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Chapter V

CANALS

CANALS

canal before the Trojan War, according to Strabo. The writer admitted that some hold the work to be that of the

Canals of the Ancients

of Psammitichus (i.e. Sesostris). Herodotus I took up the story, said Strabo, but he, too, admitted it was not his

EGYPT -- Man-made rivers, or canals, played a leading role in the development of the civilization which sprang up around the Nile, for the drainage of lands and irrigation of crops were of fundamental necessity. Later these waterways built for drainage and irrigation were improved to serve a more advanced need, that of water transportation, and in time, canals devoted primarily to navigation were constructed. Unfortunately most of our information of these early works near the Nile

is non-Egyptian in origin. Herodotus tells us that Menes (3200 B.C.) banked up the Nile at a bend below Memphis, laid the ancient channel dry, and dug a new course for the stream half-way between the two lines of hills. Strabo noted that between Alexandria and Canopus the canal was loaded with boats of revellers day and night. The Rosetta stone found near Port St. Julian by Boussard in 1799 revealed that Ptolemy Eupator (175 B.C.) used seven and one half years to clean out and re-new the canals of Egypt.

Although ancient historians may not agree as to the time and place of a waterway between the Mediterranean and the Red Sea, the evidence given would indicate that some such canal existed prior to Roman times. Herodotus claimed that a canal navigated in four days between the Nile and Red Sea was begun by Necho (616 B.C.)--who lost 120,000 men in the attempt--and completed by Darius (512 B.C.). Sesostris began work on the

canal before the Trojan War, according to Strabo, but the writer admitted that some held the work to be that of the son of Psammitichus (i.e. Necho). Darius I also took up the job, but he, too, abandoned it when it was near completion, convinced that the Red Sea was higher than Egypt and that if the intervening isthmus were cut all the way through, Egypt would be inundated by the sea. However, the Ptolemaic kings succeeded in cutting it through and in

making the strait a closed passage. Diodorus Siculus stated that the work abandoned by Necho and Darius was completed by Ptolemy Philadelphus (280 B.C.) and Pliny maintained that the canal had been "contemplated" by Sesostris as well as by Darius and Ptolemy II (Philadelphus). The latter, he said, built a canal 100 feet in width and 40 feet deep, extending a distance of 37½ miles as far as the Bitter Springs. Ptolemy did not proceed further, said Pliny, because of the alleged difference in elevation between the Red Sea and Egypt.

The Nilometer, a measuring pillar, played a very important part in the lives of the ancients living in and around Cairo. When the waters of the Nile rose to a certain mark on the Nilometer the Khalig, or grand canal, was opened to admit the water which then proceeded to flow through numerous smaller canals to reservoirs and cisterns from which it was distributed among fields and gardens. Whereas the ancient Egyptians sacrificed a young girl annually to the Nile, Caliph Omar (seventh century A.D.) substituted a pillar of earth at the opening of this canal. The Nilometer which has survived was completed on the island of Rhoda opposite Old Cairo in A.D. 715 during the

reign of Umayyad Caliph Sulaiman.

No great technical skill was exhibited by the Egyptians in the construction of their canals, for they were simply large ditches which directed the flow of level reaches of water. It is probable, however, that the sluice or flood gate was invented by the Egyptians after the time of Alexander, an invention which was made independently by the Chinese and which was known to the later Romans.

THE ROMANS -- Very little in the way of tangible evidence, either archaeological or historical, concerning Roman canals has been uncovered to date. There was probably little economic or military justification for the creation of monumental navigational waterworks in most of their territories, although their aqueducts for fresh water supply would indicate their engineering ability to accomplish such feats.

Even before the time of the Romans the Etruscans had been engaged in improving the valley of the Po with the Fossa Phyllistina (great canal). At a later date Augustus drew a canal from a branch of the Po, the Fossa Ascon, across the city of Ravenna. Nearer Rome the drainage of the Pontine Marshes was of prime importance during many administrations. A canal serving the dual purpose of drainage and navigation had been completed from the Forum Appia across the Pontine Marshes to a point near Terracina in 162 B.C. A century later this canal had fallen into decay, and Caesar proposed to renew it. Still later, workmen under Trajan took ten years to restore the drains of the Marshes, a job which was again taken up by Theodoric in

the fifth century A.D. Camillus Scaurus is reputed to have drawn navigable canals from Placentia to Parma in the second century B.C. Claudius in A.D. 52 caused a canal to be built to carry off the dangerous rainy season floodwaters from Lake Fucinus to the River Liris. This channel, according to Pliny, was cut through a mountain at a cost beyond calculation by a "countless multitude" of men who worked for "many years." Other Roman canal projects met with even less success. Caesar, Caligula, and Nero all tried unsuccessfully to split the isthmus of Corinth. A snip canal from Ostia to Lake Avernus near the Bay of Naples was left uncompleted by its engineers Severus and Celer.

Historical references are few and time has acted to cover most of the canals which the Romans did build. Comparison, therefore, with surviving monumental works such as roads, bridges, and buildings is difficult. Most important, however, is the fact that Roman canal construction had very little, if any, influence on the subsequent development in this field.

Dynasty (1368-1644). CHINA -- The construction of canals in China is so interwoven with myth and legend that it is difficult to find a starting point in the subject. It appears that some work of this nature was done during the Han reign (202 B.C. - A.D. 220) when a general revival was evidenced through^{out} the country. New areas were opened up and trade flourished. As the centuries passed, dynastic wars acted to bring about a shift in capitals and hence, a shift in trade routes. Naturally such shifts brought about a demand for more navigational facilities. After the fall of

the House of Han the country plunged once more into disunity, not to be reunited until the advent of the Sui (A.D. 589-618) and T'ang (A.D. 618-907) dynasties. During this period we learn that many old canals were enlarged and some new ones were opened, especially from the Yellow River to the Kiang. Some of these canals were faced with stone and those running from north to south--the main arteries--were made particularly broad. By the middle of the eleventh century the Yellow River had been turned into the Gulf of Leao-Tong, and in 1369 we find the founder of the Ming Dynasty, Hung Wu, repairing the waterways neglected by his predecessors.

Most renowned of the Chinese canals was the Great Canal traversing a distance of about 900 miles from Canton in the south to Peking in the north. Some writers maintain that it took 30,000 men forty-three years to construct, being completed in 980,¹¹ but Marco Polo writing from Tartary in 1278 spoke as if the canal were then in the course of construction. Further accounts maintain that it was completed during the Ming Dynasty (1368-1644). Regardless of its date of completion we do know that it consisted of two major stretches, one from Peking to the Yellow River, and the other from the Kiang River to Canton. The first mentioned stretch was known as the Imperial Canal, so-called because of the preponderance of the Emperor's barks upon it. A cha, a type of sluice of which there were 45 on this canal, regulated navigation by penning up a slug of water which was released behind a barge to enable it to pass safely over an ordinarily shallow spot. Louis le Compte, the early Jesuit missionary, reported that the canal with its

breadth of 50 feet and depth of 9 feet ordinarily accommodated 80-ton barges. From the Yellow River to the Kiang River certain dykes were required, and the waterway from the Kiang to Canton was broken only by a 30-mile portage spot across the mountains. Differences in elevation as much as 15 feet were overcome by cumbersome inclined lifts of stone. Vessels were simply dragged up or lowered down these stone faces, and thus were enabled to continue their journey despite the differences in water level.

Such was China's contribution. The cha, the crude inclined plane, and great physical labor were the hallmarks of canals and canalized rivers in China, and progress beyond that level remained static until the present day.

INDIA -- Small irrigation ditches had existed in various parts of India from earliest times, but it was not until the fourteenth century that artificial canals appeared to any extent, and these were confined largely to the Punjab. The country between Delhi on the Jumna, a branch of the Ganges, and the Punjab on the Indus was frequently without water, a situation which led Feroz III in the middle of the fourteenth century to undertake a series of improvements which were pursued--according to some ancient accounts--for thirty-seven years. These projects were designed to aid commerce as well as to stimulate agriculture. A few miles north and west of Delhi the prince built a city bearing his name and had two canals drawn to it. One canal was drawn from the River Sutlej and the other was an extension of a 60-mile canal

stretching from the Jumna to his hunting lodge. The latter canal, 4 yards in breadth, thus reached a total length of 114 miles. A new canal from the site of the lodge to Delhi was made in the seventeenth century by Shan Jahan who is best remembered for that marvel of Indian architecture, the Taj Mahal.

Apart from this period there appears to have been little in the way of canal improvement until the British took over the task in the nineteenth century. As had been the case with most of the older civilizations, nothing of particular value in the art of canal building was passed on by the Indians to posterity.

European Developments Prior to the Seventeenth Century

THE LOW COUNTRIES -- The canalization of Holland and the Low Countries has been a slow, steady development, dating from the pre-Christian Roman era. From Tacitus we learn that the Canal of Drusus, extending from the Rhine to the Yssel at Daesburg, was executed about 12 B.C. The Rhine and Meuse were joined by a 23-mile canal excavated under the direction of the Roman general Corbulus, and a river now called the Leck was formed by Claudius Civilis. Following the Roman occupation, work still continued. In the middle of the fifth century the channel of the Merwede from the Meuse to the Waal at Dordrecht was improved by Meroveus, King of the Franks, and in the tenth century a canal from Ghent to the sea was cut by the Emperor Otto.

Draining and reclaiming of land from the sea was of prime

importance from earliest times. The plassen or plasnes were surrounded by dykes, on the outside of which were run ringslooten or surrounding drains. The water was raised from the interior polder by windmill to the ringsloot, conducted from there to larger canals, and thence to the sea. By the end of the seventeenth century most of northern Holland had been reclaimed in this way. In time it became apparent that these drainage canals could serve for navigational purposes as well, and designs were altered accordingly.

A jurisdiction of canals of the Rhineland is known to have existed prior to 1253, the year in which William, Earl of Holland, granted a charter for the Canal of Spaarndam. Of particular note is the Vaartsene Rhyne, a 5-mile canal from Utrecht to the Leck at Vreeswyck, constructed in 1373. The lock at Vreeswyck dates from this period and may be the oldest lock on record. Bruges owed its early position of supremacy as one of the three leading cities of Europe to the canal built in the thirteenth and fourteenth centuries connecting it with the North Sea. Another early canal of importance was the 15-mile Canal of Brussels (1550-61) built by the engineer George Rinaldo for the use of coasting sloops. It overcame a fall of 50 feet by means of five locks. Thus gradually, the tiny drainage streams developed into broad navigational canals, promoting prosperity and trade and enriching the cities which bordered them.

THE LOCK

ITALY -- Canal development in Italy began at about the same time as in the Low Countries, but here the accent was more on

irrigation than on drainage, although the latter was necessary to some extent. In Lombardy the Naviglio Grande, an irrigation canal dating from 1177 or earlier, commenced at Tornavento on the Ticino and was gradually extended a distance of over 30 miles to Milan by 1257. It was enlarged in 1269, varying in depth from $4\frac{1}{2}$ to 15 feet, and in breadth from 75 to 160 feet. Also active at an early date were the Venetians who in 1201 drew a canal from the River Bacchiglione to allow passage for the stones of Venice. From the River Adda near Concessa the Milanese constructed the Martensena Canal, 24 miles in length, and sustained in some places by thick walls and earthen mounds 110 feet above sea level. The work has been variously ascribed to Louis XII, Francis I, and Francis Forza I, but it is certain that the latter appointed a commissioner of the works in 1457 who was responsible for rendering the canal navigable around Milan. In Piedmont large irrigation canals such as the 20-mile Caluso Canal (1556-60), and the 45-mile Ivrea Canal (1468) played an important part in developing the agriculture of the section. As in the low countries, though not to the same extent, the canals of Italy gradually developed so that one prime purpose was joined by another--first irrigation then navigation.

Lifting Devices on Canals

THE LOCK -- We have noted that the forerunner of the lock, the sluice or flood gate, was known by the early Egyptians, Romans, and Chinese, but even the simplest form remained until

that the aqueduct from the River Lock at Westbury was a modern times. Such a device--composed of two abutments of stone, one from each bank with space between wide enough for the passage of a vessel--was snut by timber bars dropped into grooves. The hazards of tending a sluice in the nineteenth century were ably remarked upon in the following passage from the Edinburgh Encyclopaedia: "---or if one beam be placed across at top, and a sufficient sill at bottom, the planks are placed upright so as to bear against the crossbeams. To open this kind of sluice, the lock-keepers place themselves on the crossbeam, and take up, one after another, the paddles or planks, not without a great deal of trouble and danger; for frequently when the plank has been cleared of the lower sill, the current carries it away with such force as not unfrequently to pitch the lock-keeper into the water." While the sluice was useful in getting a vessel over shoal waters it cannot be strictly classed as a device to lift a vessel from one level to another such as the lock, which made its first appearance in about the fourteenth century.

While rival claims for its discovery have been advanced by both countries, it would seem, on the basis of present evidence, that the lock was known in Holland a century before its independent discovery was made in Italy. It is possible that the sluices of Spaarndam (1253) were in the nature of a lock, although not necessarily so. To all intents and purposes the Basin of Leidsendam with stop gates at either end was a complete lock, it being a part of the canal from Delftland to Leyden completed in 1255. Hada in his history of Utrecht states

that the aqueduct from the River Leck at Vreeswyck was deepened in 1371 and that double stop gates of timber were placed at the back of the Leck. The addition of a third gate during the same century turned the device into a double lock. Writing in the late sixteenth century Simon Stevin, in "Nieuwe Maniere Van Steretebou door Spilshuysen" (Rotterdam, 1617) stated that modern locks had been known in Holland from earliest times. He then proceeded to describe a new sea lock which would admit masted vessels, and gave credit to two carpenters, Adrian Janssen of Rotterdam and Adrian Dirricksen of Delft, for inventing and improving upon a lock for lock gates.

In Italy Petentino, architect of Mantua, had made an attempt at lockage in 1188 when he constructed his dykes on the Mincio at Governolo. However, we have every reason to believe that the result was merely a weir and single flood gates, for Bertazolo in his discourse on the sluice of Governolo (Mantua 1609) proposed a lock with a chamber as a new thing. Lecchi in his "Di Cannali Navigabili" gives credit for introducing the lock (1420) in the navigation of Milan to Filippo Maria Visconti. The hydraulic engineer Venturi is in essential agreement noting that Visconti erected a double-gated lock about 1440. In the building of the Duomo of Milan the marble from the Alpine quarries had to be unloaded at the suburbs of the city until Visconti solved the problem of raising the laden barges by means of a lock.

Zendrini, the mathematician, in his "Delle acque corrente" (Venice 1746) mentions two clockmakers, the brothers Denis and Peter Domenico, as being the inventors of a lock at Stra near

Viterbo, they having obtained a patent for its construction from the Senate of Venice in 1481. According to Zendrini, "To these then, at least within the Venetian States, we may ascribe the honor of this invention, not finding anyone else who had conceived or put into practice the idea---without traction from one water level to another." Frisi, a Milanese, in a work on navigable canals published in 1762 and 1770 agreed with Zendrini, but in 1782 he stated that the staircase locks of Venice, Bologna, and Milan, the most ancient known to him, had been invented by Leonardo da Vinci about 1484. In his book on the antiquities of Milan Pumagalli claims three firsts in lock construction for da Vinci, (1) gates on hinges, (2) gates meeting at an obtuse angle, and (3) the insertion of small doors in gates. It is not clear from da Vinci's notes and writings as to whether he considered his contributions in this field wholly original or simply the modifications of the works of previous inventors.

From the evidence we may conclude that the modern lock, which by impounding and releasing water can float a vessel to a higher or lower level, was definitely known in Italy by the fifteenth century, having been known in Holland a century before. It was this invention which made possible the great navigable canals of succeeding centuries and so influenced the destinies of nations and of men.

THE INCLINED PLANE -- While the inclined plane had been used extensively to overcome differences in level in China from earliest times, its use in the Western world is comparatively

recent. In many parts of Europe "rolling bridges" similar to the Chinese planes came to be used to prevent the transference of water from one tract of country to another where jealousy of drainage was an important factor. The probable parent of the Western inclined plane can be traced to Lizzafusina near Venice, but its use in high lifts was unknown until introduced by William Reynolds of Shropshire in 1788. His plane with a rise of 73 feet was put into operation at the Ketley Iron Works to convey coal, iron, and stone.

Aside from the primitive method of simply pulling a barge over a slippery stone incline, three major methods came into being. Barges with wheels attached were used with some success in isolated cases--as on the Bude Canal--but traffic was limited to small flat-bottomed boats about 20 feet in length. A cradle on wheels supporting the barge was used with considerable success on the early nineteenth century Morris Canal in New Jersey. Here 70-ton barges were carried on eight-wheeled cradles running on steel rails with a gauge of 12 1/3 feet. There were twenty-three of these inclined planes, varying in length from 500 to 1500 feet, and in lift from 44 to 100 feet. Engineers calculated that the expenditure of water on these planes was only one twenty-third of that required for a flight of locks with the same lift. The Oberland Canal (1844-61) was built by the engineer Steenke between Elbing and Osterode in East Prussia to accommodate 60-ton barges 80 x 10 feet in a like manner. It was essentially this scheme, a ship-railway, which Captain Eads, of St. Louis Bridge fame, urged at Tehuantepec in lieu of a canal at Panama or Nicaragua.

at Arderton was introduced. A third method of using the incline, that of a wheeled caisson filled with water supporting a barge, was introduced on the Chard Canal in Somersetshire about 1840. Its caissons, 28½ by 6½ feet, were soon surpassed in 1850 by those on the Monkland Canal measuring 70 by 13 1/3 by 2½ feet. With a total rise of 96 feet the caissons were arranged in pairs so that one would ascend while the other descended. In 1876 a still larger caisson, 112 by 16½ by 7 5/6 feet, made its appearance on the 39-foot high Georgetown incline connecting the Potomac with the Chesapeake and Ohio Canal. The total weight of 390 tons was supported on three trucks, each having twelve wheels running on four steel rails. This arrangement was used for a year, but it was found that a badly damaged road had resulted, and so the water in the caisson was eliminated from that time on.

THE LIFT -- Apparently the earliest vertical lift of any significance was erected in 1809 at Tardebigge on the Worcester and Birmingham Canal. It consisted of a timber caisson weighing 64 tons when filled with water, and was counterpoised by heavy weights on a timber platform. The lift of 12 feet could be accomplished in three minutes by two men turning winches. On the Grand Western Canal (1834-36) between Wellington and Tiverton seven lifts were installed, smaller than the above mentioned, but acting in pairs and lifting to a height of 46 feet.

A significant advance was made in 1875 when the hydraulic lift connecting the River Weaver and the Trent and Mersey Canal

at Anderton was introduced. Here barges up to 100 tons were lifted a height of 50 1/3 feet in two and one-half minutes. The water-filled caisson, 75 by 15 1/2 by 5 feet, was raised and lowered on a hydraulic ram 3 feet in diameter, the total operation of getting a barge through taking about eight minutes. The advantage of this device is readily seen when compared with the locking through of barges at Runcorn, where the time consumed in attaining the same height amounted to about one and one quarter hours.

Similar to the Anderton lift was the one erected in France at Fontinettes (1883-88) on the Neuffosse Canal near St. Omer. An even larger caisson was used lifting 300-ton vessels a height of 43 feet. This lift was then surpassed by the lift completed at La Louviere, Belgium, in 1888 on the Canal du Centre. Here 400-ton vessels could be raised over 50 feet in two and one-half minutes. A single ram, over 6 1/2 feet in diameter and almost 64 feet long, acted to lift the caisson, water, and barge--a total weight of over 1000 tons. This caisson measured approximately 141 by 19 by 8 feet, and was constructed for the Belgian government by the Societe Cockerill of Seraing.

For almost half a century the Belgian lift remained supreme in its field until the opening of the Niederfinow Barge Lift (1926-34) on the Honenzollern Canal between Berlin and Stettin. Here the trough size had been increased to a length of 278 feet, a width of 40 feet, and a water-carrying depth of 8 1/2 feet. Thus the 1000-ton barge lift had become an actuality. Weighing approximately 4200 tons, the steel trough was designed to ascend 116 feet in five minutes--a considerable saving over the two

hours required for ascending through the four locks which it replaced. Since the trough was counterbalanced by huge concrete blocks, only for 75-HP electric motors were required to drive the trough up and down.

SUMMARY -- Though the incline and vertical lift have been used successfully in the raising of small barges, these two types seem to have reached their economical if not physical limit. Assuming the continued use of present materials in the construction of ships and lifting devices it is difficult to envisage a radical increase in the size of lifts beyond that of the Niederfinow type. Relative costs of construction and operation seem to favor the lock over the lift and plane when one gets out of the small barge field. To date the lock appears capable of increasing in size with the vessels it has to serve, as testified by the 1350-foot locks at Sault Sainte Marie. It would appear therefore, that the lock, though antedated by the plane and antedating the lift, has the best chance for survival and development in the commercial world of today.

Barge Canal Development from the 17th Century to the Present

FRANCE -- The first name in history connected with the canals of France is that of Lucius Verus, commanding general of the Romans in Gaul in the time of Nero, who undertook to join the Moselle and the Rhine. Vernon-Harcourt notes that the St. Julian Canal was constructed to work a mill in the twelfth century, and that it was extended for irrigation in the thirteenth

century and later. In 1554 the engineer Craponne started a canal, 6½ feet in depth, from the Durance--a canal which in later years was extended a distance of 90 miles. The first canal in France with locks, however, was the Briare, 35 miles in length, connecting the rivers Loing and Loire and thus uniting two of the three great river valleys of France, the Seine and the Loire. Construction was begun during the reign of Henry IV (1605) at the urging of Sully but was suspended in 1610 when Henry was assassinated. Work was resumed in 1638 and was completed in 1642 under orders from Richelieu, acting for Louis XIII. Executed by the engineer Hughes Cromier, the canal varied in breadth from 25 to 32 feet and boasted of locks varying in length from 124 to 164½ feet, with a width exceeding 14 and a depth exceeding 5 feet. This work was particularly significant for it was the first canal outside of China to surmount a watershed.

Cutting across the Iberian Peninsula a short distance north of the Pyrenees, the Languedoc Canal, or Canal du Midi, connecting the Bay of Biscay with the Mediterranean, was the engineering wonder of its day. Leaving the Garonne at Toulouse the canal rose 207 feet in 23½ miles to the summit, and then descended gradually by way of Carcassonne and Béziers some 620 feet to the Golfe du Lion at Site. The 148-mile canal was built with over one hundred locks varying in rise from 5 to 12 feet, fifty-five aqueducts, and ninety-two road bridges. One of the outstanding construction feats was the drilling of the Malpas tunnel, over 500 feet in length. Designed to accommodate vessels 65 feet in length carrying 100 tons, the canal

was made 64 feet wide at the surface, 34 feet wide at the bottom, and almost 6½ feet deep. With the backing of Colbert, Baron Paul Riquet de Bonrepos (1604-80) transformed this dream of Charlemagne, Francis I, and Richelieu into a reality. It appears that the Italian engineer, General François Andreossi, worked on the preliminary plans for the canal from about 1660 until 1664, but actual construction was not begun until 1666, and the first stone not laid until 1667. The success of this great work was due almost entirely to the untiring efforts of the project manager, Riquet, who died six months before its completion in 1681. In the eighteenth century the canal was extended down the Garonne Valley to Bordeaux, making its total length over 300 miles.

Departing from the Loire at Dijon and ending in the Saône at Chalon, the Canal du Centre, or Charolois, completed the water route from the English Channel to the Mediterranean. Though conceived in about 1555 by the first French canal builder, Adam de Craponne, most of the work on this 71-mile canal was accomplished between the years 1783 and 1792 by a large soldier force working under the engineer Émiland Marie Gauthey. Ascending 240 feet by means of thirty locks from the Dijon side and then descending 400 feet by fifty locks, this canal was slightly smaller than the Languedoc Canal, utilizing a depth of only 5½ feet with locks 100 by 16 feet.

Even earlier in the eighteenth century fine results had been achieved in canal construction. Completed in 1715, the Canal of Mardick had been cut by M. Le Blanc to discharge superfluous waters after the demolition of the fortifications at

noteworthy additions is the Canal de la Saône.

Dunkerque. Cut to a depth of 21 feet, its lock was the finest in Europe, being composed of two passages, one 47 feet wide and the other 27 feet, and having a length of 295 feet. Regimorte had completed the canals of Picardy and of Orleans in the first half of the century, and on the reduction of the army and navy-- in order partially to solve the unemployment problem-- construction was begun in 1792 on the Canals of Denune, Burgundy, and Neufbrissac.

Tremendous interest in canals continued until about 1830, when the railroads became a serious rival. Although there were a few exceptions such as the 51½-mile Marseilles Canal (1837-48), the waterways of France were neglected until 1860. At about this time a new interest in the waterways arose with a view toward keeping down railroad rates and fulfilling commercial treaties. The Franco-Prussian War brought a temporary suspension in most canal activity, although the Verdon Canal-- noted for its use of siphons in crossing several valleys--was built during the years 1863-75. Interest was aroused again in 1876, resulting in the uniformity laws of 1879, applicable to all canals of France and specifying the following minimum dimensions for locks to serve 300-ton vessels: length 126 1/3 feet, breadth 17 feet, depth 6½ feet, and headway 12½ feet. Enlargement of sub-standard canals was soon undertaken by the State and tolls were abolished in 1880. By 1893 France had 2986 miles of canals, exclusive of improved waterways and canalized rivers.

Construction of new canals as well as maintenance of the old has continued into the twentieth century. Among the more noteworthy additions is the Marseilles-Rhône Ship Canal,

traversing the distance of 48 miles to Arles with a depth²⁵ of almost 10 feet, a bottom width of 75 feet, and possessing three locks measuring 525 by 52 feet. Another canal of note is the Canal du Nord, begun in 1907 and connecting the Sensée and Oise Canals, a distance of 58 miles. It accommodates 300-ton barges, having a depth greater than 8 feet, a bottom width of 33 feet, and using a total of nineteen locks. A comparison of modern figures with those of the earliest canals reveals a steady trend toward wider and deeper canals, and larger and fewer locks with greater lifts. While it is true that automotive transport and the railroad have taken from the barge canal the near monopoly on inland transport it once held, it still is not a fact that these new modes have rendered the canal obsolete in France.

GREAT BRITAIN -- As in France, canals in Great Britain date back to Roman times. Urns and medals dug up near the 40-mile Car Dyke running from the River Nyne to the River Witham give rise to the belief that the cut dates from the first century A.D. Camden in his Britannia states that the Fosse Dyke, also of Roman origin, was widened and used in 1121. On a survey in 1762 Smeaton and Grundy found its depth to be 2 feet 8 inches, and in 1782 Smeaton deepened the navigation to 3½ feet by raising the sides. In 1840 Stevenson joined the Dyke to the navigable channel of the Witham, widening it to 45 feet and deepening it to 6.

One of the earliest English canals on record dates from 1566, a 3-mile ditch from Exeter to Topsham, executed by John

Trew of Glamorganshire. Although various monarchs had approved Acts of one sort or another and a few attempts such as Trew's had been made, artificial navigation did not begin until the time of the Stewarts. The Dutchman, Sir Cornelius Vermyden, invited by James I to come to England to solve certain drainage problems, stemmed the breach in the Thames embankment near Dagenham in 1621 and later drained the Royal Park at Windsor. Under Charles I in 1626 he built "Misterton Sas" in the River Idle, possibly the first lock with a chamber in England. Vermyden's greatest work was the drainage of the Fens, a job which he pursued until the middle of the century. This work was essentially drainage and not navigation, however. Until the middle of the eighteenth century, canalization was confined to the dredging of streams and rivers already present. With this system, gravel and sand swept down stream and deposited in banks and shoals below, resulting in a still-crooked stream, laborious to navigate.

First to depart from the traditional canalized river or ditch was the Sankey Canal, authorized in 1755 and constructed in 1760. A separate cut paralleling Sankey brook from the Mersey River to a point near St. Helen's (10 miles east of Liverpool) was made, but this was more the rectification of a brook than the construction of a canal proper. It remained for Francis, Duke of Bridgewater, "Father of British Inland Navigation," to be the first to back a canal project which struck out boldly across dry land.

The Duke, disappointed in love, turned his energies toward commerce, and with the aid of his engineer, James Brindley

(1716-72), succeeded in producing a canal 10½ miles in length from his coal mines at Worsley Hill to Manchester. Planned and constructed by Brindley, the Duke of Bridgewater's Canal (1759-61) was particularly noted for its "castle in the air," the Barton aqueduct, 200 yards long and 12 yards wide, running 39 feet over the River Irwell on three semi-circular stone arches. Extension of the canal was begun almost immediately and by 1767 the 28-mile level stretch from Longford Bridge just outside of Manchester to the upper part of Runcorn had been completed. The 82-foot drop from upper Runcorn to the Mersey River was overcome by ten locks which were opened in 1772, thus completing the Liverpool to Manchester waterway. The immediate result of the Duke's canal was to halve the price of coal at Manchester, of great significance in the subsequent development of the city as an industrial center. This then opened English eyes as to the possibilities of still-water navigation, and ushered in the golden age of canal building which was only halted by the railroad some seventy years later. By 1830 2400 miles of such artificial waterways had been built in England.

It might be well to pause here a moment to speak of Brindley, first of the British canal engineers. Born near Macclesfield in humble circumstances, he had little or no formal education and was early in life apprenticed to a wheelwright. His mechanical genius was soon apparent, and by the time he entered the Duke's service his reputation as a civil engineer was well known. Following his initial success at canal construction he went on to build more than 350 miles of inland waterways and to give his advice on many more. One of his

basic principles was to avoid locks if at all possible--such as he did with the Barton aqueduct--and to go around an elevated object rather than through it. His canals were characterized by their long level reaches and concentration of locks in as few spots as possible. His favorite formula for stopping the leakage of any canal or aqueduct was to "puddle it," a process which was essentially the working and chopping with spades of a mixture of well-tempered clay and sand reduced to a semi-fluid state. Three or more strata were built up to a total thickness of about 3 feet, and a layer of common soil was placed over the top course.

Another of Brindley's triumphs, a success also shared by the engineers John Smeaton, Hugh Henshall, and John Rennie, was the Grand Trunk Canal (1756-77) connecting the Mersey, Trent, and Severn rivers, and thus uniting the ports of Liverpool, Hull, and Bristol. It was the most formidable attempt of its kind in England, being 139½ miles in length, and possessing seventy-five locks, five tunnels, one hundred and sixty minor aqueducts, and one hundred and nine road bridges. The Harecastle tunnel, 2888 yards in length and 70 yards below the surface of the earth, was a magnificent feat in itself, being 9 feet wide and 12 feet high. Minimum dimensions of the canal proper were 28 feet at the surface, 16 feet at the bottom, and 4½ feet in depth. One of the earliest effects of this canal was to enrich and enlarge the pottery business in which Josiah Wedgwood was the leading figure.

Canals followed one another in rapid succession, encouraging trade and enriching the kingdom. To Thomas Telford fell the

task of directing a great portion of this work in the early nineteenth century. His Ellesmere Canal (1793-1805) was a series of navigations proceeding from the River Dee in the vale of Llangollen, extending for a distance, including the Chester Canal, of 112 miles. Of particular note on this work were two aqueducts, the Chirk Aqueduct and the larger Pont-Cysylltau Aqueduct, crossing the Dee. The water in the latter was carried, not in the usual puddled stone trough, but in a cast-iron trough which rested on nineteen arches extending to a length of 1007 feet. A towing path took 4 feet 8 inches off the 11-foot 10-inch waterway whose level stood 127 feet above the lowest part of the valley. Truly a monument to rival the achievements of the Romans, this aqueduct took eight years to build.

In Scotland Telford embarked on the tremendous job of cutting the Caledonian Canal (1804-22) which united the Atlantic Ocean and the North Sea. A government project, the canal was constructed to allow vessels of war to pass quickly from one sea to another, to afford merchantmen protection from privateers, and to spare sailing vessels the arduous passage around Pentland Firth. Serious plans for such a canal had long been considered, for the area had been surveyed in 1773 by James Watt and again in 1793 by John Rennie. In 1801 Telford, accompanied by William Jessop, commenced his surveys, and construction began in 1804. The canal was opened in 1822 before it had really been completed, and parts of it fell into decay. Construction was resumed after a group of experts had examined it in 1832, and it was opened once more in 1847. In a total

length of over 60 miles only a little over 20 miles had to be made artificially. Twenty-eight locks (170 to 180 by 40 by 20 feet) were installed to allow vessels to surmount the 102-foot summit level at Loch Oich. Although constructed and classed as a ship canal, this work in 1849 was only able to accommodate vessels with a length of 160 feet, a beam of 38 feet, and a draught of 17 feet. While costs amounted to almost double the estimates, the canal was still a fine engineering work worthy of Telford and his resident engineer, Mathew Davidson; but it never was a financial success, for ocean going vessels soon increased in size all out of proportion to what could be foreseen when this canal was planned, privateers disappeared from the seas, and steam replaced sail, rendering Pentland Firth much less hazardous than before.

At an earlier date (1790) the 35-mile Forth and Clyde Canal had finally been completed after a long and stormy career, having been proposed to accommodate men-o-war over a hundred years before in the time of Charles II. Smeaton was engaged and work was begun in 1768, only to stop because of no funds in 1775. In 1777 the work was partly finished to Glasgow and in 1785 full work on the canal under Robert Whitworth was again resumed. Possessing thirty-nine locks and excavated to a normal depth of 7 feet, this canal was the largest in Scotland until Telford's Caledonian Canal was built. Relatively few canals were built in Scotland, however, due partly to its pastoral nature and mainly to the fact that it is accommodated by numerous arms of the sea.

Consideration was given to inland navigation in Ireland

as early as 1703, and parent laws were established in 1715 for the draining and improving of bogs as well as for making the River Shannon navigable. In about the middle of the eighteenth century work was begun under Thomas Orme on the Royal or Grand Canal from Dublin to the Shannon, with a view toward promoting agriculture in the fertile interior, creating trade where none had before existed, and furnishing employment for the poor. Work on the project continued sporadically for several decades and was finally completed, meeting the Shannon between Lough Derg and Lough Ree. On the whole, relatively little was done to canalize Ireland, British financiers preferring to invest in England first, and the government interesting itself in other matters.

From 1760 to 1830--from the Duke of Bridgewater's Canal to the emergence of the railroad--artificial navigation flourished in Britain--it was the Canal Age. Countless advantages, real and supposed, of this new type of transportation were loudly claimed. Among others J. Phillips in "A General History of Inland Navigation" published in 1792 offered the following:

- (1) fewer horses needed to haul produce, thus more oxen could be raised and the price of meat would be cheaper;
- (2) manufacturing encouraged because of lower price of materials;
- (3) new mines and quarries opened;
- (4) work provided for old sailors and a training ground for sailors-to-be;
- (5) landed estates aided, more settlers encouraged;
- (6) charity to the poor, for living expenses were reduced.

Promoters and speculators, engineers and industrialists, were all involved in the great scramble to cover the kingdom with canals, and by 1830 there

was not a place south of the River Dee more than 15 miles away from a navigable waterway. The tremendous construction was accomplished almost entirely by private planning and with private capital, and as a result, suffered greatly from a lack of standardization. Thus, barges making a long journey were limited in size by the smallest lock on the route and were subjected to varying tolls as they moved from one canal company's property to another. It was the uneconomical non-uniformity of the British canals which assisted the railroads in eliminating them as a serious competitor in the transportation field. The last extensive barge canal was constructed in 1834, a slow decline setting in from thenceforward. The Report of the Select Committee on Canals (1863) showed the existing canal system of Great Britain to be 2240 miles long. In this distance were 1901 locks (one for every 1.37 miles of canal), of which 931 were 80 feet or more. Although a small amount of commerce continues on some of the canals of the present day and many of them thrive by selling water, there seems no probability--especially now that the automobile has entered the picture--that canals will ever again achieve a portion of the prominence they held in Britain during the great Canal Age of the eighteenth and early nineteenth centuries.

RUSSIA -- Fired with ideas he had acquired on a trip to Western Europe, Peter the Great returned to Russia in the latter part of the seventeenth century determined to modernize his country. He engaged Colonel Breckell, a German, in 1698 to connect the Don and the Volga, but the colonel was much better

at building fortifications than he was at canals. His first sluice was a failure, so he quickly and quietly left the country and was never heard from again. That same year Captain John Perry, induced by Peter to leave England, began his first canal job in Russia in the province of Astracan, where he worked for three summers with a large conscript force. Perry was recalled from the project in 1701 for the more urgent job of constructing dockyards and other war-time structures at Veronize. Thus, the effort to unite the Don and Volga was abandoned the second time, having first failed with a Turkish attempt in the sixteenth century. Though taken up again in 1771 in Empress Catherine's time, the uniting of these two great rivers was not accomplished until the end of the century.

Perry was later engaged in surveying three different possible canal routes from the Volga to St. Petersburg from 1707 to 1710. The 30 $\frac{1}{2}$ -mile Canal of Vishnei-Voloshok was then completed during Peter's reign and remained until the end of the eighteenth century the only connection--imperfect though it was--between the Volga and St. Petersburg. Actually this canal united the Shlina, which communicates with the Baltic, and the Twertza, which flows by the Volga into the Caspian Sea. Also begun in Peter's time (1718) but completed under his successor (1731) was the Ladoga Canal. Navigation on Lake Ladoga itself had proved too dangerous for small craft, so this and other canals aggregating 104 miles were dug at this time. The main canal had a regulating lock at each extremity, a breadth of 70 feet, and was excavated to a depth varying from 7 to 10 feet. Later, from 1861 to 1886, 101 miles more of canal were constructed in the same area along the southern shore of the lake,

uniting the mouths of the rivers Volkhov, Syas, and Svir with the Neva at Schlüsselburg.

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J. Phillips writing in 1792 paid tribute to Russian inland navigation with the following: "There is no part of the world where inland navigation is carried to such an extent of country as in Russia, it being possible in that empire to convey goods by water four thousand four hundred and seventy-two miles, from the frontiers of China to Petersburg, with an interruption of only about sixty miles; and from Astracan to the same capital, through a space of one thousand four hundred and thirty-four miles; a most astonishing tract of inland navigation, almost equal to one fourth of the circumference of the earth."

Extensive construction continued well into the nineteenth century. Connecting the Baltic to the Black Sea by 408 miles of waterway--105 miles being canalized--was the Beresinsky Canal (1797-1805). The Marie Navigation, an excellent waterway, was formed from works commenced in 1799, uniting the Caspian and Baltic by connecting the Volga at Rybinsk with the Neva south of Lake Ladoga. In the 2507 miles from the Caspian to St. Petersburg (Leningrad), 668 miles were formed as part of the Marie Navigation, 200 of these miles being canals. Locks 1050 by 42 feet were constructed in the latter part of the nineteenth century and the summit level was lowered to 420 feet above sea level (1882-86). Designed to accommodate 655-ton vessels, the minimum depth on the route was cut to 6½ feet and thirty-seven locks were installed.

As in other countries the railroad acted to curtail barge canal construction in Russia and little was done other than to

enlarge existing navigations and to canalize certain rivers during the rest of the nineteenth century. During this period the Moskva River was canalized from Moscow to its confluence with the Oka, a tributary of the Volga. The twentieth century saw a ship canal evolve from this effort, the Moskva-Volga Canal, 80 miles long and representing the greatest excavation (201,900,000 cubic yards)²⁰ ever made next to Panama. Completed in 1937 this navigation contained eleven locks, 95½ by 98½ by 18 1/3 feet, ten on the canal proper, capable of serving vessels 613½ feet in length and 88½ feet in breadth. Throughout their history barge canals in Russia were created almost solely to connect the great navigable rivers, a policy which has kept a great portion of them open to this day.

SWEDEN -- Old laws and regulations for canal cutting in Sweden date back to the fourteenth century, and subsequent construction has been devoted mainly to the task of cutting across the kingdom, thereby connecting Göteborg on the Kattegat with Stockholm on the Baltic and making Swedish trade independent of the Sound. Today three ship canals, the Trollhättan, the Göta, and the Södertälje, have evolved to form that link, having developed more or less as individual units at different times. An early exponent of a canal across the kingdom was the Catholic Bishop Brask, who brought forward in 1526 a plan to join Lake Vänern with the Baltic. The plan made little headway for the bishop was expelled from the country for his opposition to the Reformation, and no vigorous canal enthusiast arose to take his place. During the next century sporadic attempts at canal

building were made but little of real value was accomplished. John III in 1581 issued orders for the construction of a canal near Trollhattan, Charles IX began a canal at the commencement of the River Göta, and Duke John of Ostragothia who died in 1619 brought forth a plan to unite the Vätter and the Baltic. The first major construction to be accomplished was the Arboga Canal joining Lakes Mälär and Hjälmär, a distance of 8 miles. Ordered by Gustavus Adolphus in 1631 shortly before his death, the work was completed in less than two years. It was reconstructed by a Dutch engineer from 1691 to 1701 and again in about 1768 by a company of merchants. The fall of almost 80 feet was overcome originally by twelve locks but this number was later reduced to eight. Another early work was the Stromsholm Canal, extending 60 miles from the province of Daleme to the Mälär with a fall of 336 feet. Plans were produced in 1765, but work was not begun until 1777 and it was not completed until 1795. The twenty-five locks varied in length from 66 to 80 feet, had a breadth of 18 feet, and had a depth over the sill of $4 \frac{1}{3}$ feet.

At an earlier date, however, the scheme for cutting a navigation across the country had caught favor again and the engineer Christopher Polhem was engaged by Charles XI and Charles XII to cut the Trollhättan section from Göteborg to Lake Vänär. Polhem's scheme to dam up the Göta River and surmount the rise of 114 feet at Trollhattan Falls with three sluices was approved in 1746 and work was carried on from 1749 to 1755. Polhem's sluice was not successful, and the death of the monarch brought a temporary end to the project.

eighteenth century, it was not until nearly that

A fresh attempt over what was largely a new route was begun under the engineer Eric Nordvall in 1793 and was completed successfully with eight locks in 1800. Considerable improvement of this 52-mile section was done during the years 1841 to 1844 under Nils Ericsson, and an elaborate building program completed in 1916 enlarged it again, the rise of 77 feet being accomplished by three continuous locks, each measuring 32½ by 45 by 50 feet.

Bishop Brask's plan for crossing the kingdom had been somewhat revised by Polhem, and in 1767 M. Thomberg produced a similar scheme which advocated connecting Lake Vänern with the Baltic by way of Lake Vättern. Thomberg's scheme lay dormant, however, until Count Platen, encouraged by the opening of the Trollhättan Canal, published a pamphlet in 1806 recommending Thomberg's scheme. At the request of Platen, Telford journeyed from England to survey the line in 1808, leaving his plans with the Count. Work was begun in 1810, but the Napoleonic Wars delayed its completion until 1832, a short time after the deaths of both Telford and the Count. As planned by Telford, the navigation extended for 120 miles, of which artificial canals composed 8½ Swedish or 55 English miles. From the Baltic to the summit the height of 307 feet was overcome by fifty-six locks, 120 by 24 by 10 feet. The Göta Canal, as this work is called, now affords two alternate routes, the Västgöta and the Östgöta.

Providing the interior link with Stockholm is the Södertälje Canal which extends from Lake Mälaren to the Baltic. Although attempts had been made in the fifteenth and latter eighteenth centuries, it was not until 1807-19 that

construction was successfully completed. At this time a surface breadth of 60 feet and a depth of 11 feet were attained, but extensive rebuilding was done in 1924 to accommodate vessels of 20-foot draught, the one lock measuring 450 by 67 by 27 feet. What may be considered the final ship canal link at Stockholm is the Hammarby Canal completed in 1926, its one lock measuring 358 by 57 by 20 feet. Thus the history of canals in Sweden is essentially one of connecting the Baltic and the North Sea with larger and larger canals until at last what may be considered as one large ship canal has resulted.

dates from 1780. Other projects were begun in 1800.

OTHER EUROPEAN COUNTRIES -- The prime position of canals in the life of the Low Countries, especially in Holland, has continued from medieval times right up to the present. Typical of old Holland canals was the 18-mile Haarlem to Leyden Canal completed in 1657, while modernity is well represented by the canal connecting Amsterdam to the Merwede, completed in 1893. Running for 42½ miles, the latter canal was constructed with a bottom width of 66 feet and a depth exceeding 10 feet, its lock measuring 393½ feet in length and 82 feet in breadth. At the beginning of the twentieth century Holland had in the neighborhood of 2524 miles of canals and canalized rivers, a density of twenty miles of waterways for every hundred square miles of area. The relative largeness of this density is better seen when compared with other countries such as Belgium with eleven, England with six, and France with three and one half miles per hundred square miles.

Barge canals as well as ship canals have also played a

large part in the development of Belgium. Antwerp is pervaded by several canals which, since the destruction of its trade, have been arched over and have become known only as sewers. The Lieve was made navigable from Dam to Ghent in the thirteenth century, and in 1613 the Canal of Albert and Isabella was begun from the Lieve at Venderhout to Bruges. From Bruges to Ostend a 10-mile canal capable of handling vessels of 500 tons was enlarged and deepened in 1665, 1728, and in more modern times as well. The Canal of Louvaine, connecting the 10-mile distance between Louvaine and Mechlin with a depth of 10 feet dates from 1750. Other projects were begun in Bonaparte's time, but with little effectual result. By the beginning of the twentieth century Belgium possessed approximately 454 miles of large canals and 143 miles of small canals, all playing a vital part in the Belgian economy.

Canal building in Germany roughly paralleled that of other European countries, the earliest in Prussia being the Muhlrose Canal from the Spree to the Oder, completed in 1688. Built originally with ten locks of wood by the engineer Philip de Chiese, the canal extended for 23 miles with a depth of 11 feet and a width of 60 feet. The number of locks was later reduced to eight which were made in stone under Frederick I. Among improvements along the River Havel made by Frederick II during the years 1743 to 1745 were the Canal of Plauen, from the Lake of Plau to the Elbe, and the Canal of Potsdam, designed to shorten the navigation of the Havel. Work on the Canal of Finaw, connecting the Havel and the Oder, was also carried on during this period, having been started in 1605.

It was finally completed in 1751, the falls of 130 feet being overcome by thirteen locks. Shortly thereafter Frederick the Great's engineer Beckenhaff dug the 16-mile Bromberg Canal (1772-75), using nine locks to overcome the fall of 67 feet. In general, canals in Germany were built mainly to connect rivers, and at the end of the nineteenth century the following had evolved as the principal routes--Ludwig's Canal from the Main to the Danube, the Oder-Spree Canal, and the Rhine-Marne Canal. Depths varied from 5 to 7 feet and lock lengths varied from 70 to 213 feet, much the same as barge canals elsewhere in Europe.

In Spain the Moors had been active in the eighth and ninth centuries and had opened a canal from Granada to the Gual^{da}quivir, thus forming a communication with the Gulf of Cadiz. Nothing on such a large scale was attempted until 1528 when Charles V began the Imperial Canal of Aragon, mainly for irrigation purposes. During the years 1770 to 1790, under the direction of the ecclesiastic Don Ramon Pignatelli, it was enlarged and made navigable for 100-ton vessels drawing 6½ feet, running a distance of almost 55 miles from Tudela to Saragoasa. Another route of importance was the Castile Canal, cut from Alar del Rey to Valladolid with a branch from Serron to Rio Seco, a total distance of 130 miles. Work on this canal, which could accommodate 34-ton barges, was carried on from 1753 to 1800 and from 1831 to 1849. The result was a waterway 6½ feet in depth with forty-nine locks averaging lifts of 10 feet. By and large, however, barge canals in Spain have played a much less important role than in any of

the countries previously discussed.

Brief mention should be made of modern Italy where, as in early times, irrigation is much more a prime function of canals than is navigation. An outstanding example of the former is the Cavour Canal (1862-66), which irrigates 490,000 acres of land in its 53-mile journey from the Po to the Ticino.

THE UNITED STATES -- Plans for constructing artificial waterways were made during the Colonial period, but little in the way of tangible accomplishment was realized until the country was able to settle down in comparative peace. Among the early canal enthusiasts was George Washington, who became particularly interested in a passage from the Chesapeake to the Ohio. Following the Revolutionary War he actually obtained a charter to form a waterway between the Great Lakes and the Hudson River. The earliest American canal of any size however, chartered in 1786 and constructed from 1793 to 1800, was the 22-mile Santee Canal in South Carolina. It was built from the Cooper River at Monck's Corner to White Oak Bluff on the Santee River, thus connecting the largest city, Charleston, with the capital, Columbia. Built by a private canal company under the chief engineer of the state, Colonel John Christian Senf, a Swede, the canal was 35 feet wide at the surface, 20 feet wide at the bottom, and 4 feet deep. It possessed thirteen locks of brick and stone with wooden gates, and accommodated boats up to 22 tons. The canal was finally abandoned in 1850 due to the changing economic conditions of the area as well as to railroad competition.

length, varied from 12 to 30 feet in width, from 3 to 34 feet in depth, and possessed an average of nearly one lock (90 by 12 feet) for every mile of navigation. It was built by the English engineer Weston for private interests, but it paid no dividends until 1819. By 1846 the competition of the railroads had forced it out of business.

Of interest are three small canals which came into use during the construction of the Santee Canal in three widely separated parts of the country. In 1787 work was begun on the Dismal Swamp Canal from Norfolk, Virginia, to Albemarle Sound in North Carolina, but by 1794 only a portion was navigable for small boats. Often referred to as the "first American canal," the South Hadley Canal on the Connecticut River in Massachusetts dates from 1793 or 94. Three men, Christopher Colles the surveyor, Benjamin Prescott the engineer, and Ariel Cooley the contractor, were responsible for this work, which extended for a distance of over 2 miles and surmounted a fall of 50 feet by five or six locks. Also dating from 1794 was the Carondelet Canal, a shallow ditch 2 miles long and 15 feet wide, connecting New Orleans with Lake Pontchartrain. When the land was ceded to the United States in 1803, the canal was enlarged and has been in use ever since. Now in a position to do the job this canal was originally designed for, is the New Orleans Industrial Canal, completed in 1923. Connecting the Mississippi River with Lake Pontchartrain, this 5½-mile canal running through New Orleans is a true ship canal, with a surface breadth of 300 feet, a bottom breadth of 150 feet, a depth of 30 feet, and an entrance lock whose usable measurements are 640 by 75 by 31 feet.

The next project of consequence was the Middlesex Canal (1794-1803) which connected the Charles River at Boston with the Merrimac River a short distance above Lowell. Built primarily for the transportation of timber and firewood from New Hampshire to Boston, the canal extended over 27 miles in 4-foot depth to accommodate 30-ton barges, the canal was

length, varied from 12 to 30 feet in width, from 3 to 3½ feet in depth, and possessed an average of nearly one lock (90 by 12 feet) for every mile of navigation. It was built by the English engineer Weston for private interests, but it paid no dividends until 1819. By 1846 the competition of two railroads had forced it out of business.

Suggested by William Penn in 1690 and roughly surveyed by Rittenhouse in the latter part of the eighteenth century, the Union Canal of Pennsylvania connecting the Schuylkill River at Reading with the Susquehanna at Middletown did not become an actuality until a quarter of the nineteenth century had passed. Three chief engineers were employed during the construction period 1821-27, William Weston, Laommi Baldwin, and Canvass White, the first two being tremendously hampered from lack of funds. The railroad also took its toll here and this 82-mile canal was later abandoned.

Of particular interest among early American works was the Morris Canal (1825-31), noted for its twenty-three inclined planes varying in length from 500 to 1500 feet and in lift from 44 to 100 feet. Designed by James Renwick--an Englishman by birth and then professor at Columbia College--the canal ran 103 miles from the Delaware River opposite Easton, Pennsylvania, across New Jersey to Jersey City on the Hudson, thus connecting the coal of Pennsylvania with New Jersey industry and the tidewater at New York. In addition to its inclined planes this canal possessed twenty-three ordinary locks which in the period 1841-45 were enlarged to a size of 98 by 12 feet. Originally designed with a 20-foot width at the bottom and a 4-foot depth to accommodate 50-ton barges, the canal was

enlarged in 1860 to suit 80-ton vessels, but it ceased to be important in 1870 when leased to the Lehigh Valley Railway Company.

While the New York State Barge Canal is basically the extension and improvement of five older canals, its main section, the Erie Canal, so overshadows the other sections that their names are scarcely known. Extending from Troy, New York, on the Hudson River, the original Erie Canal ran over 350 miles across New York State to Buffalo on Lake Erie, thus becoming the first commercially practicable waterway from New York City to the Great Lakes. Surveys were begun in 1808 and construction commenced in 1817 under the engineers James Geddes, Benjamin Wright, and Charles Bradhead, all Americans without formal engineering training. Completed in 1825, the canal had surface and bottom widths of 40 and 28 feet respectively, and a depth of 4 feet, thereby allowing the passage of 60-ton vessels. Two aqueducts constructed on this job received favorable comment in their day, one extending 802 feet across the Genesee River at Rochester, and the other which carried the canal 40 to 50 feet above the river at Little Falls. The effect of this new waterway was summed up by E. Sweet in the Transactions of the American Society of Civil Engineers for 1884 thusly: "The Erie Canal, conceived by the genius, and achieved by the energy of De Witt Clinton, was, during the second quarter of this century the most potent influence of American progress and civilization. It developed the northwest, by giving an outlet to the commerce of the great lakes, and it made New York the Empire State, and New York City the imperial mart of the New World."

Also begun in 1817 was the Champlain Canal, branching from the Erie Canal and running 63 miles northward to Whitehall at the foot of Lake Champlain. Completed in 1822 under the engineer Geddes, it was in reality a part of the Erie Canal system. In the period 1835 to 1862 enlargement and realignment of not only the Erie and Champlain Canals took place, but of the Oswego to Lake Ontario, the Cayuga and Seneca canals as well. A 7-foot depth was obtained, a depth which remained static for fifty years, allowing 240-ton vessels to pass.

Although a period of modern improvement was begun in 1884, great political agitation in the early 1900's forced still greater improvements to be started in 1905 under the State Engineer, H.A. Van Alstyne. Various considerations came into play but the opening of the rival St. Lawrence waterway to Lake Ontario undoubtedly had considerable influence in the final decision to deepen the canal to 12 feet and increase its bottom width to 75 feet. The standard lock length adopted was 310 feet along the center line, with a width of 45 feet and a depth of 12 feet over the sills. In the resulting construction, distances between locks varied, the least being 338 feet, while individual lifts ranged from 6 to 40½ feet. In all, there were thirty-five locks constructed on the Erie Branch, eleven on the Champlain, seven on the Oswego, and four on the Cayuga and Seneca. At Waterford a remarkable series of five locks was installed, varying in lift from 32½ to 34½ feet, giving an aggregate lift of 169 feet, the greatest series in the world.²³ The first locks went into operation in 1910, and in 1918 the canal, now under State Engineer F.M. Williams, was opened

throughout its entire length. Thus, not all canals fell victims to the railroad in the nineteenth century rush. State control and foresight saved this magnificent work for future useful service and it has easily fitted into the modern economy.

The lead taken by the State of New York was soon followed by Ohio, which joined Cleveland to Portsmouth and Toledo to Cincinnati with public canals large enough for 30-ton barges. Indiana and Illinois soon followed until at one time there were over 5000 miles of canal lines in operation built at a cost exceeding \$150,000,000. Enthusiasm for canals reached such proportions that in the middle of the nineteenth century the legislatures of some states enacted prohibitive laws against railroads in favor of canals. Among the more important works of this period was the Chesapeake and Ohio Canal, 6 feet in depth, and completed in 1851, connecting the Potomac and Ohio rivers and piercing the Allegheny mountains with a tunnel 3118 feet in length. The longest abandoned line of the period was the 379-mile Wabash and Erie Canal, constructed during the years 1832-51 to connect Evansville, Indiana, and the Ohio State line. In the last decade of the century the famous Drainage Canal of Chicago was constructed from Lake Michigan to the Desplaines River at Lockport, thence to the Illinois River, a total distance of 38 miles. Varying in depth from 22 to 26 feet, it was given a bottom width of 160 feet in rock and 202 feet in clay. The final linking of the Great Lakes to the Mississippi was accomplished by the 7-foot Illinois and Michigan Canal, running a distance of 97 miles from Chicago to La Salle

on the Illinois River. 274

In the western part of the United States the need for irrigation caused the settlers to begin canal operations about 1860. Large scale operations date from about 1872 when the large canal starting from the River Fresno in California was dug. Though it was built primarily for irrigation, being 8 feet in depth and 20 feet in width, some navigational benefits did result. Following closely was the 32-mile Calloway Canal begun in 1875 from the River Kern, also in California. Since that time irrigation canals have steadily increased in size and number in the West, while in the East many small navigation canals have been relegated to oblivion by the railroads. Those navigation canals which have remained have been improved and deepened at the public expense, and give promise of continued valuable service to the country as a whole, and especially to those local communities through which they pass.

HAULAGE -- From earliest times manpower, and later animal power, has been used as the prime-mover in towing barges along canals. Pottery taken from the Car Dyke and dating from the first century A.D. has reliefs showing men towing barges by means of long lines, and even today in parts of China such a system is used. Development beyond the horse or oxen stage was impossible, however, until the steam engine could be adapted to the purpose. The steam tug experiments at Worsley by Captain Shanks R.N. of Deptford failed during the period 1796 to 1799, but in 1802, on the Forth and Clyde Canal, a tug boat fitted with steam engines by W. Symington drew two barges 19½

miles in six hours in the teeth of a strong headwind. The advance is more readily appreciated when it is realized that the average English horse of the time could draw one narrow canal boat 2 miles per hour loaded, or 3 miles per hour unloaded, under normal weather conditions. The first systematic steam tug service from Paris to Montereau (65 miles) was finally inaugurated in 1846. Later in the century towing by means of steam locomotives was tried briefly in France, Germany, and England, but was abandoned for economic reasons. Electrical towage, as exemplified by the cars at the locks of the Panama Canal, has found its place in special circumstances but has never become widespread. Today the steam tug and, to a lesser extent, the horse remain the principal prime-movers for those barges moving through canals not under their own power.

Other variations in haulage systems came into use during the eighteenth and nineteenth centuries. On the Elbe in 1720 a hempen rope was fastened to a point on shore and was then wound up by manpower on the boat, propelling the vessel forward. Messrs. Tourasse and Courteaut in 1820 designed special tugs with horse capstans; subsequently these horse capstans were replaced by 6-HP steam engines. Chains then replaced hempen ropes on the Seine between 1820 and 1830, and in 1865 M. de Meseil, a Belgian, introduced wire in place of chain. A submerged towing chain, operating over a distance of 45 miles, was introduced on the lower Seine in 1856, while a similar project on the Elbe, 407 miles from Hamburg to Aussig, was laid down from 1869 to 1874. Endless chain systems were experimented with on the Rhône in the latter nineteenth

century, but no practical results were obtained. An endless travelling wire cable--first tried by M. Riche on the Sambre at Maubeuge in 1874--was, however, finally established in a practical form in 1894 for hauling barges through the tunnel of Mont-de-Billy on the summit level of the Aisne-Marne Canal. Of particular interest were the grappling wheels used on the Rhone, such as the "grapin," an iron wheel 20 feet in diameter, weighing 17½ tons, furnished with projections or picks and fixed in a well-hole amidships. It was worked by a chain attached to the paddles of the boat and was lowered whenever a tough ascent had to be made. Most of these developments, however, have had limited application. Today simple towing lines of fiber or of wire are used by tugs or tow path animals or machines, and elaborate systems have passed from the scene.

SHIP CANALS Ship Canals

No hard and fast rule obtains for the distinguishing between a barge and ship canal other than the fact that ship canals usually accommodate larger vessels. As ocean going vessels increased in size, the original ship canals were not always increased in proportion and so dropped from the ship to barge canal category. Today very few canals with less than 20 feet of depth are called ship canals, and so, in the interests of simplification, it is at this depth that we shall distinguish between the two types.

NORTH HOLLAND SHIP CANAL -- Amsterdam, following the

Napoleonic Wars, found that she was in danger of losing her commerce for her only outlet to the sea was via the Zuider Zee which had an available depth of 11½ feet, and vessels had begun to increase greatly in size. To remedy this situation the engineer Jan Blanken (1755-1838) was employed to cut a canal from Lake Y, opposite Amsterdam, over 50 miles north to Nieuwediep adjoining Texel Roads. When completed after eight years of work (1817-24), the canal had a surface width varying from 120 to 125 feet, a bottom width of 33 feet, and a depth varying from 18 to 20 feet. It contained a tidal lock at either end plus three intermediate locks, which were made double to accommodate large and small boats economically. Half a century later it was rendered obsolescent when most of its sea-going trade switched over to the new Amsterdam Ship Canal.

GHEENT-TERNEUZEN CANAL -- Connecting Ghent to the sea with a substitute run of approximately 20 miles instead of one of 105 miles by the circuitous Schelde, this canal had its beginnings in the sixteenth century. A canal from Ghent to Sas-de-Gand, where it entered a tributary of the Schelde, was opened in 1561, but it was closed in 1648 by the Treaty of Munster and remained closed until 1815. In the years 1825 to 1827 the canal was extended from Sas-de-Gand to Terneuzen with a depth of 13 feet for purposes of navigation and drainage. An enlargement was effected in 1879, making the bottom width almost 56 feet, and increasing the depth in the Belgian section to 21 1/3 feet, and in the Holland section to 20 feet. Another enlargement took place from 1891 to 1908 when the depth was increased to

27 feet, and in 1911 when the depth was increased to 28 feet. In such a manner the canal has kept pace with the increases in ship sizes, and thus continues to shape the commercial destiny of Ghent and the territory surrounding her.

SUEZ CANAL -- Long after Egyptian and Roman canals uniting the Pelusiac branch of the Nile with the Red Sea had silted up, the Arabs were successful in cutting another canal across the Isthmus of Suez. The last attempt to unite the Red Sea to the Nile was made by Amru ibn el Aas, general of Caliph Omar, who took Egypt in the seventh century A.D. When a great famine threatened Mecca, Amru was ordered to get Egyptian grain there as quickly as possible, a problem he solved in 639 by following Trajan's Canal to a great extent and cutting through to the Nile at Cairo. However, the canal was destroyed in 767 by Caliph Abou Giaffar el Mansour who wished to prevent insurgents from receiving food at Medîna. Desert sands and the passage of time completed the job of destruction.

From the fifteenth century onwards various schemes, mostly commercial, were advanced for uniting the Mediterranean and the Red Sea, but nothing concrete was accomplished until a French company under Ferdinand de Lesseps (1805-1894), a retired diplomat, undertook construction in the middle of the nineteenth century. At the end of the preceding century when the French were occupying Egypt, Napoleon ordered a survey to be made, a hurried job under M. Lépère which indicated that the Red Sea was approximately 30 feet above the Mediterranean. This information caused Napoleon to drop the canal project, but later surveys in 1847 under Robert Stephenson showed that the levels

of the two bodies of water were practically identical. Fortified with this knowledge de Lesseps gained support for his sea-level canal proposals, and obtained concessions in 1854 and in 1856 from the Viceroy of Egypt, Said Pasha, for the organization of the Compagnie Universal de Canal Aratan de Suez. Preliminary work was begun in 1856, construction in earnest commenced in 1859, and the canal from Port Said to Suez was officially opened in 1869.

Construction until 1864 was largely a primitive affair, most of the work being done by the forced labor of twenty-five thousand natives furnished by the Viceroy. When Ismail Pasha came to the throne in this year, forced labor was discontinued and the company turned to Europe for labor and machines. Starting from Port Said the canal was dredged from the beds of lakes Menzaleh and Ballah, and then pierced the lower part of a ridge some 54 feet above sea level (deepest cut). From here it passed through Lake Timzah, through the Serapeum ridge to the Bitter Lakes, and on to Suez, an approximate distance of 100 miles. The present canal is 87½ miles long from Port Said Lighthouse to the junction with Suez Bay. Of this length, 66 miles is actually dug channel while the remainder consists of dredged channels through the lakes. The size of the undertaking can be better appreciated when it is realized that one of the side jobs was the digging of a small canal to carry fresh water 132 miles from Cairo to Suez. While the name of de Lesseps was immortalized as the promoter of this tremendous engineering feat, no less credit is due the chief engineer, Voisin Bey, or the contractor, M. Lavalley, both of whom played a great part in

making the venture a success.

Originally cut to a depth of 26½ feet, the canal has been enlarged so that at no place is its depth less than 34 feet. The surface width, in general, varies between 400 and 500 feet while the narrowest bottom width is 148 feet. The maximum speed allowed by the canal company is seven and a half knots, meaning that the average peace time transit is about thirteen hours, eleven of which are actual steaming time.

The importance of the Suez Canal on the political and economic history of the world is too long and involved to discuss here, although its commercial advantages are evident with one example. On a voyage from London to Bombay the route by way of the canal saves five thousand five hundred and twenty miles, or 44 per cent of the mileage over the Cape of Good Hope route. In the original agreement the company was to hold the concession for ninety-nine years, at the end of which time possession of the canal was to pass into the hands of the Egyptian government. Egypt also received company shares which were sold by the bankrupt Kadive Ismael in 1875 to Disraeli, acting for the British government. It gave the British, for sixteen million dollars, 7/16 interest in the project they had denounced only a few years before and which was to have a profound effect on their policy of Empire from that time to the present day.

AMSTERDAM SHIP CANAL -- The construction of railroads throughout Europe brought an increase of trade to the ports south and east of Helder and awakened the merchants of Amsterdam to the fact that they would have to provide a better communication

with the North Sea than was provided by the North Holland Canal. As early as 1629 a proposal had been made to cut an east-west drainage canal from Amsterdam direct to the North Sea, and in 1817 a similar proposal was rejected as impractical. Between 1852 and 1863 a great number of projects were proposed, a concession being granted in 1863. The Amsterdam Ship Canal Company got the concession in 1865, and work was begun in the same year under the chief engineer John Hawkshaw, an Englishman, and his resident engineer, J. Dirks of Amsterdam. Work on the 16-mile canal was completed in 1876 at which time the depth was 23 feet. A set of locks was installed at both ends of the canal, the gates at the seaward ends being of malleable iron and those at the inboard ends being of wood. Originally the largest of the three locks at the Zuider Zee end measured 315 by 59 by 14 feet, while the larger of the two Ymuiden locks measured 393 by 59 by 23 1/3 feet.

Almost immediately following its completion the canal and locks were enlarged. The first decade saw the depth increased to 25 1/2 feet and the next decade saw it increased to 28 feet. By 1928 the canal had the largest lock in the world, measuring 1315 by 164 by 50 feet. While the original work cost much more than had been anticipated, much land was reclaimed and sold at a profit. The immediate effect of the canal was to draw sea-going trade away from the North Holland Canal and to increase the trade at Amsterdam. Over the period of years it has kept Amsterdam in the front rank as a maritime city and gives every indication of continuing in that role in the future.

MANCHESTER SHIP CANAL -- The merchants of Manchester, to avoid high docking and railroad rates from Liverpool, had early in the nineteenth century listened to proposals to form a canal from the city to an estuary of the Dee, and, indeed, a company was formed in 1825 but no results were obtained. In 1877 the Chamber of Commerce strongly urged a canal and by 1882 two schemes had been submitted. An Act authorizing the work was passed in 1885, construction under chief engineer E. Leader Williams was begun in 1887, and ships began to pass regularly through in January of 1894. From Manchester the canal descended 60½ feet past Runcorn along the River Mersey to Eastham where it joined the Mersey 35½ miles away.

Upon completion, the canal had an average width of 172 feet at the water line, a minimum width at the bottom of 120 feet, and a minimum depth of 26 feet. Tidal locks were installed at Eastham and double lift locks at Latchford, Irlam, Barton, and Mode Wheel, the largest measuring 600 by 65 by 28 feet. This, then, became the first large ship canal to have locks other than the tidal regulating type at the end such as were present in the Amsterdam Ship Canal. The number of employees averaged 10,500 a year although as many as 17,000 men were at work at times. In all, 223 miles of railway were laid in or alongside of the canal bed. Among the victims of modern progress was Brindley's Bridgewater Canal stone aqueduct which was replaced by a swing steel tank 90 by 19 by 6 feet. As in the case of most other ship canals the estimated cost was less than half the final cost of £ 15,000,000, but the benefits, real and intangible, to Manchester in having this

outlet to the sea have justified the expense in the eyes of most of its citizens.

POUTILOFF CANAL -- With a view toward converting St. Petersburg into a port a commission reported in 1872, the plan was adopted in 1874, and construction began in 1877. Also known as the St. Petersburg and Cronstadt Ship Canal this work began at the Neva below St. Petersburg and continued 17½ miles to Cronstadt on the Baltic. Constructed by the government it was in operation by 1884 with a surface width of 426 feet, a bottom width of 275 feet, and a depth of 22 feet.

Construction of the present canal was primarily a German

CORINTH CANAL -- As early as 600 B.C. Periander proposed to unite the Gulf of Corinth with the Gulf of Aegina by a canal cut through the Isthmus of Corinth, and work on the project was actually begun in Nero's time but abandoned on his death. The modern effort dates back to 1870 when a concession was given to Maxime Chollet and his engineers Gerster and Kauser. Little was done until 1881, however, when the Hungarian General Etienne Turr, having relinquished his concession at Panama to de Lesseps, obtained the one at Corinth. Construction was begun in 1882 but was stopped in 1889 from lack of funds. A new company was formed, the Société Hellénique du Canal de Corinthe, which completed the job in 1893. Cut through solid rock the depth of the cutting averaged 190 feet, the maximum cut being 287 feet. Slightly over 3 miles in length--6937 yards to be exact--the canal was given a bottom width of 72 feet and a depth of 26½ feet. Sea level throughout, the canal continues to play

an important part in the Mediterranean trade, especially where Greece is concerned.

KIEL CANAL -- The first waterway of importance to cut across Schleswig and unite the Baltic and North Seas was the 26-mile Eider Canal, begun in 1777 and completed in 1784. It connected the Baltic at Holtenau near Kiel with the River Eider flowing into the North Sea, and enabled 120-ton vessels to make a 100-mile transit. Possessing three double locks, all measuring 100 by 27 by 10 feet, the canal had a rise of 23 feet and surface and bottom width of 100 and 54 feet respectively.

Construction of the present canal was primarily a German naval scheme originated after the separation of Schleswig-Holstein from Denmark in 1864, but the wars of 1866 and 1870 postponed activity. Investigations were resumed in 1878, the plan was approved in 1886, and construction by the government began the following year. A force varying in number from 3000 to 8000 men worked for eight years excavating some 105,000,000 cubic yards of material. As completed in 1895 the canal varied in surface width from 217 to 283 feet, had a bottom width of 72 feet, and a minimum depth of 29 feet. It was one level reach throughout, with two regulating locks side by side measuring 492 by 62 by 33 2/3 feet at each end. A ship starting from Holtenau on the Baltic would pass through three lakes, Flemhude, Mechel, and Kuden, and enter the Elbe near Brunsbüttel 61 1/3 miles away after ten to twelve hours steaming time.

During the years 1907 to 1914 the canal was enlarged and

deepened to strengthen Germany's naval position for the coming conflict. Surface and bottom width were increased to 335 and 144 feet respectively, the depth was extended to 36 feet, and the locks were increased to a length of 1082 feet, a width of 147 feet 7 inches, and a depth of 45.9 feet. A quick glance at the map will show the strategic value of the canal in any naval warfare involving Germany, for it would enable her to transfer fleets quickly between the Baltic and North Seas without subjecting them to the delay and danger of traversing the Kattegat and Skagerrak. In like manner the canal has been a boon to private vessels where time is money in the commercial world.

SAULT SAINTE MARIE CANAL --- Uniting Lake Huron and Lake Superior at Sault Ste. Marie are two canals, one with four locks on the American side, and the other with one lock on the Canadian side. The first lock in Canada was built here during the years 1796 to 1798 by the Hudson Bay Company, but that lock has long since been replaced. By 1894 in Canada a 3500-foot cut through St. Mary's Island at a depth of 22 feet had been completed, in addition to the modern lock measuring 900 by 60 by 20½ feet over the sills.

On the United States side the State of Michigan took an early interest, authorizing a survey in 1837, issuing an appropriation in 1838, and commencing construction in 1839. Difficulties with the federal government concerning jurisdictional rights held up progress for a few years, so authorization for recommencement of the work was not obtained until 1853. The

canal was finally opened in 1855, its locks measuring 350 by 70 by 13 feet. In 1880 the federal government took over the canal and began improving it almost immediately. In 1881 the Weitzel lock, 515 feet long, was constructed, followed in 1896 by the 800-foot Poe lock. In 1914 and in 1919 the Davis and Sabin locks were completed, measuring 1350 by 80 by 24½ feet, and giving a maximum lift of 21 feet. Although only open seven months of the year, this canal, less than a mile long, has carried for many years the most tonnage of any canal in the world. Of prime importance in traffic on the Great Lakes, it has played a great part in the development and enrichment of the Middle West.

WELLAND CANAL -- To date there have been four Welland Canals in Canada joining Lake Erie to Lake Ontario, the original having been built by a private company during the years 1825 to 1831. Traversing 27½ miles, this first work possessed forty wooden locks, the smallest being 110 feet in length and 22 feet in width. Bought by the government in 1841, a new and larger set of works was constructed during the period 1842 to 1849. A still larger canal was constructed from 1873 to 1881, branching off from the old canal 19 miles from Lake Erie and rejoining it again at Lake Ontario. A difference in level greater than 300 feet was overcome by twenty-five locks with lifts varying from 12 to 16 feet. These locks, measuring 270 feet in length and over 40 feet in width, had sides of limestone ashlar, floors of pine, and gates of white oak. The 12-foot draught of the canal was increased to 14 in 1887.

Begun in 1913, the present canal was opened to navigation in 1914, being 25 miles in length and having a total lockage of 325½ feet. To overcome this differential four single locks, one flight of three double locks, and a guard lock were constructed, measuring 820 by 80 by 30 feet, and giving individual lifts of 46 feet. Surface and bottom widths were made 310 and 200 feet respectively, while the depth was cut to vary between 25 and 26½ feet at low water, with a provision for deepening in the future. As has been the case with the "Soo" Canal, this work has been instrumental in developing traffic on the Great Lakes and has reacted to the benefit of Canadians and Americans alike.

PANAMA CANAL -- Four hundred years were to elapse from that day in 1513 when Balboa, standing on a peak in Darien, first gazed upon the Pacific Ocean until that ocean was united with the Atlantic some 50 miles away. Though men were seeking an already existing waterway through the New World to the Indies, it was not long before plans for a canal at Panama were discussed. According to the Portuguese historian Antonio Galvão, the first proposal for such construction came in 1529 from Saavedra de Ceron, a lieutenant of Cortes, who had previously served with Balboa in Darien. Charles V in 1534 ordered the governor at Panama, Francisco de Barrionuevo, to conduct a survey with a view toward determining whether a canal could be cut to the Chagres River. Throughout the rest of the sixteenth and seventeenth centuries the thriving trade between Spain and Peru brought wealth and prosperity to the Isthmus

and stimulated thoughts for a canal. Scientific parties from all nations of the world explored and surveyed up and down the coasts of North, Central, and South America in an endeavor to find the most likely site for such a canal. Fresh attention was focused on Panama when the gold rush in California in the middle of the nineteenth century brought East Coast adventurers across the Isthmus in an endeavor to beat their competitors travelling the difficult overland route in the United States.

The first concrete step toward construction was taken in Paris at the Congrès International d'Études du Canal Interocéanique in 1879. Here 74 year-old de Lesseps, fresh from his triumph at Suez and possessor of the most celebrated name in France, convinced the assembly, over two-thirds of whom were not engineers, that the construction of a sea-level canal at Panama was a practical venture for a private company. Preliminary work at Panama was begun in 1880 and the company, the Compagnie Universelle du Canal Interoocéanique, was formally incorporated in Paris in 1881. During the first period, which lasted until 1883, all work was done under one general contractor. The desired results not being obtained, the company acted as its own general contractor until 1885, but that solution was equally unsatisfactory. In the third period, covering 1886 and 1887, work was let out to six large firms. In the final period these firms continued to act as before, but the scheme was changed, at the suggestion of Phillippe Bunau-Varilla, from a sea-level to a lock canal for financial reasons. The change had come too late, however, and the company went into the hands of the receivers in 1888.

to put the project in charge of men who will stay on the job

A fresh attempt to revive the project was made by the Compagnie Nouvelle du Canal de Panama which lasted from 1894 to 1903, but its work was largely confined to preserving what had been left by the first company. In the meantime, agitation for a canal which had been growing in the United States was given greater impetus in 1898 by the dramatic 13,000-mile dash of the battleship Oregon in sixty-eight days from San Francisco to Key West via the Straits of Magellan. Now commercial and military interests of the country were truly allied. Difficulties in negotiating with Colombia led the United States to give official recognition almost immediately to the new Republic of Panama which came into being in November 1903. From this new government the United States received a strip of land ten miles wide in perpetuity, excluding the terminal cities of Panama and Colon, and in return the United States agreed to pay \$10,000,000 on exchange of ratifications and an annuity of \$250,000 to commence nine years later.

Within three years, from 1904 to 1907, President Roosevelt found himself obliged to appoint three different commissions, the first under Rear Admiral J.G. Walker USN, the second under Theodore P. Shonts, and the third and final under Major George W. Goethals. The first chief engineer, John F. Wallace, stayed only a year, until 1905, and his services were largely concerned with preliminary investigations. John F. Stevens succeeded him, remaining in office until his resignation in 1907. During his tour Stevens did a fine job in developing plans for excavation and in solving rail problems, but he had no great desire to stay to the end. Tired of resignations, the President decided to put the project "in charge of men who will stay on the job

until I get tired of having them there, or til I say they may abandon it. I shall turn it over to the Army." ²⁶ Accordingly Major, soon Colonel, Goethals took over the job as chief engineer and remained in that post until the canal was completed in 1914.

The personality of West Pointer Goethals so completely dominated the construction period of the last seven years that the names of his chief technical aides, to whom he would be the first to give full credit, are often forgotten. All were civil engineers, three from the army, Hodges, Sibert, and Gaillard; one from the navy, Rousseau; and one from civil life, Williamson. Practically all the work was done by the government itself, only a few items such as lock gates and emergency dams being let out to contractors. During some years the force at work averaged almost 57,000 men, a considerable increase over the maximum of 19,000 employed by the French twenty years earlier. Though his work was not actually concerned with construction, the contribution of Colonel Gorgas of the Army Medical Corps in stamping out yellow fever and malaria cannot be over-estimated. His men transformed the pest-hole that was Panama into a model tropical community.

An international board of consultants in 1905 recommended a sea-level canal, but the minority report of the American engineers recommending a lock canal was adopted in 1906. As finally constructed, the canal extended 47 miles from the Atlantic entrance in Limon Bay, through a short channel at sea level, up the triple flight of Gatun locks to the 85-foot summit level of the artificial Gatun Lake (164 square miles in area) across the lake to the outlet of the Chagres at Gamboa,

through the 10-mile Gaillard Cut to the Pedro Miguel Lock, across the artificial Miraflores Lake, down the double flight of locks at Miraflores, and out through a dredged channel in Panama Bay to deep water in the Pacific. All locks were made in pairs for two-way traffic, each lock measuring 1000 by 110 by 40 feet. During the construction years some 287,750,000 cubic yards of material were excavated, an amount never before nor since exceeded.

While full credit is due American engineers for carrying this greatest of engineering projects to completion, due regard must be had for the French legacy. Plans and surveys were especially useful, and of the 80,000,000 cubic yards excavated by the French almost 30,000,000 representing about one-tenth of the total necessary were useful to the Americans. Quantities of machinery and material, though housed and in good condition, had become obsolete, but more than half of the French buildings were usable after repair. Many reasons have been advanced for the French failure, extravagance, corruption, incompetence, and disease, but these points have been over-emphasized. For example, even though at the time it was not known that a mosquito was the deadly bearer of yellow fever and malaria, the death rate from disease on the Isthmus as computed by the French for the period 1851-88 was 59.7 per 1000, and Gorgas' calculations for the same period showed 63.1. During the Compangie Nouvelle's period Gorgas calculated the rate to have averaged 25.5 per 1000; scarcely the 60 per cent claimed by some extremists but considerably higher than the American average which descended from a peak of 39 to 7 per

1000. There was some corruption and incompetence in the French project, to be sure, but one great cause of the failure was the insistence of de Lesseps on a sea-level canal. Working with private capital with an obligation to make money for the backers was a handicap which might have been overcome had he changed his plans earlier to the less expensive lock canal, but his success at Suez had influenced his decisions to the detriment of the whole project. Perhaps even the lock canal project would have proved too costly for a private company. Certainly the American success can be attributed to the fact that it was a government project which did not need to reap a financial reward to be successful, and one which was headed by men like Goethals and Gorgas to whom the motto of the Panama Canal was not only a challenge of the moment but a dream of the future, "The Land Divided, the World United."

Summary

Canals for drainage and irrigation became identified with the early prehistoric civilizations which sprang up in the neighborhood of rivers and their tributaries, and, in time, the use of these canals was extended to navigation as well. In Egypt in the pre-Christian, and Rome and China in the pre- and post-Christian eras built extensively, as did the Arabs in the Dark Ages, but no real legacy was handed down by these people to their successors, the medieval Europeans. With no examples from the past, such as was the case with roads and bridges, to influence their design these early Europeans may be characterized by shallow drafts usually varying from 4 to 6

be considered the originators of canal design as we know it today.

The urgent need for drainage in Holland and the Low Countries caused the people there to become great canal builders as early as the thirteenth century, and possibly earlier. The advantage of navigation on these drainage canals was soon apparent, a factor which brought about the discovery of the greatest single advance in the history of canals, the lock. No longer was it necessary to build a level stretch or not build at all, canals could be built over mountains if necessary. It was these navigation canals which fostered trade and enabled a few Dutch and Flemish cities to become the foremost in medieval Europe. The discovery of the lock in Holland dates back at least to the fourteenth century, probably a hundred years before its use in Italy, where irrigation had given the original impetus to canal building.

France was awakened to the advantages of navigation canals early in the seventeenth century, and much progress was made under the prodding of such ministers as Sully, Richelieu, and Colbert. Construction in France increased in tempo in the next century, the one in which a rash of canal building was to break out all over the world. In Russia it was Peter the Great, in England the Duke of Bridgewater, in Sweden Count Platen, who fired the minds of their countrymen with visions of extensive systems of canals stimulating and enriching their lands. Almost every civilized country in the world embarked upon canal projects during the latter half of the eighteenth and first third of the nineteenth century. Canals of the period were characterized by shallow drafts usually varying from 4 to 6

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feet, many small locks, and animal towpaths.

In about 1830 the railroad made its appearance as a commercial carrier and all but rendered the small barge canal obsolete in every part of the globe. While the small barge canal did not go out of existence entirely, it suffered a blow from which it never recovered. Brief efforts, successful in spots, in the latter half of the nineteenth century to bolster the small canal in order to keep the railroad in line were made, but subsided with the passage of time.

Canal history entered a second era with the completion of the Suez Canal in 1869. The clamor for large ship canals to unite the world's great bodies of water became more insistent now that de Lesseps had shown that such a feat was possible. Though these canals would serve commercial interests, their strategic value from a military standpoint became more evident as the world grew smaller and nineteenth century nationalism became more manifest. The opening of the Panama Canal in 1914 signalized the completion, at least temporarily, of imperialistic dreams to unite the world by water.

Coincident with the interest in inter-oceanic ship canals was the rise of ship canals for ports, a revival of the commercial schemes of the Middle Ages. Though others had come into being before it, the Amsterdam Ship Canal of 1876 marked the beginning of the modern movement which has continued to the present. Ocean transport for bulk commodities still remains the most economical form of transportation, and until air power can replace it, cities will clamor to be sea-ports.

Though still in use in some parts of the world, the

small barge canal has bowed to progress by simply fading out of the picture or by increasing in size until it resembles the ship canal of yesteryear. This tendency to become larger or die is a familiar pattern in the history of all canals. As machines have developed to create and drive larger ships so have they developed to dig deeper canals and to make larger and hence, fewer locks. This development in the canal has been reflected in the development of world affairs as well. Not only has modern strategic warfare, and thus modern history, been closely allied with canals, but so have trade and commerce, and therefore the prosperity of all ages.

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Chapter VI

TUNNELS

TUNNELS

Ancient & Medieval Tunnels

OCCURRENCES IN NATURE -- In past times both rock shelters, formed mainly by weathering at the surface, and caverns, formed by the action of percolating water through limestone, dolomite, or marble rock have served as refuges for primitive man and animal. Still to be seen, these natural excavations abound on the west coast of Ireland, in the western Highlands of Scotland, and in certain limestone districts in Asia Minor and in the Americas. For example, in southeastern New Mexico the Carlsbad Caverns extend down to a depth of more than 1300 feet and include one chamber 4000 feet long, 625 feet wide, and 350 feet high. As civilization advanced, man substituted artificial for natural excavation, putting his works to a variety of uses such as dwelling places, tombs, and tunnels for mining, water supply, drainage, transportation, and services.

EGYPT -- About 100 feet below the base of the Great Pyramid (c 2900 B.C.) at Gizen is a subterranean chamber cut out of rock with a sloping chamber leading to it. Presumably this excavation was accomplished during the time of the erection of the pyramid, meaning, of course, that the art of tunneling can be traced back at least 5000 years. Evidences of other man-made excavations in existence as early as 2000 B.C. are available at various places in Egypt today. Remains in the grottos of Samoun, the tombs near Thebes and Memphis, the catacombs of Alexandria, and the

temples of Ipsamboul all serve as mute testimony to the skill of the engineers of a by-gone age. A tomb hewn out of solid rock at Abydos probably dates back to the Twelfth Dynasty (c 2000 B.C.) and the temple of Abu Simbel built by Ramses II dates back to the thirteenth century B.C. At Thebes a tunnel was driven at a slope for 350 feet into a hill, at which point a shaft was sunk and the tunnel continued on for another 300 feet. At the end of this excavation the tomb of Mineptan was made by enlarging the space into a chamber.

To do this work the Egyptians had the ordinary hand tools such as the hammer and chisel, and, when working with granite, used saws of copper either fed with emery powder or set with teeth of that abrasive. In removing rock they cut grooves 4 to 20 inches in thickness on four sides of the block and inserted wooden wedges in the grooves. Water was then poured on the wedges with the result that the block was broken out by the resulting swelling action.

GREECE -- Near Lake Kopais in Boetia a series of sixteen shafts exist, 200 to 1000 feet apart, 6 to 9 feet wide, and reaching a maximum depth of 100 feet. It is commonly supposed that these shafts were made by the Minyae sometime around 2000 B.C. in order to ventilate a drainage tunnel which was probably the enlargement of a natural watercourse. On Samos a tunnel 6 feet by 6, extending "7 furlongs" through a mountain of limestone rock "150 fathoms high" was described by Herodotus as the work of the engineer Eupalinus (6th century B.C. or earlier). Apparently the separate headings driven from either side of the mountain did not

quite meet the first time, for when this work was rediscovered in 1882 an S-bend near the middle was found. Dating from approximately the same time was the Babylonian tunnel under the Euphrates described by the Sicilian, Diodorus Siculus.⁴ He notes that upon orders from Queen Semiramis the river was temporarily diverted and construction carried on in the dry. Archaeology has revealed nothing concerning this "first subaqueous tunnel," but according to Diodorus the side walls of the passageway were made twenty bricks thick and the vaulted chambers were coated with a waterproofing of hot bitumen. The tunnel measured 12 by 15 feet and extended for a distance of over 3000 feet, connecting the Royal Palace and a large temple.

INDIA -- Underground work in the pre-Christian era in India was almost wholly confined to the construction of chapels or monasteries, of which about a thousand are now known. The construction imitated contemporary wooden types, the columns sloping inward in the early works such as the Sudama or Nigope (260 B.C.) and the Nassick (129 B.C.) caves. In later works the columns of the nave were made plumb, as in the Karli caves (78 B.C.) and subsequent works up to the Gwalior caves of the fifteenth century A.D.

PRE-HISTORIC BRITAIN -- During the Neolithic Age, which began in Britain about 2500 B.C., specialists engaged in supplying flint tools were obliged to adopt not only quarrying but tunneling methods as well to obtain their flint. In southern and eastern England pits were sunk through the chalk to depths as

great as 50 feet, and in many cases, underground galleries were made to follow up rich seams. It was not uncommon for a good seam to have several hundred shafts sunk into it with a vast number of interconnecting galleries underground. Several examples of this type of excavation may still be seen in the Worthing region and at the famous site of Grime's Graves in Norfolk.

In Cornwall, subterranean galleries known as fogous date from a much later period, but may well be pre-Roman. These tunnels were lined with perpendicular slabs and were also roofed over with slabs. Archaeologists conclude that they were apparently used as hiding places against attack.

ROME -- Remains in Italy, France, Switzerland, Portugal, Spain, Algiers, and Constantinople give ample evidence as to the skill of the Roman tunnel experts who embarked upon a far more ambitious program of construction than had any of their predecessors. Whereas previous civilizations had employed tunnels largely as dwelling places or burial spots, the Romans used them widely for drainage, water supply, mining, and passage. As early as 359 B.C. Lake Albanus, 15 miles from Rome, was tapped for its water supply by a tunnel some 6000 feet long, high enough for a man to walk through and varying in width from 3½ to 5 feet. Strabo mentioned two road tunnels built in the latter half of the first century B.C. by Agrippa's engineer, L. Cocceius Actus. The first ran from Avernus to Cumae and the second through Posilipo Hill from Diccaearchia near Baiæ to Naples. The latter extended "many stadia" in length and was wide enough to allow teams going in

opposite directions to pass with ease. Another great undertaking was the tunnel completed by Claudius in A.D. 52 which aided in draining Lake Fucino, 75 miles east of Rome. Extending under Mt. Salvino for a distance of over 3 miles it was driven from shafts, some of which exceeded 400 feet in depth. When opened in 1862, the work in many places measured more than 19 by 9 feet in cross-section.

Also of note, dating from the early Christian days of Rome, were the catacombs, still ranking high among the places of interest seen by modern visitors to the Eternal City. Some early writers held that the catacombs were originally excavated by the Romans for the extraction of sand and other building materials, but more recent research indicates that they were, from the first, designed as burial places. It is quite possible that the earliest catacombs were excavated in the first century B.C. by Jews who were opposed to the Roman rites of burning their dead, but the greatest number of these excavations were made by the early Christians. Apparently these excavations were started as small individual burying places and connected by tunnels at a later date when persecutions increased. The tunnels were cut in the granulated, grayish breccia or tufa which abounds in the neighborhood of Rome. In the catacombs which can be explored today main corridors vary from 3 to 5 feet in width, but lateral passages often afford room for only one person to pass. Heights will average about 8 feet, although some go as low as 5 feet and others extend to 15. The guiding principle seems to have been to secure the greatest amount of space for graves with the least excavation. Probably no one knows the extent of these works, but

reliable estimates have placed the total length at several hundred miles.

Mining adits in Roman Spain dating from the early Christian era throw more light on the versatility of these engineers of antiquity. For the most part these tunnels were small in cross-section, one typical work being 5 feet high, 16½ to 36 inches wide, 1850 feet long, and reaching a maximum depth of 183 feet. Timber supported sections were found measuring 5 feet by 1 foot 1 inch in the clear. Yet another major accomplishment was the so-called Hadrian Aqueduct (A.D. 115-130) which aided in supplying the ancient city of Athens with fresh water from the streams of Mount Pentelikon and Mount Parnes. This tunnel became forgotten during the Turkish occupation and was not re-discovered until 1840. In 1925 American contractors partially reconstructed the work and connected it in with a new system.

Methods used by the Romans to make their openings varied little from those used by their predecessors. The work was accomplished by chipping, channeling, wedging, and fire setting. The latter method, still popular in the Middle Ages, consisted of heating a surface by fire and then suddenly cooling it with water, thus cracking the stone and expediting its removal. The use of vinegar as the cooling agent was mentioned by Pliny, and Livy attributed Hannibal's conquering of the Alps in part to his use of fire-setting and vinegar. This idea of vinegar probably came from some muddled idea in Livy's mind about the effect of acids on limestone. That such vast quantities of it should be used in this way seems very unlikely. Almost invariably the Romans drove their tunnels through self sustaining material so

that elaborate bracing and lining was unnecessary.

THE MIDDLE AGES AND RENAISSANCE -- As in most other branches of engineering, tunneling became a lost art after the decline of Rome, but it was revived to a certain extent in the subterranean drains and watercourses of medieval establishments. For example, in the thirteenth century, tunnels were cut in the rock which underlies much of the city of Exeter. In some places the rock was left exposed, but to a large extent the walls were lined with red breccia, red sandstone, and various other local stones. A coarse jointed rubble masonry was then used in vaulting the courses over. Though this use of tunnels under cities was not common, such a practice was not uncommon under monasteries of the period. Generally speaking, they were constructed by the cut and cover method and were, but modern standards, very modest works. History has recorded by few major attempts of the period to drive anything larger than the moderate water tunnel or drain. In 1450 a road to pierce the Maritime Alps under the Col di Tende, and thus connect Nice and Genoa, was begun by Anne of Lusignan, but the project was soon dropped. It was revived again in 1782 by Victor Amadeus III but was abandoned once more, twelve years later, after some 8000 feet had been completed. Napoleon finally solved the problem by building a carriage road over the 6000-foot pass. Twentieth century construction workers on the Moscow subway discovered another bit of early work, the dungeon tunnels of Ivan the Terrible dating back to about 1565.

Though the subject of mining is beyond the scope of this work, it must be remembered that it was mining which inspired

much of the early modern progress in the excavation of tunnels for water supply and for communication. With the Renaissance came a revival in the interest in mining, but it was not until 1556 that the first important book on the subject appeared. Written by a German, Georg Bauer, whose name was latinized to Georgius Agricola, "De Re Metallica" stood as the technical bible on mining for two-hundred years. Among other important subjects he described the tools in use at the time such as crowbars, pikes, shovels, hoes, and hammers--little advance over Roman practice. Agricola simply reported the practice of his time, and there is little doubt that tunneling in European mining existed long before he wrote. A significant advance did occur in the first quarter of the seventeenth century, however, when Martin Weigel introduced the use of gunpowder in mining. Records indicate that powder was purchased for the Harz mines in 1634, drill holes were reported at Dölln in 1637, and blasting was introduced in the Freiberg district in 1643.

But through a mile and a half of solid rock the height of 10 feet and width

Early Modern Hand Driven Tunnels

CANAL TUNNELS -- Modern commercial tunnels appeared as a necessary adjunct to canals when it became more economical to go through a mountain rather than over or around it. First of these tunnels to be built on a large scale was the Malpas Tunnel (1679-81) on Riquet's Languedoc Canal. Driven a distance exceeding 500 feet through a soft limestone, the tunnel had a minimum height of 27 feet and a width of 22 feet. Subsequent French canals followed in a like manner, the boldness of the

enterprise increasing with the years. In 1770 the Rive de Gier tunnel, 1656 feet in length, was holed through on the Givors canal, only to be exceeded by the Center Canal's 3970-foot Torcy tunnel in 1787, and the 39,400-foot Noiron Tunnel on the St. Quentin Canal in 1822. Also of note on the St. Quentin Canal was the Tronquoy tunnel (1803), probably the first tunnel to use timbering and arching to hold back the loose ground. Construction continued at such a pace in France that by the middle of the nineteenth century some twenty canal tunnels totaled 93,500 feet in length.

In England the impetus given tunnel construction by the Canal Age was the same as in France. Thus it fell to Brindley, the first of the English canal builders, to lead the way in commercial tunnel construction. The mile-long cut driven on his Bridgewater Canal can hardly be classed as more than a mining tunnel, so his Harecastle Tunnel on the Grand Trunk Canal (1766-77) may be regarded as the first real canal tunnel in England. Cut through a mile and a half of solid rock its height of 12 feet and width of 9 feet often made it necessary for bargemen to lie on their backs and propel their barges through by shoving their feet against the sides and the top of the tunnel. Traffic increases soon rendered Brindley's tunnel obsolete so it was replaced by a slightly longer tunnel, 2926 yards in length, parallel to the original. Built by Telford during the years 1824 to 1827, the new work was brick-lined and measured 16 feet in height and 14 feet in width, 4 feet 9 inches of which were taken up by a tow path. Other hand-driven tunnels of note constructed at this time included the 12,500-foot Sapperton Tunnel on the

Thames-Medway Canal (1783-89), the Blisworth Tunnel on the Grand Junction Canal (1798-1805), and the Marsden Tunnel extending for over three miles of the Huddersfield Canal north-east of Manchester. By 1856 over forty-five canal tunnels in England totaled some 220,000 feet in length.

In the United States the first tunnel of consequence was also built as part of a canal--the Auburn Tunnel (1818-21) at Orwisburg Landing on the Schuylkill Navigation in Pennsylvania. Originally 18 feet high, 20 feet wide and 450 feet long, it ran under a hill whose summit was only 40 feet over the top of the tunnel. The years 1834-37 and 1845-46 saw the tunnel shortened, and during 1855-56 the whole thing was finally converted to an open cut. Following closely was the "Summit Level" or Lebanon Tunnel on the Union Canal near Lebanon, Pennsylvania, built under the direction of Canvass White and Simeon Guilford, and dating from about 1827. Extending a distance of 720 feet, its cross-section measured 15 feet in height and 18 feet in width, and it stands today the oldest tunnel in existence in the United States.

shafts on the Marcellus aqueduct.

MINING AND WATER TUNNELS -- Many long mining tunnels were drilled by hand tools before machine drills made their appearance. One of the more prominent in early days was the Tiefe Georg Stollen (1777-99) in Saxony whose main tunnel through graywacke was 34,519 feet in length and whose branches added 25,319 feet more. About the same time (c 1782) the Joseph II Stollen in Schemnitz, Hungary, was drilled 10.27 miles for mine drainage, measuring 9 feet 10 inches in height and 5 feet 3 inches in width. Hand drilling and black powder were used until 1875 on the

Rothschoenberger Stollen (1844-77) which was built to drain the mines of Freiberg, Saxony. Averaging 9 feet square in cross section the main portion of this tunnel extended for a total length of 95,149 feet. Below the Tiefe Georg Stollen a new tunnel, the Ernst August Stollen, was constructed during the period 1851-64 to increase the drainage depth 315 feet. Also built by hand drilling and black powder, its main tunnel measured 34,218 feet in length, the total amounting to 74,452 feet. With a cross section of 11 feet in height and 5½ feet in width it was driven at a rate of 50 feet per month when the men were on seven hour shifts, a rate which was increased to 78.7 feet per month when the shifts were shortened to four hours. The first large work in the United States was the "Hackelbernie" tunnel (1824-27) near Mauch Chunk, Pennsylvania, drilled through hard conglomerate. Measuring 8 feet in height and 16 feet in width, it was stopped at 720 feet, but was resumed again in 1846 and reached a length of 2000 feet. Also belonging to this period was the Taillades tunnel (1839-46) driven from fourteen shafts on the Marseilles Aqueduct.

45,106 meters; Austria 24 1/2 miles tunnels totalling 13,000 meters.

RAILROAD TUNNELS -- As canals had before them, railroads provided the necessary incentive and capital to send tunnel construction into a new and advanced phase. Probably the first railroad tunnel worthy of the name was the Terre Noir tunnel near St. Etienne, France, on the Roanne-Andrezieux horse railroad. Begun in 1826 this work measured 16.4 feet in height, 9.8 feet in width, and 4920 feet in length. It was soon followed by a tunnel on the Liverpool and Manchester Railway

(1826-30), the first tunnel for a steam railroad. The United States was represented early (1831-33) by the Allegheny Portage Railroad's tunnel at Staple Bend on the Conemaugh River near Johnstown, Pennsylvania. It had a maximum height of 21 feet, a width of 25 feet, was lined with 18 inches of masonry, and extended for a distance of 901 feet. Belgium followed in 1835 with the Cumprien tunnel on the 'Chemin de l'Etat', and France's first steam railway tunnel appeared on the St. Germain line in 1837. Germany's first, the Overau tunnel on the Leipsic-Dresden line in Saxony, was built in 1839. Other English tunnels gained great prominence during these early years of the railroads, notable among them being Brunel's Box Hill tunnel for the Great Western Railway near Bath, and Stephenson's mile and a half Kilsby tunnel on the London and Birmingham Railway south-east of Rugby. The extent to which railroad tunnels had multiplied by the middle of the nineteenth century is apparent from some of the following figures. The United States had forty-eight tunnels by 1850, and in 1856 France had one hundred and twenty-six tunnels totalling 65,106 meters; Austria had fifty tunnels totalling 13,522 meters, and Italy's total came to 10,161 meters. This progress, it will be remembered, was the product of hand drilling, only a beginning, which was to be greatly surpassed by machine work of the second half of the nineteenth century.

Machine Driven Rock Tunnels

ALPINE TUNNELS -- Piercing the northern spur of the Cottic Alps

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several miles west of the actual mountain it was named for, the Mount Cenis tunnel (1857-71) was the first of a long line of brilliantly executed Alpine railroad tunnels. A peasant of Piedmont, Giuseppe Medail, as early as 1838, proposed the line which was finally taken between Modane in French Savoy, and Bardonnèch in Italian Piedmont. A Dutch engineer, Mauss, and an Italian geologist, Sismonda, were employed by Piedmont in 1845 to draw up preliminary plans, but it was not until the French and Italian governments agreed to share expenses with the Victor Emmanuel Railway Company that actual construction was begun, with the Italian government in charge, in 1857. The chief engineer, Germain Sommeiler, had little precedent to go on for the largest railroad tunnel than existing was England's 1.8-mile Box Hill tunnel (1837-41), and this new work was to stretch to a distance of 7.97 miles through tough granitic material a mile below the surface at some spots. Hand drilling was used until 1861 when Sommeiler introduced his improved machine drill, an innovation which allowed ten times as much work to be accomplished as formerly. Drilling only from either end with no intermediate shafts between proved an arduous task, rock temperatures reaching 85° F., but the tunnel was finally completed in 1870 and opened to regular traffic in 1871. As finally completed the tunnel averaged slightly under 25 feet in height and slightly over 26 feet at its widest point. This work was the first in which compressed air equipment such as the drill, aspirator, air compressor, and turbine, was put to extensive use, and its completion encouraged subsequent successful attempts to pierce the mountains which had once appeared impregnable.

Soon to follow was the 9.3-mile St. Gotthard tunnel (1872-82) in Switzerland, connecting Göschenen and Airolo. Determination of the vertical plane for the meeting of the headings necessitated a fine job of triangulation by Otto Gelpke in 1869, but it was not until a joint treaty had been signed by Germany, France, and Italy in 1872 that actual construction was begun. M.L. Favre of Geneva posted a bond of \$1,600,000 guaranteeing completion of the work in eight years, a deadline which was not met though the tunnel was holed through by 1880. In all, eight hundred men, including Favre himself, lost their lives in pushing this great work to completion. Maximum rock temperatures reached 86° F. at a distance of 5575 feet below the surface, and cave-ins and wash-outs from underground springs were not uncommon. Though the same size in cross section as the Mont Cenis tunnel and over a mile longer, the St. Gotthard job progressed at a much greater rate because of the use of improved explosives and machinery, such as Ferroux and McKean drills, and because of the added experience of the engineers.

Work was still going on at St. Gotthard when the third great Alpine tunnel, the Arlberg, was begun. Connecting Innsbruck to Bludenz in the Tirol it was the direct result of Austria's desire to have a straight railroad to France, passing neither through Germany nor Italy. With a width of 25½ feet and a length of approximately 6 1/3 miles it was completed in a little over three years (1880-83) at a rate of advance practically double that at St. Gotthard. The Ferroux percussion air drills and Brandt rotary hydraulic drills played a large part in rushing this job to its quick, successful conclusion.

In 1898 the longest railroad tunnel in the world, the Simplon, was begun under the direction of Alfred Brandt, the inventor of the rotary hydraulic drill. He did not live to see the completion of the job, however, for he died in 1899, and the tunnel, finished in 1905, was not opened for service until 1906. Two parallel single-track headings, 56 feet apart from center to center and connected at intervals of 660 feet by oblique galleries, made up the work which extended a distance of 12 1/3 miles from Brig, Switzerland, to Iselle, Italy. One heading was cut full size, 19 feet 6 inches high by 16 feet 5 inches wide, while the other, much smaller, was used to facilitate drainage and aid in ventilation. The second bore was enlarged to full size during the years 1912 to 1921 and put into service in 1922. Among the many problems facing the constructors was that of dealing with enormous underground springs. Cold water springs at times gave off as much as 17,000 gallons per minute, while hot water springs, reaching a temperature of 116° F., yielded a total of 4330 gallons per minute. In some spots the earth pressures were so great that the roof and sides could only be held in place by ramming quick-setting concrete between heavy steel I-beams. In all, sixty men lost their lives on the project, an indication that Alpine tunnelers were progressing certainly, but still had a great deal to learn.

The last link in the Swiss railroad system between Berne and Brig was finally completed with the Loetschberg tunnel, first discussed in 1886, proposed in 1889, and constructed from 1906 to 1911. Originally designed to be approximately 8 1/2 miles in length, the tunnel ended up slightly in excess of 9 miles between

Kandersteg and Gopperstein, for uncontrollable waters forced a detour inside of the mountain. The Kander River, flowing through a valley 600 feet above the tunnel, drained through a sand-filled crevice into the original bore and almost stopped the work until the detour was found feasible. Myers drills and Ingersoll-Rand drills were used in giving this tunnel a better average daily heading advance rate than had been made by any of its Alpine predecessors.

1867, patenting it in 1868.

EARLY DRILLS AND BLASTING AGENTS -- Drinker in his admirable work, "Tunneling",¹² set forth in detail the history of blasting agents and machine drills, a subject of prime importance in the study of the development of mountain tunnels. Only a few of the highlights recorded by him are noted here. Experiments in 1848 by J.J. Couch and J.W. Fowle of Philadelphia led to the patent of the first percussion rock-drill in 1849 by the former, and to the patent of the first direct-action percussion drill in 1851 by the latter. Cavé in Paris obtained his patent for a percussion drill in 1851, and still another percussion type was produced by Schumann at Freiberg in 1854. Sommeiller invented a rock drill in 1857 for use at Mont Cenis, but it was not until 1861 that he produced his improved drill which speeded up the work so considerably. During this early period of development Fowle sold his patent rights to Charles Burleigh who produced in 1866 a compressed-air drill which was used with success at the Hoosac tunnel. Many improvements have, of course, come about in the drills since that day, and two main types, the hydraulic and electric drill, have come along to challenge the supremacy of

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the pneumatic type. In the blasting field gunpowder was the original agent. In 1847 Sobrero discovered nitroglycerine, and its use as a blasting agent was first tried by Nobel in 1863. The frequent fatalities from the premature explosions of nitroglycerine made workers chary of its use, however. A solid, more inert explosive, sufficient in blasting power yet convenient to handle was needed. Nobel supplied that need when he went on to invent dynamite in 1867, patenting it in America in 1868.

OTHER RAILROAD MOUNTAIN TUNNELS -- First to use power drills and high explosives in the United States were the engineers of the Hoosac tunnel in Massachusetts. In 1819 proposals were made to connect Boston with the Hudson River by a canal--surveys being run in 1825--but the project went no further. A revival of the scheme in the form of a railroad appeared in 1850 when surveys from Greenfield to Williamstown were run by the Troy and Greenfield Railroad Company. The 4 $\frac{1}{2}$ -mile tunnel, begun in 1858, was not completed until 1874 and almost bankrupted the State of Massachusetts which had underwritten its construction. When the second contractor gave up in 1861 the State, with Thomas Doane as chief engineer, took over the construction work. Hand drilling was continued until 1866, at which time Burleigh drills were introduced, and within a year nitroglycerine was substituted for black powder. Dogged by financial and political troubles, the State in 1869, with the work one-third completed, turned it over to the Shanley Brothers of Toronto who saw the job to the end. The final holing-through blast was made in 1872 and

probably gave rise to the Tama tunnel (1876-84), a 5-mile double-

trains began using the tunnel in 1875. It had been an expensive project, much more costly than any of the contemporary railroad tunnels in other countries, so it is not surprising that pamphleteers criticized the mounting state costs with such offerings as "The Last Agony of the Great Bore." Nevertheless the introduction of power tools and high explosives represented a step forward in American, and world, tunnel practice and considerably eased the task of succeeding tunnel engineers.

Since the pioneer attempts, there have been many successful mountain railroad tunnels built in all parts of the world. Peru gained the distinction of having the highest railroad tunnel in the world when the Caldera tunnel, 9240 feet in length and 15,775 feet above sea level, was opened in 1893. Another work of distinction, the "British Empire's longest tunnel," was the Otira tunnel, connecting the east and west coasts of South Island, New Zealand. Begun in 1908 and completed in 1923 the job was taken over from the contractor by the government in 1912. Concrete-lined and with an official length of 5 miles 445 yards, its cross section, measuring 15½ feet above the rail and 15 feet across, was designed to accommodate a single standard New Zealand track of 3 feet 6 inches. Between Berne and Scenic in Washington State the Great Northern Railroad built the Cascade tunnel (1925-29) with a force of eighteen hundred men under chief engineer J.R.W. Davis. Stretching a distance of 7.79 miles it thus gained the distinction of being the longest railroad tunnel in the United States. Possessor of a more doubtful honor, that of encountering more trouble than any other tunnel in history, probably goes to the Tanna tunnel (1918-34), a 5-mile double-

track job between Tokyo and Kobe built by the Imperial Government Railways of Japan. Here the engineers encountered tough rock, underground springs, slides, cave-ins and all of the rest of the difficulties ever encountered by tunnel engineers. Persistence and engineering skill finally prevailed, however, and the tunnel took its place along with other monuments to man's progress.

MINING AND WATER TUNNELS -- First broached by Adolph Sutro in 1860, the tunnel to drain the mines of Virginia City (the Comstock lode), Nevada, was not begun until 1869. Drilling was done by hand until 1872 when diamond drills were tried. Pneumatic Burleigh drills were introduced in 1874 and used successfully until the work, extending 20,000 feet horizontally and 1922 feet vertically, was completed in 1878. Progress on the tunnel, which measured 10 by 14 feet in cross section, varied from 19 to 417 feet per month, averaging 192.3 feet per month.

Another interesting work was the Big Bend Tunnel on Feather River in Butte County, California, (1883-87) designed to divert the river and leave the bed dry for gold mining. Its original cross section of 12 by 13 feet was enlarged to 18 by 14 feet in 1907-08, and its original length of 3 miles was increased another 3400 feet by the power company which bought it.

The original scheme for the drainage of Mexico City, formulated by the Viceroy Martin Enriquez, was based on a 4-mile tunnel, 11½ by 14 feet, drilled through the hill of Nechnistengo-- according to one authority-- by 470,000 Indians in two years.

Neglected and then restored, the tunnel afforded only partial relief. To solve the problem completely a canal starting at the city gates was led 22 miles to the new tunnel which discharged the water into the Valley of Tequizquiac. Built under the direction of J.F. Toomer, the major construction period extended from 1888 to 1895, during which time the greatest advance was 182 feet in one month. Brick-lined, with an ovoid section whose greatest dimensions were 14 feet in height and 13 feet 9 inches in width, the tunnel was driven $6\frac{1}{2}$ miles through sand, mud, and soft calcareous limestone.

Tunnels drilled through rock for water supply can hardly be classed as a modern innovation as evidenced by the ancient water tunnel south of Seleucia in Turkey in Asia. Measuring 23 feet in height and 20 feet in width the excavation was carried through rock so hard that the chisel marks can still be seen, though the work is probably more than 1600 years old.¹⁴ However, many modern machine-drilled works have achieved a certain prominence for their boldness and utility. Among them may be classed the Kelty tunnel (1887-89) on the Glasgow Waterworks System, 9 feet square and extending a distance of 2.6 miles through material ranging from soft shale to hard conglomerate. During this same period New York City was building its "New Croton" Aqueduct (1885-91) from Croton Lake to the Central Park Reservoir, a distance of 33 miles. Most of the work was done by tunneling, $30\frac{1}{2}$ miles of the work being lined with brick masonry.

New York City's growing population demanded a more adequate water supply, however, with the result that plans were drawn for

the construction of the Catskill Water Supply System. The first stage of this work (1907-17) was concerned with drawing on the Esopus watershed and included the boring of the 18-mile "City Tunnel No. 1." The magnitude of the task may be judged from the fact that over 17,000 men were engaged on the line in 1911. The system was extended and the aqueduct completed during the second stage (1917-27), a period which saw the completion of the famous 18.1-mile Shandaken tunnel (1917-24), 40 miles southwest of Albany. Concrete-lined and bored through from seven intermediate shafts, it was cut in a horse-shoe section measuring 11½ feet in height and 10½ feet in width. Seven pressure tunnels running beneath river valleys were cut on this line, the deepest being the one between Storm King and Breakneck Mountain, 1114 feet below sea-level, 14 feet in internal diameter, and running for a distance of 3022 feet between shafts. By 1927 almost 200 miles of works, most of which were tunneled, had been completed and another construction period was begun, designed to connect the waters of the Delaware River to the system with over 100 additional miles of cuttings. Outstanding during this period (1928-36) was the 20-mile concrete lined "City Tunnel No. 2" extending from Yonkers to Brooklyn. Most of the work measured 17 feet in diameter and all of it was bored through at a low level, some parts being as much as 766 feet below the surface. Also begun at this time was the 45-mile Delaware Aqueduct, destined to be the world's longest tunnel.

San Francisco's 25-mile East Range tunnel, measuring 13½ by 14½ feet unlined is yet another example of long modern water tunnels. Of interest, too, is the Rove canal tunnel (1911-26)

on the Marseilles-Rhône Canal. Bored over 4½ miles through limestone, it gained the distinction of being the largest tunnel ever excavated from the total volume standpoint, having a cross section which measured 50 feet 6 inches in height and 72 feet 2 inches in width (less two side paths standing 10 feet above the bottom and extending 6 feet 6 inches in width). The Boulder Dam tunnels (1931-32) give some idea of progress through rock with twentieth century methods. Here 1800 pounds of dynamite were used for each blast in the main heading, 48 holes being drilled to a distance of 20 feet in the rock facing. Using 15 delays each blast broke out 2160 tons of rock and advanced the heading 16 feet.

TUNNELING MACHINES -- Man has not been content to merely drill and blast through rock, he has also endeavored to bore his way through with various types of tunneling machines. The earliest on record was constructed at Boston in 1851 for use in the Hoosac tunnel. Weighing 70 tons, it was designed to cut a circular groove in the tunnel face 13 inches wide and 24 inches deep by means of revolving cutters. It proved unsatisfactory, however, and was abandoned after a cut of 10 feet had been made. Shortly thereafter (1853) the Talbot tunneling machine, designed to make an annular cut 17 feet in diameter leaving the cylindrical core to be removed by blasting, was tested unsuccessfully near Harlem, New York. Success did come with the 6½ foot diameter Beaumont machine invented by Major English but developed and operated by Major Beaumont. Though patented in 1864 it was not completed until

1883. Used only in soft rock it bored through 6000 feet during tests with a maximum rate of 40 inches per hour and an average rate of 50½ feet per day over a period of fifty-three days. Another success was the Brunton tunneling machine, patented in 1868, and designed primarily for driving in the chalk formation under the English Channel. This machine could bore a 7-foot tunnel and load cuttings on a car at a rate of advance of 30 inches per hour. Over two miles were bored under the channel with this cutter before the British Parliament called a halt to the tunnel's construction. The problem of cutting easily through any kind of rock remains unsolved, however, a gentle reminder to the engineer that he has not yet achieved a complete triumph over the forces of nature, despite the amazing progress he has made in rock tunnel construction during the past century.

Early Tunnel Shields and Compressed Air

FIRST THAMES TUNNEL -- As we have previously noted, tunneling through rock was accomplished in ancient times, but subaqueous tunneling in soft materials was a problem which was not really solved until the advent of the shield in the nineteenth century. Ralph Dodd brought forth a scheme in 1799 to burrow under the Thames from Gravesend to Tilbury, but nothing ever came of it. Then, in 1807 Richard Trevithick was engaged by a promoter named Vasey to make a second attempt. Trevithick did manage to bore a tunnel about 5 feet high and 1046 feet in length, only a few hundred feet short of his goal, but his efforts were ended in 1808 when the works were flooded.

Shortly thereafter Marc Isambard Brunel, Frenchman turned English, devoted his thoughts to the problem and, after observing the marine borer, the Teredo Navalis, conceived the idea of a shield, a "casing or cell intended to be forced forward before the timbering which is generally employed to secure the work." In his patent of 1818 Brunel showed a circular shield and a cast iron shell, but in the actual construction of the tunnel, begun in 1825, he used a rectangular group of cast-iron frames forming 36 cells, and a lining of brick. His first shield remained in use until 1828; it was removed and replaced by an improved shield during the final period of construction from 1835 to 1843. The second shield had a width of 37½ feet, a depth of 22½ feet, and a length of 9 feet, and its maximum rate of advance never exceeded 14 feet in one week. His frames formed a temporary roof over the heading and were a means of supporting the breasting boards used to brace the soil of the heading face. When completed, the tunnel (its top 13 feet below the river bed) was made into two parallel horseshoe passageways measuring 16 feet in height and 13½ feet in width, separated by a thick brick wall. Connecting Wapping and Rotherhithe, the tunnel was constructed in nine working years, and had, until the construction of Germany's Elm Railway tunnel in 1913, the greatest cross section of any shield constructed tunnel. Though the tunnel was a magnificent feat of engineering, gaining a knighthood for its builder, it was in its early years more of a curiosity than anything else, and was devoted simply to pedestrian use until bought by the East London Railway Company in 1865.

part Barlow's ideas played an important part in the construction of the tunnel.

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SHIELD PATENTS FROM BRUNEL TO GREATHEAD -- Brunel's success, startling though it was, brought forth no great wave of sub-aqueous tunneling, though various plans for shields gradually appeared. In 1849 Samuel Dunn of Doncaster patented a tunneling machine for sand and soft mud. Though his device was never used, it assumes an importance for his was the first suggestion that the shield should move all in one piece. Along the same lines M. Giubel in 1857 devised a vertical shield for use in running sand. A patent similar to Brunel's, with the exception that the shield moved forward in one piece, was taken out by the Englishman Peter W. Barlow in 1864. Two years later Barlow described his improved shield which incorporated the following features: (a) a cast-iron lining to the tunnel, with cement grouting behind it, (b) a cylindrical overlapping skin of the shield, (c) the use of screws or presses to move the shield forward, and (d) a transverse escape partition and diaphragm. Between these two patents came one in 1866 by R. Morton of Stockton-on-Tees, but his work was destined to remain in obscurity. It was not until 1869 that a device, incorporating the essentials of the modern shield, was used in actual practice in both London and New York.

Promoting the second Thames or Tower tunnel in 1869 was Peter Barlow (1809-85), but it appears that he left the actual construction details to the contractor, James H. Greathead (1844-96) of South Africa. To accomplish the job Greathead designed and used a shield similar to that described in Barlow's provisional patent of 1868. It is difficult to judge just what part Barlow's ideas played in this work, for Greathead later

stated that he was unaware of Barlow's 1868 patent until 1895. At any rate, the engineering world seems to have given the major portion of the credit to Greathead for it is his name and not Barlow's which has come to be associated with the shield. The tunnel itself, lined with cast iron, was completed in eleven months, measuring 7 feet in diameter and 1350 feet in length. Used at first for passenger-carrying cable-cars it was later turned to pedestrian use until the completion of the Tower Bridge in 1894, at which time the tunnel was converted to carry water lines.

In the United States Alfred E. Beach (1826-96) working independently of the English inventors, designed his shield in 1865, put forth a working model in 1868, and started full scale work under Broadway in New York in 1869. His brick-lined tunnel, roughly 300 feet long and 8 feet in diameter was designed to demonstrate the practicability of constructing a subway from the Battery to Harlem. The shield, similar to the one described

in Barlow's patent of 1864, was the first to use hydraulic rams. One car, propelled by air and sucked back, was demonstrated in the tunnel, but with no franchise forthcoming the project was bricked up and abandoned. It was finally destroyed in 1912, nearly half a century later, by contractors excavating for the subway which had now become a "practical" venture.

EARLY USE OF COMPRESSED AIR -- While repairing the foundations of a bridge over the River Tyne in 1778 Smeaton used, for the first time, a pump to inject fresh air into the caisson. The use of compressed air in tunnels, however, was a long time in

sickness which ranged from giving its victims a slight sore coming, although, as the result of observations in 1826, Dr. Collodon of Geneva is reputed to have recommended its use to pressed air had been noted by M. Triger and others, but a patent Brunel in 1828. The year 1830 marks the first complete scheme for the use of compressed air in mining in subaqueous or water-bearing material, for the wording of Sir Thomas Cochrane's patent of that year covered all the essential features developed since.

First to put Cochrane's ideas into actual practice was the Frenchman, M. Triger, who sank a pit shaft at Chalonnnes on the Loire in 1839. Compressed air came to be used in many shaft and caisson sinkings shortly thereafter, and by the early sixties its use was quite common throughout Europe. It was not until 1879, however, that compressed air, as a means of holding in check soft material and water, was used in a tunnel. M. Hersent, pioneering the method, drove a small rectangular tunnel at Antwerp in that year.

Later in the same year Dewitt C. Haskin, an American railroad and mining man, commenced the first Hudson tunnel between New York City and Jersey City. The idea had been conceived in 1871 and a shaft had been sunk in 1874, but legal difficulties prevented actual tunnel construction until 1879. Here was the first use of compressed air in a large tunnel, and it was also the first and only attempt to build a large subaqueous tunnel in sand without a shield. Though the project failed under Haskin, it was later revived and driven to a successful conclusion early in the twentieth century.

With the introduction of a compressed air working atmosphere a new industrial malady was born, "caisson disease," a

sickness which ranged from giving its victims a slight case of cramps to violent death. In early works the effects of compressed air had been noted by M. Triger and others, but a solution to the problem did not readily appear. In 1868 Dr. Jaminet wrote the "Physical Effects of Compressed Air" (published 1871), as the result of his observations on the St. Louis Bridge, the largest scale compressed air job (50 pounds per square inch) up to that time. This was followed shortly by "Compressed Air" (1866) written ^{mainly} in the early 1870's by Dr. Smith of Brooklyn Bridge fame. Among other things Dr. Smith recommended a practical remedy for caisson sickness--the lock chamber hospital--a device which was first built and employed successfully on the Hudson tunnel by E.W. Moir in 1889. The conclusion was reached that the sickness could be attributed to four main factors, (1) excessive pressure, (2) impurity of atmosphere, (3) too prolonged an immersion, and (4) too rapid a decompression. In Paris in 1878 Paul Bert in his "La Pression Barometrique" struck at the core of the matter, noting that the mechanical effects of air compression are negligible and that the symptoms after decompression are due to bubbles of nitrogen in the blood, the formation of which can be prevented by lengthening the decompression period. Subsequent standard practice was adopted whereby slow decompression would be used for all exposures to pressures exceeding 20 pounds per square inch gauge. Working periods were steadily decreased with the rise in pressure, stopping at the practical limit of one hour under 50 pounds pressure.

Thames at London Bridge. This line gave better protection when its original cable drives were discarded and it became the

The Subways

first electrically operated subway in the world. This added 1.5 miles to the system. During the period 1883-85 the original LONDON -- Coincident with the development of modern shield and compressed air construction came the underground railways, or subways, though many of them were constructed without the aid of shield or compressed air. Mainly "cut and cover" was London's first Underground, the "Metropolitan", largely the idea of Charles Pearson, a city solicitor. Authorized by Parliament in 1856, the first section, 3½ miles in length from Bishops Road to Farrington Street, was opened in 1863. It consisted of a single brick-arch tunnel carrying four tracks, each of which had three rails to accommodate both standard (North Western Railway and Great Northern Railways) and broad gauge (Great Western Railway) trains. The third broad gauge rails were removed in 1869. Progress continued with the opening of the first section of the London "District" Railway in 1868 and the "Inner Circle," connecting the District and the "Metropolitan," in 1884.

The original London tubes of the City and South London Railway, authorized in 1884 and constructed during the years 1886 to 1890, provided the first large scale test of the Greathead shield. Here the first use of compressed air in conjunction with a shield was made, a practice which became standard for all wet-ground tunneling thereafter. Sir John Fowler acted as consulting engineer and Mr. Greathead as contractor on the twin tubes extending 3 miles in length and passing under the Thames at London Bridge. This line gained another distinction when its original cable drives were discarded and it became the

first electrically operated system in the world. Time added miles to the system. During the period 1922-23 the original twin tubes were enlarged from their 10 feet 2 inches and 10 feet 6 inches (internal) diameter to 11 feet 8½ inches, thus bringing them into line with the standard size of the other tubes. By 1937 the London system had grown to include 157 miles of single track lines.

BOSTON -- Following Budapest's example...

GLASGOW -- A system including two miles of tunnels underneath Glasgow was built for the Glasgow City and District Railway from 1883 to 1886, and this was soon augmented by a second subway, the "Central Low Level" (1889-96). Constructed by cut and cover methods almost entirely, it was built to accommodate steam locomotives. A short time later the world's second tube railway, the Glasgow District Subway, went into operation. Proposed in 1890 and constructed from 1891 to 1897, the system consisted of a 6½-mile loop of double tube. While attempting to burrow under the Clyde the construction forces had ten serious blow-outs in the first 80 feet, a major factor in the contractor's decision to give up the job. George Talbot then took over and succeeded in placing a parallel tube 410 feet long in three and one half months, where it had taken his predecessors five months to progress 80 feet. His success was due mainly to his insistence that the work never be allowed a chance to rest, so work progressed day and night, Sundays and holidays, until its completion. His attention to details included varying the air pressure to balance the depth of the water in accordance with the tides. Only about two miles of route were actually constructed

by shield, although in all, sixteen shields were used. In some cases the top of the tunnel was as much as 155 feet below ground, and rarely did the depth ever get less than 20 feet. Sections varied from semi-liquid mud to solid rock, providing a real test of engineering skill for these men who were still pioneers in subway construction.

BOSTON -- Following Budapest's 2-mile cut and cover tunnel for street cars (1894-96) was the double-track Boston Subway (1895-98), the first underground railroad built outside of Europe. It extended over $1\frac{1}{2}$ miles, mostly cut and cover, with a steel beam and concrete roof. This project represented the first successful use of the roof shield in the United States inasmuch as the earlier attempt in 1892 by the Baltimore Belt Railroad had proved unsuccessful. At about the same time as Boston's success New Orleans constructed a series of sub-surface canals, 9 by 22 feet, to carry off flood waters and sewage.

PARIS -- Proposals for a subway in Paris had been made as early as 1855 and had been revived again in 1871, but actual construction did not begin until 1898. The original section, from Porte Maillot on the west side to Porte de Vincennes on the east side, was completed in 1900, a distance of $8\frac{1}{2}$ miles. Most of the original route was accomplished by cut and cover construction, only 18 per cent being done under a shield. Under chief engineer F. Bienvenu and contractor L. Chagnaud the street was excavated to the tunnel roof; the roof was

then built, the street replaced above it, and the rest of the construction proceeded under the roof. Walls were then excavated for and erected while the roof was supported by underpinning. Next came the main excavation and finally the floor. The Parisian lines were extended at intervals, mainly in shallow cuttings, until there were 62 miles of double track in place in 1920.

BERLIN -- The initial Untergrundbahn or "U-bahn" in Berlin (1898-1902) was the east-west line from Potsdamer Platz to the Zoological Garden. By 1937 the city had 39 miles of underground construction, all of it being cut and cover.

NEW YORK -- Forerunner of the modern subway, New York's Park Avenue tunnel enjoyed a conspicuous place in the city's development. The 12 1/2-mile New York and Harlem Railroad began operation in 1837 from City Hall to Fordham along a right-of-way which was mostly open cut, though the line did include a 3-block tunnel bored through rock at 91st Street. Northward expansion of the city brought about pressure from the offended citizens to cover over a large section of the open cut, resulting in the "Murray Hill Tunnel" of 1850.

The first section of the subway system, which had expanded to 136 miles by 1937, was begun as a city project in 1900 by contractor John B. McDonald under chief engineer William B. Parsons. Regular operation was started in 1904 on the Bronx-Manhattan line from Brooklyn Bridge to 145th Street and Broadway. Other sections were soon under way, the type of construction varying with conditions encountered. In shallow cuttings

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a flat roof near the surface consisting of I-beams and concrete was the rule. Reinforced concrete was largely used in all places except under the rivers where cast-iron lined tubular tunnels were run.

New problems and experiences confronted the constructors every day. The unique experience of being blown up through the tunnel roof and on up to the river's surface, and coming out none the worse for it, was the lot of one Richard Creegan, who was repairing a leak under the Brooklyn shield in 1905. The force of the compressed air in the working space forced him through the 5-foot roof of mud which was topped by a 15-foot depth of water. For the first time a shield tunnel was built on piles when in 1907, twenty pile foundations were sunk from 10 to 50 feet to bedrock to support the East River tubes. The extent to which this underground construction expanded can be appreciated by considering the intersection at Broadway, 6th Avenue, and 33rd Street, where five levels of transportation resulted, an elevated railroad, the regular street, and four sets of tunnels in three layers.

CHICAGO -- Compared with the subways of other large cities Chicago's rapid transit subway is still in the experimental stage. Little known but well developed, however, are the city's freight subways running at least 40 feet below the streets. A franchise was granted to the Illinois Telephone and Telegraph Company in 1899, and construction from 1901 to 1903 resulted in some 20 miles of tunnels. The original company failed in 1903, its place being taken by the Illinois Tunnel Company,

which extended the system until 1909. It found few customers, however, and ownership passed to the Chicago Tunnel Company in 1912.

The tunnels were constructed under a very low precautionary air pressure and were lined with a foot of concrete. Measuring approximately 7½ feet in height and 6 feet in width each tunnel was provided with a 2-foot gauge track. Just prior to World War II the system had one hundred and fifty locomotives and thirty-three hundred cars which were used to carry freight, excavations, demolitions, and other pay loads.

varying from shallow cut and cover to 110 feet below the surface.

PHILADELPHIA -- The original franchise, granted in 1901 and acquired by the Union Traction Company in 1902, provided for an elevated line and not a subway. However, in the business district the line did go underground for about 2½ miles, being known as the Market Street Subway. Some interesting excavation was done on this section, for it brought to light some hemlock logs of 6-inch bore which carried water as early as 1799. From 1915 to 1919 the expensive 750-foot Broad Street Subway near the city hall foundations was under construction, soon to be followed by an increased construction program in 1924.

thickness of 3 feet in thickness of nearly identical was provided

MOSCOW -- Construction of Moscow's first subway was carried on from 1931 to 1935, though talks for the project had begun during the Czarist regime in 1902. Progress being poor at first, Lazar M. Kaganovitch, Commissar of Railways, changed the construction set-up by bringing in a tremendous number of state-conscripted workers whose ranks at times included as many as

75,000. With this large cheap labor pool the Russians were able to complete 6 miles of the subway within one year, a rate which surpassed that of any other city's underground. As a matter of comparison, it took between seven and eight years to complete 13 miles in New York, five years to do 6 miles in Philadelphia, two and one half years for 4 miles in Tokyo, and twenty-one months for 4½ miles in Buenos Aires. Moscow's first section extended over 7 miles, and in 1937 a second section, exceeding 9 miles in length, went into operation.

Construction conditions were varying and adverse, the depths varying from shallow cut and cover to 118 feet below the surface. Underground mining methods accounted for 55 per cent of the work, less than 3000 feet being accomplished by shields. Another 25 percent was open-cut and cut and cover, and a small amount was accomplished by sinking pneumatic caissons. Almost two miles were made by the "Parisian" method whereby the side walls were excavated for and constructed first. To get through soupy quick sands the engineers resorted to "freezing" the material by the injection of sodium silicate followed by calcium chloride, or common salt and cement, through 1-inch pipes varying in length from 15 to 30 feet. In this manner the material, hardened to a thickness of 3 feet in fifteen or twenty minutes, was prevented from oozing into the heading and excavation could proceed. The project was more than just a subway, it was a monument of national importance to the Russians who took great pride in pointing out that all equipment used on the job, except one British shield, was Russian produced.

made part work of the transportation of the city...

UNDER SEVERN AND MERSEY -- Carrying the Great Western Railway under the estuary of the Severn River from England to south Wales, the Severn tunnel (1873-86) was the first long submarine tunnel through rock. Charles Richardson had conceived the idea as early as 1862, but ten years were to elapse before an act authorizing construction was passed. Running 4.35 miles through a variety of strata ranging from limestone to sand and gravel, construction of the double-track tunnel was delayed for long periods by intruding waters which were pumped out at rates reaching 20,000 gallons per minute.¹⁸ The contractor, T.A. Walker,¹⁹ later reported that for over a year it was necessary to pump 24,000,000 gallons per day, four of eleven shafts being utilized for that purpose alone. Sir John Hawksnaw, seventy-six years of age when the tunnel was completed, served as chief engineer on the project and was ably assisted by his son and by A.G. Luke, the resident engineer. At its maximum depth the tunnel ran 145 feet below the water line and 50 feet under the river bed. It measured 24½ feet in height and 26 feet in width, and was brick-lined to a thickness of 3 feet. Over thirty-six hundred men were engaged at one time on this project, which at last provided the shortcut between Bristol and Newport.

During this same period the Mersey Railroad tunnel (1880-86) had a comparatively easy time of it through sound red sandstone, 24 feet beneath the river bed. The heading advanced as much as 30 feet per day in 1883, a rate of progress which soon made short work of the three-fourths of a mile submarine

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portion of the tunnel. In 1858 the first tunnel under the Hudson River at New York by using compressed air. The two oval tubes,

ST. CLAIR RIVER TUNNEL -- Following the formation of a company in 1886, work was conducted from 1888 to 1890 on the St. Clair River tunnel between Lakes Huron and Erie. Designed to carry the Grand Trunk Railroad just below Sarnia and Port Huron, the project under chief engineer Joseph Hobson consisted of a tunnel 21 feet in outer diameter and 6000 feet long plus open cut on both American and Canadian sides. Cast-iron lined and constructed with shield and compressed air it was the first extensive completed subaqueous tunnel in America.

one-third completed, work was resumed for a short time the next

EAST BOSTON TUNNEL -- First extensive work in mass concrete carried out by means of a shield was the 4250-foot tunnel (1901-03) connecting Boston and East Boston near Sumner Street. More elliptical than circular in shape, the tunnel measured 20½ feet in height and 23 1/3 feet in width, and was built with its bottom 90½ feet below mean high water. Though the first of considerable size, this tunnel was not the first built entirely in concrete, for in 1897 a small circular tunnel, 6 2/3 feet in diameter, had been constructed as part of a drainage works near Paris. It is also interesting to note at this point that the French were the first to deviate from the circular shield as devised by Greathead. Typical was M. Chagnaud's main sewer of Paris, the Collecteur de Clichy (1895-99), which had an elliptical roof, a horizontal floor, and was masonry-lined.

were encountered, a problem which caused delay by water over

FIRST HUDSON TUBES -- We have previously noted briefly the

attempt made by D.C. Haskin to push a tunnel under the Hudson River at New York by using compressed air. His two oval tubes, formed by an outer shell of thin steel plate and lined with 2 feet or more of brickwork, each measured 18 feet in height and 16 feet in width. During the course of the work construction engineer Anderson developed the "pilot tunnel" scheme, whereby the preliminary shell of the main tunnel was braced against the pilot tunnel shell through which the initial excavation was carried out. Work seemed to be progressing nicely under chief engineer General William Sooy Smith until it was stopped for lack of funds in 1882. With the New Jersey northern tunnel nearly one-third completed, work was resumed for a short time the next year and again in 1887. In 1888 British capital was invested in the project when the firm of Fowler and Baker, builders of the Forth Bridge, took over. In 1890 S. Pearson brought over a Greathead shield, changed from a masonry to cast-iron lining, and enlarged the tunnel to a 19½-foot diameter. With the project almost 70 per cent completed work was again stopped for want of funds in 1891, and in 1899 the assets of the company were sold.

A syndicate of business men under William G. McAdoo was formed in 1902 with the purpose of completing the work for the New York and New Jersey Railroad Company. Directing the final construction period, which was essentially ended by 1905, were the engineers Charles M. Jacobs and J. Vipond Davies. On occasion, rock at the bottom and silt at the top of the heading were encountered, a problem which Jacobs solved by using compressed air and kerosene blowpipes to "bake" the silt and

harden it to the stiffness of dry clay. Thus progress was accomplished by alternately baking, drilling, blasting, and excavating. Progress under such conditions was bound to be slow, but Jacobs and Davies showed that an excellent advance could be made under favorable conditions. In some places the silt was pushed aside by the shield, and as much as 72 feet of progress was recorded in a twenty-four hour period.

OTHER NEW YORK TUNNELS -- A "mixed working face" was no novelty to Jacobs when he took over the job on the Hudson tubes, for he had encountered a similar problem in constructing the Ravenswood

Gas tunnel (1892-94) from the East River Gas Company's plant in Long Island City to Manhattan. Prior to Jacob's appointment to the job pressures up to 52 pounds per square inch (since prohibited) were used in a section through disintegrated rock. Measuring 8½ feet in depth, 10 feet in width, and 2516 feet from shaft to shaft, the tunnel was bored to run from 114 feet to 127 feet below mean tide level.

Another famous gas tunnel was the Astoria Bronx tunnel (1910-16) which was driven 250 feet below the river surface. Measuring 18 feet in height and 16½ feet in width it extended a distance of 4662 feet.

Extensive developments were carried on by the Pennsylvania Railroad Company under the Hudson and East Rivers during the first decade of the twentieth century. Contracts were let and the ground was broken in 1904 by the O'Rourke Engineering Company of New York for the Hudson River job, and by S. Pearson and Son of London for the East River work. Actual construction,

Shortly thereafter (1844-55) in Stockholm, Captain Lindbergh began in 1905, was completed in 1906 on the Hudson River and built 50 feet of his 753-foot tunnel for pedestrians by freezing in 1909 on the East River. At the time the design was made, little was known as to the movement of tunnels in silt, so plans were made to rest the tubes on piles going to bed rock. Only one experimental pile was put down for it was discovered that the movement was less than that experienced by a bridge undergoing ordinary temperature changes. It was found that the tides caused a rise and fall of 1/8 inch, that the tunnel would rise slightly over 1/2 inch in the summer and fall the same amount in the winter, and that a slight gradual settlement set in which finally became negligible.

Typical of work of the period was that done under the East River where the shield designed by E.W. Moir was used. Measuring 23 feet 6 1/2 inches in outer diameter, the shield possessed two air locks near the bottom and one at the top, 6 feet in diameter and 20 feet long, and a one inch pipe, 30 feet long, with a gate valve at either end. As the tunnel progressed, bulkheads of brick or concrete were erected at intervals not exceeding 1000 feet to prevent an unexpected break-through from flooding the whole works. When holed through, the tunnel extended 1760 feet from the Manhattan side and 2142 feet from the Long Island side.

Although the shield method of construction was most satisfactory on this job, freezing was tried as well. A few brief words concerning the origin of the freezing method might be of interest. Probably the first use of freezing was made by F.A. Poetsch, a German engineer, who used the method to sink a shaft at the Archibald lignite mine of Schneidlinger in 1883-84.

Shortly thereafter (1854-56) in Stockholm, Captain Lindmark built 80 feet of his 758-foot tunnel for pedestrians by freezing the material with a dry air machine, which reached a temperature of -55° C. The tunnel, measuring 12 feet 8 inches in height and 13 feet 2 inches in width, was driven through a coarse gravel which contained large stone and some clay.

ENGLISH CHANNEL TUNNEL -- Many a channel passenger suffering from mal-de-mer would be surprised to learn that the cause of his misery might have been eliminated in the nineteenth century had it not been for a decision of the British Parliament. ²¹ Proposals to bridge the gap between France and England with a tunnel have been eagerly made ever since the mining engineer, M. Mathieu, pointed out its possibilities to Napoleon. Thomé de Gamond, hydrographer and mining engineer, made extensive investigations in 1834 which were followed by fresh proposals in 1838-39 and again in 1857. One Hector Horeau, Paris architect, advanced the idea of laying an iron tube on the channel floor. Sir John Hawkshaw became interested in the project in 1865, and surveys taken during that year and the next indicated that the chalk visible at Dover continued in the bed. He enlisted the aid of the Southeastern Railway in England while the Rothschild brothers lent support to a French company.

Finally the Channel Tunnel Company was incorporated in 1872 and its French counterpart in 1875. Work was begun under the English engineer, Francis Brady, in 1882 but was stopped the following year when the British Parliament found that such a tunnel was not in accord with interests of British security.

Excellent progress with a specially designed boring machine had been made, for when the work was stopped the English heading stood 6200 feet from the Dover shaft and the French heading reached 6027 feet from the Sangatte shaft. The bores, remarkably water-tight, were later sealed to await more favorable action at a future date. Plans and consultations were held to no avail in 1916, and in 1924 the forces of insularity won out once more. The prospect of making the venture pay proved the stumbling block in 1930 and placed the channel tunnel once more on the list of "unfinished business."

EARLY CONSTRUCTION -- Almost ten years elapsed before the first "built and sunk" Early "Trench" Tunnels laid 1250 feet of heavy cast-iron water pipe.

EARLY PROPOSALS -- Prior to 1885 schemes for various types of pre-formed tunnels lowered into place were ridiculed in most quarters as being "visionary" and "wild" ideas. Probably the first serious proposal for such an undertaking was "Miller's Submarine Avenue" pamphlet published in 1854 which described a cast-iron shell lowered as a unit and anchored to the bottom of a river bed. In the April 4th issue of the "Scientific American" (1857) Joseph de Sendzimir of Long Island, New York, proposed a "submarine thoroughfare" made of iron pipe, and in 1867, in "The Engineer" of London, J.J. Morris claimed that he had published a plan eleven years earlier in which sections were floated into place and then pumped out.

J.L. Haddan, Director of Public Works at Aleppo, North Syria, proposed in 1870 to float a tunnel 30 feet below the surface of the Bosphorus and anchor it to the bottom under 120

feet of water and 30 feet of soft mud. The tunnel was to be of heavy wrought-iron plate, 10 feet in diameter and 1200 feet long, but the dream never materialized. When the eminent engineer, John C. Trautwine, took out his patent in 1876 describing trenching in a river, the idea of a pre-formed tunnel no longer seemed so visionary. His plan involved constructing the tunnel on a wooden platform above the water, sinking the pre-cast tunnel into a trench in the river, and then covering over with the excavated material.

vide a double-tube tunnel for the Michigan Central Railroad

EARLY CONSTRUCTION -- Almost ten years elapsed before the first "built and sunk" tunnel became a reality. In 1885 Hayden H. Hall laid 1230 feet of heavy cast-iron water main across Sydney Harbor by assembling his tube sections in a travelling box, or caisson, which was jacked forward along the bed. This was followed by H. A. Carson's first subaqueous "trench" tunnel in 1893-94 in the outer portion of Boston Harbor. Sections 52 feet in length and weighing 210,000 pounds were constructed on shore, floated to the site, and sunk in a trench. Designed as a portion of the metropolitan sewer outlet, each section was 9 feet in outer diameter, and was made of brick and concrete with a wooden skin.

Example.

HARLEM RIVER TUNNELS -- Construction of the New York rapid transit tunnels under the Harlem River (1904-05) brought forth another variation to the trenching method. As finally completed, the two tubes were approximately 15 feet in internal diameter, and the surrounding cast-iron shell was, in turn, encased in concrete, giving an outer width of 33 feet. D.D. McBean, a

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sub-contractor, used two methods to complete the job, the second method proving the more satisfactory. Here he excavated the trench, drove sheet piles and cut them off at the mid-height of the tunnel. He next lowered the pre-fabricated roof into place on the piles, covered it over, and proceeded to pump out and excavate underneath the roof.

DETROIT RIVER TUNNEL -- A board of consulting engineers headed by Colonel William J. Wilgus found that the lowest bid to provide a double-tube tunnel for the Michigan Central Railroad under the Detroit River was that of the Butler Brothers Construction Company, who proposed a trench tunnel. Accordingly they constructed the tubes in ten sections, each 262 feet long with a "closing" section of 64 feet in length. The sections, built side by side in wooden boxes open at the top and bottom, were sunk in a trench 48 feet in width and varying from 30 to 50 feet in depth. Concrete was then poured into the boxes and the whole was covered over with the river bed. When all sections had been sunk and concreted on the outside, the tubes were pumped out and concreted on the inside. The successful conclusion of the work (1906-10) thus marked another milestone in the progress of trench tunnels.

Modern Motor Tunnels

EARLY VEHICULAR TUNNELS -- Although the twentieth century automobile has brought a great demand for a new type of tunnel, some vehicular tunnels did exist in the nineteenth century. For

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example, the first vehicular tunnel in the United States, the Washington Street tunnel under the Chicago River at Chicago, dates back to 1866. It was constructed by cut and cover means in a cofferdam. Three tunnels, two vehicular and one foot, were bored under Glasgow Harbor from 1890 to 1893 by the contracting firm of Hugh Kennedy and Sons. Over 700 feet from snaft to shaft, the main sections were 16 feet in diameter and lined with cast iron. Another early work of this type was Sir Alexander Binnie's Blackwall tunnel (1892-97) under the Thames, built by S. Pearson and Sons. It was 3116 feet long, had an external diameter of 27 feet and an internal diameter of 24½ feet, and possessed a 16-foot roadway and two 3-foot sidewalks.

HOLLAND TUNNEL -- First of the long tunnels to be specifically designed for heavy motor traffic was the Holland tunnel (1920-27), named for its first chief engineer, Clifford M. Holland. Authorized by New York and New Jersey in 1919, the tunnel was built by shield under the Hudson as two tubes, one for east bound and the other for westbound traffic. The iron shells, 59 feet from center to center at mid-river and 29½ feet in outer diameter, were lined with concrete, extending 5480 feet under the river and a total of 8463 feet from portal to portal. Each roadway was made 20 feet wide with a headroom of 13½ feet. An outstanding feature of this work proved to be the operating ventilation systems with its "vertical transverse flow." The system was so designed that fresh air, after being forced into large ducts below the roadway, would be led to expansion chambers from which it could be released gently at intervals just above the curb

level. Here it would mix with exhaust gases and float to the ceiling into another duct from which the mixture would be sucked into the open air. Engineer Holland was succeeded on his death in 1924 by M.H. Freeman, engineer of construction, but Freeman died the following year and was succeeded by the engineer of design, Ole Singstad, who saw the work to completion.

OAKLAND - ALAMEDA TUBE -- Known also as the Goerge A. Posey tube, this tunnel was constructed over a three year period under the guidance of chief engineer Posey, and had, on its completion in 1928, the largest diameter of any subaqueous trench tunnel. It was built in twelve cylindrical sections, each 203 feet in length and weighing 5000 tons. The tubes, their tops 42 feet below water level, were of reinforced concrete, 37 feet in outer diameter, 30 inches thick, and enveloped in 3-ply water-proofing. Steel plates on steel frames were coupled together by divers when all units were in place and the tube was then pumped out. The resulting tunnel was put into operation complete with side walks, two lines of tracks, and a 23-foot roadway for vehicles.

ANTWERP -- In 1931 Antwerp began two shield tunnels under the Scheldt, one a 31-foot highway tunnel 5801 feet in length, and the other, a half a mile away, a 15½-foot pedestrian tunnel 1750 feet in length. The lowest point reached by the constructors was 116 feet below the river. This work is of significance in view of the use made of freezing to hold back the ground water. Here 6 inch pipes encompassing 2-inch pipes were placed in the soil around the shaft to form a ring 100 feet in diameter.

Refrigerated brine was run down the smaller and up the larger pipes until the adjacent soil was frozen to form a ring of ice 10 to 15 feet thick. The center core of soft earth was then excavated and the work was enabled to proceed.

OTHER AMERICAN TUNNELS -- Another California project of note was the Goat Island tunnel, a part of the San Francisco Bay bridge development. Though only 540 feet long, it became famous for its large cross section, which measured 76 by 58 feet in the rough, and 66 feet in height and 52 feet in width with its concrete lining. Other outstanding American tunnels worthy of mention are the Detroit-Windsor tunnel (1928-30) built by the trench system, the Boston Traffic Tube (1931-34), and the Lincoln tunnel, begun in 1933 to connect New York City and Weehawken, New Jersey. One shield on this latter tunnel, 31 feet in diameter, pushed ahead at the phenomenal rate of 1040 feet in twenty-five working days.

QUEENSWAY -- At the instigation of Sir A. Salvidge a committee was formed in 1922 to determine which would offer the best solution to crossing the Mersey between Liverpool and Birkenhead, a bridge or a tunnel. The report from Sir M. Fitz Maurice, Sir B. Mott, and J.A. Brodie favored the latter, which was begun under Mott's direction in 1925 and completed in 1934. Shafts, over 21 feet in diameter, were sunk to a depth of 190 feet on either side of the river and two exploratory headings measuring 12 by 15 feet were advanced. A shield was used, but the cutting was through sandstone rock. The upper half of the tunnel was lined first.

and while it rested on rock, the lower half was excavated. Lining the work were cast-iron segments 6 feet long, 2 to 2½ feet wide, and 13½ inches in flange depth, weighing slightly less than a ton each. Possessing inner and outer diameters of 44 and 46½ feet respectively, the tunnel was thus provided with a 36-foot roadway and a headroom of 23 feet. Ventilation was provided for by the supplying of fresh air from two ducts beneath the roadway, whose lowest point reached 148 feet beneath the river. In all, the main tunnel measured 3751 yards in length, and the branch tunnels, 26 feet in diameter, brought the total up to 5064 yards. The bottom half was built so that if future demand should warrant it, a second roadway could be built.

Summary

At some early period in his existence primitive man found the rock shelters and caverns provided by nature suitable for dwelling places. As his knowledge grew and crude tools made their appearance, he was able to improve somewhat on nature's excavations to increase his comfort. As civilization developed, the cave-dweller disappeared, but tunneling, after a primitive fashion, still went on to provide impressive burial places for the dead. Such man-made excavations may still be seen in Egypt and India today. Evidences of early tunnels still exist in Greece as well, but it was the Romans who developed ancient tunnels to their greatest extent, using them for water supply, drainage, mining, and passage. Such tunnels were bored through self sustaining material, usually rock, and were accomplished, of

were familiar sights in every part of the world. In the course, with only simple hand tools and a great deal of back-water tunnels also kept pace with the progress of the breaking manual labor.

Upon the eclipse of Rome, tunneling, with a few isolated exceptions, became a lost art. It was revived again in medieval times for the purpose of providing drains and watercourses under certain towns and monasteries, but projects of this sort were, for the most part, very modest. Relatively large-scale operations were commenced during the Renaissance in the field of mining, the first important writing on the subject coming from Georgius Agricola in the sixteenth century. Essentially the same tools and methods which had been used by the Romans were used by the central Europeans in Agricola's time and continued in use until the introduction of gun-powder as a blasting agent early in the seventeenth century. Later in the same century the first commercial tunnel of modern times, the Malpas tunnel on the Languedoc Canal, was successfully completed. This work was only the first of many canal tunnels which were to be bored through hills and mountains for the next century and a half.

The emergence of the railroad over the canal simply brought on a fresh wave of tunnels, for the same conditions, such as the avoidance of steep grades, which had made the tunnels necessary for canals made them necessary for railroads as well. The second half of the nineteenth century saw not only a tremendous increase in railroads but a corresponding increase in railroad tunnels, made possible by the introduction of machine drills and high explosives. The Alps served as pioneer ground for the long railroad tunnels which, by the early twentieth century,

were familiar sights in every part of the world. Mining and water tunnels also kept pace with their railroad counterparts, far surpassing any accomplishments of preceding ages.

While tunneling through self-sustaining material had been accomplished by the ancients, subaqueous tunneling in water-bearing material was a problem which was not solved until the nineteenth century. Brunel and his shield produced the answer with the first Thames tunnel, and later engineers, notably Greathead, improved Brunel's concept of the shield and introduced the use of compressed air. The shield and compressed air then made the extensive subway systems of large cities like London and New York feasible, and the early decades of the twentieth century saw the remarkable growth of these underground railroads. Soon to follow were the modern motor tunnels, some built by shield, others by blasting through mountains, and still others in the "built and sunk" form. As canals and railroads had in the past, automobiles were destined to once more give added impetus to tunnel construction.

Throughout their long history tunnels have been dirty, hard, and dangerous work reaping their creators more illness and death than fame. Hidden beneath the earth these works, monumental in character though they might be, have earned the appreciation of few and the acclaim of still fewer. They are perhaps more symbolical of the engineer than any other of his works, for they are the unspectacular public servants, doing their job quietly and efficiently, taken for granted in the every-day bustle of life where the true appreciation of their worth could only be made by removing them from the scene, to the detriment of society.

FOOTNOTES

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Chapter VII

SURVEYING

LEVELLING -- Ancient Surveying Instruments times is the plumb level, consisting of the suspension of a plumb line from

DISTANCE MEASUREMENT -- From earliest times man was accustomed to measuring off distances in arbitrary units chosen from parts of the body, in order to lay out boundaries and to estimate crop yield. Just how early he began marking boundaries is difficult to ascertain, but we do know that the practice was known in ancient Egypt. One evidence is the surveying party depicted on the walls of the tomb of Menna, a land overseer and inspector of boundary stones of Amon (c 1400 B.C.), at Sheikh Abdel Qurna in Thebes. Here two "rope-stretchers" or "chainmen" are measuring a field of corn with a cord knotted at intervals, while three officials and a boy carrying writing materials look on. Mechanical measurement of distance was to come much later, the invention of the land counter often being attributed to Hero of Alexandria. Though probably not a contemporary, he may be said to date from the same historical period as Vitruvius who wrote about such a counter in the first century B.C. In his work on architecture Vitruvius described the ¹nodometer, (called a "waywiser" in its early modern development) a device which, by a series of cogwheels and other mechanisms attached to a cart wheel, would drop a stone into an urn beneath the carriage at the end of each mile traversed. Vitruvius made no claim to having invented the machine nor did he name the inventor, so all that we can say with certainty is that a mechanical device for measuring distance was used before

the Christian era. 55

LEVELLING -- Also dating back to prehistoric times is the plumb level, consisting of the suspension of a plumb line from the apex of an isosceles triangle. Two such examples from ancient Egypt may still be seen in the Cairo Museum. Stone and bronze were used by early peoples for the weight or "bob", and these were replaced by lead (Latin for lead, "plumbum," hence derivation of expression 'to plumb') during Roman times. Vitruvius, in writing of the levelling instruments used by the Romans, regarded the dioptrae and water levels as deceptive and favored the chorobates, a kind of super-plumb-level. This latter instrument was a straight-edge 20 feet long, with perpendicular legs at either end, to which were attached vertically marked cross-pieces. A plumb line at either end hung from the straight-edge and marked the inclination on the cross-pieces. For use in a wind the instrument had a groove in the top of the straight-edge, 5 feet long, 1 "digit" wide, and $1\frac{1}{2}$ "digits" deep, which was filled with water and levelled by observing the water line.

ANGLE MEASUREMENT -- Primitive notions of direction were probably derived from celestial observations, as indicated by the orientation of many ancient temples. The antiquity of the plummet as a sighting appliance for determining the direction and time is illustrated by the Egyptian merkhet, used by the astronomer-priests to determine the meridian line, and it is quite possible that the Chaldean gnomon was derived from the merkhet. In its simplest form the gnomon was an upright rod placed in a

circle on a horizontal section of ground. By observing the shadow's path across the circle the ancients were able to determine the meridian line and latitude. This instrument was introduced from Babylon into Greece by Anaximander (c 611-547 B.C.), who is also reputed to have made the first map and to have discovered the obliquity of the ecliptic. With the gnomon Pythias (326 B.C.) calculated within one minute the true latitude of Marseilles, if we exclude his omission of the effect of the sun's semi-diameter.

Aristarchus of Samos (310-230 B.C.) improved on the gnomon with his scaph--an upright rod in the middle of a hemispherical bowl--the first type of instrument with a divided circle for measuring angles. Hipparchus of Nicaea (c 180-125 B.C.), the father of trigonometry, is the first whose name is associated with the division of the circle into 360 degrees, although it is probable that the Babylonians used this system centuries before. He found it possible to measure small angles, such as the diameter of the sun and moon, with an early astrolabe which resembled Hero's dioptra. Essentially the dioptra was a sight rule which rotated over a circular plate set in any desired plane. It was used to mark off similar angles and to solve problems of heights and distances.

The Roman groma, or surveyor's cross, was an instrument used to lay out right angles. It consisted of two sight rules crossing at right angles with plumb lines at the four extremities, and the whole was supported by a single pole at the center where the rules crossed. The carving on the tombstone of a Roman "Mensor" L. Aebutius Faustus (c A.D. 100) at the Municipal

Museum in Ivrea, Italy, shows a crude representation of this device. In the excavations in the Via Abbonanza at Pompei (1912),⁵ under the direction of Cav. M. Della Corte, several fragments of a groma were found and pieced together to give us one of the oldest surveying instruments in the world. The instruments they used and the results they obtained indicate that the Romans relied on the direct measurement of the sides of triangles and the use of right triangles, supplemented by a theory of similar triangles.

Much of the early development of surveying came as the result of advances in astronomy and astrology which played such an important part in the lives of the ancients. An important astronomical instrument which soon found its way into surveying was the astrolabe, an early form of which was reputedly invented by Hipparchus.⁶ This instrument in its simplest version included a rotatable rule or alidade carrying sight vanes, the position of which could be read by a circle of degrees hung in a vertical plane from the thumb of the observer. Ptolemy's planisphere, on which the planispheric astrolabe of the Arabs was based, had in turn been derived from the instrument of Hipparchus. Two early treatises on the astrolabe have been preserved for us, one by John Philoponus (c A.D. 625) and the other by Severus Sabokt (c A.D. 650) of Syria. In the Athens National Museum is a piece of apparatus which might be a Greek astrolabe (c A.D. 250), having been dredged from the bed of the sea off Anticythera. However, the earliest known undoubted astrolabe is Persian, made by Ahmad and Mahmud of Isfahan (A.D. 984), on display in the Museum of the History of Science at Oxford. Until the middle of the sixteenth century the astrolabe was used almost exclusively in the

vertical position. The change to a horizontal position with the inclusion of a specially fitted mariner's compass was probably done at the suggestion of Gemma Phrysius (or Frisius) of Louvain.

POST-ROMAN SURVEYING -- The lay-out of public buildings in ancient Greece and Rome illustrates one phase of the surveyor's work which was not apparent in the early post-Roman years.

Nevertheless the surveyor at the beginning of the Dark Ages still occupied a position of respect, as noted by Cassiodorus (A.D. 468-568) minister to the Ostrogoth, Theodoric the Great:

"The professors of this science are honored by a more earnest attention than falls to the lot of any other philosophers.

Arithmetic, Theoretical Geometry, Astronomy, and Music are discoursed upon to listless audiences, sometimes to empty benches.

But the land surveyor is like a judge, the deserted fields become his forum, crowded with eager spectators. ----He shows what he is saying; he proves what he has learned; by his steps he divides the rights of hostile claimants; and, like a mighty river, he takes away the field of one side to bestow them on the other. Wherefore, acting on our instructions, choose such a land surveyor, whose authority may be sufficient to settle this dispute, that the litigants may henceforth cultivate their lands in peace."

Arabic astronomers and mathematicians enlarged their knowledge and improved upon the instruments and methods which they had inherited from Greece and Rome, and were thus able to play a great part in influencing the revival of scientific knowledge

in western Europe. Their development of trigonometry and of portable astronomical instruments such as the astrolabe and quadrant led to a modification of surveying methods. An increased substitution of angular for linear measurement was brought about, with the subsequent evolution of various instruments which could measure angles in any plane.

European Beginnings

EARLY MAPS -- First of the maps in a modern sense were the twenty-six included in the manuscripts of Ptolemy's geography (A.D. 140). The oldest surviving of these manuscripts listing the latitude and longitude of various places date only from the eleventh century, but the view is held that they are descended from contemporary maps originally part of the work. These maps were engraved in several editions before the end of the fifteenth century, the finest probably being the copper engraved Rome editions of 1478 and 1490. With new discoveries in the world modern maps were added to the original, the Strasbourg edition of 1513 having twenty for a start. Deriving from Ptolemy, but with additions, was the famous map of al-Idrisi made for Roger of Sicily about 1150. Other maps, non-Ptolemeic in origin and dating from this period, have been discovered in various parts of the world. One Chinese example dates from 1137, being engraved on both sides of a stone. There is a possibility that much remains to be discovered in the Arabic world, for the Arabs were skilled geographers. Among their best known savants was Abu'l Fida

(1273-1331), whose Geography, "Takwim al-buldān," was published in 1321. Single parts of it were published in Europe by 1650. In the Leyden Library is a copy of the work (M.S. No. 727) corrected in his own hand.

Rough maps of the country, noting roads, rivers, and towns were drawn up in many medieval monasteries to aid the pilgrims of the time. Such a map was that made by Mathew Paris and his pupils of the English Benedictine Abbey at St. Albans about 1250. It was probably not meant to be accurate, for no scale was assigned it and obvious distortions indicate that it was designed primarily as a schematic map. Of particular interest is the fact that this map was oriented to the north, whereas most contemporary foreign maps were oriented to the east. Also worthy of mention as belonging to this period--though grossly unscientific--is the circular map of the world belonging to Hereford Cathedral. Drawn by Richard of Belleau in Lincolnshire in 1280, the map was made on parchment with the details picked out in fine colors and gold. The northern part of Africa and most of Europe and Asia appear in distorted form surrounded entirely by a circular ocean, and blank spaces have been filled in with graphic pictures and written descriptions of marvels and monsters.

Playing an important part in the early Renaissance period were the Portolan charts of the Mediterranean and Atlantic coasts. The earliest dated of these charts known (1311), the work of Petrus Vesconte of Genoa, now rests in the Archivio di Stato in Florence. A good example of the type still extant is the Este World Map (c 1400) at the Biblioteca Estense in Modena, and the series culminates in the map of Fra Mauro (1459) at

introduced about the middle of the sixteenth century--
 Venice. These were mariners' maps, based on estimated bearings
 in his world map of 1492 and in his atlas, the first to use
 and distances between principal ports and capes. Chief of their
 name ("Atlas sive Cosmographicae Meditationes"), which was
 characteristics were the numerous lines of loxodromes or compass
 bearings, the faint coast lines, and the lack of inland geogra-
 phy. The magnetic compass bearings are particularly interest-
 ing for it was at about this time that the compass came into gen-
 eral use. The magnetic properties of lodestone--a crystalline
 oxide of iron found as a mineral (Fe_3O_4)--were known at an early
 date, but it is doubtful that either it or steel rubbed by it
 were used for compass work before the Christian era. Thales is
 reputed to have stated in the sixth century B.C. that "the magnet
 has a soul because it draws the iron," but we have no evidence
 that he knew anything of its directional properties. Though it
 is possible that the Chinese knew its properties several cen-
 turies before Christ, the oldest Chinese compass to be definite-
 ly established dates only to A.D. 1293, three centuries after
 its use by the Amalfi.

Degree lines on maps followed the translation of Ptolemy in
 Latin by Jacobus Angelus de Scarparia (1410), and terrestrial
 globes first came into general use about the time of Columbus.
 Probably the last representation of the world without the in-
 clusion of the Americas was the Nuremberg globe of Martin Bethain
 (c 1492), while the earliest surviving work including the New
 World is the manuscript map of Juan de la Cosa (1500) in the
 Naval museum at Madrid. The first really new atlas to appear,
 apart from Ptolemy's, was that of Ortelius of Antwerp (1570),
 the "Theatrum Orbis Terrarum." Mercator's projection--which he

introduced about the middle of the sixteenth century--was used in his world map of 1569 and in his atlas, the first to use the name ("Atlas sive Cosmographicae Meditationes"), which was published in its completed form in 1595.

EARLY EUROPEAN MATHEMATICS -- The astronomy, geography, and mathematics of the Arabs had a great influence in the creation of the early European maps, an influence which was still to be felt when geodetic surveying arose in the seventeenth century. Early translations of Euclid from Arabic to Latin made by Adelard of Bath (1120) and Gerard of Cremona (1186) foreshadowed the flood of knowledge which would soon flow from East to West. In the early thirteenth century Arabic numerals were introduced, and by 1250 Euclid, Ptolemy, and scant parts of Archimedes and Apollonius, were accessible to western students.

From these beginnings knowledge was not only expanded but new mathematical concepts were evolved. The long story of the development of medieval and renaissance mathematics cannot be told here, but a few points particularly significant in the development of surveying deserve comment. In 1614 Napier of Merchiston (1550-1617) made known his discovery of logarithms which he had developed as early as 1594. Logarithmic tables were then calculated and first published in 1617 by Henry Briggs (1561-1631). Shortly thereafter (1620), Edmund Gunter (1581-1626), who had brought out his first table of sines and tangents, invented a straight logarithmic scale. William Oughtred (c 1621) slid two of Gunter's rules along side by side and thus developed

and yard which served as a standard until the nineteenth century.

the slide rule. With these developments, along with those of more accurate instruments, the rise of geodetic surveying became possible.

STANDARDS OF MEASUREMENT -- From the earliest days of surveying some standard of length, of necessity, prevailed. Usually it derived from a part of the body as evidenced by the name assigned to units such as digit, palm, and foot. In 1850 the Senkeren Tablet, possibly dating back to 2500 B.C. was discovered in a small Arab village on the site of the ancient city of Larsam or Larsa. Now in the British museum, it affords a great deal of information as to early Babylonian measures and methods of computation. In their turn various civilizations used varying standards, often determined by the physical measurements of the sovereign. Until well into the nineteenth century a great diversity of systems existed, separate and distinct with each principality, free city, and kingdom. Today two major systems are in use, the English and the Metric systems.

The standard of length in the English system has scarcely changed from Anglo-Saxon times; indeed, the surviving standards of the time of Henry VIII and Elizabeth do not vary more than a hundredth of an inch from the present imperial yard. Tradition states that the early yard was fixed by the length of the sovereign's arm. The earliest English standard of length, the Exchequer standard yard of Henry VIII (1496), was a brass rod of octagonal section, divided into inches and also into sixteen different parts. It was replaced in 1588 by the Elizabethan standard yard which served as a standard until the nineteenth century.

In 1758 a Committee of the House of Commons prepared a standard yard which was described as "the first scientifically constructed measure of length in this country." This standard was legally adopted by Parliament in 1824, but was destroyed in a fire in 1834. It was replaced by a bar of Bailey's metal (copper, tin and zinc) which was legalized by the Standards Act of 1855 and confirmed in the Weights and Measures Act of 1878.

A more "natural" system of weights and measures had been urged by various men of science and commerce for years, but it was not until the end of the eighteenth century that any concerted action was taken. Upon decree of the French National Assembly the Academy of Sciences at Paris took up the work in earnest in 1790. After a committee had adopted the decimal system for a start, another committee composed of Borda, Lagrange, Laplace, Monge, and Condorcet recommended as a basis for the system the quadrant of a great circle of meridian. After an arc of a meridian had been measured, the length of a quadrant could then be computed, and one ten-millionth of its length (the meter) could be taken as the base or fundamental unit of length. The most important of the operations, the measure of the arc from Dunkerque to Barcelona, was begun in 1792 and carried out under difficult political conditions by Méchain and Delambre. In 1799 when calculations had been made, a platinum meter, constructed by Lenoir, was adopted as the "true meter" and deposited in the Archives of State.

With the growing use of the meter for scientific work, not only in France but in other European countries as well, the accuracy of its fundamental units became a matter of interest to

geodesists and mathematicians in several countries. The calculations of Bessel (c 1841) showed that the adopted meter was not $1/10,000,000$ th of the distance from the equator to the pole as originally planned and was not therefore, the "natural" unit for which the scientists had aimed. His figures showed that 10,000,665 of the official meters represented the true quadrant distance, but it was decided to leave the length of the official meter unchanged in the interests of practicability.

Geodetic Surveying

BACKGROUND -- Geodesy, the science which treats of investigations of the form and dimensions of the earth's surface, has evolved under four main headings, (1) arcs and astronomical positions, (2) measurement of lengths of sides of triangles, (3) measurement of variation of gravity, and (4) systematic allowance for the earth's curvature. The first authenticated hypothesis of the spherical form of the earth was advanced by Pythagorus (b. c 582 B.C.), and the first determination of the earth's circumference is attributed to Eratosthenes (230 B.C.), who deduced the size of the earth from a measured meridional arc. Another famous arc measurement was that done by the Arabs in A.D. 827, who measured directly with wooden rods along 2° of the meridian. Jean Fernel (1497-1558) counted the number of revolutions of his carriage wheel from Paris to Amiens in 1525, and by an astounding series of compensating errors computed the circumference of the earth to be only one tenth of one per cent in excess of its true value. But it was the development of the

general science of measurement which brought about the rise of geodetic surveying in the seventeenth century.

EARLY MODERN ARCS -- The first account of the method of triangulation appears to have been published by the Flemish mathematician and cosmographer, Gemma Phrysius (b. 1508), in a "Libellus" bound up with the 1533 Flemish edition of Peter Apian's "Cosmographia." In this work Phrysius claimed to have produced an entirely new method of surveying a large area without having recourse to direct measurement. In his survey he used a makeshift horizontal circle and alidade arrangement--apparently a novelty in its time. Later his nephew, Gualterius Arsenius, was among the first of the instrument-makers to construct astrolabes with compass inset, specially adapted for plane-table survey.

True geodetic surveying may properly be said to have begun with Willebrord Snell van Roijen (1581-1626), a Dutch professor of mathematics at the University of Leyden, who was the first to use, on a grand scale, the principle of triangulation. In 1615, with thirty-three triangles, he triangulated some 80 miles between Alkmaar and Bergen op Zoom, using a chain for the base measurement, and a sector for the angles. From the meridional arc of 1° 11' he computed a circumference of the earth which was 3.4 per cent too small, but his work will be remembered as the first in which scientific geodetic methods were used for determining the size of the earth.

Richard Norwood (c 1590-1675), a London "reader of mathematics," made the next prominent attempt in 1633. He measured directly along the road from York to London, 180 miles, with a

99-foot chain and paces. Taking the meridian altitude of the sun at both places he determined the length of a degree "within a scantling of the truth."

A more significant contribution was made by Jean Picard (1620-82) who in 1669 triangulated a distance of approximately 70 miles from a point near Paris to a point near Amiens. He measured his angles with a sector of 10-foot radius upon which he placed telescopes with spider line cross-hairs. His triangulation, starting from a base line of nearly 7 miles, covered an arc of approximately 1° 23' and enabled him to calculate the most accurate degree length thus far given. It was this measurement which was later used by Newton in his "Principia" of 1687. From 1685 to 1716 Picard's triangulation was extended each way from Paris by J. and D. Cassini, who thus established an astronomical basis for the government survey of France.

GOVERNMENT SURVEYS -- A third member of the Cassini family, César François Cassini (1714-84), continued where his grandfather and father left off, covering the country with a triangulation system of eighteen bases and four-hundred triangles. After publishing a skeleton map of the country in 1744, he continued with the work, assisted by his son, who had almost completed it when the French Revolution broke out.

Largely the result of the suggestions of the fourth Cassini, Jean Dominique, England's triangulation was begun in 1783 under the direction of Major-General William Roy (1726-90) in order to check the relative astronomical positions of the observatories at Greenwich and Paris. However, official mapping in Britain, the

Ordnance Survey, dates from the time of the rebellion in the Highlands (1745), when Lt. General Watson, Deputy Quartermaster General, made an elaborate compass sketch of the territory for military reference. This work was afterwards extended over the whole of Scotland, General Roy playing a large part in the development. Triangulation had been contemplated as early as 1763, two years before Roy became Surveyor General of Coasts, but an unsettled state of affairs prevented the start of the work for twenty years. In 1784 a base of over 5 miles was measured on Hounslow Heath near London, from which the triangulation was extended toward Dover. A tie-in with the French system was accomplished by 1787. On Roy's death in 1790 the Duke of Richmond, Master General of Ordnance, determined that the trigonometrical survey should continue, and accordingly appointed two artillery officers in 1791 to carry on the work. The initial result was the map of Kent and southern Essex, with a scale of 1 inch to the mile, published in 1801.

Geodetic work had, in the meantime, been going on in other parts of the world. To settle the question of the earth's shape, international bodies, predominately French, had gone to measure an arc in Peru in 1735 and another in Lapland in 1736. It was the Peruvian arc along with the French arc from Dunkerque to Barcelona upon which the meter was based. In America the English astronomers, Mason and Dixon, fixed a parallel of latitude forming the southern boundary of Pennsylvania. They then made a measurement with wooden rods for a degree determination, extending over 100 miles from the southwest corner of Delaware well into Pennsylvania.

chains were connected, as were the Survey and ... chains.

Other names which became well known in America were those of David Hittenhouse (1732-96) and Andrew Ellicot (1754-1820), remembered for their contributions in fixing state and national boundaries. A Coast and Geodetic Survey was authorized in the United States in 1807, but lack of funds and war prevented little from being accomplished apart from small detached surveys until 1832. The initial surveys were begun in 1811 by a Swiss mathematician and instructor at West Point, Ferdinand R. Hassler (1770-1843). Upon his death he was succeeded by Alexander D. Bache (1806-67), a military engineer, who greatly enlarged the work of the survey. The accuracy achieved in these early surveys may be gauged by the fact that in a 300-mile network containing thirty-two triangles, the second measured base differed from its calculated length by only 4 inches.

The French example soon made its mark on the rest of Europe. Joseph de Ferraris, an army engineer, mapped the Austrian provinces in the Low Countries during the period 1770-78, turning out two-hundred and seventy-five sheets in color. Geodetic work was begun in 1802 by von Zach in Prussia, and this was soon followed by extensive operations in Switzerland and Italy from 1811 to 1832. Russia followed with work by Tenner and F.G. Struve during the period 1817 to 1855. From 1821 to 1844 Gauss labored in Hanover, later extending his work, and being the first to apply the method of least squares to the adjustment of triangulation. The second quarter of the century saw the connecting up of the various systems. In 1831 F.W. Bessel and Beyer began to connect the triangulations of France, Hanover, Denmark, Prussia, Bavaria, and Russia. From 1847 to 1851 the Russian and Austrian chains were connected, as were the Swiss and Lombardian chains.

1858 saw work commence in Spain under Colonel Ibañez, and by 1861 England and Belgium had been linked together. Also deserving of mention is the work in India of Lambton, Everest, and Walker (1800-80) who had, by the latter date, largely completed a system of triangulation which, for extent and accuracy, was not equalled until well into the twentieth century by the United States and Russia.

Though much work was done around Japan by American and British seafarers in the middle of the nineteenth century, it is interesting to note that surveying had long before been introduced to the Far East. Legend attributes the oldest map of the country to a civil engineer priest, Gyogi (c 7th or 8th century A.D.), but history records that the western method of surveying was introduced during the Kwan-ei era (1624-43) by a Dutchman named Casper, who taught the fundamentals to Gon-emon Higuchi of Nagasacki. This knowledge was passed on from one generation to the next, and culminated in the work of the astronomer, Tadataka Inō (1745-1818) known as Japan's greatest surveyor. His geodetic survey, begun in 1800 and continued after his death, resulted in the great map of Japan (somewhat inaccurate), published in 1821.

These great strides in geodetic surveying were reflected by increased precision in plane surveying, where the curvature of the earth was ignored. This latter type of measurement, sufficient for the needs of the average engineer in locating lines, became, essentially, a method of filling in the geodetic framework. Increased precision resulted from the development of the instruments whose story represent the core of the history of

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surveying.

Modern Development of Surveying Instruments

DIRECT MEASUREMENT OF DISTANCE -- Little progress in distance measuring devices had been made from early Egyptian times until the early seventeenth century when Edmund Gunter of Christ Church, Oxford, introduced (c 1620) his famous 100 link chain, 4 poles, or 22 yards, in length. Though the most popular, his chain was not the first metallic type to appear, as evidenced by the illustration of a "wyer line" in Cyprian Lucar's treatise of 1590. As early as the seventeenth century we find a description in S. Sturmy's, "The Mariner's Magazine,"¹⁴ of the common practice of the leading chainman carrying ten arrows, and placing one in the ground every time the chain is laid to insure a correct count at the end. Snell's introduction of the method of triangulation from a fixed base (1615) brought new emphasis to the need for accurate distance measurement, for the accuracy of the whole survey could be no greater than that of the initial base line. The problem resolved itself into two parts, (1) the disturbance of one unit when the next was placed in contact, and (2) the effect of temperature on the length of measure. An early, but unsuitable solution was made by Picard (c 1669), who used wooden rods tipped with brass. The "contact" portion but not the "temperature" portion of the problem was solved by Boscovitch (1750) who, in measuring the Rimini base in Italy left space between successive rods and measured the difference with a beam compass. When measuring the base on Hounslow Heath in 1784

General Roy used glass rods whose expansions were checked by a "microscopic pyrometer."

In 1792 Borda utilized the principle of the unequal expansion of two dissimilar metallic rods to measure more exactly the temperature of either rod, and thus calculate the true length. Major General Colby of the Royal Engineers also made use of the principle in constructing his Compensation Bars, which were used to measure a base in northern Ireland (1827-28) and on the Salisbury Plain (1849). Two reference marks on metal tongues attached to the bars (one of iron, the other of brass) remained an unvarying distance apart regardless of the temperature. He used double compensating microscopes to gauge the distance between successive bars which lay 6 inches apart. Using 10-foot rods he was able to average an advance of six bars an hour. The "metallic thermometers" used by Gauss and Bessel on the Hanoverian and Prussian arcs of 1820 and 1830-35 were similar to the device of Borda, and the "bimetallic" Brünner apparatus simply made independent measures of the base with each rod. Dr. E.C. Guillaume's invention (1896) of "Invar," a nickel-steel alloy with a low temperature coefficient (1.0×10^{-6} per $^{\circ}\text{C}$), marked a significant step in the endeavor to solve the "temperature" problem.

Traditionally, precise measurements were made with rigid rods until the end of the nineteenth century. An exception was General Roy's use at Romney Marsh (1787) of Ramsden's 100-foot flexible steel chain supported at intervals. The first patent for a steel "tape" was granted to James Chesterman and John Bottom, "mechanists" of Sneffield, England, in 1842, but this was not designed for measurements of geodetic precision. Jäderin of course, eagerly sought after by the early surveyors. An

of Sweden introduced (1835) the method of using two independent light metallic wires freely suspended under constant tension, a system which has now been improved by the use of "Invar" wires.

INDIRECT MEASUREMENT OF DISTANCE -- Thales of Miletus in the sixth century B.C. is reputed to have used geometry to gauge distances, and Hero described the use of his dioptra in range-finding. Computing distances with angle instruments was a well-known practice during the Middle Ages, and will be discussed later, but this section will deal with the relatively modern optical methods of gauging distance. The instrument known as the rangefinder was, and is, primarily military, being directly connected with gunnery. One of the earliest of rangefinders to use two view finders was made by the optician Magellan in 1775, and a similar instrument was developed by General Clark in 1858. P. Adie, an Englishman, who made the first coincidence rangefinder in 1860 by rotating one of the end reflectors, was followed closely by Steinhilf of Germany and Tavernier of France. Probably the first use of pentagonal prisms was made by Colonel Goulier in 1864, while Barr and Stroud added a further improvement in 1888 by interposing a deflecting prism between the central telescope and the end prism. Foundations of the stereoscopic rangefinder were laid by Wheatstone in 1832 and by Helmholtz in 1855-58, but it was not until 1893 that de Groussilliers brought out the first instrument of this type which was subsequently developed by Zeiss.

An instrument which, at one setting, would give distance, (by measuring a very small angle), altitude, and azimuth was, of course, eagerly sought after by the early surveyors. An

Englishman, Gascoigne, in 1639 fitted a movable micrometer diaphragm of metal threads in his Keplerian telescope, but this improvement was little known to scientific men until 1667. Hooke's suggestion of hairs was taken up by Montanari (1674), who used twelve to fifteen hairs in his telescope and a vertical staff of constant length in terrestrial work. The method was not generally known to surveyors, however, until the publication of a book by William Green in 1778, wherein he described his stadiometer. A similar contrivance had been used by James Watt in 1771 when he was surveying for the Tarbert and Crinian Canals. Porro introduced an "anallatic" telescope in 1823 which reduced the calculations which had hitherto been necessary for tachymetry. A variation to the scheme was provided in 1868 by an Austrian engineer, A. Gentilli, who devised a short play between vertical stops. Subsequent developments tended to simplify the operation even more. Modern stadia surveying is carried out with a transit and rod, and distances from the transit to the rod are computed from the interval observed on the rod between two horizontal cross-wires in the telescope. It is a useful and economical method of surveying in work where a precision of 1 in 500 or less is sufficient.

THE QUADRANT -- Arabian in origin was the surveyor's square, or quadrante, a square board, marked with horizontal and vertical lines, used for measuring heights and distances. By sighting along one edge of the board and observing the position of the plumb line from the top corner on the cross-hatched section, the surveyor was able to read off immediately tangents and

cotangents of the angle observed. In time a circular arc was struck from one corner to the opposite, forming a quadrant of a circle, and rendering it possible for the observer to read off the angle in degrees. Some versions of the quadrant found the cross-hatched square inscribed within the arc. Such a device was the quadrant of Leonardo of Pisa (1220), which had a circular section divided into sixteen parts and a square with ten parts to a side.

Early among European treatises on the subject was the fourteenth century translation of the second part of a work of Robertus Anglicus entitled "Ars metrica." This period was particularly marked by contributions of the Merton school of mathematicians which included such illustrious names as Richard of Wallingford and Johannes Maudith. Further writings, improvements on the original, continued to appear in the sixteenth century. In his "Nova Scientia Inventionum" (1537) Niccolo Tartalea advocated elongating the leg carrying the sight vanes, and Dr. William Cunningham (1531-86) of Norfolk described "A New Quadrant, by no man ever published." In the first book written in English on surveying, "A Geometrical Practise, named Pantometria" (1571), Thomas Digges described and illustrated the geometrical square. In Paris Jean de Merliers added to the literature on the subject with his "L'Usage du Quarre Geometrique" (1573).

One of the most interesting of the early quadrants still extant is George Purbach's (c 1423-62) "Quadratum geometricum," which he dedicated to John, Archbishop of Gran, Hungary. Containing scales known as *latus versum* and *latus rectum*, the sides were divided into 1200 parts, each division being equal to one

millimeter. In addition to the usual plumb line the instrument was provided with an alidade with sights fixed at the apex and swinging free over the scales. Another early instrument, the geometer's quadrante of Christophorus Schissler (1579), operated on the same principle as Purbach's. Framed in a series of reliefs of geometers engaged in surveying, the working portion of the instrument was designed for observation and for ready reckoning.

JOINT RULES -- The origin of the measurement of angles by two sticks to obtain similar triangles and thus deduce heights and distances is lost in the pages of time, but we do know that mathematicians of the sixteenth century were familiar with the method. Daniel Speckle in 1589 described a proportional compass and sector, and in the following year John Blagrave of Swallowfield, by Reading, Gentleman and 'well wisher to the Mathematickes', published in London "A Booke of the making and use of a Staffe, newly invented by the Author, called the Familiar Staffe." This instrument consisted of a pair of compasses with legs 5 feet in length, one of the legs being graduated. By the eighteenth century the sector in general use was simply a pair of graduated rulers about a foot long joined at one end by a swivel. With this device the surveyor could mark off proportional distances on the scales and on the ground and thus could easily calculate lengths, heights, areas, and volumes.

Three-ruled instruments, known as Ptolemy's rods or triquetrum, were also used briefly to measure heights and distances. In 1624 Robert Fludd of St. John's and of Christ Church, Oxford,

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invented the baculus geometricus, a device with a crosspiece which moved up and down a vertical graduated 6-foot rod, while a third stick, swivelled at the top of the vertical rod, acted as the inclined sight. Fludd's parallelogrammum of the same year was the same instrument but in a different form. Similar to a sector, but having three arms, was the trigonometre of M. Jobst Burgi, illustrated with engravings by Benjamin Bramer in 1684.

OTHER STICK INSTRUMENTS -- Similar to the triquetrum, where the chord of an angle was measured on a linear scale, was the cross-staff or Jacob's staff. Though Levi ben Gerson of Bañolas in Catalonia dedicated a description of this instrument to Pope Clement VI in 1342, it does not appear to have had much use among land surveyors nor to have been used commonly by seamen for sun sights before the sixteenth century. It was mentioned by Nuñez in 1537 but was not mentioned by Columbus or Da Gama. It was a simple instrument in which the observer sighted along a graduated horizontal rod and moved a vertical crosspiece along it until the sun, or other object, was visible over the crosspiece.

To avoid the necessity of looking directly into the sun Captain John Davis of Limehouse improved on the "crosse-staffe" and produced (c 1540) the "back-staffe," in which the chord shadow and horizon line had to coincide. One of the earliest representations of his invention was shown in a woodcut in Davis' "Seamen's Secrets" of 1594.

Belonging to the same class of instruments was the cumbrous

"crosse-bow" with which the altitude of the sun could be determined by one reading of the position of a movable eyesight on a graduated arc. This instrument was described, along with the crosse-staffe, sector and quadrant, in "The Works of Edmund Gunter" published in 1624.

1757. Though reflecting devices have doubled the useful range

OCTANTS AND SEXTANTS -- The transition from the quadrant and stick instruments to the modern sextant took several centuries, although an early relative of the modern sextant was used by the Arabs as early as the tenth century. In A.D. 992 Chogandi erected a huge octant--said to have a radius of 60 feet--near Bagdad, in order to measure the obliquity of the ecliptic.

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Tycho Brane (1546-1601) constructed several sextants, one of which had a 5½-foot radius and turned on a vertical axis, while one end radius was kept horizontal.

The modern origin, however, dates from 1666 when Hooke found that the use of a reflecting mirror in a quadrant made it possible to see two objects, between which the angle was to be measured, superimposed on each other. A serviceable reflecting octant was finally produced by John Hadley of Britain in 1730 and described by him in the following year. At about the same time Thomas Godfrey of Philadelphia invented, quite independently, a sextant which was remarkably like the one in use today. The invention of Hadley must have been better known at the time, however, for octants dominated the field during the next thirty years. Hadley's original description included telescopes, but pin-hole sights were long used. Since the reflecting mirrors doubled the angle swept through on the instrument, an eighth of a circle

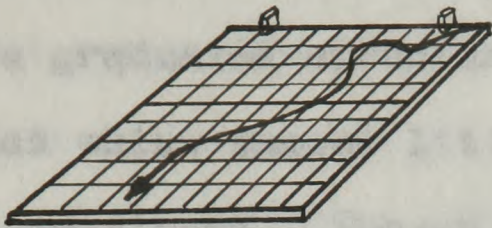
was all that was necessary to accommodate angles formerly measured by the quadrant. Thus, in the original instrument, the octant was often referred to as the quadrant. To increase the available arc measurement from 90° to 120° the sextant came into favor, probably at the suggestion of Captain Campbell, about 1757. Though reflecting devices have doubled the angles swept through, the names 'octant' and 'sextant' still remain to designate the actual angles of 45° and 60° between the two legs of the instruments.

Primarily, the sextant and its predecessors had been used to measure vertical angles, and were, therefore, more concerned with astronomical observations than with plane surveying problems. By rotating the instrument into a horizontal plane the observer could, of course, measure horizontal angles, a practice still often used with the sextant by coastal survey parties operating from the moving deck of a small boat.

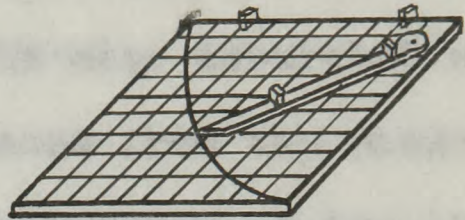
(3)
Quadrant

THE THEODOLITE -- In the modern sense the quadrant was the forerunner of not only the vertical angle measuring instruments but of the horizontal types as well. Unwittingly, Nicolas Bion in "The Construction and Principal Uses of Mathematical Instruments" (1723), traced the early development of the modern theodolite by describing the principal surveying instruments in use at the beginning of the eighteenth century. The quadrant he described had sight vanes along one straight edge and on the alidade attached to its apex, which permitted the observer to measure an angle up to 90° in the horizontal, as well as in the vertical plane. His "semi-circle" extended the quadrant's arc

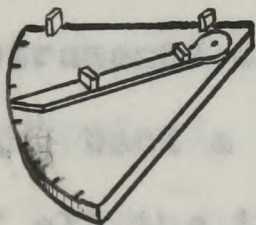
EVOLUTION OF THE THEODOLITE



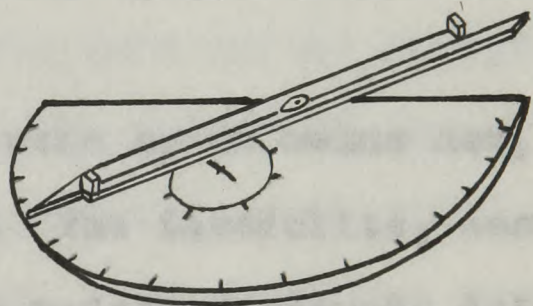
(1)
Geometrical Square
with plumb bob



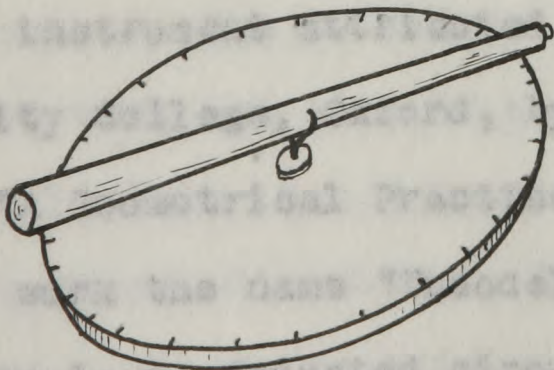
(2)
Geometrical Square
with alidade
and degree marker



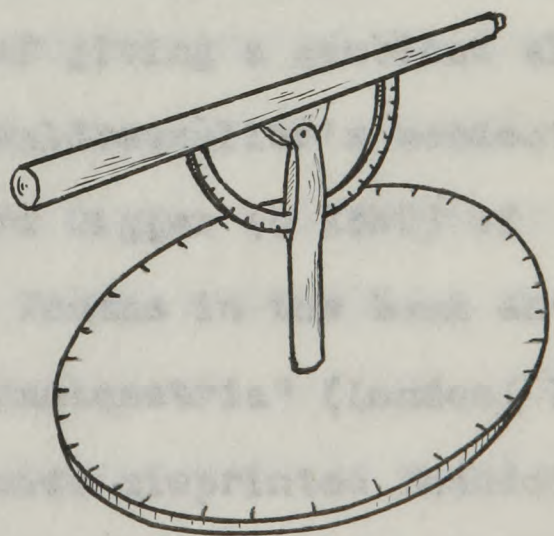
(3)
Quadrant



(4)
Semi-circle



(5)
Bion's "Theodolite"
measuring
horizontal angles



(6)
Final stage of theodolite
measuring
horizontal and vertical angles

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to 180° and became primarily a horizontal instrument. An alidade with sight vanes and a magnetic compass made the "semi-circle" essentially half the "theodolite" he described. This theodolite consisted of a simple telescope which rotated through 360° over a graduated circular plate. He also described a surveying cross which showed little difference from the Roman groma previously mentioned. Though Bion did not speak of the circumferentor, his English translator, Stone, did describe it in a separate section. This instrument, very popular throughout the eighteenth century, was another variation of Bion's "theodolite", where a sighting alidade was mounted directly over a magnetic compass, and readings were taken by measuring the angle between an object and magnetic north.

The instruments described by Bion were by no means new, most of them dating back a century and more. The theodolite, most important of all the instruments to the modern surveyor, dates back to the sixteenth century at least. An old woodcut accompanying a tract written by Waldseemüller and painted in the 1512 (Strassburg) edition of Reison's "Margarita Philosophica" depicts a "Polimetrum," an instrument capable of giving a combined altitude and azimuth. Closely resembling Waldseemüller's woodcut was the instrument attributed to Leonard Digges (c 1550) of University College, Oxford, by his son Thomas in the book entitled "A Geometrical Practise, named Pantometria" (London, 1571). In this work the name "Theodelitus" (twice misprinted Theodolitus) was given to a graduated circular plate which carried an alidade with sight vanes (the same instrument called a theodolite by Bion). Though the "Theodelitus" gave its name to the modern theodolite, it was the "Topographical instrument" of Digges which was the

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true ancestor of the modern instrument.

To form the "Topographical instrument" Digges simply joined a double "Quadrant Geometricall" in the vertical plane with a "Geometricall Square" and a "Theodelitus" in the horizontal plane. The earliest known example of this instrument, and therefore probably the oldest theodolite in the world, now rests in the Museum at Greenwich. It is dated 1574 and has inscribed upon it the name of its maker H. Cole, the foremost instrument-maker of the Elizabethan period. The instrument coincides in detail with that depicted by Digges and is in an excellent state of preservation. So well preserved, in fact, is the instrument that it may never have been used in the field at all.

A slightly later instrument, showing more of the ravages of time and possibly of use, is located at the Museum of the History of Science at Oxford. Clearly inscribed on its upper section are name and date, Humphrey Cole and 1586. Although the horizontal circular plate is missing, holding down brackets on either side definitely indicate that they clamped to a horizontal indicator which rotated through 360° . At the same level with the holding down brackets on the vertical center-line of the instrument is the compass box, directly above which hangs a small plumb line about an inch in length. Above the plumb, swivelled to a graduated vertical bar, is a graduated semi-circle with a radius of slightly less than 3 inches, which can rotate through 180° in the vertical direction. Within the semi-circle is a modified geometrical square containing Umbra Versa and Umbra Recta scales. The actual sighting bar runs along the flat part of the inverted semi-circle at a height of about 6 inches above the swivel base. Approximately 9 inches long, the bar contains open and peep

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sights, and is too long to be transited. Apart from the longer-sight bar which extends beyond the ends of the semi-circle, this instrument of Cole's appears in every way to have been the instrument described and illustrated in Digges' work, and, aside from telescopic sights, this device contains all the essential elements of the modern theodolite.

Almost a hundred years later Blaeu's Atlas of 1664 described practically the same instrument as the one devised by Digges. A much more modern version of the theodolite appeared in the appendix of John Hammond's "Practical Surveyor" (1749-50). Made by Heath of London, this instrument possessed four levelling screws, a telescope with cross-hairs, a level bubble, and vertical limb. The era of modern precision theodolites dates from about 1763, the time of the instrument maker Ramsden, whose instruments were used by General Roy in the first trigonometrical survey of England.

THE PLANE TABLE -- Laying out angles by direct observation and mapping in the field probably goes back to the Greeks, but the first description of a completely fitted out plane table goes back only as far as the sixteenth century. An early stage of this instrument was described by Abel Foullon in his "L'Holometre" (Paris, 1551). The table, which could be turned horizontally on a ball and socket device, had one edge divided into 1000 equal parts. At either end of this scale were placed graduated sight rules, one pivoted and the other able to travel along the base scale. Each of the side rules was furnished with a vertical semicircle mounted on a vertical rod (with sights and plumb line), and in the middle of the board was a compass inset.

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In about 1590 Cyprian Lucar in "A Treatise named Lucar Solace" described the plane table of Jean Praetorius (1537-1616), a mathematical professor in Wittenberg. This table was set on a portable tripod and was equipped with a magnetic compass, two alidades with sights, a plumb line, a plumb level, a levelling staff, a vertical scale for altitudes, apparatus for measuring a base line, and drawing instruments.

Similar to the table of Praetorius was the graphometre invented by Philip Danfrie of Paris in 1597. It possessed two alidades, one fixed and the other movable, both with slit and pinhole sights. The device was mounted on a portable tripod, possessing a ball and socket joint and hinge, and could be inclined to give vertical as well as horizontal angles. By the seventeenth century standard works on surveying included the plane table in with the description of other regular instruments. An early example was Aaron Rathborne's "The Surveyor, in Foure Bookes" (1616) in which he described the "playne table" along with the "theodolite" and "chaine."

LEVELLING AND ALTITUDE MEASUREMENT -- During the sixteenth and seventeenth centuries normal surveying instruments were adapted to the measurement of angles in any plane, a factor which encouraged indirect methods of calculating differences in elevation rather than direct levelling. With the rise of canal and aqueduct construction in the latter part of the seventeenth century, however, more precise measurements became necessary, and elaborate levels and telescopes were developed. Until this time some form of plumb line was sufficient to level an instrument. In

1661 Melchisedech Thevenot described a compact "air bubble in water" type of level, but his invention remained in obscurity for years because of the difficulty of accurate manufacture. Hooke in 1666 produced a new type of air-bubble water-level which was sealed at both ends. In his "Geometrie pratique" (1702) A.M. Mallet described several air levels, and Bion's work of 1723 was among the first to recommend the use of wine or spirit "not subject to freeze" in an air level. In the eighteenth century the air bubble rapidly superseded the cumbersome plummet and water levels, and in the following century, canal and railroad work saw the introduction of an instrument, not part of a theodolite, used purely for levelling.

A less precise method of levelling has resulted from the development of pressure measuring instruments. Five years after Torricelli invented the barometer Pascal used it (1648) in the Puy de Dome area, to investigate the diminution of atmospheric pressure with the increase in altitude, but the exact law was not determined for a hundred and fifty years. A slightly different approach to the problem was taken by Wollaston who in 1817, devised a boiling point thermometer. Gay-Lussac and Fortin produced important modifications to adapt Torricelli's instrument to the determination of altitude, but it was Vidie (1847) who finally developed the portable aneroid barometer.

OPTICS -- Though it appears that the first man to use telescopes for surveying was Picard (c 1666), it was the earlier invention of a special eyepiece by the German astronomer, Johannes Kepler (1571-1630), which made the telescope part of the surveying instrument. Of course, the telescope was no longer a new

thing by Picard's time. Burning glasses had been used by the ancients, and Roger Bacon in "Opus majus" (c 1265) indicated that he knew the principle of the telescope. Thomas Digges in "Pantometria" (1571) told of his father's use of lenses for telescopic purposes in the following words: "---, my father by his continual paynfull practises, assisted with demonstrations MATHEMATICALL, was able, and sundrie times hath by proportionall Glasses duely situate in convenient angles, not onely discovered things farre off, read letters, numbered peeces of money with the very coyne and superscription thereof, cast by some of his freends of purpose uppon Downes in open fieldes, but also seven myles of declared what hath been doon at that instante in priuate places:"

Despite the claims of Digges, however, it is generally recognized that the first commercial telescopes originated in Holland early in the seventeenth century. Three names, Zacharias Jansen, James Metius, and John Lippersney, are associated with the origin of refracting telescopes with concave eyepieces, and conflicting evidence makes it difficult to judge just who was first among them. Undisputed is the fact that Lippersney of Middleburg received 900 florins for one telescope on October 6, 1608. Information of the Dutch work became known to Galileo (1564-1642), who constructed a crude telescope with two lenses and a lead pipe in 1609, turned it toward the heavens, and brought about a revolution in astronomy.

Although the use of telescopes in astronomy became universal shortly after Galileo's discoveries, it was not until the eighteenth century that telescopes replaced sight rules in surveying.

The use of the telescope restricted the field of vision, and brought about vertical movement, in addition to the horizontal movement to which most theodolites had been limited previously. The latter half of the century saw a great increase in instrument precision which accompanied the tremendous interest in geodetic surveying. In the nineteenth century the trend was toward reducing the size of instruments without reducing their precision, and it was this period which saw the development of the transit principle in small and medium-sized theodolites.

AUXILIARY DEVICES -- The precision realized as the result of optical advances depended primarily, of course, on the mechanical measuring devices on the instruments. Mechanical improvements, which were spread over the centuries, appeared at an early date. Pedro Núñez (1492-1577), a Portuguese of the University of Coimbra, was the first to show (1542) how to subdivide an arc of moderate size with some degree of accuracy. His device, which he called a "Nonius," contained forty-four arcs inside and concentric with the graduated 90° scale of a quadrant. Each succeeding scale was divided into eighty-nine, eighty-eight, eighty-seven, etc. parts. Tycho Brahe (1564) used a cross-staff divided by dotted transverse lines which gave a finer degree of accuracy than could be obtained with a scale marked out on a line coincident with the edge of the instrument, but it is probable that the method was used prior to his time. In 1631 Pierre Vernier published a paper on the scale which still bears his name. In the original instrument, designed for use with the quadrant, thirty divisions of the vernier scale were equal to

thirty-one divisions of the quadrant scale, which was divided into half degrees. With this device degrees and half-degrees could be read from the quadrant, and the remaining minutes from the vernier. Gascoigne of England used yet another fine measuring device, the thread micrometer, as early as 1640.

A different type of auxiliary device was the heliotrope devised by C.F. Gauss. In 1818, while observing at Luneburg, a station of the Altona-Hamburg meridian arc, Gauss noted that windows lit by the setting sun facilitated the directing of his theodolite. This suggested to him the sextant-heliotrope which he made in 1820. Most of the other improvements to the basic instruments have been relatively minor, more the result of improved technique of the instrument-makers, rather than the development of any new fundamental concepts.

understood photographically "the axis circumscription" in 1842

Fox Talbot patented a Photogrammetry picture by exposing paper coated with silver iodide

EARLY DEVELOPMENTS IN PHOTOGRAPHY -- A relative of the camera obscura was mentioned as early as the fifteenth century by Leonardo da Vinci, but it was not until the nineteenth century that any real progress was made in the field of photography. By 1802 Thomas Wedgwood and Humphrey Davy succeeded in printing silhouettes on leather sensitized with silver nitrate, but without fixation. About 1813 or 1814 Joseph Nicéphore Niépce of Châlons began his experiments on different means of direct photography. It appears that he had, by 1826, succeeded in producing some fair engravings on tin sensitized with bitumen. Experiments along the same lines as Niépce were begun by L.J.M. Daguerre

about 1824, and in 1829 the two men entered into partnership. Following the death of Niépce in 1833 Daguerre persisted in the research which finally resulted in the production of the famous Daguerreotype. He had evolved a method of direct photography on a plate of silver superficially converted into silver iodide, where the subsequent development of the latent image was accomplished by mercury vapor. His process was patented in England on August 14th, 1839, and five days later it was explained publicly in Paris and given free to all the world except England.

In the same year John F.W. Herschel recommended in a paper to the Royal Society the use of hyposulphites for fixing; as early as 1819 he had discovered the hyposulphites and their property of dissolving silver chloride. Herschel introduced in the next year the terms "positive" and "negative" as they are now understood photographically "to avoid circumlocution." In 1841 Fox Talbot patented his Calotype process wherein he obtained a picture by exposing paper coated with silver iodide and sensitized with silver nitrate and gallic acid; it was developed with the same materials and fixed by sodium thiosulphate. Niépce de Saint Victor made the first negatives on glass by an albumen process in 1847, and in the following year Edmund Becquerel made the first attempts with color photography. The next advance in photography was the use of collodion as a substratum for the silver haloid instead of albumen. Its use was first suggested by Gustav le Gray in 1850, and in the following year F. Scott Archer made it available in a practicable form. Soon after the collodion wet plate had appeared attempts were begun on a dry plate process. Collodion dry plates were attempted by Taupenot in 1855, and by graphic arts. He completed the mathematics of converting

1861 Colonel Russell had developed a really useful method. His first conception of the utilization of terrestrial
 TERRESTRIAL PHOTOGRAPHY -- Older than photography itself is photogrammetry, the science of measurement from photographs. As early as 1435 Leone Battista Alberti used a frame covered with threads, through which he viewed the landscape and sketched. The scientific fundamentals of photogrammetry, being the converse of the principles of perspective, were known by the seventeenth century, but were not applied cartographically until about 1794. In that year the hydrographer Beautemps-Beaupré utilized these fundamentals in connection with a series of survey sketches of the coastal regions of Tasmania. Because of the skill necessary in making the free-hand sketches, however, the method never achieved any measure of popularity.

In 1832 Wheatstone began experiments with stereoscopy which resulted in the construction of the first modern mirror stereoscope in 1838. Following the prismatic stereoscope of Brewster (1844) Abbé Moigno began his work (c 1850) with stereoscopic photography. Shortly before this time Arago, of the French Academy of Science, had demonstrated the application of photography to topography, architecture, and archeology, a study which was taken up in detail by Meydenbauer in 1858. Of great significance at this time were the works of Porro who, in 1853, established his principle of observation through lenses.

Photogrammetry as we know it may properly be said to have begun (c 1852) with Captain Aime Laussedat, an officer of the Corps of Engineers of the French Army, who crystallized the idea of utilizing terrestrial photography in the compilation of topographic maps. He completed the mathematics of converting

overlapping prospectives into orthographic projections on any plane. His first conception of the utilization of terrestrial photographs consisted of replacing the plane table with photo-theodolites by means of which image points could be intersected in space. An outstanding example of his practical work was the survey of Buc and environs near Versailles in 1861.

From France the idea spread to Canada, then Austria, Germany, and England. Captain Deville, Surveyor-General to Dominion Lands, introduced the method to Canada in 1888, and joint operations in Alaska in 1893 led to its adoption by the United States Coast and Geodetic Survey.

Once the method had become established, an improvement of instruments followed soon after. The photo-theodolite with an eccentric telescope, invented by Paganini, was constructed by the Officine Galileo at Florence in 1884. Five years later Paganini developed his photo-theodolite for precision surveying, which made use of the camera lens as an objective for pointing the telescope. In 1896 the invention of the first automatic plotting instrument by Deville in Canada opened the field for better utilization of photographs obtained by means of the photo-theodolite.

Credit for conception of the idea of stereoscopic telemetric measurement is generally attributed to Hector de Groubilliers of Charlottenburg, and it is probable that the first stereographic surveys were made in Austria with the stereocomparator of Pulfrich. In 1894 Colonel Von Hubl, chief of the topographic section of the Geographic Institute (Austria), adopted the methods of Laussedat to work in high mountains, and through his

by the Egyptians, Greeks, and Romans, but its use was largely

efforts the stereocomparator became a recognized instrument of industry (1903). Shortly thereafter, Lieutenant von Orel of Vienna transformed the stereocomparator into a drawing instrument and developed the stereo-autograph (1906).

AERIAL PHOTOGRAPHY -- The development of the airplane, with its facilities for covering wide areas rapidly, has relegated terrestrial photogrammetry to obsolescence. Probably the first attempt to photograph from the air was made from a captive balloon by Nadar at Paris in 1858. He was unsuccessful, however, for his collodion plates were unsuitable for the task. Tissandier and Ducom used gelatin plates and were rewarded with good results at Paris in 1865. A method of map-making from photographs taken from balloons was patented in the United States by Adams in 1893, but the first comprehensive use of aerial photographs was made by the Japanese in their Manchurian campaign of 1904. In the early days not only balloons, but kites as well, were often used to take cameras with sails aloft.

The strides taken in the development of the airplane have been matched by advances in photographic instruments and technic, and have resulted in a greater application of photogrammetry than has ever been known before. For economy and speed in mapping large areas the aerial photogrammetric method has yet to meet its match.

Advances in the airplane industry were largely theoretical, but the developments in the Summary development in the science of measurement which marked the real beginning of geodesy.

An elementary type of plane surveying was known successively by the Egyptians, Greeks, and Romans, but its use was largely

confined to the staking out of boundaries and public buildings. The early interest developed by the ancients in astrology and astronomy probably had the greatest influence on the subsequent development of surveying, for the early surveyors derived their instruments from the astronomers. In the Dark Ages the Arabs preserved much of the scientific knowledge of the past and added contributions of their own in the fields of astronomy, geography, mathematics, and instrument making. This knowledge was passed on to the medieval Europeans who utilized and expanded it during the great exploration period of the Renaissance.

Most of the surveying done during the Renaissance was nautical in nature, and was, therefore, more concerned with the measurement of vertical rather than horizontal angles. Variations of the quadrant derived from the Arabs, appeared in the hands of seamen, and these devices such as the cross-staff, back-staff, and cross-bow were used well into the eighteenth century, when the octant and sextant replaced them. Another Arabian heritage, an interest in geometrical and trigonometrical problems, brought forth, especially in the sixteenth century, many treatises on angle measuring instruments and the calculation of distances therefrom. If we may judge from old prints, much of the interest in angular computation was stimulated by a desire to lay cannon for accurate fire. Similarly, fortifications and their construction were the subject of many treatises.

Advances in the sixteenth century were largely theoretical, but the seventeenth century saw a development in the science of measurement which marked the real beginning of geodesy. Vertical angle instruments were turned into the horizontal plane and particular attention was drawn to direct measurement methods.

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Triangulation, the great arc measurements, and the telescope were all developments of this century. and geodetical surveys.

The telescope soon replaced the sight bar, and the bubble level replaced the plumb level on precision instruments during the first half of the eighteenth century. The restriction of the field of vision by the inclusion of a telescope necessitated freeing the theodolite for vertical as well as horizontal motion. Though this principle had been used in the sixteenth century theodolite of Digges, most instruments made just prior to the introduction of the telescope into surveying work were restricted to motion in one plane. Precision instruments, such as those made by Ramsden, were an outstanding feature of the latter half of the century, and made a great contribution to the accuracy of the initial government geodetic surveys which continued well into the nineteenth century.

Canals, railroads, and the settling of new lands created a demand for surveying in the nineteenth century which had never before existed. One result of this demand was the construction of smaller and more compact instruments which retained, or improved upon, the precision of their larger predecessors. During the latter half of the century photogrammetry began to enter the field, and the twentieth century's airplane fully established this new science as an important branch of surveying.

Thus the art of surveying has kept pace with the times as a very important adjunct of engineering and science. Derived from many sources such as astronomy, mathematics, optics, metallurgy, chemistry, and aeronautics, its importance can be more readily appreciated by noting the many branches into which it may

be divided, e.g. geodetic triangulation, levelling, nautical, cadastral, engineering, topographical, and geographical surveys.

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FOOTNOTES

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Chapter VIII

WATER SUPPLY

Indians of the Chase **WATER SUPPLY** from the leaves of 398
agave plant. Pre-Roman Times

A kind of natural supply and artificial storage combined
NATURAL SUPPLIES -- Early man solved his potable water supply
problem by settling immediately next to some natural source
such as a stream or river, spring or pond. Some idea of how
he conveyed the product from the source to his hut for cooking
or drinking purposes may be gained by observing primitive
tribes in various parts of the world today. Apart from scoop-
ing the water up with the hands, the carrying of water in skins
appears to be almost universal and probably dates from very
early times. In the Congo men still carry water in calabashes;
coconut shells are used in the Solomons, and Australian ab-
origines use sea shells or bark. Organ-pipe-like rows of
bamboo, gourds, ostrich eggs, clay-lined baskets, and pottery
are other modern indications of life in early times, but many
of these picturesque containers have been replaced by tin cans
where "civilization" has made its mark.

Just as springs, rivers, and streams were nature's exam-
ples of a distribution system, so too were water holes and
natural pools the forerunners of tanks, cisterns, and reser-
voirs. In times of drought early man was driven to scoop out
the river bed to maintain his water supply, a step which even-
tually led to more adequate conservation measures. The natural
sequel to the ordinary water hole was the excavated pit, but
other storage methods evolved as well. Even today in the pro-
vinces of Kordofan and Dafur in the Sudan, natives still store
water in the curved out trunks of baobab trees, and the Lengua
very primitive method of doing this was accomplished by two

Indians of the Chaco collect water from the leaves of the caraguala plant.

A kind of natural supply and artificial storage combined is represented by the "dew" or "mist" ponds on the hills of southern England. Whether some of these ponds date back to Neolithic times or not is debatable, but there is little doubt that many of them are centuries old. Probably the most perfect example of its kind is the one at Worthing, a shallow bowl-shaped hollow disk excavated in chalk, about 60 or 70 feet in diameter. It has been lined with dry straw or reeds, puddled with clay, and strewn with stones on the clay surface. In common with other ponds of its type it is not spring fed nor does dew play an important part in filling it, but it is filled by rainfall and the moisture from low lying clouds and mists.

EARLY WELLS -- Many of the "wells" of early times were untouched pools or springs, so despite several biblical references, it is difficult to ascertain just when man began constructing them. Their origin probably springs from the custom of scooping out a river bed in a drought to reach the water table. To date we know that regular wells were constructed at least five thousand years ago, for the excavations at Chandudaro, Sind, have revealed a circular well with fine brickwork dating back sometime around 3000 B.C.

EARLY PUMPING DEVICES -- It is probably that the first devices for raising water from one level to another were used for irrigation rather than for domestic water supplies. A very primitive method of doing this was accomplished by two

men swinging a basket between them, scooping the water out of the river and dumping it into furrows on an adjoining field. An improvement on this method was accomplished when the "shaduf", still to be seen in Egypt, was introduced. This machine-- probably in use as early as the sixteenth century B.C.-- consisted essentially of an upright post with a movable cross-piece, having a counter-weight hung from one end and a water vessel from the other. Neuberger in his "Technical Arts of the Ancients" stated that in the seventh century B.C. in Nineveh, three persons working the machine could raise three cubic meters of water an hour.

The date of the "Saqiya," or Persian wheel, is uncertain, but Vitruvius describing it in the first century B.C. did not seem to regard it as anything new. Animals or men acted as the prime mover by turning a huge horizontal wheel whose projecting spokes engaged those of a vertical wheel. Attached to the same horizontal axis as the second wheel was a third, sometimes 10 feet in diameter, around whose periphery (top half) moved an endless chain of buckets which would scoop the water from a depth and empty it on a trough at a higher level.

Another early device, the link chain pump--attributed by some to the ancient Chinese--consisted of an open trough with pieces of wood fitting full width which pushed water before them in the manner of a continuous conveyor. The water screw of Archimedes (287-212 B.C.) was described by Vitruvius, and Diodorus Siculus mentioned its use in connection with pumping out the mines of Spain. Yet another early device was the leather bucket, hauled up with a rope and pulley arrangement

by an animal who walked down a sloping incline as he pulled the rope. At Ras-el-Ain, near Tyre, consisting of four octagonal towers containing deep wells.

NORTHERN AFRICA AND THE NEAR EAST -- Although we know something of irrigation in Egypt, the evidence concerning organized domestic supplies of water in that country is very meager. One well-known bit of antiquity is Joseph's Well at Cairo, drilled through solid rock to a depth of 297 feet. It was constructed in two lifts, the upper section being 165 feet in depth and measuring 18 by 24 feet, and the lower section measuring 9 by 15 feet. Access stairs were made to the first level where mules operated an endless bucket chain.

Certain archaeological finds have suggested the existence of organized water supplies other than irrigation at an early date. Among these may be included the square bath at Gaza, dating possibly to the third millenium B.C., and the palace bathroom at Mari, Syria, (c 2000 B.C.) which was served by a large tile drain running beneath the doorway. At Nippur in Chaldea pipes of baked clay with bends and tees have also been uncovered.

Jerusalem's most famous ancient water system, the tunnel from the Virgin's fountain to the pool of Siloam, might possibly have been the work of Hezeniah (late eighth and early seventh century B.C.) who is said (II Kings xx 20) to have "made the pool and the conduit, and brought water into the city." Though the straight line distance between the two points is only 1100 feet, the actual tunnel, now varying from 2 to 11 feet in height, winds and has a length well over 1700 feet. Another

ancient waterworks, attributed to the Phoenicians, has been discovered at Ras-el-Ain, near Tyre, consisting of four octagonal towers containing deep wells.

At a much later date (c 332 B.C.) Dinocrates, engineer of Alexander the Great, included a water system in the layout of Alexandria. An underground conduit built of stone and lined with cement was led from the Nile to private reservoirs in the city, and the story is told that Ganymed, the Alexandrine general, turned salt water into these aqueducts when Caesar occupied the place. Reservoirs found at Carthage indicate that it, too, enjoyed the advantages of an organized water system. One great public reservoir near the sea was found to measure 37 by 139 meters, being divided into eighteen compartments opening onto a common corridor. The compartments measured nearly 20 by 100 feet, with a height to the crown of the vault of approximately 27½ feet, and it has been estimated that they could hold four million gallons of water.

ANCIENT GREECE -- Numerous springs no doubt account for the few bulk supplies of water from a common source in Greece, for all evidence points to the fact that the Greeks did know how to organize a distribution system when the need arose. On Crete in the Palace of Minos at Knossos terra cotta pipes about 2½ feet long with cement joints (c 2000 B.C.) have been found, embodying the bell and spigot principle. Each pipe was tapered, a projecting flange or lip protruding a short distance from the smaller end. Excavations at other sites in ancient Greece have revealed that the use of clay pipes for water supply

was fairly extensive, and that some were even glazed on the inside.

Extensive operations for bringing water to a city ^{were} accomplished as early as the sixth century B.C., for it was during that century and possibly earlier that Eupalinos was employed by Polycrates of Samos to bring water to the city of Vathy. The tunnel constructed for this job measured approximately 8 by 8 by 4200 feet and contained a second cutting 3 feet broad and "20 cubits" deep. At about the same time Athens received a supply from the hills which was distributed throughout the city in stone block channels laid dry below ground. Excavations have indicated that Olynthus had an elaborate supply from mountains 10 miles away as early as the fifth century B.C. Terra cotta pipes in a subterranean tunnel 4 feet 7 inches high have been discovered at intervals, and similar pipes found in the hill to the north indicates that long distance piping was involved.

A long distance high-pressure supply was enjoyed (c 200 B.C.) by Pergamum in Asia Minor, whose reservoir stood at a height of 1220 feet on Mt. Hagios Georgios. From this reservoir the water was conducted through pipes--whose material is subject to guess at this date--over lower intervening ground to a cistern at an elevation of 359 feet. The pipes were led through rectangular stones pierced with circular holes about 1 foot in diameter, standing about 4 feet apart in a trench.

The Aqueduct of Patara in Syria was another pressure system which crossed a 200-foot ravine with an inverted siphon, originally made of earthen pipes and later of bored stone

blocks. Each block measured approximately 3 cubic feet with a bored diameter of about 13 inches, and had a projection and recession which made a type of bell and spigot joint. The blocks were united by iron clamps and run with lead, and the joints were sealed with cement. Air holes 7 inches in diameter were inserted at intervals of 20 feet. Similar to Patara was the Aqueduct of Laodicea in Asia Minor which conveyed water across a valley by means of two stone pipe siphons, about 8 and 10 inches in diameter, under a pressure of about 60 pounds per square inch. Other late Greek pressure supplies have been found at Methymna, Catania, Selinus, and Syracuse.

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 and Carian springs, and also wells, which brought water

The Romans

THE AQUEDUCTS -- Despite archaeological finds the scarcity of written records on the subject of water supply prior to Roman times renders tracing its early development difficult. The task is lightened when we come to Rome, however, for Sextus Julius Frontinus (c A.D. 35- c 104), who became the Water Commissioner of Rome in A.D. 97, set forth in his "De Aquis" an account of the then current water situation and a brief history of public water supplies in Rome. According to Frontinus, the citizens of Rome, for the first 441 years after the founding of the city, satisfied their water needs privately from the Tiber and from wells. Then, in 312 B.C., Censor Appius Claudius, builder of the famous Appian Way, brought the first public water supply to Rome from the Lucullan estate, some 7 or 8 Roman miles away, (Roman mile = 1616 English yards)

by means of a conduit over 11 miles in length. All but approximately 100 yards of this aqueduct was underground, and, indeed, the length below ground of all succeeding Roman aqueducts always exceeded the exposed portion on arches.

Following Anio Vetus (272 B.C.) came the third aqueduct Marcia (146-140 B.C.), which was the first to have a considerable portion of its length (of almost 62 Roman miles) on arches. Restorations and the additions of Tepula (127 B.C.), Julia (33 B.C.), Virgo (21 B.C.), Alsietina (A.D. 10), Claudia (A.D. 38), and Anio Novus (A.D. 50) brought the number of aqueducts supplying Rome to nine in the time of Frontinus. Probably the two most important of these aqueducts were Claudia, second only to Marcia for the quality of water it brought from the Caerulean and Curtian springs, and Anio Novus, which brought river water from 42 Roman miles away.

Other aqueducts were added to the system after Frontinus, but most of the conduits were broken when the city was besieged by the Goths in A.D. 537. Partial restoration by substitution of underground conduits for overhead arches was begun in A.D. 776 by Pope Adrian I, but the system never again reached its old perfection. In 1870 an English company tapped the sources of the Marcian aqueduct above Tivoli and brought in a supply in modern pipe. Three others of the old aqueducts are still functioning today, the Acqua Vergine (Aqua Virgo), restored 1570, Acqua Felice (part of Alexandrina, A.D. 226, restored and altered by Sextus V in 1585), and Acqua Paola (restoration of Trajana, A.D. 109, by Pope Paul V in 1611).

Throughout what was once the Roman Empire stand many

edifices, nor were they any indication that the Romans were monuments which testify to the hydraulic skill of the Roman ignorant of the fact that water will flow uphill to the level of the engineers. Largely because of the remaining arched sections of aqueducts the word "aqueduct" is often used in the special sense as a bridge rather than in its more general sense as a water conduit. It is probable that the remains of more than two hundred of these old Roman aqueducts are still extant. Prime among these is Agrippa's Pont du Gard, near Remoulins, which was damaged by the barbarians in the fifth century A.D. but repaired in 1743. The structure itself is only a small section of 25 1/2 miles of conduit, mostly underground, which was used to supply the French city of Nîmes from the Eur and Airon rivers. Three tiers of arches with spans measuring approximately 80, 63, 51, and 11 1/2 feet support the water channel, 4 feet in width and almost 5 feet in depth.

Constructed in the time of Trajan, the famous Devil's Bridge of one hundred and nine arches at Segovia, Spain, was restored by Queen Isabella in the fifteenth century to bring water from the River Frio 10 miles away. Near Carthage the aqueduct of Zaghounen, erected in Hadrian's time, has had a long and exciting existence, being wrecked by the Vandals, restored by the Byzantines, demolished by the Spaniards, and used in part again by the Bey of Algiers in the nineteenth century. In Istanbul the aqueduct of Valens, also dating from Hadrian's time, was rebuilt by Valens, the Roman Emperor of the East, in the fourth century A.D., and restored by Sulieman the Great in the sixteenth century.

These spectacular bridges were not the result of a desire on the part of the Romans to awe the world with striking

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edifices, nor were they any indication that the Romans were ignorant of the fact that water will rise again to its own level. The truth of the matter is that where they constructed their arches, the Romans had no material which could economically be used to contain the high heads which would result if deep inverted siphons were used. This siphon type of construction was known, of course, for Rome itself was honeycombed with hundreds of relatively shallow inverted siphons, and evidences of other inverted siphon systems have been found throughout the Empire. Notable among these were the three sets of inverted siphons crossing valleys near Lyons, built in the time of Claudius (10 B.C. - A.D. 54). Typical of the group was the aqueduct of Mt. Pilate over the Garonne Valley. Nine lines of lead pipe $8 \frac{5}{8}$ inches in diameter and $1 \frac{3}{5}$ inches thick were laid in lengths of 18 to 20 feet. The rising ends were carried on masonry at an angle of approximately 45° , and at the middle of the slope the number of pipes was increased to eighteen, while their diameters were reduced to $6 \frac{5}{8}$ inches.

Lead was chosen for high pressure. The pipes were at times
PIPES -- Pliny noted the most convenient method of conveying
water to be by earthen pipes, but "Where the water is wanted to ascend aloft, it should be conveyed in pipes of lead: water, it should be remembered, always rises to the level of its source." Vitruvius also had a word to say on inverted siphons by cautioning that extensive valleys should be crossed by directing the course of the conduit down, and continuing level at the bottom as long as possible to avoid bursting the pipes. He also recommended clay pipes as being easier to repair and

not harmful to the human system, whereas he was suspicious of the effect of white lead which was derived from lead.

Many lead pipes have been found in Rome, up to 27 inches in diameter. They were made of sheet lead folded into an oval or ovoid tube soldered along the edge and usually came in 10-foot lengths. Thicknesses increased to as much as 1½ inches on a 5-inch diameter.

More common, however, were the cylindrical earthenware bell and spigot pipes, jointed with a mixture of quicklime and oil. When the pipes were first laid, it was the practice to send through ashes mingled with water to seal the cracks. Examples of this type of pipe have been found in various spots throughout the Empire, in Arles, Nîmes, and Cheshire, to name only a few. Typical specimens found at Folkestone measured 2 feet 10 inches in length, 3½ inches in internal diameter, and 6 inches in external diameter at one end, and 4 inches at the other.

Wood and stone were also used occasionally for pipe material, as was bronze for high pressures. In the museums at Rome and Naples are many fittings dating from the Roman period, such as four way branches, brass stop cocks, wipe joints, bronze spouts, and bronze and marble bathtubs.

ELEMENTS OF ROME'S SYSTEM -- Selecting a source of good water was, of course, a very important operation which entailed careful observation. Vitruvius observed that water was probably good if (1) the general health of the people living near the source was good, (2) the water could be sprinkled into a

Corinthian vase or other sort of good bronze without leaving a spot, (3) the water could be boiled and then poured off without leaving sand or mud, (4) green vegetables could cook in it quickly, (5) the water was clear and moss and reeds were absent when it was flowing. Waters flowing into Rome were kept separated when there was a great difference in purity, so that Marcia was used only for drinking purposes while Anio Vetus was used for such tasks as washing clothes.

We have little evidence that Rome's water was treated, though settling tanks were usually placed near the middle and at the ends of aqueducts, and "piscina" performed a kind of filtering operation by catching pebbles to keep them from clogging the pipes. Private treatment was no doubt used on occasion for Pliny tells us that "It was the Emperor Nero's invention to boil water and then enclose it in glass vessels and cool it in snow. ----Indeed, it is generally admitted that all water is more wholesome when it has been boiled."

The water--brought into the city in elevated troughs of brick or stone lined with cement and covered with coping-- usually ran in the trough directly, but sometimes it ran in pipes of lead or terra cotta laid in the trough. In the time of Frontinus five of the aqueducts had sufficient head to supply any part of the city, but illegal tapping sometimes disrupted the system. In the words of the water commissioner himself, "The cause of this is the fraud of the water men, whom we have detected diverting water from the public conduits for private use; but a large number of proprietors of land also, whose fields border on the aqueducts, tap the conduits; whence

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it comes that the public water courses are actually brought to a standstill by private citizens, yea for the watering of their gardens."

Most of the water brought to the city went to public fountains, from which people carried it to their homes. Supplies were also piped to private residences through lead pipes, which, by law, had to have the same size as the tapping for a distance of 50 feet. Though Strabo and Vitruvius both wrote of water wheels, and Vitruvius further discoursed upon the tympanum, water-screw, and pump of Ctesibius, we have no evidence that Rome's water supply was anything but gravity-fed. After examining the ground and Frontinus' writings closely, ¹⁵ Herschel has come to the conclusion that the nine aqueducts delivered within the walls of Rome in A.D. 97 a quantity of 38,000,000 gallons per day, plus or minus 20,000,000 gallons depending upon certain factors such as the time of year. Based on a population of a million, this means that the Roman engineers supplied 38 gallons per capita per day, a figure not uncommon in European cities of the twentieth century.

The Middle Ages

EARLY POST-ROMAN PERIOD -- Sixth century Byzantium under Justinian witnessed the last flash in the twilight of Roman constructive genius in the erection of two great cisterns. The two-storied Hall of a Thousand and One Columns (A.D. 528) was built with a floor plan measuring 60 by 70 yards, and its domed roof was supported by sixteen rows of fourteen columns

each. Built by Constantine and improved by Justinian, the Yeri Batan Serai contained three hundred and sixty-five marble columns in twenty-eight rows, 12 feet apart, each column being over 40 feet high. When the Goths broke the Roman conduits in A.D. 537, however, an epoch of water supply engineering was brought to an end. Though Theodoric, with the construction of the aqueduct of Spoleto (A.D. 541) and other works, attempted to revive the municipal supply, the population was forced to return to the use of wells and local sources. Pope Adrian's efforts to restore the Roman aqueducts in the eighth century were only partially successful, as were the sporadic attempts of his successors.

During the Dark Ages the Moors had some municipal supplies, though it can hardly be claimed that their works approached the extent and utility of the Romans. In the eighth century Caliph Hisham had installed in his winter palace in the Jordan Valley a subterranean bath hall which received water through pottery

pipes. At the end of the following century the engineer Ibn Katib al Faighani, in carrying out the plans of Sultan Ahmed of Egypt for building the new city of Cairo, sank a well in the southern desert and brought the water into the city in an arched conduit. Evidences of cisterns of an early date may still be found throughout the Arab world.

Further north the strongest Norman castles had wells right in the last stronghold. An early example is the Tower of London whose well was in the basement, but later castles often had the well-head carried to the first story.

THE MONASTERIES -- As with other branches of knowledge, engineering found its medieval spiritual home in the monasteries of Europe. Prosaic underground sewers and occasional large water channels in these monasteries were no doubt the basis for the more romantic "underground passage stories" of medieval times. The earliest plans for a water supply extant are those of the Benedictine Priory of Christ Church, Canterbury, carried out by Prior Wibert in 1160. Wells already existing in the cloister infirmary and outer cemetery were used for reserve and the main supply was brought from springs three-quarters of a mile from the monastery. The water was brought to a circular conduit house, thence through a perforated plate which caught large impurities, and on through five settling tanks. It then crossed the moat on a bridge, penetrated the city wall and entered the monastery, where it was conducted underground to various points such as lavatory basins.

Another early system was the Parisian aqueduct of Pres-Ste. Gervais, which was in existence by 1182 for the purpose of supplying the Abbey of St. Laurent, or St. Lazare. At Southampton in 1290 the Franciscans received a grant to enclose the fountain of Colwell, and twenty years later they gave the use of their surplus supplies to the town. Also of early origin was the Beaulieu Abbey--founded by the Cistercians in the thirteenth century--where earthenware pipes approximately two feet long, collared lead pipe, and a three-sided wooden conduit have been discovered. And at Exeter a well preserved medieval water system, ecclesiastic but not monastic, has been explored

seven years the line of the stream is "permanently" by the

at length by the Devon Archaeological and Exploration Society.

Documentary history here begins with a grant in 1226 of one-third of the water from St. Sidwell's Well, some distance outside the east gate of the city, to the Priory of St. Nicholas. The tunnels carrying the water were cut in rock lined with stone to a great extent, (presently) varying in height from 3 feet 4 1/2 inches to 14 feet 9 inches, and in width from 1 foot 7 inches to 3 feet. These tunnels acted as unlined conduits, and "dipping" places, provided at intervals, acted as final distribution points.

About the middle of the fourteenth century a piped supply was introduced. Ovoid lead pipes on private lands dating to the fifteenth century have been found, measuring 2 5/8 by 3 1/2 inches in outer diameter and 1 15/16 by 2 inches internally.

In the fourteenth century the Franciscans brought supplies into Chester, Grantham, and Lincoln, among other places, and built primarily for irrigation. all Europe was dotted with the efforts of the engineer church-day towns like Korman from 20 miles away, and from 20 miles away, at a depth below the ground which exceeds in fact the ecclesiastics, and toward the latter part of the Middle Ages most construction passed out of the hands of the clergy into those of their lay successors.

LEATS AND KANATS -- Leats, or open channels, were often used as a source of water supply in medieval times, especially in the west of England. In the middle of the thirteenth century Tiverton, Devon, got water rights to certain springs 5 1/2 miles to the north, rights which still hold. A good section of the open channel may still be seen in Castle Street, and every seven years the line of the stream is "perambulated" by the

good folk of the town to assert the ancient rights.

The name of Sir Francis Drake as probable agent for a water corporation is associated with the 17-mile leat (1590-91) which formed Plymouth's water supply for three hundred years. In the town itself the water was run through wooden and lead pipes, and wealthier inhabitants had their own private supply. On special occasions, such as at the Restoration, the conduits supplied wine instead of water.

In Persia and in Syria some of the kanats--subterranean conduits running from the mountains--are at least seven hundred years old, and some have been in the same family for three hundred years. These tunnels, often lined with oval hoops of baked pottery and provided with air holes at intervals, are, and have been, the property of private individuals, who appoint maintenance men and turn-cocks to keep the service functioning. Though built primarily for irrigation, the kanats also supply to this day towns like Kerman from 20 miles away, and Yezd from 50 miles away, at a depth below the ground which exceeds 80 feet in some places.

WELLS AND FOUNTAINS -- Little need be said here concerning wells other than that they were, in general, the main urban "Waterworks" of the medieval period. The history of improved wells up to this time had been a long one, for, according to Mr. Parsons of the American School of Classical Studies (1939),¹⁶ the first lined wells in Athens appeared in the fourth century B.C. This lining was made of terra cotta drums in sections, and sometimes possessed leaded joints and hand holes. Rome had

few wells at the height of her power, but isolated houses in the country had them, and Pompeii had one drilled through solid rock 5 feet wide and 116 feet deep. During the Middle Ages many wells--because of their curative powers, real or supposed--gained a reputation as "holy" or "wishing" wells. Thus they developed a spiritual significance as well as a physical one--a significance which really traced its origin back to pagan days. Wells probably reached their zenith from an aesthetic standpoint in Italy from the fourteenth to the sixteenth century. During this period wells, fountains, and cisterns were decorated with ornamental stone, and the foremost architects and sculptors of the day found the adorning of these utilitarian objects worthy of their greatest attention. This attention to the aesthetic side of water supply did not confine itself to the Renaissance Mediterranean world but spread further north to Switzerland, Tyrol, Germany and what is now Czechoslovakia.

Early Modern Beginnings

LONDON -- Though London was not the first modern city to get a public water system, its influence on the subsequent development of other systems has rendered its position of prime importance in the history of water supply. Much of our information on London's early days is derived from J. Stow, whose "Survey of London," first published in 1598, contained many interesting additions in its 1633 edition. The Anglo-Norman chronicler William Fitzstephan had stated, said Stow, that for

Bridge remained in existence until 1831, being finally destroyed two hundred years after William the Conqueror Londoners had supplied their water needs privately from rivers, springs, wells, and ponds, the most famous of the wells being Holy Well, Clarkes Well, and Clement's Well on the outskirts of the city. These waters declined, however, so "they were forced to seek fresh waters abroad; whereof some, at the request of King Henrie the third, in the 21 yeare of his reigne (1236), were (for the profit of the Citie, and good of the whole Realme thither repairing; to wit, for the poore to drink, and the rich to dress their meat) granted to the Citizens, and their Successors, by one Gilbert Sanford, with liberty to convey water from the Towne of Teybourne, by pipes of lead into their Citie." Stow goes on to tell us that the first cistern of lead castellated with stone, the Great Conduit in Westcheap, was begun in 1285 when Henry Wales was mayor, and that several "conduits" (cisterns) were built throughout the city between 1285 and 1610. These conduits were, in later times at least, cisterns with running overflows, usually under cover.

In 1582 Peter Morice, a Dutchman, installed under one of the arches of London Bridge an undershot waterwheel arrangement with which he amazed the population by pumping Thames water over the steeple of St. Magnus the Martyr. He was allowed to install a second wheel under another arch, and soon five arches were being used to give London its first pumped supply. The water was pumped to a high square tower at the bridghead from whence it was distributed by gravity. Morice's franchise, which was to last five hundred years, actually remained in his family until 1701, and the works under London

Bridge remained in existence until 1831, being finally abolished when the old bridge was destroyed in accordance with an Act of Parliament of 1822.

Although Queen Elizabeth and King James had previously granted Acts for the conveying of water to London from a distant source, no concrete action was taken until Sir Hugh Middleton, "Citizen and Goldsmith of London," formed the New River Company early in the seventeenth century. According to Stow, the construction period lasted from 1608 to 1613, during which time waters were drawn from the Chadwell and Amwell near the town of Ware and conducted in an open ditch some 38 1/2 miles long to a reservoir in London. Much of the original ditch, which measured 4 feet in depth and 10 feet in width, still exists, but it has been shortened to 28 miles by the elimination of many twists and turns. Thirteen wells along the way augmented the supply which originally totaled 13,000,000 gallons per day and which was subsequently doubled. The New River Company remained in existence as a private concern until 1904 when London's Metropolitan Water Board took over its functions.

Before the seventeenth century private services were few, most individuals carrying water from the neighborhood cistern or buying it from a water carrier. By 1720, however, practically every house in London renting for £ 15 or £ 20 had a private supply, as did many tenements, and by the middle of the nineteenth century nearly every house had a cistern filled at stated times. A constant 24-hour supply was not introduced in London until 1873, and even as late as 1891 35 per cent of the total supply was on an intermittent system.

The great era for the private water companies came in the eighteenth and nineteenth centuries, although a few had been established prior to that time. In 1681 the Shadwell Water Works for east London was established, and ten years later the Yorks Buildings Water Works Company began supplying Westminster. Various private companies sprang up at intervals, the Grand Junction Water Works Company being the last (1811).¹⁹ Amalgamations of certain companies took place after that time, and by 1867 a total of nine companies supplied London with 103,000,000 gallons daily. However, all private water companies (eight) were dissolved in the first decade of the twentieth century when the municipal authority assumed control by purchasing the companies at what was generally regarded as a fabulous figure.

Great strides were made in the nineteenth century when
 PARIS -- Apart from medieval ecclesiastical efforts, the early French water supply systems were, in general, more devoted to beauty and display than to utility. Typical was the work of Jean Lintlaer, a Flemish engineer, who, under orders from Henry IV, supplied the gardens of the Louvre and Tuilleries in 1608 from an undershot pump at Pont Neuf. In the following year Henry IV entertained the idea of restoring the ancient Roman aqueduct of Arcueil, but research indicated that it would be better to build a new one. Accordingly, work was carried out by one Jacques de Brosse under Marie de Medici during the period 1613 to 1624.²⁰ By this aqueduct water was brought to Paris from springs at Rungis 7 or 8 miles to the south, its main purpose being to supply the fountains at Luxembourg Palace.

Near Paris, at Versailles, a tremendous project for supplying the palace, gardens, and fountains was begun in the late seventeenth century but never fully completed.

Isolated attempts were made to provide utility supplies before the nineteenth century, but these attempts were only partially successful. Three throw-pumps which were installed at Pont Notre Dame about 1670 remained in existence until 1858, supplying 1758 cubic meters a day by raising water to a tank which fed forcing pumps. In the latter part of the eighteenth century two brothers, Jacques and Auguste Perier, formed a company for the purpose of supplying Seine water to Paris by steam engines. After approximately ten years of operation the company failed (in 1787), and its works were taken over by the government in 1807.

Great strides were made in the nineteenth century when long aqueducts were built to bring far off waters to the city. Particularly outstanding were the Dhuys aqueduct (1863-66), bringing spring waters a distance of 81.48 miles, and M. Belgrand's Vanne aqueduct (1867-77), carrying spring water from Villeneuve l'Archeveque, some 106 miles southeast of Paris. By 1890 the per capita supply of water in Paris had reached 65 gallons per day, but only about 16 gallons were being used for domestic supply. The total figure reached 100 gallons by 1934, half of it being filtered surface water and the other half coming from springs and wells.

OTHER EARLY WATERWORKS -- Bruges, a flourishing trading town in the Middle Ages, had, by the end of the thirteenth century,

a water system whose underground conduits supplied public cisterns, fountains, and bathing establishments. The water was collected in a large reservoir outside of the city, conveyed to the Bruges "Waterhuis," and raised to a high level cistern by a wheel with buckets on a chain. In the sixteenth and seventeenth centuries the good burghers of the town added variety to the system by installing, at different places, little men and lions of brass which spouted water from various openings on the unwary.

600. Waterworks existed in Germany by 1412 and pumps were introduced at Hanover in 1547, but no great construction program followed in the country. As late as 1864 there were only twenty-four waterworks in all of Germany. At Toledo in Spain Giovanni (Juanelo) Turriano, a machinist or watchmaker by trade, constructed (1568) a device, apparently a wheel turned by the swift current of the Tagus below Alcántara Bridge, which connected to pumps forcing water 300 feet vertically to the level of the Alcázar. The Spanish influence was carried to the New World where a Franciscan monk directed the construction of the Mexican aqueduct of Zempola (1553-70). This work had three arch bridges, extended a length of 27.8 miles, reached a maximum height of 124 feet, and served for two centuries to convey water from Zempola to Otumba. Roman type aqueducts continued to appear at a relatively late date at various places throughout the world. One was built at Lisbon in the sixteenth century, another at Malta by the Order of St. John (1610-15), and still another at Rio de Janeiro (1750).

ARTESIAN WELLS -- The word "artesian" is derived from the French "Artésien," meaning an inhabitant of Artois, a district in northern France. It is probable that the word even goes back further, to the Latin designation for Artois, "Artesium." The name is generally given to a well whose shaft penetrates to a water-bearing stratum--surrounded by impervious strata--which is under sufficient head to cause the water to flow spontaneously. Although wells whose depths reached 600 feet and more in cases were mentioned by Olympiodorus as early as A.D. 600, the original "artesian" well seems to have been the one bored in 1126 at the monastery of the Chartreux monks in Lillers. Deep wells have been bored occasionally from the seventeenth century onwards. Professor Cassani of Bologna referred (1650) to deep wells in Modena and Bologna, and built one himself at the castle of Urbin. Abbé Imbert told of Chinese wells in Ou Tong Kiao, 1500 to 1800 feet deep, and 5 to 6 inches in diameter. It is generally conceded, however, that the first modern deep artesian well was sunk in the Grenelle quarter of Paris by M. Mulet, a smith, who commenced operations in 1833 and finally struck water in 1844 at a depth of almost 1800 feet. Since that time borings have increased in number and depth, Germany, Australia, and the United States being the leaders in this field. At Athens, Los Angeles County, California, one well has been drilled to a depth of 7591 feet.

The finding of water at great or small depths by water divining is a subject which has held the interest of many for centuries. In 1500 Sebastian Munster's "Cosmography" mentioned a diviner with a forked stick of hazel, and diviners are still

to be found in the twentieth century. While many have misrepresented their powers, there are several authenticated cases which indicate that certain people do react in the presence of water in a fashion analogous to that of hay fever sufferers in pollen-laden air.

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MATHEMATICAL FOUNDATIONS -- Though early waterworks were, for the most part, constructed by "practical" men, scientific minds became interested in hydraulics at an early date. The experimental method for deducing natural laws, advocated by Da Vinci (1452-1519) in the fifteenth and sixteenth centuries, was used by Galileo (1564-1642) almost a century later in his experiments with falling bodies. It was Castelli (1577-1644), a Benedictine monk and pupil of Galileo, who showed that the efflux was a function of the depth of the water in a bowl, but he wrongly stated it as a direct function. Torricelli (1608-47) went a step further in proving that velocities of efflux vary as the square roots of the head, and in 1673 Huygens (1629-95) found the numerical valuation of the acceleration of gravity, "g". Daniel and John Bernouilli combined all these concepts in 1738 and laid the foundation of modern hydraulics with their equation $v = \sqrt{2gh}$. To Da Vinci and Galileo we are indebted for "v", to Huygens for "g", to Castelli for "h", to Torricelli for the square root sign, and to the Bernouillis for the combination which took over two hundred years of experiment and observation to form.

Research in the eighteenth century, which was dominated by the French investigators was largely concerned with specific

facts on the flow of water through pipes and channels. Investigating flow in long pipes, Henry Pitot in 1728 proved that resistance to flow varies inversely as the diameter. Four years later Couplet at Versailles was credited with the first gauging on record of flow through pipes. The first practical formula dealing with the loss of head due to curves was formulated in approximately 1777 by Bossut. Chezy's flow formula (1775) was followed by many similar ones in the nineteenth century, notable contributions being made by Darcy in 1851, by Bazin in 1865 and in 1897, and by the Swiss engineers, Ganguillet and Kutter in 1869. Thus theory founded on experimentation prepared the way for the economic construction of the huge urban waterworks of the late nineteenth and early twentieth centuries.

entirely disappear, modern pipe is made of
 Ryckoff of Elmira, New York, patented a new pipe made
 by a band of iron, Modern Pipe Development

pipe. The outside was protected by a coat of red lead.

WOOD -- Though wooden water mains had been used occasionally by the Romans, and still find favor under special circumstances today, the main period of their extensive use came during the seventeenth and eighteenth centuries, when many waterworks were being constructed for the first time. Typical were the mains of London's New River Company which, at the beginning of the nineteenth century, extended some 400 miles in length, exclusive of the lead services. They were usually bored logs of elm with the bark left on, varying in bore from 2 to 10 inches, in outer diameter from 6 to 13 inches, and in length from 10 to 22 feet. The joints were of the spigot and socket

type, the smaller tapered end being coated with white lead and driven into the larger end, which was reinforced by an iron band.

Bored logs formed the basis of practically every water-works system established in America well into the nineteenth century. Boston boasted of the first public water supply in the country when it laid its wooden mains in 1652, and it was almost two hundred years later (1846) before it abandoned the logs for cast-iron pipe. Relatively high maintenance charges including the great loss from leakage and the competition from the superior cast-iron pipe drove the bored log off the market in England early in the nineteenth century, and by the middle of the century most of the other countries followed suit.

Wood did not entirely disappear, however, for in 1855 A. Wyckoff of Elmira, New York, patented a wood pipe strengthened by a band of iron, steel, or bronze wound spirally around the pipe. The outside was protected by asphalt 1/8 inch thick, and the pipe was designed to stand pressures up to 172 pounds per square inch. Internal diameters varied from 2 to 6 inches and length up to 12 feet could be had. At about the same time continuous wood stave pipes, which are used in many places to this day, made their appearance. As early as 1851 B.H. Hull made pipes in 12-foot lengths of 2-inch pine planks. A fine twentieth century example of this type was the mile-long, 13 1/2-foot diameter continuous pipe built in 1913 by the Pacific Coast Pipe Company for the N.W. Electric Company of Portland, Oregon.

iron in 1809.

CAST IRON -- In the sixteenth century cast-iron cannons up to three tons were made, and it is possible that some waterpipe of the same material was cast at about the same time. We have no record of its extensive use, however, until the next century, when over 15 miles of mains, varying from 1½ to 20 inches in diameter, were laid (1644-88) by orders of Louis XIV to supply Versailles from the reservoir of Picardie. In 1901 some of these pipes were taken up and found to be of good grey iron, clean on the inside and but slightly rusted on the outside. ²⁷ They were all about 1 meter long and were joined by bolted flanges.

Despite its early use by the French, cast-iron water pipe remained largely in the experimental stage throughout the eighteenth century. In 1745 the London Bridge Waterworks Company had over 54,000 yards of wooden pipe, 3860 yards of lead, and only 1800 yards of cast iron. In the following year the Chelsea Water Company of London laid a 12-inch cast-iron flanged pipe, but was forced to relay it in 1791 because of a defective joint. Jointing trouble prompted Thomas Simpson of the company to design the first bell and spigot and lead joints in 1765. The ball and socket flexible joint was devised some years later (1810) by James Watt, when he was engaged in laying a 15-inch main on the bed of the Clyde for the Glasgow Water Company.

The second half of the century saw a few other sporadic attempts to change over to cast iron, such as that by Edinburgh, which replaced a lead line with a 5-inch cast-iron main in 1755. Dublin contracted for iron pipes in 1797, laid more wooden pipes in 1806, but finally started a complete change-over to cast iron in 1809. Lengths were formerly ~~various~~ to about 5 feet.

During the first decade of the nineteenth century the change-over to cast iron was rapid in England--especially in London--and in France. The practice spread to the United States when the Watering Committee of Philadelphia imported from England in 1817 some cast-iron pipes to replace the old bored logs. The first waterworks in Cincinnati, established in 1820, played no favorites in its choice of pipe materials. A force pump, operated by a horse or ox treadmill, pumped river water through 3½-inch wooden pipes to a reservoir of oak timber, 150 feet above the river. From here the water was distributed in 8-inch cast-iron mains, 1½ to 3½ inch wood branches, and lead services. Nine years later Lynchburg, Virginia, installed cast-iron pipes in what was claimed to be the first modern high-pressure main in the world. The use of cast-iron pipe was further extended in 1848 when Dr. Robert Angus Smith, an Englishman, patented a cheap, effective exterior coating for protection from corrosion. His mixture of gas-tar, pitch, linseed oil, and resin has come down to the present day with only a few minor changes. The coating, both inside and out with a hydraulic cement mortar, on sheet-iron water pipes was invented about the same time by Jonathan Ball and was used for domestic supplies as early as 1845 in Saratoga, New York.

Over the course of years the pipe itself underwent a great evolution as engineers were called upon to lay more pipe and provide for increased loads. The earliest pipes were about 2½ feet long and were bolted together. Later, longer pipes appeared, with screw joints at first and then with cylindrical socket joints. Lengths were further increased to about 9 feet,

and the bell and spigot with wooden wedge packing gave way to lead packing. The twentieth century saw lengths increased to 16 feet, while the technique of coating the interior with cement improved with the advances in the cement industry. Today, when routine water mains are contemplated, cast iron stands in a class by itself as the most likely choice.

WROUGHT IRON AND STEEL -- Most of the development of wrought-iron and steel pipes for water carrying has been American in origin, although these materials were rarely used for that purpose prior to 1853. The first large scale use of wrought-iron pipes was made in 1856 in certain hydraulic mining operations in California. Between 1862 and 1892 some 72 miles of wrought-iron pipe, 22 to 44 inches in diameter, were laid in connection with the San Francisco waterworks. In addition, a wrought-iron submarine pipe, 13,800 feet in length, was laid across San Francisco Bay. About 1890 soft steel began to supersede wrought iron, both in conduits and pen-stocks on water power developments and in inverted siphons on aqueducts. New York's Catskill aqueduct, built early in the twentieth century, was provided with a number of inverted siphons of riveted steel pipe, 9 to 11 feet in diameter, made of plates 7/16 to 3/4 inches thick.

STONE AND CEMENT -- Terra cotta and stone pipes were not uncommon in the waterworks of ancient civilizations, but their inability to give satisfactory results under pressure has rendered them impractical for modern usage. While steam pumping was still in its infancy the Weymouth Water Company experimented

with stone pipes in 1797, as did the West Middlesex Water Company of London early in the nineteenth century, but the results were unsatisfactory. A coarse glass, covered on the outside, was also tried unsuccessfully for a brief period in France.

Advances in reinforced concrete construction brought this form into favor for large inverted siphons early in the twentieth century. Of particular interest are two siphons in the province of Huena, Spain, the Sosa Siphon and the Albelda Siphon (1909). The latter, and larger of the two, was built to accommodate a head of 97 feet, measuring 13.12 feet in diameter, 2363 feet in length, and 7.87 inches in thickness. A portion of the Los Angeles aqueduct, measuring 10 feet in internal diameter, was constructed for heads from 40 to 75 feet, and on the Catskill aqueduct heads less than 50 feet were provided for at various points by reinforced concrete siphons varying from 7 1/2 to 17 feet in diameter.

About the time of World War I asbestos cement, or transite, pipe began to appear commercially. Its facility of handling, ability to withstand pressures (heads up to 500 feet) and chemical inertness have proved great factors in its increase in popularity. It is by no means the answer to the search for the perfect pipe, but its development indicates that the future trend may be toward a non-metallic type which will discard the disadvantages of the metallic pipe (corrosion, weight, difficulty of handling) without losing its advantages.

PUMPS -- There is lack of evidence that pumps were used from the close of the Roman era until the sixteenth century, and even then their use was devoted more to irrigation than to water supply. It is probable that the earliest of the water supply pumps originated in Germany, for we know that Hanover had a pumping system installed in 1547, and that the "hydraulic engines" of Augsburg, Bavaria, raised water to a height of 130 feet in the following year. The earliest engines were forcer pumps in which wood forcers covered with leather worked in barrels of wood. Power was supplied by water wheels installed under the arches of bridges where the current could best be utilized.

Best known of the early works of this type was the installation made by Peter Morice under London Bridge in 1582. One hundred years later Rannequin of France reached the ultimate in this type of construction with his pumping system for the palace, fountains, and gardens of Versailles. In all, the system--known as the Marly Waterworks--contained fourteen water wheels and two hundred and fifty three pumps, the most distant pumps being more than 600 yards from the river. By motion of the water wheels sixty-four forcing pumps raised the water 160 feet to a reservoir; from here eighty pumps raised it to a higher level, from which it was raised by eighty more pumps to the top of a tower. From here the water flowed along an aqueduct on thirty-six arches to its destination.

In the Museum of the History of Science at Oxford is an

interesting seventeenth century advertisement by Sir Samuel Morland (1625-95) which gives some idea of the state of pump development in England at that time. Under "Engins for Mines or deep Wells" he advertises: "For such an Engin, being divided into two parts, the one to be placed at the bottom of a well, or pit, and the other at the top, with Fourscore Foot of Leaden Pipe, of two Inches Diameter, and an Iron Rod, and five Brass Valves, with double Bridges, and all things else fit for use (of?) it, and setting up and fixing them within Twenty Miles of London. If further, the Workman must be paid for his journey a(s) labour over and above. (price) Sixty one pound ten shillings." The bulletin also advises that engines with forcers up to 10 inches in diameter may be had and that machines capable of forcing water out of a well 50 or 60 feet deep are available. Though this advertisement is not dated we may assume that it appeared about 1675, the year in which Sir Samuel raised water by means of a plunger pump to the top of Windsor Castle.

Toward the latter part of the seventeenth century George Scorrold of Derby developed a method for raising water which he installed successfully in many provincial towns such as Derby, Exeter, and Norwich. The essential feature of his system was that the water wheels rose and fell with the stream, an idea which was patented by John Hadley in 1693. When the York Buildings Waterworks of London were established in 1691, a horse wheel was first employed to pump water from the Thames. Water wheels, however, continued to provide the power for most of the large waterworks up to, and in some cases well into, the nineteenth century. As late as 1859 the Marly works of Rannequin

still had iron water wheels and force pumps. 431

From the sixteenth to the eighteenth century small pumps were often made of lead with handles of iron, and brass or wooden pumps were also seen occasionally. Practically all of the larger pumps were of wood, but a transition to iron in all sizes came gradually throughout the eighteenth century and became practically complete in the early nineteenth century. This transition was reflected in the first attempt in the United States to pump a public supply. In 1754 at Bethlehem, Pennsylvania, a Danish millwright, Hans C. Christianson, forced spring water with a lignum vitae pump of 5-inch bore through hemlock log pipes to a wooden reservoir 400 feet away. Though he was able to raise water to a height of 70 feet, the builder was not satisfied with the pump and replaced it in 1762 with three cast-iron pumps of 4-inch bore and 18-inch stroke.

The use of steam followed closely behind the development of the cast-iron pump, but early workers in this field were more concerned with dewatering mines than with pumping a public supply. Intermittent efforts were made throughout the eighteenth century to apply the steam engine to water supply, but no substantial results were achieved until early in the following century. At the York Buildings Waterworks the horse wheel was replaced by a Savery engine which, in turn, gave way, about 1720, to a Newcomen engine. But it, too, was soon removed. John Smeaton in 1779 designed a steam engine for the same company, and in 1787 one of the first Boulton and Watt engines was installed successfully. The Watt steam engine soon found favor among some of the more progressive waterworks, installations at

Hull (1795), Marly (1803), and Chelsea (1810) leading the way. The secondary consideration given to water supply problems when compared with dewatering operations was still evident in 1838 when a London waterworks company tried out a standard Cornish mining pump for its own use.

From England steam pumping operations soon spread to other countries. Benjamin H. Latrobe introduced the practice in the United States by installing pumps--built (1799-1801) by Nicholas J. Roose--to raise the waters of the Schuylkill at Philadelphia. Thus the steam engine, with its ability to pump great volumes of water economically, and cast-iron pipe, with its ability to stand the great heads made possible by the steam engine, ushered in the era of the modern waterworks early in the nineteenth century.

NEW YORK CITY -- No story of modern waterworks is complete without reference to the New York system, for its growth has been an excellent example of the trend in waterworks practice throughout the world since the early nineteenth century. The first recorded project, the digging of a public well in 1658, was not carried out, but shortly after 1667 the first pump in the city was installed at a public well near Bowling Green. The earliest attempt to provide a real waterworks was made by Christopher Colles (1738-1821), an Irishman, who labored at a project to pump water from several wells during the period 1774 to 1776, but whose efforts were cut short by the Revolution. Aaron Burr and his Manhattan Company, formed in 1799, were more successful, for by 1836 they had managed to lay 25 miles of

Wooden mains--mostly bored cedar logs--which supplied some two thousand houses. ²⁸ Two 18 HP steam engines pumped well water to an iron tank near Collect Pond, from which 700,000 gallons of water a day, "poor in quality and quantity" were distributed. By a wording in its charter the company was allowed to open a bank with its proceeds which lasted to the twentieth century, although the water operations ended when the Old Croton system went into operation in 1842.

In 1829 a scheme was adopted, and in 1832 the steam engine was installed, for New York's first municipal-owned supply. The 12 HP engine pumped 21,000 gallons a day from a well at 13th and Broadway to an elevated tank with a capacity of approximately 230,000 gallons. Cast-iron mains from 6 to 12 inches were installed, and by 1833 about seven miles of pipe had been laid. However, it was obvious from the start that this supply was no answer to the growing city's demand for water, so far-seeing municipal planners looked beyond the city limits for the next extension. Surveys begun under Colonel DeWitt Clinton in 1832 resulted in the tapping of the Croton River near its mouth and in the /conducting of water to the city through a brick aqueduct 6 feet square and almost 41 miles in length. Work was begun in 1837 under the direction of chief engineer David B. Douglas and completed in 1842 under John B. Jervis, thus giving New York its first adequate public supply.

Less than half a century elapsed before the supplies of the "Old" Croton aqueduct became inadequate and plans for a "New" Croton aqueduct were laid. In 1882 chief engineer Isaac Newton proposed that the new aqueduct be constructed to supply

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250,000,000 gallons a day, a figure which was later raised to 300,000,000. An Act was passed in 1883 and construction was carried on from 1885 to 1891, the bulk of it being under the direction of chief engineer Alphonse Pteley. Except for a little over a mile in deep open cut, all of the aqueduct was placed in tunnel, the total distance from Croton Lake to the gatehouse at 135th Street exceeding 33 miles. Constructed with a total fall of nearly 1 foot to the mile, the system was designed to deliver water at a head of 160 feet. One of the most notable features of the project was the construction of the Harlem River Siphon, 160 square feet in cross-section, carrying water 420 feet below hydraulic grade.

The short-lived opportunistic Ramapo Water Company, which flourished about 1899, awakened New Yorkers to the fact that once more they would have to augment their water supplies to keep pace with the growing city. Municipal action soon followed with the appointing in 1903 of a commission, which reported in the following year. Actual construction on the first phase of the Catskill watershed project was carried out from 1907 to 1917, mainly under the direction of chief engineer, J. Waldo Smith. Cut and cover, grade tunnels, pressure tunnels, steel-pipe siphons, and flexible pipe lines were the principal types of construction used on the 92-mile line, 14 miles being devoted to tunnels, 23 to pipes, and 55 to cut and cover. Drawing on the Esopus, Rondout, Schoharie, Catskill, and other lesser creeks, the system was designed to deliver, at a head of 295 feet, 500,000,000 gallons of water a day, later increased to a figure of 600,000,000. As noted in the previous chapter on

"Tunnels" the expansion of the system has continued to the present, and shows no indication of becoming static or retrogressive in the foreseeable future.

OTHER MODERN CITY SYSTEMS -- Apart from the efforts in a few special cities, such as in London, little was done to organize municipal waterworks, as we know them in the modern sense, until the nineteenth century. A case in point is that of Edinburgh, which had a water Act passed by the Scottish Parliament in 1621, but which took no action until 1672. At that latter date the Town Council resolved to bring a supply from Comiston Springs, and engaged a Dutch contractor named Bruschi for the job. A few more springs were tapped during the eighteenth century, but it was not until the Edinburgh Joint Stock Water Company was formed in 1819 that real progress was made. Engineers Rennie, Telford, and Jardine provided an excellent example for subsequent works by bringing mountain water from a spring-fed brook at Glencorse, in the Pentland Hills, 8 miles south of the city.

Early American waterworks developed along the same lines, and at about the same time, as their European counterparts. Growth beginning in the second half of the nineteenth century was rapid; for example, the 83 waterworks in operation in the United States in 1850 had increased to 12,760 by 1939. The first public supply in the United States, established at Boston in 1652, was spring-fed water which was conveyed by gravity through wooden pipes to a reservoir. In 1796 the Aqueduct Corporation brought water into the city from Jamaica Pond in Roxbury 4 1/2 miles away, and in 1848 a supply was drawn from Lake

The trend continued in the nineteenth century with Vienna's Couchituate, 18 miles distant. The latter supply, developed by J.B. Jervis and E.S. Chesbrough, was brought by gravity through an oval brick conduit to a reservoir in Brookline.

Montreal, the first Canadian city to have a waterworks system, developed in a similar fashion to Boston. In 1800 a private company furnished spring water through wooden pipes from Mount Royal, and by 1815 water was being pumped from the St. Lawrence to elevated reservoirs. In common with many other cities Montreal finally went outside of the city limits to bring in a water supply. Built under the direction of Thomas C. Keefer, the 5-mile "Canal Aqueduct" bringing water from the river above the Lachine Rapids, went into service in 1854.

As the nineteenth century advanced, more and more cities sought water supplies at great distances from their outskirts. Glasgow became the first city in Britain to bring water from a distant upland source when it brought in the waters of Loch Katrine. Built during the period 1855 to 1860, the aqueduct extended a distance of 25 1/2 miles from the Loch to the reservoir at Mugdock, 8 miles from Glasgow. Of this distance, tunnels accounted for 13 miles, cut and cover for 9 miles, and iron pipes across valleys for 3 1/2 miles. Toward the latter part of the century (1886-95) Manchester developed an even greater system by tapping Lake Thirlmere 95 7/8 miles away. Under the direction of chief engineer George H. Hill, 14 1/8 miles of tunnels, 36 1/2 miles of cut and cover, and 45 miles of cast-iron pipe siphons were constructed to supply the city with 50,000,000 Imperial gallons a day.

Now, when a local water supply failed, through river contamination or pollution, the community was no longer moved to a fresh

The trend continued in the twentieth century with Vienna's "Second Emperor Franz Joseph High Springs Aqueduct" (1901-10), planned by Francis Berger. Of its 113 1/3 miles, almost 44 miles were made by tunneling. On the Pacific coast of the United States two cities, San Francisco and Los Angeles, dwarfed all previous projects with aqueducts extending 155.8 miles and 223.41 miles respectively. In the San Francisco project 84.9 miles were tunneled and the remaining 70.9 miles were laid with pipe. Starting from the Owens River in the Sierra Nevada Mountains, the Los Angeles aqueduct, with 42.9 miles of tunnels, 166.46 miles of cut and cover and 14.05 miles of pipe, was built (1907-13) under the direction of William Mulholland to supply 280,000,000 gallons a day. One notable feature of this job was the construction of a 5-mile pressure tunnel through the Sierra Madre Mountains near the Fairmount Reservoir, measuring 10 feet 10 inches in height and 9 1/2 feet in width. Also worthy of note among modern works is the Apulian aqueduct in Italy, which was designed to bring 110,000,000 Imperial gallons of water a day from the Caposile Springs in the Apennines through a 67-mile horseshoe tunnel, 9 feet 5 inches in height and 8 feet 9 inches in width. In 1937 this system utilized 841 miles of main and branch pipes, and 550 miles of distribution pipes.

A brief glance at the above few examples reveals one clear trend, a move to bring water into the urban center from great distances. Increasing populations not only exhausted the capacities of local wells, but polluted the near-by large supplies of water which had attracted the settlers in the first place. Now, when a local water supply failed, through either exhaustion or pollution, the community was no longer moved to a fresh

source of supply; the fresh source of supply was moved to the community. Where the economics of the situation prevented such a solution, the problem of pollution had to be attacked in a more direct way. A major step in that direction came with the introduction of water treatment.

Water Treatment

SIMPSON'S FILTER -- As far as modern progress is concerned, filtration and water treatment in general were innovations of the nineteenth century, but the subject was not entirely unknown before then. Occasional passages in the Bible refer to "sweetening waters," and we know from Pliny that boiling water was practiced on occasion by the Romans. The Doge's Palace in Venice had a system whereby rain water was directed from the roof through a sand filter to the cistern from which the water was finally drawn. No filtration of a public supply was accomplished successfully, however, before the English experiments of the early nineteenth century.

Installation of slow sand filters began in Lancashire and Scotland about 1810, but their capacities were relatively small. James Simpson, an engineer for the Chelsea Water Works of London, visited several of these installations, and conducted extensive experiments on freeing water from turbidity during the period 1825 to 1828. The result was the first satisfactory full-scale municipal slow sand filter, one acre in extent, which went into operation in 1829. Simpson's filter was a reservoir in which succeeding layers of large and small stones,

gravel, and sand were placed on top of each other. Water was then allowed to flow onto the top sand layer and penetrate to the bottom, where it was drawn off.

Early sand filtration was introduced with a view toward getting a clear, though not necessarily safe, water. Clarity, odor, and taste were the main items under discussion in 1627 when a group of London citizens complained against the water supplied by the Junction Water Company, whose intake was only 3 yards from the outlet of the great sewer on the Thames. The company first moved the inlet further out in the river, and then moved it to the other side and installed precipitation reservoirs. What was regarded as a filter's main function in the early days was well expressed by W. Matthews in his "Hydraulia" (1835): "As the different establishments at present supply it (water) at a very cheap rate, if it were filtered, and the price proportionally increased, the cost would still be trivial, and it would moreover effectually obviate what has hitherto furnished the chief ground of complaint--its feculent and turbid condition."

MEDICAL DISCOVERIES -- Though London had a record typhoid fever rate in the same year that James Simpson installed his filter, there is no evidence that anyone suspected the water supply of being connected with the disease. No doubt the suspicion that water could harbor diseases was held by many, but the serious outbreak of Asiatic cholera in Britain in 1849 focussed attention on the subject. Writing in the same year, physician John Snow, in "The Mode of Communication of Cholera,"

accused water of carrying excreted matter from a diseased person to the mouth of another, thence to the alimentary canal. Largely as the result of this and other pertinent investigations, an Act of Parliament of 1852 decreed that commencing in 1855 all water for domestic use in the metropolitan area would have to be filtered, except that pumped from wells to covered reservoirs.

It was not until the last quarter of the century, however, that positive proof was obtained which showed that clear water is not necessarily safe water. Real progress began with the experiments of the brilliant French chemist, Louis Pasteur. In 1866 Pasteur succeeded in proving that the disease devastating the French silkworm industry was caused by a living organism. Later his work was extended to the diseases which affect man. The first of these upon which he was able to throw light was Anthrax, a disease which he and Dr. Robert Koch of Berlin labored over separately but simultaneously. In 1875-76 Koch proved beyond a doubt the correctness of the germ theory of transmission of disease, when he convicted the *Bacillus Anthracis* in sheep and sheep workers. He later headed a German expedition to Egypt and India in 1880 to investigate the cholera epidemic raging in those countries, and succeeded in showing that the disease was water-borne. Karl J. Eberth discovered the bacillus of typhoid fever in 1880, and four years later George Gaffky, Koch's pupil and successor in Berlin, procured the first cultures of the "*Bacillus typhosus*." Koch then proceeded to introduce his bacterial water tests in 1885. In the same year Escherich became the first to show that the presence of the

E. coli is direct evidence of sewage pollution. Victor Hensen of Kiel University in 1887 invented the collective term "plankton," from the Greek "I wander," to designate the smaller floating organisms, animal and vegetable, found in water. Thus, within a decade, the importance of the relationship between bacteriology and a proper water supply leapt from almost total obscurity to great prominence.

BACTERIOLOGICAL FILTRATION -- The discoveries of Koch and his colleagues, closely following the fundamental work of Pasteur, ushered in a whole new era in thought on the subject, for it was now realized that the primary function of water treatment should be to remove pathogenic organisms. Investigators found that the true value of the slow sand filters already in operation was not so much in their mechanical ability to free water of turbidity, but in the bacteriological activity which took place in their beds to free the water from pathogens. They found the layer of material which gradually formed at the surface of the filter--the "schmutzdecke"--to be the point where most of the biological metabolism was taking place. In effect, these living organisms on the bed were "eating" the pathogens in the water as it came through. Once the bacteriological requirements were known, greater progress toward the creation of more efficient filters became possible. Much of this progress was American in origin, though filtration had only been introduced into the country shortly before Koch's discoveries.

Concerned with the unsuitability of the turbid waters of the Mississippi, the St. Louis Board of Water Commissioners storage the use of coagulants was tried.

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sent James P. Kirkwood to Europe to examine the methods of filtration then in use. He concentrated on England and Germany from 1866 to 1868, and on his return to America produced his "Report on the Filtration of River Waters for the Supply of Cities, as Practised in Europe" (New York 1869). Kirkwood's findings resulted in a marked advance in American waterworks' practice, though the designs he submitted for St. Louis, based on his European experiences, were unsuitable for treating the Mississippi water. His plans for Poughkeepsie, New York, were acceptable, however, and it was there that the first American municipal sand filter was built (1872-73).

Experiments carried out by the Massachusetts State Board of Health at Lawrence, under H.F. Mills, produced further improvements. After concentrating for some time on sewage treatment, the board turned its serious attentions toward water treatment about 1890. The resulting sand filter, built in 1893, was the first constructed in the United States with the specific purpose of reducing the death rate. A comparison of the five year period preceding the filter's installation with the five year period following showed a drop of 79 per cent in the typhoid fever death rate.

It came to be realized that pathogens could be eliminated not only by filtration but by storage as well. When water is stored and sedimentation takes place, the pathogenic bacteria die out due to the unfavorable environment, lack of food, the activities of predatory organisms, and other conditions. Long storage may have its bad effects, too, wherein odor, taste, and general potability decline. To aid and speed up the process of storage the use of coagulants was tried. The addition of a

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coagulant in water treatment was introduced for the first time in a public water supply by A. Hyatt, who used alum for this purpose at Somerville, New Jersey, in 1884. In the same year a similar English patent was taken out by Lake, who used iron salts and subsequently precipitated the iron. Hyatt's system was a forerunner of the mechanical or rapid sand filter, for after being treated by the coagulant, the water was passed through a sand layer which could be mechanically washed by a reverse current of water, aided sometimes by other appliances. Following valuable work at Providence, Rhode Island, by E.B. Weston in 1893, a practical and scientific basis for the rapid sand filter was finally established at Louisville, Kentucky, by C. Hermany and G.W. Fuller, during the years 1895 to 1897. A unit which could give practically the same results as the slow sand filter, but in a fraction of the time and in a fraction of the space, had become a reality. The first important rapid sand filter plant went into operation at Little Falls, New Jersey, in 1902.

STERILIZATION -- Koch's discoveries led not only to research on how to prevent the development of bacteria, but how to kill them as well. Sterilization by boiling was found to be effective enough, but impractical on a large scale. In 1888 C. Herscher invented a large boiling apparatus which proved to be, as have all similar heating devices for the purpose, too uneconomical to run, except under very unusual circumstances. Other physical methods, such as exposure to various forms of light or electricity, were also tried with varying

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success. Two Englishmen, Downes and Blunt, discovered in 1877 that ultra-violet rays have the power of killing bacteria, but it remained for the Frenchmen Courmont and Nogier, to apply the discovery successfully to drinking water. ³⁷ Mechanical methods, such as the rapid and violent agitation in closed receptacles or Kestner's (1906) treatment with a volatile anti-septic, received less attention.

Chemical methods of sterilization, however, made the most practical progress in the field of water treatment. The use of chlorine for the purpose was not entirely revolutionary, for "Oil of sulphur" and "aqua vitae" had been used for reviving putrid water in the Middle Ages, and Javelle water had been in use in France since 1792. In 1894 Traube showed that small amounts of free chlorine could kill bacteria, and in the following year Bassenge found that 0.0978 grams of chlorine per litre of water would produce complete sterilization in ten ³⁸ minutes. One of the earliest full-scale uses of a chlorine compound came in 1908, when hypochlorite of lime was added to the water drawn from the Boonton reservoir supplying Jersey City. The suggestion by Lieutenant Nesfield of the Indian Medical Corps that chlorine gas might be used to disinfect water was followed, in 1910, by the extensive experiments along this line by Major Darnall of the United States Army. Then conditions on the home front and in the field in World War I accelerated the acceptance of chlorine in water treatment. Sir A. Houston, in order to save coal used in pumping Thames water to storage reservoirs, by-passed the reservoirs, and dosed London's water with chloride of lime before allowing it

to pass to the filters. His experiments showed that introduction of 15 pounds of chloride of lime to 1,000,000 gallons of water destroyed the microbes derived from previous sewage contamination far more effectually than passage through a reservoir containing 88 days' supply. Following the war chlorine dosage became accepted practice in modern waterworks.

Among other chemical methods of sterilization which have been tried is the use of ozone. As early as 1899 Siemens Brothers & Company took out an English patent which described the mixing of water with iron compounds and blowing with ozone. An experimental plant for treating 15,000,000 gallons of water a day with ozone was installed at London in 1933. Though many advantages of this treatment were noted, it was also found that the water became more corrosive. Treatment with hydrogen peroxide, permanganates, excess lime, or various metals has also received a great deal of attention in the laboratory.

Chemistry has been called upon to combat more than pathogens, however, in the quest for potable water. In 1904 Dr. G.T. Moore, of the U.S. Department of Agriculture, issued a report on the extensive use of copper sulphate in impounding reservoirs, to poison organisms which produce objectionable odors and tastes. Many other solutions to the taste and odor problem have been offered along the same lines, especially in view of the fact that the addition of chemicals, such as chlorine for other purposes, has, in turn, created new tastes and odors. Baker and Schmelkes produced an answer to the latter problem in their American patent of 1932. They found that the addition of iron as ferrous sulphate prior to chlorination prevents odors

and tastes, and accelerates reaction. The use of finely divided coke or coal to remove substances causing these objectionable features was patented by Rodman in the United States in 1933.

WATER SOFTENING -- Removal of temporary hardness by the addition of hardness (lime) was proposed by Thomas Henry about 1798, but the method did not become successful until patented by Clark of Aberdeen in 1841 and was not put into effect on a large scale until adopted at Canterbury in 1860. In time, soda-ash was added to the process to remove permanent hardness as well, the combined operation being known as the lime-soda process. Softening by electrical means was introduced, in what was probably the first electrical treatment of water, by Jewel of England in 1888. His patent called for treating the water first with a softening agent and then electrolizing it to purify or assist precipitation. Of considerable industrial importance was the Permutit softening process introduced by Dr. Gans of Berlin in 1906. By a base exchange, or zeolite process, magnesium and calcium salts were replaced by those of sodium, thus rendering an extremely soft water.

The modernity of water treatment is made clearer when we realize that all of London's river water for domestic use was not filtered until 1855, and that, in 1890, only 1.5 per cent of all the urban population of the United States received filtered water. Experiment and practice in less than a century had made the treatment of water a complicated engineering problem, for it now involved sedimentation, with or without a

coagulant, filtration, sterilization, softening, and other miscellaneous processes.

Summary

Early civilizations clustered about natural watering places and satisfied their water needs by individual action. Consumers acted as their own distribution systems by scooping up and carrying the water in containers fashioned by nature or by crude manufacturing methods. In time, individuals discovered that wells would not only save steps to the local stream or pond, but would prove reliable insurance against the ravages of drought.

From hand-drawn to pipe-carried supplies was a long step. Archaeological discoveries have indicated the existence of isolated organized piped supplies as early as five thousand years ago, but even in Classical Greece the practice was far from universal. The large number of mountain springs in Greece no doubt accounts for the lack of many municipal systems in the country, but this factor did not prevent the Greeks from acquiring extensive hydraulic knowledge. Where necessary, they put this knowledge to good use in the installation of inverted siphons and pipes of stone, lead, and terra cotta.

It remained for the Romans, however, to develop the art of water supply engineering in its fullest sense. Until 312 B.C. the citizens of the city of Rome supplied themselves individually from the Tiber or from private wells. From that date, which marked the construction of the first aqueduct

bringing in water from outside the city, until A.D. 537, when the Goths over-ran Rome, its citizens enjoyed all the advantages of a well-organized municipal water supply system. Public cisterns, filled in some cases with water from almost 60 miles away, furnished a plentiful supply to all desiring it, while private conduits to the houses of wealthy and important citizens were not uncommon. Lead, terra cotta, stone, wooden, and, on rare occasions, copper pipes were used in carrying the supply. Though pumps were known by the Romans, there is no evidence that their municipal water supplies were anything but gravity fed along their great aqueducts. Many of the arched portions of these aqueducts still stand, visible symbols of the power and genius that once was Rome.

Sporadic attempts were made to revive some of the Roman systems, following Rome's fall in the sixth century, but little was accomplished. The Moors built a few public systems, but all evidence indicates that their efforts were insignificant in the over-all story of water supply. Little of importance in the field was accomplished until about the twelfth century, when engineer-churchmen began to emerge from the monasteries. The projects to supply their monasteries with water were later followed by projects to supply the communities in which their monasteries were located. Usually this involved the conveying of water from a spring or well relatively close by, to public cisterns by means of open troughs or pipes of lead or wood.

The knowledge and skill necessary for such undertakings gradually passed from the clergy to the laity, and the town burghers became responsible for initiating such public projects.

Such a policy was not always the best answer, however. In most countries water supply remained a public function, but in England private companies slipped unobtrusively into the scheme of things, and came to dominate the scene during the eighteenth and nineteenth centuries. London, early a leader in organized water supply, had pipes laid in the thirteenth century, and by the end of the sixteenth century, the pumping of public supplies was no longer a novelty. Throughout the seventeenth and eighteenth centuries London's private companies laid miles of wooden pipe, a practice which spread throughout the world. As the eighteenth century drew to a close, however, a fundamental change in waterworks' practice appeared.

Improvements in the steam pump and in cast iron brought about the revolution. Replacement of the old clumsy water wheel pumps by compact efficient pumps driven by steam was a very natural, and very gradual, development. Greater water pressures now became possible, but the wooden pipes in use could not efficiently contain them. So, cast-iron pipes began to replace those of wood, and steam pumps replaced the waterwheels at the turn of the century.

As the nineteenth century wore on a new problem presented itself--pollution. Communities growing rapidly were gradually polluting their own supply or the supplies of others downstream. The new pumps and cast-iron mains provided an answer for many cities; they would bring in fresh supplies from far-off sources. Thus, the story of many urban waterworks throughout the nineteenth century was one of going further and further afield to bring in fresh waters in aqueducts of great length.

Such a policy was not always the most economical, however, and another answer had to be found. Water treatment by sand filtration, successfully carried out on a large scale at London in 1829, seemed to be the solution, for the water was freed of its turbidity. Clearness and freedom from taste and odor were the main criteria of good water at the time, for the disease-carrying potential of "clear" water was not yet known. In the latter half of the nineteenth century experiments by Robert Koch of Germany, based on earlier observations by Louis Pasteur of France, showed conclusively the lethal possibilities in water. Now a more scientific approach to the problem of getting satisfactory water could be made.

Filtration methods were reviewed and overhauled, and a new rapid sand filter made its appearance in America at the end of the century. Chemistry was brought in to make its contribution to sterilize, soften, and remove objectionable tastes and odors from the water. As the twentieth century advanced more water-works made their appearance in every part of the globe, and science continued its fight for safer, more potable water.

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