The Development of Water Pipes: a Brief Introduction from Ancient Times until the Industrial Revolution

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Summary

For as long as humans have built cities they have been concerned with the supply of water, for drinking and irrigation, and its removal to prevent flooding. With the exception of plastics, all of the materials we use today for pipes for the conveyance of water have been in use for centuries. This paper seeks to explore exactly how long each material has been used and by doing so to bring together the diverse sources for the history of the water pipe into one single paper, which will hopefully act as a useful guide for any historian seeking to start out on a study of water supply and drainage.

Definition

There are many ways of conveying water. For the purposes of this paper a pipe is defined as a hollow tube that is designed to be completely filled with water. This distinguishes it from a tunnel or an open conduit. Of course the pipe may not always be full of water. If it is for drainage it will probably be empty for much of the time. However when operating at full capacity or when used for supply it will probably be full and the water may be stationery or moving through it. The problem of making pipes is thus how to create a long tube that keeps the water in and is strong enough to resist breaking from the ground pressure above and from the water itself. As such tubes are of a finite length, the problem of making pipes is also the problem of joining those pipes together to form a pipeline without the water leaking out at the joints, which are inevitably weaker than the pipe itself and in providing an airtight seal at those points. Pipes need valves and taps (faucets) but these are not the subject of the current paper. What is of interest here is purely the pipe and the pipeline it is used to make. Pipes are discussed (usually in passing) in books on water supply and drainage.

Introduction

The literature on water supply is very extensive and too large to give but the briefest of summaries here. A good reasonable introduction can be found in Steven Solomon's *Water* [1]. The *Evolution of Water Supply Through the Millennia* [2] provides a good overview through the ages, with papers written by experts in each field. It lacks an overall bibliography, but the key works can be found in the notes in each section. This provides a good survey of the archaeological evidence for the pre-Roman period. A.Trevor Hodge's *Roman Aqueducts and Water Supply* remains the best source book for Roman water supply [3]. David Yeomans elsewhere in this current volume of proceedings notes its occasional lapse in technical understanding of hydrodynamics, but in terms of history and archaeology it remains sound and by far the best introduction. More recent research on Roman topics can be found in *Evolution of Water Supply Through the Millennia* cited above. Roberta J.Magnusson, *Water Technology in the Middle Ages* remains the best introduction to medieval water supply [4]. It has an excellent bibliography and much of the key information is in the notes. See also K. Grewe (ed), *Die Wasserversorgung im Mittelalter* [5] in the series of books produced on water supply by the Frontinus Society in Germany, which is the most important society for the study of water supply [6].

Because each of these texts concentrates on a particular period, none of them provides a summary across periods, so this is what the current paper sets out to do. The aim is to provide a very basic summary of early pipe technology from the

first pipes to the eighteenth century- that is ending before the mechanisation of pipe manufacturing that would begin the extrusion of ceramic pipes in the nineteenth century and the later extension of extrusion technology to metal pipe mass production which is a different story deserving of a paper in its own right. Pipes before mass production were made in seven materials: stone, terracotta, copper, lead, timber, brass/bronze and iron. Each will be examined in turn, each section attempting to identify when the materials were first used, how the pipes were made and the various types found and their uses for dating. The paper is organised roughly chronologically, with the earliest material first, although all these materials had a long usage, so once invented they carried on being used in various regions throughout the period.

Stone Pipes and Conduits

As we know that the Neolithic age predates the invention of ceramics, it might be assumed that the first pipes were in stone not clay. In fact, while the earliest settlements often required drainage and irrigation and occasionally this involved cutting channels in stone, these are invariably conduits or tunnels, not pipes. A conduit is an open topped trough through which water flows. It can be covered by a flat slab to create a covered waterway, but this is not a pipe. Many aqueducts from ancient times used stone conduits. Tunnels through rock also date from remarkably early periods, being covered conduits carved from solid rock, large enough for a man to crawl through. Hezekiah's tunnel in Jerusalem [7], the qnats in Iran [8] and the Epauline tunnel in Samos [9] are all early examples. Pipes are not tunnels or conduits. They are made in sections. A pipe is usually tubular on the inside (the external shape is irrelevant).

Manufacture

It is extremely difficult to create pipes out of stone. It involves boring or carving a hole through a block. This was time-consuming before the invention of metal tools and powered drills. Even when it could be achieved the joints were difficult to make. While stone pipes are not as common as pipes in other materials, there are still a remarkable number of examples. While other types of pipe tend to be cylindrical on the outside, stone pipes were often square in section with a cylindrical hole drilled down the middle. Where they were cylindrical on the outside this was to reduce weight which was a significant problem. A continual problem with stone pipes was pore selection of stone which subsequently proved to be porous and thus led to water loss (see below).

Examples

Perhaps surprisingly most stone pipes date from the Roman period where they were used in aqueducts. Stone pipes have been found in Amathus in Cyprus [10]. The site dates back to the Classical Period (750-325BC) but the pipes are probably related to the Roman repairs and improvements carried out after the earthquake in 77/78. The pipes are carved by hand with an internal dimension of 240mm and an external dimension of 700mm. The walls of the pipe are thus comparatively thick (220mm+) so that the pipe remains structurally sound. The pipes have a projecting rim on the male side which connects with a recessed edge on the other, the joints being sealed with lime mortar. Occasion rectangular holes in the upper surface allow air pockets to be removed. These stone pipes were part of a much larger water system and aqueduct which also used terracotta pipes. The stone pipes were used in the last section closest to the fountain. The reason for their use here is unclear. Perhaps they were thought to offer greater resistance to tremors. Stone pipes were also sometimes found in Roman aqueduct siphons, built into the structure and the Roman also used them occasionally for 90 degree joints in terracotta pipelines and in very short lengths as outlets in fountains. The principle use of stone pipes in Roman times was in aqueducts, particularly for siphons. Hodge provides a great many examples with pictures [11]. Particularly worth noting are Cadiz in Spain; Aspendos and Patara in Turkey; Zadar in Croatia; and the Bethlehem Siphon in Israel (sections of which are preserved and on display in the Museum of Israel). The Cadiz blocks are typical- they 860 x 800 x 280-

500mm and similarly had projecting rims. The holes to create the pipe were drilled and were 220-250mm in diameter [12].

Fig.1 Roman stone pipe from Bethlehem (photo by Ian Scott, commons licence

https://commons.wikimedia.org/wiki/File:Roman_water_pipes_(3743430835).jpg)

The stone pipes are also occasionally found in later periods, although they are generally rare, no doubt due to the difficulty of their manufacture. For instance, in the Middle Ages stone pipes are recorded for wall of Mildenburg, in Miltenberg, dating from before the 14th century and possibly even re-used from much earlier [13]. The stone pipes specified for use in Renaissance Rome were notable failures. In June 1571, Guilielmo della Porta began constructing a new trunk line in a type of travertine made out of "stone from the Orta quarry" which he described as "a type of travertine" [14]. The pipes were in three sizes, 1.3m, 1.8,m and 2.7m in length and 350mm in bore [15]. Problems became immediately apparent when tests were carried out in October 1571 on the first 100m laid and the pipes were found to "leak like a sieve" [16]. Elsewhere in this volume Dermot O'Dwyer discusses the manufacture of stone pipes by William Colles (1702-1770) in Kilkenny in the 18th century and how these were also unsuccessful. Similarly Victorian stone pipes are also on display in the Manchester Museum from the ill-fated Stone Pipe Company that in 1812 won the contract to supply pipes for the Manchester Water Company that proved too porous to use [17]. All these, however, are rare examples. Stone was difficult to make into pipes and the resulting sections were heavy. Clay and terracotta was lighter, cheaper and easier to use.

Terracotta Water Pipes

Throughout the world, from the earliest periods, pipes were created out of fired clay and ceramic water pipes of stoneware or terracotta remain in use to this day. Whilst today ceramic water pipes tend to be used for drainage systems and sewers, in the earlier examples they were used for water supply as well as water removal. The earliest known fired clay pipes are found in the Bronze Age with well-recorded examples in Mesopotamia, Mohenjo-Daro in the Indus Valley, and in Minoan Crete. Such systems were also widely used in Mesopotamia and in Archaic and Classical Greece, in Egypt and in China. They seem to have been less common in early settlements in North and South America.

Manufacture

It is possible to make clay pipes by rolling clay flat and then winding it round a central wooden form but it is difficult to form the seam. A more practical method is to roll the clay by hand and bend the rolls into loops and put the loops on top of each other, smoothing out the ridges by hand. Such pipes are rough on the inside and irregular in shape. For this reason, although occasionally found, the method was rarely used and most clay pipes seem to have been generally made on a potter's wheel. The potter's wheel seems to have been in use in Sumeria and the Indus valley around 3500 BC which coincides with the earliest pipes.

Pipes are made in exactly the same way as pots or vases. The clay is spun and lifted into the tubular shape. When complete, the base is removed with a knife and the finished pipe lifted off. The use of a wheel puts a practical limit on the length of pipe that can be produced, which is roughly 300-500mm long. This meant that, before machine production, clay pipelines had to have many joints and the pipes had to be designed to fit together as tightly as possible to avoid leakage. The diameter is typically 100-150mm. Very occasionally clay pipes were made by re-using other vessels: for example, in Bibracte, in Burgundy in France, a Roman pipeline is made entirely from re-used amphorae with their tops and bottoms sawn off [18]. As they tapered they fit into each other. The typical bore is up to 110mm [19]. The clay was fired in pottery kilns. No evidence has been found that specific kilns were set up for pipes, the presumption being that pipes were made and fired alongside other types of pottery vessels, the technology being the same and the size (before mass production) comparable. Glazing seems to have been applied to interior surfaces from early periods but more study needs to be done on how this was carried out. Glazing is rarely mentioned in texts. The easiest method, salt-glazing, damaged kilns and thus salt-glazed pipes would have been made alongside other salt-glazed products, but I have not seen this mentioned in existing texts.

Jointing

The making of clay pipes on wheels menat that lengths tended to be short and there were many joints. The four basic forms of clay pipe are found. The simplest type are conical. In this form, each pipe is inserted in the next in the direction of flow. In the second type, a projecting flange on one end fits into a flared end at the other. In the third socket type the pipe is outer surface of the pipe slightly recessed at one end, fitting snugly into the normal end of the pipe at the other. Lastly there is the form found commonly today, called the bell and spigot where the end of the pipe flares out in bell shape, into which the other regular end of the tube fits. All types of joint will be caulked with mortar. The Romans used a mixture of lime putty and oil.

Some Early Examples

There is some discussion over the identification of the first clay water pipes. It is doubtful that there was a single source: it is more likely that the same idea rose to prominence at about the same time in a number of regions, not long after the invention of the potters wheel that made the manufacture of pipes a realistic possibility. Certainly there are surviving ceramic pipes found in a number of sites in ancient Mesopotamia [20]. At more or less the same time extensive terracotta pipe systems were employed at Mohenjo Daro in the Indus Valley, where the water system was so complex that it included

large pools or baths [21]. Early Minoan Crete (3200-2300 BC) developed a sophisticated water system which included wells, cisterns, piped water and aqueducts [22]. Those in Knossos were conical in design, about 800mm long and 170mm at the widest end, tapering to 85mm at the narrow end. As Angelaskis et al. observe, this shape was inefficient in terms of water flow but made the pipes easier to make and seal [23]. The Ancient Greeks used conical pipes but they also used cylindrical ones. For instance, examples in the aqueduct at Naxos constructed in the late sixth century BC are jointed using sockets [24]. In China stoneware and terracotta pipes were used extensively from the time of the first Emperor onwards [25]. The earliest examples from the 3rd century BC from buildings near the tomb of the first emperor in Lintung are pentagonal in cross section (and thus made by hand by folding a flat sheet), but elsewhere conventional cylindrical pipes were normal. These had socket joints [26]. The Romans took and developed Greek water technology to a new level of sophistication. Roman terracotta pipes are made in variety of forms with the most sophisticated have bell and spigot joints sealed with lime mortar and sometimes with lead [27]. Earthenware pipes continued in use throughout the Middle Ages, particularly for drains, while lead or wood piping was more popular for supply [28].

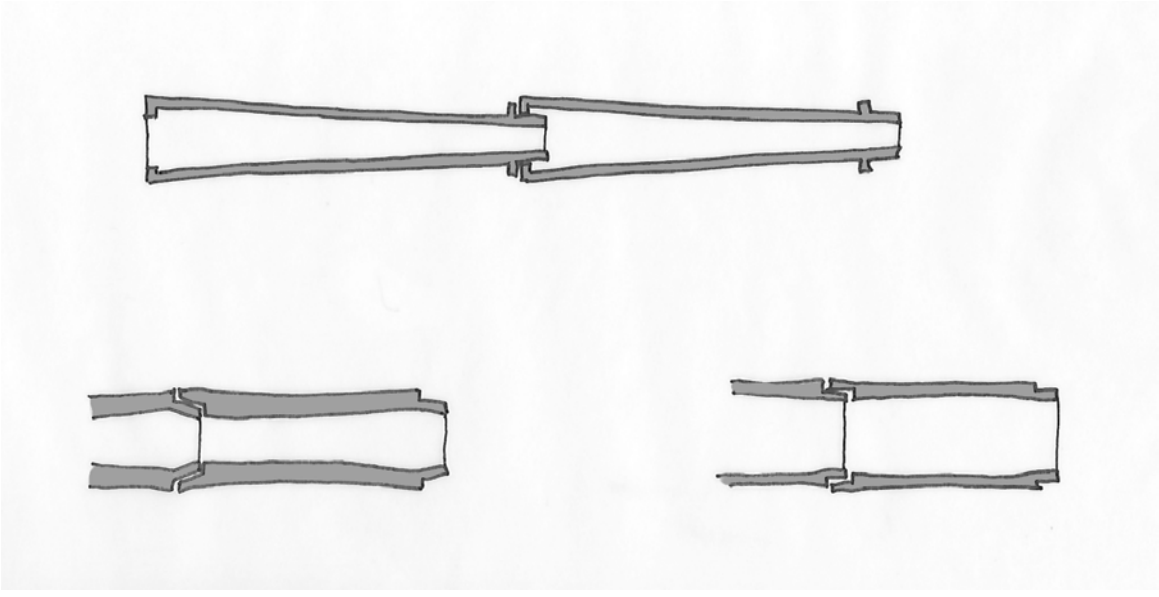

Fig. 2 Three sets of pipes from the ancient world showing the sophistication of jointing systems. Top: pipes from the palace of Knossos, Crete, which was constructed around 1600BC. Earlier pipes were often simply conical but these have complicated joints. The bottom two examples are from Athens and Corinth, possibly both Roman in period.

Industrialisation

Remarkably few innovations were made in the manufacture of ceramic pipes before the 19th century. The horse drawn pugmill, invented in the late 18th century, helped to improve the quality of clay. The horse driven pugmill led in the 1840s to the first patents for horse driven extruded pipe machinery which appeared at this time in the UK and US and would rapidly replace traditional handmade pipes [29].

Timber pipes

Today we find it difficult to understand how timber can ever have been considered suitable for making pipes but from Roman times timber pipes were routinely used. In the Medieval period timber pipelines were the most common and timber pipes were still being used in gardens for water and fountains well into the 18th century where they are frequently found in accounts and occasionally dug up. Examples can be seen in Museums all over the world [30]. Urban timber water supply systems included New York and London [31].

Manufacture

The manufacture of timber pipes is illustrated in Agricola [32] and this illustration is often featured in articles on the subject and reprinted here.

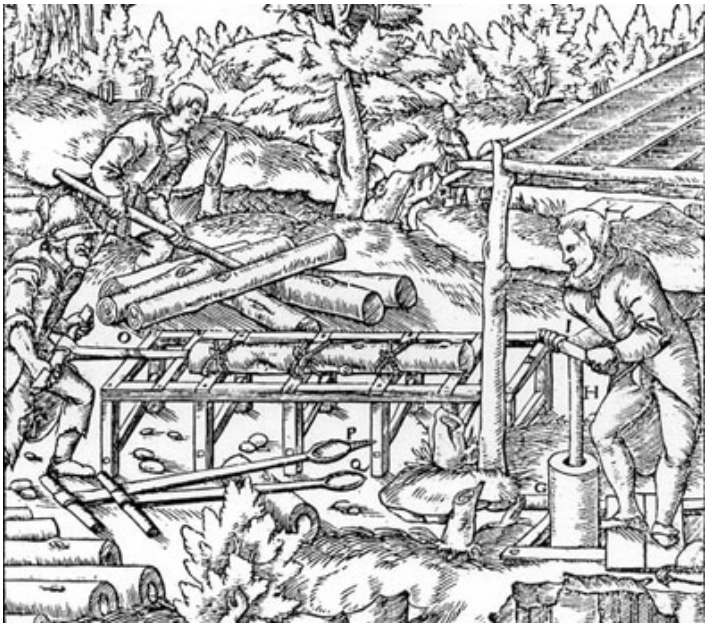

Fig. 3. Carpenter boring wooden pipes. Image from Agricola's De Re Metallica (1556)

Large trunks from trees are sawn down, the outer branches are removed but otherwise the outside can often be left relatively unfinished. Trunks are chosen that are particularly straight. The trunk is secured to keep it completely still and then an auger is used to bore out a hole through the centre. The two ends are more carefully worked to produce a projecting flange on one end and a corresponding rebate on the other. Joints in Roman times were often reinforced with iron collars (short iron pipes) fitted into the internal edges of the pipe between pipes. These are often the only surviving evidence of the wooden pipe [33]. Pliny notes that pipes are normally made of oak, but pitch pine and alder are also suitable [34]. Elm was also used in the Middle Ages [35]. Sizes varied accordingly to the trees available. Timber pipes could be used for larger bore pipes over 100mm diameter, whereas terracotta pipes were rarely over 100mm and lead ones generally about 40mm. In the 19th century in the US pipes were also manufactured using wooden staves bound together like barrels [36].

Examples

It is not clear when timber was first used. Timber does rot so evidence in archaeological remains is often difficult to find. It has been estimated that the typical useful lifespan of the Medieval pipe was 10-40 years [37]. The pipes last well if the wood can be completely saturated, but that requires quite high pressures [38]. In Roman times timber pipelines tended to be used outside major towns in rural areas and encampments, presumably where timber was plentiful [39]. In towns, the Romans generally preferred terracotta or lead [40]. The great advantage of timber pipelines was that the pieces of pipe could be as long as the tree trunk - lengths in Roman times were typically in the range 1.5-7metres - and this meant fewer joints [41]. What is remarkable is the continued use of timber pipes well into the 18th century. The pipes in many gardens driving fountains were timber, which implies that they could used under pressure, although generally lead would be used close to the fountain head and where areas needed to resist higher pressures. Timber pipes were used both at Sanssouci in Potsdam [42] and at Hellbrunn, Austria where they can be seen on display in the museum in the house.

In China, it was common to use bamboo [43]. Strictly speaking bamboo is a grass, not a timber. Its huge advantages were that it was hollow (although the dividing walls internally still need to be removed) and that it grows extremely fast, ensuring a ready supply. It is also light. However in tropical climates where it typically grows it tends to deteriorate quite fast so bamboo pipelines were typically supported on bamboo trestles above ground where the line could be continuously examined an maintained. Bamboo water systems were certainly in use in palaces and elsewhere from the Han Dynasty (202-220AD) [44].

Metal Pipes

Metal pipes have been used from ancient times. They are more expensive than timber or ceramic pipes but they can be made in greater lengths and can be made considerably stronger than other materials. Historically the chief materials used in water supply are: lead copper; brass or bronze; and iron.

Lead Pipes

Lead is a soft heavy metal which can be easily worked cold with a hammer and this made it perfect for the creation of complex pipes, connections, boxes and gutters. It was never a cheap metal and throughout the ages subject to theft or removal when buildings were abandoned. It was so common that we derive our word plumber from the Latin word for lead, *plumbum*.

Manufacture

Lead has a relatively low melting point and can thus be easily cast into thin sheets. These could then be bent by hand and using a soft mallet round a timber or brass mandrel while still warm. In fact the metal is so soft it could continue to be shaped at room temperature. The resulting tubular shape would have two edges that needed to be joined at a seam. This was sealed with molten lead. The usual Roman method was to make a prominent seam and then bore the lead on top using clay ridges to keep the molten material in place until it set. The resulting pipe was egg-shaped but the pressure of the water quickly re-shaped the interior to a perfect circle. Joints were formed by overlapping and similarly pouring molten lead round the joint to form a seal. By this relatively simple method a completely air-tight pipeline could be created which could create siphons, feed fountains and generally resist pressure [45]. There are some examples of cast lead piping [46]. The technology was not complicated but the folded sheet method remained by far the most common method up until the nineteenth century. In the Renaissance lead became common for rainwater drainpipes on the side of buildings. The seam was hidden at the back.

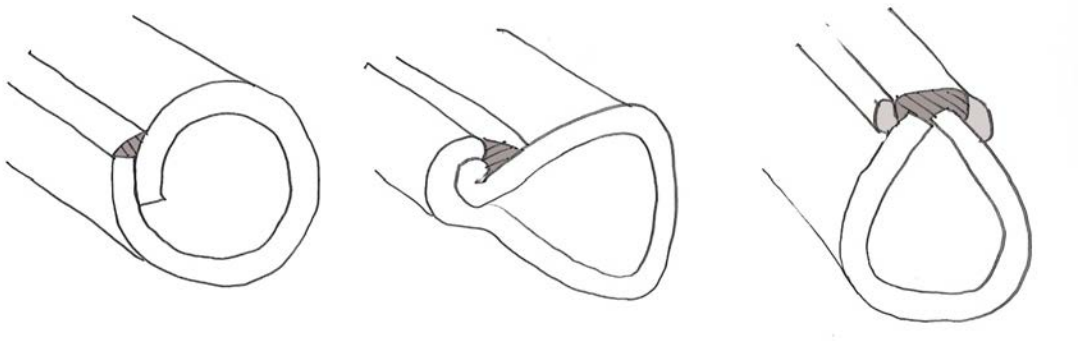

Fig. 4 Manufacture of lead pipes. The lead is folded round a mandrel (a wooden rod). The joint is formed either by pouring molten lead in the bare seam (left), folding the seam on itself and pouring the molten lean in the gap (centre) or in the manner favoured by the Romans, using two beads of clay to form a trough and pouring lead in to seal the two butt jointed ends (right). The irregular shape of the pipe corrects when water is passed through it under pressure to a round shape (author).

Examples

Lead was the material of choice for pipes in Roman times [47]. Frontinus even gives the standard sizes of pipes to be used in ancient Rome [48]. Lead continued to be used throughout the Middle Ages in Western Europe, where monasteries often contained surprisingly sophisticated water systems for which plans have survived [49]. Urban systems in the Middle Ages sometimes relied on timber but monastic systems, perhaps reflecting the greater wealth of the church, were generally in lead. The use of lead became widespread when domestic water supplies grew in the nineteenth century so that in most areas of North America and Western Europe had drinking water supplied through lead pipes until the end of the 1960s.

The issue of poisoning

No discussion of lead piping can avoid touching on the issue of lead poisoning. The subject has particularly exercised those looking at ancient Rome. The Romans were aware of the risks of lead poisoning and Vitruvius discusses it [50]. Although some scholars have made claims that lead poisoning from the water supply caused major health damage in Rome [51], the general consensus is that the build up of limescale would have prevented it being an issue in the water supply and various other sources have been pointed at to explain those cases recorded [52]. There is medical evidence however that the Romans did suffer from the effects of lead [53] so the jury is out on whether the source was lead piping or something else. A good summary of the discussions on both sides can be found in the paper by Monica Aneni [54]. The widespread use of lead piping in the 19th and 20th century in water supply installations continues to be a health concern in modern day America where many people are still drawing from theses supplies.

Copper

The earliest known example of copper piping was found in Ancient Egypt. Copper pipes are recorded in Mortuary Temple of King Sahura at Abusir dating from 2500BC. In this complex there was a system for draining off rainwater but there was also an elaborate system of water supply for five limestone basins each of which had a lead plug to stop the water flowing out attached to a brass ring pull. The drains for these basins consisted of copper pipes, the total system being over 1330ft (405m) long. Only one piece of pipe was fully intact. It was mortared into groove in the stonework. It was formed from a thin copper sheet 1.6mm thick that had been bent around a wooden mandrel to create a 48mm bore pipe, the seam

being simply bent over and hammered flat without any soldering [55]. Copper bowls are well recorded in Egyptian work but this is a rare (possibly unique) surviving example of the use of copper for piping.

Despite this early occurrence, copper piping is not widely reported elsewhere in ancient times and indeed is not found in Roman work or in the Middle Ages. There is one account of it being used in China for water supply in the Ming Dynasty in Nanjing in the Wumiao Sluice which also had iron pipes [56]. There is however no mention of the use of copper pipes in Gwilt's Encyclopedia of Architecture (1872) which gives an extensive account of the use of lead piping and an account of copper for roofing [57]. Copper sheet was increasingly used for roofing from the 17th century onwards.

Despite its early use in Egypt at Abusir, copper piping seems to have only caught on again in the early twentieth century. It started being used in the UK for hot water systems in parts of the country with soft water which corroded lead pipes [58]. The reasons why it was not commonly used may lie in the problems associated with manufacturing satisfactory pipes in copper before mechanisation. A chapter in Sutcliffe's *Modern Plumber* describes how the pipes are cast but then need to be rolled while on a mandrel as otherwise the pipes are "spongy" and unsatisfactory [59]. By the early 20th century this could be done by machine. By the end of the twentieth century concerns about lead poisoning had led to the widespread adoption of copper piping for hot and cold drinking water supply in the UK and elsewhere.

Brass and Bronze

Neither brass nor bronze were used to make pipes but they were commonly used to make taps and valves in pipework systems. They were also used to create the spouts for fountains where a hard or decorative material was required. The bronze or brass was cast in a mould made for the purpose. Examples of bronze spouts can be found in many museums throughout the world from the Roman period onwards. It used to claim that the Madradag siphon built by Eumenes II (197-159 BC) at Pergamon was contructed using bronze pipes but testing of the soil in 1976 showed that the pipes were lead [60].

Iron Pipes

Short iron pipes had been used to join wooden pipes (collars) in Roman times (see above) and there is a suggestion of iron pipes in China in the Ming period (see above). However iron was not generally used in pipemaking in quantity in Europe before the Renaissance. Cast iron pipes were famously used in very large numbers to provide water for the fountains of Versailles. These pipes are well-recorded and indeed much of the system still survives in operation to this day. The pipes are in stone conduits. While this was a hugely expensive arrangement it was considered essential to allow regular maintenance and inspection. The chief problem was with the joints. The cast iron pipes used at Versailles were in short lengths (1m), bolted together with flanges, the joint being sealed with leather or lead gaskets [61]. It is often assumed in the literature that these were the first cast iron pipes used and this may indeed have been believed at the time, but iron founding began in the Middle Ages and it would perhaps not be surprising if earlier iron pipes appeared in areas known for iron making.

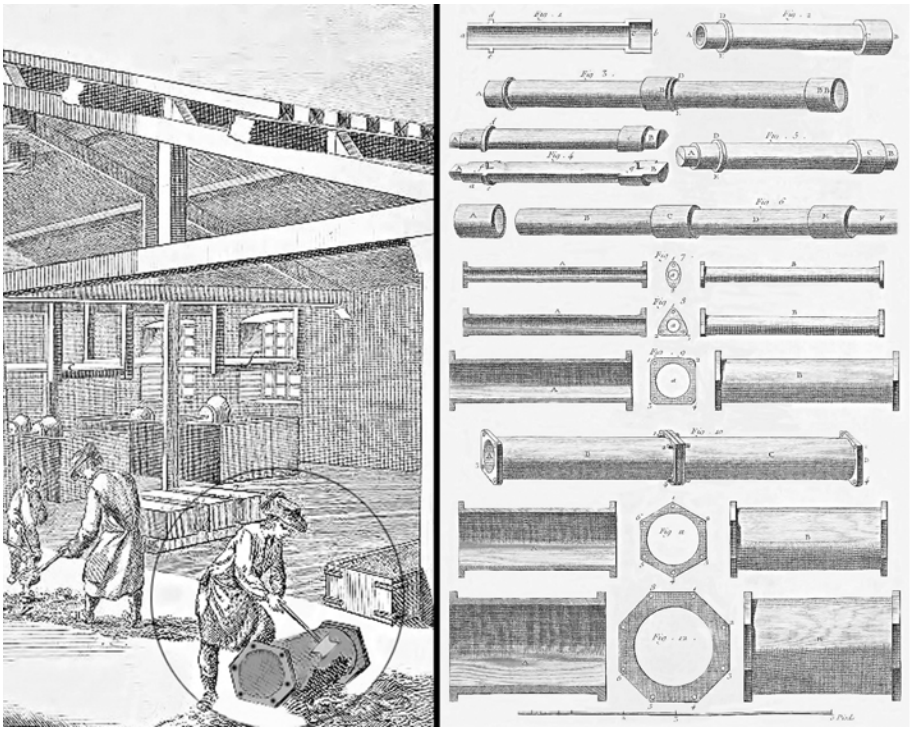

Fig. 5 Two pages from Diderot's Encyclodpedia (1777) showing (on the left) the finishing of an iron pipe which has just emerged from the mould. The pipe is similar to those used at Versailles. On the right is a page showing different forms of pipe joint and iron pipe used in the late 18th century.

There is considerable debate in the literature about when the first cast pipes were made and it is fair to say that there is currently no agreement. It terms of technology, it was certainly theoretically possible to cast pipes from the 15th century when the techniques were used to make cannons and shot, however it would seem unlikely that just because the technology was there it was immediately applied to pipes when other technologies were well-established. The earliest known example of an iron pipe dates from 1455 found in excavation of the Medieval remains of Dillenburg Castle [62]. These iron pipes were similar in form to clay examples in terms of jointing. There may be other isolated examples in iron-making areas but it seems likely that iron pipes were extremely rare before Versailles and that the production facilities set up to produce the very extensive pipework at Versailles led to the development of the technology and the continued us in 18th century France and its diffusion elsewhere. Certainly the manufacture of iron pipes was sufficiently widespread in the 18th century for Diderot and Alembert to include descriptions of the process in the Encyclopedia [63]. It was only in the 19th century that iron pipes started to be used in very large quantities for urban water supply, supplanting timber and lead pipes.

Manufacture

Pipes were cast from iron in wet sand held in boxes. The technology was familiar from canon manufacturing. Molten iron was pored into moulds. The whole process is illustrated in detail in the Encyclopedia which includes diagrams of how to make simple pipes and more complex junctions [64].

Conclusion

The development of pipes, as can be seen in this paper, was like so many areas, one of step changes, where many technologies are established early on and then remained in use continuously with minor improvements in manufacturing and form being introduced over time. Contrary to intuition, the earliest closed pipes were ceramic, rather than in stone. Stone pipes were used but were comparatively rare. Caly pipes were much more common. More work needs to be done on the types of clay pipes, their jointing and shapes, and whether they were glazed, and, if so, how. Timber and lead pipes were both used in Roman times but almost certainly were use much earlier elsewhere. The lack of survival of timber pipes is a problem. Lead has survived better and was used more widely than one might expect, particularly in the Middle Ages. More work needs to be done on when the first complete pipes were cast from lead rather than the pipes being made from folded sheets. Copper, despite it common use today, was rarely used. There is one known instance in Ancient Egypt and some evidence that it may have been used in China. This may be a problem of survival, however, it seems likely that copper piping was rarely used at all in Europe before the 19th century. Similarly bronze piping was not used despite claims otherwise. Bronze was, however, used for spouts and valves. Iron pipes appear in the 15th and 16th century but only in very rare cases. They remain rare even after their well-publicised use at Versailles in the 17th century and really only become common in the 19th century when ductile cast iron allows for easier manufacture in greater lengths. Early cast iron was useful for its strength and thus typically appears in those areas where pressures were known to be very high. Nevertheless timber and lead piping predominated in the 17th and 18th century. This paper has touched on the changes that came about in the 19th century. This is an area that certainly warrants further research and one or more papers exploring how mass-production techniques changed the way pipes were made and thus used in the 19th and 20th century. These changes included the ability to extrude and roll pipes and the introduction of completely new materials (most notably steel, and plastics).

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[16] ibid.
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[19] Magnusson, (Note 4), p.77.
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[25] J. Needham and W. Ling, *Science and Civilisation in China: Volume 4: Physics and Physical Technology Part II Mechanical Engineering*, Cambridge: CUP, 1965, 127-134, p.130.
[26] ibid.
[27] Hodge, (Note 3), pp.111-115.
[28] Magnusson, (Note 4), pp.72-76.
[29] The story of the introduction of extruded pipes is found in Kathleen Watt, 'Making drain tiles a "home manufacture", Agricultural Consumers and the Social Construction of Clayworking Technology in the 1840s', *Rural History*, 13 (2002), 39 - 60.
[30] For instance, Abbey Mills pumping station museum, London see http://www.sewerhistory.org/photosgraphics/pipes-wood/, accessed 13 July 2021. This site also has illustrations of stave pipes made from multiple pieces of timber held together with iron hoops.
[31] For London see J-C Shulman, *The Tale of Three Thirsty Cities*, Leiden: Brill, 2018, p.221; for New York see J.Goldman, *Bulding New York's Sewers*, West Layfayette: Purdue University Press, 1997, p.16.
[32] G.Agricola, *De Re Metallica,* Basel, 1556, trans. HC.Hoover and L.H.Hoover, New York: Dover, 1950, p.177.
[33] Illustrated in Agricola. For survival see Hodge, (Note 3), p.112.
[34] Pliny, *Natural History*, XVI, 81.
[35] Magnusson, (Note 4), p.76.
[36] For plans and photographs of stave pipes for sewers see http://www.sewerhistory.org/photosgraphics/pipes-wood/, accessed 13 July 2021.
[37] Magnusson, (Note 4), p.78.
[38] *ibid.*
[39] Hodge, (Note 3), pp.111.
[40] *ibid.* pp.315.
[41] *ibid.* pp.112

[42] R.Calinger, *Leonhard Euler*, Princeton: Princeton University Press, 2016, p.311
[43] J. Needham and W. Ling, (Note 24), pp.128-29.
[44] *ibid.*
[45] For a detailed explanation of the process of manufacturing and excellent diagrams see Hodge, (Note 3), pp.307-320.
[46] K.Grewe, (Note 12), p.41
[47] Hodge, (Note 3), p.307
[48] See J.Gelder, Roman Services and Architectural Manuals, in J.Campbell et. al., *Studies in the History Services and Construction History*, Cambridge: Construction History Society, 2018, 31-42, pp.33-35.
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[59] *Ibid.* pp.20-23.
[60] Hodge, (Note 3), p.43.
[61] M.Tournier, *Versailles: the fountains of the Sun King,* Les Loges-en-Joas: JDG, 2000, p.32. Tounrier claims these were the first iron pipes but this is no longer thought to be the case.
[62] Grewe, (Note 12), p.40.
[63] The relevant sections are reproduced in [D.Diderot and Alembert], *L'Encyclodpédie Dierdot et D'Alembert: Forges ou L'Art de Fer,* Paris: Inter-livres, 1988, Plates IX-XII
[64] ibid.