong is similar to that of the eating bowl but for its final shape (circular plate) and thickness decreasing towards the outer edge (4 -7 mm thick). The chief artisan listens to the sonority of the gong by holding it at different locations along the outer edge and hitting it by wooden mallet and identifies the best location for drilling holes through which a thick thread will be introduced and made into a loop to enable holding the gong during use. Fig. 9 shows the photograph of a finished gong. It may also be noted that there is no change in the composition of the Cu-Sn alloy used for the gong.

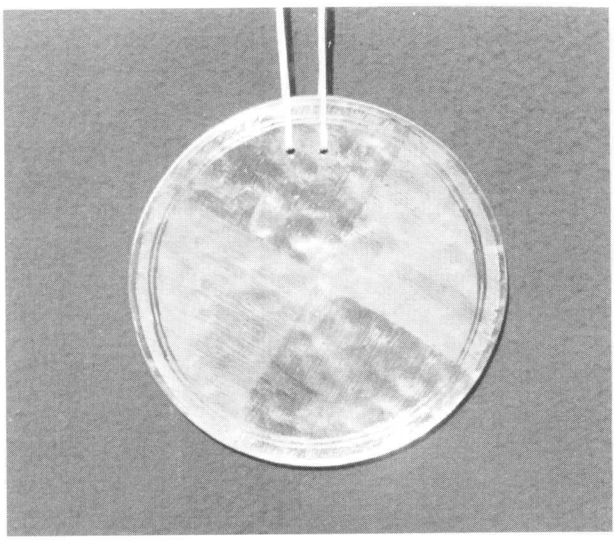


Fig. 9 : Photograph of finished gong.

5. METALLURGICAL ASPECTS OF ARANMULA METAL MIRROR AND KADAVALOOR EATING BOWL AND GONG

Table 1 presents the chemical composition of the bronze used for both Aranmula mirror and Kadavaloor eating bowl and gong. Composition of the Cu base alloy used for Aranmula mirror is Cu-30% Sn bronze. As hypothesized prior to the analysis, the alloy does not contain any special or secret elements. On the other hand, Kadavaloor eating bowl and gong are made of Cu-22% Sn bronze. When high tin bronzes containing more than 20wt% tin are slowly solidified,

Table 1

CHEMICAL COMPOSITION OF BRONZES USED FOR ARANMULA METAL MIRROR AND KADAVALOOR EATING BOWL AND GONG

Element	Wt % in Aranmula Mirror	Wt % in Kadavaloor Eating Bowl and Gong
Sn	29.4	21.68
Pb	Not Detected	0.80
Zn	0.06	0.04
P	0.02	0.02
Fe	0.034	Not Detected
Si	Not Detected	Not Detected
Al	Not Detected	Not Detected
Ni	0.052	Not Detected
Bi	Not Detected	Not Detected
Sb	Not Detected	Not Detected
Cu	Balance	Balance

precipitation of a hard and brittle phase, $Cu_{31}Sn_8$, takes place. The slowly cooled Cu – 30% Sn disk containing $Cu_{31}Sn_8$ phase on polishing gives distortion free images. This is the metallurgical principle involved in Aranmula mirror making. The Vickers hardness number of metal mirror measured using micro hardness tester under a load of 0.4903 N falls in between 520 and 540, which is near to that of hardened steel, which clearly explains the mirror's brittleness. The macrostructure (Fig. 10) of the mirror shows columnar and equiaxed grains as well as coarse structure revealing the direction of solidification of the disk and a very slow cooling rate to which it was subjected to. Figure 11 shows the microstructure.

Cast high tin bronze (containing more than 20 wt% Sn) thick disk containing α and β phases, when heated to a temperature between 586 and 798°C, is highly malleable. At temperatures higher than 798°C, peritectic melting takes place. On the other hand, at temperatures lower than 586°C, a hard and brittle $Cu_{31}Sn_8$ phase precipitates. Shaping Kadavaloor eating bowl and gong utilises the malleability exhibited by high tin bronze between 586 and 798°C and quenching the eating bowl and gong in water to avoid precipitation of $Cu_{31}Sn_8$ phase. The Vickers microhardness numbers of both Kadavaloor eating bowl and Kathakali gong measured at a load of 0.2452N fall between 130 and 147 for α phase and 220 and 264 for β phase respectively.

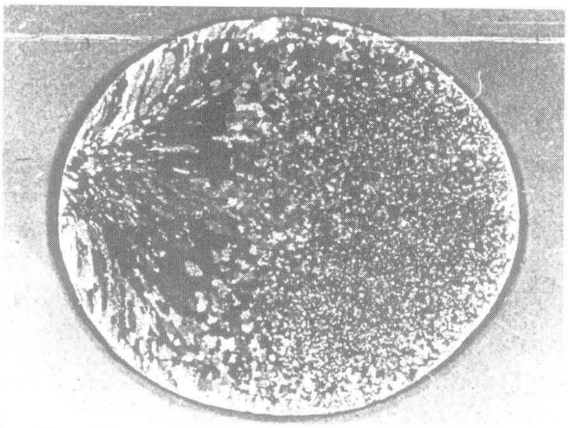


Fig. 10 : Macrostructure of Aranmula Metal Mirror etched with α ferric chloride solution.

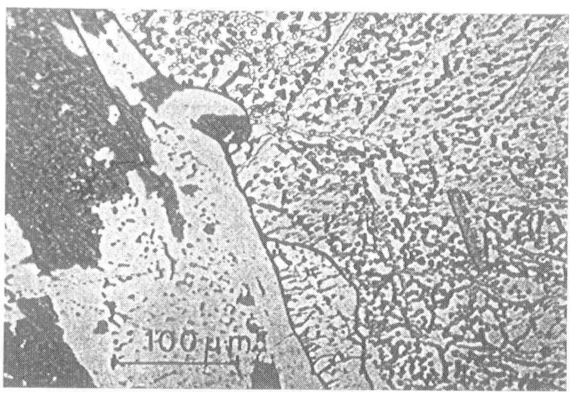


Fig. 11 : Photomicrograph of Aranmula metal mirror etched with α ferric chloride solution

Metallographic examination of the as cast thick disk reveals an α phase (solid solution of tin in copper) and an intermetallic brittle phase, $Cu_{31}Sn_8$ (Fig. 12 (a-b)). However, the microstructure of hot worked and quenched eating bowl and gong consists of recrystalised light α and dark β phases. Twins seen in a few a phase grains (Fig. 12(c)) are the characteristics of hot working. Further, martensitic structure of the quenched β phase is also clearly revealed (Fig. 12(d)). The repeated thermomechanical processing has sealed all the porosities observed in the as cast microstructure (Fig. 12a) as clearly revealed by the microstructures of hot worked and quenched sample (Fig. 12b). Photomicrographs of gong taken at edge, middle and centre showing exactly the same features of eating bowl are shown in Fig. 13(a-c) respectively. Although the hot working of bronze with as little as 10 wt% tin is considered difficult, the high-tin Kadavaloor bronze eating bowl and gong are hot worked with comparative ease.

The phase diagram of copper-tin system shown in Fig. 14, wherein the alloys used for both Aranmula metal mirror and Kadavaloor eating bowl are marked, is useful in understanding the solidification sequences of these alloys. The slow cooling of a 22 wt% tin bronze leads to significant amounts of the hard and brittle phase δ ($Cu_{31}Sn_8$) precipitation in the α matrix to yield a brittle material. However, when heated between 586 and 798°C, the same alloy consists of varying amounts of the α and β phases, both of which are relatively ductile constituents, with α being face-centered cubic and β being body centered cubic. Hence, the material exhibits hot workability. Within these limits, temperature must be strictly controlled; a high temperature would lead to peritectic melting and a lower temperature would result in brittleness. Further, the material must be quenched to retain the α + β, microstructure; otherwise, brittleness will result. Articles so produced can be used only at or

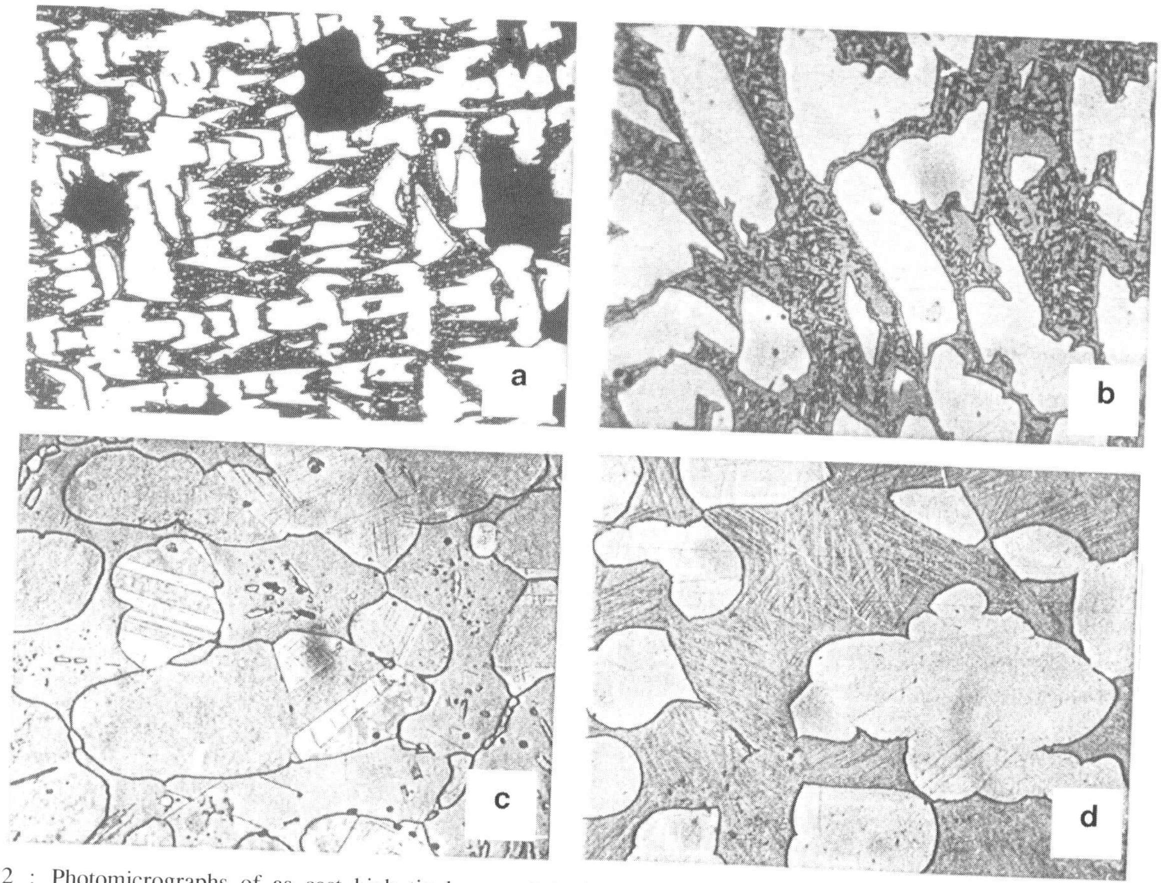


Fig. 12 : Photomicrographs of as cast high tin bronze disk (a-b) and hot worked and quenched high tin bronze bowl (c-d). [Magnification – a (X60) and b-d (X200)]

slightly above room temperature; heating to temperatures greater than about 100°C could lead to precipitation of the ε phase and, hence, brittleness.

6. ICON MAKING AT SWAMIMALAI, TAMILNADU

August Rodin, the famous sculptor has described the bronze icons of South India as 'the most perfect representation of rhythmic movement in art' [11]. These icons were and are still cast by Cire Perdue (cire and perdue meaning wax and lost respectively) or lost wax process [11,12,14] or madhuchistavidhanam in Sanskrit, which is now known as the investment casting process after thorough modification and used for gas turbine blade, body implants, etc. This has been the name used for all types of casting wherein wax model forming the core of the image is drained out prior to replacement by metal in the actual casting. This replacement can take place by two processes – solid casting (ghana) and hollow casting (sushira), both find a reference in the Rig Veda. Solid casting is still prevalent in the South India (Swamimalai, Tiruchirapalli, Madurai, Chengleput, and Salem in Tamilnadu, Bangalore and Mysore in Karnataka, Mannar, Iringalakuda in Kerala, Tirupathi in Andhra), while the latter is largely prevalent in Central and Eastern India. The 'Silpasastra', the most elaborate treatise on the process believed to be compiled during Gupta period and now available in other Indian languages have laid down the composition and preparation of the different alloys to be used, the measurements and relative proportions of the different parts of icons, the method of preparing the wax model, making the mould and casting.

The unit of measurement in icon making is 'tala' which is the distance between the hairline and the end of the lower jaw, which is divided into 12 equal parts called angulas (equivalent to the breadth of a finger). Each angula is divided to 8 yava (size of a barley grain and so on till the smallest unit 'paramu' (smaller than the end of a single hair). The craftsmen

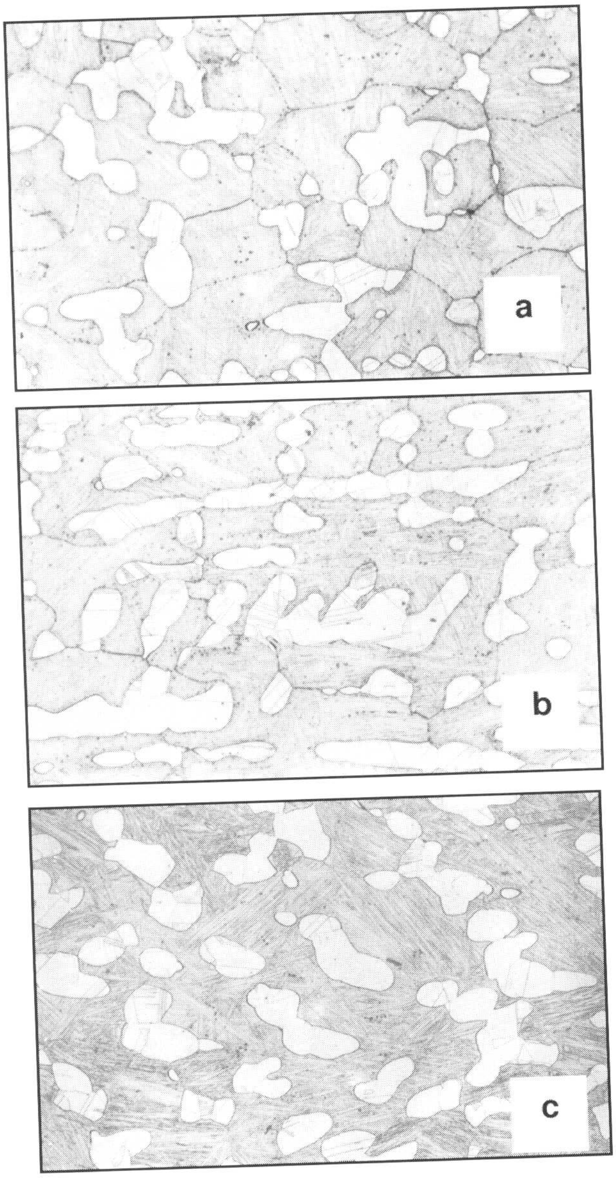
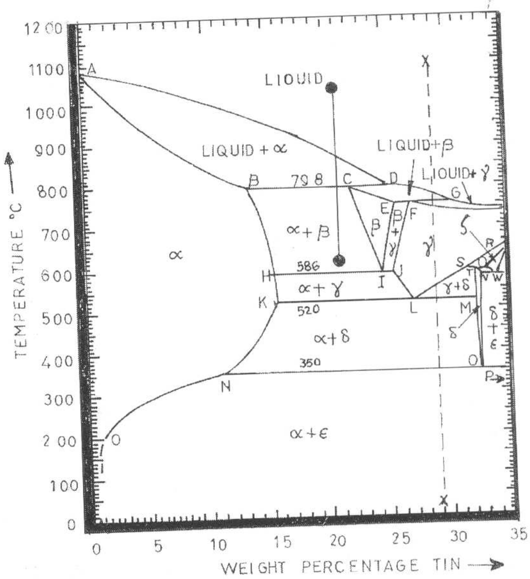


Fig. 13 : Photomicrographs of hot worked and quenched gong at the edge (a), middle (b) and center (c). [Magnification X200]



POINT	A	B	C	D	E	F	G	H
°C	1083	798	798	798	755	755	755	586
Sn %	0	13.5	22.0	25.5	25.9	27	30.6	15.8
POINT	I	J	K	L	M	N	O	P
°C	586	586	520	520	520	~350	~350	~ 350
Sn %	24.6	25.4	15.8	27.0	32.4	11	32.55	37.8
POINT	Q	R	S	T	U	V	W	
°C	200	640	590	590	590	582	582	
Sn %	1.2	34.2	31.6	32.3	33.1	32.9	34.1	

●——● Composition of Kadavaloor eating bowl & gong

×- -× Aranmula metal mirror Composition

Fig. 14 : The phase diagram of Cu-tin system

use traditional tools, most of which were made by them. Of late, use of electrically operated drills, blowers, files, etc. is started.

Icon making consists of the following four major steps :

I. Pattern / Model making
   1. Odiolai Making
   2. Preparation of wax
   3. Wax model making

II. Mould making
   1. Mould materials preparation and investing
   2. Melting and draining of wax from the mould cavity

III. Melting and Casting
   1. Preparation of alloy
   2. Casting

IV. Fettling and Finishing
   1. Mould opening
   2. Finishing, engraving and polishing
   3. Colouring

Initially, the artisan takes note of the 'talas' as laid down in silpasastras for icon making and prepares 'odiolai' which is a narrow ribbon of coconut tree leaf cut to the icon length requirement and folded at different lengths in proportion to the length of various parts of the icon.

Wax for making wax model of icon is prepared by mixing pure bee wax, resin from the tree Damara Orientalis and ground nut oil in the ratio 4:4:1. Powdered resin is mixed with ground nut oil and the mix is heated till a thick liquid forms. Now, bee wax is added to this thick liquid and stirred with a stick till it liquefies and gets well mixed. This wax melt is sieved through a fine metal sieve / coarse woven cloth into a container containing cold water, thus allowing it to solidify, which is then used for wax model making.

Wax model making is a crucial stage, wherein, the craftsman's creativity decides the excellence of the model which in turn that of the icon to be cast. Head, body and limbs of an icon are made separately by hand roughly using the wax after making it malleable by warming it and later shaping it well using spatula, knife and scraper. The different finished parts of the icon are joined together using a heated iron tool used as soldering iron. Pedestal of the icon is joined to icon if it is small and is kept separately for larger icons. In order to strengthen the wax pattern as well as to facilitate easy flow of molten metal into various parts, a few wax cross strapping and a wax rod ending with a funnel shape (sprue and runner) are also joined to the pattern at appropriate locations. The wax pattern or model of the icon with gating system for metal flow is thus prepared.

Mould making involves coating wax pattern with layers of clay, known as investment - three layers for small icons and more layers for larger icons and a different clay is used for each layer. Fine loam or alluvial soil collected from the Cauvery river bed locally called 'vandal mann' is finely ground along with charred paddy husk and mixed with cow dung to make a thick mixture, which is used to give the first coat of about 3mm thickness. This first coat performs two important functions, namely, protection of wax model and the reproduction of minute contour of the wax model in the cast icon. These functions warrant that no portion of the wax model should be left uncovered except the wax runner, which is the outlet for melted wax. Further, no air bubbles should be allowed on the surface of this first coat. During application of clay coating, the wax model is kept either on a piece of paper or cloth kept on the floor depending upon the size of the model to avoid possible deformation and one side is given the coating . The model is turned after drying of the first investment coats to coat the other portion with clay. It is crucial that drying of coating is done either under mild sun light or in the shade to prevent melting of wax model.

The second coat or investment is made with a paste obtained by thorough mixing of clay from paddy fields and sand mixed in 1:2 ratio with water and its thickness varies from 12.5-50mm depending upon the size of the icon. The third coating containing a mixture of coarse sand and clay paste is applied once the second coating is dried up. A fourth coat is given only if necessary based on the size of the icon. Reinforcement of the mould with iron rods and wires is a must with large size icons to prevent giving way of the mould during liquid metal pouring . Some craftsmen still follow the old method of using broken earthern ware pieces as reinforcement. Drying of the last coat makes the mould ready with wax model in.

The next step of melting and draining the wax from the mould is carried out by heating the finished mould with wax model inside in an open ground oven using cow dung cakes / coconut shells as fuel and collecting the molten wax coming out through the runner in a vessel containing water . This wax collected can be reused after removing foreign matter, if any.

Silpasastras prescribe the composition of alloy to be chosen for casting sacred icons. Earlier, five metal combination, i.e., 'panchaloha' i.e., an alloy containing Cu, Au, Ag, Pb and brass was considered to be highly auspicious and is still used for icons for worship. However, gradually, incorporation of Au and Ag was stopped for general purpose icons because of their high cost. An alloy made by mixing Cu, brass and lead in the ratio 29:2:1 is a common one for general purpose icons. Further, tin addition is also made to the tune of Pb content in some cases. Pb is added to make the alloy more malleable so that chiseling and engraving of the icon will be easy. The artisans believe from their experience that if the icon is made with copper alone, it will not have a lasting shine whereas, addition of a little brass to Cu results in lasting shine as well as lowers the melting point. It may be noted that brass is added as a master alloy to introduce Zn. The thumb rule used by the artisans for the weight of alloy for occupying by mould cavity is generally 8 times the weight of the wax model. Melting is carried out in a coke / charcoal fired furnace using a crucible, which is either made by the artisans in clay or commercially available clay graphite one. When alloy is being melted, the hollow mould is heated to red hot condition to drive away air bubbles from the mould cavity as well as to prevent sudden cooling of molten metal leading to uneven surface and explosion of the mould because of high heat content of filling liquid metal.

When the metal and mould temperatures are sufficient as per the judgement of the artisan for casting, the red hot mould is firmly placed / buried inside the ground so that only runner portion protrudes out. A cloth wound metal ring is placed on the runner top to support the hot crucible with metal as well as prevent overflow of metal while pouring into the mould. Care is exercised so that the metal stream does not cover more than half of the runner opening to allow escape of displaced air from the mould cavity. In order to prevent entry of any impurities floating on the surface of the molten metal, a piece of knitted jute cloth is used to cover the mouth of the crucible while pouring. The filled mould is allowed to cool down gradually, which normally takes a day or more depending on the size of the icon. However, in case of urgency, it is doused with water after 2-3 hours of casting.

The breaking of the mould to get the icon out is of great significance to the craftsman, since it is not merely an object but a transcendental entity. The breaking of the mould is initiated only when the mould has sufficiently cooled. The mould portion holding the icon head is always broken first followed by remaining portions. The iron rods and wires used as reinforcements are separated and preserved for reuse. The scrapping of the clay sticking to the icon is carried out first followed by removal of connecting rods used as support in complicated icons by chiseling. The contours and details of the original wax pattern is recaptured by smoothening the uneven surfaces followed by chiseling. The details of dress and ornaments as well as other final touches essential to make the icon perfect in all aspects are given by engraving. Further, smoothening of the icon surface is done by rubbing with fine grade emery paper. In the last stages, the icon is cleaned with tamarind and soap nut water and scrubbed with a wire brush. A last touch is given by brushing with polishing sand and water.

The various steps described above and involved in making an icon, namely child Krishna on banyan tree leaf (Aal elai krishna) are depicted in Fig. 15–20.

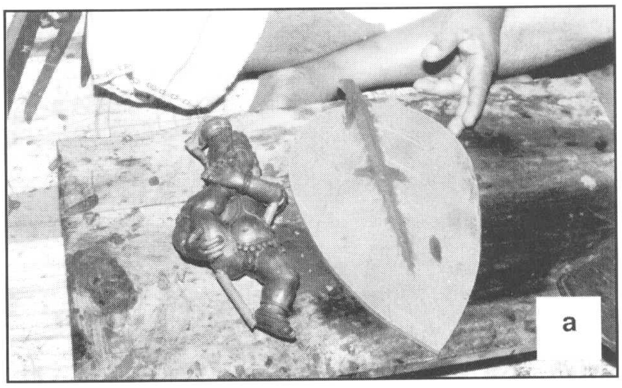


Fig. 15 : a) Completed individual wax model/pattern of child Krishna and banyan tree leaf (b).Completed wax pattern of child Krishna on that of banyan tree leaf.

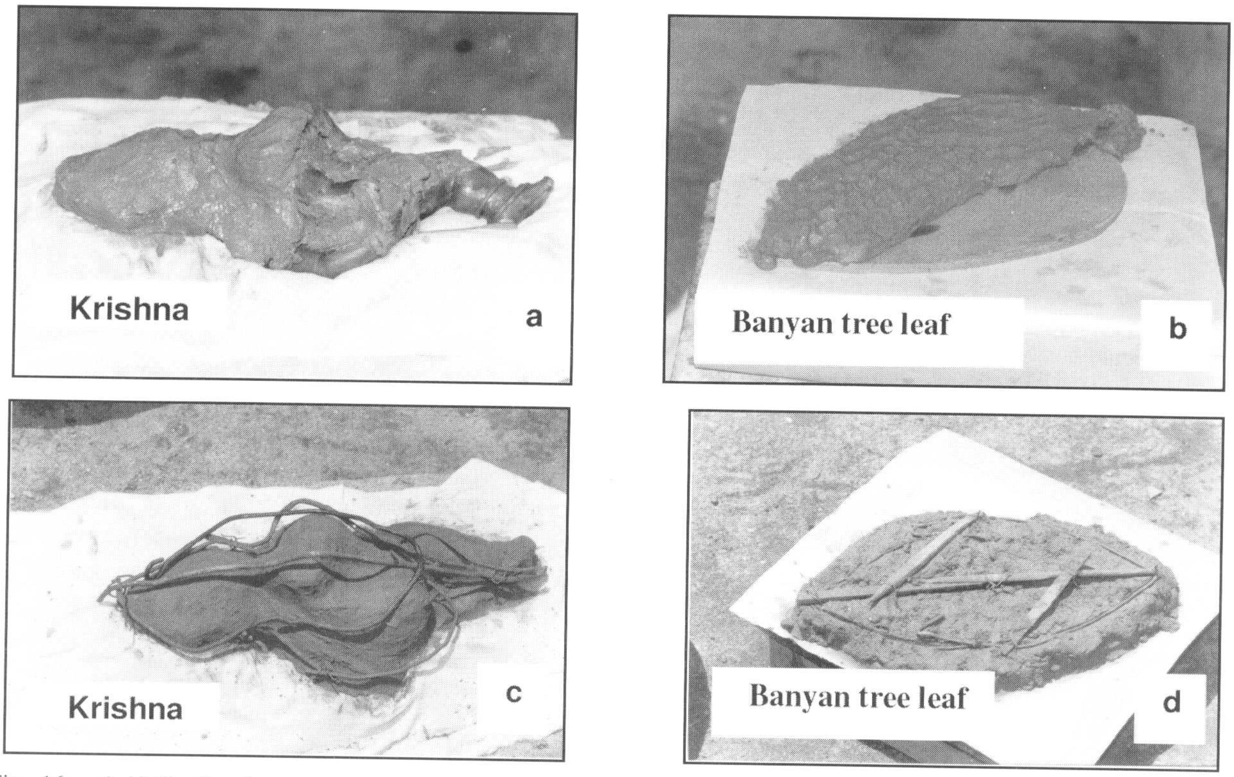


Fig. 16 : (a-b) Coating the wax patterns with first investment layer and (c-d) Placing MS rods /wires as reinforcement over the first layer of coating.

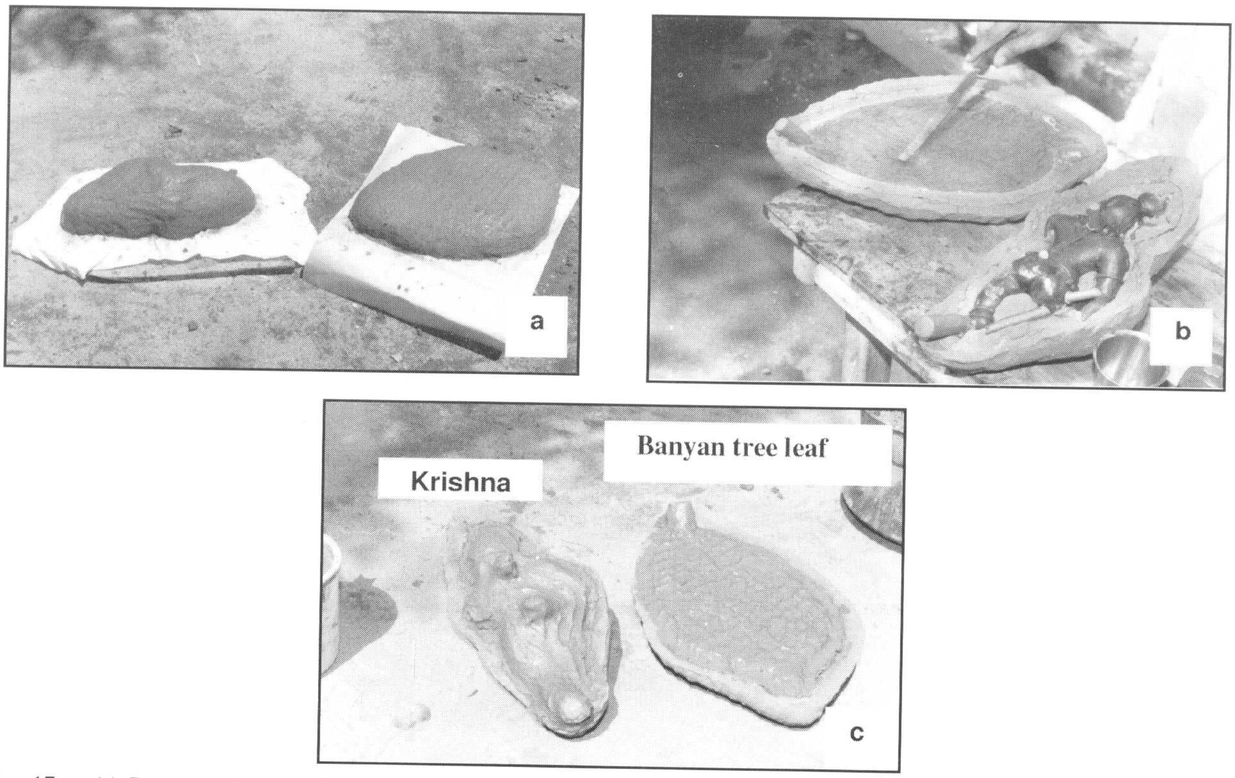


Fig. 17 : (a) Patterns after completing required second layer of coating kept for sun drying. (b) Reversed patterns after sun drying kept ready for initiating preparation of other mould half. (c) Progress in preparation of second mould half.

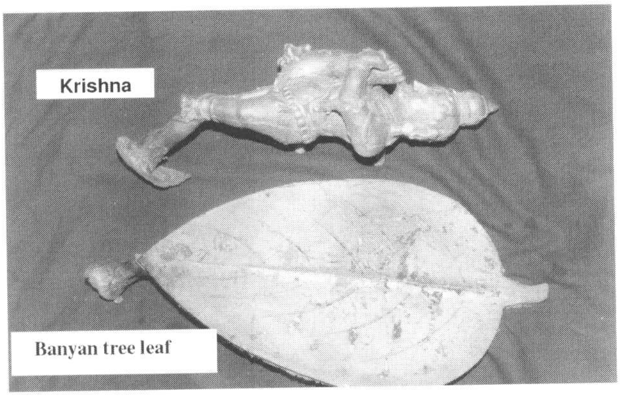


Fig. 18 : Fettled castings of child Krishna and banyan tree leaf.

Fig. 19 : Fixing child Krishna casting on wax bed spread over a wooden plate for finishing operation.

Fig. 20 : Completed icon of Krishna on banyan tree leaf (Aal elai Krishna)

Generally, 80% Cu, 20% Brass and 5% Pb are melted to make the alloy for general purpose icons. However, use of panchaloha containing 50% Cu, 16% Gold, 8% Silver, 10% Brass and 16% Pb is resorted to for icons to be installed in temples for worship[11].

7. VESSELS, LAMP AND BELL MAKING IN MANNAR, KERALA

The process followed in Mannar for making vessels, lamp and bell is, in general, similar to that followed in Swamimalai for icon making. A major deviation is making portion of the mould first over which the required thickness of wax is deposited followed by making the other half of the mould covering the wax pattern. The various steps involved in making a vessel (urli) are shown in Figs. 21-26 and that of making a bell are depicted in Figs. 27-29. A family of brass and bronze are the alloys used for making utensils and bronze (Cu-20%Sn) alone is utilised for making bells.

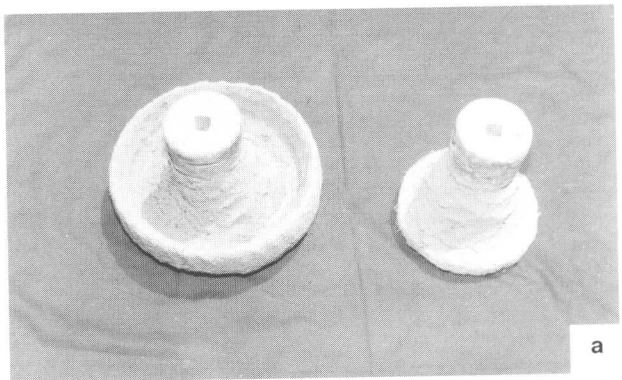


Fig. 21 : (a) Portion of the mould built over the disc made out of a mixture of clay, well ground broken mould powder and jute fiber

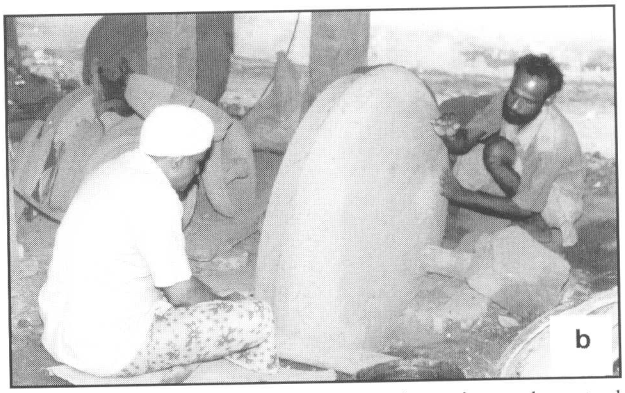


Fig. 21 : (b) Turning the mould portion using a sharp tool to make it concentric by rotating the same by hand

Fig. 21 : (c) Applying a layer of fine powder mix followed by wax layer required to achieve the thickness of the vessel

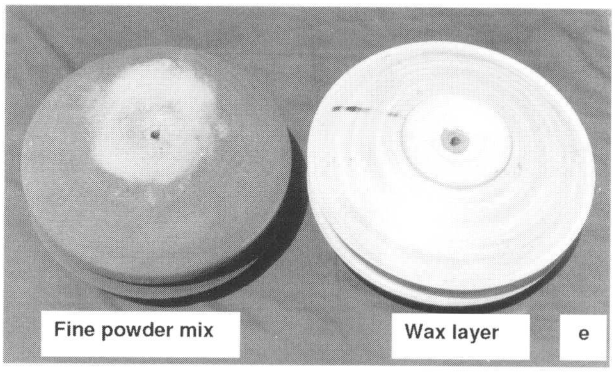


Fig. 21 : (e) Mould portion with fine powder mix layer and wax layer

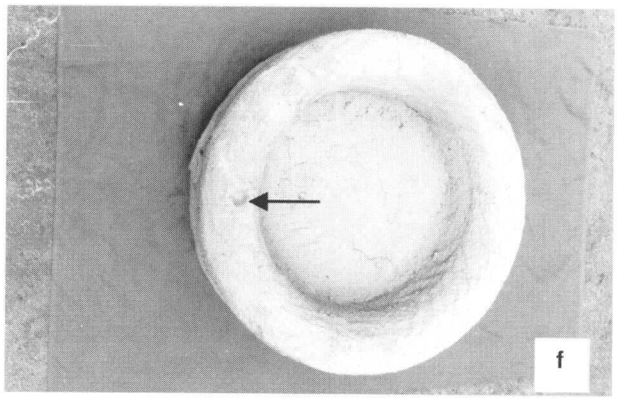


Fig. 21 : (f) Mould with fine and coarse powder investment layers covering the wax layer. The orifice (shown by arrow) is the portion through which molten wax comes out during dewaxing

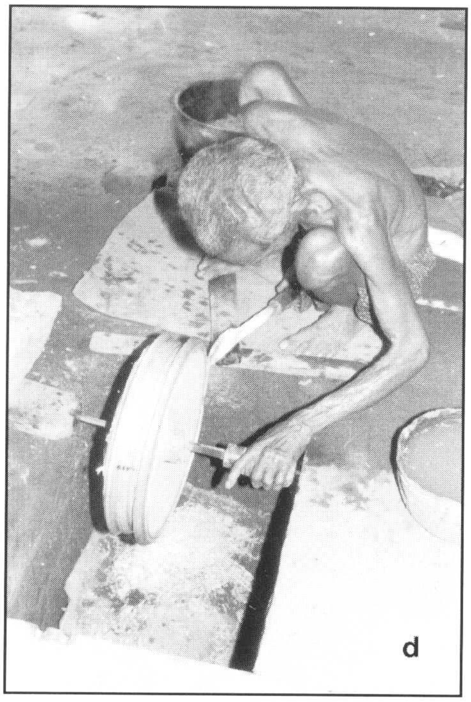


Fig. 21 : (d) Removing excess wax from the mould portion

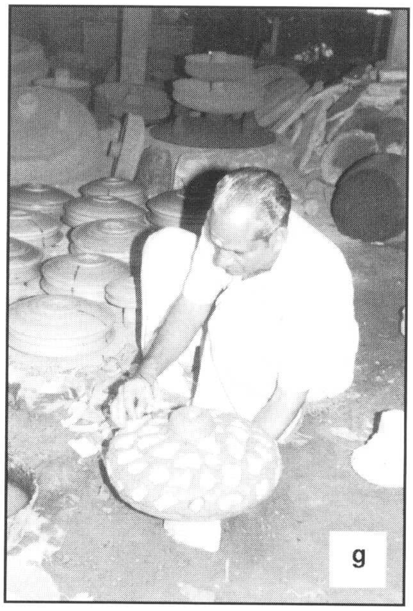


Fig. 21 : (g) Fixing broken pieces of used mould as reinforcements

Fig. 22 : Dewaxing by heating the moulds by coconut shells (shown by arrow) in progress and collection of molten wax in vessel for three moulds.

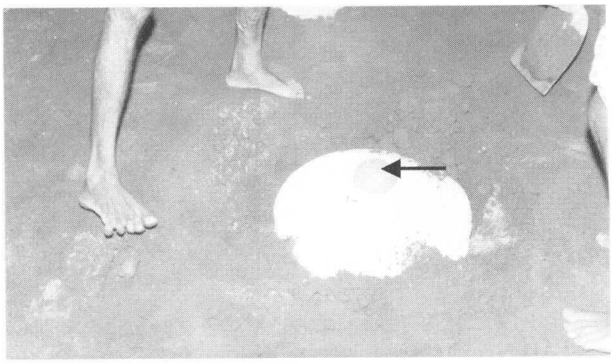


Fig. 23 : Buried mould backed by loose sand and with sprue covered with a (half) coconut shell (shown by arrow).

Fig. 24 : Fettling castings from the moulds

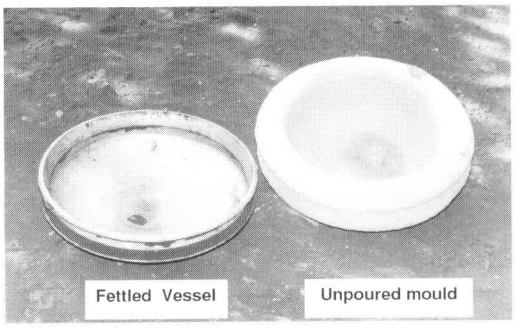


Fig. 25 : Vessel (urli) removed from the mould and a completed unpoured mould.

Fig. 26 : Photograph of finished vessels of different sizes

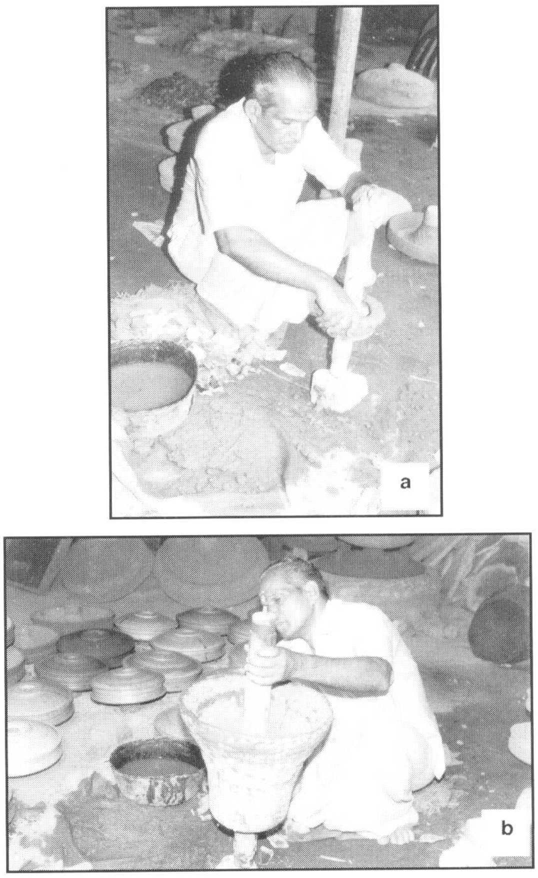


Fig. 27 : Initial steps in making one half of bell mould

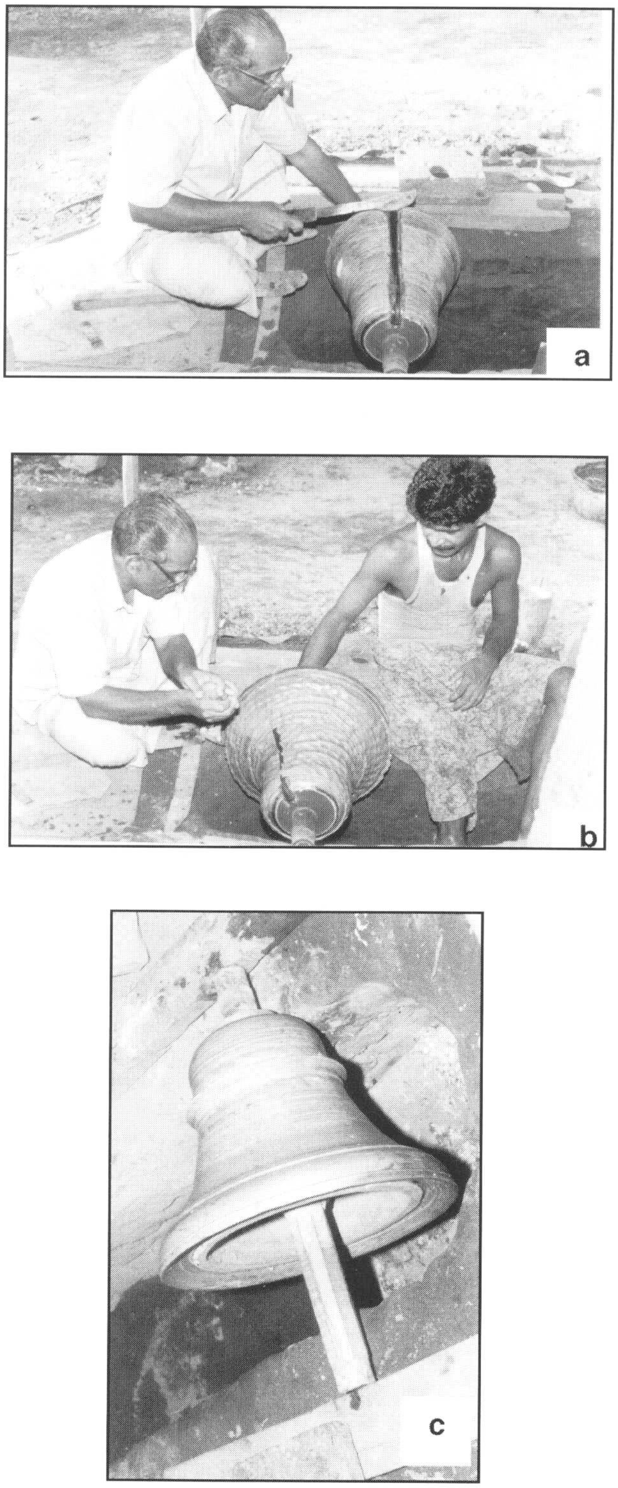


Fig. 28 : (a) Fixing a strip of hard wax with required thickness protruding out, which is equivalent to the thickness of wax layer to be given over the pattern half (b) Progress in wax layering (c) Bell mould with smoothened wax layer over which the other mould half is to be completed.

Fig. 29 : Bell castings as separated from the mould.

8. CONCLUSIONS

The two unique routes evolved at least 300 years ago by unlettered Kerala Artisans for shaping high tin bronzes, viz., Aranmula metal mirror making (a casting route) and Kadavaloor eating bowl making (a repeated thermomechanical processing route) are remarkable contributions to the metallurgical heritage of India. On the other hand, lost wax process followed both at Swamimalai and Mannar for making icons and vessels and bells respectively is the oldest metal shaping technique for which India is well known since 3rd millennium BC.

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ASPECTS OF THE HISTORY AND METALLURGY OF GOLD IN INDIA IN EARLY TIMES

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ABSTRACT

Gold has fascinated the mankind worldwide, and India is no exception. In fact, India has a very old and rich history of gold. In the present paper, various aspects of the history and metallurgy of gold in India from the earliest times till the beginning of the Christian era on the basis of literary evidences have been discussed. It has been shown that India had an abundance of gold right from the beginning of the *Ṛgvedic* age. Various aspects of mining, extraction, refining, melting and fabrication were known to people, and these are discussed. A novel variety of gold powder known as *Pipīlika* or Ants' gold as described in the great epic *Mahābhārata* has also been discussed. *Suvarṇabhūmi* and *Suvarṇadvīpa* were a sort of El Dorado for the traders and explorers in ancient India. It has been shown that gold was brought to India from these places in the ancient time.

1. INTRODUCTION

Gold is the royal metal without equal. It has greatly fascinated the mankind, ever since people saw flakes or grains of gold gleaming in streams or happened to dig out bits of shiny metal. Gold has a very rich and interesting history in India. It has been referred to several times in the *Ṛgveda Saṁhitā* or popularly known as the *Ṛgveda*[1] the oldest amongst the four *Saṁhiās*, viz Ṛgveda, *Atharvaveda*[2], *Yajurveda*[3] and *Sāmaveda*[4]. The words for gold in the *Ṛgveda* associate it with fire, lightning and sun (6.16.38, 1.10.1, and 1.46.10). In the *Śukla Yajurveda* (34.50) it has been stated that it gives strength and longevity to people:

āyusyaṁ varasvaṁ rāyasthosha maudbhim |
idaṁ hiraṇyam varsvajaitrāyāvisatadumām ||

Acquisition of gold was one of the important and popular wishes of the Vedic seers, as reflected in various hymns of the *Ṛgveda*. The attributes of gold influenced the mind and heart of the early Indians of the *Ṛgvedic* age so deeply that *Prajāpati*, the progenitor of the universe was described as *hiraṇyagarbha* - the golden egg:

hirṇyagarbhaḥ samavartātagre bhūutasya jataḥ patireka āsīt |

sa dādhāra pṛirthivīm dyāmutemām kasmai devāya havishā vidhema ||

(*Ṛgveda*,10.121.1)

The characteristics of gold, such as pleasing and untarnishing colour, excellent oxidation and corrosion resistance, ease of forming, and limited availability made it an ideal metal for ornaments, decoration, currency, and store of wealth. Its characteristics also made it a symbol of sacredness. The craving for gold had not only brought evil thinking in the mind of people, but also acted as a catalyst for the development of metallurgical knowledge in the early times.

There are a number of sources through which the historical and metallurgical details of gold in ancient times can be derived. The articles found in archaeological excavations provide valuable evidence in this regard. Important information may also be obtained through the study of ancient literature, traveler's record, inscriptions, ancient paintings, and monuments. It must be recognized that the information derived from all these sources are complimentary to each other. Two types of literary sources are recognized -direct and indirect. 'Direct' literature is the one which is on the subject of metals and metallurgy, whereas 'indirect' literature is either on an unrelated or remotely related topic, giving information about metals and metallurgy. Unfortunately, there is no ancient Indian text available today that deals solely with metals and metallurgy. However, a large number of ancient Indian texts are available on religion, literature, economics, grammar, sculpture, painting, medicine, *tantra*, alchemy, etc. These give much information on metals and their history, the techniques used for extracting them from their ores, and their subsequent shaping into useful products.

In the present paper, an attempt has been made to trace out the historical and metallurgical aspects of gold in ancient India in early times dating up to the beginning of the Christian era. The information has been drawn mainly from literary sources composed in the pre-Christian era, but some selected information based on archaeological findings has also been incorporated.

2. SANSKRIT NAMES FOR GOLD

The *Nighanṭu* is the earliest available lexicon, in which various words used for the same meaning in the Vedic literature have been compiled. Yaska has written *Nirukta*[5], which is a commentary on the *Nighanṭu* available in his time, and it is dated 700 B.C. There are fifteen synonyms for gold stated in the *Nighanṭu* (1.2). These are -*hema*, *candra*, *rukma*, *ayasa*, *hirṇaya*, *peśaḥ*, *kṛśanam*, *loha*, *kanaka*, *kāñcana*, *bharma*, *amṛta*, *maruta*, *datram* and *jātarūpa*. These are considered to be the words used for gold in the Vedic literature. Out of all these, *hiraṇya* has been the most widely used word for gold in the *Ṛgveda* and other Vedic texts.

In the epic *Rāmayāṇa*[6], the usage of the following synonyms for gold, as mentioned in the *Nighanṭu*, is available -*hema*, *rukma*, *hiraṇya*, *kanaka*, *kāñcana*, and *jātarūpa*. But some new synonyms for gold, such as *jāmbūnada*, *hāṭaka*, *suvarṇa*, *mahārajata*, *śātakumbha*, and *cāmīkara*, have also been mentioned. These synonyms for gold are also stated in the epic *Mahābhārata* (500 B.C. - 600 B.C.)[7].

Kauṭilya (4th century B.C.) has mentioned in his famous *Arthaśāstra*[8], that there are five varieties of gold and depending upon the place of the origin different names have been assigned to each. These are *jāmbūnada*, *śātakumbha*, *hāṭaka*, *vaiṇava*, and *śṛngiśuktija*. Ganapati Shastri[8] has quoted in his commentary on *Arthaśāstra* some earlier explanation for the word *śṛingiśuktija*, according to which it is the name given to the gold obtained from *Suvarṇabhūmi*. As explained later in the present paper, *Suvarṇabhūmi* was the name given to some area of the South-East Asia by the ancient Indians.

3. SOURCES OF GOLD

In Indian mythology, the earth has been considered as mother of every one:

mātābhūmiḥ putroham pṛithivyāḥ |

(Atharvaveda,12.1.12)

In the *Athrvaveda*, the earth has been referred to as *hiraṇyavakshā,* i.e. the one containing gold in her chest:

viśvambharā vasudhānī pratiṣtha hirṇyavakshā jagato niveśanī |

vaiśvānaraṁ bibhratī bhūmiragnimindraṛishbhā draviṇe no dadhātu ||

(Atharvaveda,12.1.6)

śilā bhūmiraśmā pāñsuḥ sā bhūmiḥ sandhṛtā dhṛtā |

tasyai hirṇyavakshse pṛithivyā akaraṁ namaḥ ||

(Atharvaveda,12.1.26)

The above hymns imply that the earth has mines of gold. The word *'bhūmi'* in the above hymns does not denote merely the surface of the plain land, but it also includes rivers and mountains apart from the interior of the earth.

In the *Arthaśāstra* (29.13), *Kauṭtilya* has mentioned three types of gold, which are obtained from different sources or origins:

jātarūpam rasaviddhamākarodgataṁ ća suvarṇam |

The first type of gold is *Jātarūpa,* which is obtained on its own in nature. This refers to the alluvial placer gold occurring in natural and unlocked state. *Rasaviddha* is that type of gold which is present in solution form. The third type of gold is the one which is obtained from mines, i.e. lode deposit.

Various specific sources of gold on the earth have been mentioned in different Sanskrit texts. These are rivers, mountains, and naturally occurring special liquids, which are discussed in the following sections.

3.1 Rivers

Rivers were recognised as an important source of gold in ancient times. Most major civilizations fluorished near the river banks. Thus it is not unreasonable to believe that the very first gold found by man was that from the river banks. Gold found near the river banks or in the river bed is known as alluvial placer gold.

The *Ṛgveda* (10.75.8) mentions that the river Sindhu (Indus) contains gold-

svaśvā sindhuḥ surathā suvāsā hiraṇyayī sukṛtā vājīnivatī |

urṇāvatī yuvatiḥ silamāva tyutādhi vaste subhagā madhuvṛdham ||

[English translation according to Sāyaṇa's commentary: "This is that river Sindhu which is full of horses, chariots, cotton, gold, grains, and wool (i.e. these materials are either produced or found on the banks or the nearby area of the river Sindhu). Its bank contains ropelike plants which are used to tie down ploughs. It bestows fortune on people, and such plants are grown on its banks that help in producing greater amount of honey".]

Again, in another reference, the *Ṛgveda* (8.2.18) mentions that the path, i.e. both banks, of the river Sindhu contains gold:

ut syā śvetayāvarī vahiṣṭhā vāṁ nadīnām |
sindhurhiraṇyavartaniḥ ||

[English translation according to Sāyaṇa's commentary: "And moreover, the river Sindhu having white (i.e. clean) water flow, and path (i.e. both banks) containing gold, praises you (*Ashwin*)". It is noteworthy that Sāyaṇa has translated *'hiraṇyavartani'* as *hiraṇyamayobhayakūlā* (i.e. both banks containing gold). *Amarkośa* (2.1.15) mentions that *'vartani'* is one of the twelve words used to denote the word 'path'.]

Thus it can be seen that according to the *Ṛ*gveda the river Sindhu (Indus) has been an important source of alluvial placer gold.

In another Vedic text *Śatapatha Brāhmaṇa*[9], it has been stated that gold is found in water, apparently referring to alluvial placer gold found from rivers:

atha hiraṇya sambharati |............................

retastasmādapsu vindantyapsu hi......................

tsmādhiraṇya sambharati |

(*Śatapatha Brāhmaṇa* 2.1.1.5)

Another important source of alluvial placer gold was the river *Jambū*, as mentioned in various classical Sanskrit texts, like *Rāmāyaṇa*, *Mahābhārata* and *Śrimadbhāgavata*. The *Mahābhārata* (2.28, *dākshiṇātya* recension) mentions that sand and mud of the *Jambū* river contain gold:

meruṁ pradakshiṇaṁ kṛitvā parvatapravaraṁ prabhu |

yayau jambūnadītīre nadīṁ śresthāṁ vilokayan ||

sa tāṁ manoramāṁ divyāṁ jambūswādurasāvaham |

haimapakshigaṇairjustāṁ sauvarṇajālajakulām |

haimapaṅkāṁ haimajalāṁ śubhāṁ sauvarṇavālukām ||

The gold obtained from the river *Jambū* was known as *Jambūnada*; after the place of its source. In the *Mahābhārata* (*Droṇa*, 68.11) it has been stated that the *Jambūnada* gold was considered to be a highly pure variety of gold and was very famous:

jāmbūnadasya śudhasya kanakasya mahāyaśāḥ |

3.2. Mountains

Mountains were another important source of gold in ancient India. The "mountain" type source includes both the hard unweathered rock and the conglomerate of weathered rocks, from which gold was recovered.

The *Rāmāyaṇa* mentions various mountains containing gold, which were situated in different parts of India. In the east direction, there are *Udai* and *Saumanasa* mountains, which were full of gold:

tataḥ paraṁ hemamayaṁ śṛīmānudayaparvataḥ |

(4.40.54)

śṛiṅgaṁ saumanasaṁ nāma jātarūpamayaṁ dhruvaṁ |

(4.40.57)

In the west direction near the meeting point of river Sindhu with the ocean, there is a mention of *Soma* mountain, which contained gold:

mahān somagirirnāma śataśriṅgo mahādrumaḥ |

....

tasya śṛingaṁ divasparaśam kānćanaṁ ćitrapādapam ||

(4.41.15-18)

Further, there are *Pariyātra* and *Varāha* mountains in the western direction, which contained gold:

kotiṁ tatra samudrasya kāñćanīṁ śatayojanām |

(4.42.19)

yojanani ćatuḥpashtivarāho nāma parvataḥ |
suvarṇaśṛiṅga sumahānagādhe varunālaye ||

(4.42.30)

In the north direction, there was a *Kāla* mountain full of gold:

kālaṁ nāma mahāsānuṁ parvataṁ taṁ gamishyatha | (4.43.14)

tamatikramya śailendraṁ hemagarbhaṁ mahāgirim ||

(4.43.16)

In the *Mahābhārata* (Vana, 104.2), there are several references stating that the *Meru* or *Sumeru* mountain contained gold:

adrirājaṁ mahaśailaṁ meruṁ kanakaparavatam |
udayāstane bhānuḥ pradakshiṇamavartata ||

The identification of the *Meru* mountain has been subject of a number of studies. In the *Mahābhārata* (*Āśwamedhika*, 4, 25/26), it has been stated that the Meru mountain is situated to the north of the *Himālayas*:

meruṁ parvatamāsādya himavatparśva uttare |
kāñcanaḥ sumahān padastatra karma ćakarsaḥ ||

Meru or Sumeru mountain has not been stated in the various *Samhitās* of the Vedic literature, but *Mahāmeru* (big Meru) and the synonym of *Meru* – "*Sudarśana*" have been mentioned in the *Taittrīya Āraṇyaka*:

kaśyapoastamaḥ sa mahāmeruṁ na jahāti | (1.7)

sudarśane ća kraunće ća |
maināge ća mahāgirau || (1.31)

Harshe[10] believes that the *Meru* mountain is no other than the Altai mountain in the Central Asia. Altai is the name given to a vast system of highlands and lofty maintains of southern Siberia and Mongolia[11]. In the older geographical system the Altai included nearly the whole of the entire northern mountain system of Asia, extending through the Yablonoi and Stanovoi ranges to the N.E. extremity of the continent[11]. The name Altai has been derived from the Turkish – Mongolian 'altan', meaning 'golden'[12] and resembles with the description of Meru as gold mountain in Sanskrit texts. There are three main prongs of the system – the Soviet, Mongol and Gobi Altai. The Soviet peak Belukha at 14,783 ft is the highest point[12]. Pathak[13] has attempted to give some fresh light on the identification of Meru on the basis of linguistic study. He also believes that the complex mountain chains from the Altai to the Upper *Himālayas* are variously termed as Meru.

3.3 Naturally Occurring Special Liquids

In ancient India gold was also obtained from certain naturally occurring special liquids. The *Atharvaveda* (5.28.6) mentions in a very concise (sutra) manner that one type of gold is the essential (*sāra*) of powerful liquids:

apāmekaṁ vedhasāṁ reta āhustat te hiraṇyaṁ trivrdastvāyushe |

Kauṭilya in his *Arthaśastra* has stated that one of the origins of gold in nature is in the form of solutions, referred to "*rasavidhha*", which is formed by the dissolution of gold present in veins of the rocks, in special liquids flowing through it. It flows through the holes and fissures of mountains. *Kauṭilya* has exemplified the characteristics of such solutions containing gold. When such solutions are mixed in water, it spreads over the water surface like oil. Alternatively, it settles to the bottom of the vessel containing water, indicating a high density immiscible liquid. *Kauṭilya* has further given a very important characteristic of such solutions, which indicates that it contains gold. He says that one pala (a measure) of such solutions converts 100 *palas* of silver or copper into gold, which refers to the cementation of gold on the surface of less cathodic copper or silver:

apsu nisṭhyūtastailavadvisarpiṇaḥ pañkamala-grahiṇasća tāmrarūpyayoḥ śatādupari veddhāraḥ |

The conversion of silver or copper into gold by such liquids, in fact, refers to the deposition of gold particles on the surface of less cathodic metals such as silver, copper, etc., when these metals are immersed into such liquids containing gold.

4. MINING AND EXTRACTION

It is evident from the earlier discussion that in ancient India, gold was mainly available as alluvial placer deposits and reef or vein deposits. It is but natural to assume that the most easy source of gold was alluvial deposit, and therefore it is not unreasonable to believe that the working of alluvial placer gold deposit proceeded vein gold mining. However, the concurrent working of these two types of deposits must also had continued throughout the ages. Literary evidences for mining methods in early times are very sketchy, despite the fact that gold and gold products are widely referred to in the earliest Vedic literature *Ṛgveda*.

The *Pāli Tripiṭaka* is a collection of the sermons and discourses of Lord Buddha, and is considered to be composed during the period of 5^th^century B.C. -3^rd^ century B.C. It is an important reference which gives an insight into the economic and social life in India in the 5^th^ century - 6^th^ century B.C. The *Añguṭṭara Nikāya* (3.10.10), a part of the Sutta *Piṭaka* of the *Pāli Tripiṭaka*, has described the process for the recovery of gold from the alluvial placer, which consisted of agitating the auriferous sand along with water in a pan. The lighter sand particles were drained out along with water, leaving behind heavier gold particles and some residual sand. This rougher concentrate was further panned several times resulting into gold dust having very little sand or other impurities. The persons engaged in gold washing were called "*pāñśudhāvaka*", and were different than goldsmith.

The basic process for the recovery of gold from alluvial placer deposit, popularly known as gold washing, has not changed since the antiquity, although some details must have been changing with time and place of operation. Documentary evidences for the washing of gold from the alluvial placer deposits in the medieval and pre-modern periods are available in plenty. On the basis of all these references the gold washing process may be summarised as follows.

Early recovery methods for gold from alluvial placer deposit were based upon the use of dish shaped pans made of wood or iron, and the technique was known as panning. The techniques differ according to custom and pan design. Most pans have one common characteristics - a large internal surface area and shallow depth. Basically, however, all methods relied upon a thorough puddling of the alluvial placer deposit mass by hand and agitation, using an oscillatory motion. As a result the heavier gold particles settled preferentially. A swirling motion of the pan under water continuously washed the top layer of light particles away until only a small amount remains. This rougher concentrate is a mixture of gold particles and lighter sand or mineral particles. Rougher concentrates from various runs were collected and further panned to a product in which the percentage of gold was high. Repeated panning resulted into gold dust having very little sand or other impurities. However, the success of the process greatly depended upon the skill of the washer. Alternatively, the gold and sand mixture was subjected to amalgamation, wherein gold combined with mercury, which was separated from the sand. The amalgam was heated in a suitable container to evaporate mercury, leaving behind gold.

If the alluvial placer deposit contained very coarse size gravels and pebbles, then the deposit was put over a sieve, made of bamboo or similar material, laid over a trough. Water was poured upon the heap of deposit, and also the deposit was stirred until all, the sand was carried through the sieve into the trough.

The remaining coarse particles lying on the sieve were rejected. The sand collected in the trough was panned for gold, as described earlier.

Archaeological evidences have given ample information for obtaining a clearer picture of the vein gold mining methods adopted in ancient India. Allchin visited Hutti area in Karnataka state in 1957 A.D., and carried out investigation into old gold mining sites and also studied the earlier work on this subject, notably of Munn, Foote and Maclaren. He in his excellent paper[(14)] published in 1962 A.D., has collected the evidences of old gold workings both by open cast and deep mining in the South Indian Dharwar rocks, which was based on the reports prepared by earlier explorers in the last phases of the nineteenth century and early phases of the twentieth century, together with his own investigations. An examination of old gold working in this area would give some insight into the mining practice used in ancient times, and much of the archaeological findings that follow is based on the Allchin's work.

At Belli -Betta (Silver Hill) situated 20 miles NW of Seringapatam, and Sonnahalli situated 18 miles SW of Mysore, Foote[15] reported old gold workings including pits and small shafts and passages choked with debris so as to make impossible the estimation of the depth. Bosworth Smith[16] has reported a large number of old gold workings NW of Halebid and at Woolagiri, situated 20 miles SW of Mysore. Maclared[17] has mentioned two dozens pits of 18 -25 ft in depth on the top of Jalgaragudda Hill (Goldwasher's Hill). He has described the old workings as often characterized by no more than shallow depressions where the grass was greener; all that remained of a pit of 80 -100 ft in vertical depth. As it would be discussed later, the upper part of the old working had been packed with large rocks and debris after the work was complete.

Foote[18] reported the details of various old workings and mines lying between Hutti and Maski in the Raichur district of the present time Karnataka state, which are perhaps the most remarkable and interesting group of old workings. In an area of about 200 square miles several hundred old workings have been located. The entire area is covered by a thick blanket of black cotton soil, which has been drifted into the old pits thus obscuring them to surface view. As a result the pit areas appear as shallow depressions in the ground. He found that all were filled with water and thus he could not explore deeper.

Munn[19], quoting from Maclaren's report submitted to the Government, has stated that 'the first modern mining started at Budini in 1887 A.D., and in the very first year's survey some 300 old workings were discovered. The mining company sank 5 shafts at Wandalli. The old workings were reached at different depths in different shafts, and in one shaft the old working had not bottomed even at 380 feet depth. At the Hutti mines, some 10 miles to the west, modem mining operations started in 1902 A.D. Here the old workings were encountered at depths of up to 640 feet.

Several explorers have reported the availability of several commodities from these old gold working sites, which throw light on the actual nature and possible date of the mining operations. Two types of crushing mills have been sighted by explorers. The first type, which Maclaren calls "rock breakers", consisted of small depressions of about 6" broad and 4" deep, in which rocks were placed and crushed to about the size of a walnut. Maclaren[17] has reported over 200 such rock breakers at old gold working site situated near Sangli. The second type crushing mill, used hugh "rocking boulders" of size about 30" x 18" x 18", weighing on an average 6 cwts. Maclaren[17] has reported that many such rocking boulders were found lying near Kabulayakatti.

Timber, semi-charred timber, ashes and iron gouges have been found in many of these old workings[20]. Timbering was used in supporting the galleries, and lengths of *babul* (Acacia arabica) were found. Some of the *babul* lengths bear the irregular marks of adze cutting, while some had been rounded off at the ends to fit into uprights. The availability of timber, semi-charred timber and ashes in old workings point towards the fact that rock faces were fire set, which were subsequently quenched with water. This enabling the rocks to fracture leading to pieces to spall off. Alternatively, the fracturing of rocks makes easy breaking of hard rocks from the main body. At depth of hundreds of feet in some old workings, the deposit of as much as 10 ft of broken water pots at the bottom of old workings has been reported. This indicates that here the mines came across a spring, and further mining was abandoned in the shaft.

Munn[20] has further observed that the upper parts of the old workings had been carefully hand-packed with large rocks and debris after any section was completed. Munn suggests that this was done with a view to prevent the surface water to flow into the mine, and perhaps also to prevent the collapse of the excavation. He is also of the view that the ancient miners were doing it to conceal the mines from the observation of invaders in time of war.

Allchin[14] has reported that Munn and Mahadevan discovered ancient crucibles near Wandalli and Honkunni workings in Hutti area of South India. The analysis of these crucibles proved beyond doubt that they had been used for gold extraction. It was most interesting to note that in both instances they showed the presence of mercury, which indicates that amalgamation process was used at some stage of the extraction of gold from the ground ore.

In 1955 A.D., C-14 analysis of two specimens of timber found at a depth of about 250 feet in the old workings at Oakleys shaft of Hutti mine were carried out in New Zealand[14]. The results were as follows: Sample No.1, 1890 ± 70 years B.P., and Sample No.2, 1810 ± 70 years B.P. Allchin[14] has quoted the dates of other objects, such as, small pot of coarse pink-red earthware, cylindrical grinding stone of pink sand stone, small stone discs of green chlorite schist, etc., found from the old workings and preserved at Hutti, which is in the range of 1st century B.C. to the 3rd century A.D. This date is consistent with the dating suggested by the C-14 analyses.

In summary, the archaeological evidence from the Hutti field suggests that the mines were being worked even at depths of 250 feet during the 1st century of the Christian era. The first stage of mining must have been mainly surface or open cast mining, wherein suitable gold bearing rocks exposed to surface were mined. Upon the exhaustion of most of the gold bearing surface areas, miners would have attempted to go deeper for mining.

Allchin[14] has further rightly argued that the mining activity in this area must have been going on for about 500 - 600 years before such a type of deep mining activity would have started. He has concluded that the large scale mining in the Hutti area began around the end of the 4th century B.C., when the colonisation of the Deccan by the Mauryan empire started.

It is rather interesting to compare the gold working in Hutti area of the South India with that of the following verse quoted by *Kauṭilya* in his famous *Arthaśātra* (7.16.12):

sthalapatheapi | "haimavato dakshiṇāpathāćchreyan hastyashvagandhadantājinarūpyasuvarṇapaṇyḥ sāravattrāḥ" ītyaćaryāḥ | neti Kauṭilyaḥ | kamblājināshvapaṇyavarjyāḥ śaṇkhavajramaṇimuktāsuvarnapaṇyaśća prabhutatarā dakshiṇāpathe |

Kauṭilya mentions that the earlier scholars have stated that among the land routes the Northern route (*Uttarāpatha*) passing through the *Himālayas* had been better than the Southern route (*Dakshiṇāpatha*), which ran southwards from the Ganges valley, as superior quality of elephants, horses, musk, elephant teeth, skin of deer, silver, and gold are available in plenty. But then *Kauṭilya* explains that it is not so, and except woolen rug, skin of deer, and horses, huge quantities of conches, diamond, pearls, precious stones and gold are available in the Southern route. It is clear from this reference of the *Arthaśāstra* that in the time of *Kauṭilya* Southern route had occupied an important place for the availability of gold, which corroborates the archaeological findings reported earlier.

On the basis of above description of old gold workings, one may reconstruct the method employed in the mines of Hutti in ancient times, which may be considered as a representative of the method used in other areas. The various steps used in deep mining and extraction of vein gold were as follows. The first step consisted of going down the dip of the reef with a small shaft or series of shafts. The ore was extracted laterally from the shaft. Excavation was achieved by means of fire setting. Auriferous rock was removed and hauled to the surface in bags or baskets by ropes and windlasses. This is supported by the appearance of smooth sides of the rock face in the shafts caused due to prolonged rubbing with ropes, as observed in old workings. Timbers were used for supporting the gallaries. The water from spring found at greater depth of mines was hauled to the surface by means of water pots passed hand -to

-hand to surface by a human chain. Such mines were subsequently abandoned, due to severe problems faced in mining. The upper parts of the old workings was carefully hand packed with large rocks and debris after any section was completed. The shattered ore was crushed in the batteries of crushers at the ground level. The sand produced by the crushing was taken to a suitable place where water was available in plenty, and washed in wooden pans of the kind used for alluvial placer mining, as described earlier. The subsequent steps of extraction were similar to those used in the extraction of gold from alluvial placer deposits.

5. REFINING OF GOLD

There are references to pure form of gold in the *Ṛgveda* (4.10.6), when it is stated that the fire glows like pure form of gold and the word used in this context is "*śući hiraṇyam*". Again in the *Atharvaveda* (19.26.2), gold having pleasant colour (*hiraṇyam suvarṇaṁ*) has been mentioned, which is also an indication of pure gold. There is also a mention of best variety of gold in the *Ṛgveda* (1.25.2) - *suhiraṇyaḥ*. All these references indicate that pure form of gold whether naturally occurring or prepared after refining impure gold was known to the people in the times of Vedas.

In the *Pañćaviṁśa Brāhmaṇa* (17.6.4), there is a mention of how gold refining was done, when it is stated that the *Agniṣṭut* purifies him by heat just as he, the (smith) would purify the gold by the heat (of the fire).

An usage, which has been widely used in early Sanskrit literatures, such as *Rāmāyana* and *Mahābhārata*, is the word for gold preceded by the qualifying term "*tapta*" or "*pratapta*", such as *taptaćamīkara, taptakāñćana, prataptajābūnada* etc., meaning heated gold. This is a clear reference to pure gold obtained after refining impure gold by subjecting it to heat in solid state, as it would become clear later. In one of the stanzas of the *Rāmāyana* (4.24.18), there is a mention of the process of gold refining which was carried out by heating impure gold in fire.

The *Arthaśāstra* of *Kauṭilya* has given two formulations for gold refining. The first formulation is based on heating impure gold in liquid state along with lead. The second one essentially consists of heating thin sheets of impure gold along with salt and soil in the solid state.

Kauṭilya has prescribed that impure gold should be melted with four times of its weight of lead for purification:

"*taććaturguṇena sīsena śodhayet*" (2.29.13)

He further states that the gold obtained from mines should also be refined in similar manner; i.e. with the addition of lead:

"*ākarodgataṁ sīsānvayena bhidyamānaṁ*" (2.29.13)

All the base metals present in the impure gold, as well as the lead which was added, combine with the oxygen in the air, forming respective oxides. The temperature of operation must have been around 1100-1150°C. If the crucible in which the gold was melted is porous, then these oxides of base metals together with that of lead would get absorbed by the porous crucible. There is a very large difference in the surface tension of Pb and PbO, and molten lead is not absorbed in the porous crucible. Elements such as Sb, As and Zn, when present in impure gold are, in part, volatilized as oxides and in part, absorbed in the porous crucible. If the crucible did not have enough porosity, then the liquid slag consisting of lead oxide and the oxides of the base metals present in the impure gold would float on top of the liquid metal, which can be tapped off leaving behind purified gold in the crucible.

As discussed earlier, the washing of sand-gold mixture, whether obtained from alluvial placer deposit or obtained from crushing and grinding of auriferous rocks, for the recovery of gold is a very skillful operation, demanding dexterity and ingenuity at each step. It is rather difficult to get rid of all the traces of undesirable fine size sand and soil from the gold particulate even after repeated washing without incurring heavy losses of gold. It is in deed very interesting to note that *Kauṭilya* has stated that the gold obtained from mine should also be purified by lead. As a result, not only the base metals present in the impure gold, but also the sand and soil present along with it are removed. The nature of soil and sand impurities present would depend upon the location of deposit, but the most frequently encountered oxide impurities would be SiO_2, CaO, FeO, Fe_2O_3, Cu_2O, ZnO, As_2O_3, Sb_2O_3 and Al_2O_3. When impure gold containing these oxide impurities is heated along with lead, say at 1150°C, then the lead is oxidized and also the base metals present in gold. The lead oxide combines with the above stated oxide impurities and also with the oxides of base metals present in gold formed during melting, leading to the formation of low melting point slag. This slag can either get absorbed in the porous crucible, or can be tapped off leaving behind purified gold in the crucible.

If the starting impure gold contains silver as an impurity, then almost all the silver would remain along with the gold after treatment with lead. It is against this background that the second formulation prescribed by *Kauṭilya* is very important, which was used for the further refining of gold, especially with respect to silver content. *Kauṭilya* has prescribed that thin sheets of impure gold should be heated with the soil of Sindhu state:

pākpatrapakvaṁ saindhavikyojjvālitaṁ |

(2.29.13)

The soil of Sindhu state had been known to contain salt. It is interesting to note that the rock salt from that state had been known as *Saindhava* salt. This is a solid state process, in which the impurities such as silver, copper. etc. form their respective chlorides which subsequently goes into the mixture along with which the gold was heated. It is rather interesting to note that *Kauṭilya* has mentioned that the starting impure gold should be in thin sheet form, as this would improve the kinetics of the refining process.

6. THE ANTS' GOLD OF THE MAHABHARATA: A NOVEL VARIETY OF GOLD POWDER

An account of gold in ancient India would be considered to be incomplete without dealing with the ants' gold. The foremost reference to the ants' gold as "*Pipīlika*" gold is found in the famous Sanskrit epic *Mahābhārata*[7]. *Pipīlika* is the Sanskrit word for ants. In the *Mahābhārata* (2.52.2-4) it has been stated that *Pipīlika* or ants' gold was presented to the king *Yudhiṣṭhira* at the time of the *Rājasūya Yagña* ceremony by the kings of various groups of people:

merumandayomadhye śailodāmabhito nadīm |
ye te kīćakaveṇūnāṁ chāyāṁ ramyāmupāsate ||

khasā ekāsana hyarhāḥ pradarā dirghaveṇvaḥ |
pāradāśćā kulindāśćā taṅgaṇh parataṅgaṇaḥ ||

tad vai pipīlikaṁ nāma uddhrtaṁ yat pipilikaiḥ |
jātarūpaṁ droṇameyamahārshuḥ puṅja śo nṛpaḥ ||

The above stanzas state that the kings of *Khasa*, *Ekāsana*, *Arha*, *Pradara*, *Dīrghavenu*, *Pārada*, *Pulinda*, *Taṅgana* and *Parataṅgana* groups of people, who reside beneath the pleasant shade of bamboo trees making sound like that of *Veṇu* musical instrument owing to air filling the pores of the bamboo, situated on the banks of *Śailodā* river flowing in between *Meru* and *Mandaraćala* mountains, presented to the king *Yudhiṣṭhira* heaps of *Pipīlika* gold drawn up by ants. The gold was in such a huge quantity that it was measurable by *Droṇa*. Dube[(21)] has dealt with the theory of ants' gold in detail elsewhere. The fact that the heaps of ants' gold was presented to the king *Yudhiṣṭhira*, and it was measured by the unit *Droṇa* is of special significance in understanding the nature of such a gold. *Droṇa* was a vessel, generally made of dried timber, and was used to measure granular, powdered and liquid materials[21] .

Ants have been, and still continue to be, known to dig out soil from beneath the earth, and make soil heaps of various sizes, popularly known as "ant-hills". The size of these ant-hills would depend upon the type of ant making the hill. Brown and black coloured ants make very small ant-hills, which are rather fragile. On the other hand, white coloured small ants having reddish tip, also known as termite, make big size hills. The size of such ant-hills or termite mounds, which may be anything up to 5 m high and 20 m broad, depends largely on the kind of soil and climatic conditions. Hesse[22] has reported ant-hills (termite mounds) as large as 84 cu.m. in volume which had weight of about 185 tons of soil above ground at Ngomeni in East Africa.

In fact, what was happening was that ants, in particular white ants, were digging out auriferous soil present in the alluvial placer deposit, and stored it at various places. Such soils were collected from these hills by people. Subsequently, the gold, designated as the *Pipīlika* gold (powder), was separated from the sand by the panning process. It is reasonable to believe that *Pipīlika* gold must have been fine in size as the ants can carry only very small particles. From the description cited in the text it seems that the banks of river *Śailodā* or the area nearby were highly auriferous, and were the source of this gold.

A question may be asked whether the *Pipīlika* gold powder was different in any respect than from other types of placer gold powder. Before answering this question, it is necessary to throw light on the nature of alluvial placer gold, in general. Alluvial placer gold varies widely in composition, depending on the characteristics of the original mineral, the distance travelled by the gold particles from the parent source, and the size of the gold particles. The purity or fineness of alluvial placer gold varies from 500 - 900; that of veins from 500-850 (1000 is pure gold)[23] . In Nature gold is alloyed with silver, copper and other metals. Depending upon the suitable environment, silver and copper are selectively leached from the gold alloy particles, e.g. as soluble sulphates or carbonates, during the transport. As a result, alluvial placer gold obtained from far removed locations from its parent source tends to become purer than the original material. Thus the fineness increases consistently in the order: primary deposit - eluvial placer deposit - alluvial placer deposit - marine placer deposit, all things being equal. Similarly, the purity of alluvial placer gold increases with the decreasing powder size. For reasons described above, the alluvial placer gold powder is generally of more pleasing colour, having natural deeper colour than the "mountain gold[24]. Some others[25] have suggested that the natural deeper colour of alluvial placer gold can also result from the precipitation of pure gold from the solution containing gold on the relatively impure gold particles during transport.

Because of the limited capacity and strength of ants to carry bigger particles of high density gold, it is reasonable to envisage that the average size of the *Pipīlika* gold powder must have been fine and smaller than that of the alluvial placer gold powder produced by the washing of auriferous sand dug by human beings, and hence of greater purity as described earlier. It is interesting to note that because of greater purity the *Pipīlika* gold powder was considered to be a novel variety of gold as it was thought to be the most appropriate item for presentation to the royalty. The amount of *Pipīlika* gold powder presented was so large that instead of weighing, it was to be measured by *Droṇa* measuring vessel. It is interesting to compare the fact that the *Droṇa* vessel was the convenient method for measuring the amount of *Pipīlika* gold powder with the observation made by Chevalier Damon in 1698 A.D. on the mining practice prevalent in the rich gold mines of Ivory Coast. He stated that the mines were so rich that about 200 men can in a single day fill with gold (powder) six boxes having all surfaces measuring one square foot.

In short, the *Pipīlika* gold of the *Mahābhārata* was high purity and fine size gold powder obtained by panning the auriferous soil of ant-hills formed by the real ants as a part of their nature on the land containing alluvial placer deposit in the *Meru* and *Mandāra* mountains region.

Greek historians and geographers, such as Herodotus, Pliny and Strabo have also referred to the ants' gold, which was obtained from panning the auriferous sand dug on rich gold field by medium size animals bigger than foxes yet smaller than dogs, who were digging up earth for making burrows and piling it up near the mouth of the pit. This has been discussed in detail by Dube elsewhere[21].

7. *Suvarṇabhūmi* and *Suvarṇadvīpa*

No discussion of gold in ancient India can be complete without discussing *Suvarṇabhūmi* and *Suvarṇadvīpa* - the two words widely referred to in many ancient Indian texts, and which are connected with some of the areas of the present South-East Asia. India's contact with the countries of modem South-East Asia dates back to pre-Christian era. The early explorers found that gold was available in large quantities in many parts of the present South-East Asia, and they named some of the areas by the word *Suvarṇabhūmi* (land of gold) and *Suvarṇadvīpa* (gold island). The lower Burma (Myanmar) was generally identified with *Suvarṇabhūmi*. It is also believed that the area stretching from Burma to Malaya was known as *Suvarṇabhūmi*. According to one theory, Sumatra was identified with *Suvarṇadvīpa*, because of large availability of gold in ancient times. Although initially some specific location/island of South-East Asia must had been recognised as *Suvarṇabhūmi* and *Suvarṇadvīpa*, later on these words were used in a broader sense to designate collectively the islands and countries of the South-East Asia, due to availability of gold in vast areas of that region. It may be said that ancient Indians designated the countries of Indo-China and Malaya Archipelago viz. Burma (Mayanmar), Thailand, Malayasia, Laos, Cambodia, Vietnam and Indonesia, by the general name *Suvarṇabhūmi* or *Suvarṇadvīpa*[26].

The earliest place names in ancient Indian literature, which can be identified with some locations in South-East Asia, are *Yavadvīpa*, *Suvarṇadvīpa* and *Rupyakadvīpa*, which occur in the fourth canto of the *Rāmāyaṇa* (4.40.30):

yatnavanto yavadvīpaṁ saptarajyopaśobhitam |
suvarṇarupyakadvīpaṁ suvarṇākaramaṇditam ||

These islands were stated to be situated in the eastern direction of India, and contained gold mines. The *Arthaśātra* of *Kauṭilya* refers to *Suvarṇabhūmi*, where *Kāeyaka* sandalwood was obtained:

kāleyakaḥ svarṇabhūmijaḥ snigdhapītakaḥ |

(2.27.11)

Kauṭilya has also used a word *Pārasamudra* for denoting collectively all the countries and islands overseas, as he has designated the pearls obtained from there as *Pārasamudraka*:

maṇiḥ kauṭo māleyakaḥ pārasmudrakaśćā |

(2.27.11)

Suvarṇabhūmi and *Suvarṇadvīpa* are much referred to in the *Jātaka* literature (3rd century B.C.), and a variety of stories related to the voyages between India, and *Suvarṇabhūmi* and *Suvarṇadvīpa* together with the difficulties faced during voyages and the availability of riches, including gold, are stated. The *Sussondi Jātaka* describes the sea voyage of Sagga along with certain merchants of Bharukaccha to *Suvarṇabhūmi* - Golden Land. During the voyage, his ship broke in two pieces, and *Sagga* lying on a plank was carried along by wind till he reached the *Nāga* islands. The story of the sea voyage of seven hundred merchants along with *Suppāraka* from the sea port of Bharukaccha is mentioned in the *Suppāraka Jātaka*. The ship passed through various seas, such as *Khuramāla*, *Aggimāla*, *Dadhimāla*, *Nīlavannakuśa-māla*, *Nalamāla* and *Valabhāmukhi*. The merchants returned to Bharukaccha along with treasures of gold, silver, emerald, coral and diamond. It is stated that the *Aggimāla* sea (area nearby *Aggimāla* sea) had abundance of gold, and the merchants got a haul of gold from it. The *Mahājanaka Jātaka* describes the story of *Mahājanaka*, who was the son of the King *Ariṭṭthajanaka* of *Mithilā*. King *Ariṭṭthajanaka* was killed by *Polajanaka*, and his kingdom was lost. *Mahājanaka* wanted wealth for the purpose of recapturing his lost kingdom. He proceeded on sea voyage to *Suvaṇṇabhumi* (*Suvarṇabhūmi*) together with stock-in-trade, for getting great riches from there. The mother of *Mahājanaka* also warned him about the many dangers associated with the sea voyage to *Suvarṇabhūmi* in the story.

The *Mahāniddesa*, composed in the middle of the 3rd century B.C., mentions the names of *Suvaṇṇakūta* (*Suvarṇakūta*) and *Suvaṇṇabhumi* (*Suvarṇabhūmi*). Similarly, the *Milindapañha* (Questions of Milinda), composed in the 1st - 2nd century B.C., has also mentioned *Suvaṇṇabhumi* (*Suvarṇabhūmi*):

"*.........vangaṁ takkolaṁ ćīnaṁ sovīraṁ suratthaṁ alasandaṁ kolapaṭṭanaṁ suvaṇṇahāmiṁ gaćchati,....*"

(*Anumanapañha*, 4.2.16)

Literature has been justly regarded as the echo of the national life. It is apparent that gold was available in the South-East Asia and was brought to India from there through trade and expeditions, since pre-Christian era. The importance of South-East Asia as a major source of gold continued even throughout many more centuries after the Christian era.

8. PRODUCTS OF GOLD

A number of products made of gold were produced and used in ancient times. Some of the important products are described below.

8.1 Ornaments

One of the most important applications of gold in ancient India, which still persists in the modern times, was in the manufacturing of ornaments. In the Vedic literature, a large number of ornaments have been mentioned which shows the antiquity of ornaments in India. The names of some common ornaments as mentioned in the Vedic literature are as follows:-

(a) Ornaments worn on head – *śipra, sraja, sraga, opasa, śringa, kurīra*

(b) Ornaments worn on ears – *karṇaśobhana, karṇa, pravarta, prākāśā, kunḍala, karṇaveshṭaka*

(c) Ornaments worn on neck – *nishka, rukma, atkā, mālya, grīvāsūtra*

(d) Ornaments worn on hand and fingers – *bhujī, khādihasta, ānūka, hiraṇyapāṇi, hiraṇyabāhu, aṅgulīya*

(e) Ornaments worn on waist – *nyocinī, varuṇapāśa, rāsanā, nināha, mekhalā, rāśnava, yoktra*

(f) Ornaments worn on legs – *nūpura*

Many ornaments have been mentioned along with the qualifying word for gold, meaning that these were made from gold. In the present discussion only these ornament names are considered, although other ornaments were also made from gold.

The *Ṛgveda* (2.24.3) mentions *śipra*, which is an ornament put on the head like a hat. In the following reference this word has been used in conjunction with the word *hiraṇya*, meaning that it was made from gold:

ukchante aśvāṁ atyāṁ ivājishu nadasya karṇaisturayanta āśubhiḥ |
hiraṇyaśiprā maruto davidhvataḥ pṛakchaṁ yātha pṛishatībhiḥ samanyavaḥ ||

Karṇa was a type of ear ring made from gold, as mentioned in the following hymn of the *Ṛ*gveda (1.22.14):

hiraṇyakarṇam manigrīvamarṇa stanno viśve varivasyantu devāḥ |

aryo giraḥ sadya ā jagmushīro srāśćākantūbhayeshvasme ||

Another gold jewellary worn on ears was *prākāśa*:
hirṇyaprākāśāvadhvaryāh |
(Āśvalāyana Śrautasūtra, uttara, 3.4.12)

Nishka was an ornament widely referred to in the Vedic and Classical Sanskrit literature, and was like a necklace. *Nishka* has been used in two senses. It signifies a necklace and also a coin. *Nishka* denoted a necklace because it consisted of nishkas - the gold coins. It was made by strewing gold coins along a thread by passing it through the holes provided on the coins. Such type of necklace made from silver coins is still being used by tribal women of Madhya Pradesh. The *Ṛgveda* has a large number of references for nishka:

ā śvaitreyasya jantavo dyumad vardhanta kṛishtayaḥ|
nishkagrīvo bṛihaduktha yenā madhvā na vājayuḥ||
(*Ṛ*gveda,5.19.3)

In the following hymn of the *Atharvaveda* (20.131.5) the word nishka has been used along with qualifying word for gold, meaning clearly that nishka was made from gold:

śatamāśvā hiraṇyayāḥ | śataṁ rathyā hiraṇyayāḥ |
śataṁ kuthā hiraṇyayāḥ | śataṁ nishkā hiraṇyayāḥ||

Rukma was another widely used ornament, which was put near the chest like a locket, as stated in the following hymn of the *Ṛ*gveda (2.34.2);

dyāvo na stṛibhiśćitayanta khādino vyamriyā na dyutayanta vṛishtayaḥ |

rudro yadvo maruto rukmavakchaso vṛishājāni pṛiśnyāḥ śukra udhani ||

The following verse of the *Śatapatha Brāhmana* (6.7.1.1-2) clearly states that *rukma* is made from gold:

rukmaṁ pratimuććya bibhartti | satya haitadyadrukma satyaṁ kva aitaṁ yyantumarhati satyenaitaṁ devā abibharu satyenaivenamet-advibhartti || tadyattattsatyaṁ | asau sa ādityaḥ sa hiraṇmayo bhavati jjyotirvvai |

There is a mention of an ornament named *sraga*, which has been used along with the word for gold, i.e. *hiraṇyasraga* in the *Atharvaveda* (10.6.4). This ornament was similar to a garland made by stringing beads of gold in a thread. This was worn on the top of the head. Another word *hiranyasraja* has also been used to denote a similar ornament in the *Śathapatha Brāhmaṇa* (5.4.5.22).

The gold rings worn on fingers have been denoted by the word *hiraṇyapāṇi* in the Ṛgveda (1.22.5 and 1.35.9). This ornament has also been stated in the *Vājasaneyi Saṁhitā* (22.10) -

hirṇyapaṇimūtaye savitāramupahvaye |
sa ćetta devatā padam | |

8.2 Images and Idols

Gold images and idols were in vogue in ancient India. The *Ṛgveda* has mentioned a few references, which may be taken as a proof of image or idol making in the beginning of the Vedic period. The *Ṛgveda* (4.24.16) has given an indirect reference to the image of god Indra when it states that who would buy Indra (image) with ten cows -

ka imaṁ daśabhinnamendraṁ krīṇati dhenubhiḥ |
yadā vṛitrāṇi jaṅghanadathainaṁ me punardadat | |

Similarly there is another reference to the image of Indra in the Ṛgveda (8.1.5), wherein it has been stated that the image of god Indra should not be bartered with one thousand or ten thousand or even immense wealth:

mahe ćana tvāmadrivaḥ parā śulkāya deyām|
na sahsrāya nāyutāya vajrivo na śatāya śatādhama | |

From these references, it is not clear as to which material was used in making these images. However, Vedic texts of later period such as the *Śatapatha Brāhmaṇa* and the *Taittrīya Saṁhitā* have mentioned gold images. In the *Śatapatha Brāhmaṇa* (7.4.1.15), a reference has been made to a gold image of a man (*hiraṇya puruṣa*), which was placed in the foundation of the altar in a particular rite:

atha puruṣamupadadhāti | sa prajāpatiḥ soagniḥ sa yajamānaḥ sa hirṇmayo bhavati......... |

With the advent of "*bhakti*" cult, the making of religious images or idols from a variety of materials including gold, got an impetus. The *Rāmāyaṇa* has an important reference on the gold image when it is stated that at the time of the performance of the *aśvamedha* sacrifice by Lord *Rāma*, a gold image of *Śītā* was substituted for her, because she was then in exile in the hermitage of *Vālmīki* (*Uttara Kāṇḍa*, 91.25, & 99.8) :

kāñćanī mama patnīṁ ća dīkshāyāṁ jāṅśća karmaṇi |

and,

yagñe yagñe ća patnyarthaṁ jānakī kāñćanībhavat |

8.3 Utencils and other products

The *Ṛgveda* has mentioned pots, known as "*kalaśa*", made of gold (1.117.12), which was used for storing different kinds of fluids, to be used primarily for religious rites. Similarly, another product known as *kośa*, made of gold is also mentioned, which was used for storing valuable goods (9.75.3). The *Rāmāyaṇa* (5.11.5, 6.112.12 and 5.1.23) has also described various utensils made of gold, viz pots such *kalaśa* and *kamanḍalu*, and wine glass. Lamps and royal canopy made of gold have also been stated in the *Rāmāyaṇa* (5.10.29, 5.18.12 and 14).

8.4. Coins and Metallic Currency

In the Vedic literature, the word *nishka* has widely been referred to. *Nishka* has been used in two senses. It means a coin and also a necklace. There is a reference in the *Ṛgveda* (1.126.2), where one hundred *nishkas* along with other things were bestowed upon *ṛishi Kakchīvat* by King Bhavayavya, which here means *nishka* coin only and not necklace. Bhandarkar[27] has rightly argued that it was customary to present one necklace to a *ṛishi* or priest, and presentation of one hundred necklaces could not be intended for the personal ornamentation of a single individual i.e. *ṛishi* or priest. In the *Atharvaveda* (20.131.5), a reference to one hundred *nishkas* (coins) of gold has been made. Again, in the *Atharvaveda* (7.99.1), it has been stated that the *nishka* (coin) was made of gold. The question arises as to whether the *nishka* was a coined money or unmarked currency. Thomas[28] has quoted a very important reference from the *Ṛgveda* (2.33.10), which points towards the fact that the *nishkas* have markings on the surface. The hymn in question is:

arhanvibharshi sāyakāni dhanvarhannishkaṁ yajataṁ viśvarūpam |

The god Rudra, to whom this hymn is addressed, is described as wearing a *nishka* i.e. necklace made from *nishka* coins, that was *viśva-rūpa*. Thomas[28] has translated *viśva-rūpa* as "covered with forms or symbols". The composer of the hymn means that the necklace worn by god Rudra was made from *nishka* coins having impressions of various *rūpas* or figures on the surface, and thus the necklace was naturally *viśva - rūpa*, i.e. covered with manifold *rūpas* or figures. Thomas has drawn a parallel between the above description of *nishka*, having various marking or figures surface with the Burnouf's reference to the description of stamped nature of the dinar coins in the following passage:

"*lakshanāhatam dīnāra dvayam*" - ("deux dinars marques de signes")

In fact gold currency without any marking was also not unknown in the *Ṛgvedic* period. There is a mention of the fact that a *ṛishi* received a gift of 10 pieces of *hiraṇya piṇḍa*, i.e. gold in roundish shape, along with other things from the king *Divodāsa*.

Thus it can be seen that both the marked and unmarked coins of gold were current during the *Ṛgvedic* period. Bhandarkar[27] has assumed that these markings were obtained by stamping on solid pieces.

Other Vedic literatures and the texts of later period have also referred to the gold coin *nishka*. For example, the *Śatapatha Brāhmaṇa* (11.4.1.8) has stated that *nishka* was made of gold. In the *Rāmāyaṇa* (2.70.21) a mention of two thousand *nishkas* of gold has been made. The *Kuhaka Jātaka* has also referred to one hundred *nishkas* of gold - *suvaṇṇanikkhasataṁ*. Similarly the *Junha Jātaka* (4.97) has also mentioned about *nishkas* of gold - *paro sahassa suvaṇṇanikkhe*.

Pāṇini (5.2.1.19) has also referred to one hundred and one thousand *nishkas*.

śatasahasrantāćća nishkāt |

Agrawal[29] has quoted the commentary given by *Kāshikākāra*, in which he asks the question as to why the word 'gold' should not be added before one hundred *nishkas* and one thousand *nishkas*, so as to make it very clear that the *nishka* was made of gold. *Kāshikākāra* has himself given the answer by saying that it is not the practice in the society, as there is no need of adding unneccessarily the word' gold' before *nishka* when it is well known that *nishka* is made of gold. *Pāṇini* (5.2.120) has clearly referred to the process of coining in the following *sūtra*, which states that the coins which have been punch-marked are called *āhata* coins:

rūpadāhatapraśaṁsayoryarpa |

Bhandarkar[27] has stated that there were other gold coins such as *śātamāna*, *suvarṇa*, *pāda* and probably *kṛishṇala* in the Vedic period. In the post -Vedic epoch, another coin named *kārshapaṇa* has been referred to, which was made of gold, silver and copper. However, gold *kārshapaṇa* was seldom referred to.

It is important to note that the names of coins are also names of metal weights. The smallest unit was *rattī*, which was the seed of the wild Licorice (*Abrus precatorius*). After the *rattī*, the second unit in ascending order, was the *māsha*. Unlike *rattī*, this is a cultivated bean, which has been identified with *Phaseolus radiatus*. According to Manu[30] (8.134-135), the following is the list of weights used for weighing gold:

(a) 5 *rattī* = 1 *māsha* (8.75 grs troy)

(b) 80 *rattī* = 16 *māsha* = 1 *suvarṇa* (140 grs Troy)

(c) 320 *rattī* = 64 *māsha* = 4 *suvarṇa* = 1 *pala* or *nishka* (560 grs Troy)

(d) 3200 *rattī* =640 *māsha* = 40 *suvarṇa* = 10 *pala* or *nishka* = 1 *dharaṇa* (95600 grs Troy)

In the first instance, it may appear that the inclusion of the smaller kinds of seed grains in the above table have been purposeless, but Thomas[28] has argued that dealings involving infinitesimal amount of gold or gold dust would not have been uncommon in an era when the people were just emerging from the primitive state of barter. This suggests that the naturally occurring alluvial placer gold in the form of dust would have been an ideal material to be used as gold currency of smaller denominations. However, it does not preclude the possibility of using such gold dust in larger quantity as gold currency of higher denominations. There are several examples in the history suggesting the use of gold powder/dust as currency in various periods. According to Herodotus[31], Darius received 360 talents in gold dust as the annual tribute from his Indian province:

"..........The Indians made up the twentieth province. These are more in number than any nation known to me, and they paid a greater tribute than any other province, namely three hundred and sixty talents of gold dust".

(Herodotus, Book III, 94).

Thus in the sixth century B.C. the gold dust served the purpose of currency[32]. Traill[33] in his statistical report on the Bhotia Mehals of Kumaon in *Himālayas* prepared in around 1830 AD has stated that weighed quantities of gold dust tied in pieces of cloth were current as currency in the region of Kumaon. Traill quotes:

"Gold is calculated (measured) by the '*Sarswo*' or '*Phetang*' equal to seven and a half *māśas*. Gold dust separated into *Phetangs*, each tied up in a bit of cloth, is current as coin at eight rupees the *Phetang*".

8.5 Medicinal Formulations

Gold in the form of very fine powder or dust was used in making various types of medicinal fomulations. The *Āśvalāyana Gṛihya Sūtra* (1.13.1) mentions that when a child is born, the father should feed him a mixture of clarified butter, honey and gold dust. This was prepared by rubbing a piece of gold on a touchstone along with honey and clarified butter:

kumāraṁ jātaṁ purānyairālambhāt sarpirmadhunī hirṇyanikāshaṁ hirṇyena prāśayet pra te dadāmi madhuno ghṛitasya vedaṁ savitrā prasutaṁ maghonam |

This rite, known as *jātakarma* was performed for the sake of longevity and promotion of intelligence in the child. It should be noted that only a minute quantity of gold dust was used for the above ceremony. A similar reference is also available in the *Manusmṛti* (2.29):

prāṅganābhivardhanātpuṁhso jātakarma vidhīyate |
mantravatprā śanaṁ ćāsya hirṇyamadhusarpishām ||

Suśruta[34] (*Śārīr.* 10,12) has also prescribed that the newly born child should be administered a small amount of gold powder along with honey and clarified butter:

atha kumāraṁ śītabhiradbhirāśvāsya jātakarmaṇi krite madhusarpiranantaćūranamaṇgulya nāmikayā lehayet |

Suśruta (*Śārīr.* 10.72-74) also gives four formulations for tonics to be prescribed to children; each of which contains well prepared fine gold powder as an important ingredient:

sauvarṇaṁ sukṛtam ćūrṇaṁ kushṭhaṁ madhu ghṛtaṁ vaćā |
matsyākṣakaḥ śaṅkhapushpī madhu sarpiḥ sakāṅćanam ||

arkapushpī madhu ghrtaṁ ćūrṇitaṁ kanakaṁ vaćā |
hemaćūrṇāni kaiḍaryaḥ śveta dūrvā ghṛtaṁ madhu||

ćatvāro bhihitaḥ prāśāḥ ślokārdheshućtashvapi |
kumārāṇāṁ vapurmedhā balabuddhivivardhanāḥ ||

Although *Suśruta* has stressed in the first formulation that the gold powder must be well prepared, it is also implicit in the other three formulations. By the term "well prepared", *Suśruta* perhaps means that the gold powder must be sufficiently fine to be suitable for oral application.

Another interesting medicinal formulation containing gold dust in ancient India was in treating the effect of poison. *Ćaraka*[35] (*Ćikitsā*, 23.10-14, 234-236) classifies various types of poisons, of which '*gara*' poison is an artificial poison prepared by treating two or more substances. The *gara* poison is slow in action and the person who has consumed it does not die immediately. The effect of *gara* poison on human bodies is that it produces a variety of ailments such as high fever, jaundice, weakness, increased heart rate, poor digestion, etc. *Ćaraka* (*Ćikitsā* 23.239-240) prescribes a treatment to overcome the effect of this type of poisoning, which consists of feeding a small amount of very fine copper powder along with honey to the patient. As a result the patient vomits and the undesirable elements are removed from the patient's body. Subsequently, the patient is given a small amount of fine gold powder along with honey.

This helps in counteracting the ill effects of all types of poison, including *gara* poison. *Ćaraka* gives an interesting similie for the use of very fine gold powder for treating the effect of poison on human beings. He states that as water droplets do not stick or stay on the lotus leaves, so there is no effect of poison on those who take very fine gold powder. The relevant passage from *Ćaraka Samhitā* (*Ćikitsā*, 23.239-240) relating to the use of very fine copper and gold powders for the treatment of *gara* poison is as follows:

sūkśmaṁ tāmrarajastasmai sakṣsaudraṁ hṛdiśodhanam |

śuddhe hṛdi tataḥ śāṇaṁ hemaćurṇasya dāpayet | |

hema sarvaviṣāṇyāśu garānśćā viniyaććhati |

na sajjate hemapāṅge vishaṁ padmadalembuvat | |

Some hymns of the *Śukla Yajurveda* and the *Atharvaveda* imply that the use of gold powder to promote longevity and better physical strength was practiced much earlier than the times of the *Āśvalāyana Gṛihya Sūtra*, *Manusmṛti*, and *Suśruta Saṁhitā*. It is mentioned in the *Śukla Yajurveda* (34.50) that gold (powder) leads to longevity:

āyushyaṁ varćasvaṁ rāyasposham audbhidam|

idaṁ hiraṇyaṁ varć asvajjaitrāyāviśatādu mām| |

The above hymn implies that gold was used for oral applications in powder form. Similarly, it has been stated in the Atharvaveda (1.35.2-3), that those who take gold (powder) attain longevity and better physical strength.

A wide variety of manufacturing processes, such as casting, hammering, drawing, bending, shearing, punching and joining were used to produce the above mentioned products.

9. SUMMARY AND CONCLUSIONS

In the present paper an attempt has been made to trace the history and metallurgy of gold in ancient India mainly from some important literary sources composed before the beginning of the Christian era. From the foregoing discussion it is apparent that India has a very old and rich history of gold. A large number of names for gold are available in Sanskrit language, many of which are not in use in modern times. However, a study of these names gives historical information about gold. In ancient times there have been two important sources of gold, namely banks and bed of rivers, and mountains, having alluvial placer deposits, and reef and vein deposits respectively. In addition, there was another interesting source of gold, which was in liquid form. Special liquids flowing through the holes and fissures of some mountains were also found to contain gold in dissolved form, and these may be considered as ' liquid ore' of gold. Although *Kauṭtilya* has given a detailed description of such special liquids containing gold, there is a mention of such liquids in *sūtra* (concise) style even in the *Atharvaveda*.

Alluvial placer gold was known as early as the time of the *Ṛgveda*. It is not surprising since the Vedic civilization was river based. It is reasonable to believe that alluvial placer mining of gold started first followed by open-cast mining in mountains. Later, deep mining of gold must have started. There are archaeological evidences to suggest that during the fourth century B.C. mining of gold in Hutti area of South India was very much in practice. Deep mining of gold was also practiced there. As a result, the "Southern" route became an important source of gold and its product in those times. It must be recognised that all the types of mining of gold must have been in vogue concurrently in different parts of the country. Panning was the most important process of separating gold particles from the sand gravel obtained either from alluvial placer or crushed lode deposits. Some archaeological evidences suggest that amalgamation process was used at some stage of the extraction of gold as early as during first century B.C. in the Hutti area in India.

Different forms of gold refining were in practice in ancient times, e.g. refining by lead and solid state refining. The roots of these processes are available in the Vedic literature. *Kauṭilya* has given a detailed account of gold refining in his famous *Arthaśāstra*. *Kauṭilya* has proposed refining of gold both in molten and solid states. For both run of mine gold ore concentrate and recycled gold, the refining in molten state was carried out by the addition of lead. As a result most base metals were removed from the gold. For removing silver present in the gold, *Kauṭilya* proposed solid state refining using a mixture of salt and soil. Some archaeological evidences suggest that the refining of gold by mercury was in practice in ancient India.

The literary data suggests that the *Ṛgvedic* age had an abundance of gold and a diversified type of gold products were manufactured and used, which continued and progressed in subsequent periods. This required the competency of the Vedic people in various manufacturing processes such as casting, hammering, shearing, punching, engraving, etc. A wide variety of gold ornaments were manufactured in ancient times as revealed from literary evidences. Images, idols, utencils and other goods used in household and religious rites were also manufactured from gold. It is believed that marked gold coin, namely *nishka*, was current during the *Ṛ*gvedic period. The use of fine gold dust for medicinal applications dates back to Vedic age, which became much more prevalent in subsequent periods.

The great epic *Mahābhārata* has referred to the *Pipīlika* or Ants' gold. This was a high purity and fine size gold powder obtained by panning the auriferous soils collected from ant -hills formed by the real ants on the land containing alluvial placer deposit in the *Meru* and *Mandāra* mountains region.

Suvarṇabhūmi and *Suvarṇadvīpa* were popular names in some ancient texts, which were given initially to some specified parts of the present South -East Asia, and subsequently the countries of Indo-China and Malaya Archipelago were collectively known by it. In ancient times, gold was brought to India from *Suvarṇabhūmi* and *Suvarṇadvīpa* through expedition, trade and commerce.

The present account of the history and metallurgy of gold from earliest times till the beginning of the Christian era is restricted to a few important texts, and much more study is needed in this area, which may bring out some more interesting facts about gold in those times.

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OVERVIEW

BRONZE ICONS

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ABSTRACT

Art objects are scientific marvels which reflect the history, tradition and cultural heritage of a country. Investigations on art objects are undertaken for scientific and comprehensive fingerprinting and authentication and also to help in restoration/conservation. One of the outstanding art objects of India is the South Indian Bronzes. Famous for their aesthetic beauty, iconometry, iconography, and casting quality of high order, they are standing examples of the fusion of technology with cultural traditions. This paper outlines the lost wax process used for making these bronzes and also the results of the non-destructive analysis carried out on more than 100 rare South Indian Bronzes. Radiography revealed the presence of porosities as the major defects while X-ray fluorescence revealed that copper is the major constituent of all icons with additive elements such as Sn, Pb, and Fe present with varying compositions. Microstructural studies revealed the presence of large pores and cavities combined with gray phases and globular particles. Analysis also revealed that the ancient science and technology of casting the icons was rather qualitative, empirical and adhoc with rather small amount of theoretical underpinning.

1. INTRODUCTION

Benjamin Rowland, rightly pointed out that " .... Indian Art of all periods is close to life, not only to the life of the Gods but to all creatures on Earth....Although the proportions, pose and gestures of an image were unquestionably based on a strict metaphysical canon designed to ensure its fitness as an object of worship, within this framework the figure was made with an understanding of actual human anatomy, not only in its general articulations, but also in the maker's concern with connoting the essential character of the flesh in terms of stone or bronze...". Thus of all the metallurgical accomplishments of South India, the bronze icons are among the finest artistic treasures cherished by national, international and private antiquarians around the world. Famous for their aesthetic beauty, iconometry, Bronzes are excellent examples of the fusion of technology with cultural traditions. The objective of this paper is to provide the readers with

(a) an outline of the ancient casting practice followed by the sthapathis,

(b) take a comprehensive look at the results of the scientific investigations using NDE techniques carried out by the authors on more than 100 icons belonging to the Pallava, Chola, Vijayanagara and modern periods,

(c) elucidate certain misnomers with respect to the composition of bronzes and

(d) highlight the fact that in spite of the heuristic approach, empirical procedures and very limited tools, our ancient master craftsmen had been able to achieve very sound castings.

2. THE MAKING OF AN ICON

The icons (solid or hollow) were made by '*Cire Perdue*' or ' lost wax' process. *Cire* in French means 'wax' and *perdue* means 'lost'. The process in ancient Hindu scriptures, such as *Manasara,* has been referred to as *madhuchchista vidhanam* (*madhuchchista* means bees' wax). The wax model prepared according to the *Agamic sastras*, served as the core of the operation and was 'lost' or drained out before the actual casting took its form after the model.

Each and every icon is made in full accordance to the *shilpasasthras* (texts that grammatically define the form and style of the icons)[1].

The *shilpasasthras*, give a broad outline of how each God or Goddess is cast into icons. They mention usually about the macro-features of the idol. The micro-features of the idol, such as the type of clothing, type of hair style, the standing or sitting posture, the style of displaying wrists, palms and hands (known commonly as the *hasthas*), the look on the face, expression of emotion, etc. are entirely left to the imagination of the artisan. If one scans a number of bronze icons made during this ancient period, it is this aspect that speaks about the cultural and technical excellence of any artisan. However, it is a commonly accepted fact that sthapatis belonging to one particular school of casting tend to cast icons in a particular fashion, that helps us in categorising the styles and finding the period or age of the icon.

The various sequential steps in the lost wax casting, as practiced by the ancient sthapatis are listed below :

a. Making of the odiolai

b. Preparation of the wax

c. Getting ready the wax model

d. Making the mould over the wax model

e. Heating the mould, melting and draining the wax

f. Getting ready the liquid metal alloy and heating the mould to higher temperature

g. Pouring the liquid metal alloy inside the mould

h. Cooling the mould and opening it

I. Bringing the cast icon outside followed by finishing, engraving and polishing and

j. Installation and opening of the eyes of the icon.

Step (j) is carried out, in case, the icon is to be worshipped. The sthapatis have developed over a period of time, a heuristic relationship between the amount of wax used in making the wax model and the amount of molten alloy that needs to be used for making the icon. That no other analytical relationships are used for this purpose, is a testimony to the empirical expertise of these sthapatis. Similarly the heating up of the clay shell to a specific temperature (which is usually not measured), before pouring the molten alloy, speaks of the qualitative yet comprehensive empirical knowledge of ancient sthapatis. These ten steps in the making of the cast icon, are exactly the same as practiced in Swamimalai a small town in Tamil Nadu today with minor variations between the methodologies and those prescribed in the *Shilpasastra* texts . These variations are not much in the actual method of casting, but on the rituals to be performed, before, during and after casting. A detailed stepwise description of the casting process can be had from ref. 2. A brief outline of the same is also presented in the paper by Pillai et al.[3] published in this special issue of the journal.

3. STYLES, INTRICACIES AND FORM

These ancient south Indian bronzes bear the mark of classical tradition in smooth modelling, aesthetic decoration and high proportions. One of the most striking aspects of these bronzes is the true and authentic representation of human and animal anatomy, and other accessories to the last detail. The expertise of the *sthapatis*, in bringing out the finer details of each part of the icon has been much appreciated, and is the prime reason for the value of these icons.

The initial wax mould of every icon is made with great care, with due attention to the structure and size of its parts. For each of the parts, an empirical association is made, which intuitively suggest to the artisan as to how the final proportion of the part should look like. These empirical associations are based on keen observations on the human (or animal, as the case may be) anatomy, with a purpose of replicating the part to the last perfect detail. For example, when a *Kannagi* statue was cast for worship, traditional descriptions of the icon were not available and the *sthapati* made a number of models based on his imagination and in tune with the features described in literature. From these models, one of them was chosen for the final wax model. These associations are called *lakshanas* and there are 32 of them mentioned in the *Agama Sastras*. However, these associations are not scriptural constraints but offer the artisan a broad yet accepted guideline. The last word in any such representation of a part lies with the artisan himself offering him the highest manoeuvrability of his creative genius. These associations, for some of the human parts are given in Table 1. The Tamil names of various terms are given in italics.

The most important aspect that gives a unique signature to any icon, and its style, is the fact that each casting process is non-repeatable, since both the wax model and the clay shell are lost forever, after each icon is cast. It is because of this fact, that it is impossible to find two icons (cast in this process) to be identical. Each icon thus becomes a designer icon. Hence the method is also called the master technique. The making of images in this process is indeed laborious. But the importance of this method cannot be overestimated when it is realised that each item is characterised by a rare individuality and provides the possibility of continuous improvement, aesthetics and technology - a hallmark achieved by ancients as a matter of course and being advocated by modern quality management gurus like "Deming", "Taguchi" or "Joseph Jurian".

4. CHOICE OF THE ALLOY - WHY BRONZE ?

An interesting aspect about the icons under study is that most of them have been cast only in bronze. The reason for this could be many, the most important being [a] castability, [b] workability after finishing the casting, [c] polishability, [d] melting point of the

Table 1
VARIOUS EMPIRICAL ASSOCIATIONS OF THE PARTS OF AN ICON

The Part / The Icon	The Association or the *Lakshana*
Leg (particularly those of females)	*Kendai* Fish
Lord Shiva's face	Hen's Egg
Lord Vishnu (S) 's face	Duck's Egg
Kataka Hastam (*Hastam* is the representation of the human palm and fingers, specifically in the dance postures; these are also called *mudras*	Crab
Nose	Gingily (*Thuthi*) Flower
Upper Lip	Bow
Lower Lip	*Kovai(T)* Fruit
Eye brows	Neem Leaf
Eyes	Fish
Ear	Lily Flower
Chin	Mango Stone
Neck	Conch Shell
Thighs	Banana Tree Trunk
Knee Cap	Crab
Shoulders	Elephant's Trunk or Banana Tree Trunk
Male figure / torso	Bull's Face
Female figure / look	Deer's figure and looks

alloy (requirement of large quantity of molten alloy) and of course [e] availability of raw materials, ore, etc.

From the sthapati's point of view, cast ability, workability, polish ability and melting point should have been the overriding factors. The shine what one gets in bronze is generally not available in brass and other alloys that were prevalent in those times. This also should have been a major reason for choice of the alloying additions for obtaining the desirable results.

The other important reason is the scriptural command of the Agamas, that prescribe metal to be used for casting idols for worship. For example, the ancient text Agnipurana states[4] that "one (image) made of wood gives greater merit than what is made of clay; one made of terracotta yields greater than a wooden one; one made of stone yields greater than (one) which is made of terracotta; images made of gold and other metals yield the greatest religious merit."

4.1 Composition of the Alloy - The Specifications

Though the term 'bronze' icons is used throughout the monograph, it must be mentioned that chemical analysis of the icons by the present and various other authors have shown that this usage may not be acceptable from a purely metallurgical viewpoint. Typical variations in composition is shown in Table 2[5].

It is to be noted here that the tin content of the icons are insignificant in some cases. The significance of the metal objects examination was the trace element analysis which was considered to play an important role in the technical excellence and finding the origin and age of the bronzes. However, Dr. Hall of Oxford University points out as "our experience at Oxford, in this field, tended to show that such analyses are a waste of time"[6]. This was so because extensive melting and reuse of scrap leads to a blurring of trace element identity. Most of the samples are taken from or near the surface, and the expected drawback of such analyses is that with passage of time, the composition of alloying elements vary at the surface due to their extensive interaction with the surroundings. All the above points make the characterisation study of the icons a very delicate and difficult job to be carried out.

At this juncture, it must be noted that in Tamil, majority of these icons are referred to as '*Cheppu Thirumaenigal*', meaning icons made of copper ('*Cheppu*' in Tamil means copper and not bronze). Bronze is known as '*Vengalam*' in Tamil. The *sthapatis* no doubt knew the existence of bronze alloy. If this is the case how did the term bronze icons come into force ? We infer that the term 'bronze' icons is a misnomer, used universally to refer to these ancient south Indian icons. However, in the absence of an uniform nomenclature, the colloquial term 'bronze' is universally used to represent even icons made with varying compositions and we follow the tradition.

It is also mentioned[7] that the *Agamas* mention the use of only gold, silver or copper for casting icons, and that most of the early bronze icons were made of either reddish or golden copper, with copper content being more than 90%. The quality and quantity of copper used declined from about 14th century A.D., with the knowledge of a number of alloying additions for achieving the desired characteristics of the icon.

Later, icons were also cast using '*Panchaloha*'. This term is derived from sanskrit in which "*Pancha*" means five and *"loha"* means metals. *"Formerly, these consisted of the following metals which were considered to be auspicious - copper, silver, gold, brass and lead. It is to be mentioned that brass is referred to as metal as copper and zinc were co-extracted as one entity. Gradually however, gold and silver were deleted for obvious economic reasons, although even today a client may commission an image to be cast in the original five metals for special devotional purposes"*[8,9]. The quantities of metal, wax and other raw materials required for each icon, depend on the size of the icon and are listed in Table 3. According to the empirical approaches developed by these *sthapatis*, for every gram of various materials required to produce the wax model, 8 grams (gms) of alloy were required (7.25 gms copper, 0.5 gms brass and 0.25 gms lead).

The bronze icons that are cast using the *lost wax* process can be classified broadly into two categories: those that are used (to be used) for worshipping and or *pooja* purposes and those that are cast mainly for ornamental purposes. The composition of the latter category is copper 82%, brass 15% and lead 3% [8],

Table 2
CHEMICAL COMPOSITIONS OF SOME ICONS[5]

Elements	9th century	13th century (Icon)	13th century (*Prabhavalli*)	16th century
Copper(wt%)	98.60	94.50	94.50	89.40
Tin(wt%)	0.88	1.10	1.80	3.40
Lead(wt%)	0.34	1.00	3.35	2.88
Iron(wt%)	0.13	0.05	0.10	0.52
Zinc(ppm)	15.00	40.00	103.00	2646.00
Antimony(ppm)	476.00	1747.00	5309.00	3095.00
Silver(ppm)	541.00	596.00	1659.00	823.00
Arsenic(ppm)	1295.00	1785.00	3341.00	1394.00
Nickel(ppm)	436.00	415.00	552.00	636.00
Bismuth(ppm)	85.00	164.00	503.00	351.00
Cobalt(ppm)	45.30	135.00	100.00	114.00
Manganese(ppm)	5.80	< 0.80	< 0.80	1.80
Total	**100.20**	**97.10**	**99.80**	**97.10**

whereas in the former category, gold and silver are added in proportions that are dictated by the *Vedas* and the *Agama Sastras*.

5. NEED FOR SCIENTIFIC INVESTIGATIONS

South Indian bronzes are scientific and art marvels which reflect the rich cultural heritage of our country. Scientific investigations on objects of cultural heritage are undertaken with a variety of objectives in mind. The most important of these include

1. Understanding the style, period, structure and metallurgy of these icons so that India's rich technological history is understood.
2. Assessing the condition of the icon to help in restoration and conservation

Table 3
RAW MATERIALS USED BY THE *sthapatis*

Category	Raw Materials
Primary Raw Materials (Metals and Alloys)	Copper, Brass, Lead, Tin, Zinc, Silver and Gold
Secondary raw materials (wax model preparation)	Bees' wax, dammar, paraffin wax, candle wax, groundnut oil and coconut oil
Tertiary raw materials (mould preparation and heating)	Charcoal, firewood, cowdung cake, metal wires, tamarind and clay

3. These bronzes famous for their aesthetic beauty and excellent craftsmanship are prone to thefts. These investigations help in scientific and comprehensive fingerprinting of icons needed for documentation and authentic identification when they are retrieved.

Scientific investigations of bronzes require an integrated approach. The most appropriate approach which can give solution to all the requirements is through the use of Non-Destructive Testing (NDT) techniques. NDT techniques as the name implies are techniques that have been developed to determine the quality of components without causing any harm or alteration to them. A variety of NDT techniques are available today, which are being successfully employed in various industries to assess the quality and ensure the integrity, safety and reliability of plants and components[10,11]. A few of these techniques have also been successfully applied for the investigation of objects of cultural heritage such as sculptures, paintings, monuments, etc. world wide[12,13,14,15]. Table 4 lists some of the major NDT techniques used for investigations on objects of cultural heritage and their capabilities.

In India, as part of the collaborative project between IGCAR, Kalpakkam and Govern,ment Musuem Chenai and funded by the Department of Science and Technology (DST), on fingerprinting of ancient South Indian *panchaloha* icons, a number of icons pertaining to the period between 9th century and 16th century AD belonging to the *Pallava, Chola* and *Vijayanagara* periods have been studied. Of the above mentioned NDT techniques, four had been identified as the major ones to be used for investigation, namely precision photography, X- and gamma radiography, X-ray emission spectrometry and in-situ metallography. While precision photography maps the overall icon and its intricate external features, radiography records the internal details, typical flaws and also provides information on the constituent and morphological elements and sequence of fabrication and repair. X-ray emission spectrometry provides information on the chemical composition of the icon while in-situ metallography characterizes its

Table 4

MAJOR NDT TECHNIQUES USED FOR AUTHENTICATION OF ART OBJECTS

Sl. No.	Techniques	Capabilities
1.	Precision Photography	Dimensions, measurements and record of intricate details
2.	Holography	3 - D Characterisation
3.	Moire Fringes	Contour Mapping
4.	Laser Excited Emission Spectrometry	Chemical Assay
5.	Mass Spectrometry	Chemical Assay
6.	Activation Analysis	Trace Analysis of elements
7.	X-Ray Energy Spectrometry	Chemical Composition
8.	IN-Situ Metallography	Microstructural Characterisation
9.	Radiography/Tomography	Internal Defects, Joints, Repair regions
10.	Physical Parameters Thermal Emf, Electrical Conductivity, Hardness	Characterisation of Material and Thermo-mechanical treatment

microstructure. Thus, on the whole, an icon is fingerprinted by the use of these techniques. Detailed analysis of these results also provides a deep insight into the metallurgical practices of yester years and helps to comment on many a misnomers on the basis of measurements and their analysis. The other techniques such as conductivity and hardness measurements lend a supporting hand in the investigations and lead to a better understanding and appreciation of the technology. In this paper, we present the results of the investigations carried out on more than 100 icons from the Govt. Museum, Madras. The Government Museum Chennai has the largest collection of South Indian Bronzes. Some of the rare bronzes investigated are shown in Fig. 1.

5.1 Results of NDT Investigations

5.1.1 Radiography

Icons are basically cast structures. During the process of casting, discontinuities or flaws are likely to be created due to a variety of reasons. Radiography is the best technique for the detection of internal features / flaws in castings. Depending on the casting process, the location of the defects if formed would be different in different icons. Thus, these defects can serve as authentic fingerprint of an icon. Duplication of these defects is not possible as the probability of the defect occurring in the same location and with the same geometric contours and area is extremely low if not zero. Apart from serving as fingerprints, the radiographs also serve as an indicator of the quality of the castings.

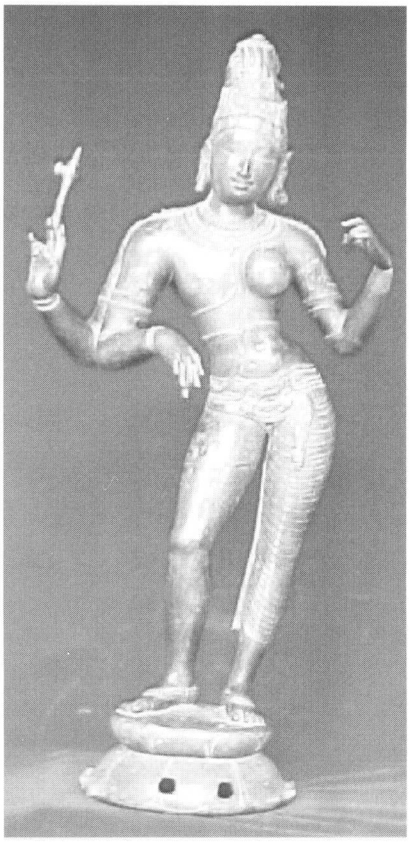
5.1.1.1 Experimental Technique

A typical icon has an intricate and complex shape with wide thickness variation and presents an interesting challenge to any radiographer. A wide range of radiographic parameters such as voltage, exposure, film types etc. are to be used to obtain the best possible radiographs. In the experimental campaign by the authors both X-ray and gamma ray sources were used. A 420 kV X-ray machine and a 200 kV X-ray machine were used for the examination of bronzes with a thickness range upto 50 mm while a Iridium 192 gamma source was used for the radiography of thicker bronzes such as Ardhanareswarar. Single wall single image technique was adopted in all the cases. To cover the thickness latitude present in the icons, multi film technique was adopted. Since the icons could be made available only for limited period of time (as they had to be removed from the Bronze Gallery), a novel multi exposure technique was adopted in which about 5 to 6 icons were exposed simultaneously. The radiographic parameters in this case had to be judiciously optimized for getting uniform densities on the radiographs.

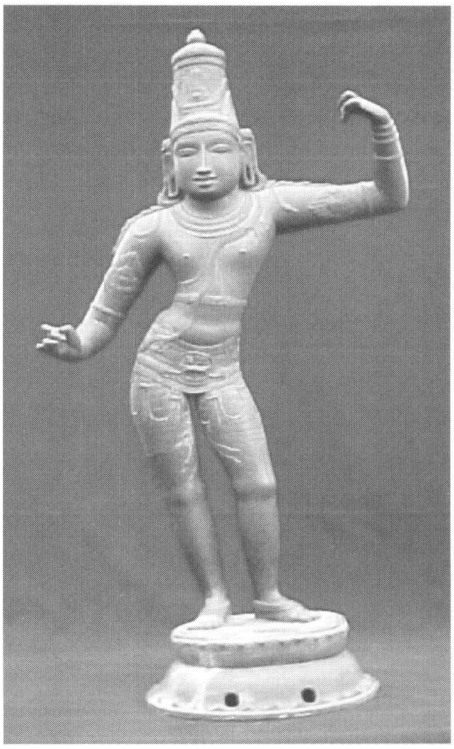
5.1.1.2 Results of investigations

Detailed analysis of the radiographs of all the icons reveal many common and interesting observations

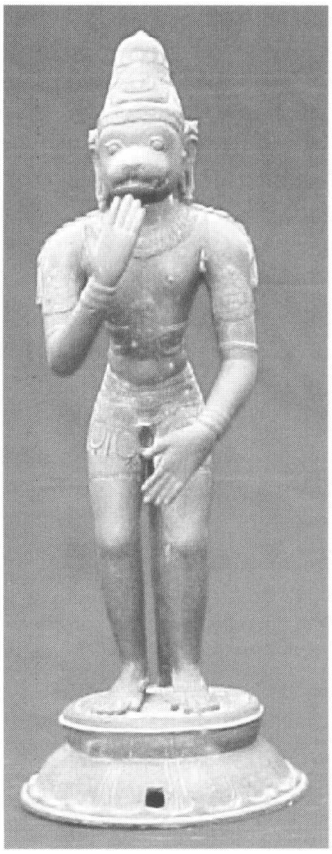
1. Most of the icons radiographed had very little defects in their main body. This is a pointer to the fact that the *sthapathis* of yester years had mastered the technology of lost wax process to perfection. This was also passed on by them to their next generation as revealed by the radiographs of the icons right from the 9^{th} century to till date.
2. Defects if any in an icon were mainly porosities. Typical size of pores and voids range from 0.1 mm to about 10 mm depending on the size of the icon. Figures 2 - 3 are typical porosities detected in some of the icons.
3. In practically all the bigger icons, it has been observed by radiography that the main body of the deity, the pedestal and associated features like *Prabhavali* etc. were cast independently and were subsequently forge welded. Joints between the body and the pedestal were revealed in the radiographs. It was observed that reference studs were used to facilitate the alignment of the red hot individual parts of the icon during forge welding.
4. While all the icons had solid body, one small size icon was found to be hollow inside. It appears to have been cast in that way intently (Fig. 4).
5. Radiography also reveals if the icon has undergone repair at a later stage. Two typical examples are presented in Fig. 5.



Ardhanareswarar – 11th Century



Rama 13th Century



Hanuman 12th Century

Closeup view of Rama. The sharp facial features, intricate ornamental design in the neck and the attractive smile enhances the icons artistic value.

Nataraja – 12th Century

Fig. 1 : Some of the rare bronzes investigated at Chennai Museum

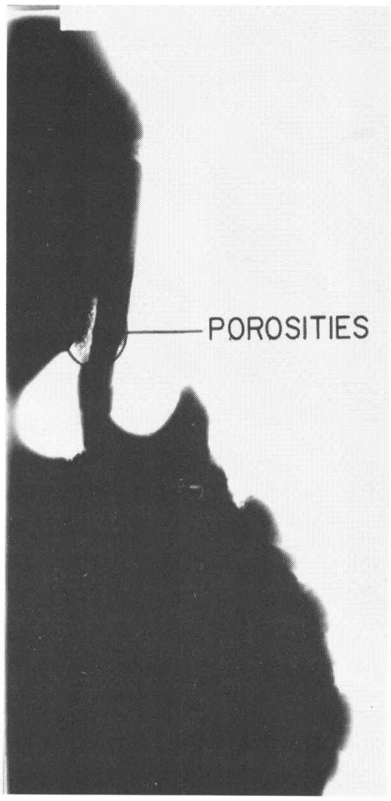
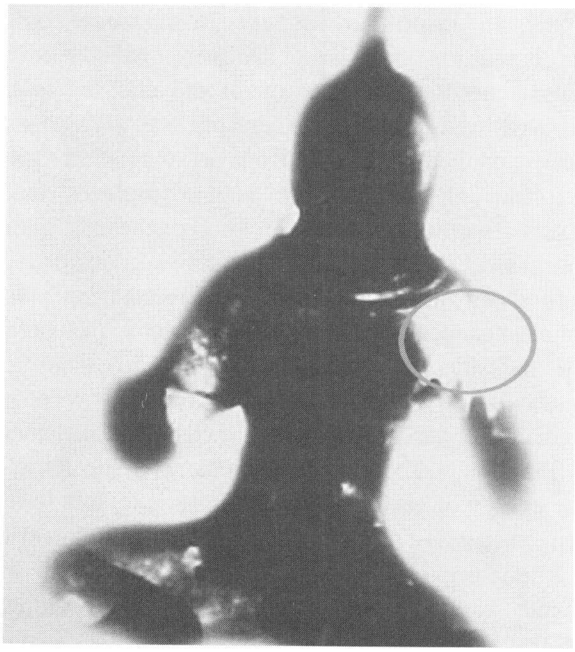


Fig. 2 : Porosities in the earlobe of 16th century Vishnu icon

Photograph of hollow idol

Fig. 3 : Porosities in the hand of a 13th century Nataraja



Positive print of radiograph

Fig. 4 : Radiography reveals hollow casting

(a) Radiograph of 9th century (Pallava) Vishnu. Repair in the leg region (indicated by an arrow) is revealed by radiography

(b) Photograph of idol

(c) Positive print of radiograph. Note the apparent discontinuity in the crown

Fig. 5: Typical repairs revealed by radiography

5.1.2 X-Ray Fluorescence Analysis

Study of chemical composition (signature) of the icon forms an important aspect in characterising (fingerprinting) the icon. Conventional chemical analysis needs some quantity of the material to be removed from the icon. Therefore we have to use specific methods where the icons and the patina which is formed on their surface as a natural and slow process over many years are not disturbed. X-ray fluorescence analysis is a completely non destructive method of qualitative / quantitative analysis for chemical elements based on measurement of the energy and intensities of their X-ray spectral lines emitted by secondary excitation. The primary X-ray beam irradiates the specimen, exciting each chemical element to fluoresce (i.e. emitting their characteristic X-ray). The energy of each element's X-rays is unique to the element (basis of qualitative analysis) and the intensity is a measure of the element's concentration in the sample (basis of quantitative analysis). The samples are not altered or damaged by the analysis. So this technique is a completely non-destructive technique for chemical analysis.

5.1.2.1 Experimental Details

Asoma 200/400 isotope based portable XRF system had been used for the investigation of the bronzes. This instrument has a remote measuring head attached to the console. There are two isotope sources Curium-244 (^{244}Cm -30 mCi), and Americium-241 (^{241}Am - 20 mCi) for primary excitation of the sample. The X-radiation fluoresced and scattered from the sample is detected by a high resolution, gas-filled proportional counter. Each photon absorbed by proportional counter gives rise to a pulse, whose height is proportional to the energy of the photon. These pulses are sent to a multi channel analyser (4096 channels). The data is acquired by a PC for further analysis.

Since the complex shapes of the icons with varying contours and flatness affect the efficiency of data collection, relatively flat surfaces of the icons were chosen for the analysis. Different regions within the icon such as crown, face, belly, back, hand, leg etc were also studied. The XRF probe was oriented so as to have maximum contact area on the surface of the icon.

Both (^{241}Am and ^{144}Cm) were used for excitation, as each of the source is sensitive in exciting a different set of elements. Americium source is used to analyse tin, lead, antimony, bismuth and silver. Curium source is used to analyse copper, zinc, iron, nickel, gold, arsenic and cobalt. Two separate spectra are recorded for analysis. An exposure time of 160 seconds has been chosen for this study so that signal to noise ratio is good. Appropriate energy calibration and background correction were incorporated during the analysis.

5.1.2.2 Results of XRF Analysis

Twenty icons belonging to Chola period were analysed. Fig. 6 is a typical XRF spectra obtained. In order to preserve the antiquity of the icon, XRF analysis was confined to the surface only and the interpretations are based on these results only.

(a) The major constituent in all these icons is copper. The additive elements tin, lead and iron were present in all the 18 icons, with varying compositions. This indicates the variation in the metallurgical practices prevalent in the Chola period.

(b) Change of composition from icon to icon: copper composition is varying from 68% to 97%, tin from 1.72% to 12.79%, lead from 1.20% to 18.35% and iron from nil% to 5.26% (except in one specific case.

(c) Change of composition was observed from region to region within the same icon. This variation was within about 10% in general.

(d) In a few cases large deviation was observed in some regions (ex: idol no. 1526/89 seat region, and 1886/96 pedestal region). This may be due to one or more of the following reasons :

i. localised differential leaching when the icon was buried,

ii. employing a different melt for that portion of the icon at the time of casting,

iii. differential segregation of alloying elements during solidification of cast icon.

iv. In general the patina appeared whitish where lead content is observed to be high.

The patina is greenish where the tin content is high.

(e) In one of the icons, in the pedestal region, Fe was the major element unlike in other places. This is adjacent to a tie-hole. The tie-holes are used to tie the icon to a platform during festival processions. It is likely that the icon was buried along with the iron support rod in the tie hole. In due course the iron rod might have disintegrated and enriched the adherent soil with Fe. An alternative possibility is that this may be due to a subsequent repair where Fe rich alloy might have been used. True picture can come out only if the metal core beneath the surface is analysed.

(f) Gold and silver could not be detected. This may be due to their absence in the patina. Due to their noble nature, gold and silver might not have participated in environmental interactions.

5.1.2.3 Effect of Patina

Most of the icons are covered with patina on the surface. The thickness of the patina is of the order of 100 to 300 µm. The penetration of X-rays is confined only to 50-1 00 µm. Thus there is every possibility of X-rays seeing only the patina but not the actual metal surface. To study the effect of patina on the XRF analysis, the region of analysis was polished in three icons to remove the patina and expose the metal body of the icon. XRF analysis was done before and after removing the patina.

It was observed that the removal of the patina has an increase in the overall counts. It can be seen that no new element is observed in the XRF spectrum after polishing. In general the copper content is more in the metal of the icon compared with that in the patina. Cu content analysis made on the patina is underestimated in the range 1.3% to 12.4%. The other elements particularly lead and tin are overestimated in the patina. Overestimation is to the tune of 13.8% to 61.3% for Pb and 10.3 to *40.07%* for Sn. Fe has shown significant variation only in one case.

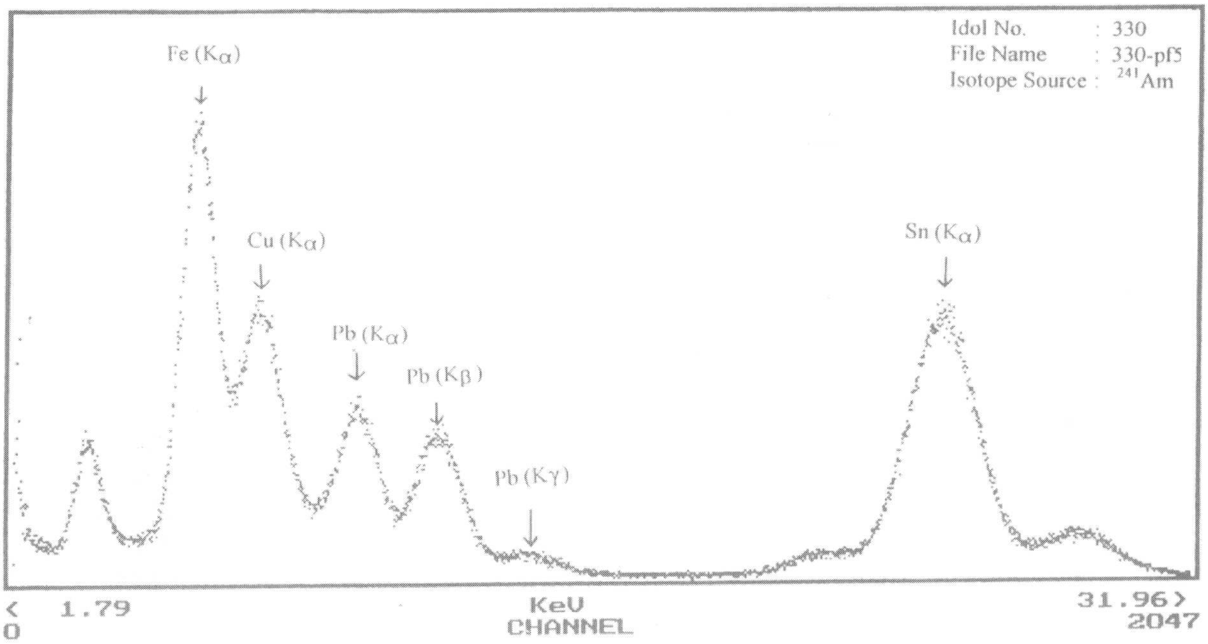


Fig. 6 : Typical XRF spectra

This variation in the elemental composition in the patina compared with that in the icon is due to differential leaching of the elements. This leaching is from the metal to adherent soil and from adherent soil to the surroundings when the icon is buried.

The variation in patina on metal composition is a very significant and unique fingerprint of great value as it cannot be duplicated by any proven scientific methodology. Its value is similar to unique defects in icon casting and both these fingerprints are completely independent of each other.

5.1.3 In-situ metallography and Microstructural characterisation

In-situ metallography was done on selective and inconspicuous regions of the icons due to constraints like retaining the antiquity of the icon. The replica technique was adopted. All the icons showed typical cast structures. Both fine and coarse grain structures were observed indicating that cooling rates in the casting process were different. Photomicrographs of some of the pedestals indicated partially /fully recyrstallised grain structure indicating working on the pedestals after casting them. Casting defects were observed in the microstructures of all the pedestals. They range from distributed porosity to interdendritic cavities and blow holes. Compared to these, the microstructure of the main icon indicates better cast structure. A typical microstructure of a 15th century *Vishnu* icon is indicated in Fig. 7. Figure 8 is the interdendritic cavity observed in the pedestal of the same icon. It is well known that from the microstructure it is possible to get an idea of the cooling rates by observing the dendritic arm spacing under magnification using a scanning electron microscope. However, these cooling rates vary depending on the addition of alloying elements and the casting procedure adopted by the sthapatis. Thus, from the microstructures obtained from icons

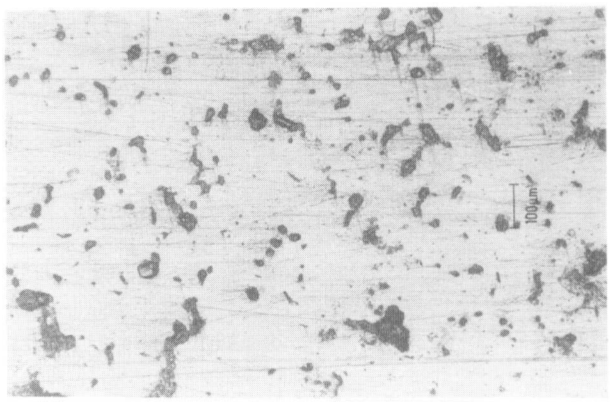


Fig. 7 : A typical microstructure of a 15th century *Vishnu* icon

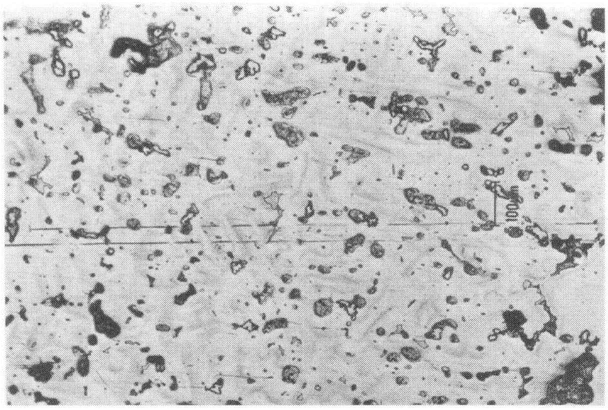


Fig. 8 : Interdendritic cavity observed in the pedestal of the 15th century Vishnu icon.

belonging to different periods, it is possible for us to get an idea of the relative cooling rates of these castings.

In general, the microstructural studies of the icons have revealed that very large pores and cavities combined with gray phases and globular particles are present. However, the present day Swamimalai icon showed small and medium size pores and particles which are homogeneously and uniformly distributed.

5.1.4 Results of other NDE techniques

The microhardness measurements indicated that all these icons fall within a range of hardness values indicating insignificant variations in their strength values. The Secondary Ion Mass Spectrometer (SIMS) analysis showed interesting observations with respect to the surface composition and distribution of alloying elements. Lead was found invariably enriched on the surface of all icons irrespective of the changes in their chemical composition as shown in Table 2. Such an enrichment of lead was reported by R. Cesareo et. al[16] while analysing several bronze icons by X-ray fluorescence method. Also depletion of tin was noticed for all the samples, and the enrichment of both aluminium and carbon is also observed. XRD analysis of the soil (Table 5) indicated that main constituent of the soil is silica and cuprous oxide and in addition copper chloride.

The presence of copper chloride indicated that the soil is corrosive and contained salt. A large variation is noticed with respect to the presence of elements including copper. For example, one of the soil samples did not show any metallic element, the other two showed the presence of all elements. The chemical analysis of the icons (Table 2) showed the presence of copper, tin, lead and zinc in all icons. However, the zinc content is lesser in comparison with lead and tin. Iron, arsenic and antimony were also present in trace quantities. The other alloying elements like silver, bismuth and nickel were found in insignificant quantities. It is clear that apart from copper, tin, lead and zinc the presence of other alloying elements could have been due to their coexistence with copper ore. The ancient technologists were not using refined copper as this was invented only in 19th century AD. The crude copper metal will invariably contain these elements in sufficient quantities. Lead is the most important alloying element[17] which can give important contribution to the casting technology of the bronze icons. The deliberate addition was demanded for the flexibility in the casting of the icons. The presence of lead which is not soluble in copper would fill up the cavities and increases the pressure tightness of the castings. In addition, during initial stages of corrosion, lead interacts with the surroundings to form lead dioxide, sulphate and carbonate particles which enrich the surface. In the ancient tin bronzes, the presence of tin was attributed to the use of copper ores containing tin stones [18]. Historical evidences show that the Sumerian civilisation was the first to develop high quality bronze articles during 3500 BC which contained about 10 to 15% tin. The tin content in the present alloys are about 1 to 5% falling in the solid solubility limit and hence the presence of delta phase compound $Cu_{31}Sn_8$ is ruled out. It has also been reported[18] that the cast bronzes containing more than 5% tin only will precipitate $Cu_{31}Sn_8$ unless it is extremely slowly cooled. In addition the presence of å-phase is not possible in these alloys as there is no thermal input of the order of 623 K for longer durations beyond 1000 hours to initiate such precipitation. It is deduced that the absence of above phases has improved the corrosion resistance of these icons. However, when zinc is added in small quantities to the bronze as in the present alloys, it goes into the primary alpha phase which would not significantly affect the corrosion resistance. The microstructure of the present alloys of Swamimalai icon have shown the presence of cored alpha-phase of Cu-Sn-Zn due to the long freezing range, with lead present as dark interdendritic globular particles in all alloys.

Table 5
XRD ANALYSIS OF SOIL SAMPLES OF BRONZE ICONS

Bronze Icon	SiO_2	Cu_2O	$Cu_3(CO_3)_2(OH_2)$	$Cu_2Cl(OH)_3$	Cu	Sn	Zn
Bhudevi - PB	✓	✓	✓	✓	_	_	_
Bhudevi - FIRH	✓	✓	_	✓	✓	✓	✓
Somaskandar	✓	✓	_	✓	✓	_	✓
Pradoshamurthy	✓	✓	✓	✓	✓	✓	✓
Bhudevi	✓	_	✓	✓	_	✓	_

6. CONCLUSION

South Indian bronzes have been the focal point of attraction for many a researcher. A number of excellent treatises are available which dwell on the aesthetic beauty, casting traditions, composition, etc. However, while all these are individual and independent texts, this paper attempts to combine and highlight in a concise manner, the salient aspects of aesthetic beauty, technological excellence of the casting technology and characterization of bronzes through scientific investigations.

It can be observed from the above that most of the ancient science and technology of casting the icons was rather qualitative, empirical and adhoc with rather small amount of theoretical underpinning. None had thought of formulating a procedure and deriving the precise process sheet which could then be tested and implemented. As indicated by Dr. R.Nagaswamy in South Indian Bronzes [7] "The bronzes were part of sacred architecture, the living legacy of an unknown master artist who rendered these subtle and fluid forms as a means of expressing the divine. Made in accordance with codified principles, and sanctified by worship, these images were the link between Man and his God". Thus the main reason for the non formulation of procedures could be that in those times, to take things out of their normal context and to study them probably appeared to ancients as violating the religion. In the absence of these procedures of formulating and validating understanding i.e. the scientific method, it is very hard to make systematic progress and to discard or improve upon any particular practice. As Whitehead once said, "The essential discovery of modern science was the scientific method itself". It is the appreciation and practice of scientific method which in the modern context, is considered to lead to the progress of science. However, as can be observed from the above, the science and technology of South Indian bronzes is heuristic and empirical, but rigorous in practice. This approach made it possible to achieve consistency and excellence as revealed by the scientific investigations.

The developments in the field of science and technology are such that current artisans and the sthapatis must be in a position, to choose a certain copper alloy, whose properties are better than that of deployed compositions in ancient times, in terms of castability, polishing, casting without defects, lower melting point, etc. However, the scriptural commands of the *Agamas* would definitely prohibit the choice of these new alloys and the use of these icons (cast with an alloy other than the traditional bronze) for religious purposes. Yet, this is one direction which can lead to professional making of icons par excellence in the modern times.

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ARCHAEOMETALLURGY OF ANCIENT INDIAN COPPER

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ABSTRACT

Copper is one of the most important metals in the history of the Indian sub-continent. Some extractive and physical metallurgical characteristics of ancient Indian copper have been reviewed. Physical metallurgical observations provide information about the extraction methodology of ancient copper. Analysis of microstructures reveals interesting and important clues about the possible material extraction and thermomechanical processing route(s) employed. These characteristics have been illustrated with examples. The need for a detailed study of ancient Indian copper objects, collaboratively involving archaeologists and metallurgists, has been set forth. As the electrochemical behavior of ancient copper is almost similar to that of modern copper, an important result of the study of ancient Indian copper is the serious consideration of selecting copper as the material of construction of canisters for long-term underground storage of nuclear wastes. Characterization of surface patina on archaeological copper objects sheds light on understanding long-term corrosion mechanisms in copper and validating theoretical models for predicting long-term corrosion.

1. INTRODUCTION

When one considers the existence of human beings on this planet, one of the earliest metals that were intelligently used for practical applications is copper[1]. The recognition of the role played by copper in the cultural development of human civilization is amply reflected in the label Copper-Bronze Age to a particular period of Indian history[2].

Interestingly, metallurgical tradition in the Indian sub-continent dates back to about 6000BC based on the discovery of copper objects (beads and ring) from the early phase of Mehergarh in Baluchistan province of Pakistan[3]. The use of copper increases gradually during the Mesolithic (6000-4000 BC), Neolithic (4000-3000 BC) and Pre-Harappan periods before we begin to notice copper objects in large amounts in the Harappan and Chalcolithic cultures (Table 1)[3,4].

Copper was widely used in the Harappan civilization[5,6]. This civilization is also generally refereed to as Indus Valley or, recently, Saraswati civilization. It must be remembered that the Harappan civilization, the most advanced civilization in ancient times in the engineering sense, was known to the world only in the late 19th century. Charles Masson first saw the mounds at Harappa in 1826 on the trade route from Lahore to Multan. Later Lt. Alexanader Burns, the British King's emissary to Maharaja Ranjit Singh in 1831, stopped for a while at Harappa, gazed at the ruins, and went away to Lahore. It was only in 1862, that Alexander Cunningham, the first Director General of the Archaeological Survey of India, during his excavations, found pottery and seals at Harappa. Evidences for extensive use of copper, sometimes alloyed with minor elements like lead, zinc and arsenic, in the Harappan civilization sites are available based on extensive excavations conducted by Indian archaeologists after Indian independence[5,6].

There is a sudden spurt in copper metallurgy during the Harappan period. This can be concluded based on the large amount of copper and bronze discovered, the wide range of objects fabricated, and the varied composition of different alloys of copper determined.

All these evidences indicate that Harappans had mastered the fundamentals of copper smelting and alloying. Copper-based objects, discovered at several Harappan sites like Harappa, Mohanjadaro, Chanhudaro, Lothal, Rojdi, Kalibangan, etc. reveal that the Harappans were well versed with casting and sequent processing of the castings. Their casting techniques were highly developed and this included the lost-wax process. Interestingly, they cast both solid and hollow forms. A wide variety of copper based objects have been recovered from Harappan sites. This includes domestic items (pots, pans, art objects, razors, knives, sickles, balance rods, etc.), surgical implements, weapons (celts, spearheads, arrowheads, shaft hole axes and swords with mid-ribs, etc.) and tools (chisels, saw with alternating teeth, tubular drills, fish hooks, etc.) [7].

Mention must also be made of the excellent bronze castings of the Harappans, the well known of them being the famous dancing girls of Mohanjadaro. A wide variety of bronze items have been discovered in Harappan sites. These include a standing deity, a horned female deity, toy carts, chariots from Mohanjadaro, Harappa and Chanudaro, animal figurines of wild buffalo, horned buffalo, elephant, gazelle, goat and dove from Mohanjadaro, short-horned bull from Kalibangan, seated bull, dog, hare and a bird head from Lothal, and, recently, rhinoceros, elephant, buffalo, and a chariot with a male rider drawn by a pair of humped bulls from Daimabad [7].

Excavations have also revealed that extraction of copper from the ore was not practiced in the Harappan civilization cities. These cities, however, had workshops in which copper objects were melted, alloyed, cast, forged and fabricated. It is now amply evident that copper was extracted from sulfide ores at sites away from the main cities and the extracted copper was supplied to the cities for their commercial use [6].

Copper based objects have also been discovered at several Chalcolithic sites outside the Harappan cultural sites (Table 1). One of the main applications of Cu-based alloys in these cultures was for the manufacture of sharp-edge cutting tools, as copper-based tools perform better than stone tools. The word *chalcolithic* itself implies "copper-stone", thereby indicating that both copper and stone tools were simultaneously utilized in this cultural phase of Indian history. The large number of carefully engineered constructions of the Harappan civilization was possible with the availability of copper-based sharp-edge cutting tools and this brings out the important role played by copper in the development of Harappan civilization [6].

Table 1
CULTURAL HORIZONS OF INDIA

Mesolithic	6000-4000 BC
Neolithic	4000-3000 BC
Pre-Harappan	3000-2100 BC
Harappan	2500-2100 BC
Late-Harappan	2000-1400 BC
Other Chalcolithic cultures outside Harappan culture	
Ganeshwar-Jodhpura	2800-2000 BC
Savalda	2000-1700 BC
Kaytha	2100-1800 BC
Ahar (Banas)	2100-1400 BC
Malwa	1700-1400 BC
Jorwe	1400-900 BC
Copper Hoards / Ochre Colored Pottery (OCP)	1800-1400 BC
Southern Chalcolithic	1800-1000 BC
Eastern Chalcolithic	1500-1000 BC
Megalithic cultures	1200-200 BC
Painted Grey Ware (PGW)	1100-600 BC
Northern Black Polished Ware (NBP) culture	800-200 BC
Recorded History	> 500 BC
Historic period	500 BC-300 AD
Gupta period	300 –600 AD
Post-Gupta period	600-1100 AD
Medieval period	1100-1800 AD
British period	1800-1947 AD
Modern period	1947 AD afterwards

In a different time zone, but around the same time frame as the Harappan civilization (Table 1), the Copper Hoards of the Gangetic plains are encountered [3]. Heavy copper objects were hoarded in large leather sachets in the upper Gangetic plains, Bihar, Bengal and Orissa. In addition to these areas there were several Chalcolithic cultures in small settlements in Gujarat, Rajasthan, Madhya Pradesh and Deccan. Figure 1 shows the location of important copper-based cultures in ancient India, which is based on sites that have provided copper objects. Most of the settlements were close to copper ore deposits. They extracted the metal and supplied it to other nearby settlements. Famous examples of copper supplying settlements are Ahar and Ganeshwar in Rajasthan. Even after the Harappan civilization dispersed (i.e. after 1500 BC), due to the shifting of the water flow in the major rivers of Northern India, the use of copper objects for a wide variety of applications continued, with the most important application being for sharp-edge tool applications.

It is in this cultural milieu that iron appears for the first time in the Indian subcontinent. An independent origin of iron in India has been firmly established [7]. Iron technology may have been an offshoot of copper technology since iron is encountered in significant amounts in ancient copper making slags. The ancient copper metallurgists were very adept in fluxing out iron oxide from copper ores, mainly chalcopyrites.

Fig. 1 : Map showing ancient archaeological sites where copper-based objects have been discovered [3].

It is also likely that the scarcity of copper available to some of the pre-iron cultures combined with their empirical technical knowledge must have resulted in the discovery of iron.

Although iron makes it appearance around 1500 BC, it is only around about 800BC that we find a huge spurt in use of iron on a large scale [7]. Archaeological evidences indicate that carburizing followed by tempering appeared around 500 BC. Even with the advent of iron, copper was still an important metal and was being widely used, for applications other than sharp-edge cutting tools. Literary sources provide some interesting details. The Greek ambassador Megasthenes, who visited India in 302 BC, mentions "vessels of Indian copper set with precious stones contributed to the brilliancy of the public ceremonies during Chandragupta Maurya's reign" [1].

In the early stage of copper use, hunting and warfare tools were fabricated out of copper. Although copper was gradually discounted from this application with the discovery of iron, it was, nevertheless, used extensively in several other applications. A wide variety of copper-based utilitarian household objects have been discovered in archaeological excavations. With the introduction of metallic coins for monetary transactions (one of the earliest instances in the world when metallic coinage was circulated was in the Indian sub-continent, beginning somewhere around 600BC), copper also found its use in this application. It is, therefore, not incorrect to conclude that copper was an important metal in most of the cultural horizons of the Indian sub-continent (Table 1).

Copper metallurgy lead to the introduction of copper-based alloys, notably brass and bronze. While the earlier brasses contained relatively lower amount of zinc, we begin to notice the appearance of high zinc brasses with the discovery and subsequent large-scale production of zinc in ancient India [3]. The tin and arsenical bronzes of ancient India are also noteworthy. The relatively high tin and arsenic contents of the Harappan bronzes indicate that the Harappan copper metallurgists were familiar with deliberate alloying of copper with tin and arsenic. Table 2 compares the average alloying element content in copper-based objects from the Harappan, Chalcolithic and Copper Hoard cultures. The estimation provided in Table 2 is based on actual analysis of 219 Harappan, 29 Chalcolithic and 33 Copper Hoard objects [6].

Meanwhile, the use of copper continued through the history of India, mainly for applications where the shapes could be processed with relative ease due to the good malleability of copper.

In the present communication, we shall not attempt to reproduce the relatively large literature available on ancient Indian copper. There are several excellent books on ancient Indian copper [1-6]. These scholarly works examine several facets of the use and application of copper in the Indian sub-continent. In this regard, the work of Neogi [1] must be viewed as path breaking because he was the first scholar to systematically catalogue the use of copper in ancient India, as early as 1917, in his book *Copper in Ancient India*. The present communication will address the archaeometallurgy of ancient Indian copper, focussing on the basics of extractive and physical metallurgy of ancient Indian copper. The paper will conclude by understanding how archaeological copper may hold the possible key for a very relevant, modern, scientific and social problem, namely nuclear waste storage.

2. EXTRACTIVE METALLURGY

The extractive metallurgy of ancient Indian copper is difficult to establish from existing literary evidences alone. Apart from being meager, the literary sources (for example, *Rasaratnasamuchchaya* II-89-90 and II-101-102) date to a much later date compared to the period when copper was extensively used in the Harappan civilization. It will be seen later that ideas about probable ancient copper extraction process(es) employed could be gleaned from physical metallurgical analysis of ancient copper. The utility and importance of material characterization in understanding ancient metallurgical practices is truly significant, but often overlooked by archaeologists. This is one area where archaeometallurgists can make a significant contribution in understanding the history of ancient metals, in general, in the Indian sub-continent.

Copper was and is mainly extracted in India from chalcopyrite ores, which abound in the sub-continent.

Some ideas about the probable copper extraction process in medieval India could be gleaned from the writings of the early British army officers in the Indian sub-continent when they reported the indigenous processes of manufacturing copper. Accounts dating from 1831 (by Captain Boilcan) and 1864 (by Captain J.C. Brooke) [1,8] provide some general ideas. The design of a typical copper-smelting furnace from Singhara near Khetri in Rajasthan was published in 1831 [8]. The chalcopyrite ores were crushed with hammers weighing 16 to 20 lbs on stone anvils. Mineral beneficiation was carried by multiple washings. It was then mixed with cow-dung and made into balls *(pindi)* and was first roasted to remove the bulk of S. The roasted ore was smelted to remove the gangue material to produce Cu matte. The charge in the furnace typically consisted of roasted ore, charcoal and iron slag. During smelting, S was oxidized to SO_2 and Fe to FeO, which was fluxed by silica (flux) to form the slag. Smelting was conducted in a blast furnace made of clay and sand. The copper-extraction furnace was generally built with refractory clay or was simply a deep hole in the ground with a clay rim at the sides and front [10]. The insides were plastered with refractory clay. Clay tuyeres in the bottom of the furnace provided the forced draught. The furnaces were filled with lighted charcoal and raised to full heat by working of the bellows attached to the tuyeres. After the furnace was lit and well heated, the roasted ore was gradually introduced alternately with charcoal and flux (called *reet*, which was essentially slag from iron making furnace). The relative proportion of materials roasted was 5 parts ore, 4 parts charcoal and 5 parts *reet* [3]. At the end of the smelting operation (lasting or about 9 to 10 hours), slag was removed from the top, leaving the heavier metal behind. When the heavier metal had solidified, it was taken out, pounded and kneaded with dung and made into balls. These balls were dried in the sun and then roasted with free access of air in shallow furnaces. The last process of refining consisted of treating the powder produced from these roasted balls in the same furnace and in precisely the same manner as the original one, the result being a fluid mass of copper was found at the bottom of the furnace which on cooling was removed.

In the period prior to the wide use of iron in Indian civilization, it is unlikely that the method, described above, was utilized for extracting copper. It is clear that iron making was not practiced on a large scale up to 800 BC. Therefore, for the case of present discussions, ancient copper would imply copper dating from a period prior to 800 BC. Material characterization of ancient Indian coppers dating before 800 BC [11-15] has provided valuable clues to the extractive metallurgy of copper in the pre-iron period. In this method, the sulfide ore was first washed and smelted in a furnace to separate gangue and CuS. The sulfide ore did not undergo any change in this operation and was left as a cake in the bottom of the furnace. The slag was run off and the copper sulfide cake allowed to cool. These cooled cakes were broken, made into balls and roasted to oxide. The oxide was later smelted in the original furnace with charcoal and reduced to metallic state.

3. PHYSICAL METALLURGY

Several benefits accrue from physical metallurgical analysis of ancient copper specimens. The probable method by which copper was extracted in ancient times can be scientifically established based on careful inclusion analysis. The characterization of surface patina will help in understanding long-term corrosion mechanisms of copper. Microstructural characterization would reveal the probable method of manufacture of the object (cast or cast+deformation processed). Possible heat treatments provided, like annealing, could be understood. Detailed composition

Table 2

AVERAGE PERCENTAGE OF ALLOYING ELEMENTS (UNDERLINED) IN COPPER-BASED OBJECTS FROM THE HARAPPAN, CHALCOLITHIC AND COPPER HOARD CULTURES [6].

Alloy	Harappan	Chalco-lithic	Copper Hoard
Cu-Sn	22.8	17.2	nil
Cu-As	11.9	nil	45.5
Cu-Pb	7.8	20.6	3
Cu-Sn-As	4.1	nil	nil
Cu-Sn-Pb	6.4	17.2	nil
Cu-As-Pb	1.4	nil	6.0

analyses of ancient copper samples are always an welcome addition, and the significant contributions of Agrawal and co-workers [2,6] need special mention. The physical metallurgy of ancient Indian copper can be gleaned from published microstructures of ancient copper and copper-based alloys [1-3,6]. This will be highlighted in the present communication, using two ancient Indian copper samples as examples [11-15]. The first sample dates to the OCP period (1800-1400 BC) 16 while the second to the Chalcolithic period (2600BC and 1800BC) [17,18]. The second sample is quite important because this was obtained from an important recent excavation at Balathal, which is the oldest known Chalcolithic village outside the domain of the Harappan civilization [17,18]. Interestingly, small stone blades and tools were completely absent at Balathal, but seen in all other Chalcolithic sites [17,18], which clearly suggests that copper metal was plentifully available.

The metallurgical nature and condition of ancient Indian copper can be understood by metallography, which is necessarily a destructive technique. Non-destructive tests, like radiography, if conducted prior to metallographic examination, will provide some ideas about inclusions present in the material. However, by taking proper care in specimen collection and specimen preparation, metallographic samples can be prepared even with small samples. The metallographic observation can be conducted by optical and scanning electron microscopy.

The material is usually homogeneous, but macrodefects (like wide cracks) can sometimes be observed in the cross section of the specimens (Fig. 2). As regards the microstructure, some salient features can be easily identified and these provide ideas on how the material was originally processed into shape. In the case of cast objects, the grains are generally equiaxed and the grain sizes are not uniform. A typical microstructure of cast ancient Indian copper (OCP copper) is provided in Fig. 2. Annealing twins can generally be identified in the microstructures. At ambient temperatures, copper deforms by slip, while deformation by twinning is possible only at low temperatures. Moreover, deformation twins appear jagged, unlike the twins seen in Fig. 2. Therefore, the twins noticed in Fig. 2 are annealing twins. This provides the first indication that the object was first cast into shape. Another characteristic feature in

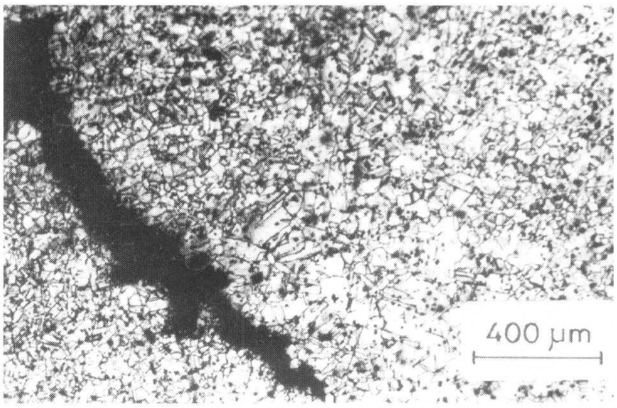

Fig. 2: Typical optical micrograph of cast ancient Indian OCP copper showing equiaxed microstructure and the presence of annealing twins and second phase inclusions. A macrodefect (crack) can also be seen.

ancient Indian copper is the distribution of inclusions, generally spherical shaped, in the copper matrix (Fig. 2). The aspect of coagulated second phase particles in ancient Cu objects indicating casting of Cu object has been addressed elsewhere in detail [19]. In some cases, the inclusions appear elongated due to further deformation processing of the cast objects. These elongated slag inclusions provide valuable clues on the direction of working of the copper objects. When equiaxed structures are revealed in different sections (parallel and perpendicular to the surface), it strongly suggests that the casting route was employed for the manufacturing the object.

Additional features can be observed in the SEM (scanning electron microscope). Coarse dendritic structures (fernlike growth) are indicative of relatively lower cooling rates after the casting process. In case of preferential grain growth, like columnar growth, chill casting of the object can be hypothesized. It is now known that sophisticated casting techniques like lost-wax process were employed by the Harappan metallurgists [7]. Moulds constructed out of stone, terracotta and sand have been discovered at Harappan sites. A detailed study of ancient Indian copper implements by Agrawal *et al* [20] had also concluded that they were essentially cast in closed moulds. They also noted the skill of the metal casters because casting of pure Cu is a difficult process.

Evidence also suggests that a wide variety of post-casting metallurgical operations (like annealing, cold working, riveting, soldering, lapping, forging, turning, drawing, filing, coloring, engraving, etc.)

were known to the Harappans [6]. Microstructural analysis also provides insights on possible thermomechanical and/or deformation processing route(s) employed to manufacture the object. For example, deformed and elongated grains indicate deformation processing. In the case of the Chalcolithic copper chisel, the microstructure from near two opposite surfaces (Fig. 3) of the sample was quite different from the interior of the sample. The grains near the surface were deformed compared to the grains in the interior. The cold worked structure was characterized by the presence of numerous slip bands. The important conclusion that was deduced from the microstructural analysis was that the initially cast chisel was cold worked only on two sides to provide the final shaping operation to the chisel [11,12].

The nature and composition of inclusions can also be analyzed in the SEM using the techniques of EDS (energy dispersive spectroscopy) and WDS (wavelength dispersive spectroscopy), units of which are normally available in the SEM. An example of inclusion analysis is illustrated in ref. 14. Using the back-scattered electron imaging in the SEM, the possible constituents in the inclusions can be deduced. For example, a bright contrast from the entrapped slag inclusions indicates that they are rich in heavy elements, notably Pb. The second phase inclusions in ancient Indian copper are generally sulfides of Cu and Fe [14]. The composition of the matrix can also be determined simultaneously in the SEM and this will provide ideas of possible alloying and/or impurity

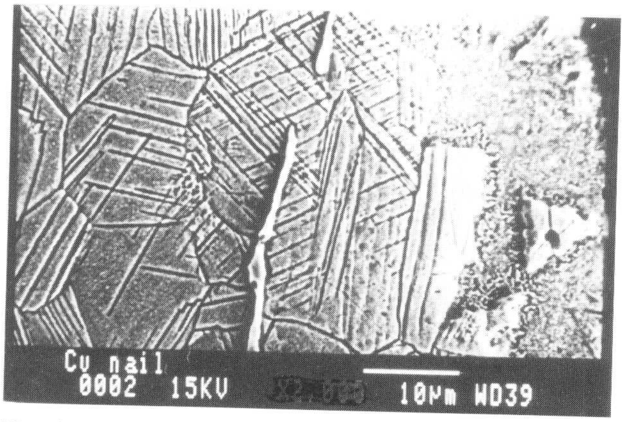

Fig. 3 : SEM micrograph photographed from one of the edges of a Chalcolithic copper chisel, showing deformed grains and incursion of corrosion products along grain boundaries. Corrosion layer is on right side of the photograph.

elements in the matrix. The elements that are encountered as alloying additions in ancient Indian copper are Sn, As, Pb, Sb and Zn. The co-relation between the composition of the entrapped slag inclusions in ancient Indian copper and their mode of extraction has been discussed in detail elsewhere [11,12].

Established image analysis procedures [21] can be applied to the microstructures to obtain further information, like the volume fraction of the second phase inclusions, their contiguity and grain size of the matrix. This has been illustrated in detail, elsewhere [13]. The volume fraction of inclusions in the ancient Indian coppers is relatively low (2-5%) [13,14].

A relatively new technique for microstructural analysis of ancient Indian copper is the use of color metallography, using suitable tint etchants [22]. Very fine details, even superior to compositional mapping procedures in the SEM, about compositional and deformation inhomogeneities can be revealed by color metallography [22].

The mechanical condition of the material can be quickly assessed by microhardness measurements. A cast structure, without any further deformation, and possessing a relatively coarse grain size (30 to 40 mm) will provide hardness typically in the range of 65 to 80 kg/mm^2. The relationship of microhardness and grain size with the possible temperature range of working for the case of Cu has been addressed elsewhere [19].

Localized deformation inhomogenities can be understood by careful microhardness profiling experiments. For example, in the case of Chalcolithic copper sample, unlike OCP copper, the microhardness was not constant in the matrix. The variation of microhardness as a function of distance from the surfaces of the Chalcolithic copper chisel is shown in Fig. 4. The hardness profiles were almost constant on two opposite faces, while on the other two faces, the hardness was much higher near the surface, which progressively decreased on moving towards the interior (Fig. 4). The hardness of the matrix in the center was almost similar for all profiles. The microhardness measurements confirmed that the chisel was fabricated after the initial casting operation by deformation on only two of the surfaces.

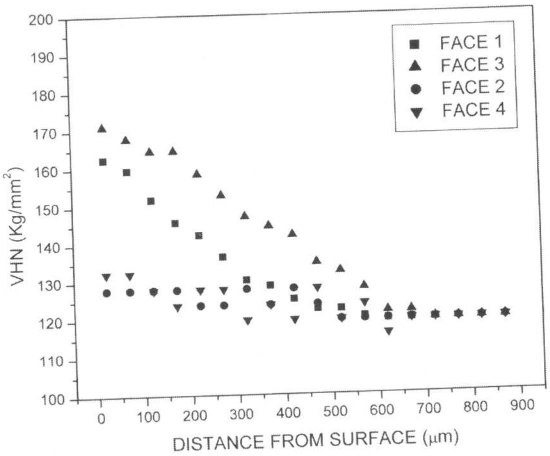

Fig. 4 : Variation of microhardness as a function of distance into the surface of a Chalcolithic copper chisel, obtained from all the four surfaces.

4. RELEVANCE TO MODERN METALLURGY: LONG-TERM NUCLEAR WASTE STORAGE CANISTERS

Archaeometallurgical studies on ancient Indian copper can provide valuable insights in a very important modern technological application, namely high-level nuclear waste storage. The basic philosophy of high-level nuclear storage will be briefly addressed before outlining the utility of copper in the overall storage scheme. It is important to distinguish between short-term and long-term storage of nuclear wastes. During the short-term storage period (which may extend up to several hundreds of years), the spent fuel, after appropriate processing, is allowed to cool down to temperatures adequate for subsequent underground repository storage. In case of long-term nuclear waste storage, the waste has to be stored for periods exceeding 100,000 years in order to allow for complete radioactive decay of the dangerous radioactive species still present in the waste. Of course, we understand that the nuclear waste is first immobilized by embedding the waste in a glassy matrix.

The nuclear waste has to be placed in suitable storage canisters for both short- and long-term storage. While the canisters will be free from environmental degradation (i.e. corrosion-related processes) on the inside surface which is in contact with the immobilized nuclear waste, they will, however, be subject to corrosion on the environmental side. In the case of canisters for short-term storage, the environment that would be "seen" by the canister would be atmosphere. In this application, the material of construction of the canister must be capable of withstanding atmospheric corrosion. In this regard, the benefits of applying phosphoric irons are readily apparent because of their excellent atmospheric corrosion resistance. A good example of archaeological analogue providing supporting validation is the example of the 1600-year-old corrosion resistant Delhi Iron Pillar [23], a classic example of phosphoric iron construction, which has withstood atmospheric corrosion due to the formation of a protective passive film on the surface[24].

In contrast to short-term storage, long-term nuclear waste storage must essentially involve storage in deep underground repositories because the time frame involved is much longer. The design life is a minimum 100,000 years. The environment to which the long-term nuclear waste storage canisters will be exposed to will depend upon the storage philosophy adopted by the respective nuclear waste producing countries. For example, the American plan consists of storing the long term wastes encased finally with a 20 mm-thick canister constructed out of a Ni-based alloy called Alloy 22 (56Ni-22Cr-13.5Mo-3W-3Fe). A 50 mm-thick type 316NG stainless steel inner container will provide the necessary structural integrity. These canisters will be stored in depository caves dug into the Yucca Mountain in Utah [24]. On the other hand, the Finnish and Swedish design of spent nuclear fuel package calls for packing the spent fuel in a canister made of spheroidal graphite cast iron, with an outer shield made of copper. The copper shield is responsible for the corrosion protection of the canister [27-29].

The design thickness of the wall of the storage canister is an important design parameter and this will be primarily based on the maximum corrosion allowance of the selected material in disposal conditions. Considering copper as candidate canister material for long term storage, the corrosion rates measured in weight loss coupon tests of relatively short duration (7 days), in bentonite clay environment, are of the order of 2 mm/year [28,29]. This corrosion rate would indicate a lifetime of roughly 2500 years for a designed wall thickness of the copper shield of about 50 mm. This is clearly lower than that required for a life of 100,000+ years. A far bigger problem confronts corrosion scientists because the actual condition of the material after long-term exposure is not known and neither is it possible to obtain such data by laboratory testing alone.

It is in this regard that archaeological copper analogues can be very useful in understanding and validating theoretical models for long-term corrosion of copper in burial conditions. For example, the ancient Indian copper samples discussed as examples in this communication, are very old samples, of conservative age of more than 3000 years. Let us explore some information gleaned about long-term corrosion processes from these samples.

Microstructural analysis of the OCP and Chalcolithic copper samples indicated that the degree of corrosion was not severe and moreover, stress corrosion cracking was not evident from the surfaces of the sample. In the case of Chalcolithic copper sample, the corrosion layer was adherent on the surface (Fig. 3). The incursion of corrosion products into the matrix appears to occur along grain boundaries of the underlying matrix (see Fig 3). The intergranular nature of corrosion attack is understandable because of the higher-energy state of material at these locations. Nevertheless, it is also important to note that the incursion of corrosion products along the grain boundaries was not deep enough to warrant the use of the term pitting to describe this kind of environmental corrosion. A complementary conclusion is the lack of any environmentally induced cracking in this material. This is understandable because dangerous chloride ions were not present in the soil environment to which the chisel was exposed [14,15]. This was also verified by the absence of chlorides in the X-ray diffraction patterns obtained from the surface patina [14,15]. Therefore in the environments where chloride ions are excluded, microstructural investigations on archaeological Indian copper confirm that there is no danger of stress corrosion cracking.

The question would then arise whether the data obtained for ancient Indian copper will apply for modern copper. Electrochemical polarization studies conducted on ancient Indian copper samples [13-15] clearly established that the coppers were electrochemically similar (see Fig. 5). The major difference between the samples was the presence of

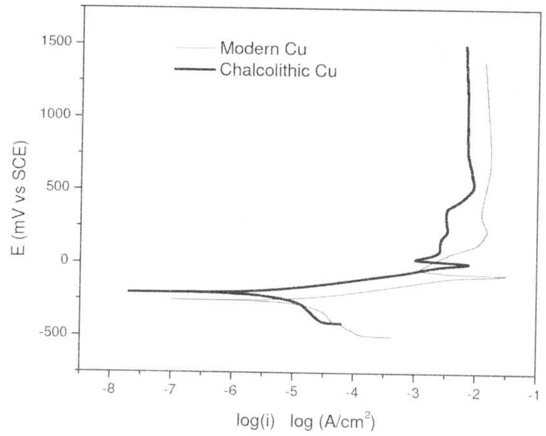

Fig. 5 : Potentiodynamic polarization curves in freely-aerated 3.5 wt % NaCl solution of Chalcolithic copper compared with that of modern Cu.

second phase inclusions in the case of archaeological Cu samples. Against the anticipation that the presence of second phase inclusions would deleteriously affect corrosion rates, electrochemically measured corrosion rates of Chalcolithic Cu sample (175 mm/y) and OCP Cu sample (185 mm/y) were only marginally higher than that of modern Cu (55 mm/y) [30]. These data co-relate well with the published corrosion rate for Cu in seawater (25-127 mm/y) [31]. In the case of both archaeological coppers, the second phase slag particles appear to have slightly enhanced the dissolution tendencies, which could probably be due to galvanic coupling action of the Cu matrix with the sulphide slag inclusions. It is to be noted that the sulfides are electrically conducting and they aid in the establishment of local galvanic cells [32]. The effect of the inclusions was not significant because the volume fraction of inclusions was relatively low and, moreover, they were not interconnected but widely dispersed.

As the electrochemical behavior of ancient coppers is almost similar to that of modern copper, it implies that ancient and modern Cu samples are almost similar chemically. As the ancient Indian copper samples have successfully withstood corrosion under *unplanned* soil burial conditions for such a long time, it indicates that modern-day *planned* burial of copper must also behave similarly. The corrosion of copper exposed to the soil environment will be the critical factor. As ancient Indian copper has proved that it can withstand corrosion in Indian soil conditions over a long period of time, it must be seriously considered as the material of construction of outer canisters for long-term underground storage of nuclear wastes.

Additionally, information about long-term corrosion processes can be also obtained from characterization of surface patina from ancient Indian coppers. In this regard, it is important for archaeologists to preserve the original surface patina in copper objects, during archaeological excavations. The nature of surface patina will help in validating long-term corrosion models. For example, X-ray diffraction (XRD) patterns, before polishing and after polishing of the sample surface, help in understanding the sequence of formation of corrosion products. X-ray diffraction (XRD) patterns of the Chalcolithic copper sample were obtained as a function of patina thickness [14], by a simple polishing procedure using emery paper. The major corrosion products on the surface of the sample were hydrated copper sulfates and oxysulfates, like $Cu_4(SO_4)(OH)_6.2H_2O$ (posnjakite), $CuSO_4.H_2O$, $Cu_3(SO_4)_2(OH)_2$ and $Cu_3(SO_4)_2(OH)_2.4H_2O$. Analysis of XRD patterns obtained from the inner regions of the patina, close to the metal-scale interface, revealed that the phases were primarily copper oxide phases. The results of the analysis agree with the known general behavior for corrosion of copper in soil environment [33]. In the corrosion of copper in soil (and also atmospheric environments), the first product to form is cuprite. In the presence of S in the environment, the formation of sulfates and oxysulfates is favored and these phases are generally found above the copper oxide-containing layer.

A significantly large amount of ancient Indian copper objects are presently locked up in Indian museums and archaeological storerooms, waiting to be analyzed. The interaction and co-operation of people skilled in metallurgical knowledge with archaeologists will greatly benefit in creating a knowledge database on ancient Indian copper.

5. CONCLUSIONS

Some extractive and physical metallurgical aspects of ancient Indian copper have been reviewed. Physical metallurgical studies provide deep insights on the extractive metallurgy of ancient copper. Analysis of microstructures provides important information about processing of ancient Indian copper. Ancient Indian coppers are electrochemically similar to modern copper. As ancient Indian coppers are fairly well preserved in soil conditions, a beneficial effect of studying ancient Indian copper will be the serious consideration of selecting copper as the material of construction of canisters for long-term underground storage of nuclear wastes. Characterization of surface patina on archaeological copper objects help in understanding long-term corrosion mechanisms and validation of theoretical models for predicting long-term corrosion.

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ZINC AND RELATED ALLOYS : THE PIONEERING TRADITIONS IN THE ANCIENT AND MEDIEVAL INDIA

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ABSTRACT

India achieved the distinction of being the only country in the ancient and the medieval world to produce pure zinc metal and high zinc-brass alloys. This article provides a brief summar of the pioneering traditions in zinc and related alloys in ancient and medieval India. It also includes hitherto unpublished material on the Bidri alloy.

1. INTRODUCTION

India achieved the distinction of being the only country in the ancient and the medieval world to produce pure zinc metal and high zinc-brass alloys. The saga of zinc in ancient India has been established only recently by a team of scholars from India (Hegde[1], Biswas[2,3]) and England (Craddock[4], Willies[5]). The present author has recorded the current status of our knowledge on the subject in a paper and in a book. This provides a brief summary and also includes a hitherto unpublished material on the Bidri alloy.

The earlier occurrence of zinc in man - made artifacts is in the form of the copper alloy known as brass. Ever since the discovery of copper and the alloying elements of tin, arsenic, lead, etc., different materials, including zinc, were used to alloy and harden copper.

The earliest method of making brass was possibly the cementation process in which finely divided copper fragments were intimately mixed with roasted zinc ore (oxide) and reducing agent, such as charcoal, and heated to 1000°C in a sealed crucible. Zinc vapour formed, dissolved into the copper fragments yielding a poor quality brass, zinc percentage of which could not be easily controlled.

Fusion of zinc with copper increases the strength, hardness and toughness of the latter. When the alloy is composed of 10-18% zinc, it has a pleasing golden yellow colour. It can also take very high polish and glitter like gold. For this property, brass has been widely used for casting statuary, covering temple roofs, fabricating vessels, etc.

Reduction of zinc oxide around 1000°C is crucially important : below 950°C no zinc is produced. Zinc is obtained in the vapour form at this temperature, since its boiling point is 913°C. With trace of oxygen, the zinc vapour would be reoxidised and hence the successful operations in the past must have been done in closed crucibles. If the temperature were higher than 1083° C during brass-making, then copper would melt and flow down to the bottom of the crucible forming a puddle there, exposing a very small surface area of the metal for alloy formation.

Brasses containing upto 36% zinc are known as α-brasses, which undergo easy cold work. Brasses containing more than 46 % zinc are brittle. With zinc content between 36 and 46%, we have $\alpha+\beta$ brasses which are lighter, harder and more suitable for casting statuary.

Werner [3] and Haedecke [4] demonstrated experimentally that brass produced by the cementation process could not contain more than 28% zinc. Brass founders trying the cementation process have verified this observation.

The materials of antiquity containing more than 28% zinc in copper matrix must have been prepared by mixing the two metals, which could have been possible only after the discovery of zinc as a separate metal and its preparation by a process such as distillation.

The antiquity of brass artifacts can, therefore, be divided into two eras, one preceding, and the other following the discovery of zinc as a separate metal.

2. BRASS BEFORE THE DISCOVERY OF ZINC

We claim that the earliest artifact noted so far containing an appreciable amount of zinc anywhere in the world is from India. Lothal (2200 – 1500 BC) showed one highly oxidised antiquity (No. 4189) which assayed : 70.7 % copper, 6.04 % zinc , 0.9% Fe and 6.04 % acid-soluble component (probably carbonate, a product of atmospheric corrosion) [5]. The material could have been prepared through smelting of zinc-bearing copper ore or the cementation route described earlier. The raw materials might have come from the Ahar-Zawar area. The Harappan site of Rosdi, also in Gujarat, has yielded a few samples of

Table 1

ANALYSIS OF SOME BRASS OBJECT IN ANCIENT INDIA

S.No	Date & Site	Object	Analysis %				Remarks
			Cu	Zn	Sn	Pb	
1.	- 1500 BC Lothal Copper Object	No.4189	70.70	6.04	-	-	Ref.5
2.	Harappan Rosdi rod, bangle	Chisel, Celt 98.5	95.5 – 1.54	Upto 1.23	Upto 1.20	Upto	Ref.6
3.	- 1000 BC - Atranjikhera	No.1 No.2	70.99 52.42	6.28 16.20	11.68 20.72	9.00 9.77	Ref.7
4.	4th century BC Taxila	Vase Bm 215-284	55.39	34.34	4.25	3.08	Ref.8
5.	2nd century BC	Bangle	73.72	19.70	0.10	5.84	Ref.8
6.	2nd Century AD Gujarat	Female figure carrying flower container Indo Parthian	88.60	7.60	0.13	2.49	Ref.6 pp.56-57
7.	5th century AD	Gandhara Buddha	68.50	20.25	3.86	3.62	Ref.13
8.	6th century AD Akota	Ambika	76.70	16.32	1.61	4.04	Ref.6, pp.104-105
9.	7th Century AD Mahudi	Rishabhanatha	66.00	12.80	5.90	1.50	Ref.6, p.66
10.	8th century AD Kashmir	Shiva	82.00	17.00	1.00	-	Ref.14
11.	9th Century AD Nalanda	Buddha	78.95	15.15	0.74	3.03	Ref.15
12.	11th century AD, W.Tibet	Manjusri	65.50	30.40	0.30	1.70	Ref.16

chisel, celt, rod and bangle, made of brass and assaying upto 1.54% zinc [6].

Similar materials might have been used for making the brass-bronze items of Atranjikhera during the PGW era (1200-600) BC [7]. One copper-based item contained 11.68% Sn, 9.0% Pb and 6.28% Zinc, while another item assayed 20.72% Sn and 16.20% Zn. Both the samples contained traces of iron and sulphur, indicating the possibility of chalcopyrite and sphalerite-galena having been the source materials, which could easily come from the Ahar-Zawar area. Most of the brass samples in ancient India contained variable proportions of Zn, Sn and Pb (Table 1).

We have drawn attention to the brass items of Lothal and Atranjikhera and their possible link with the 1260 ± 160, 1136 ± 160 BC and 1050 ± 150 C-14 dates of the timber samples in the Rajpura – Dariba silver-lead-zinc mine near Udaipur. [17-18]

During the Harappan era, copper used to be alloyed with tin and arsenic; since these were scarce commodities, alternative alloying elements had to be looked for. Artisans in the Rajasthan-Gujarat region might have stumbled on to zinc ore deposit as a new source of alloying element.

Craddock et al [19,20] surveyed the evidences of early brass artifacts in the West. The earliest brass artifacts known in the West come from excavations at the Gordion Tomb in Phrygia, dating from the 8th and 7th centuries BC onwards. These came after the Lothal and Atranjikhera traditions. From the 7th Century BC, the Greeks commented upon brass or oreichalkos, but always as an expensive, exotic metal not produced in Greece. There was no zinc in the early Greek bronzes, Etruscan bronze of the 5th century BC contained 11% zinc.

3. ZINC METAL AND HIGH ZINC BRASS

The earliest brass containing more than 28% zinc, which could be made only after the isolation of pure zinc metal [3,4] came from Taxila [8]. Craddock [21] pointed out the overriding importance of the vase (BM 215-284) excavated from the Bhir Mound at Taxila and dated to the 4th century BC. This brass sample contains 34.34% zinc, 4.25 % Sn, 3.0 % Pb, 1.77% Fe and 0.4% Nickel. This is very strong evidence for the availability of metallic zinc in the 4th century BC. Possibly India was the first to make this metal zinc (rasaka) by the distillation process, as practised for the other metal mercury (rasa).

There are references to zinc and brass in the lost (4th century BC) text Philippica or Theopompus, quoted by Strabo in his *Geography* :

"There is a stone near Andreida (north west Anatolia) which yields iron when burnt. After being treated in a furnace with a certain earth it yields droplets of false silver. This added to copper, forms the so-called mixture, which some call oreichalkos" (Strabco, *Geography*, Book XIII, Sec 56).

The above reference pertains probably to the process of downward distillation of zinc ('droplets of false silver') and its subsequent mixing with copper to make brass oreichalkos (arakuta in Kautilya's Arthasastra) described in detail in the post-Christian era Sanskrit texts.

It is quite possible that the zinc making technology travelled west from India during 6th-5th centuries BC, as it did later again in the 18th century AD. The pseudo-Aristotelian work 'On Marvellous Things Heard' mentioned :

"They also say that amongst the Indians the bronze is so bright, clean and free from corrosion that it is indistinguishable from gold, but that amongst the cups of Darius there is considerable number that could not be distinguished from gold or bronze except by colour" (quoted by Craddock [19])

The Indian emphasis was on the 'gold-like' brass and not on the zinc metal. The Greeks, however, used zinc metal as such in a few cases. In the course of the excavation of the Agora in Athens, a roll of sheet zinc was found in a sealed deposit dating from the 3rd or 2nd century BC [9]. Analysis showed it to be nearly pure zinc with 1.3% lead, 0.06 % Fe and 0.005% Cu with traces of Mn, Mg, Sn, Ag and Sb (quotated by Craddock [19]). Although Needham and Forbes doubted the above evidence on the ground that 'the pieces were beyond the contemporary technology' [21]. Craddock certifies this to be a genuine sample [21]. It is quite possible that the Greeks had carried the material or the technology which had existed in Taxila as early as 4th century BC and possibly much earlier in Rajasthan.

4. MINING ARCHAEOLOGY AND SMELTING RELATED TO INDIAN ZINC ORE

The recent pioneering work on the zinc-lead-silver mining archaelogy in the southern part of Rajasthan by Willies et al [18] and the relevant C-14 dates have firmly established India's primacy in non-ferrous ore mining in the ancient world.

The ancient workings in the South Lode (100 m depth) of Rajpura-Dariba mine (80 km north-east of Udaipur) have been C-14 dated as 1260 BC, 1050 BC and the East Lode workings as 375 BC, 360 BC, 250 BC, 120 BC, 150 AD etc. Thus, it is clear that the tradition of underground mining in India goes back to the thirteenth century BC, if not earlier. The earliest emphasis was possibly on copper ore; at Rajpura-Dariba, the other targets were lead, silver and possibly zinc ore, which is strongly suggested by the brass artifacts of Lothal and Atranjikhera.

The art of smelting zinc ore and recovery of zinc metal by distillation must have been discovered before 4th century BC when Taxila produced the brass vase containing 34.34 % zinc [8]. This possibility is reinforced by the facts of mining archaelogy. Starting from the 5th century BC, we have many C-14 datings in Rajpura-Dariba, Rampura-Agucha (40 km south of Ajmer) and most crucially, in the Zawar mine systems. Zawar (24°21' N, 73 °41'E) is about 30 km south-west from Udaipur, where the ancient mines (earliest C-14 date obtained so far is 430 BC) are found, both opencast and underground. Zawar Mala, Mochia and Balaria are some of the specific mines in this area. The host rock of the Zawar mines is sheared dolomite, the result of metamorphism of sedimentary dolomites. The ore was geologically deposited syngenetically as disseminated lenses within the dolomite beds. Zinc occurs as sphalerite or as marmatite in which zinc sulphide is in solid solution with iron sulphide. Also associated with the rock are galena, hydrozincite, pyrite, silver, etc.

Ancient workings are found at outcrops on the ridge of Zawar Mala, and as deep as the 470 m (above sea) levels of the modern Zawar Mala mine, some 120 m below surface. The upper parts accessible from there were a few tens of metres below surface, isolated by a roof fall. At the surface, mine openings occur at intervals of 50 m or so. Willies [18] investigated one mine of more commodious proportion – Pratapkhan or Pratap's mine – in which Rana Pratap Singh, rival of Akbar, took refuge during 1595 – 1600 A.D. A flat 'room' floored with phyllite slabs is inferred as Pratap's refuge. The quarried materials used to feed a zinc smelter just below the narrow valley.

The earliest C-14 datings in the Zawar mines are 430 $\pm$ 100 BC of the PRL 932 sample from the Zawar Mala mine and 380 $\pm$ 50 BC of the BM 2381 sample from the Mochia mine. Similar datings from Rajpura – Dariba (e.g. 375 BC), Rampura Agucha (370 BC), etc. confirm widespread underground mining of lead-zinc ores in the southern Rajasthan during the fifth-fourth centuries BC onwards.

Subsequent C-14 datings in the said mining area are : 250 BC, 200, 170, 140, 120 BC, 60 AD, 110AD, 150 AD.

As regards the recovery of zinc from the ore, the crucible reduction/distillation method was put to large scale commercial practice in the 13th century AD; this will be described later. Indirect and circumstantial evidences suggest that distillation method was in vogue much earlier, probably from the 4th century BC onwards, although not on a large scale, as we find in the 13th century AD context.

In this connection, we recall the evidence from Rampura Agucha [10]. The zinc-lead-silver ore at the site was selectively mined at least as early as 370 and 250 BC. An appreciable amount of zinc must have been separated from the zinc-rich ore (present-day ore in the site contains 13.5% zinc), as revealed from the low-zinc content slag. One sample of slag assayed as low as 0.01% zinc [10]. Near the slag dump area several retort-like pieces were reported. When assembled, their appearance suggested a cylinder approximately 20 cm long with walls 4-5 cm thick and an innermost pipe-like feature with a coating dirty white material, mainly zinc sulphate. They could be mistaken for tuyeres but for their closed pointed ends. This is highly suggestive of a used retort. Along with this, some thin walled tube-like object containing a thin coating of blister type material was also found. It is conceivable that the retorts were being used in the said context for roasting zinc ore to obtain the light, white, smoky zinc oxide, which the ancient Greeks called pompholyx or philosopher's wool. In the modern zinc plant at Udaipur, roasting of zinc sulphide concentrate produces not only zinc oxide (and sulphur dioxide gas) but also some zinc sulphate, which was detected in the 4th-3rd century BC retort in Rampura Agucha. The said retorts, already found sealed at one end, must have been closed or sealed at the other and also to prevent the escape of smoky zinc oxide into the atmosphere. The retorts were possibly modified to serve as reduction distillation chambers (to produce metallic zinc), the final version of which, notified in the 13th century AD context, would be described later. Very significantly, Tiwari et al. [10] noted that the slag sample from Agucha containing only 0.01% zinc but as high as 9.30% lead, was 'attached to baked earthen materials which could be part of the earthen appliance used for smelting'. We suggest the possibility that the earthen appliance was a zinc distillation retort. Remains of zinc furnaces have been found at Sojat in Jodhpur also.

5. BRASS AND ZINC IN ANCIENT INDIA

We may now turn our attention to the antiquity of brass in ancient India. Before the discovery of zinc metal in India (made by the distillation route) sometime during the fifth-fourth century BC, brass could be made, as in Lothal and Atranjikhera, only by the cementation route in which one of the following was smelted along with copper ore : zinc ore, sphalerite concentrate or the roasted product, philosopher's wool or zinc oxide. The traditions of making philosophers' wool and cementation brass could have persisted even after the discovery of the distillation process of making zinc. We invite attention of the readers to the analysis of some Indian brass objects made before 4th century BC (Table I)

As we have indicated earlier, the distillation route of making zinc and alloying this with molten copper was the only way of making high-zinc (more than 28%) brass, such as the 4th century BC Taxila vase (34.34% zinc). The said vase (BM 215-284), excavated from the Bhir Mound site, was made before the Greek settlement in Sirkap [8]. One bangle from the second century BC Sirkap settlement assayed 19.70% zinc. The Dharmarajika settlement of the post-Christian era produced brass objects like bangle and pot with controlled compositions 77-79% Cu, 12.88-13.07% Zn, 2.5-3.5% Sn and 3-6% Pb. Some of the other early brass samples from ancient India have been reviewed by Neogi and Ray [12], an extract of which is presented below :

Brass articles of 1st century BC or AD have been found on excavation of some ancient stupas. General ventura executed operations for the examination of the stupas at Manikyalaya in 1830. Three deposits were obtained, of which the third, at a depth of 64 ft. consisted of a copper box enclosing a brass cylindrical box cast and a beautifully turned on the lathe. The lid of brass casket was found on cleansing to be inscribed. From the inscriptions on the various articles of this deposit and the accompanying Indo Scythian coins, the great tope at Manikyalaya has been identified to be a mausoleum of the Indo-Scythian King Kanishka (1st century BC or AD).

Another inscribed brass urn of the same date as the former has been discovered in a tope about 30 miles west of Kabul in Wardak district. This urn, which in shape and size approaches closely the ordinary water-vessels in use in India to this day, was originally thickly gilt and its surface has in consequence remained well preserved.

As regards coins, both brass and bronze were used in ancient India for coinage. Circular punch-marked brass coins of Dhanadeva and Aryavarma of Ayodhya (c, 1st century BC) have been found. Brass coins of kings of several other dynasties living at that time have also been collected. From these archaeological and numismatic evidences it is clear that brass was in common use in ancient India during the first century BC. A small number of die-struck coins of the Pre-Gupta and Gupta periods, including a piece attributed to Chandragupta II, are considered to be made of brass.

Table I features some of the typical brass objects in ancient India up to 11th century AD, before the advent of Muslims in the country.

6. DISCOVERY OF THE MEDIEVAL ZINC SMELTING OUTFIT AT ZAWAR, NEAR UDAIPUR, RAJASTHAN

In April 1980, the Hindustan Zinc Limited (HZL) sponsored a three-year research project on recovery of zinc from the ancient slags which was successfully conducted at the Indian Institute of Technology (IIT) Kanpur by the present author. In 1982, HZL collaborated with British Museum Research Laboratory (P.T.Craddock, Lyon Willies, etc.) and the Department of Archaeology, M.S.University of Baroda (K.T.M.Hegde) on archaeological investigations, and this led to the spectacular discovery of the zinc distillation outfit, including furnaces and retorts showing the production strategy, Craddock described the exciting discovery.

"On the third day of the excavation (December 1983), one of the Baroda team (Hegde) spotted the corner of a refractory plate sticking out from a heap of spent retorts beside a goat track in a valley on Zawar Mala ...With mounting excitement we cleared a small area above and around it to reveal first, the edges of furnace walls, and then the tops of retorts still in situ." [24]

Extensive archaeological and archaeo-material investigations followed : we now present the summary of the results of the historical experiments performed in two continents.

7. ANCIENT RETORTS AND FURNACES AT ZAWAR

During the 1983 excavations, two groups of furnaces were uncovered. A single bank of seven furnaces upon Zawar Mala contained small retorts 20 cm long and 10 cm in diameter. In old Zawar, there was a more extensive arrangement of furnaces using a larger retorts (30-35 cm long and 10-15 cm diameter). In both groups, 36 retorts in a 6 x 6 arrangement were contained within the truncated pyramid of each furnace. Thus, no less than 252 retorts were fired simultaneously in a single bank. The retorts were supported vertically on perforated bricks through which the condenser tubes passed into the cooler zinc collectors beneath.(Figs. 1-3).

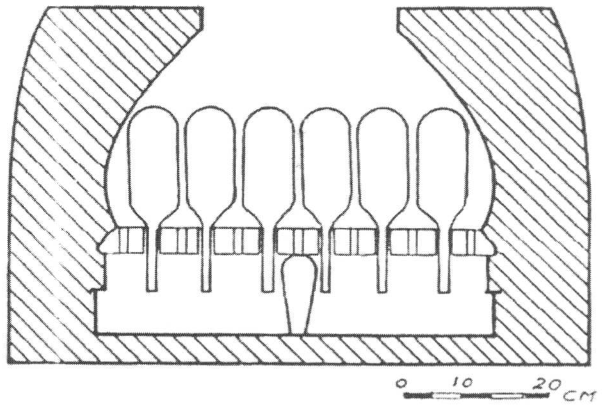

Fig. 1 : Midpoint vertical section through a zinc reduction - distillation furnace at Zawar Mala (Craddock et.al.[26])

The furnaces are in two parts consisting of a zinc vapour condensation chamber at the bottom and a furnace chamber at the top. The two chambers are separated by a perforated terracotta plate. The condensation chamber measures 65 x 65 cm and 20 cm in height. The perforated terracotta plate that separates the two chambers is a composite unit made up of four equal segments of 35 cm^2. It is 4 cm thick, well-baked, and sturdy. Its perforations include circular holes of two sizes : larger ones of 4 cm diameter each of which is surrounded by a number of smaller holes of 2.5 cm diameter. Within the furnace, the composite terracotta plate was found to be supported on a ledge in the furnace walls on all

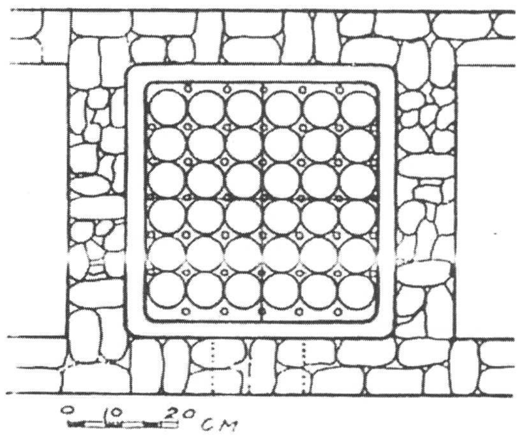

Fig. 2 : Horizontal section through the furnace in Fig.1 at perforated plate level (Craddock et.al.[26])

four sides and a single solid terracotta pillar placed below the junction of its four segments [26].

Up above the perforated terracotta plate is the furnace chamber, in which 36 charged retorts (Figs.1-2) were arranged, inverted vertically; it may be presumed that 36 vessels were placed, one underneath each retort, to collect the condensed zinc vapour. This arrangement of downward distillation retort with the condensing unit underneath or 'distillation per descensum', is precisely what had been described in Rasaratnasamuccaya text (2,157-166, 9.48-50). The brinjal-like retorts in Zawar (Fig.3) are also similar to the vrntakamusa described in Rasaratnasamaccaya (10.22-23).

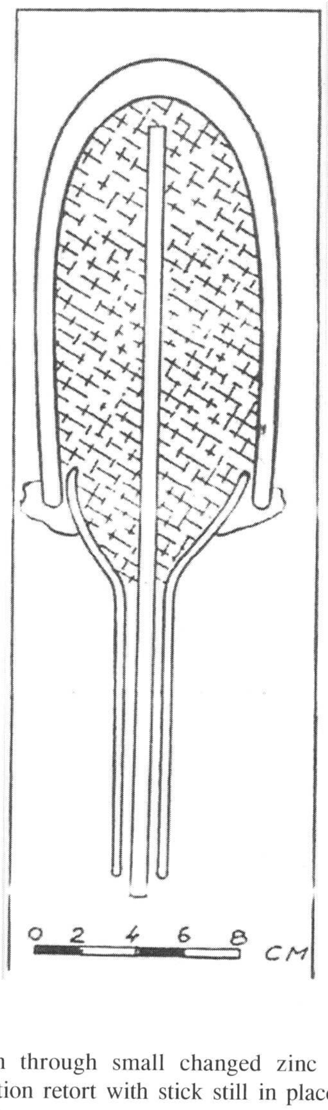

Fig. 3: Section through small changed zinc reduction - distillation retort with stick still in place (Craddock et.al.[26])

It appears that a cylindrical reed of 1.5 cm diameter was inserted into the retort after it was charged and the funnel part was luted on it (Fig.3); this is evident from the central hole which is preserved in many retort residues. The reed helped to keep the charge within the retort when it was inverted and placed in the furnace. When the furnace was fired, the reed burnt away leaving behind a cylindrical flow channel for the zinc vapour to flow freely out of the retort. The ore must have been roasted before smelting.

The smelting charge must have included a small quantity of common salt (as surmised from the chlorine and sodium contents in the retort residue) and an adequately large quantity of carbonaceous matter, apart from the calcined ore, and then rolled into pellets of 1 cm^3 volume (Rasa Ratna Samuccaya or RRS 2.163-164 refers to the gutikakrti pellets containing sodium bicarbonate and borax). The charge (about 1.5 kg per retort) was loaded into clay retorts fitted with funnel like condenser tubes, as described before (Fig.3). These were indeed the brinjal-shaped crucible or vrntakamusa, as described in RRS(2.157, 2.163, 10.23-24, etc.). On heating in the furnace, zinc oxide was reduced by a carbonaceous matter to zinc vapour. The reducing blue flame of carbon monoxide was observed to be substituted by white flame of zinc vapour, indicating that reduction had taken place (bhavet bila sita yadi – RRS 2.159-160).

Using a scanning electron microscope and observing the vitrification textures of the Zawar retort and clay materials, Freestone [25] estimated that the temperature reached in the Zawar zinc distillation furnace was of the order of 1150-1200°C, and that this temperature was maintained for 5 hours ore more. The highly endothermic reduction of zinc oxide must have been achieved at a very low partial pressure of oxygen (less than 10^{-20} atm) to prevent re-oxidation of the metal. Zinc vapour condensed in the tube, the temperature being around 500°C, and collected in the vessels placed below. This kind of downward distillation or tiryakpatana of zinc vapour, produced under a highly reducing atmosphere, has been described in RRS (2.163-168, 10.48-50).

A part of the zinc oxide was converted to well-identified silicate phases and thus could not be recovered as reduced metal.

Freestone et al [25] estimated that 200-500 g zinc was extracted per retort, or 7-18 kg per smelt of 36 retorts. Each retort weighs about 3 kg. Thus, the debris of around 6 lakh tons of spent retorts corresponds to about 1 lakh ton of zinc, according to Freestone et al [25] which might have been produced at Zawar during 13th-18th centuries AD. This has been indeed one of the most outstanding levels of industrial production in the medieval world.

8. PHASE STUDIES ON ZAWAR SLAGS AT IIT, KANPUR

Six lakh tons of spent retorts contain two lakh tons of residues within, assaying about 3% zinc. Therefore, some 6000 tons of zinc metal remain within the retort residue, and probably another 1000 tons in the lead slag. Our research at the Indian Institute of Technology (IIT) Kanpur, sponsored by the Hindustan Zinc Limited, was directed towards the recovery of zinc from these two kinds of slags. The first step in our world was characterization of these residues, which turned out to be very useful and relevant to the archaeo-metallurgical problem. The phases identified by X-ray and electron diffraction studies by Biswas et al [23] are summarized in Table 2.

The results show that in the roasting operation prior to retort distillation, a small part of sphalerite was not converted into oxide and remained in the retort as ZnS and $ZnSO_4$. The presence of goslarite or $ZnSO_4.7H_2O$ (hydrated at a later stage) was confirmed by the endothermic DTA peaks apart from X-ray and electron diffraction studies. Some ZnO might have remained unconverted in the retort to undergo atmospheric conversion to basic carbonate at a later stage. While most of the ZnO was reduced to metal, a part of it must have been converted at a high temperature to phosphate and silicates from which the metal could not be recovered. Biswas et al. detected a number of zinc, calcium-zinc, lead-zinc, calcium-lead-zinc and magnesium-aluminium silicates [23]. Later, Freestone et al [25] reported that lead slag contained iron, calcium-iron, calcium-zinc, magnesium and calcium-magnesium silicates. The only silicate phase that Freestone et al [25] could report in the retort residue was $CaMgSi_2O_6$ or diopside.

Biswas et al [23] obtained secondary electron images of retort residue samples and found that the particles have a variety of morphology : plates, needles and spheres. Scanning electron microscopy and X-ray microanalysis showed characteristic peaks of many elements, the most prominent being those of silicon

Table 2

PHASES IDENTIFIED IN ZAWAR RETORT (CONTENT), WALL AND (LEAD) SLAG BY X-RAY AND ELECTRON DIFFRACTION STUDIES (BISWAS et al [23])

Sample	Phases identified	
	X-ray diffraction	Electron diffraction
Retort content	$Zn_2P_2O_7.5H_2O$ Goslarite $ZnSO_4.7H_2O$ Hemimorphite,$Zn_4(OH)_2Si_2O_7H_2O$ Esperite $Ca_2Pb\ (ZnSiO_4)_4$ Sphalerite Zns, Chalcopyrite $CuFeS_2$, larsenite, $PbZnSiO_4$	$Zn_2P_2O_7.5H_2O$, goslarite, hemimorphite, esperite, quartz. $Mg_2Al_2Si_4O_{18}$ $Ca_2ZnSi_2O_7$, hardistonite or aurichalcite $Zn_5(CO_3)_2(OH)_6$
Retort Wall	Goslarite, hardistone, hemimorphite, $Zn_2P_2O_7.5H_2O$ aurichalcite, quartz, sphalerite	Goslarite, hemimorphite, willemite Zn_2SiO_4 hardistone
Slag	Quartz, goslarite $Zn_2P_2O_7.5H_2O$, hemimorphite Sphalerite, chalcopyrite, hardistone	Hemimorphite, goslarite, hydrozincite, quartz. sphalerite

and calcium. Scanning was done using a fine electron probe on the zinc-containing particles in the size range of 0.5 - 40 mm.

Several of the small particles (0.5-8.0 mm) show approximately constant values for the ratio of intensities corresponding to the elements Si, Ca, Mg, Fe, Al, Zn, Pb, Mn, Na, K and S (in decreasing order of occurrence), indicating that these particles containing a few of the above elements are homogenous in nature. The larger particles show wide variation in intensity ratios and hence variation in the chemical composition of the grains from point to point. Thus, the approximate size of the zinc containing and other homogenous grains in the retort residue is in the range 0.5-8.0 μm.

The size of the particles in the lead slag sample was found to be lower than that in the retort residue. The size of the zinc-containing grains was estimated to be in the range 0.5-6.0 mm. mm, by carrying out point to point analysis. The X-ray spectrum showed the presence of titanium apart from the other elements noted in the retort residue.

The work at IIT Kanpur was directed primarily towards the recovery of zinc from the siliceous retort residue and slag at Zawar. We found that the non-silicate phase, such as hydrozincite $Zn_5(CO_3)_2(OH)_6$ could be easily leached by acid. A special 'fast leaching' technique, making use of the water-starved nature of the silicate-sulphuric acid system, could recover more than 80% of the zinc contained in the silicate phases, such as hemimorphite $Zn_4(OH)_2Si_2O_7H_2O$, willemite Zn_2SiO_4 etc.

The characterization work done at IIT, Kanpur [23], has established the existence of complex zinc phosphate-silicate phases in the slag which could have been produced only by the above 1000°C pyrometallurgical smelting process. This corroborates the conclusions reached by Craddock et al [26].

The large scale manufacture and widespread use of zinc and brass in medieval India need to be fully chronicled. Table 3 records a few brass icons of India for the period 1350-1752 AD; the high zinc content, sometimes in the range 35-40%, in these icons is particularly not worthy. Item No.9 in Table 3 is dated 1752 AD - five years before the War of Plassey, and eight years before the Zawar production was slowed down on account of the Maratha invasions. During the medieval period, the Moghuls had used brass (as well as bronze) for manufacturing guns and artisans of Bidar (83 km from Hyderabad) used high zinc (84%) brass or bidri alloy for ornamentation over it by gold or silver ware.

The etymology of the words denoting zinc became clearer. Madanapala - Nirghantu of 1374 AD mentioned yasadam vangasadrsam or the 'zinc metal (yasada) like tin' (Table 4). Yasada means that which gives yasa or fame; the connection was clear in so far as zinc was known to produce the famous gold-like yellow alloy of brass (vide 2nd century AD text Rasaratnakara 1.3). The European word 'zinc' was probably derived from yasada; the Sanskrit word became jast (Abdul Fazl) and dasta in several Indian languages.

In 1597, Libavius (AD 1545-1616) received Indian zinc, which he called 'Indian or Malabar lead'. He was uncertain what it was. Although Paracelsus (1616 AD) is generally credited to have given the name 'zinc' to the metal, large scale export of the metal from India to the West started later in 17th century, and according to Roscoe, the identification of zinc as the metal from blende or calamine was accomplished by Homberg in 1695.

9. BIDRI AND OTHER ART WORKS IN PRE-MODERN INDIA

In pre-modern India several traditions of art works based on metals, alloys, gems and stones flourished and became internationally famous. Many of these traditions started in ancient India and continue vigorously in modern India.

Bidri ware, the sleek and smooth dark coloured metalwork with intricate eye-catching designs on its glossy surface, is famous all over the world. This metalwork as well as the technique to produce it are found in India alone [28-32].

Bidri is an alloy which contains 76 to 98 % (normally in the neighbourhood of 95 %) zinc, 2 to 10 % copper, upto 8 %. lead, 1 to 5% tin and trace of iron (vide Table 5). Occasionally high percentage (19.9) of lead and (11.4) tin have been noted. However mostly it is high zinc low copper alloy. Up to 1 % copper in the zinc forms the terminal solid solution

Table 3
BRASS ICONS IN INDIA (1350-1752 AD)

S.No.	Site	Item	Elemental percentages					Impurities
			Cu	Sn	Zn	Pb	Fe	
	Medieval	Period						
1.	Gujarat 1350 AD	Ambika	68.4	1.6	18.5	9.5	-	Fe, Ag, Bi
2.	Gujarat, 1480 AD	Model Temple with four doors 10 x 24.5 cm	68.6	0.2	28.9	1.6	-	Fe, Mg, Bi
3.	Gujarat 1485 AD	Vishnu-Narayana	58.9	0.5	36.8	2.1	-	Fe, Al, Ag, Si, Mg, Bi
4.	Rajasthan 15-16 AD	Rajput Prince on Horse	72.9	0.4	21.8	2.7	1.0	Al 0.3, Ag, Mg
5.	Gujarat 1554 AD	Kal Bhairava	76.7	1.2	13.8	6.3	1.5	Al, Mg
6.	Gujarat 17 AD	Chauri-Bearer	58.3	1.5	35.5	2.3	-	Fe, Ni, Al, Ag, Cd, Si, Mg
7.	Rajasthan 17 AD	Dipalakshmi Rajput Girl	58.8	0.9	33.2	4.5	0.8	Al 1.6, Mg
8.	Gujarat 18 AD	Dipalakshmi	52.8	1.1	39.9	2.9	-	Fe, Al
9.	Gujarat 1752 AD	Tirthankara-Seated	62.3	-	36.0	0.5	-	Fe, Ag, Bi
10.	Nepal	Sadakasari Lokesvara Form of Avalokitesvara	60.5	2.75	35.3	2.37	-	Fe, Ni, As, Au

η ; above 1 % copper the ϵ phase precipitates at the grain boundaries in this phase field. The usual yellow brass may contain not more than 40-50 % zinc, often less; copper constitutes the remainder or the predominant phase. Thus brass and bidri represent the two opposite ends of the zinc- copper phase diagram.

The Bidri ware's surface is first made smooth and a solution of copper sulphate applied to it to darken it temporarily for engraving. The engraving tools cut the intricate but delicate tapestry of design into the metal which is then lighter in colour than the darkened surface and enables the pattern to be seen clearly.

The piece is then handed over to the inlayer. The inlay may be of silver, brass or occasionally gold. The final stage after the inlay has been burnished, is to blacken the surface of the piece so that the inlay

Table 4
SOME LITERATURE ON ZINC

Period	Topics
1374 AD	Madanapala – Nighantu refers to Yasam vangasadrsam (zinc – tin like) : Yasada means that which gives yasa or fame, converts copper into yellow gold-like brass
1597 AD	Libavius receives a sample and calls it Indian or Malabar lead
1616 AD	Paracelsus calls it 'zinc' from Yasada, in several Indian languages : dasta
1695 AD	Homberg identifies Indian zinc as the same metal from European calamine
Before 1730 AD	An Englishman transmitted Zawar technology to the West – identity not known
1730 AD	William Champion's experiment at Warmley near Bristol; patent in 1738. Cost of metal ≤ 260 a ton, whereas calamine cost only £ 6 a ton
1743 AD	Champion starts manufacturing zinc by distillation per descensum – process 'notoriously close to the Zawar process' (Morgan and Craddock)
1751 AD	Postlewayt's Disctionary of Trade and Commerce admits ignorance about zinc technology. India continues making high Zn brass statues
1800-1820 AD	Zawar zinc industry devastated by famine and Marhatta invasion
1886 AD	V.Ball quotes Beckmann's History of Inventions (Bohn's Edition, ii.p.32) : "An Englishman went to India in the 17th century to discover the process used there in the manufacture of zinc, and returned with an account of distillation per descensum. I have not yet been able to identify this Englishman".

stands out. This is done by applying a paste of ammonium chloride, potassium nitrate, sodium chloride, copper sulphate and mud which darkens the body by producing a characteristic black patina while having no effect on the inlay. The paste is later washed off and finally oil is rubbed into the piece to deepen the blackness of the patina. The result is a lustrous dense black body to contrast with the shining lining – white (silver) or yellow (brass or gold).

10. REPLICATION EXPERIMENTS AND CHEMICAL HYPOTHESIS

La Niece and Martin [32] performed some replication experiments to show that the black colour of the patina was due to copper. The recipe for blackening the bidri metal has the main constituents in a warm solution of potassium nitrate (one part) often substituted by well-urinated soil, and ammonium chloride (four parts).

In a replication experiment a clean pure zinc sheet was immersed in the above solution, when a pale grey patina of zinc oxide and chloride was produced. When the experiment was repeated with the addition of copper sulphate, a reasonably good but superficial black patina formed almost instantaneously. Again only zinc oxide and chloride were the main crystalline products. XRD analysis identified $Zn_5(OH)_8Cl_{12}H_2O$,ZnO and Cu_2O (cuprite) as the crystalline phases. None of these explains the blackness of the patina which was amorphous and contained copper.

Similar experiments were performed with a specially prepared alloy of zinc containing 3 % copper. When this alloy was dipped in a warm solution of potassium nitrate and ammonium chloride, it turned as deep black instantly and the patina was even and adhered well to the metal surface. This was found to be non-crystalline. Scanning electron microscopy showed the patina to be about 10 mm thick assaying 30 % copper

Table 5

RESULTS OF ATOMIC ABSORPTION SPECTROMETRY ANALYSIS OF BIRDI WARE (Taken from La Nilece et al [32])

Victoria & Albert Museum Acquisition nos.	Description	Percentage by weight content				
		Zinc	Copper	Lead	Tin	Iron
2539-1883 I.S.	Huqqa	91.2	3.2	2.9	1.2	0.2
1578-1904	Huqqa	98.0	3.3	1.4	0.1	0.2
45-1905	Huqqa	88.2	3.0	2.9	0.7	0.5
I.S. 46 - 1977	Weight	92.6	4.7	1.4	5.7	0.1
1479 - 1904	Ewert	89.3	4.8	0.8	< 0.1	0.8
I.S. 10 - 1973	Bowl	92.1	3.6	1.4	0.3	0.1
02942 (I.S.)	Huqqa	84.6	3.3	1.0	0.1	0.5
I.S.131 - 1958	Pan box	95.0	3.1	1.5	0.1	0.1
I.S. 181 - 1965	Huqqa	76.1	10.1	8.2	11.4	0.6
I.S. 31 - 1976	Bottle	98.6	2.6	1.0	0.4	1.2
857 - 1874	Huqqa	92.1	3.6	0.8	0.6	0.4
I.S. 17 -1 1970	Pan box	81.3	2.0	2.0	< 0.1	0.5
02949	Bottle	83.8	2.5	6.6	< 0.1	0.2
02949	Bottle	93.2	2.4	1.1	0.1	0.2
855 - 1874	Huqqa	99.2	2.6	0.4	0.2	0.6
02941 (I.S.)	Basin	91.2	2.8	2.1	0.1	0.2
I.S. 4 -1977	Huqqa	83.6	3.7	0.8	< 0.1	0.6
I.S. 19 - 1978	Huqqa	85.3	4.6	3.0	1.3	< 0.1
120 - 1886	Bottle	86.7	5.3	1.9	0.2	0.1
I.M. 224 - 1921	Bottle	91.7	3.6	0.7	0.7	0.7
2066 - 1883	Box	79.6	2.7	19.9	0.1	0.5
1402 - 1903	Huqqa	95.3	2.7	1.1	3.0	0.5
I.S. 11 - 1973	Vessel	97.6	3.4	1.8	< 0.1	0.1
I.S. 39 - 1976	Huqqa	89.2	3.4	0.5	0.7	0.7
I.S. 19 - 1980	Huqqa	80.6	3.6	7.3	6.4	0.9
856 - 1874	Huqqa	77.4	4.4	0.9	0.4	0.1

as a contrast to 3% in the bulk. Zinc and chlorine were the other elements detected.

La niece and Martin [32] have postulated that ammonium chloride preferentially dissolves the zinc from bidri and the resulting copper-enriched surface or the copper-rich $\in$ phase precipitate gets oxidised by potassium nitrate producing the black colour. The use of clay does not seem to be crucially important. It could merely serve as a source of alkali nitrate and as a poultice to absorb the unwanted zinc chloride formed during the process. The matt black patina is easily damaged by the standard cleaning techniques designed to remove the white decomposition products from the zinc [29].

11. HISTORY OF THE ART TRADITION

The mystery of the black patina is not yet fully solved. The inventors of the tradition did not have any ideal about the underlying scientific principles; they merely hit upon the arts and crafts aspect of the process.

The craft of bidriware is a kind of damascene work which has been defined by Sir George Birdwood as 'the art of encrusting one metal on another, not in crustae, which are soldered or wedged, but in the form of wire, which by undercutting and hammering, is thoroughly incorporated into the metal which it is intended to ornament. The original tradition at Damascus was to encrust gold wire, and sometimes silver wire, on the surface of iron, steel or bronze.

A group of the damascene craftsmen moved from Syria or Iraq to India. Some of them were at Ajmer in Rajastan and hit upon the idea that damascening could be done on the base of high zinc low copper alloy. Zawar in Rajastan was the major zinc production center in the medieval world. the said craftsmen moved down south during the 15th century A.D. and settled at Bidar (17 °55'N and 77°3' E) near Hyderabad. when the art flourished in that place for centuries, it became known as Bidriware crafts.

The earliest known craftsmen like Abdullah-bin-khaiser and his pupil Sivanna worked at Bijapur. Historical evidences indicate that the beautiful articles presented to Alauddin Bahamani II (1434-1457 A.D.) on the occasion of his coronation impressed him very much, and he invited the craftsmen of Bijapur to settle at Bidar itself. The workers used to prepare beautiful huqqa base, ewer bowl, pan box, basin, bottle, slabchis, cot legs etc. The varieties of workmanship of the design consisted of tarakashi (inlay of wire), taihnishan (inlay of sheet) zaranishan (low relief, inlay levels with surrounding area) ,zarabuland (high relief, for examples silver over a lead pad, aftabi (design in overlaid sheet) etc.

The russian traveller Althanasins Nikitin, who visited Bidar during 1470-1474 A.D., took with him some of the early Bidriware specimens for presentation to the Russian Emperor. A large number of articles of Bidriware were made for presentation to the Prince of Wales when he visited India in 1875. These now adorn the collection of the Victoria and Albert Museum which has published a comprehensive bibliography and illustrated catalogue on the subject. Bidar and Hyderabad museums also have beautiful collections of this kind of ware.

Mahmud [28] has given some details about this craft under specific heading such as raw materials, tools, implements, process of production, preparation of alloy, mould making, casting (such as goblet) etc. The manufacture of Bidriware has been carried on under a system of division of labour. The moulder prepares the alloyed metal, casts the vessel and turns it to its proper shape by his lathe. The carver engraves the patterns on the surface of the vessel, and the inlayer designs the patterns, inlays the ornament of gold, silver or brass, and finally polishes the article. In the pre-modern India there have been four seats of Bidriware manufacture: Bidar, Lucknow, Purnea (Bihar) and Murshidabad (Bengal).

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