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H I S T O R Y

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C I V I L   E N G I N E E R I N G

by

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Early Drainage Systems

PRIMITIVE DISPOSAL -- Sewerage as we know it--a system of pipes and other conduits, appurtenances, and works for the collection, treatment, or disposal of sewage--is relatively new in the history of man's progress, for it was essentially a product of the nineteenth century. Disposal pipes had been used long before the nineteenth century, of course, but such instances were rare and had little effect on the progress of sanitary engineering. One early example of planned sanitation has been revealed[1] by the excavations at the city of Mohenjodaro, located on the west bank of the Indus River. Here bathrooms, believed to be over 5000 years old, were provided with latrines occupying recesses in the walls. Vertical pipes led the effluent from the latrines to drains underneath the house floors; water chutes were cut in the outer walls of the houses and a large sewer was cut along the street to carry away drainage. Dr. Halbherr,[2] Director of the Italian Archaeological Mission to Crete, noted that the hygienic appliances were also good at Knossos. He found elaborate drainage with lavatories and traps, and a main drain 3 feet high coated with cement.

A much more usual method of disposal in early times, however, was indicated in Deuteronomy (xxiii 12, 13), which advised that all excreta shall be covered with earth, following the instinct of many animals. When men congregated in settlements, special disposal places were set aside--as indicated by the midden heaps which have been discovered near aboriginal villages. Later on, trenches were dug for human excreta, and, as civilization advanced, the addition of cooking and washing water brought about the creation of large pits at isolated spots. In time these were covered over, partly to keep out the rain, and partly to get the mess out of sight. The next step was to line the cesspool with brick, arch it over, and then connect it to the houses by brick or flagstone drains. As a rule, no cement was used in the construction, for then the sewage would slowly seep into the ground making the emptying of cesspools in crowded districts less frequent.

THE CLOACA MAXIMA -- Surprising as it may seem to many moderns, the original sewers did not carry household wastes at all, but were designed simply to take away surface and ground waters. Indeed, it was a penal offense until 1815 to discharge domestic sewage into the London sewers, and a similar ordinance remained in effect in Paris for several years more. Probably the most famous of all the ancient sewerage systems was that of Rome, attributed[3] by Livy (59 BC - AD 17) to Lucius Tarquinius Priscus (616-528 BC) and to Lucius Tarquinius Superbus (534-510 BC). Of the former Livy stated, "---he drained the lowest parts of the city about the Forum, and the other valleys between the hills, which were too flat to carry off the flood waters easily, by means of sewers so made as to slope down toward the Tiber." In speaking of the latter Livy noted, "I mean the erection of seats in the circus, and the construction underground of the Great Sewer, as a receptacle for all the offscourings of the City--two works for which the new splendor of these days has scarcely been able to produce a match." Pliny (AD 23-79) also remarked on the sewers of Rome, stating that seven rivers were made by artificial channels to flow beneath the city and adding, "It is said that Tarquinius made these sewers of dimensions sufficiently large to with hay passing among them."

The Cloaca Maxima, or Great Sewer, has survived to this day, although the oldest part of the present structure is probably no older than the third century BC.[5] Originally the sewer was constructed of large blocks of Albano stone, called pepperino, laid in an arch of three rings of voussoirs, measuring 14 feet in diameter and 32 feet in height. Its path was made crooked, no doubt following the line of the original stream; and, during the Empire, many repairs were effected, resulting in a concrete roof in some places. This giant sewer was, however, no larger than another discovered in 1742, which passed under the Comitium and Forum "40 palms" below the present surface. Smaller cloacae honeycombed the imperial city, the street openings to them rendering a walk along a dark unlighted street something of an adventure. Though some household wastes undoubtedly found their way into this system, it remained, first and foremost, a gigantic drainage net to convey surface waters to the river.

MEDIEVAL CASTLES -- Largely as the result of his investigations at Windsor, Robert Rawlinson in his "Report on the General Regulations of Sanitary Works at Windsor Castle" (1863)[7] traced the development of sanitary--if sanitary they could be called--facilities in old castles of medieval origin. He found that in the earliest days of the castle the floors were of mud, covered with reeds and litter; externally there were heaps of ordure and refuse, but neither sewers nor cesspools were present. When chamber floors were added, square stacks or vertical openings were formed in external walls to serve as privies. Known as "Guard de robe towers" these conveniences were louvred at each floor to serve as a protection against the splashings of excrement thrown out of floors above. In some castles crude sewers were installed, being of square construction with rubble side walls, uneven in line and gradient. These conduits led from internal rooms to the external walls where they were usually terminated. The obnoxious accumulation just outside the walls eventually brought about the construction of open cesspits and then covered cesspools.

Also belonging to the same period was the "necessarium" or "redorter" (meaning behind the dormitory or dorter), a feature common to most medieval monastaries. Generally, this chamber was built directly over a flowing stream, a practice which probably inspired the invention of the water closet. Apparently the first to write about the water closet was the Elizabethan courtier, Sir John Harington, whose treatise entitled "A New Discourse upon a Stale Subject called the Metamorphosis of Ajax" received scant attention at the time.

EARLY DRAINAGE OF CITIES -- Early European cities at first constructed irregular gutters leading to natural watercourses, with the sole object of clearing the streets of rain water. Naturally, the refuse which cluttered the streets was soon washed into these watercourses and deposition and putrefaction followed. As early as 1290 the Whitefriars Monks complained that the stench from the Fleet River, into which drainage from the City of London ran, was so bad that "it even occasioned the death of some of the brethren". Covering the offending stream was the usual method of attack it the stream were small enough. By 1637 the Fleet, north of Holborn Bridge, was arched over: by 1765 the river--then an open sewer--was entirely covered, as far as Fleet Bridge at Blackfriars;[8] and Wallbrook, which divided the city into two parts, was similarly covered.

Thus the large brick-arch sewer evolved with all its drawbacks and evils. Cracks between bricks caught bits of debris which held up other solids, and, in time, the conduit became choked with a great putrescent mass. Workers strong enough to stand the onslaughts of sewer gas were engaged to dig out the muck and haul it away in carts. Since man-holes were negligible or non-existent, such a cleaning operation invariably involved breaking through a sewer top and repairing the break again when the passage had been cleared.

Early Parisian sewers developed in much the same fashion as those of London (whose first common sewer was laid in 1666 in Ludgate near St. Paul's). Surrounding old Paris north of the Seine on three sides, the first sewer of the city was an open ditch, more or less following two ancient rivulets. By 1663 1½ miles of this ditch had been covered, but 5 miles of open ditch remained. Early in the eighteenth century the main belt line sewer was rebuilt with a paved invert and elaborate masonry walls, and by the end of the century some 16 miles of sewers traversed the city. M. Duleau (1789-1832), director of Public Works in Paris, played a large part in modernizing the system--such as introducing intercepting sewers in 1824--but again, the primary purpose was surface drainage and not sewage disposal.[9]

PRE-NINETEENTH CENTURY DISPOSAL -- Sewage disposal in crowded towns prior to the nineteenth century was usually taken care of by back yard middens or by the dumping of household wastes into streets. Early each morning--except Sunday--hired scavengers would clear the streets of refuse, leaving a certain amount of odor behind. "Rackyers", with equipment consisting of twelve carts and two horses, were employed as early as 1357 to remove the London refuse to dung boats. The indiscriminate tossing out of wastes from an upstairs window was usually prefaced by a cry which varied slightly from place to place, but which sounded like "Gardy loo!" in Scotland. This custom was practiced on the continent as well as in Great Britain, and it is probable that the cry was derived from the French, "Watch out for the water"; some English translators gave the call a broader meaning, "Lord have mercy upon you!" That travel in a district with such a system presented its hazards was revealed in a letter from Captain Burt, an English officer of engineers, who found himself in Edinburgh on an assignment about 1725.[10] Burt wrote, "Being in my retreat to pass through a long narrow wayside or alley, to go to my new lodgings, a guide was assigned me, who went before to prevent my disgrace, crying out all the way with a loud voice, 'Hud your haunde!' The throwing up of a sash, or otherwise opening a window, made me tremble; while behind and before me at some little distance, fell the terrible shower."

Although the invention of the water closet had been

[11] attributed to Sir John Harington of Kelston near Bath as far back as 1596, the device had not become particularly popular even by the middle of the nineteenth century. The crux of the argument against it was summed up by G.R. Clarke in "The Reform of the Sewers" (1860), in which he stated,[12] "But grant that a water closet in good order is a luxury; why should we actually compel the people to submit to an artificial system; to pay this tax; to make this waste; to poison these rivers; when the people did not want it; but only wished the cesspools to be better contrived, and more frequently and skillfully cleaned?" Even the Royal Commission of Metropolitan Sewage in 1882 discouraged the use of water closets as being productive of river pollution. Some type of pail system had long been in vogue in the better houses at least. Each night small pails were taken from under the seats of the closets and the contents were emptied into ditches or pits--a practice which sired the term "night soil". The pits into which the pails were emptied soon became the cesspools which Clarke favored, and their frequent need of cleansing rendered them a nuisance in most neighborhoods. In 1863 Moule offered a substitute for the pail system with his earth closet. By a mechanical arrangement similar to that of a water closet the pull of a handle would release approximately a pound and a half of earth to cover the discharge of faeces. The earth, which was baked daily in an oven and distributed by a central agency to the householders, had the effect of removing odors, but it was not necessarily disinfecting. Combining the "earth" and "pail" methods was the Goux-Thulasne system, which achieved a measure of popularity for a time.

AWAKENINGS OF SANITARY CONSCIOUSNESS -- The first great revolution in sewage disposal came in the form of the water-carriage system, wherein household wastes were carried into the sewers by a flush of water which mingled with the sewage and bore it to its final destination. The introduction of this system of disposal was not just a happy accident, but came as the result of events of world-shaking consequence; in general terms, it was a product of the Industrial Revolution. Pastoral people had had little difficulty in the matter of sewage disposal, but now that they were suddenly moved to great industrial centers the problem became very acute. England, first to reap the benefits of this new industrial age, was also the first to feel its attendant evils. In 1800 no town in Great Britain, with the exception of London, had a population greater than 100,000, but in a few short years several had exceeded this figure. In less than fifty years many towns had trebled their populations, and some, like Manchester, had quadrupled them. Such rapid and unprecedented expansion spawned slums with a myriad of jerry-built shacks jammed close together with little or no provision for sanitary conveniences. For example, as late as 1869 Manchester's population of 350,000 was served by only 10,000 closets and 35,000 privy-middens.[13] In the dank crowded courtyards seepage from middens and cesspools to local shallow wells was annoying, the foul stench which filled the air was irritating, but the epidemics and deaths which followed in the wake of these conditions were intolerable; some new means of disposal was necessary.

That epidemics and deaths did spring from these putrescent sources was an idea which gradually took shape as England's social consciousness was aroused. Practical Christian works of middle-class religious societies and ideals of the eighteenth century philosophers on the essential equality of man were merged at the beginning of the Victorian era, resulting in a concerted effort to help the poor and oppressed. The Government officially entered the sanitation field in 1834 when it passed the Poor Law Amendment Act, setting up the Poor Law Commission. Secretary to the Commission was Edwin Chadwick, a life-long sanitary reformer, who recommended the establishment of water carriage sewerage systems in his report to the Commissioners in 1842. In the following year a Royal Commission on the Health of Towns was appointed, and in 1844 its report on sanitary conditions among the poor shocked the nation into activity. Dr. Southwood Smith pointed out in the report that the incidence of fever was much greater among the poor than among the well-to-do, and that in London it could always be told where the sewers were and where they were not by the presence of the fever. The immediate result of this report was a law--which became effective in 1847--making the discharge of sewage into sewers obligatory, and prohibiting the use of cesspools in towns.

THE MIASMA THEORY -- Though attention to the horrible sanitary conditions of the poor had initiated the move for sewerage reform, it was the threat of pestilence and death to all in the community that brought about real action. Asiatic cholera epidemics in 1831-32, 1849, 1853-54, and 1866, and frequent bouts with typhoid fever stirred Londoners to think more of their lives than their sovereign purses and made them enthusiastic supporters of any plan which might free them from these dangers. Decaying matter was to be avoided at all costs, but this avoidance of putrescence was based on more than the unpleasant smell alone--it sprang from the generally-held opinion that miasmatic vapors in the air were the cause of fever. It was thought that fever patients, decaying matter, septic wounds, and marshy ground exuded a stealthy vapor, or miasma, which caused disease. Malaria, for instance, then called ague, was usually traced to marshy regions which gave off bad air or "mal aria", and thus the appelation "malarial fever" came into being. Though many had suspected the true nature of the usual transmission of diseases such as cholera and typhoid--i.e. the drinking of water carrying the wastes of infected persons--the official theory held until the 1860's was the miasmatic one. In condemning the miasmatic theory in 1861 William Budd deplored[14] "---the attempt recently made by a distinguished physician to replace the names by which typhoid or intestinal fever has hitherto been known, by the word PYTHOGENIC (i.e., born of putrescence)."

BEGINNINGS OF THE WATER CARRIAGE SYSTEM -- Prior to the appointment of the Health of Towns Commission in 1843 the sewers in England were constructed for the disposal of surface water only, under Statute 23, Henry VIII, c.5. When the discharge of sewage into the sewers became mandatory in London in 1847, it became obvious that a new sewerage system would have to replace the old, whose crooked drains varied in size and shape and were altogether unsuited to their new task. In order to cope with the problem the numerous, and often obstructive, Commissioners of Sewers of the various sections of the city were replaced by a single authority, the Metropolitan Commissioners of Sewers. Many small rectangular drains, 12 inches in depth and 10 to 12 inches in width, were then installed, as were brick-built culverts large enough for a man to enter. At about this time Robert Rawlinson in London published his "Suggestions for Main Sewerage and Water Supply", a work which advocated such principles as the construction of sewers in straight lines and the inclusion of man-holes--a work which soon furnished a standard for European practice. This decade also saw the introduction of circular pipes in sewerage practice, a suggestion advanced by Chadwick in his recommendation of the water carriage system. Salt glazed sewage pipes, the idea of John Roe and John Phillips, appeared in 1846, and Manchester became one of the first large cities to install them in 1849. Plans to replace the outmoded system in London with a gigantic sewerage net were begun by Joseph W. Bazalgette in 1852, and by 1865 the system was essentially complete. The magnitude of the task is indicated by the fact that in 1841 the city possessed 83 miles of covered main sewers and 16 miles of smaller sewers, whereas in 1865, the figure had grown to some 1300 miles of ordinary sewers and 82 miles of intercepting sewers. While the sewers were being installed, cesspools were being removed, approximately 100,000 of them disappearing in the twenty years preceding 1862.

Not only was sewerage reform being felt in England at this time, but in America and on the continent as well. Late in the seventeenth century Boston had constructed its first sewers, and from 1709 to 1823 all of its works were constructed by private enterprise. Despite these early beginnings in Boston, however, the first modern sewerage system in America was installed at Chicago in 1855 under the direction of E.S. Chesbrough, an able engineer who had studied English methods. Five years later the English engineer, William Lindley introduced English methods to the continent by constructing a remarkable system at Hamburg, whose original works had been destroyed by fire in 1842.

The original aim of the water carriage system was merely to get the refuse away from the vicinity of the houses by washing it down to the river, where dilution would do the rest. In the cases where small communities were located on large rivers with long runs, disposal by dilution seemed an admirable solution, but in the cases of cities like London--where low summer tidal waters carried the floating sewage back and forth for days--the new water carriage system merely brought new problems. The state to which the Thames had descended during the summers of 1858 and 59 was ably described[15] by William Budd in his work "On the Propagation of Typhoid Fever" (1861) :- "Stench so foul, we may well believe, had never before ascended to pollute this lower air. Never before, at least, had a stink risen to the height of an historic event. Even ancient fable failed to furnish figures adequate to convey a conception of its thrice Augean foulness. -----The river steamers lost their accustomed traffic, and travelers, pressed for time, often made a circuit of many miles rather than cross one of the city bridges."

The immediate solution to London's problem was to install intercepting sewers which carried away the metropolitan filth and dumped it in the Thames 12 and 14 miles below the city. Of course, this did not eliminate the disease and stink, but merely transferred it to another point. Sanitarians, realizing the lethal potentialities of this effluent, were forced to look for a more satisfactory system of sewage disposal than mere dilution in the river.

The Beginnings of Scientific Sewage Disposal

BACKGROUND IN ENGLAND -- Briefly reviewing the rise of sanitary consciousness in England, we see that the period from 1839 to 1842 was dominated by reports from the Poor Law Commissioners, who proposed the construction of sewers, the elimination of cesspools, application of sewage to the land, and the like. In general, the period from 1842 to 1857 was marked by the moving of excretal matters from the vicinity of dwellings without regard to final disposal. A real campaign for public health was begun following the report of the Health of Towns Commission in 1844, and the Public Health Act of 1848 was followed by sewerage schemes in many towns. However, a new problem was, in turn, created--the excessive pollution of many rivers and streams. Passage of the Nuisance Removal Act in 1855 at the close of the third severe cholera epidemic probably marked the beginning of the serious scientific study of the chemistry and biology of sewage in order to combat the problem of stream pollution. Following closely was the appointment of a new Royal Commission on sewage in 1857. The theme of its preliminary report in 1858 was essentially the same as that of its final report in 1865 which concluded, "---the right way to dispose of town sewage is to apply it continuously to land, and it is only by such application that pollution of rivers can be avoided."

EARLY LAND DISPOSAL -- Although the 1858 report of the Sewage of Towns Commission was followed in the next two decades by an almost feverish construction of sewage farms in England, the application of human excreta to agricultural ends was by no means a new thing. Chinese and Japanese had, for centuries, used human manure on their little plots of land, and the custom was not uncommon in Europe. Dr. A.B. Granville in his "Report to the Board of Directors of the Thames Improvement Company" (1837) was highly enthusiastic about the possibilities of "Flemish manure" stating,[16] "Night soil is husbanded in every part of the continent I have visited without exception, with a jealousy and care which proves how valuable it is considered by the people." He urged its use as a means of profit to the householder, middleman, and farmer, and praised the town of Strasburg, where every house was provided with two air and watertight cesspools. Granville noted that originally Paris was going to conduct all its wastes to the Seine, but the arguments of scientific men, agriculturists, and political economists for cesspools and "for conservation" won out. Once more the doctrine of returning to the soil matter derived from the soil became an important issue.

The next step from here was the "separate" system of sewerage, in which household wastes were run through one set of pipes and storm waters through another. Edwin Chadwick proposed it in 1842 and the cry was taken up by others. In his paper[13] read before the Sanitary Congress in Brussels (1856) F.O. Ward called for a water carriage system of small pipes to fertilize the land in the country, and pressed the theme, "the rainfall to the river, the sewage to the soil." Despite the relatively high cost, some few towns did adopt the practice shortly thereafter, but the movement never became widespread.

BROAD IRRIGATION -- The discharge of sewage in a liquid sheet over large tracts of land for fertilizing purposes had been practiced to a limited extent before the nineteenth century. Medieval Lausanne discharged all of its sewage into a small brook, whose use for irrigation was regulated by a law passed in 1400. Farms around Milan and other Lombardy cities of the fifteenth century were often fed by sewage-carrying canals. Probably the first city in Europe to take sewage directly from the house to the farm was Bunzlau, Prussia, where in 1559 a water supply was brought in wooden pipes from a famous spring, and sewers were installed with individual house connections. The system continued in operation for over 300 years, supplying sewage to an area of about 35 acres. In the early eighteenth century the practice was instituted at Ashburton and other towns in Devonshire, but not to any great extent. Another famous system was the sewage meadow of Craigkentinny, Edinburgh, dating from 1760.[17] We are left to our own conclusions as to the success of this venture, for advocates of broad irrigation and sewage farming in the second half of the nineteenth century never seemed to cite Craigkentinny as a worthy example to follow.

Several factors combined to make the broad irrigation of farms popular in England, but the two main elements were (1) the desire to get rid of the sewage without polluting the streams, and (2) the lucrative attractions which sewage farming seemed to possess. For a time these two reasons held equal priority, but it soon became evident that farmland was not always going to be readily accessible for every community, and it also became evident that sewage farming would not make the profits its ardent supporters claimed. However, the third quarter of the nineteenth century saw a tremendous spurt in the method, and by 1883 over two hundred irrigation areas were in operation in England alone. From England the practice spread to the continent, the first large-scale unit being that built by the English engineer, Alexander Aird, at Danzig in 1869. Experiments at Paris in 1865 under Mille and Durand-Claye led to the establishment of an enormous sewage farm system for that city. Flowing by gravity through the sewers designed by M. Belgrand (1865), the sewage passed to the Clichy Pumping Station, thence to the second station Colombe, from here it was conducted under the Seine in two inverted siphons, one to the farm of Achère and the other to Gennévilliers. Berlin, too, adopted the system on a wide scale, establishing its four original farms at Osdorf in 1876, at Gross Beeren in 1882, at Falkenberg in 1879, and at Malchow in 1884.

In America the State Insane Asylums at Augusta, Maine, and Concord, New Hampshire, irrigated hay fields and vegetable gardens with sewage prior to 1875, but the attempts were not entirely successful. Probably the first American success in this line was enjoyed at the Worcester Hospital in 1876. Generally speaking, broad irrigation became more popular in the drier Western states because of the greater need to conserve water. The system inaugurated at Cheyenne, Wyoming, in 1883 set a pattern for the many western projects which followed it; here the sanitary question of sewage disposal was only incidental, the great problem of getting any and all waters to the crops was paramount.

CHEMICAL PRECIPITATION -- It was realized generally that broad irrigation would never be able to solve the sewage disposal problem in many communities, and that other suitable methods would have to be found. Plain sedimentation was tried prior to discharging the effluent into the stream, but this method proved inadequate. Thus the failure of sedimentation to clear sewage thoroughly, and the hope of financial gain, brought about the introduction of several chemical precipitation methods in England in the 1860's. It was hoped that the heavy chemical flocs would not only clarify the sewage but would yield a valuable sludge manure as well. A patent for the chemical treatment of sewage had been taken out as early as 1762 by de Boisseau, but now the idea took on new life, and during the period 1856 to 1876, four hundred and seventeen patents on this subject were issued in England alone.[19] Lime was used as the precipitant in most cases, alone or combined with chloride of lime, chloride of magnesium, sulphate of alumina, phosphate of alumina, green copperas, black-ash waste, herring brine, and others.

Several commercial processes were evolved, all more or less doomed to failure. One of the better-known schemes was the Spencer Alumino-Ferric Process, in which a mixture of ferrous and ferric salts was combined with aluminum sulphate alone or with lime. The International Process involved adding "ferrozone"--a patented product from a Wales iron deposit--to sewage, and filtering both through "polarite"--another patented product from the same deposit. Also well-known was the ABC Process (Alum, blood, charcoal, and clay) of 1868 which was advocated primarily for the fertilizer it produced.

Following Clark's successful softening of water in 1841, A. Aiken advised in 1845 that milk of lime was best for clarifying sewage. The lime process was then introduced at Croydon in 1853, but was found to be unsatisfactory, and experiments on precipitation with milk of lime alone were pronounced a failure by the British Rivers Pollution Commission of 1868. The effluent, clear but not sterilized, became alkaline; ammonia developed and the whole became foul. Legal proceedings in many cities resulted from the nuisances caused by the use of lime alone. Early failures did not dissuade other towns from adopting some type of chemical scheme, however, and during the decade 1880 to 1890 nearly all sewage plants installed in England were of the chemical precipitation type. Among the cities which could not use broad irrigation, but which did regard this solution as practical, temporarily at least, was London. Covered reservoirs had been built at the outfalls of its intercepting sewers at Crossness (1862) and Barking (1863-64) in order to store the sewage for discharge on the outgoing tide. When it was found that the capacities of the reservoirs were too small, chemical precipitation--lime and copperas--was introduced at Barking in 1889 and at Crossness in 1892. No attempt was made to utilize the sludge, which was carried to the sea in ships. The English example carried over into[20] Germany, when in 1882, the government forced Dortmund to install a precipitation plant to deal with the bad odors introduced to the Emster by the effluents from the breweries.

Although it had become somewhat popular in England, chemical precipitation never achieved any wide-spread use in the United States. Coney Island, New York, became the first city in the country to adopt the scheme when a unit designed by J.J. Powers was installed about 1887. This was followed by an installation at Worcester, Massachusetts, the first large city in the country to treat sewage before dumping it. In 1867 the town, whose population was 30,000, built a sewerage system which emptied into various brooks, but serious complaints from downstream on the Blackstone River became particularly strong by 1880. As a result, the town in 1890 installed a small chemical precipitation plant, with six settling basins and a lime house. In 1893 the settling basins were increased to sixteen, and five years later a sludge pressing plant and 14 acres of intermittent sand filtration beds--a new approach to the problem--were added to the system. The experiments carried out by the Massachusetts State Board at Lawrence around 1890 stopped the chemical trend in America, for they showed the system to have the drawbacks of (1) incomplete purification--clear liquid held soluble organic matter and was putrescible, (2) high cost of operation, and (3) difficulty of disposing of the large sludge volume. When it was determined in England that only a small return of manure was realized at great expense, the scheme lost popularity, and, in time, the same reasons which caused its abandonment as a primary purificant of sewage in the United States operated with the same effect in England and elsewhere.

ELECTROLYTIC AND THERMAL PROCESSES -- At about the same time that broad irrigation and chemical precipitation methods came into vogue, experiments with electrolytic methods were begun. In 1859 Charles Watt found that when a solution of chloride of alkalies or alkaline earths was electrolysed, a solution similar to bleaching powder was formed. His work was followed by Chisholm's unsuccessful attempt to purify sewage at Watford in 1860. Almost thirty years later, in 1888, William Webster introduced a process at the Southern Outfall Works, Crossness, whereby the active precipitation of ferric hydroxide was obtained by passing a weak current through iron plates in the sewage. Another variation was produced shortly thereafter by M. Hermite, who electrolysed sea water and added it to sewage or flushed latrines with it. The system was tried in 1894 at Worthing and later at Ipswich and at Nice with indifferent success. A liquid similar to "Hermite" called "Electrozone", produced by electrolyzing brine containing 2 or 3% sodium chloride or sea water, was introduced in the United States by Woolf about 1895 for the purpose of purifying water. It was used for sewage at Maidenhead in 1897, after previous precipitation with "ferrozone" and filtration through "polarite", in the ratio of 1 part to 400 to 600 parts of effluent. Though its germidical action was stated to be good, the system was soon abandoned in Maidenhead, but subsequently adopted in Havana in 1899. In the early twentieth century extensive electrical experiments were conducted at Elmhurst, Long Island, Decatur, Illinois, and Allentown, Pennsylvania, but all led to the conclusion that the electrical treatment of sewage is probably no good.

Another minor method of sewage purification which appeared in the latter part of the nineteenth century was the thermal method of disinfection. It grew out of the system introduced by Captain Liernur, a Dutch engineer, in which faecal matter and closet waters, kept separate from the storm, slop, and surface water, were sucked through the pipes by large air pumps.[21] Advocated in 1868, Liernur's system was first tried on a large scale at Amsterdam in 1871, when a quarter containing 15,000 people was put to the test. The method was soon applied in other towns, one notable example being that of Trouville, France, which combined a policy of conservancy, pneumatic removal, and disinfection. Here the sewage, stored in a covered brick tank for about a week, was treated with sulphuric acid, heated to 120° C in tubular boilers, evaporated until semi-solid, and then reduced in a rotary chamber to a dry powder.

Trends in sewage purification today have shown, however, that the chemical, electrolytic, and thermal processes of the late nineteenth century were but digressions from the main stream of development of sewage disposal, and that modern bacterial methods may be traced back to the days of broad irrigation and its natural successor, intermittent filtration.

Bacterial Purification

BACKGROUND OF BACTERIAL STUDY -- Partial recognition that natural putrefaction is due to living organisms was arrived at early in the nineteenth century when, following Cagniard de la Tour's discovery that yeast is a living plant, Schwamm demonstrated that putrefaction is due to something in the air which heat will destroy, and that meat will not putrefy in calcined air. Even prior to this time men such as Kircher (1671), Leeuwenhoek (1695), and Baker (1743) had laid the foundations for suspecting the existence of organisms, but Liebig (c 1840) and his "Catalytic" school delayed the acceptance of the germ theory for about thirty years. Liebig termed the slow destruction of organic matter "eremacausis" (slow burning), assuming that the action was a direct combination of the matter with oxygen, rather than the working of the bacteria under aerobic conditions. The "Catalytic" view was the accepted one until Pasteur (c 1862) proved that fermentation and putrefaction would not take place in the absence of living organisms, aerobic and anaerobic. Koch then went forward to elaborate on the life history and character of these organisms.

Bacteriology in its early years concentrated mainly on the pathogens, but as the science developed, more attention began to be paid to the larger class of non-pathogenic bacteria. It was the investigation in this latter field which played such an important part in the development of subsequent bacterial methods of sewage treatment. Pasteur, who had expressed the conviction in 1862 that the process of nitrification would eventually be shown to be due to the activity of living organisms, was soon proved right by the French chemists, Schloesing and Müntz. In 1877 they showed that the process must be due to living organisms, for nitrification did not occur in soils sterilized by heat or by chloroform. In the following year Dr. Alexander Mueller, City Chemist of Berlin, took out a patent for the purification of sewage by the cultivation of "yeast-like organisms". This was no new idea with Mueller, for as early as 1865 he had described the purification of sewage as a process of digestion and mineralization carried out by minute animal and vegetable organisms, and the 1872 report of the Berlin Sewerage Commission noted that sewage matter was converted to nitrates, not only by a simple molecular process, but by organisms present in the sewage and soil.[23] Observers in England verified the continental reports. Warrington in 1882 showed that boiling prevented the nitrification of urine or ammonium salts until fresh soil, with living organisms, was added. A year later Dr. Sorby remarked on the large proportion of detritus of faeces lost in the river due to the action of "countless thousands of living creatures"; but it should be noted that he was referring to the larger organisms which he could see under his microscope. Then Dupré, in a report (1884) to the Local Government Board on experiments with aeration, stated that consumption of oxygen from the dissolved air of a natural water is due to the presence of growing organisms without which little or no oxygen would be consumed. Two years later he proposed to treat sewage by cultivating low organisms on a large scale and throwing them in the river with the effluent. When a Royal Commission on Metropolitan Sewage Disposal recommended disinfection or sterilization--owing to the failure of most large sewage farms--Mr. W. J. Dibdin (1887) countered with the statement that thé "antiseptic process is very reverse of object to be aimed at."

INTERMITTENT FILTRATION IN ENGLAND -- The natural outgrowth of broad irrigation, intermittent filtration, was not regarded as a bacterial method of purification when it was first introduced in England. Dr. Edward Frankland, guiding spirit of the Third Rivers Pollution Commission formed in 1868, had originally thought that green plants played an essential part in the purification process in sewage farming, but the fair results he saw on uncropped land gave him an idea. He began experimenting with various soils in cylinders 6 feet high and 10 inches in diameter, in which sewage was applied continuously and intermittently, upward and downward. Continuous operation soon clogged the filters--which these giant test tubes had become--

but judicious intermittent application allowed the filters to work without cleaning for much longer periods of time. Frankland believed that the purifying action of the soil was both mechanical and chemical, but he was not cognizant of its bacterial effects. The essence of the Commission's report which appeared in 1870 was to the effect that "Such a combination of a chemical method with intermittent filtration offers the most hopeful process, both as regards economy and efficiency, in cases where irrigation is impractical. In all practicable cases, however, we strongly recommend the adoption of irrigation in preference to filtration."

A year after Dr. Frankland's report the first large-scale intermittent filter was put into operation at Merthyr Tydfil, Wales. On the eve of the completion of the main sewers of the town in 1868, Messrs. Nixon, Taylor & Company downstream got an injunction against the town's connecting up any more sewers and thus adding to the pollution of the Taff River. A solution to the town's dilemma was offered by J. Bailey Denton, who recommended (1870) intermittent filtration on farm land. He laid down as conditions for successful operation the proper preparation of the soil and the intermittency of application. Sewage was turned on the land at Merthyr Tydfil in 1871, a process soon followed at plants designed by Bailey Denton in other towns. Under this new system the raising of crops was subordinated to the treatment of sewage at a more rapid rate, and, in time, the agricultural aspect of the scheme was abandoned altogether. As a general rule, however, English engineers were not impressed with the scheme, which was more than overshadowed by the enthusiasm for broad irrigation.

THE MASSACHUSETTS STATE BOARD OF HEALTH (1887-90) -- English reluctance to give up broad irrigation was not shared in America where the system had never achieved much popularity. As a result, the introduction of intermittent filtration in America received much greater attention. Credit for the introduction of this new method into the practice of modern sewage treatment must go to the Massachusetts State Board of Health, whose extensive experiments marked a milestone in sanitary progress throughout the world. A background to this work was begun in 1872 when the State Board of Health was directed[24] by the Legislature to "consider the general subject of the disposition of the sewage of towns and cities--(and)--report to the next legislature their views, with such information as they can obtain upon the subject from our own or other lands." A committee under Professor W.R. Nichols set to work on the problem and, as late as its seventh annual report, recommended irrigation. By 1880 the increased settlement and pollution, especially around Boston and vicinity, had reached a stage similar to that reached in England some twenty years before. New special commissions were appointed in 1881 and 1884, the second one recommending the setting up of a permanent commission in 1886. The main conclusion reached in the report of 1886 was to the effect that intermittent filtration is the converse of irrigation; disposal of the waste, and not crops and profit, is its function.[25]

Investigations at a permanent station on the Merrimac

River at Lawrence were then begun under the immediate supervision of Allen Hazen in 1887. In the previous year at Medfield, Massschusetts, E.C. Clarke had utilized preliminary sedimentation, upward filtration through excelsior, and intermittent filtration through natural soil to good advantage. The Lawrence experiments developed along broader lines, however. Ten circular cypress tanks, 17 feet in diameter and 6 feet deep, were filled with various types of filtering material such as sand, gravel, and peat, and sewage was applied in various ways. At first the engineers aimed at the removal or destruction of bacteria by straining and chemical means without practical success; later they shifted to the use of the bacteria under aerobic conditions. It was found that working aerobically the filter rapidly choked, and putrefaction occurred on the interior owing to the deficiency of aeration. The remedy was to apply the sewage intermittently, allowing the bed to "rest" for certain periods of time, and the material best suited for the job was determined to be sand. From these tests the true nature of sewage purification as the working of bacteria growing on the filter in the presence of oxygen was clearly brought out. The process had been more or less clearly understood by Mueller, Schloesing, Müntz, Warington, and Frankland, but its details were elaborated upon and the practical importance of the method was proved for the first time here. One of the earliest practical results of the Lawrence experiments was the installation of the intermittent sand filter at Framingham, Massachusetts, in 1889 under the direction of S.C. Heald.

CONTACT BEDS -- In his work "Drainage" (London, 1889) G.J.C.

Broom commented that "Irrigation is considered the best mode of utilizing the sewage (land being a natural filter), and there is no doubt that it is so." Two years later, however, the Main Drainage Committee of the London City Council authorized investigations at the Barking outfall similar to those which had been carried out in Massachusetts, for the sewage farm, chemical treatment, and precipitation methods had all proved inadequate. W.J. Dibdin, Chemist to the London Council, saw that the Massachusetts experiments gave better promise than did the sewage farms, but that certain modifications would have to be made. The Lawrence method was unsuitable for non-sandy regions, for instance, and it required a greater purification area than could be obtained for London. Use of a material coarser than sand was indicated to cut down on the required area, but such a change would hinder frictional resistance and the purifying agencies would not have time enough to work. Dibdin then hit upon the idea of a watertight filter in which the sewage could remain "in contact" with the filter material and its growth of organisms for the required length of time.

Dibdin, who had previously worked with Dupré (1884) on the aeration of sewage, began his experiments at Barking in 1891 with the principal aim of reducing the area needed in sand filtration. He tried several filtering materials and found coke breeze to be the best, though subsequent contact beds were constructed with coal (for chemically precipitated effluents), broken slate, pounded glass, burnt ballast, clinker, cinder, slag, "polarite", iron, and sand. In 1893 the first unit went into operation, consisting of a 1-acre bed with 3 feet of coke covered by 3 inches of gravel. After further experimentation a cycle was established which called for $1\frac{1}{2}$ hours filling, 2 hours standing, $2\frac{1}{2}$ hours emptying, and 6 hours aeration.

Though Dibdin's first scheme involved subjecting the sewage to the contact bed only after chemical precipitation had clarified it, his best-known work at Sutton, under construction by C. C. Smith in 1894 and in operation by 1896, abandoned the preliminary precipitation phase and substituted "double contact" beds. Here the crude sewage, after passing through large screens, was introduced to the coarse contact bed, $3\frac{1}{2}$ feet in depth, consisting of 2 to 4-inch lumps of burnt clay ballast; from this point the sewage was conducted to the fine filter of $\frac{1}{4}$ to $\frac{3}{4}$ inch pan breeze. "Double contact" units were later installed in such large cities as Leeds and Manchester, and the Hampton Sewage Works went so far as to introduce "triple contact" treatment in 1899. The Hampton Works were dismantled in 1907, however, and replaced by percolating filters. As the century drew to a close Drs. Clowes and Houston continued the Dibdin experiments, but the contact type of filter seemed to have reached its ultimate development, with a usual depth of 3 to 4 feet and the maximum area of $\frac{1}{2}$ acre in England.

TRICKLING OR PERCOLATING FILTERS -- During the decade 1890 to 1900 many new filter types were patented and placed in operation, all with a view toward speeding up the time of operation and confining it to a smaller space. The keynote seemed to be more aeration which would eliminate the idle "resting" time of the intermittent and contact filters. A forerunner of the trickling filter appeared in the Massachusetts State experiments (1887-90) when the sewage was filtered intermittently through gravel stones. Colonel George E. Waring sought to improve on this arrangement by forcing air into the interior of the filtering medium: his scheme was patented in 1891 and tried with no great success at Newport in 1894. A similar arrangement was tried in 1892 at Malvern, England, by S.R. Lowcock who constructed a gravel filter with a top sand layer, and forced air under pressure into the middle of the bed. In the same year Hazen started a filter with 1/5-inch material which was artificially aerated.

Aeration of the filtering material being unsatisfactory, the emphasis shifted to aeration of the sewage before hitting the filter. Although Garfield of Litchfield had used perforated pipes to distribute sewage in 1892, the first description of the application of sewage by a fine spray spread evenly over the whole surface of the bed was made by Wallis Stoddard in 1893. His experiments, begun in that year with a small trickling filter at Bristol, culminated in the construction of the first successful filter of this type at Horfield, near Bristol, in 1899. Quite independently J. Corbett, borough engineer of Salford, carried out similar experiments from 1893 to 1898, continuously passing sewage and air through the filters simultaneously. He first distributed the sewage by wooden troughs on the filter, then he raised the troughs several feet above the bed, and finally he sprayed the sewage over the surface from sprinkler nozzles. Thus, Corbett's work played a large part in developing the details of the process. Another detail which merited a great deal of attention was the first reaction-propelled sewage spray distributor constructed by Caink of Worcester, England, in 1897.

Other pioneers also played a part in developing the percolating idea. Colonel Ducat's filter, installed at Hendon in 1897, was an aerating type, coarse-grained above and fine-grained below, which had hot water pipes for heating the sewage in winter. In the following year Whittaker and Bryant introduced their "Thermal Aerobic Filter" at Accrington, for which they obtained a patent in 1899. Following treatment in an "open septic tank", the effluent was spread over a filter bed--of 2 feet of broken stones and 6 feet of gas coke with limestone chippings on top--by means of an automatic revolving sprinkler. A small steam jet was placed in the delivery pipe to raise the temperature of the sewage when needed to obtain more favorable bacterial action. Several filter chambers, circular or polygonal, 61 feet in diameter with filtering material 9 feet in depth, were used "continuously", but it was found that satisfactory operation still demanded a "rest" period at longer intervals than had been necessary with previous filters.

The trickling filter seemed to be the most satisfactory answer to the sewage disposal problems in places where large areas of sand could not be found. Typical of the English cities which adopted trickling filters is Birmingham which, in 1852, dumped its sewage untreated into the river. In 1859 experiments were begun which led to the installation of chemical precipitation tanks and sewage farms in 1872. Under John D. Watson in 1901 the precipitation basins were converted to septic tanks and the first trickling beds were built in 1903. Adoption of this method lagged somewhat in the United States, really dating from the Columbus, Ohio, experiments of 1904-05, although a few small plants had been in operation prior to that time. Suggestions for a system at Columbus had varied with the years--it was double filtration through coke in 1898, then septic treatment in 1900, and intermittent sand filtration in 1903. Experiments begun under G.A. Johnson in 1904 brought the trickling fliter into prominence and pushed the other ideas into the background. Widely scattered experiments conducted along the same lines at about the same time confirmed the practicability of the system, and the first large American plant at Reading, Pennsylvania, went into operation in 1908.

Although the quality of effluent was not improved, much progress had been made in a decade in cutting down on the filtering area required, and in furthering the idea of artificial filtration. While 1 acre of intermittent sand filtration could handle the sewage of 500 to 1000 persons, the same area of double contact beds could handle that of 4000 to 5000 persons, and the 1-acre trickling filter could take care of at least 10,000.[27] For almost half a century British Royal Commissions had advocated the application of sewage to land; a noticable change occurred in the 1908 report of the Fifth Royal Commission on Sewage Disposal which stated: "We are satisfied that it is practicable to purify the sewage of towns to any degree required, either by land treatment or artificial filters, and that there is no essential difference between the two processes---."

THE SEPTIC PROCESS -- The study of filtration methods of sewage disposal was paralleled on a much smaller scale by a study of septic methods. Use of a septic tank was not particularly a new idea, however, for it was no more than the old cesspool, regulated and controlled. Its rise in popularity was brought about by the difficulty and cost of sludge disposal from plain sedimentation tanks. Under this system the sewage solids were retained to foster the decomposition of settled solids anaerobically, and it was originally thought that complete liquifaction of the suspended solids could be obtained in this manner. Henry Austin's "Report on Means for Deodorizing the Sewage of Towns" (1857) described a tank--to separate the solids from the liquids before treating with lime--which gave indications of having the elements of a successful septic tank. Probably the first successful modern septic tank, however, was the "Automatic Scavenger", devised by Louis H. Mouras of Vesoul, France, about 1860. It consisted of a closed vault with a water seal, and was self emptying and continuous in operation. Widely used in Paris because of the ordinance forbidding the discharge of solid material into the sewers, Mouras' scavenger was not patented in France, England, or the United States until 1881-82, some twenty years after its first use. It did not achieve universal popularity, however, for its effluent was not sufficiently purified without further nitrification. For a decade, in the eastern United States, widespread use was made of Colonel Waring's Newport tank, described in "The Sanitary Drainage of Houses and Towns" (1876). The essential feature of the system was the storing of sewage in a tank whose inlet and outlet were both submerged.

Probably the first to point out and apply practically the two-stage purification of sewage was W.D. Scott-Moncrieff of Ashtead, England, who started his experiments before the Massachusetts results were known, and who constructed the first biological bed in England.[28] In 1891 he erected a plant in which the crude sewage was filtered upward through stones anaerobically, thus partially liquifying the solids. From the anaerobic tank the effluent passed to the second, or aerobic stage, by trickling downward through three superimposed 7-inch coke beds separated by air breaks. In 1893 the same design was used successfully at the borough of Towchester.

Shortly thereafter, in 1895, Donald Cameron, City Surveyor of Exeter, installed his continuous flow septic tank, and in the following year the main sewer of St. Leonard's, a suburb of Exeter with a population of 1500, was connected to the tank. From the tank the effluent was directed in a thin stream over an aerating weir onto a filter of coke breeze or clinker. A submerged inlet conveyed the crude sewage to a grit chamber--in reality a section of the septic tank--which allowed the floating organic matter to pass, but which collected the detritus. The sewage then flowed through the tank anaerobically, taking twenty-four hours to pass. As a result of this septic treatment the total solids were decreased by one-half, and the organic consistency was decreased by two-thirds of its initial value. Cameron's tank attracted world-wide attention, and experiments soon confirmed his work in Leeds, Manchester, and elsewhere. The main result was to establish anaerobic preliminary treatment as one of the most valuable processes in sewage disposal. It helped to form a basis for Dr. S. Rideal's assertion in his "Sewage and Bacterial Purification of Sewage" (London 1900) that sewage purification may be considered to take place in three stages: (1) anaerobic--hydrolytic solution and ammoniacal change, (2) partially aerobic--nitrites and simplified bodies, and (3) complete oxidation and nitrification.

In line with Cameron's work, Professor A.N. Talbot installed one of the first continuous flow septic tanks in the United States at Champaign, Illinois, in 1897. Saratoga, New York, followed in 1903 with an excellent system of septic tanks and sand filters which became noted for the clarity of their effluent. Litigation and wrangling in the courts over patent infringement resulted from the Saratoga installation, however, and this had a bad effect on further development of the septic tank in America. Most communities were unwilling to invest in a process which might involve them in costly patent fights, especially when that process did not give the complete answer to the problem whey were trying to solve.

It was not long before the septic tank began to undergo extensive changes. Sedimentation and digestion had been carried out in one big compartment in the Exeter tank, but the 1899 Report of the Massachusetts State Board forecast the new trend by mentioning the separation of the two processes. Dr. W.O. Travis took the first practical step in this direction in 1904 with his 2-storied "Hydrolytic Tank" at Hampton, England. It was separated into three compartments--two lateral ones through which the fresh sewage flowed, and a third one between and below the others into which the sludge settled. A portion of the fresh sewage was allowed to enter the third, or liquifying chamber, as well. Dr. Karl Imhoff of Essen, Germany, went further still in 1909 in keeping the flowing liquid and septic sludge separate. In the upper portion of the tank which bears his name he installed a sedimentation chamber with slots at the bottom to allow the sludge to settle in the digestion chamber below. Vents at the sides of the sedimentation chamber were added to carry away the gases generated by the digesting sludge in the lower compartment. Use of the Imhoff tank was widely advocated by the Emscher Drainage Board in Germany, and with the help of Dr. Rudolf Hering the tank was introduced in the United States, where it gained great popularity. The first small Imhoff tanks in America went into operation in 1911 at Madison, Wisconsin, and at Chatham, New Jersey, while the first large ones were installed at Atlanta, Georgia, in the following year.

The Imhoff tank principle gave birth to other ideas which resulted in separate sedimentation and sludge tank systems. Such units were installed at Birmingham and Baltimore in 1912, and in the following year J.W. Alvord introduced an original tank in Madison, Wisconsin. At about the time of the first World War L.S. Doten devised a unit for army cantonments whose chief purpose was to avoid the frothing and foaming common to Imhoff tanks overdosed with fresh sewage. In general, however, the early separate systems ran into difficulties because of the failure of those in charge to realize the importance of seeding, reaction, and temperature. Research since 1925 and the operation of plants since 1929 have placed added emphasis on these factors.

THE ACTIVATED SLUDGE PROCESS -- Purifying sewage by agitating it in an open tank along with sewage sludge was a development which did not come until the twentieth century, although many pioneers in the late nineteenth century had approached it by passing air through clarified sewage and through filters. In 1882 Dr. Angus Smith of Britain tried aeration of sewage in tanks, a method experimented with by Dupré and Dibdin two years later. Hartland and Kaye-Parry took out an English patent in 1888 on a system which included an aerating sewage chamber. During the years 1890 and 1891 Dr. Brown carried out extensive experiments on agitation and aeration at Lawrence, Massachusetts, and Mason and Hine, at Rensselaer Polytechnic Institute, did more work on aeration. Further investigations on the aeration of filters were then carried on in 1892 by Waring in America and by Lowcock in England. Apart from aeration, the use of sludge to clarify sewage had a forerunner in the suggestion made by William Foster in his "What to Do With and How to Treat Sewage" (Leeds, 1901). He recommended burning street sweepings, market refuse, ashes, and the like, so as "not to produce the least quantity of ashes." The ashes, when ground, were to be added in such quantities to the sewage as to absorb the nitrogenous matter in solution, and then the whole was to be run through settling tanks and filters alternately or as desired.

More valuable knowledge on the subject was gained as the result of extensive experiments conducted by W.M. Black and E.E. Phelps between 1909 and 1911 on the aeration of sewage in New York Harbor. Their work was followed in 1912 by that of H.W.

Clark, S.D. Gage, and G.O. Adams of the Lawrence Experimental Station, who placed sewage in bottles and in tanks partially filled with roofing slate, spaced about 1 inch apart, and showed that in aerated sewage growths of organisms could be cultivated which would increase the degree of purification. Dr. G. J. Fowler, impressed by the results shown during his trip to the Massachusetts station, returned to England with the idea of continuing experiments along the same lines. Working with Mumford in 1913 he did away with the fixed surfaces and employed a specific organism in combination with a dose of ferric salt. Fowler's suggestions were adopted by Dr. E. Ardern and W.T. Lockett of Manchester in the same year, but they dispensed with the extraneous bacterium and chemical and relied solely on the organisms already in the sewage. The result, reported in 1914, was the activated sludge process. The number of micro-organisms serving to break down the organic solids in the process of digestion was increased by passing air continuously through the sewage, thus producing an intensive culture--called "activated sludge" by Dr. Fowler. It was found that the agitation and diffusion of sludge through the sewage gave the same purification as treatment on land, through contact beds, or through percolating filters. The laboratory experiments of Ardern and Lockett were followed by the installation of two continuous-flow units, converted from existing tanks at Manchester's Works at Withington in 1917.

Blowing air into the sewage was the first method tried in the new activated sludge process. Such a unit was installed at Salford in 1914, followed two years later by England's first large activated sludge plant at Worcester. Here Messrs. Jones and Attwood, who were allowed to experiment with two-thirds of one of the tanks, substituted diffusers for the old perforated pipes. This method was soon largely superseded by bio-aeration, or the mechanical activation of sludge, in which the sewage was mechanically agitated in the presence of air rather than having air blown through it. John Haworth of Sheffield, whose experiments with aeration were begun in 1912, developed the mechanical scheme after the findings of Ardern and Lockett had been made known. His first tank was installed in 1916, and the first large-scale plant of this type was erected in 1919-20. During the next decade many purification works based on this principle were erected throughout Great Britain.

The activated sludge principle began to make headway in other countries as well, the United States and Germany being particularly outstanding in this respect. By 1914 extensive experiments had been carried out at Milwaukee, and in the following year T.C. Hatton installed a full-size unit there. Two years later the Commission decided definitely in favor of the activated sludge process for the city. Houston, Texas, was also among the earliest of large American cities to adopt this new scheme, installing its first plant in 1917. In Germany Drs. Imhoff, Pruss, and Fries combined the mechanical agitation and air blowing methods in an experimental unit at Rellinghausen in the Ruhr Valley in 1924-25. After being screened and having its grease removed, the sewage, flowing by gravity, travelled through shallow detritus channels to the Imhoff tanks; from here the supernatant liquid was subjected to gravity, activated sludge from the final settling tank, compressed air, and rotating paddles; it was then settled in a tank from which the excess activated sludge was pumped back to the Imhoff tank. Digestion tanks were used for the final treatment of the Imhoff tank sludge, and the gas produced was used to heat sewage in the winter and was taken by a public company in the summer. The digestion was measured in terms of destruction of organic matter, the changes in solid matter, and the volume and composition of the gases produced.

SLUDGE DISPOSAL -- The problem of what to do with the remaining sludge was a major problem from the earliest days of sewage disposal. Simple application to land as a fertilizer was not always the best answer, for often a reeking bed of sewage resulted, such as at Birmingham in 1859. This state of affairs led to trenching and lagooning, and also brought the dumping of sludge at sea into popularity. About 1880 E. Monson developed the idea [29] of making building brick of clay and sewage sludge. Although some bricks of this kind were made at Birmingham, Leicester, and elsewhere, the scheme was uneconomical and never received a great deal of attention. The introduction of septic and Imhoff tanks did not materially change the problem, although the spreading of well-digested--hence, relatively inoffensive--sludge on land now became more acceptable. In some cases this sludge was used for filling in land. Largely a development of the twentieth century, was the drying on prepared beds and under glass. Experiments at Cleveland, Ohio, in 1912-13 led to the early establishment of this method in other towns in the state such as Alliance, Canton, and Marion, and the idea gradually spread from there. Burning was another solution adopted by some communities, notably Paris in 1912 and Leeds in 1922. Until about 1928 the only practical means of dewatering activated sludge was by filtration, which was impossible without conditioning the sludge. A solution to the problem was offered as the result of a series of notable experiments at Milwaukee. Sludge in a large tank was mixed with sulphuric acid or ferric chloride by compressed air and baffles; the mixture was then taken to filters from which the liquor was returned to the screened sewage channel, and the pressed sludge was carried to driers. The dried product was then marketed for commercial use as a fertilizer.

Apart from yielding a fertilizer or fertilizer base, sludge digestion has been utilized to provide power and light as well. Donald Cameron of Exeter pioneered the use of sewer gas about 1895, obtaining many patents in this field. Of particular note was his lighting of the tank installation at Belle Isle, Exeter, with gas thus derived. Extensive experiments along this line were also carried out by Dr. L.P. Kinnicut and H.P. Eddy at Worcester, Massachusetts in 1901, and two years later C.C. James at Bombay pumped sewage to the filter beds by using gases from the digestion tank. The use of the gas and sludge commercially has by no means become universal, many engineers preferring to get rid of them as quickly and as easily as possible, but it is significant that so much attention has been given to recapturing the value of the wastes once the primary end of sewage disposal has been achieved.

CHLORINATION -- Among the earliest sewage plants to attempt chlorine treatment was the one at Brewster, New York, where attempts to use hypochlorites on a full-scale in 1875 were unsuccessful. The process was not yet fully understood, for it was not realized that treatment could be better applied to purified effluents than to crude sewage, and that absolute sterilization was not required. Further progress was made at Brewster in 1892 when an electrolytic plant for the production of chlorine from a salt solution was set up.[30] Dr. S. Rideal in his experiments at Guildford in 1905 concentrated on making the chlorination process primarily one of bacterial removal rather than one of chemical purification. During the next two years Phelps demonstrated the economical and practical utilization of chloride of lime at Boston and Redbank in Massachusetts, and at Baltimore, Maryland. Continued experimentation and usage have demonstrated the value of chlorine treatment on clarified sewage for the protection of public water supplies, bathing beaches, and shellfish areas; and in addition, it has been found useful in controlling odors, filter flies, and clogged filters.

DILUTION -- The final stage in most modern sewage disposal methods is the dilution of the effluent in natural waters. A few important studies were made on the "self purification" of streams in the nineteenth century, but, by and large, the subject did not receive the attention its importance warranted. One of the earliest discourses on the subject appeared in 1864 when S. Macadam discussed the water of Leith at length in the Third Report of the Sewage of Towns Commission. In 1884 Dr. Beale wrote of the sewage in the Thames mud, and in the following year Dr. H.C. Sorby's very important "Report of a Microscopical Investigation of Thames Muds" appeared in the report of a Royal Commission. Shortly thereafter, in 1887, Rudolf Hering began investigating the factors entering into the problem of dilution--an investigation which resulted in Chicago's Main Drainage Canal, completed in 1900. Prior to 1900 Chicago's sewage went to the Chicago River, which emptied into Lake Michigan, the source of the city's water supply. The Drainage Canal changed the course of the sewage from the lake to eventual delivery to the Mississippi River. As a result, the State of Missouri instituted proceedings, complaining that Chicago's sewage was contaminating the water supply of St. Louis. The sewage took from eight to eighteen days to flow a distance of 357 miles, during which time sufficient purification took place to warrant a dismissal of Missouri's case as unproved.

Varying situations demand varying degrees of purification prior to dilution. Generally speaking, the amount of dilution necessary decreases with the mode of purification in the following order: crude sewage, grit chambers, coarse screens, fine screens, sedimentation, septic tanks, Imhoff tanks, contact beds, trickling filters, activated sludge, and intermittent sand filters. The usual course has been to combine several of the methods to achieve the desired effluent; for example, a typical combination might consist of grit chamber, coarse screens, Imhoff tanks, and trickling filters. In the final analysis it is the amount of dilution possible in the end which dictates the size and type of purification plant needed at the beginning of the sewage disposal process.

Summary

Prior to the nineteenth century the disposal of household wastes was at best taken care of by dumping in covered cesspits or by allowing natural drainage and scavengers to clear the city streets onto which the wastes had been flung. Some early cities such as Rome had sewers, to be sure, but their primary purpose was to carry off excess storm and ground waters. Thus, most early sewers developed along crooked and winding lines, being for the most part, simply small streams covered over.

As the first half of the nineteenth century was drawing to a close, England, which had struggled along with the same primitive sanitary system used in other civilized countries, suddenly found itself greatly in need of sewerage reform. The Industrial Revolution brought great cities into being almost overnight--and one result of this rapid building was slums and poverty, dirt, and disease. A growing social consciousness on the part of the bourgeoisie and intellectuals brought about inquiries concerning the welfare of the poor, inquiries revealing conditions which shocked the nation into action. The gross amount of stink and dirt, combined with the lack of adequate sanitary facilities, seemed to go hand in hand with the incidence of disease which well might spread to even the most prosperous sections of the community. This threat of cholera and typhoid hanging over the whole population was enough to drive out the backyard privies and middens, and bring in the water carriage

system of disposal in large cities such as London.

Sending most of the city wastes through the sewers brought forth a new problem, however--stream pollution. This threat to the water supplies of the nation was almost worse than the one which had just been cleared up, and it was necessary to take further action. Since the sewage could not be dumped in the river, the next logical place was to dump it on land. As long as it was being dumped on the land, some fertilizing value might be obtained from it. Thus, broad irrigation came into vogue in the third quarter of the nineteenth century, first in England and later on the continent. Many farms soon became overloaded with reeking sewage under the broad irrigation scheme, however, and experimenters found that by applying the sewage to the land at intervals rather than continuously that land could be kept "sweet."

Many towns were not in a position to apply their sewage to land, so they were forced to seek more compact methods of treatment. Plain sedimentation, chemical precipitation, and electrolytic methods were all tried with varying success, the most popular being chemical precipitation during the 1880's in England. The natural successor to broad irrigation and intermittent filtration was the more compact intermittent sand filter, whose bacteriological properties were elaborated upon for the first time by the Massachusetts State Board of Health (1887-90). Although it yielded an excellent effluent, the sand filter still required more space and sand than most communities could afford. Thus, the decade beginning in 1890 was marked by the introduction of several filters with reduced areas and increased rates of filtration. English contact beds, which retained the sewage on smaller areas than did the sand filters, were largely superseded by the more rapid trickling filters.

During this decade it was brought out that anaerobic as well as aerobic conditions could play a part in sewage treatment. The continuous flow septic tank of 1895 was improved by separation of the sedimentation and digestion compartments in the Imhoff tank of 1909. Then, the purification of sewage by agitating it in an open tank with sewage sludge--the activated sludge process--made its appearance in 1913. Before the decade was out many plants were operating on this principle, both in England and America.

Thus, in less than a century, sewage disposal was raised from a nonentity to a highly-developed, scientific, essential community service. Tangible results of its contributions have been reflected in national and local health progress charts, and millions of people today live in comfort undreamed of before the advent of modern sanitation. Working in cooperation with the doctor and chemist, the sanitary engineer has played a great part in raising the standards of health and comfort throughout the world, and there is every reason to believe that his future contributions will be worthy successors to his past.

FOOTNOTES

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3. Livy, transl. by B.O. Foster, book I, chap. xxxviii & Lvi.

4. Pliny, transl. by J. Bostock & H.T. Riley, book xxxvi, chap. 24.

5. Gest, A.P., "Engineering," pg. 186.

6. Cresy, E., "Encyclopaedia of Civil Engineering," pg. 192.

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13. Taylor, F. Sherwood, "The Century of Science," pg. 82.

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15. Ibid., pg. 12.

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17. Broom, G.J.C., "Drainage," pg. 61.

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24. Rafter, G.W. & Baker, M.N., "Sewage Disposal in the United States," pg. 34.

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27. Kinnicut, L.P., Winslow, C.-E.A., & Pratt, R.W., "Sewage Disposal," pg. 372.

28. Moore, E.C,S., op. cit., pg.590.

29. Monson, E., "Metropolitan Sewage," pg. 62 f.

30. Metcalf, L. & Eddy, H.P., op. cit., pg. 12.

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Chapter X

HYDRAULIC and COASTAL WORKS

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Irrigation and Flood Control

EGYPT -- From earliest times the chief source of Egyptian wealth has been its agriculture, made possible by the periodic floods of the Nile which have left a rich top dressing over the land. Originally the farmers simply followed as the flood waters receded, planting over the recently inundated land and retreating once more when the waters began to rise again. From accounts more legendary than historical it appears[1] that Menes of the First Dynasty (c 3200 B.C.) was the first to attempt regulation of these floods on a national scale. He is reputed to have put up a long dyke parallel to the Nile on its left bank, and then to have erected cross-dykes or intercepting canals which acted to carry the waters into pockets or basins in the Libyan Hills. Thus was born the "basin" system of irrigation which depended upon the regular overflow of the river for its successful use.

This basin system served Egypt for centuries--up to modern times, in fact--but under the Pharoahs of the Twelfth Dynasty, the Amenhats and the Usartsens (probably before 2000 B.C.), even more extensive works were constructed and more land was made available for farming. In reclaiming land on the right bank of the Nile the engineers did not construct a dyke similar to that on the left bank, for they realized that the sudden confinement of the river would have disastrous effects further down the river at Memphis and in Lower Egypt. Instead they widened and deepened the Fayum depression in the Libyan Hills and created the famed Lake Moeris. Herodotus writing in the fifth century

B.C.[2] claimed that the lake had a circumference of 60 schoenes or 3600 furlongs, a length equal to that of the entire sea-coast of Egypt. He also noted that the lake must be artificial, for two pyramids stood at the middle, extending fifty fathoms (300 feet) below the water level and 50 fathoms above. Water was admitted to the lake from the Nile, he said, by means of a canal. Five hundred years later Strabo[3] confirmed the presence of Lake Moeris, but he considered it largely a work of nature, noting, however, that engineers had placed locks at either end of the regulating entrance canal. The lake was of such extent that it was capable of absorbing the Nile floods; then at lower phases of the river, irrigating waters were released from this reservoir as needed. As a result, "perennial" irrigation was introduced, wherein water was carried to the land regardless of the state of the Nile, and the widespread inundation of former times was considerably reduced.

Apart from the control afforded by Lake Moeris in ancient times, the primary method of irrigation in Egypt remained the basin system from the time of the Pharoahs, through that of the Ptolemies and Romans down to the Arab conquest in the seventh century A.D. From A.D. 700 to 1800 the population of the country slowly dwindled while most attempts at systematized irrigation were abandoned over a large part of the Delta. Then early in the nineteenth century Mohamed Ali[4] changed the system and basin irrigation was confined largely to Upper Egypt. Beginning in 1874 a large part of Upper Egypt was converted to perennial irrigation, and as the century drew to a close, British engineers commenced the modern construction of irrigation works which have proved so beneficial to the country.

BABYLONIA -- Irrigation and flood control were also known and practiced by the Babylonians but to a lesser extent than that of the Egyptians, according to the meager evidence available. The Code of Khammurabi (c 1900 B.C.) stated that if a landowner caused damage to his neighbor's land by neglecting that portion of a canal for which he was responsible, he had to pay damages in full; if insolvent, he could be sold up. At a much later date Nabopolassar (625- c 605 B.C.) and his son, Nebuchadnezzar (c 605-562 B.C.), were credited with many hydraulic and other public improvements in the famed city--so great, in fact, was the extent of these improvements that the name Babylon has come down through the ages as being synonymous with worldly pomp and pride. One of the most important of the works attributed to these kings was the digging of the bed of the Euphrates from Babylon to Sippara and the lining of the banks with brick and bitumen. Near Sippara a huge reservoir for irrigation was then made by Nebuchadnezzar.[5] Possibly it was this same reservoir which Herodotus attributed to Queen Nitocris; at any rate, there are still traces today of a great dam above Babylon.

GREAT DRAINAGE PROJECTS -- The Greeks, living in mountainous country, developed few irrigation or flood control schemes, and they did not particularly concern themselves with drainage problems. Such was not the case with the Romans, however, for they devoted much thought and effort to canals and tunnels for draining certain areas. One of their most famous projects was the reclamation of the Pontine Marshes, approximately 180 square miles in extent, near Rome. Originally the area had been made somewhat habitable by its settlers, the Volsci, but the unsettled conditions occasioned by Roman conquests reduced the area once more to its marshy state. Various attempts to drain the place properly were made during the time of the Republic, then under Caesar and Trajan. Theodoric named Cecina to do the job once more, and, for a time, much of the country was useful again. Decline soon set in and the project was not revived until 1777, when Pope Pius VI called in the engineers Rappini, Zanotti, and Boldrini.[6] Parallel to the Appian Way they built a canal called the Linea Pio which still survives as the central artery of the Pontine district. Modern improvements were begun in 1926 under Mussolini with the result that more main canals have appeared, model towns have sprung up, and useful land has been recovered.

Another historic reclamation project has been the drainage of the English Fens of Cambridgeshire and Lincolnshire. The first successful assault on this area was made by Cornelius Vermyden, who left Holland about 1621 to stem a breach in the Thames embankment near Dagenham. After draining the Royal Park at Windsor, the Hatfield Chase, and the Royal Chase on the borders of Yorkshire, Vermyden was called upon to reclaim the lowly Fens. Essentially the problem was solved (1) by clearing rivers of accumulated silt, to afford free passage of waters from the uplands, and (2) by erecting dykes to keep back the tidal waters of the sea. Many drainage canals were also made during this time, following the Dutch practice (as previously noted in the chapter on Canals). Despite the forceful protests of the Fenmen Vermyden continued, with the aid of several of his countrymen, to drain the area for many years, making his last appearance in connection with the project before Parliament in 1656. Various engineers followed the Dutchman in this great task, Rennie in the eighteenth century and Hawkshaw in the nineteenth among them. New sluices, causeways, embankments, and dykes were formed, and eventually six hundred and eighty thousand acres, an area equal to that of North and South Holland, were converted from dreary waste to productive plain.

For centuries the Dutch have been engaged in reclaiming land from the sea in their own as well as in other countries. Work begun shortly after the close of World War I still continues on the winning of land from the Zuider Zee. Thus, from the time of the Egyptians up to the present day, man has been continually at work on some phase of hydraulic engineering, be it irrigation, flood control, or drainage.

MODERN FLOOD CONTROL AND IRRIGATION -- Previous mention under "Canals" has been made of the early irrigation works of India, China, and Italy, but many other countries deserve mention as well. In Western Australia, for instance, a great pipeline completed in 1903 brings water across parched land to the gold-bearing district of Kalgoorlie from a reservoir in the Darling Range, 350 miles away. Modern control projects in almost any part of the world could be cited as typical of present-day practice, but few can be compared with the magnitude of the job of controlling the Mississippi River. Rising in Minnesota, the Mississippi flows 2910 miles to the Gulf of Mexico, draining some 1,250,000 square miles of country enroute. Combined with its tributary, the Missouri River, it becomes a waterway 4500 miles in length--one of the longest and most important streams on earth. Between 1874 and 1937 eighteen disastrous floods struck the Mississippi Valley, resulting in extreme misery and hardship for thousands, taking countless lives, and destroying vast amounts of property. To fight these inundations engineers have erected levees along the banks of the river ever since the days of M. Blond de la Tour who, in 1717, constructed a mile-long levee in front of New Orleans. Prior to the Civil War the basins of the Mississippi Valley were protected by levees weak in profile and insufficient in height. During the war these lines were cut indiscriminately by armies, and the floods of 1862-65 gradually destroyed the remains. Following the particularly disastrous flood of 1872 a measure of federal control under the U.S. Army Engineers was inaugurated, but local and State controls remained in effect as well. By 1900 110,000,000 cubic yards of earth had been utilized in constructing 1283 miles of levees on either side of the river below Cario,[7] and less than forty years later their total length had stretched to 2500 miles. These levees, as they have been since the earliest days, are for the most part earth dams, varying from 10 to 40 feet in height and from 80 to 250 feet in thickness at the base. Besides erecting levees to contain rising waters the engineers have made liberal use of "revetments"--huge mats of saplings, often measuring 250 by 1000 feet, weighted down by huge stones--

to strengthen the long banks of soft mud. Despite huge expenditures and great construction feats of the past, however, the problem of containing the Mississippi has not yet been completely "solved," and there seems little likelihood that a full solution will be reached before many years have passed.

In the field of irrigation, progress has been particularly marked during the past century, especially in the arid western portions of the United States. The beginnings of American irrigation are usually attributed to Brigham Young and his Mormons, an agricultural people who settled in the Salt Lake Valley in 1847. Apart from that serving the farming lands of the Mormons, early irrigation in the West was largely incidental to mining and stock raising. A great boom in irrigation came in the late eighties and early nineties, financed by promoters who hoped to make large quick returns on relatively small initial investments. The boom was followed by a depression which lasted until about 1902, the year that the Federal Government passed the Reclamation Law. A Reclamation Bureau was set up and the construction of irrigation works by the Federal Government was begun with the proceeds from the sale of public lands. At about the same time private activity was resumed and private and public works proceeded side by side. In less than forty years from the time of its inception, the Reclamation Bureau had built more than one hundred dams--some of them the greatest in the world--and had reclaimed some twenty million acres.

EARTH DAMS -- The brief sketch above on irrigation and flood control gives some indication of the great importance which dams have played in the history of hydraulic engineering. Probably the earliest dams made were simply earth mounds, and the type has survived to this day with certain modifications and improvements. Not only is earth handled in the dry now, but in the wet as well. In many modern jobs the hydraulic excavating, transporting, and depositing is done by pressure from a jet or gravity from a flume. Apart from consisting wholly of a homogeneous bank of earth the modern earth dam may have a watertight puddle core--consisting of earth, clay, and sometimes gravel thoroughly mixed and compacted--or a masonry core wall. Many earth dams have also been provided with puddle on the water slope. As a general rule, the upstream slope will vary from 1 on 2 to 1 on 3 while the downstream face will vary from 1 on 1½ to 1 on 2½.

Old earth dams, several centuries old, may still be seen in many parts of India, and indeed, many of them are still in use to make up the reservoirs known as "tanks." These native-made dams aggregate some 30,000 miles in length, providing in all about ninety thousand tanks.[8] One of the most famous of these very old dams is the one at the Poniary Tank of Trichinopoly which is no longer in use. The water area of this tank was somewhere between 60 and 80 square miles, and the dam itself stretched for approximately 30 miles. Equally famous is the Veranum Tank still in use, with a water area of 35 square miles and a dam length of 12 miles. Of the smaller types, the Chumbrumbaukum Tank is a fine example, its embankment varying from 16 to 28 feet in height and stretching 19,200 feet in length. Yet another of these important works is the Cauverypauk Tank, which has been in use almost five hundred years. Its embankment--which extends for 3½ miles--is revetted on the water side by a stone wall 22 feet high, 6 feet thick at the bottom and 3 feet thick at the top, and the exposed face has been carefully turfed. In Ceylon some of the ancient works have exceeded even those of India in extent and grandeur. The Tank of Kalaweva (A.D. 459) had a circumference of about 40 miles, and its 12-mile long embankment was covered with a spillway of stone. Similarly the Tank of Padavil was faced throughout its entire length of 11 miles with layers of squared stone, the embankment measuring 30 feet in width at the top, 200 feet at the base, and 70 feet in height. Still largely intact is the Mudduck Masur Tank over 400 years old. The central of its three dams ranges in height from 91 to 108 feet, and its base varies in thickness from 945 to 1100 feet.

Coming down to more modern earth dam construction we find a good example in R.K. Martin's Druid Lake Dam (1864-71) built for the storage reservoir of Baltimore's waterworks. The earth portion was built with an inner slope of 1 on 4, an outer slope of 1 on 2, a top width of 60 feet, a bottom width of 640 feet, and a height of 119 feet. A stone wall at the base was surrounded by a puddle core wall 36 feet wide at the bottom and 17 feet at the top. Shortly thereafter (1874-76), the San Leandro Dam for the Oakland Waterworks was built with an even wider base--

one of 1700 feet. This figure was then upped to 1930 feet on the 2-mile North Dyke of the Wachusett Reservoir built under the direction of F.P. Stearns from 1898 to 1905. Still greater was the twentieth century's Gatun Dam at Panama, measuring 2019 feet in thickness at sea level and 390 feet at the lake's surface, 85 feet above sea level. While the above examples represent success in this type of dam, failures have also marked its progress. One of the most disastrous failures occurred at Johnstown, Pennsylvania, on May 31, 1889 during the course of the great flood. Over two thousand lives were lost when the earth dam gave way before the onslaughts of the raging waters. In retrospect many engineers felt that the dam would not have failed completely if it had been provided with a core wall. Modern construction has, therefore, been particularly marked by the inclusion of core walls, as well as by the great increase of base thickness and a leveling of face slopes.

THEORY OF MASONRY DAM PROFILES -- As engineers continued to construct dams containing greater heads of water, the need for a building material more suitable than earth became apparent. A substitute was introduced in southern Spain in the form of masonry dams which seem to have come in about the sixteenth century in connection with large irrigation reservoirs. A rather haphazard development in masonry ensued, and it was not until the middle of the nineteenth century that a truly scientific approach to the problem of design was accomplished. First to investigate the matter satisfactorily was De Sazilly, whose findings were published in the "Annales des Ponts et Chaussées" in 1853. He argued that the safety of a dam depends primarily on two factors--viz., (1) the pressure sustained by the masonry or its foundation should never exceed a certain safe limit, and (2) there should be no possibility of a portion of the masonry sliding nor of the whole wall moving on its foundation. Accordingly, he recommended a stepped profile, tapering towards the top, with the greater portion of the base on the water side of the structure.

The investigations of De Sazilly were soon followed by those of another Frenchman, M. Delocre, who was called to his task as the result of the frequent inundations of the valley of the Loire. It was determined by the French engineers that the flood problem could be solved by the construction of large reservoirs to contain the overflow, but sufficient storage was only possible by constructing dams up to 50 meters (164 feet)--a height at which earth dams would have been hazardous. Hence, the concentrated studies on the best type of masonry profile. Delocre's solution was similar to that of De Sazilly, but he eliminated the steps and smoothed out both faces. His conclusions, which formed the basis for the design of the Furens Dam near St. Étienne, were known by 1858, but were not published in the "Annales des Ponts et Chaussées" until 1866 when work on the dam had been completed.

The next investigator of importance to add his contribution to the subject was Glasgow University's Professor Macquorn Rankine (1820-72), whose advice was requested in connection with some proposed reservoirs at Bombay. His calculations led him to be the first to insist that the lines of pressure should be kept in the middle third of the masonry. He used a higher limit of pressure at the inner than at the outer face and thus reduced the batter of the former considerably. More principles were formulated by M. Le Blanc, appearing in the "Annales, etc." of 1856, '59 and '69, and these new ideas were used by Bouvier (1874) in making calculations for France's Ternay Dam. Analytical solutions were offered by Pelletrou in 1876, '77, '79 and '97, and trial calculations were advocated by Professor A.R. Harlacker of Prague in 1875. Guilleman and Hétier argued that the gravity dam should have a greater section toward its base than that given by De Sazilly and his followers. Then Clavenad, a member of the commission investigating the failure of the Havra Dam in Algiers, recommended that the resistance of a dam to shearing along inclined joints should be included with calculations of horizontal joints. The development was carried over into the twentieth century by L.W. Atcherly of London who pointed out in 1904 that vertical joints should also be tested, and that, as a matter of fact, they should be given first place in the considerations. Since that time development in theory has largely been concentrated on concrete dams, which have steadily been suplanting the older types of masonry construction.

MASONRY DAMS -- Spain is generally regarded as the original home of the masonry dam, the earliest of importance being the Almanza Dam in the province of Albacite. Its exact date is unknown, but old records indicate that the structure was in use before 1586. Like most of the early Spanish dams it was built primarily for irrigation. Founded on rock and built of rubble masonry, the dam was faced with cut stone throughout except on the upper 20 feet, which were made of rough ashlar with courses of cut stone at intervals. The structure was 292 feet long, and its greatest height reached 67.86 feet. In profile one face was made vertical and the other was stepped back irregularly; the lower portion was built convex upstream. An overflow was provided at the side by excavating in the rock for a distance of about 39 feet at a depth of 6 1/3 feet. The solidity of the dam is indicated by the fact that for over three hundred years it withstood a pressure of 14 1/3 tons per square foot. The next dam of note was Juan de Herreras' Alicante (1579-94), built to a curvilinear plan across the gorge of Tibi. Like the Almanza, it was also built of rubble masonry and faced with large cut stones. Only 30 feet across at tis base, the dam fanned out to a distance of 90 feet at the top, reaching a maximum height of 134½ feet. Originally the dam had no waste weir, but one was built in 1697. In the great flood of 1792 water rose 8.2 feet over the top of the dam with no harmful effects, so the waste weir was then closed and has remained that way ever since.

Spanish tradition was carried on in what was considered one of the greatest engineering achievements of the reigns of Charles III and Charles IV--the Puentes Dam (1785-91), erected where the waters of the Velez, Turilla, and Luchena unite to form the Guadalatine River. The whole wall of this dam, which had a maximum height of 164 feet and a crest length of 925.3 feet, was of rubble masonry faced with large cut stones.

Unfortunately the structure was short-lived, being destroyed in 1802 when the pile foundation at the center gave way. The piling had been undermined by the water pressing its way through the soft material underneath--an error which cost not only the dam, but six hundred and eight lives and nine hundred and eight houses as well. A more permanent structure replaced the original in 1886. Another ill-fated work was the Dam del Gasco, begun in 1788 but stopped in the following year by a heavy flooding from a rainstorm. At the time the dam was already 187 feet high, and was to have been ultimately 305 feet. One more Spanish masonry dam worthy of note is the Villar (1870-78) on the river Lozoya, designed and built under the direction of José Morer to furnish an additional water supply for Madrid. It was built entirely of rubble masonry except for some cut stone on the crown, and reached a height of approximately 170 feet.

Despite the much earlier Spanish examples, no masonry dam of any extent was erected in France until the latter part of the eighteenth century. At that time, on the Canal of the South, the Lampy Dam (1776-82) was constructed, bearing the following approximate dimensions: height 54 feet, base 36½ feet, and top 16 feet. About 1843 the Zola Dam for the reservoir of Aix-en-Provence gained the fame--which it retained for several years--of being the only dam unable to resist the water thrust by its weight alone. Being circular in plan it was stable solely because it acted as a horizontal arch abutting against the sides of the valley. Standing 119¾ feet it had the relatively slim profile of a base width of approximately 42 feet and a top width of 19 feet. Shortly thereafter studies were begun which resulted in the Furens Dam, generally regarded as the first correctly designed masonry dam in the world. When it was decided in 1858 to erect the structure to protect St. Étienne from inundation and also to provide a water supply, M. Graeff, the chief engineer, assigned M. Delocre to the profile studies and M. Montgolfier to construction. Their combined efforts produced what was then the greatest of dam heights--183.72 feet on the upstream face. It was also the first French curvilinear dam, a form adopted mainly to give it more pleasing lines. Practically the whole wall, including the facing, was made of rubble masonry and was completed during the period 1862-66.

The French encouragement of rational design methods was soon reflected in a marked increase in the construction of masonry dams throughout the world. Hardly in the French tradition, however, was the heavy Gileppe Dam of Belgium, built to form a reservoir for regulating stream flow and supplying water to the cloth factories of Verviers. Engineer Bidault began his studies of the project in 1857, but numerous delays prevented him from getting the plans to the ministry until 1868. The major part of the construction work was carried out in six years (1870-75), a total of 325,000 cubic yards of masonry being laid during the period. Foundations were placed 1 meter in rock, and the whole dam was constructed of rubble masonry, except for bands of cut stone at the top and bottom and at points of batter change. Standing 154.2 feet at its highest point, with top and bottom lengths of 771 and 269 feet and breadths of 49.22 and 216.5 feet respectively, it was criticized by many engineers for its extraordinary width at the top--not scientific like the Furens

Dam, for example--and so it came to be known as the strongest dam in Europe.

Shortly after the Gileppe project had been completed, the English began work on a very fine structure on the Vyrnwy River for the purpose of creating a storage reservoir for the water supply of Liverpool, more than 50 miles distant. The dam (1882-90) was constructed straight in plan with a length along the top of 1350 feet and a maximum height above the foundation of 136 feet. "Cyclopean rubble," stronger than regular rubble, was used throughout, the stones weighing about 2 tons per cubic yard. More than half of the stones placed weighed more than 2 tons and a third of the total weighed between 4 and 8 tons. Extreme care was taken with joints, and each stone before being placed was subjected to a 140-pound water jet. On completion the dam was hailed as the greatest in Great Britain.

The highest dam of its kind in Europe soon followed (1901-04), the Urft Dam near Aachen, Germany. Designed and built under the direction of Professor O. Intze, it attained a maximum height of 190 1/3 feet above the foundation. A paved earthen embankment with a slope of 2 on 1 was placed against the upstream face for half its height to complete the reservoir of about twelve billion gallons, used to regulate the river flow and to provide power and irrigation.

Outside of Europe the British became particularly active in dam construction in India and Africa during the latter part of the nineteenth century and well into the twentieth. One of the largest pieces of construction accomplished was the Tansa Dam, first proposed in 1870 by Major Hector Tullock for the water supply of Bombay. Final plans and construction were executed under W. Clark, who headed a force varying from nine to twelve thousand men during the construction period from 1886 to 1891. Some idea of the magnitude of the job--the dam being 8800 feet long and 118 feet high--may be gained from a glance at the following items:[9] total excavation 257,127 cubic yards, loose rubble stone 544,700 cubic yards, lime 81,700 cubic yards, washed sand 122,555 cubic yards, and rubble masonry 408,520 cubic yards.

Along the Nile, where the natural rise is 40 to 45 feet in Upper Egypt and 20 to 23 feet at the Delta, a number of fine dams known as barrages have also been erected for the purpose of perennial irrigation. Of particular interest are the Rosetta and Damietta Dams across the two branches of the Nile bearing those names. Napoleon, when he was in Egypt in 1798 and 99,[10] had predicted that such a venture would be undertaken eventually. Work was begun with a will in 1833 under the Viceroy Mohamed Ali, who proposed to tear down the Pyramids at Gizeh to obtain the necessary building materials. He was only dissuaded from this act of vandalism by the engineer who produced figures to show that quarrying stone would be cheaper. For several diverse reasons, matters lagged until the scheme was revived in 1842 by M. Mougel--afterward Mougel Bey--who interested Mohamed Ali in a combination of forts and dams by modifying somewhat the original plans. As finally constructed, each barrage was composed of two locks and sixty-one arches, with movable gates for damming the waters or allowing them to flow freely as required. The Rosetta dam was made 465 meters (1524 feet 8 inches) in length, and the Damietta 535 meters (1754 feet 3 inches).

Mohamed Ali's eagerness to get the job done led him to impose many impractical conditions on his engineers, one of them being his insistence that 1000 cubic meters of masonry be laid every day regardless of the situation. Ali did not live to see the work completed and Mougel was replaced in 1853 by Mazhar Bey on orders of the new Viceroy--an individual who shared none of his predecessor's enthusiasm for the project. Although he would have allowed the job to lapse, the new Viceroy was goaded into action by popular demand, and things moved slowly toward completion. Then in 1867 part of Rosetta failed. Restoration was not accomplished satisfactorily until the Englishman, Sir William Willcocks, took over the task in 1887 and completed it in 1890.

Willcocks was also prominent in many other projects on the Nile, one of the best known of which was the granite-rubble Aswan Dam,[10] converter of four hundred and fifty thousand acres of basin land to land under perennial irrigation. Following Willcocks' design in 1895, the contract was let in 1898 and construction was carried on from 1889 until its official completion in 1902. No sooner was it completed than enlargements were begun which were carried on until 1907; later, a second period of enlargement was conducted from 1929 to 1933. The redesign for enlarging to a height of 130 feet and length of 6400 feet was chiefly the work of Sir Murdock Macdonald, another great engineer of the Nile.

Probably the boldest masonry dam erected in the latter part of the nineteenth century was F.E. Brown's Bear Valley Dam (1884) in the Bernardino Mountains of California. Of rough granite ashlar with a hearting of rubble, its curved form enabled it to act as an arch, with the line of pressure of the full reservoir lying almost entirely outside of the profile. Measuring 300 feet along the crest and 64 feet in height, it continued to serve for a quarter of a century until replaced by a larger and more conservative structure 200 yards downstream. With the perfection of the technique of using concrete, horizontal arch dams have become bolder and more commonplace. As part of the Los Angeles flood control project the Pacoima Dam (1928) illustrates this advance, with a height of 380 feet, a thickness varying from 8 to 101 feet, and a maximum radius of 340 feet.

A much more important American structure was the New Croton Dam (1892-1907), designed under the direction of A. Fteley for part of New York City's water supply system. Originally the structure was to be part earth dam and part masonry, but it was later changed to all masonry except for a short piece of 128 feet. One of its outstanding features was the foundation preparations, with excavations amounting to 1,821,400 cubic yards of earth and 400,250 cubic yards of rock. The greatest depth to which the foundation was carried was 123 feet below the river bed, the maximum rock excavation amounting to 54 feet. This meant that the greatest height of the structure was almost 300 feet, since the top was carried 169 feet above the river bed. Rubble masonry faced above the backfilling with ashlar was used in most parts of the dam, but the extension which replaced the earth dam was made of cyclopean masonry. The top of the structure was then fittingly capped with a 19½-foot roadway.

In 1933 a special Act of Congress created the Tennessee

Valley Authority for regulating the Tennessee River by means of ten dams from Paducah, Kentucky to Knoxville, Tennessee, 650 miles upstream. Typical of its works was the Norris Dam, with a total height, from the lowest point in the power house to the crest, of 265 feet, and a base thickness at the spillway of 204 feet. The masonry section of the dam was made 1570 feet in length in addition to a 302-foot rolled earth embankment with a reinforced concrete core wall. One more twentieth century American dam deserves mention before turning from masonry construction. It is the Roosevelt Dam across the Salt River in Arizona, 280 feet high and 1125 feet along the crest. Designed to play a part in the desert reclamation of the West, it was made of rubble masonry with coursed rubble faces.

REINFORCED CONCRETE DAMS -- With the beginning of the twentieth century a new type of structure, the reinforced concrete dam, was gradually introduced. The early concrete dams were relatively low structures, generally used as an improvement on wood, and were usually characterized by buttresses and much broader bases than is now customary. Typical of this early type was the dam built at Schuylerville, New York, in 1904 for the American Wood Board Company on the Batten Kil River. The structure was hollow, but the abutments, wing walls, and bulkheads were of solid concrete. Its length was 250 feet between abutments, and its average height above the river bed was only 25 feet. Higher works were erected during these pioneer years, however. In South Australia the Barossa Dam (1899-1903) was built on a curved plan with a maximum height over the foundations of 112 feet, its top width being 4½ feet and its bottom width above the foundation being 34. Another early "high" concrete dam in use by 1909 was the Douglas Dam in Wyoming, standing 135 feet above the water line.

More recent years have seen a tremendous increase in the size of concrete dams, the Boulder Dam in Nevada being an excellent example. As early as 1902 government and private engineers had selected likely sites for controlling the erratic Colorado River, but it was not until 1919, when the possibility of developing water power on a paying basis seemed likely, that progress was realized. In 1921 the Colorado River Commission was formed under the chairmanship of the then Secretary of Commerce, Herbert Hoover, and surveys were begun. The contract was let in 1931 and the dam was completed in 1936, four and one-half years after the commencement of the work. Under Construction Superintendent F.T. Crowe foundations were begun 139 feet below water level, and some 3,400,000 cubic yards of concrete were used to raise the structure 727 feet above the river bed.[11] Approximately 800,000 linear feet of 2-inch boiler tube were embedded in the concrete to carry the circulating cooling water. When the structure--whose crest length measured a quarter of a mile--was placed in operation the level of the dammed river was raised 584 feet.

An even greater project in concrete was the Grand Coulee Dam on the Columbia River, 90 miles west of Spokane, Washington. Irrigation, power development, and river regulation were the major aims of the work, begun in 1935. Approximately 11,250,000 cubic yards of concrete were used making the dam, the principal dimensions being: height 550 feet, length along crest 4200 feet, base width 500 feet, and top width 30 feet. It raised the surface of the river 355 feet and has enabled an electrical energy output of 2,700,000 horsepower to be obtained--an output of six times that developed at the famous Dnieper Dam in Russia.

OTHER TYPES OF DAMS -- Wooden dams of brushwood, logs, cribwork, or framed timber have long been used for minor works, and some attempts have been made in the twentieth century to erect dams of steel. Much more extensive works known as rock-fill dams have come into use, however, especially in western portions of the United States. In this type of structure the rock is dumped rather loosely except at the faces, and watertightness is insured by a sheeting of concrete on the water slope or by the erection of an earthen dam in connection with the rock fill. One of the finest examples of this type is the Dix River Dam (1923-25) in Kentucky, built to a height of 275 feet with a concrete skin varying from 8 to 18 inches. The earlier dams of the West were composed largely (60 to 70 percent) of big stones laid by hand, but this practice was followed by the more modern cyclopean concrete containing a smaller percentage (25 percent) of the large stones. Still more recent examples have abandoned the "plums" altogether and have been composed of concrete throughout, with cobble rock in the more massive portions.

WATER POWER

EARLY MILLS AND WHEELS -- One of the greatest effects of the dam on modern life has been the development of hydro-electric power, accompanied by its vast number of benefits. Long before the electrical end of the combination was discovered, however, men were experimenting with various types of wheels and turbines as prime movers. It is possible that the waterwheel turned by the flow of a river was used by the Sumerians, for they are reputed to have had a month called "The Month for raising Waterwheels." The earliest known reference to a watermill appeared in a poem of Antipater of Thessalonica (c 65 B.C.),[12] and Strabo noted that Mithradates, King of Pontus, had at about the same time, a hydraulic machine at Cabira. Vitruvius contributed more specific evidence by describing with illustrations a geared undershot mill. Little is known as to just when water mills came into general use, though. We gain the impression that water mills were common in Rome by the fourth century A.D. at least, for in 398 Honorius and Arcadius issued an edict to protect the water supply used in driving the mills of the city. A fifth century reference appeared in the collection of Irish laws known as the "Senchus Mor"--whose origins are said to date to the time of St. Patrick, but whose written versions are of a considerably later date. Here the parts of a horizontal wheel for application to grinding were set forth in detail. Several centuries then elapsed before the appearance of the first known drawing, subsequent to Vitruvius, of the gears of a mill. This drawing was produced by the Abbess

Harrad of Landsberg in his "Hortus Deliciarum" (1169). No evidence has come down to us as to whether the horizontal ("Greek") or vertical ("Roman") wheel was first, although many of the early drawings favored the vertical type. The more usual type of wheel in the Middle Ages seems to have been the undershot kind, for explicit illustrations of overshot wheels were relatively rare and were not made, apparently, before the middle of the fourteenth century. Apart from an isolated reference in Ausonius to a water-driven saw for cutting marble, the earliest use to which the mill was put--aside from the grinding of grain--seems to have been in connection with textiles.[13]

Less practical than the early water mill, but significant in the over-all development of the turbine was Hero's "whirling eolipile." Steam was introduced to a pivoted ball and then allowed to escape through two nozzles. The nozzles were so arranged that the ball was whirled around by the reaction of the escaping steam--in the same way in which a type of modern garden sprinkler rotates as the water leaves it. Hero's eolipile was really a toy, but the principle behind it stimulated a spirit of research when it became known to the thinkers of the Renaissance world. The earliest translation of Hero's "Pneumatics" appears to have been made by Regiomontanus, a German astronomer and mathematician, who went to Italy in 1461 to learn Greek. It was not until 1575, however, that the first translation (in Latin) to be printed was made by Frederick Comandine. Influenced no doubt by Hero's work, both Branca (1629) and Kircher (1656) illustrated wheels rotated by jets of steam, and the former is credited with being the first modern writer to suggest a way of moving solids by steam.

During the fifteenth century illustrations began to appear showing a water jet acting against the blades of a horizontal wheel. Leonardo da Vinci added his contribution by depicting the vanes as curved instead of straight, and further development was shown by Besson in his "Theatrum instrumentorum et marchinarum" published in 1578. A wheel similar to that of Besson was given in Belidor's "Architecture Hydraulique" (1737). Shortly thereafter the prototype of the reaction turbine was developed. Suggested by Robert Barker and constructed by Desaguliers about 1743, it was a small reaction water wheel on a vertical axis, similar in action to Hero's steam eolipile. Throughout the remainder of the eighteenth century many men prominent in the field of scientific research devoted considerable thought to the improvement of efficiency in water wheels. Among these pioneers may be included Polhem (early part of century), Segner and Euler (1750-54), Defarcieux (1753), Smeaton (1752-59), Papecino d'Antoni (1759-62), Bossert (1770), and Nordwall (1790-1800). Special mention must be accorded the father of Sadi Carnot, L.N.M. Carnot, who first clearly enunciated in 1787 the proposition that for the maximum effeciency in a water engine, the fluid must enter without impact and leave without energy. Thus the turbine, which was finally developed in the nineteenth century, resulted (1) from the critical revision of various horizontal water wheels common in southern Europe in the fifteenth and sixteenth centuries, and (2) from the development of mathematics, hydraulics, and the experimental method in the eighteenth century.

EARLY WATER TURBINES -- Apparently the word "turbine" was coined by the Frenchman Claude Burdin in 1828 to describe a machine he had designed in 1824. Derived from the Latin "turbo", meaning that which spins or whirls round, the word is still amply descriptive of the modern machine, for today's turbine is a rotary engine actuated by the reaction, impulse, or both, of a current of fluid. In principle Burdin's machine was similar to Barker's mill, but it was improved in that water entered the rotating part with an initial angular velocity and left without velocity. Burdin spent several years trying to improve on the reaction wheels of Segner and Euler, producing many low efficiency types, but his main contribution to hydraulics was the knowledge and stimulation he imparted to his pupil, Benoit Fourneyron, at the École des Mines at St. Étienne.

Between 1823 and 1827 Fourneyron constructed a reaction turbine on a vertical axis superior to anything yet designed. By 1832 he had built a turbine with an efficiency between 70 and 80 percent developing 50 horsepower--a machine which he described before the Society for Industrial Encouragement in 1834. In recognition of his feat he was awarded the prize of 6000 francs which had been offered by the Society in 1823 for the most satisfactory improvement of the turbine-like wheels of Belidor. The prize-winning machine was of the "outward flow" type, water entering the moving vanes from a fixed cylinder inside and leaving at the periphery of the wheel. Industry was quick to take advantage of this new device, and one of Fourneyron's first turbines was a 14-inch wheel operating under a head of 350 feet at a cotton factory in St. Blasien, Germany.

Now that the reaction turbine had been proved to be an economic asset, various modifications and improvements quickly followed. About 1837 the "axial flow" Jonval turbine appeared, in which blades and guides were set around cylindrical drums and the water was made to flow parallel to the axis of rotation. An "inward flow" turbine was designed by an American engineer, S.B. Howd, in 1838 but it was considerably modified by J.B. Francis of Lowell, Massachusetts, about 1849. In the Francis turbine the rotating wheel was placed within fixed guide blades which formed part of an annulus surrounding the wheel. This rendered it smaller and more compact than the Fourneyron machine. Though more efficient, the latter required a larger wheel for a given power, and operated at a lower speed. Despite the introduction of other types of flow, however, the Fourneyron type continued to attract designers desirous of improving on the original. The first real turbine designed in the United States--by Boyden of Lawrence, Massachusetts, in 1844--was based on the Fourneyron wheel, and the improved machine of Girard in 1856 was also a direct descendant of the original. In this outward flow turbine he ventilated the wheel passages and widened them towards the outlet to relieve the water of all pressure above that of the atmosphere. Though he had started out with a reaction turbine, he ended up, in fact, with an impulse turbine.

Thus far we have discussed only the reaction type, but the impulse turbine also reached maturity during the nineteenth century. In 1824 J.V. Poncelet brought forth a prototype of the impulse turbine which very nearly met the requirements for an efficient water engine as laid down by Carnot some years before. Poncelet's machine was an undershot water wheel in which the water ran smoothly up curved blades and smoothly back, leaving without motion relative to the earth. This wheel was suitable for low heads, but with moderate or high heads the water ran so far up the blades that energy was lost in impact against the drum. In 1856 Cheetham remedied this defect by designing blades formed like double buckets, with a center ridge on which water at entry impinged. Lester A. Pelton then improved the shape of the buckets and arranged for the incoming water to be directed by a single jet. Completion of the transition from the water wheel to the impulse water turbine was officially acknowledged in the granting of an American patent to Pelton in 1880.

MODERN WATER TURBINES -- From the earliest days of the water wheel there has been no extension of the single and simple function--rather, progress has been made in increasing the efficiency of that function. Undershot wheels have not achieved an efficiency much over 30 percent, but breast and overshot wheels have been improved to a rating between 60 and 80 percent. Once the basic problems of the reaction turbine had been solved, designers then embarked on a program of increasing the speed. This was accomplished by lessening the wheel diameter, increasing the length of the runner, and using fewer but larger blades which extended towards the center of the wheel. Axial discharge was thus accentuated with the result that the machine came to be known as the mixed flow turbine. Essentially the reaction turbine has come to be a high-speed, low-head machine, the highest head yet used being that of about 1180 feet at the Zappello plant in Italy. At the other end of the scale, a French plant has operated at a head of 31 inches.[14]

The impulse turbine, on the other hand, has developed as a low-speed type, utilized where considerable fall or head is available. Its most efficient linear speed has been found to be one-half of that of the jet of driving water--a fact established by Eytelwein in 1801. The efficiency of the Pelton wheel was further increased by Doble of San Francisco who cut away the outer lip of the buckets. Heads have steadily increased with the years with the result that heads exceeding 5400 feet are now being used in Europe.

Harbors

HARBORS OF THE ANCIENTS -- Returning momentarily to the dam, we note that not only has it played a significant part in the development of irrigation, flood control, and water power, but that it has also cast its influence on harbor and breakwater construction as well. When the early engineer found it necessary to form a harbor with a protecting breakwater, he simply transplanted a dam from the shore to the sea. Early among the sea-faring folk requiring harbors in the Mediterranean were the Cretans, whose pre-Hellenic port (c 1900-1800 B.C.) on the Island of Pharos remained undiscovered until the early twentieth century. An interesting account of the ancient port has been presented by M. Gaston Joudet, Chief Engineer, Egyptian Ports and Lights, in his "Les Ports Submergés de l'ancienne

Ile de Pharos" (Institut Egyptien, 1916). West of Ras-el-Tin, and between it and the rock of Abu Bakar extends a depression according to Joudet, with a present depth of 6 to 10 meters. The entrance of the deep sea channel is marked just off the point of Ras-el-Tin by a landing quay 14 meters wide, built of rough-hewn blocks, some of which are almost 5 meters long. A great breakwater facing the sea to the north has been traced for 2000 meters, and Joudet estimates that the great western basin, 2360 meters long and 300 meters wide, could hold four hundred galleys or triremes 90 feet long. The works were buried in sand beneath the sea bottom when found by the modern discoverers, and there is nothing to show just how far back they were known. There is no evidence that Alexander knew anything of these works when he linked Pharos with the mainland and built the harbors of Alexandria, some fifteen hundred years after the Cretans.

The Phoenicians are well-remembered as a sea-going race, but relatively little information concerning their harbors has come down to us. Sidon (now Saida) was reputed to have two harbors with an internal connection, but no trace now remains and the modern anchorage is only protected by a ledge of rock. Tyre, 20 miles south of Sidon, apparently had a much more extensive harbor system, but here again we have little definite information. The original city--from which, according to legend, Dido fled and founded Carthage--was destroyed by Nebuchadnezzar after a siege of thirteen years. A second city was then established half a mile from shore, and it was here that two harbors were built, one on the north side of the island and the other on the south side. A canal cutting through the city served to connect one harbor with the other. The breakwaters which served to enclose the harbors on the seaward side were made of massive blocks of masonry in mortar, and chains were drawn over the openings when it was desired to close the port entirely. Legend relates that Alexander demolished (332 B.C.) the old city, previously sacked by Nebuchadnezzar, and used the rubble to build a causeway 200 feet wide to the island to bring up his siege engines. In time the causeway was buried by sand from the littoral drift and the island became completely united to the mainland.

Facts concerning the port of Carthage are also meager although traces of masonry still exist at the borders of the Cothon. It appears that the island was the center of the port, which was made up of an outer harbor for merchantmen and an inner harbor for men-of-war. The plausible theory has been advanced by Beulé in his "Fouilles à Carthage" that the quays were in the form of "abris", or small docks radiating like wheel spokes. A small port judged by modern standards, the diameter of the inner harbor was only about 325 meters while that of the island approximated 106 meters. The masonry work consisted of heavy blocks of stone secured by iron cramps fixed in holes and run in with lead.

Many ports were built or improved upon by the Greeks throughout the Mediterranean, one of the most important of them being the port of Alexandria on a strip of land separating Lake Mareotis from the sea. Dinocrates, builder of the Temple of Diana at Ephesus, was the engineer and architect for this great work. He formed two separate harbors by uniting the mainland and the Island of Pharos with a mole known as the Heptastadion, 7 stadia--about 4200 feet--long and 600 feet wide. Drift through the years has widened the strip considerably, but the original work is estimated to have been composed of over two million cubic yards of material. Within the harbors themselves semicircular moles were erected which provided tying-up facilities in addition to more security from wind and weather. Few traces of the Alexandrine harbors exist today, for in its long and tumultuous history the city has been subject to conquest by Caesar in 48 B.C., the Arabs in A.D. 641, the Turks in 1517, the French in 1798, and the English in 1801.

The original port of Athens consisted of the small, almost entirely land-locked harbor of Phalerum, about a thousand feet in diameter, protected at the mouth by two masonry moles which were closed by chains. Themistocles transferred the port to the peninsula of Munychia, where a near land-locked basin about 1400 feet in diameter occupied the east side, and three larger harbors, all interconnecting, occupied the west. In order to protect communications between these harbors and Athens from land attack, the Greeks, sometime after 485 B.C., built a series of long walls from Athens to Piraeus.[15] About 330 B.C. Philon, under orders of Demetrius Phalerus, enlarged the harbors of Piraeus and built around them shelters for four hundred triremes. These shelters, used for protecting the planks of ships against the sun when laid up, later became a common feature in many of the more important ports of Rome.

A good example of a natural harbor improved by the Greeks was that of Cnidus, a tideless spot facing the island of Rhodes. Here two harbors, for separating the military vessels from the commercial, were obtained by linking the island to the mainland with a man-made isthmus. An arch in the mole for allowing water to pass unrestricted from one side to the other was still visible in 1847. The substratum consisted of rubble thrown in until it reached a natural slope; regular masonry was then built above the water line. Syracuse, defended by Archimedes but taken by the Romans in 213 B.C., was also favored with a natural harbor. Its entrance was protected by chains drawn across from the extremity of Ortygia to the promontory of Plemmyrium opposite, a distance of approximately half a mile. A small basin east of Ortygia, named Portus Marmoreus, had walls and floors of marble. There is no record of a caisson or cofferdam being used on this job, so it may reasonably be assumed that the blocks were lowered into place from the surface of the water with the utmost of care.

Passing on to the Roman world we find a decided advance in the art of harbor construction. Italy is not supplied with the natural harbors of North Africa and of the Aegean, so it was only natural and necessary during the rise of Rome that her engineers should seek advanced methods of providing the harbors which nature had not. Harbors built by the Romans were surrounded by breakwaters of solid masonry brought up from the sea bed, often resting on piles. In many places arched moles were used, giving economy in foundations and masonry, and serving to keep the harbors clear of accretions of mud. One such example was the mole with a double wall at Misinum, where each wall was pierced by a series of arches not opposite to one another. Cellae, those covered recesses for war vessels surrounded and roofed over with masonry, were another distinctive feature of important Roman ports. In some places these cellae were also slip-ways on which ships could be drawn out of the water for repairs.

The modern port of Rome is at Civita Vecchia, site of the ancient port of Centum Cellae which contained, as its name implies, one hundred covered docks for galleys. It resembled the port of Antirhodus at Alexandria, containing an upstream and downstream ship entrance. The cellae were concentrated along the shore side of the harbor, and two curved moles extended from the extremities of the cellae toward a center point well out in the water. Seaward of, and across the opening where the two moles nearly met, was a third mole, which served the dual purpose of completing the encirclement of the harbor and of providing the upstream and downstream ship entrance previously mentioned.

The ancient port of Rome at Ostia, then at the mouth of the Tiber but now some miles from the sea, was a much greater port than Centum Cellae. Apparently work was begun there under Augustus, or possibly under one of his immediate successors, and was considerably extended under Claudius and Trajan. The outer harbor, or Claudius' Port, was formed by two parallel moles, housing cellae, which curved toward each other at their seaward extremities. In the entrance between the ends of the moles stood a small island dominated by the statue of Claudius. Further inland, surrounded by wharves, was the commercial harbor, knwon as Trajan's Port. Skirting close to the docks of the inner harbor was as Trajan's Canal which permitted smaller vessels to by-pass Ostia and enter the Tiber in order to approach Rome more closely. This great harbor has long since been silted up, even as it was in Strabo's time, but ruins still remain which give ample evidence of its former size and importance.

Strabo has given us some indication of the extent of water-front construction near Capuàe, on the northern shore of the Bay of Naples, which was served during Roman times by the ports of Cumae, Misenum, Baiae, and Puteoli (Pozzuoli).[16] He noted that the Gulf of Lucrinus which broadened out as far as Baiae was shut off by a mound "8 stadia in length and as broad as a wagon road." Its original construction was attributed to Heracles who, according to tradition, employed it in driving the bulls of Geryon across the swamps. Whatever its origin, it subsequently fell into decay and was again repaired and improved upon by Agrippa. A portion of it, about 250 yards in length, is still visible beneath the water. At Puteoli bricks and a mixed sand-ash or pozzuolana were used to run jetties into the sea. Sixteen of the original twenty-five buttresses of the ancient pier still remain, bearing an inscription to the fact that the pier was restored by Antonius Pius.

A brief review of the ancient works reveals the most common method of breakwater construction to have been simply the dumping of rock continuously until a base was built up, after which erection was continued up solidly or on arches. Essentially, the method has continued up to modern times, but with certain variations. The seventeenth century breakwater of

Richelieu at Rochelle, 1000 meters in length, affords an early modern example of the beginning of a break with the traditional past. Here, at the shore ends, stonework on piers was the rule, while further out the foundations were made on boats sunk full of stonework cut and shaped to the sides of the boats. A tempest overturned the boats, so the breakwater was finished by rock thrown on and between the overturned craft. Though the breakwater itself was destroyed in 1628, the foundations remained and gave Cessart an idea for the breakwater at Cherbourg over a century later.

A plan to shelter the French fleet in a man-made harbor at Cherbourg had been advanced as early as 1679 by Vauban, who proposed to unite Homet to the Isle de Pelée, but a century elapsed before any real progress was made.[17] Cessart's idea, approved in 1781, called for a disconnected mole, 4180 yards in length, from the point of Querqueville to the Isle de Pelée, based on ninety cones, 130 feet in diameter at the bottom, tapering to 64½ feet at the top, and 65 feet high. Placed close together, the wooden frames were to be filled with rough stone and topped with concrete masonry. The first trial cone was placed in 1782, and by 1788 eighteen cones were in position when a tempest destroyed the works and brought about an abandonment of the cone plan. Work was stopped completely in 1790 because of the French Revolution, but was resumed intermittently during the time of Napoleon and later, and was finally pursued vigorously to completion from 1830 to 1853. In constructing this first modern breakwater of any considerable size the engineers arrived at the conclusions that in this type of construction large rocks were necessary in depths above 5 or 6 yards and that the use of hydraulic mortar was indispensable.

Two other harbors of the nineteenth century, one English and the other American, are generally considered as being among the foremost of their time. Begun under John Rennie in 1812 and completed in 1847, the harbor at Plymouth was the first important work of its kind in England. The breakwater was a single mole whose center part measured 714 yards in length, and whose two arms, making 135° angles with the center portion, measured 320 yards in length. The mole was constructed of "pierre perdue," the dropped rocks varying in size from ½ to 2-yard cubes. At Cape Henlopen, Delaware, the breakwater was made of two arms meeting at an angle of 135°, one being 700 yards long and the other 500. It, too, was a massive undertaking, for the upper blocks, weighing 4 to 4½ tons, were regularly placed and laid on edge with an outer slope of 2 on 11. Begun under Simon Bernard, a general in the Engineer Corps of France, and William Strickland, the job was completed in 1869.

Twentieth century harbor works have incorporated increasingly bold designs, an interesting example being that of the Port of Bordeaux' landing stage at Le Verdon in the estuary of the River Gironde. Connected to land by a 1258-foot viaduct, the landing stage, 1256 feet in length, was built on reinforced concrete cylinders which were filled with concrete after being sunk. The cylinders, bell-shaped at the bottom, came in sizes up to 87 feet in length and weighed about 290 tons each. A large hydraulic type of shock absorber, essentially a large pendulum structure, was the designers' unique way of protecting the concrete superstructure from the impact of mooring ships.

During Warld War II a temporary type of modern breakwater was made (1944) by the Anglo-American forces who stormed the beaches of Normandy between Cherbourg and Le Havre. Open concrete caissons, made in England and towed across the channel, were flooded and sunk at the site. Old ships were also sunk in a line to complete the job. Inside the harbor thus created were placed floating pierheads connected to the shore by pontoon bridges.

Of great importance in the planning of modern hydraulic works are the scale models and preliminary theoretical calculations. Mention has previously been made of the contributions of some of the earlier hydraulicians such as Castelli, Torricelli, and Bernouilli, and also of some of the later ones such as Chezy, Bazin, and Kutter. The first serious attempt to construct a model of a tidal river along scientific lines was made by Professor Osbourne Reynolds in 1885. This first model, which represented a region between the Liverpool narrows and a point above Runcorn, had a horizontal scale of 1:31,800 and a vertical scale of 1:960, giving a distortion of approximately 33:1. Since the time of Reynolds many improvements in this type of model have been made. Engineers have come to realize the value of such studies to the extent that very few large hydraulic works are carried out today without preliminary model work.

Docks

WET DOCKS -- Commercial expansion and the rapid increase in the size of ships during the seventeenth and eighteenth centuries brought forth a new type of waterfront construction--the dock--an artificial basin for the reception of vessels, with gates to keep in or shut out the water. At ports with large tidal ranges, such as London, the most economical way to accomodate the large ships proved to be the placing of them in restricted slips--called wet docks--at high tide. Gates were then closed and the vessels remained in their same relative buoyant position, although outside the dock the waters receded during low tide.[18] The first mention of a dock--as it is understood today--on the Thames was the note in Pepys Diary (1661) referring to his visit to Blackwall, where he viewed the dock (dry) and the new wet dock of 1½ acres, for fitting out new vessels after launching. The latter was eventually absorbed in the Brunswick Dock at Blackwall in 1789.

Practically the whole of the wharf and warehouse accommodation of the port of London was wiped out in the Fire of 1666, and it was not until toward the end of the century that a revived interest in wet docks took place. The Howland Great Wet Dock at Rotherhithe, which survived almost in its original form until the end of the nineteenth century, was then constructed during the period 1695 to 1701. Trees were planted around the 10-acre dock to break the force of the wind. Its lock was 150 feet long and 44 feet wide, and at full spring tides it had 17 feet of water over the sill. The dock itself was 1070 feet in length and 500 feet in width and could accommodate one hundred and twenty merchant ships of the largest size. Though other docks were constructed during the rest of the century, it remained the largest in the port for about a hundred years. During the same period a number of magnificent docks were constructed at Liverpool, the Act for the first of these being passed in 1708.

William Vaughan in his treatise of 1793 "On Wet Docks, Quays, and Warehouses for the Port of London, with hints respecting Trade" suggested the sites of St. Katharine's Church, Wapping, the Isle of Dogs, and Rotherhithe. Within thirty years after the publication of his work all the sites were occupied by docks. High in importance among the docks constructed during this period were those of the West India Dock Company, opened in 1802 and essentially completed in 1805. Together the docks covered an area of 54 acres, the Import Dock measuring 2600 feet in length and 500 feet in breadth, and the Export Dock measuring 2600 by 400 feet. At that time (1802) the principal lock was only 45 feet wide and the deepest water was only 21 feet. Several prominent engineers of the day were engaged in creating this work, among them being the elder John Rennie as "consulting surveyor," Ralph Walker as "surveyor," and William Jessop as designer and builder.

Half a century later, work was begun at London on what was to become the largest enclosed dock system in the world,[19] aggregating some 247 acres. First of the series of docks was the Royal Victoria (1855), and it was followed in 1880 by Alexander Rendel's Royal Albert Dock--at the time the finest in the world. It was made approximately 1¾ miles long, enclosing a water area of 87 acres, with an entrance lock measuring 550 feet in length, 80 feet in width, and 30 feet in depth. It was later exceeded in 1921 by the third of the interconnecting docks--the King George V Dock--whose entrance lock was given the dimensions of 800 by 100 by 35½ feet, with provisions for achieving a depth of 38 feet by pumping when required.

DOCK WALLS -- Early dock walls had a cross section which was radial or curved, both on the face and back of the wall. This shape probably came from the "pitched" or stone-faced banks in use before actual walls were built, which roughly conformed to the ships' shape. Most generally the construction was of rubble masonry in lime mortar with an ashlar facing, although timber was also widely used. Excavations, introduced on a sizeable scale in the latter part of the eighteenth century, were carried down in the open in series of steps or benchings. Walls were then built up and a filling was deposited behind the walls, which were backed in many cases with a layer of loose rubble stone. Until about 1900 most dock walls were faced with masonry and backed by concrete, but after that time the all-concrete walls came to the fore. In special cases sheet piling has served for a wall, as have cellular or pontoon blocks.

Special foundation procedures evolved as docks, for lack of other space, were placed in spots with difficult soil conditions. In England "monoliths" of brickwork, concrete, or other material have been used successfully as bases for walls at various ports of the country, being sunk from ground level by excavation within them. Excavation is carried on in the open by making the monoliths in the form of boxes or cylinders open at the top and employing grabs, or by manual labor under compressed air. One notable early type was that designed by Sir John W. Barry for extension of the Surrey Commercial Docks in 1898. Here the monoliths themselves were of concrete, while the cutting edges consisted of steel over timber. This system, with variations, is known and used almost universally, of course. Walls on caissons sunk by compressed air have found favor in France especially, being known as the "systéme des caissons perdus." As the caisson sinks, the wall erected above it continues to add weight and thus aids the sinking. This system was used at Le Havre where each caisson measured 141 by 26 feet.

GRAVING DOCKS -- The maritime Greeks on occasion dry docked their ships by floating them into an excavation on the foreshore, building an earthen dam across the inlet, and then removing the water from the area. That, basically, is how the modern drydock operates, but development to the present state has come along slowly. Prior to the nineteenth century the usual way of getting at the bottom of a ship to scrape and repair it was by the method of "careening." A ship was dragged up on the beach as far as possible, and then pulled over on one side and then on the other. "Public hards," prepared by laying down chalk or stone on a tidal flat, came as the logical successor to the careening beaches. Such hards are still used today for servicing tugs, barges, and other small craft. It was but a short step from the hards to a gridiron composed of a timber framework on piles on the riverbottom. From this beginning both the marine railway and graving dock evolved.

Marine railways, on which a ship is hauled up an incline until completely out of the water, have been restricted to the service of relatively small craft, but graving docks have kept pace with the increase in size of the largest ships. Probably the first modern drydocks of importance were the 324-foot long masonry docks built for the United States Navy at Boston and at Norfolk during the period from 1827 to 1834. Built from identical plans under the direction of Laommi Baldwin and his assistants, Captain A. Parris and W.P.S. Sanger, they remained in operation for over a century, unexcelled examples of their era. During the remainder of the nineteenth century many timber as well as masonry docks made their appearance throughout the sea-faring world. Typical of the old masonry type of this period was the Number 1 Drydock at Glasgow, completed in 1875. Its side walls and upper floor surface were constructed of ashlar masonry, while the body of the floor was made of concrete, in which was imbedded a brick invert. Like most of the other docks of its time its walls were curved to the lowest altar course. Its more important dimensions included a length on the floor of 551 feet, a width at the coping of 72 feet, and a depth over the sill at high water spring tide of 22 feet 10 inches.

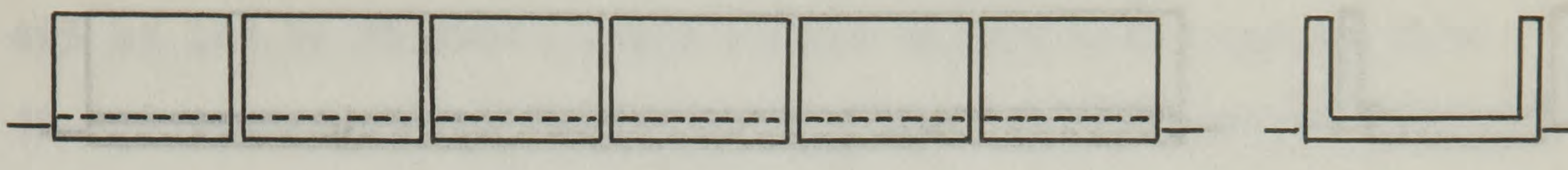
Tremendous increases in the size of ships during the twentieth century brought about a like increase in the size of the drydocks. At Boston in 1918 the Navy acquired from the Commonwealth of Massachusetts one of the earliest of docks exceeding 1000 feet--this particular dock being 1176 feet in length, 149 feet wide at the coping, and 43 feet in depth from mean high water to the top of the keel blocks. In 1926 the French placed a dock in commission at Le Havre with a length on the blocks of 1024 1/3 feet, a width at the entrance of 124 2/3 feet, and a depth over the sill at high water spring tide of 52½ feet. Still greater was the King George V Dock at Southampton which was opened in 1933. Capable of handling ships up to 100,000 tons it was constructed with a length of 1200 feet, a width of 135 feet, and a depth from floor to coping of 59½ feet. Measuring 165 feet across at the cope level, it was designed to have a depth of 45 feet of water over the blocks at high tide. Four hours was set as normal pumping time to get rid of the 58,000,000 gallons of water held in the dock when devoid of ships. Like the dock at Le Havre, it was given a concrete floor 25 feet in thickness. Also worthy of mention among the large graving docks of the world is the dock at Toulon, 1384 feet long and 114.8 feet wide, and that at St. Nazaire, 1148 feet long, 164 feet wide, and 43½ feet deep. A comparison of these dimensions with those of only a hundred years before indicates the great strides which have been made in this type of construction. Apparently the practical limit will be determined only by the size of the ships of the future.

FLOATING DRY DOCKS -- Many harbors needing drydocking facilities but having, for one reason or another, no suitable site for such a structure were forced to turn to the expedient of the floating drydock. An early forerunner of the type--a hydraulic lift dock with a lifting capacity of 5780 tons--was installed at the Victoria Docks (1855) at London and remained in use until 1896. Thirty-two hydraulic rams were used to hoist the vessels which, when raised, were supported on floating pontoons. Closer to a true floating dock was the device patented in the United States in 1816 by J. Adamson. Apparently the idea originated from the wreck of an old hull lying on a sloping beach. An opening was cut in the stern and gates were installed similar to those of a canal lock. The vessel to be docked was led into the hull at high tide, and when the waters had receded the gates were then closed to permit working in the dry. Strictly speaking this was not an actual floating dock except by accident, for it was expected that the docking hull would remain aground. Similar to Adamson's dock was the Old Balanced or Gravity Dock with a gate at each end, built in Brooklyn between 1845 and 1850. It was a large structure for its time, being 330 feet long and 100 feet wide, and it gained the reputation of being the largest structure in wood undertaken for a floating dock.[20]

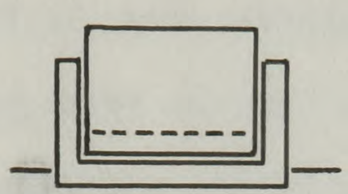
When it was found that the length of a solid wooden dock was limited by strength considerations, the trend shifted to the sectional dock of several separate parts. With this new type another advantage was also gained; the dock could be made self-docking to facilitate its own cleaning and repairs. An early example of this type was the Dodge-Burgess Sectional Floating Dock patented jointly by them in America in 1841. Essentially it consisted of a number of pontoons connected together by a locking log. One such dock, composed of eleven sections 30 feet long and 100 feet wide with a total lifting power of about 3500 tons, served on the New York water front for many years. A notable example of this type in steel was that of Blohm and Voss, in Germany, with a lifting capacity of 17,500 tons. However, the sectional dock also had its disadvantages in that great care was necessary to preserve the alignment, and much difficulty was experienced in adjusting the lifting force of each section so that the docked vessel would not be unduly strained or injured. During the second half of the nineteenth century a great deal of attention was turned to the problem of creating a dock with all the advantages of both the balanced and sectional docks, with few of the disadvantages of either.

The first compromise structure of importance was the Rennie dock, invented by the celebrated English engineer, George B. Rennie. In this type the side walls were made solid, extending the entire length of the dock, while the pontoons were sectional. Mr. Lyonel E. Clark of Clark and Standfield, London, introduced the next important type--a modified Rennie dock, in which the pontoons were placed between the side walls instead of under them. Clark later devised a bolted sectional dock for the Austrian Naval Station at Pola, a type which was also proposed in a modified form by A.C. Cunningham of the United States early in the twentieth century. Variations and improvements to these types continued throughout the early 1900's and sizes increased tremendously. Prior to the Second World War several large floating docks had been pressed into service in various parts of the world. Southampton boasted of a structure with 60,000 tons lifting power, measuring 960 feet in length

FLOATING DRYDOCK TYPES

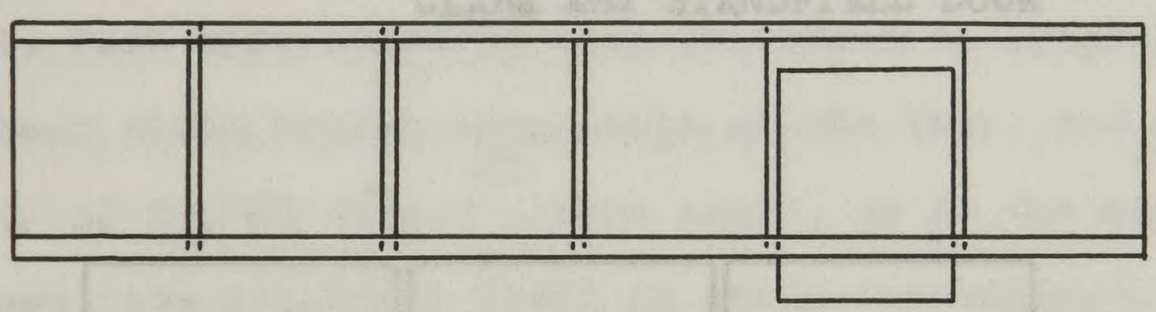


Side and end elevations

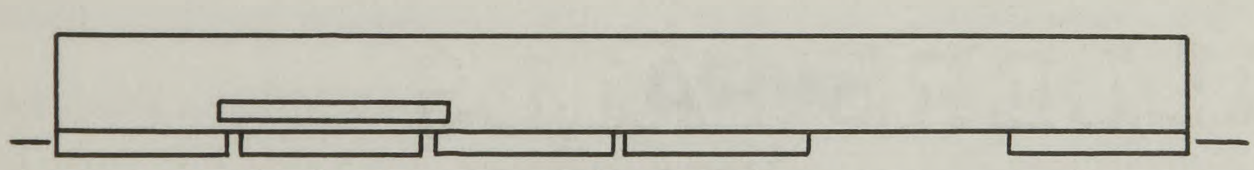


End elevation showing section self-docked

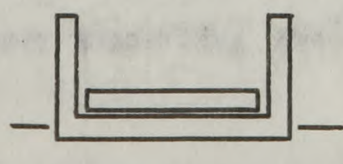
SECTIONAL DOCK



Plan showing pontoon being withdrawn
preparatory to self-docking



Sectional side elevation
pontoon self-docked

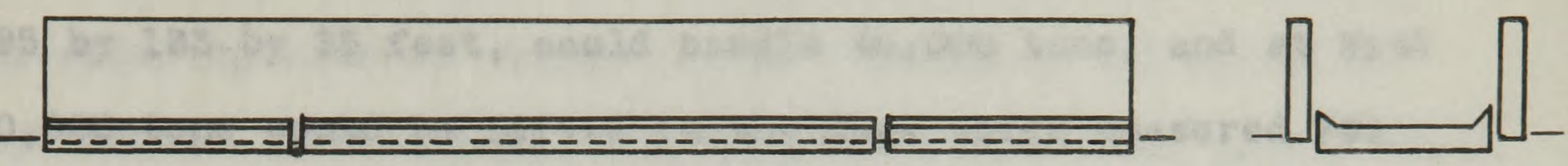


End elevation
pontoon self-docked

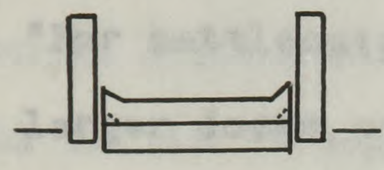
RENNIE DOCK

Fig. 6

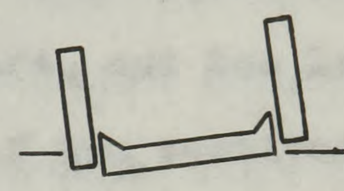
FLOATING DRYDOCK TYPES



Sectional side and end elevations

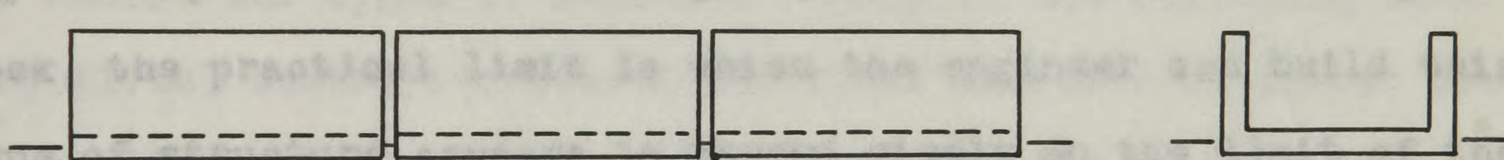


End elevation section self-docked

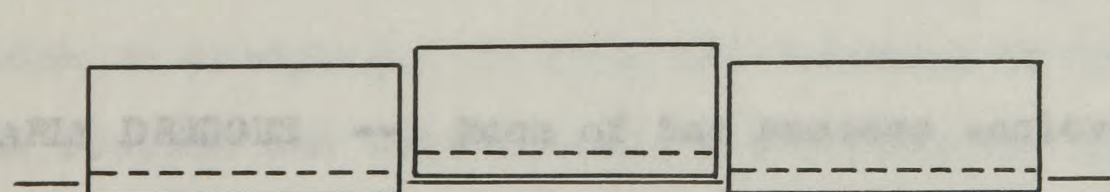


Dock careened to expose side wall

CLARK and STANDFIELD DOCK



Side and end elevations



Side elevation showing self-docking

CUNNINGHAM DOCK

Fig. 7

overall, 130 feet 8 inches in clear width, and 38 feet in depth over the keel blocks. At Rotterdam the dock, measuring 695 by 133 by 35 feet, could handle 46,000 tons, and at Kiel 40,000 tons could be lifted in the dock which measured 721 feet 9 inches by 147 feet 6 inches by 35 feet. Even these giants were exceeded by the Advance Base Sectional Docks used by the United States Navy in its world-wide operations in World War II. "For battleships, carriers, and the largest auxiliaries, the larger docks consisted of ten sections, each 256 feet long and 80 feet wide, and with a nominal lifting capacity of 10,000 tons. When assembled to form the dock these sections were placed transversely, with 50-foot outrigger platforms at either end of the assembly, making the dock 927 feet long and 256 feet wide overall, with an effective length of 827 feet, a clear width inside wing walls of 133 feet, and a lifting capacity of 90,000 tons."[21] Here again, as in the case of the graving dock, the practical limit to which the engineer can build this type of structure appears to depend simply on the limit of the size of ship which will use it.

Equipment

EARLY DREDGES -- Much of the success achieved in harbor and dock construction has depended upon the capacity and efficiency of the dredging equipment used. Earliest of the relatively modern types known were of Dutch, Italian, and French origin. As early as the middle of the fourteenth century the Venetians scraped the harbor bottom with iron harrows attached to long wooden handles. The scraping was done during ebb tide so that the suspended materials could be carried out to sea by the receding waters. Dekker in his "Dredging and Dredging Appliances" (London 1927) has shown some old dated prints which indicate the early progress of this type of equipment in Holland. A primitive bag and spoon is shown, dated 1565, followed by an endless chain mud dredger (1600), operated by men on a tread. Also shown is a grab dredger with a date of 1617. According to Prelini in his "Dredges and Dredging" (New York 1912) the first mention of a rude dredging machine by a writer was that of Veranteus in 1591. Though the mud dredger of 1600 mentioned above was probably operated by horse as well as by man power, we have no direct evidence of it. Thus, the first dredge driven by horse power is generally considered to have been that invented by Cornelius Meyer about 1685, for use in constructing the canals and dykes of Holland. Early in the following century (1718) Savery introduced the first elevator or ladder dredge, and by 1750 the French were using iron buckets on this type.

EARLY STEAM DREDGES -- It was not until the end of the eighteenth century that any attempt on a large scale was made to apply steam to dredging. In 1796 Mr. Grimshaw of Sunderland, England, had Boulton and Watt install a 4-horsepower engine in a 60-foot scow to aid in deepening the Sunderland Harbor. The experiment was not particularly successful, so Watt followed with a similar machine but of heavier design in 1804. John Rennie, in using the modified Grimshaw dredge with a 6-horsepower engine, was able in that year to raise mud and gravel from a depth of

22 feet in his excavations for the docks at Hull. John Hughes, a contractor, also used a steam dredge in 1804 while working at the moorings opposite the East India Dock gates. In that same year the steam dredge was introduced in America by Oliver Evans for the purpose of work at the docks of Philadelphia. Thus, with the beginning of the nineteenth century the steam dredge took its place as a regular part of water front construction equipment.

LATER DEVELOPMENTS -- Generally speaking, dredges have developed in two main classes--the continuous type, represented by the ladder, hydraulic, stirring, and pneumatic dredges, and the intermittent type, represented by the dipper and grapple dredges. The year 1867 might be designated as the beginning of the era of the modern dredge, for in that year the Frenchman Bazin first suggested the hydraulic or suction dredge. Its use was again suggested in the United States by C. Randolf in 1870, and in the following year it was used successfully at the mouth of the St. Johns River, Florida, by General Q.A. Gillmore. Further improvement to the hydraulic dredge then came in 1878 when cutters were first used. Also deserving of mention is the steam shovel which has been found useful for dry land operations as well as for dredging. In 1838 William S. Otis of Massachusetts invented a shovel on wheels which handled 1000 cubic yards daily. It was put into early use by Mr. Whistler on the Western Railroad in Massachusetts. Similarly M. Gervais of Caen introduced a locomotive excavator at about the same time known as the "Terassier Locomoteur." Basic types have, on the whole, remained the same as they were in the latter part of the nineteenth century, but increased strength of materials and other technological advances have increased the output of modern machines so greatly that in performance, at any rate, they bear little relationship to their predecessors.

Lighthouses

PHAROS -- Another phase of coastal work to which engineers have turned their energies for centuries has been the construction of lighthouses. Most famous of all in the classical world was the lighthouse on the island of Pharos in the harbor of Alexandria. Apparently this magnificent structure, which gained wide acclaim among the ancients, was constructed by Sostrates of Cnidos during the reign of Ptolemy Philadelphus (c 283 B.C.), but the rest of its details are vague. Pliny[22] mentioned that it cost 800 talents to build, but he gave no dimensions. Smeaton[23] noted that according to a twelfth century writer the structure was 300 cubits in height, a distance equal to one hundred statures of a man or 547 feet. On the other hand, Abu'lfida, an Arab of the fourteenth century, said that it stood 180 cubits in height. Yet another account stated that it was 450 feet high with five stories, the first three hexagonal, the fourth square, and the fifth circular, holding the beacon fire. It is reputed to have been made with the hardest Tibertine stones joined together with melted lead. Though research to date has failed to identify its dimensions positively, we can be certain from the various reports which have reached us that it was a good-sized structure worthy of remembrance.

Much less important but remembered as a good example of Roman construction was the tower at Boulogne, originally known as the Turris Ardens and later as the Tour d'Ordre. Probably built during the time of Caligula,[24] it was repaired by Charlemagne and remained in existence until the sixteenth century. Octagonal in shape, it had a circumference of 192 feet, a diametrical distance of 64 feet, and rose two stories into the air. Another tower of Roman origin was the Pharos at Dover, octagonal without and square within, with a diameter of 33 feet and a height which originally might have been as much as 72 feet.

TOUR DE CORDOUAN -- Earliest of the celebrated "modern" lighthouses, the first Tour de Cordouan is believed to have been built by the Saracens on a small island near the mouth of the Garonne in the Bay of Biscay. Next came a structure built by the English, when Edward the Black Prince was Governor of Guienne (1362-71). The third tower, whose lower portion forms part of the present structure, was constructed by the French engineer, Louis de Foix, during the period 1584-1611. It had a base circle with a diameter of 135 feet, and stood 162 feet above the surface of the rock. Later, in 1727, it was raised to a height of 186½ feet. It is best remembered by many as the first lighthouse to be provided with a revolving light.

EDDYSTONE -- Probably the best remembered work of John Smeaton (1724-92), first man to call himself a civil engineer, was the Eddystone Lighthouse 14 miles from the Port of Plymouth. The earliest lighthouse on the rock was erected by Henry Winstanley, who began operations in 1696 and labored over four years on his "wooden pagoda." Its life was short, however, for it was blown down in a storm in 1703. The next venture was more successful, though it, too, came to a violent end. During the years 1706 to 1709 John Rudyard constructed a tower in the shape of a frustum of a cone, but it was also essentially of wood, and fell victim to a fire in 1755.

Smeaton was called upon in the following year to erect yet another tower on the same spot. He began operations immediately and carried out actual construction on the rock from 1757 to 1759. Nearly a thousand tons of granite went into this structure, which was made up of forty courses of dovetailed masonry. When completed, the tower was over 90 feet high with a base 26 feet in diameter. Late in the nineteenth century it was discovered that the rock underneath the tower was being undermined, so a new tower was erected (1877-82) nearby under the direction of J.N. Douglass. Smeaton's upper tower was dismantled and re-erected on the Hoe above Plymouth harbor as a fitting tribute to its great builder.

OTHER LIGHTHOUSES OF NOTE --

"When the Rock was hid by the surge's swell, the Mariners heard the warning Bell;

And then they knew the perilous Rock, And blest the Abbot of Aberbrothok."

Thus with his pen did the poet Southey immortalize the famous Inchcape or Bell Rock, 22 miles east of Dundee, Scotland. After visiting this site of many a shipwreck in 1800 Robert Stevenson later designed and built the great lighthouse marking the reef. With occasional advice from Rennie he carried out the construction during the years 1807 to 1810. Ninety courses of masonry brought the tower to a height of 102½ feet, and an oil light was placed 108 feet above the medium level of the sea. The solidity of construction is indicated by the fact that at one time during a storm, spray reached a height of 104 feet on the tower. Robert Stevenson was later followed in his profession by his son Alan, who is well-remembered for his structure at Skerryvore (1838-43) 12 miles from the island of Tiree.

The first lighthouse to be erected in the United States was a tall masonry tower at the entrance to Boston Harbor, completed in 1716 but later replaced. Probably the most notable of the early American structures, however, was that at Minot's Ledge, 15 miles southeast of Boston. The masonry design was made by Joseph G. Totten, and the actual construction was carried out from 1855 to 1860 by Captain Barton S. Alexander of the Corps of Engineers. Successful completion of the job was particularly outstanding, for the ledge was lower than any of its forerunners, being only partly bare at low tide. Shortly thereafter (1870-74) another bold project was completed at Spectacle Reef in Lake Huron, 10 miles from the nearest land. Under Orlando M.Poe a lighthouse was erected at a point where the rock was 11 feet below the water level, and where pressures from ice packs rising to 30 feet were to be expected.

Also of interest are the types of beacons which have served in the lighthouses over the years. Earliest and simplest were wood fires, later replaced by pitch pots and coal fires. In 1822 the last English coal fire beacon was extinguished at St. Bees. Smeaton's Eddystone Lighthouse burned huge candles, as did many other towers of the period. Oil was introduced at Liverpool in 1763, coal gas at the Light of Troon in 1837, electricity at South Foreland, England in 1858, incandescent mineral oil at L'Ile Penfret in 1898, and acetylene at Chasseron, France, in 1902.

Soil Mechanics and Piles

SOIL MECHANICS -- Not only in dam and waterfront construction has a knowledge of the action of soil under pressure been valuable, but in all other foundation problems as well. The French, possibly as early as the sixteenth century, engaged in a study of earth pressures, particularly where applicable to fortifications. In 1773 the French scientist Coulomb published a work on earth pressures, and almost a century later--about 1856--Professor Rankine developed a theory of equilibrium of earth masses and applied it to elementary foundation problems. Both of these authors--whose works are often referred to as the "classical theories of soil mechanics"--considered "idealized fragmental masses," consisting of grains like sand and possessing some friction and cohesion at times. Within certain limits these theories have been found useful.

It was not until the twentieth century, however, that any concerted move was made to remove the subject from the sole realm of theory to the practical laboratory where physical properties could be studied under actual conditions. In 1913 committees on soil research were established by the Swedish State Railways and by the American Society of Civil Engineers. Perhaps future historians will mark 1925 as the date of the real beginning of the study of soil mechanics, for it was in that year that Professor Karl Terzaghi published his famous "Erdbaumechanik." Among other points in this work he developed a "Theory of Consolidation" which has come to be regarded as one of the most important theoretical contributions to the field of Foundation Engineering. He not only followed this work with many papers on the subject, but also founded a laboratory in Vienna and taught at the Massachusetts Institute of Technology. In 1936 an international conference on soil mechanics was supported by countries where research had been in progress such as in England, Germany, Holland, Japan, Russia, Sweden, and the United States, and in 1948 another such international gathering was held. It is felt by many that real research did not begin until 1935 when actual structures rather than models came in for their share of study. Soil mechanics is still far from being an exact study, and is still very much in the empirical and experimental stage. However, it does offer some hope for a solution to those many soil problems which have for so many generations plagued the civil engineer.

PILES AND PILE DRIVERS -- The use of piles to support a ver-

vertical load on unstable soil was well known in Roman times, but the method did not come into the extensive use it has today until the advent of the steam pile driver in the nineteenth century. Sheet piling for cofferdams also belongs to the era of the nineteenth century. A short time prior to 1822 Mr. Mathews used cast-iron sheet piles in constructing the north pier of the harbor of Bridlington on the east coast of England. His piles had a U-shaped interlock, were 21 to 24 inches wide, ½ inch thick, and 8 or 9 feet long. In 1822 Peter Ewart of Manchester patented a non-interlocking pile which came in lengths from 10 to 15 feet. The original pile had a cross section similar to the letter "E" with the ends bent toward the middle, but it was modified in 1824 by a flattening out in order that it might penetrate the hard material at Downes Wharf, London. A novel scheme was then introduced by Mr. Sibley in building an iron wharf on the Lea Cut at Limehouse (c 1833). He drove hollow cast-iron guide piles, elliptical in section with a pair of exterior guide ribs on either side, at intervals of 9 feet. Between the guides he placed flat plates which extended to within 6 feet of the bottom, the piles themselves being 20 feet in length. The piles were then filled with concrete and tied to the land. Another contribution of the decade was the invention in 1838 of the screw pile by Alexander Mitchell for use in connection with the building of a lighthouse on the Malpin Sands in the Thames estuary. No patents for wrought-iron or steel sheet piles were issued in the United States or Europe from 1863 to the end of the century, and it was not until 1902 that they were used successfully in construction. Since that time sizes and shapes, encompassing everything conceivable, have appeared in an abundance too great to mention here.

In 1839 James Nasmyth at the Bridgewater Foundry, finding the existing tilt hammers worked by a big cam inadequate, sketched a steam hammer to mold a 30-inch shaft for the projected paddle steamer "Great Britain." Apparently the French were the first to use the hammer for driving piles, and Nasmyth later patented the idea in 1842. The first extensive use of it in England came in 1846 when Stevenson drove piles for his High Level Bridge at Newcastle. In America steam pile drivers on wheels were used on the railroads at least as early as 1841, but their origin is obscure. The jet method of sinking piles was probably introduced by James Brunlees who, in 1850, used it in a railroad construction job across the sandy Morecambe Bay on the west coast of England. The twentieth century has brought reinforced-concrete piles into competition with the older wooden and metallic types, and variations of the types have also appeared. Few will say that piles or pile drivers have yet reached their ultimate stage, meaning that the future holds wide opportunities for engineers interested in this type of development.

Summary

Hydraulic and coastal works have always been of great importance in the engineering profession, from the time of the ancient Egyptians right down to the present. Irrigation and river control, carried out along the Nile well before the

Christian era, are still of prime concern in that area, as well as many other parts of the world. Theoretical and practical knowledge have been expanded, dams have been improved, and construction equipment has undergone a great evolution, but the basic problem of controlling the waters has remained the same, as has the basic solution to that problem. Today engineers all over the world are engaged in protecting valuable land from inundation on the one hand, and in supplying the life-giving waters to lands parched by drought on the other.

Basically, from ancient times to the present, river control has been accomplished by means of dams. At the outset these dams were simply huge mounds of compacted earth, based on a design which evolved after generations of practical experience. Truly scientific and rational design in this field did not appear until the nineteenth century when French engineers set about to improve the masonry dams introduced over two centuries previously in Spain. The scientific approach rapidly increased the size and use of the masonry dam throughout the world, and the introduction of the reinforced concrete dam in the twentieth century brought ever bolder designs to the fore. The result has been not only to aid in flood control and irrigation problems, but to utilize water power on a scale undreamed of in the nineteenth century when the first commercial water turbines were introduced.

Closely allied to flood control and dam erection has been the harbor and dock construction necessary to the life of maritime nations. Many of the early trading peoples, such as the Phoenicians, found it necessary to make certain improvements on their natural harbors, but it remained for the Romans to bring harbor construction to its highest peak in Classical times. Following the fall of the Roman Empire there was relatively little maritime activity until the fifteenth century, and then we find little in the way of harbor work until the seventeenth and eighteenth centuries. It was during the latter part of the eighteenth and early part of the nineteenth centuries that England launched an almost feverish program of wet dock-building designed to accommodate the trading vessels which reached out to every port on the globe. As ships increased in size throughout the 1800's, wooden and masonry graving docks evolved to take the place of the old careening beaches. Floating drydocks also were developed during this period, being of wood at first and of steel later. Continued increase in the size of ships during the early twentieth century was more than matched by a similar increase in the sizes of both graving and floating docks.

Throughout these periods of great construction engineers were finding out more and more about soil and foundation conditions. Practical experience seemed to be the only reliable guide to the solution of these foundation problems until the study of soil mechanics from a scientific standpoint was begun in the twentieth century. The study is still too much in an experimental stage to be called a science, but it shows intriguing possibilities and serves as an excellent example of the fact that the engineering profession is never static but is constantly rising to the challenge of new and interesting problems.

FOOTNOTES

1. Vowles, H.P. & M.W., "The Quest for Power." pg. 42.

2. Herodotus, transl. by G. Rawlinson, book II, chap. 149.

3. Strabo, transl. by H.L. Jones, book xvii, chap. I, V. 37.

4. Willcocks, W. & Craig, J.I., "Egyptian Irrigation." 3rd ed., part IV, pg. 43.

5. Souttar, R. "A Short History of Ancient Peoples." pg. 95.

6. Ellis, C.H., "Reclaiming the Pontine Marshes." in "Wonders of World Engineering." pg. 711.

7. Dawson, E.F., "Notes on the Mississippi River." pg. 67.

8. Wegmann, E., "The Design and Construction of Dams." 6th ed., pg. 233.

9. Ibid., pg. 117.

10. Ellis, C.H., "The Nile Under Control." in "Wonders of World Engineering." pg. 146.

11. MacArthur, D.W., "Building the Boulder Dam." in "Wonders of World Engineering." pg. 47.

12. Strabo, op. cit., book xii, chap. 3.

13. Usher, A.P., "A History of Mechanical Inventions." pg. 143.

14. Vowles, H.P. & M.W., op. cit., pg. 196.

15. Du-Plat-Taylor, F.M., "Docks, Wharves, and Piers." 2nd ed., pg. 11.

16. Strabo, op. cit., book V, chap. 4, V. 6.

17. Humber, W., "A Record of the Progress of Modern Engineering." pg. 5.

18. Broodbank, J.G., "History of the Port of London." pg. 64.

19. Gould, R.T., "Story of London's Docks." in "Wonders of World Engineering." pg. 1284.

20. Donnelly, W.T., "Floating Drydock Construction." in "Floating Drydocks." pg. 317.

21. "Building the Navy's Bases in World War II." vol I. pg. 212.

22. Pliny, transl. by J. Bostock & H.T. Riley, book xxxvi, chap. 19.

23. Smeaton, J., "The Edystone Lighthouse." 2nd ed., pg. 3.

24. Smiles, S., "Lives of the Engineers." (Smeaton & Rennie) pg. 32.

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Chapter XI

RAILROADS

The First Railroads in England

EARLY HORSE-DRAWN RAILWAYS -- The rough state of the floors of early mining tunnels rendered the hauling of carts by man or animal extremely slow and difficult. While it would have been possible to smooth the floors to a much greater extent, such a course of action would hardly have been economical, so a much simpler solution to the problem was devised. Wooden boards or rails were laid in the ruts made by the previous passage of the carts, and thus the traction difficulty was eased considerably. Such wooden tracks were used as early as the fifteenth and sixteenth centuries in the German mining tunnels of the Harz and Erz Mountains. Similar "wagon-ways" inside the tunnels and outside of the mines have been traced to the sixteenth century in Britain. A statement of the charge, receipt, and delivery of coals at Wallaton, Nottinghamshire from October, 1597 to October, 1598 mentioned "railes", and in a letter dated 1 May, 1610, Robert Fosbrooke of Nottingham wrote[1] to Sir Percival Willoughby: "I beseech you to take order with Sir Thomas that we maie have liberty to bring coals down the railes by wagen, ---, for Strelby cartway is so fowle as few cariadges can pass." Such rails were found particularly in the coal districts of the North, where they became known as "Newcastle roads" in the latter half of the seventeenth century. Speaking of this district Roger North in his "Life of Francis North, Baron Guilford" (1676) noted:[2] --

"The manner of the carriage is by laying rails of timber, from the colliery, down to the river, exactly straight and parallel; and bulky carts are made with four rowlets fitting these rails; whereby the carriage is so easy that one horse will draw down four or five chauldron of coals, and is an immense benefit to the coal merchants."

Earliest known of the British Railway Acts was 31st George II 1758 concerning a "waggon-way for conveyance of coal to Leeds." As time passed, horse-drawn railways continued to multiply in the mining districts of Wales and the North of England, but until the nineteenth century they were wholly private and almost exclusively used for hauling coal. With the dawn of the new century, however, men of vision saw the possibilities of their adaption to wider fields. On February 11, 1800 Mr. Thomas, of Denton, read before the Newcastle Literary Society a paper on "the propriety of introducing roads on the principle of coal-waggon ways, for the general carriage of goods." In the following year Dr. Anderson in his "Recreations in Agriculture" urged that tramroads should be laid down and worked with horse power in places where canals could not be made. His proposal envisaged an organized system of railroads which would be put on the same footing as the public roads.

First of the public lines of this type was the 9-mile Surrey Iron Railway from Wandsworth on Thames, London, to Croydon, with a branch to Carshalton. Chartered in 1801, opened in 1803, and abandoned in 1846, the road was constructed with the object of facilitating the conveying of agricultural produce to London and the return of manure to the country. It was built by William

Jessop who laid cast-iron rails with a gauge of 4 feet 6 inches on wooden sleepers. During the next quarter of a century some twenty-nine different railway companies were authorized, and all but one of these actually began operation. Some of the more important of these lines included the Kilmarnock and Troon (1808), the Gloucester and Cheltenham (1809), the Plymouth and Dartmoor (1819), the Stratford and Moreton (1821), and the Bolton and Leigh, the Canterbury and Whitstable, the Cromford and High Peak, the Nantile, and the Rumney (all incorporated 1825).

THE STOCKTON AND DARLINGTON -- Most famous and most important of all the roads of the first quarter of the nineteenth century was the Stockton and Darlington Railway, designed to connect the coalfields of Durham with the navigable waters of the Tees. During the latter part of the eighteenth century a canal for this purpose was proposed, and the idea was not abandoned until the results of John Rennie's 1813 survey were made known. At a meeting in 1818 a tramway was decided upon, Thomas Overton being selected to draw up the plans. The Act to which Royal assent was obtained in 1821 called for the conveyance of merchandise by horse traction, but on the recommendation of George Stephenson--who succeeded Overton as chief engineer in 1821--the Act of 1825 included the locomotive as a means of traction. On the 27th of September, 1825 the line was opened with Stephenson himself driving the locomotive. Following the locomotive and tender were six wagons filled with coal and flour, then a covered coach with its "important" passengers, twenty-one wagons carrying passengers, and six coal wagons at the end. At one point on this initial trip some four hundred and fifty passengers helped to boost the total load plus carriages to almost 90 tons. After six carriages had been dropped at an intermediate station another informal count indicated that some six-hundred passengers were now enjoying the 12 miles-per-hour ride on the first public steam road.[3]

The main line of 25 miles from Witton Park colliery to Stockton-on-Tees was joined by 15¼ miles of branch lines, making the total road over 40 miles in length. It was a single-track type, the rails being chiefly of malleable iron, with passing places provided every quarter of a mile. The gauge was fixed at 4 feet 8½ inches to conform to that peculiar to the Killingworth mine tramroads where Stephenson did the early work on his locomotives. In addition to locomotives, stationary engines were used to haul trains up grades then considered difficult, and horses were used on certain portions of the line until 1833. Much of the credit for the success of this railroad must be accorded to its main promoter, the Quaker Edward Pease, and to its chief engineer, George Stephenson, who has fittingly earned the title of "Father of the Railway." It was only a few short years after the opening of the Stockton and Darlington that the construction of steam roads to carry passengers and merchandise was begun in earnest.

OBJECTIONS TO THE RAILROADS -- Prior to the opening of the Stockton and Darlington there were several railways spread throughout England, Scotland, and Wales carrying a daily load of about 1000 tons of merchandise, with--excluding collieries of the North--a total trackage exceeding 200 miles. Nevertheless, the idea of a railroad was not one which met with the approval of many sections of the citizenry, such as the canal owners, the turnpike trusts, and the landed gentry. The emergence of the locomotive brought forth even more violent opposition. When the plans for the Stockton and Darlington became known a member of Parliament wished to know "what was to become of the coach makers, harness-makers, coach-masters, coachmen, inn-keepers, horse breeders, and horse dealers?" He prophesied that iron would be raised in price 100%, or, more probably, would be exhausted altogether. "Was the House aware of the smoke and noise, the hiss and the whirl which locomotive engines, passing at the rate of 10 or 12 miles per hour would occasion? Neither the cattle ploughing the fields or grazing in the meadows could behold them without dismay." Other projected railroads suffered similar abuse. The "Quarterly" (1825)[4] commented in the following vein: --

"The gross exaggeration of the powers of the locomotive steam-engine, or, to speak more plainly, the steam carriage, may delude for a time, but must end in the mortification of those concerned----. It is certainly some consolation to those who are to be whirled at the rate of eighteen or twenty miles an hour, by means of the high pressure engine, to be told that they are in no danger of being sea-sick while they are on shore, that they are not be be scalded to death nor drowned by the bursting of the boiler, and that they need not mind being shot by the scattered fragments, or dashed in pieces by the flying off, or breaking, of a wheel. But with all these assurances we should as soon expect the people of Woolwich to suffer themselves to be fired off by one of Congreve's ricochet rockets, as trust themselves to the mercy of such a machine going at such a rate. ----We will back old father Thames against the Woolwich railway for any sum."

Even the younger Stephenson's 112-mile London and Birmingham Railway (1833-38)--though begun at a relatively late date--received like treatment. The Countess of Bridgewater and Lord Brownlow declared that the advantage to the public would not equal the injury to the estates; "not only would it be a nuisance to the country, it would positively be a nuisance to my Lord Southampton." Brunel's Great Western Railway (1835-41) received opposition from another quarter, Eton College, whose authorities opposed it on the grounds that "it would be injurious to the discipline of the school, and dangerous to the morals of the pupils." Despite the flood of protests and denunciations the protagonists of the railways proved to be the stronger, and what has been termed the "Railway Age" was ushered in with the Liverpool and Manchester Railway in 1830.

THE LIVERPOOL AND MANCHESTER -- As trade increased between the port of Liverpool and the manufacturing town of Manchester, the canal facilities became clogged, carriage became uncertain, and tolls became excessive. One notorious result was that cotton could be shipped faster from America to Liverpool than it could from Liverpool to Manchester, some 31 miles distant. The Exchange at Liverpool resounded with the complaints of merchants, and manufacturers in the counting houses of Manchester echoed that disapproval. Clearly some form of transportation to rival the canal had to be established.

As early as 1797 William Jessop had run a survey between the two cities but nothing definite resulted. It is not clear as to just who first proposed the idea of a steam railroad, but it is known that Thomas Gray of Nottingham was one of its earliest enthusiastic supporters. His enthusiasm for the locomotive was well illustrated in his treatise entitled: "Observations on a general iron railway, or land steam-conveyance, to supersede the necessity of horses in all public vehicles; showing its vast superiority in every respect over all the present pitiful methods of conveyance by turnpike-roads, canals and coasting traders. Containing every species of information relative to railroads and locomotive engines." In 1820 he urged the use of Blenkinsop's rack-and-pinion locomotive for the Liverpool-Manchester run. Two years later William James of Snowford Manor, claimed by many to be the originator of the freight and passenger railroads, submitted to Lord Stanley certain plans and sections for the proposed road. In 1824 a committee was formed, in 1826 an Act was obtained--work commencing under George Stephenson--and in 1830 the line was opened to the public.

A committee called in 1828 had studied the various methods in use on the Stockton and Darlington--the locomotive, stationary engine, and horse traction--and arrived at the decision to favor the stationary engine. Stephenson's insistence on the superiority of the locomotive, however, finally encouraged the directors to give that mode a test. Trials held at Rainhill in the following year convinced them of the possibilities of the locomotive and resulted in the selection of Stephenson's "Rocket" as the type of locomotive the line would use. It was able to negotiate the 31-mile trip in the average time of 90 minutes. Thus, from the outset, the Liverpool and Manchester was destined to be a steam road, and settled once and for all the question of the steam locomotive versus the stationary engine on regular operating lines. Definitely built to carry passengers and freight, this road convinced many skeptics that the new form of transportation carried the key to a wealth and prosperity never known before.

SUBSEQUENT DEVELOPMENT IN BRITAIN -- The commercial success of the Stockton and Darlington and Liverpool and Manchester Railways started a boom in railroad construction which slowly gathered momentum during the next decade, and then suddenly burst into the "Railway mania" of the 1840's. By 1846 some twelve hundred and sixty-three railway bills had been presented to Parliament although only one hundred and twenty became Acts. The success of this new form of transport was recognized by Parliament in 1838 when it passed an Act transferring the mails from stage coaches to trains on routes then operating. Top engineers were constantly in demand during this feverish period, Brunel being engaged on fourteen different lines, Locke on thirty-one, Rastrick on seventeen, Sir John Rennie on twenty, Robert Stephenson on thirty-four, and Vignolles on twenty, to mention but a few. Hard-headed investors and wild-eyed speculators clamored alike to get aboard the iron road for El Dorado, and the tremendous speculation bubble continued to grow at a frenzied pace. The Marquis of Londonderry stated that in Durham three railroads--all parallel lines--were attempted by one projector; one was at par, the other bankrupt, and he believed that the third would never pay. All sorts of schemes were advanced to increase the earnings of the railroads--sails, rockets, and wooden elevated lines all having their advocates. Property prices soared; the appearance of a railroad surveyor was enough to double the value of the meanest strip of land. One nobleman, enraged at the desecration of his estate, was hardly mollified by an offer of £ 30,000 from the railroad company, but he was more enraged when a second survey took the line away from his land and with it the £ 30,000. Subscribers were drawn from all walks of life, many hardly realizing their responsibilities and caring less. One common type was the man with a £ 60 income who subscribed for £ 35,000. This wild state of affairs persisted until October, 1845 when the Bank of England raised its rate of interest. The bubble broke, money became scarce, and the whole culminated in the financial crisis of 1847.

Many small companies went under financially and many others tottered at the edge of bankruptcy. Quite naturally a large number of amalgamations resulted, although the general legislative policy throughout the nineteenth century was aimed at keeping competition alive. The great amalgamations of 1872 served in many ways to intensify the competition, if anything, for hundreds of small lines with local monopolies gave way to a few big lines which overlapped to such an extent that most large communities were served by two of them. World War I broke down that competitive policy and a complete reversal was created with the Railways Act of 1921, which amalgamated practically all of the railways into four groups, i.e., (1) London Midland, and Scottish, (2) London and North Eastern, (3) Great Western, and (4) Southern. Final amalgamation came after World War II when, in 1948, the English railways became the property of the State.

Development of the Locomotive

EIGHTEENTH CENTURY STEAM ENGINES -- The phenomenal growth of the railroads in England was due, of course, to the development of the steam locomotive which had its beginnings in the seventeenth century. Learned and scientific men, according to the times, were the principal investigators of the properties and uses of steam in this early period, such men as Porta, Rivault, De Caus, the Marquis of Worcester, Huyghens, Papin, and Savery being particularly outstanding. With the advent of the eighteenth century the investigations passed out of the hands of the philosophers into those of the mechanics, the men who could translate the scientific theories into practical realities. Thus, early in the new century Thomas Newcomen, a Cornish mechanic, was able to combine the cylinder and piston of Papin with the condensing system of Savery to produce his atmospheric engine for pumping out mines. Fire produced steam which, when condensed under the piston, caused the pressure of the atmosphere to do the pumping. Smeaton constructed many Newcomen engines whose performances exceeded those usually encountered prior to his time, but he did not improve on the basic Newcomen principle. In 1763 James Watt began repairs on a model Newcomen engine at the University of Glasgow, an event which proved to be a turning point in his career. With much thought and experimentation he gradually developed the low-pressure steam engine.

Throughout its development up to this time the steam engine was designed primarily for pumping out mines, but in 1769 the first steam locomotive made its appearance in France. The product of Nicholas J. Cugnot, this carriage was designed to haul heavy artillery over ordinary roads. It was a three-wheeled machine, with two ordinary gun wheels on the sides and one driving wheel in front, over which was placed the two-cylinder engine. Encouraged by his first attempt, the government assisted[5] Cugnot to build a second engine which he exhibited at Paris in 1770. With several passengers he drove the vehicle along a public road at a slow walking pace, but faulty steering, due to the disposition of weights over and forward of the guiding wheel, brought the engine into a wall. This disaster marked the end of government support and the locomotive was relegated to the role of a scientific curiosity. It now resides in the Conservatoire des Arts et Métiers in Paris.

William Murdock, the pioneer of gas lighting and the mechanic responsible for the working of Boulton and Watt's mining engines in Cornwall, was the next to make an attempt in this field. It is believed[6] that he constructed three working models of a steam locomotive between 1782 and 1786, and it is certain that he tried one three-wheeled locomotive on a highway at Redruth in the latter year. His employers discouraged his efforts, however, and nothing fruitful resulted. He was followed in 1788 by a Yorkshireman, Robert Fourness, who designed a three-cylinder steam traction engine, but who died before he could fully develop his invention. Thus, as the eighteenth century drew to a close, the principle of the steam engine was well understood, but its practical application in the field of locomotion had yet to be proved.

RICHARD TREVITHICK'S LOCOMOTIVES -- First to connect the plateways and railways then in existence with the steam road carriage was Richard Trevithick, brilliant British engineer, who seemed doomed never to enjoy the fruits of his genius. In 1797 he built a model which, with the help of his relative Andrew Vivian, he expanded to a full-size steam carriage in 1801. On Christmas Eve of that year the carriage was given its first road trial at Camborne, but the effort could hardly be called a success. One version of the story states that after a run of 300 or 400 yards the locomotive broke down and was then placed in a shed, while the party withdrew to an inn. The fire was left under the boiler which soon burst, and the ensuing flames devoured the shed and most of the locomotive. A second and later account tells us that the ill-fated locomotive simply turned over when it ran into a gully. Stephen Williams, who claimed to have been an eye-witness, stated in 1858 (when he was 87 years of age) that the machine successfully negotiated a hill, was turned around, and came down again to the shop. He heard that it had been tried again the following day but that some of the castings had broken.

Whatever the true outcome, Trevithick was not discouraged, and on February 21st, 1804 he ran the first successful locomotive on rails from the Pennydarren Iron Works to the Glamorganshire Canal. Ten tons of iron, seventy men, and five wagons made the trip of over 9 miles in four hours and five minutes, attaining at times a speed of almost 5 miles an hour.[7] Not only did he prove the sufficiency of smooth wheels for adhesion, but he also introduced the factor that made the locomotive practical--high-pressure steam. Referring to Boulton and Watt who had opposed the high pressure idea he stated:[8] "Let me meet them on fair grounds, and I will soon convince them of the superiority of the pressure of steam engine." He was also the first to observe and record the stimulation of combustion by exhaust, or waste steam passing up the chimney. No definite statement in contemporary accounts has come to light to show whether this first engine had the horizontal cylinder commonly represented, or the vertical cylinder which was a feature of Trevithick's high pressure engine for general purposes. John Farey, the well-known historian of the steam engine, writing in 1815 stated that it was vertical, but most of the subsequent accounts of other writers have declared it to be horizontal. The project was not as successful as it might have been for the railway was not really strong enough to carry the engine. The flimsy cast-iron rails, designed only to carry light horse-drawn wagons, were continually breaking.

Trevithick was again in the news in 1808 when his 10-ton locomotive was run at a speed of approximately 12 miles an hour on a circular track near what is now Euston Square in London. He was diverted by other projects, however, and left England for Peru in 1814. His multitude of interests kept him from concentrating on any one aspect for very long, so his valuable contributions in the locomotive field were left to others to develop more completely.

OTHER LOCOMOTIVES PRIOR TO 1829 -- Generally speaking, the early development of the steam locomotive was entirely British in character, and as such, had a profound influence on its growth in other parts of the world. Prior to 1829 there were few attempts outside of England to nurse this infant industry along, largely because few countries had the industrial capacity to launch such a venture. One such early non-British attempt was that by Oliver Evans of Philadelphia, who produced in 1801 a wagon with a steam engine to go along a regular road. Another was that by Mr. Friedericks in the Herrynian district of Hanover. In 1811 the King and Queen of Westphalia and their party rode with great ceremony on the line whose locomotive and iron rails had been invented by Friedericks. However, the next inventor of importance to follow Trevithick was John Blenkinsop, colliery viewer of the Middleton Colliery.

In 1811 Blenkinsop designed a successful colliery locomotive for Charles Brandling M.P., which was built by Fenton, Murray, and Wood of Leeds, and tried in June of 1812. The engine cost £ 380 including the royalty of £ 30 to Trevithick for patent rights, and was the forerunner of several others of the same type, some of which continued in operation until 1853 at Leeds and elsewhere. Their distinguishing feature was their rack-and-pinion arrangement; motion was provided by a toothed wheel working along a rack at the side of the line. The early engine was capable of drawing 94 tons at a speed of 3½ miles-per-hour on a level, and its rack-and-pinion device enabled it to surmount grades up to 5½%. A practical limit was placed on the speed of the rack-and-pinion locomotive, however, thus eliminating it from competition on ordinary lines as the modern locomotive increased in size and power.

With full knowledge of Trevithick's and Blenkinsop's engines, William Hedley, colliery viewer to Christopher Blackett of Wylam-on-Tyne, produced after one failure, a successful locomotive differing from those of either of his predecessors. Known as "Puffing Billy" this new engine began making the Wylam Colliery to River Tyne run in 1813. Its wheels were flangeless to suit the plate rails then in use which themselves had flanges on the inside. After 1825 edge rails replaced the plate rails at Wylam and flanges appeared on the locomotive wheels.

The next significant contribution came from George Stephenson (1781-1848), the man popularly regarded as the founder of the railways. Born at Wylam-on-Tyne, he began working at an early age, and did not learn to read or write until he was eighteen. His natural mechanical genius combined with his ability to learn rapidly soon won for him the responsibilities of superintending the collieries at Killingworth and elsewhere. By 1813 he had become "a civil engineer generally" and had suggested a considerable number of alterations and improvements on the engines and railroads belonging to these collieries. Profiting by the experience of Trevithick, Blenkinsop, and Hedley, he produced his first locomotive, "Blücher," at Killingworth for Sir Thomas Liddell. The engine, tried for the first time on the Killingworth Colliery Railroad on July 27, 1814, was used to work coal trains of 30 tons at 4 to 5 miles-per-hour. Stephenson followed

Blenkinsop by placing two cylinders axially along the center-line of the boiler, but he adopted Hedley's method of drive through gears. His first design, therefore, was a compromise between two previous types rather than an improvement on either. In the following year he patented--in conjunction with Ralph Dodds--a connecting rod which eliminated the cog-wheel driving system.

Stephenson followed up his first success with a series of locomotives, each of which contained some improvement over its predecessor. In his experiments he found the same improvement in the draught by mingling the exhaust steam with the smoke ascending in the chimney as had Trevithick some years before. In later years, sometime after the Rainhill Trials of 1829, a great controversy arose over who had discovered the "blast pipe", Trevithick, Hackworth, and Stephenson all having their respective supporters. The best evidence indicated that Trevithick was aware of the phenomenon as early as 1804 and that Timothy Hackworth improved on the idea by discharging the steam through a constricted orfice to add to its velocity. George Stephenson either re-invented the ideas or simply used them as common knowledge, and incorporated them successfully in his locomotives.

Until the opening of the Liverpool and Manchester Railway, the collieries of the North--Hetton as well as Killingworth--were the trial grounds for innumerable experiments. The Hetton Railway, about 8 miles in length from the colliery to the coal staiths on the River Wear, was laid out by George Stephenson and executed by his brother Robert in 1822, the line passing over a hill 330 feet in height and being worked partly by stationary engines and partly by locomotives. In 1825 the line[5] was said to be "the most perfect having locomotive engines." It was on these colliery roads, therefore, that Stephenson was able to bring his locomotives to such a high state of development. He stated in April, 1825 that to his belief he had up to that time constructed fifty-five engines, sixteen of which he classed as locomotives. Most famous of all his engines up to this time, of course, was the 6½-ton "Locomotion," the original locomotive on the Stockton and Darlington Railway.

THE RAINHILL TRIALS AND STEPHENSON'S "ROCKET" -- When the Liverpool and Manchester Railway was projected, the locomotive had not yet fully established itself as being superior to horse traction or to stationary engines. Largely at the insistence of George Stephenson the directors were goaded into holding a competition to determine whether or not a locomotive could be built which would satisfy certain conditions and thus prove its superiority. Briefly, the main conditions specified[9] were that (1) the engine should consume its own smoke, (2) if of the 6 tons maximum weight allowed the engine had to draw a twenty-ton load (including the tender and water tank) at 10 miles per hour, (3) the boiler pressure was not to exceed 50 pounds per square inch, and (4) its price should not exceed £ 550. At the suggestion of a Mr. Harrison a prize of £ 500 was offered by the directors for the best locomotive which would fill the specified conditions on the railway on a certain date. Quite naturally the competition evoked a great deal of interest in scientific and lay circles as well.

The competition, known as the Rainhill Trials, was held in

October, 1829 on the Manchester side of Rainhill bridge at Kenrick's Cross, about 10 miles from Liverpool. As laid out, the course was 1½ miles each way with 220 yards at each end for stopping. Each engine was required to make twenty round trips during the course of one day. Originally ten locomotives were scheduled to compete, but only five appeared on the program. One of the five, Mr. Brandreth's "Cycloped," was not admitted to the competition, and another, Mr. Burstall's "Perseverance," was unable to exceed 5 or 6 miles an hour and so withdrew from the contest at an early period. Of the remaining competitors the "Novelty" of John Braithwaite and John Ericsson, and the "Sanspareil" of Timothy Hackworth broke down repeatedly during the trials. The only locomotive which did fulfill all the conditions was Stephenson's "Rocket," and it was therefore declared the winner. As a matter of fact, the Rocket not only fulfilled the conditions but also exceeded the speed requirement by a great margin, attaining a maximum speed of 29 miles-per-hour and averaging 15 for the course.

The far-reaching result of these trials was, of course, the establishment of the locomotive as the supreme type of prime-mover on the railroads. By combining the blast effect and the multitubular boiler Stephenson had developed an engine of greater power than had ever been known before, and thus laid the groundwork for greater development in the future. The skeptics were now convinced--the locomotive had arrived--and the great Railway Age was about to begin.

POST-RAINHILL DEVELOPMENT -- The effects of the Rainhill Trials were world-wide, for in the early years of the industry practically all locomotive knowledge emanated from Britain. As early as 1828 Marc Seguin of France and Horatio Allen of America had visited works at Newcastle, and had ordered locomotives which were delivered in their countries late in 1828 and early in 1829. By 1840 one of the leading British manufacturers, Robert Stephenson and Compnay, had supplied locomotives to America, Austria, Belgium, France, Italy, Germany, and Russia. It was not long, however, before many of these countries were making their own locomotives, based largely on English precedent. Peter Cooper of New York exhibited his famous "Tom Thumb" late in 1829, and by 1835 Cockerill at Seraing, Belgium, had built his first engine modeled after Stephenson's patent type of 1833. As 1840 approached, St. Léonard at Liège, Schubert in Saxony, Borsig at Berlin, and Haswell at Vienna had established themselves as locomotive makers, and after 1845 the French builders began to supply their own needs.

Locomotives gradually became larger, heavier, and more powerful, and details were added to increase their efficiency of operation. Peter Cooper's flexible wheel base which permitted the locomotive to take curves was an important contribution, as was Ross Winan's four-wheeled truck and antifriction journal. The "expansion gear" of 1842 which allowed a more efficient use of steam in the cylinder was another step forward, and the introduction of Sir Daniel Gooch's "Great Western class singles" on a 7-foot gauge set a new high standard of efficiency. Despite the number of changes and excellence of improvements, however, the steam locomotive still remained basically the engine that Stephenson had introduced to the world at Rainhill.

ELECTRIFICATION -- Although the steam locomotive continued to be the dominant type of prime-mover on the railroads, the latter part of the nineteenth century saw the evolution of a new type--the electrified locomotive. Among its advantages could be included: (1) the elimination of smoke and steam, (2) the greater power obtained from any given axle load, and (3) the quicker acceleration and the rapid reversal of trains as a result of being able to drive "multiple unit" locomotives in either direction. Countries low in coal found it particularly useful, especially those mountainous countries rich in water power. No great revolution in laying the road-bed ensued except that overhead collectors or third rails had to be installed to convey the electricity from the power plant to the engine. The introduction of the self-contained Diesel-electric engines eliminated those extra features, and, of course, the same has been true in the case of straight Diesel and other oil-burning locomotives. Generally speaking, the main electrified systems have developed along three lines: (1) continuous or direct-current, (2) single-phase alternating-current, and (3) three-phase alternating current. Countries in which this new type of locomotive has played an important part in terms of road mileage include Germany, Italy, Sweden, Switzerland, the United States, France (the Midi Railway), and to a lesser extent, Austria and Norway. The essential character of the railroad has not been transformed by the introduction of this new type of power, but has simply been altered in an orderly fashion consistent with technological advances.

Although the electric locomotive was a technical possibility when the "Railway Age" began, it did not become a commercial possibility until half a century later. Three years after the American physicist Joseph Henry had invented the electric motor, Thomas Davenport, a blacksmith of Brandon, Vermont, mounted a toy motor and primary battery on a small vehicle and ran it (1834-35) on a short circular track. His experiment was followed by the more elaborate one of Robert Davidson of Aberdeen, who built (c 1838) a 5-ton locomotive with which he made several trips on the track of the Edinburgh-Glasgow Railway. Further development came with the English patent taken out in 1844 by Henry Pinkus, which envisaged the use of rails to conduct current. The use of a third rail was indicated in the following year when Major Bassolo took out patents in France and Austria. Until the last quarter of the century, however, the making and utilizing of electricity was inefficient and costly, so the electric locomotive did not get beyond the primary battery stage.

The proximity of commercially sound electric traction was made apparent at the Berlin Exhibition of 1879, when the Siemens firm gave the first public demonstration of a dynamo-electric machine. A small locomotive and three cars with a capacity of about twenty people ran along a track one-third of a mile in length. Current was supplied through a central rail and returned through the running rails. Shortly thereafter, in 1881, the first regular line was opened at Lichterfelde--a short run with one motor car which achieved a speed of 30 miles-per-hour.

The motor was placed on a frame underneath the car between the wheels, and power was transmitted to the axles by steel cables. By 1887 there were ten similar installations in America and nine in Europe. In that year the Union Passenger Railway of Richmond, Virginia, installed a 12-mile line with overhead distribution and began experimental operations. Regular service began in 1888, making this the first of the large railways to be electrically equipped and operated under service conditions. Replacement of steam locomotives by electrical types on heavy lines was introduced in 1892-93 with the 1000-H.P. machine designed by Sprague, Duncan, and Hutchinson for experimental operation out of Chicago. A larger machine built by the General Electric Company began regular operation in the Baltimore and Ohio Tunnel in 1895. Since that time there has been a slow shift from steam to electricity in many parts of the world on many different types of lines, but whether or not this shift will continue is difficult to prophesy. No doubt the steam locomotive as we know it will, in time, be replaced, but it is probably too early to say with certainty what form that replacement will take.

Development of the Rail and Roadbed

PRE-NINETEENTH CENTURY RAILS -- Early rails were, as we have previously noted, simply bits of wood placed in ruts to accommodate the wheels of the coal wagons in the mines. The placing of parallel logs, with or without the ruts, gradually developed during the first half of the seventeenth century, and by 1676 the practice had become general in England.[10] By 1765 a system of trackage bearing a strong resemblance to the modern road had developed. Pieces of wood roughly squared, 6 feet in length and 4 to 8 inches square, were laid across the road at a distance varying from 2 to 3 feet. Above these cross-ties, and fastened to them with wooden pegs, were the rails, 6 or 7 inches wide, 5 inches deep, and about 4 feet apart.[11] The road was then completed by filling in the spaces between the cross-ties, or sleepers, with gravel, stone, and clinkers. Then came the next stage of development, the placing of additional rails on top of the first in order to save tearing up the cross-ties and rendering them useless from enlarged peg holes. This improvement also had the advantage of allowing more ballast to be placed over the ties, thus protecting them from the horses' feet.

As early as 1716 it became the practice to nail thin plates of malleable iron on the surface of wooden rails where an ascent or sharp curve rendered the draught more difficult than usual. By lessening the friction at such points the horses' burden was lessened, and he was better able to maintain a more uniform rate of speed. Outright substitution of cast-iron rails for wooden ones was attempted in 1738, but the wagons proved to be too heavy for the light and brittle iron. Then at the suggestion of one Mr. Reynolds, iron plate rails came into being about 1767 at the Coalbrookdale Iron Works.[12] The price of iron then being low, it was proposed to cast iron bars to place over the wooden rails of the company's railroad, with a view toward picking them up again and selling as pigs at some future time when iron prices had risen. In the meantime the furnaces would be kept at work, and probably some savings would be realized on repairs to the tracks. In all, between five and six tons of rail were cast, the "scantlings of iron" being 5 feet long, 4 inches broad, and 1¼ inches thick. The superiority of these "plate rails" over the wooden was soon apparent, and the custom rapidly spread throughout the industrial centers of Britain.

Nine years after their initial use at Coalbrookdale, cast-iron rails with upright flanges were introduced at the colliery of the Duke of Norfolk near Sheffield. The rails, spiked to wooden cross-ties, were simply angle-irons with the vertical flanges acting as guides inboard of the flangeless wagon wheels. Some later roads had the rail flanges outboard of the wheels, but there is no evidence that one system ever completely gained favor over the other.[13] The story is told that the first flanged rails laid at Sheffield by Benjamin Outram were torn up by enraged colliers who feared that fewer horses and men would be needed to haul coal once the improved rail became established. His workers became "plate-layers" and his roads became known as "Outramways," later shortened to "tramways." In 1793 Outram replaced the wooden sleepers under his rails with stone supports, about 1 foot square and 8 or 9 inches deep, with wooden plugs in the center for spiking in the rails. Plate rails continued to be popular into the early nineteenth century, being installed on such well-known lines as Outram's Ticknall Tramway (1799), the Surrey Iron Railway (1801), and the Silkstone Railway (1809). With the advent of the steam locomotive, however, a new type soon became almost universal--the "edge" rail.

THE "EDGE" RAIL APPEARS -- William Jessop, engineer of the

Butterly Iron Works near Derby, is generally credited with having turned the plate rail on edge to secure a smooth level top, thus bringing the "edge" rail into existence on the line from Loughborough to Nanpantan in 1789. It appears that objections were raised to the projecting flange on the regular plate rail to be placed on the turnpike road near Loughborough, so Jessop devised this substitute rail and put flanges on the wheels of his wagons instead. As he gained experience with this new rail, Jessop devised many refinements. To strengthen the rail he made it fish-bellied in the longitudinal direction, and then added feet at either end to secure the rail to the sleepers. When cast as an integral part of the rails, however, the feet were frequently broken off, an important factor which led to Jessop's introduction of the separate chair or rocker between rail and tie at Newcastle-on-Tyne in 1797.

In the early years of the edge rail many different cross-sections appeared--some in a rough T-shape, others square, and still others oval. One early extensive use of the oval type was made on the road completed in 1801 to convey slate from the quarries of Lord Penrhyn. Here the wagon wheels were given a concave groove around their circumference to conform to the oval rail, but excessive wear soon led Mr. Wyatt to flatten both the groove and rail, maintaining the double flanges on each wheel. Wyatt also introduced a hexagonal rail in North Wales in 1802, but it never achieved the popularity of the flattened oval type. The double-flanged wheel was short-lived, however, and the single flange returned to popularity as rails grew deeper while maintaining a concentration of metal at the top.

Originally of course, these rails were of cast iron, but cast iron came to be gradually replaced early in the nineteenth century by the tougher malleable iron in the square or flat form. As early as 1808 malleable iron rails had been laid at the Earl of Carlisle's Colliery at Tindal Fell with very satisfactory results.[14] Malleable iron rails, 1½ inches square, resting on 10-inch square stones a yard apart, had been serving 4-ton carriers successfully for eight years, according to a survey made at this same colliery in 1819. Possibly the earliest use of this new type of rail was made by George Grieve at Sir John Hope's Collieries near Edinburgh. Using them for light underground work, he rested bars, 1¼ inches square and 9 feet long, on one or two sleepers in the middle, and increased the depth of the bars to accommodate heavier loads. Despite these isolated instances, the use of malleable iron did not become a commercial possibility until 1820, when John Birkinshaw of Bedlington, England, patented a rail which could be rolled to lengths of 15 or 18 feet and shaped as desired. Birkinshaw did not claim the invention of rolling rails, but merely asserted his right to manufacture and sell wedge-formed bars for railroads. Until this time most rails were confined to a length of about 4 feet.

The Birkinshaw rails, used for the first time at the Killingworth Colliery in 1820, were readily recognized by George Stephenson as being superior to any cast-iron rails then in use. When it came time for him to recommend the type of rail to be used on the Stockton and Darlington Railway, Stephenson unhesitatingly chose malleable iron, despite the fact that he shared a patent for cast-iron rails with William Locke and thereby stood to lose money by not recommending the inferior cast iron. Accordingly "half-lap" malleable iron rails, weighing 28 pounds per yard, were placed on the famous road.

DEVELOPMENT OF IRON RAIL SHAPES -- The longitudinal fish-bellied shape which had been introduced in the latter part of the eighteenth century did not last fifty years, although it probably reached the peak of its popularity in wrought iron during the 1830's. It was also during this period that the parallel upper and lower flanges became popular, the Liverpool and Manchester installing this type in 1834. In 1841 the Penny Cyclopaedia noted the fish-belly's passing with the remark:[15] "The experiments of Barlow and others leave it questionable whether any additional strength is obtained from a given weight of iron by the fish-bellied shape, and therefore parallel (top and bottom) rails are now almost universally adopted." Thus, before 1850 the longitudinal shape of the rail had reached its modern form.

The evolution of the cross-sectional shape was, however, another matter. In 1830 Robert L. Stevens, Chief Engineer and President of the Camden and Amboy Railroad, designed the first modern T-section and gained the reputation of being the inventor of the flat-footed rail. Independently apparently, and at about the same time, Charles B. Vignolles of England designed a similar T-section, somewhat broader and flatter than the Stevens' rail. The Vignolles rail which eliminated the chair and could be spiked directly to the cross-ties, appeared in 1836 and rapidly became popular throughout Europe. The shape remained undisturbed for many generations although sizes increased up to as much as 136 pounds per yard. In the heavier sizes it then became practice to spike the rail to a metal plate rather than directly to the tie. To accommodate the heavier loads on his Great Western Railway Isambard K. Brunel introduced the bridge rail, which was used by that company until 1892. Essentially, the bridge rail was shaped as its name implies, with a pair of flat feet supporting an inverted "U." In 1835 yet another type was introduced by Joseph Locke, the double-headed rail. Theoretically, this rail--which looked like a dumb-bell--could be reversed, but in practice the cracking, breaking, or even wear of one end would render it unsuitable for further use, reversed or not. From the double-headed rail evolved the "bull" or single-headed rail which simply concentrated more metal at the top to resist the wear and tear of increasing wheel loads. Thus, by the time that Bessemer steel rails began to appear in 1862, a great deal of experimentation and practical application had gone into the makeup of the cross-sectional shape.

THE STEEL RAIL -- The effect of Bessemer steel on the development of the railroad was summarized by W.H. Sellew[16] in "Steel Rails" (New York, 1913) as follows:- "The outgrowth of an attempt to make wrought iron cheaply, it came in just at the time when wrought-iron rail was beginning to demonstrate its unfitness to stand the increased wheel loads then coming into use. It perhaps is not too much to say that the Bessemer steel rail has made the modern railroad possible, and that without it, or its equivalent, the world's development would be half a century behind its present advanced position." Increased loads were not, of course, the only reason for rail wear--which took the form of crushing or lamination--for in many places the quality of the iron had decreased. In the United States, for instance, the price of iron rails was gradually reduced to one-third of the original cost during the twenty years preceding 1868, but an inferior type of rail resulted. The world was ready for it, therefore, when the steel rail arrived.

There were some lines that had steel rails prior to the introduction of Bessemer's rail in 1862, but they were few in number and unimportant from the point of view of their influence over subsequent developments in the steel rail. In 1859 the Northern Railway of Austria, connecting Vienna with Cracow, installed rails of puddled steel manufactured at the Works of Archduke Albrecht at Carlshütte. Steel rails had also made an appearance before the end of 1861 on such English roads as the Caledonian, Lancashire, and Yorkshire, the London, Brighton and South Coast, the London and Northwestern, and the Rhymney Railways. Then, following the development of the Bessemer process, steel rails began to appear in all parts of the world. By 1864 they were in use in America on the Chicago and Northwestern, the Philadelphia, Wilmington, and Baltimore, and the Old Colony and Newport Railroads. In France the Paris, Lyons, and Mediterranean Railway decided in 1867 to use only steel in relaying its permanent way on 860 kilometers of the Paris-Marseilles line. Before 1872 Russia had also investigated the possibilities of steel by laying the experimental Nicholas Railway. Her first extensive use of the new material then came on the lines from Wjasma to Tula, Rjask, and Jetetz, and from Morschunsk to

Siezran--a total length of 1200 kilometers.

Adoption of the steel rail was particularly rapid in the United States where new roads were constantly being pushed across vast spaces of wilderness. For this reason it might be well to note briefly some of the more important features of American development which were representative of the over-all progress of this new type of rail. Originally, all steel rails used commercially in the United States were imported--mostly from England, though some came from Germany. The Pennsylvania Railroad was among the first to import the new product,receiving in 1863 a shipment which was not laid down, however, until 1866. Domestic production began on May 24, 1865 at the North Chicago Rolling Mill where the first rail was rolled from hammered blooms manufactured at the experimental steel works of Wyandotte, Michigan. Two years later the Cambria Iron Company of Johnstown, Pennsylvania, began rolling the first rails for commercial use in the country. The rapid growth of the use of the steel rail in America was illustrated by a survey whose results were issued in 1869. Of the fifty-six railroads from which reports had been obtained, twenty-six were using steel. The bulk reported amounted to 49,800 tons, equal to 518 miles of track; estimates at the time indicated that the actual amount in use throughout the country was more than double the figure actually reported.

Early steel rails were shaped very much like their iron predecessors, being, for the most part, pear-headed to prevent the side of the head from breaking down. Naturally, this shape made fishing the ends together difficult and spurred many on to devise new shapes which could be economically rolled and yet incorporate all the necessary and desirable features. In 1866 Ashbel Walsh designed a section, differing but slightly from the modern rail, with the following dimensions: height 4 inches, head 2 3/8 inches wide, stem 7/16 inches thick, length 30 feet, weight 53 pounds per yard. Sections of this rail were then tested successfully in 1867-68 on heavy traffic spots between Philadelphia and New York. Walsh was also chairman of the committee set up by the American Society of Civil Engineers in 1873 to determine the size, shape, weight, composition, and material properties of rails, with a view toward producing some sort of standard rail. The "standard rail" program was difficult to translate into practice, however; in 1881 one hundred and nineteen patterns of twenty-seven different weights per yard were being manufactured, and one hundred and eighty older patterns were still in use. A standard section of the same general shape as Walsh's design was adopted by the A.S.C.E. in 1893, with three different weights, 60, 80 and 100 pounds per yard, being specified.

Quality of the metal itself, as well as the shape of the rail, was another problem which cried for solution. When iron rails replaced the old strap irons, they were satisfactory for the lighter loads, but the picture changed completely when heavier loads were introduced. Similarly, the mild steel rails introduced about 1865 to replace those of iron were suitable for the comparatively light loads of the seventies, but they proved to be too soft for the equipment of the next decade. Relief was found by the addition of hardening constituents to the steel,

RAIL CROSS-SECTIONS

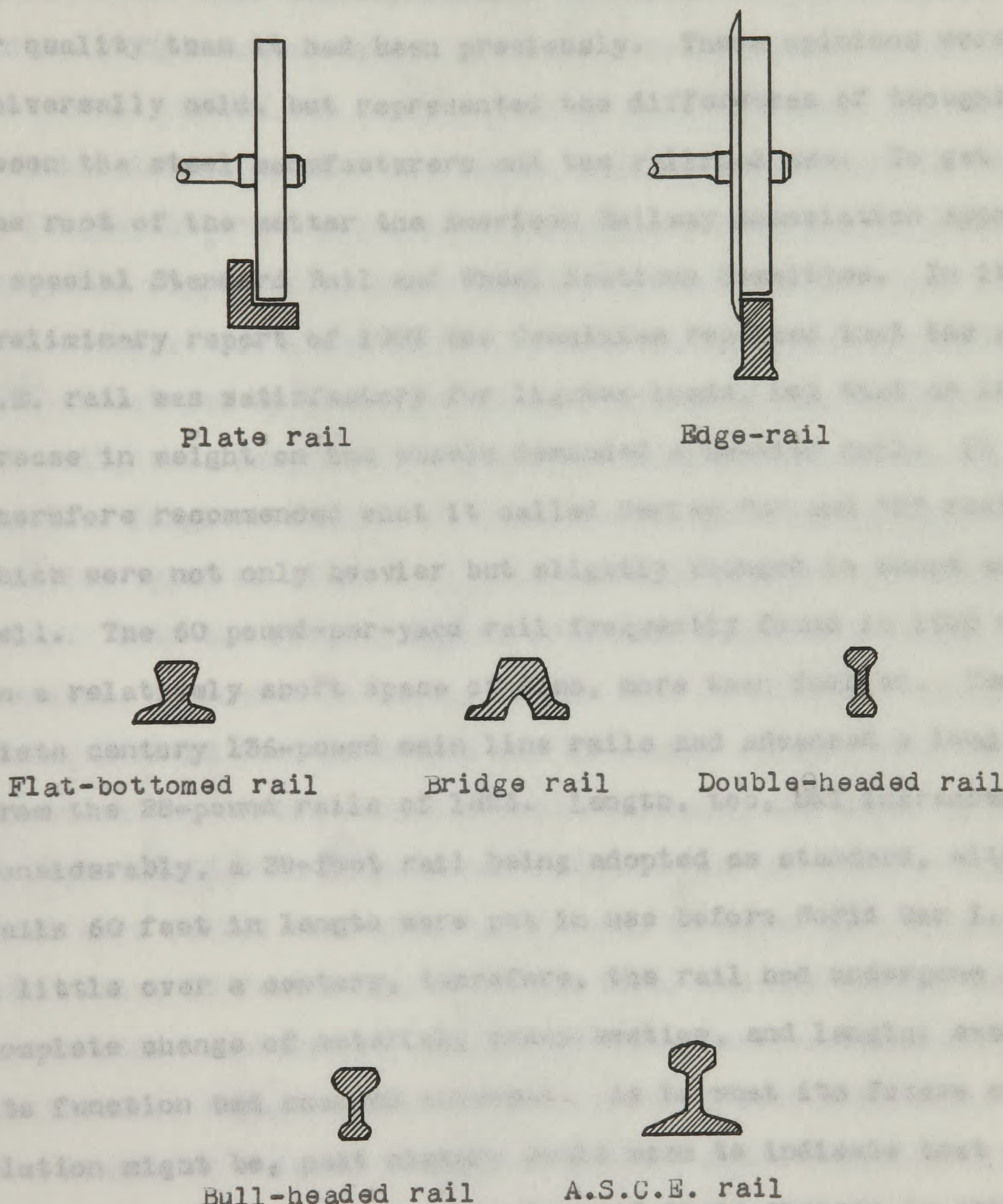

Fig. 8

but by 1905 failures again became acute. Among the reasons advanced for this new wave of failures were that wheel loads were exceeding the limits of the steel strength in the rail, a heavier A.S.C.E. rail was impractical to roll, and steel was of poorer quality than it had been previously. These opinions were not universally held, but represented the differences of thought between the steel manufacturers and the railroad men. To get to the root of the matter the American Railway Association appointed a special Standard Rail and Wheel Sections Committee. In its preliminary report of 1907 the Committee reported that the A.S.C.E. rail was satisfactory for lighter loads, but that an increase in weight on the wheels demanded a heavier rail. It therefore recommended what it called Series "A" and "B" rails, which were not only heavier but slightly changed in shape as well. The 60 pound-per-yard rail frequently found in 1900 was, in a relatively short space of time, more than doubled. Twentieth century 136-pound main line rails had advanced a long way from the 28-pound rails of 1825. Length, too, had increased considerably, a 39-foot rail being adopted as standard, although rails 60 feet in length were put in use before World War I. In a little over a century, therefore, the rail had undergone a complete change of material, cross section, and length; even its function had changed somewhat. As to what its future evolution might be, past history would seem to indicate that changes will continue, but the exact nature of those changes is still obscure.

TIES AND ROADBED -- The varieties of roadbed and rail in use on early railroads can be clearly seen from a few American examples of the first half of the nineteenth century. According to Cresy[17] in his "Encyclopaedia of Civil Engineering" (London 1861) the 26-mile Harlem Railroad had plate rails, 2½ inches in width and 5/8 inches thick, secured to longitudinal timbers 77 feet long. These, in turn, rested on ties of locust and cedar, 3 feet 6 inches apart. The Camden and Amboy Railroad, 61 miles in length, had "H" rails, 16 feet long and weighing 41 pounds-per-yard, supported on stone blocks, 18 inches square and 12 inches deep. The stone blocks, placed in a continuous trench, were surmounted by pieces of wood, 2 inches thick, to adjust the rail; and fishplates, 4 inches in length, joined the rails together longitudinally. On the Columbia and Philadelphia Railroad two types of track came into use--the granite and timber types. With the former, layers of broken stone were placed in trenches, 22 inches in depth, in the line of advance. Granite sills, 3 to 12 feet in length and 12 inches square, were then placed on top of the broken stone foundation, and holes 3½ inches in depth and 5/8 in diameter were drilled in the sills. These holes were filled with plugs of locust, to which were spiked the iron rails, 15 feet long, 2½ inches wide, and 5/8 inches thick. Construction features of the timber track were somewhat different, the trenches being cut across the road at 4-foot intervals. Cut to a length of 8 feet, a width of 1 foot, and a depth of 16 inches, the trenches were rammed with broken stone. On this were placed sills of chestnut and white oak, 7½ feet long, and 7 inches square, notched to receive yellow pine stringers, 6 inches square. Flat iron bars were then placed on top of the stringers to provide the final rail surface.

From the above few examples we can see that two main ideas predominated--one, that the roadbed should be rigid, and the other, that the roadbed should be flexible. In England Brunel is especially remembered for his attempt to adopt a rigid base for his Great Western Railway, which began operation from Paddington to Maidenhead in 1838. He declared his intention of carrying his rails throughout their length on longitudinal timbers, these to be supported at intervals on piles. His scheme was soon abandoned, however, for the road was too rigid and the rails too light to take the heavy pounding from the large rolling stock. As wheel loads increased the same trouble was noted in all rigid track lines, and the relatively flexible type of track, consisting of ties resting on well-drained crushed rock ballast over a firm foundation, came into almost universal popularity.

Important in maintaining the desired flexibility of a road are the ties or sleepers which, from the earliest days of the railroad, have generally been of wood. Before the first World War 7-inch wooden ties were thought to be adequate, but since that time the size has increased to 8, and even 9 inches. Where formerly only sixteen ties per 33 feet of rail were used, the number of ties has since been increased to twenty. These two features alone have increased by 50% the amount of rail directly supported on ties. Another important feature of the use of wood has been the increased attention given to preservation methods such as creosoting.

Though most common, wood is not the only material which has been used for ties. Granite was among the earliest substitutes, being used in Dublin and on the old Boston and Lowell Railroad. Concrete, which came in during the first decade of the twentieth century, was similar to granite in many respects, but it received more wide-spread attention. One of the earliest on trial was the Buhrer concrete tie, which was used on the Pennsylvania lines west of Pittsburg. Six hundred ties were laid in 1903-04, but they failed under traffic and were all taken up in 1906. The Percival concrete tie had a similar fate on the Pittsburg and Lake Erie Railroad, where after two years of use it was removed as a failure in 1908. Better results were had with the Kimball tie on the Chicago and Alton Railroad where sixty ties were still in use in 1912 after seven years of service. One of the largest of the many concrete sleepers introduced was the Riegler tie, weighing 850 pounds, with a bearing surface of such size that only fifteen ties were needed for 33 feet of rail. In Europe combinations of wood and metal, known as the Sarada and the Adriatic Railway ties, achieved a measure of popularity, and in the United States similar combinations came into limited use. Several types of all-steel ties, such as the Hanson, Carnegie Steel, Universal Metallic, and Snyder Steel, were introduced into American practice early in the twentieth century without conspicuous success. There were exceptions,[18] however, for on the Union and on the Bessemer and Lake Erie Railroads over a million steel ties, accommodating 300 miles of track, were serving successfully in 1913. Nevertheless the schemes to displace wood as the primary material for ties have not, on the whole, been successful, and the general trend has been more directed towards finding better methods for the successful preservation of wooden ties.

Accompanying the improvements in track, tie, and foundation have been the improvements to the accoutrements which enable the main parts to operate efficiently. Early rails were not linked together rigidly in a longitudinal direction until Stevens of the Camden and Amboy Railroad introduced the fishplate for "fishing" the ends together. After being introduced into England in 1847 by W.B. Adams, the fishplate gradually expanded into the full-fledged angle splice bar. Spikes, originally of wood, have changed as have the rails with the advances of metallurgy. Generally speaking they have been smooth, but screw spikes, apparently used first by the French, have also seen a great amount of service since the middle of the nineteenth century. Increased attention has also been given to the distribution of metal in switches, frogs, and crossings to provide a uniform strength throughout. Now that railroads have passed through the heyday of rapid construction--where quantity and not quality was the criterion--the emphasis has shifted to safety, comfort, and durability.

TRACK GAUGE -- Almost universal in the United States, Canada, and Great Britain, and in use in many other places throughout the world, the "standard gauge" of 4 feet 8½ inches between rails did not become fixed as the result of deliberate engineering calculations, but, in a sense, simply "happened." Many of the early coal wagons used in the Newcastle coal district had their wheels placed about 5 feet apart, and as the rail developed, it became easier to work with distances in the clear between railheads--hence, the adoption of the rather odd measurement 4 feet 8½ inches. Some have suggested, with very little concrete evidence, that the wheel spacing of the Newcastle wagons was, in turn, derived from the ruts left by Roman carts of centuries before. While highly improbable, the thought that the Romans may have played an important part in determining the track gauge of the modern railroad is intriguing, to say the least! Stephenson's locomotives, built to this standard guage, soon influenced most lines in England to adopt it, and other countries importing the locomotives were similarly influenced. Stephenson had no great convictions about this gauge except that once it had been adopted he condisered that the most economical course was to continue it. He argued that new lines springing up in isolated places would some day be joined to the main lines already established, and that the interchange of rolling stock between the adjoining lines would be of paramount importance in the future development of railroading and commerce.

Despite the logic of his arguments and the eminence of his position in the field of railroading, George Stephenson--and later his son Robert--found himself in bitter controversy over the gauge question with Isambard K. Brunel. When the Great Western Railway Bill had passed in 1835, Brunel announced his intention of building a 7-foot gauge, not primarily for the purpose of creating a larger engine, but rather to obtain higher speeds and greater comfort with less accident risk. He wanted the wider gauge in order that he might provide wider carriage bodies between the wheels, but in 1840 he shifted to the same outside bearings which made wider carriages possible on the standard gauge roads. Brunel felt that the Great Western would be operating all alone in its area and would not, therefore, be concerned with the interchange of rolling stock with other lines. When the problem did arise, though, third rails were laid so that wide and standard gauge stock could use the same roadbed. Far-seeing men, seeing in rival main-line gauges a danger to the future economy of the country, called for a clear-cut decision as to what future policy should be. Both Stephenson and Brunel had their enthusiastic supporters, but the views of the former finally prevailed. The Gauge Commissioners' Report of 1846 eventually led to legislation preventing the further extension of the broad gauge, but it in turn brought on a tremendous competition in speed between the rival gauges. As the nineteenth century drew to a close, the Great Western gradually changed over to the standard gauge, the last job of conversion being the change-over of 170 miles of track between Exeter and Penzance in thirty hours on the 21st and 22nd of May, 1892.

A similar confusion of gauges grew up in many other countries, some of which eventually adopted the Stephenson gauge and some of which did not. Certain southern roads in the United States had a gauge of 5 feet until after the Civil War, and the Erie Railroad had a 6-foot gauge until 1878. The first locomotive sent to Canada by Robert Stephenson and Company in 1856 had a gauge of 5 feet 6 inches, decided upon by the Canadians who had been advised by leading railroad men of the United States. At the time American main lines varied from 4 feet 8½ inches to 6 feet. Spain and Portugal in the first half of the nineteenth century (1844) also began developing a compromise gauge of 5 feet 5¾ inches, but they retained it for economic reasons, and possibly for military reasons as well--feeling that a difference between the French gauge and theirs would be a safeguard against aggression. Over most of the rest of Europe, main lines of 1.45 meters (4 feet 9 inches) gauge have developed, making the interchangeability of English and continental rolling stock possible. Continental countries whose main trunk lines are, for all practical purposes, standard gauge include Austria, Belgium, Bulgaria, Denmark, Czechoslovakia, France, Germany, Holland, Hungary, Italy, Jugoslavia, Norway, Sweden, and Switzerland. Many of these countries, especially those with mountainous terrain, also have considerable mileage in meter gauge and smaller. In other countries--even those which imported English locomotives at an early date--different gauges have prevailed, although a variety may still be present. For instance, in Ireland the gauge is mainly 5 feet 3 inches, in Russia 5 feet, in India 5 feet 6 inches, in Japan 3 feet 6 inches, in South Africa and the Sudan 3 feet 6 inches, in Kenya and Uganda 1 meter, in South America 5 feet 6 inches, and in Australia a generous mixture of 3 feet 6 inches, 4 feet 8½ inches, and 5 feet 3 inches. From the above list we can see that most main line development has clustered close to Stephenson's "standard" gauge. Probably the minimum gauge which has been developed for practical purposes has been that of 1 foot 3 inches, although British model engineers have exhibited one of 2 inches on which three grown men could be pulled. In looking over the past course of history of gauges one can see the gradual standardization of all contiguous lines, but there is little to encourage the belief that roads separated by oceans will ever feel the necessity for scrapping their present well-established gauges in favor of a universal standard.

Development of the Railroad in the United States

EARLY YEARS -- Following closely in the wake of British development, American railroading soon captured the fancy of the infant country, and proceeded to expand at a rate matched only by the growth of the country itself. Probably the earliest rail line in America was the inclined plane road constructed in 1795 at Boston for the purpose of moving brick. The next tramroad in the city, attributed to Silas Whitney, was built in 1807 for the purpose of hauling stone. Two years later Thomas Leiper at Avendale, Pennsylvania, built an experimental road and followed it up with a second of less than a mile in length, also for the purpose of transporting stone from quarries. The next tramway of significance was the 3-mile road at Quincy, Massachusetts, built by Gridley Bryant in 1826, for carrying stone for the Bunker Hill monument. In 1827 Josiah White and Erskine Hazard built the longest and most important railroad in the United States up to that time--the 9-mile Mauch Chunk Railroad in Pennsylvania--which was used for conveying anthracite from the mines at Summit Hill to the Lehigh River.

Up to this time horses and oxen were used for motive power, but the steam locomotive was not unknown. As early as 1812 John Stevens produced his "Documents Tending to Prove the Superior Advantages of Railways and Steam Carriages over Canal Navigation" in which he predicted future speeds of 100 miles-per-hour. In 1825 he actually built a small locomotive which he ran on a circular track in Hoboken. Over a decade and a half elapsed from the time of his dissertation, however, before the first successful steam locomotive appeared on American rails. Imported from the firm of Foster and Rasterick of England by Horatio Allen, the "Stourbridge Lion" made the first run in 1829, 3 miles into the woods and 3 miles back, at Honesdale, Pennsylvania, on tracks later owned by the Delaware and Hudson Canal Company. In all, the line extended 17 miles from the coal mines at Carbondale to the canal at Honesdale, remaining in operation until 1931. In less than a year after the run of the "Stourbridge Lion," Peter Cooper exhibited his "Tom Thumb," weighing less than a ton, on the Baltimore and Ohio's rails from Baltimore to Ellicott's Mills. The locomotive performed well enough on its outward journey, but was somewhat degraded by losing a race to a horse on the run back into town. Although the Baltimore and Ohio Railroad, which helped th promote this trial, was the first in the United States designed for the general transportation of freight and passengers, it was not built exclusively as a steam road. At first it was horse-drawn, and even sails were experimented with, but the horses gave way to locomotives as a result of the "Tom Thumb" trials. Construction of the road was begun in 1828, and by 1830 almost 15 miles had been completed. It continued to push westward under chief engineer Jonathan Knight and then under Benjamin H. Latrobe, reaching Wheeling in 1853. Its place in history was prophesied by Charles Carroll of Carrolltown, Maryland, then the only survivor of the signers of the Declaration of Independence, who remarked, when he "laid the first stone" for the B. & O. on July 4, 1828, that it was one of the greatest acts of his life, second only to signing the Declaration of Independence, if indeed it were second to that.

First railroad in the United States, and possibly in the world, to be built from its inception as a steam road was the South Carolina Railroad, built by Horatio Allen, from Charleston to Hamburg. In February of 1829, 150 feet of track were laid on Wentworth Street in Charleston, and by the end of 1833 the line of over 135 miles had been completed, making it then the longest railroad in the world. Nominally the road was opened to traffic in January, 1830, but the real opening came later in the year when the first American-built locomotive designed for commercial use, the "Best Friend," went into operation. This famous locomotive never reached a museum though, for one day the fireman, annoyed at the popping noise, held down the safety valve too long, and gained the doubtful distinction of being the first casualty in American railroading.

Most of the early roads followed a similar pattern, striking westward from the Atlantic seaboard to the interior with little attempt to parallel the coast line. Typical was the progress of the Pennsylvania Railroad, known then as the Philadelphia and Columbia Railroad, which was begun as a public project by the State of Pennsylvania in 1829 to form a link connecting Philadelphia and Pittsburg. At the eastern end,20 miles of line were opened in 1832, and in 1834 the entire double track was placed in operation. Private individuals or companies supplied their own rolling stock, and paid a toll to the State in the same manner as did people using the turnpike roads. In 1834 the State installed two locomotives on the line, and the horses gradually disappeared. The company later passed to private hands, continuing to grow by new construction and by amalgamation with other roads until it included properties once held by more than four hundred different companies.

Prior to the middle of the nineteenth century the railroads were still more or less experimental, and did not exercise the great influence in the country's expansion to the westward which they did in later years. There were only two transportation routes of significance from the Atlantic seaboard to the Middle West, viz., the Erie Canal and the state route through Pennsylvania, consisting of part railroad and part canal. The Pennsylvania route was too slow and cumbersome, and too expensive, operating during the relatively short period from 1834 to 1854. During that time the annual traffic over the route only amounted to about 20,000 tons, whereas the traffic over the Erie Canal was somewhere between 1,000,000 and 2,000,000 tons. Meanwhile other roads were slowly pushing to the west. The Baltimore and Ohio Railroad, begun in 1828 to connect the Mississippi Valley to Baltimore, was completed by 1853. A line stretched from Albany to Buffalo by 1842, and in 1858 the Pennsylvania had extended a thousand miles into the interior to Chicago, with the completion of the Pittsburg, Fort Wayne, and Chicago Railroad. Four years prior to that the Rock Island Railroad had reached the Mississippi River. Thus, as the second half of the century began, it was clear that the experimental period in American railroading was over and that a new vital force had entered American life.

TRANSCONTINENTAL ROADS -- The great impact made by the railroad on the social, political, and economic life of the country was particularly apparent in the decade from 1850 to 1860, when the railroad mileage increased 240% and the center of population shifted 81 miles to the west--the greatest shift it has ever made.[19] The steady march of the iron road to the west made it evident that it was only a matter of time before the Pacific would be reached. As early as 1832 a writer in "The Emigrant" at Ann Arbor, Michigan, suggested, with apologies for so visionary a scheme, a rail route up the Platte, along the Snake, and down the Columbia River to the Pacific coast--a route very similar to that ultimately taken by the Union Pacific Railroad. Prior to 1850 Asa Whitney, a wealthy New York merchant, had spent his entire fortune urging a railroad to the Pacific. The discovery of gold in California in '49 accentuated the cry for a transcontinental road, but results were not immediately forthcoming. Technically the project was feasible long before it was financially so, for running a line through hundreds of miles of virgin territory occupied only sparsely by hostile Indians could hardly be considered a good business risk. Fortunately the federal government stepped in and offered a bounty of $30,000 per mile of line and a grant of land every alternate section for 20 miles on either side to any private companies which might take up the task. After the offer had been accepted by the Union Pacific at Omaha and by the Central Pacific at San

Francisco, Congress passed the final Bill for the project in 1864. Work was begun that same year at San Francisco and two years later at Omaha. On May 10, 1869 the task of spanning the continent by rail was completed when the two lines were joined at Promontory Point, Utah.

The government surveys of 1852-54 had indicated five possible routes for getting through to the West Coast, all of which were eventually taken by the following roads: the Northern Pacific, the Union Pacific, the Denver and Rio Grande, the Atchison, Topeka, and Santa Fe, and the Southern Pacific. More recently two other great lines have been added to the list--the Great Northern, and the Chicago, Milwaukee, and St. Paul. There is little doubt that these lines played the major part in developing the West by providing an outlet to eastern markets for its agricultural products, while at the same time bringing to it the goods of the industrial East. Encouraged by the opportunities unfolding before them as the result of the penetration of the railroads, people migrated westward in ever-increasing numbers, spreading to the natural boundaries, and thus fulfilling what was considered by most the Manifest Destiny of the United States.

Early railroads in the United States had been largely community products, but the latter part of the nineteenth century witnessed a period of great combinations which confused even the initiated. C.C. Williams in "The Design of Railway Location" (New York 1917) noted the following:- "For example, the Chicago, Burlington and Quincy Railroad comprises about 60 or 70 such small roads, averaging about 100 miles in length, but the majority of them being less than 50 miles long. The Burlington owns the majority of stock of the Colorado and Southern, which in turn owns the Colorado Midland, the Colorado R.R., the Trinity and Brazos Valley, and the Wichita Valley, and the last named owns the Wichita Falls and Oklahoma, the Abilene and Northern, and the Stanford and Northwestern. To show further the corporate complexity of railroad ownership, it may be stated that the Burlington is owned equally by the Great Northern and the Northern Pacific Railways. The case of the Burlington, moreover is not exceptional. Many of the American railroads are as complicated or more so than it is."

As the companies increased to larger and larger units, trackage also increased until it reached a peak of over a quarter of a million miles in 1916. The rapid growth of the railroads may be gathered by looking at mileage figures for a few key years.[20] In 1830 the United States possessed 230 miles of track; in 1850 the mileage had jumped to 9,021 miles; the greatest increase came between 1880 and 1890, there being 93,671 miles of track in the former year and 159,271 miles in the latter. Since 1916 there has been a decrease in mileage, a decrease of about 11% in the thirty years following the peak year. While it is true that some of this falling off has been due to increased competition from other modes of transportation, it is equally true that increased efficiency in operation has eliminated many near duplications, and that constant improvements, in bridges, roadbeds, rails, and curves have also acted to cut down the amount needed.

SAFETY -- Safety devices are far from being exclusively

American in origin or in use, but with more than one-third of the total railway mileage in the world the United States has, naturally, played a leading role in safety development. One of the most significant of all inventions has been that of the compressed air brake, perfected in 1867 by the American engineer, George Westinghouse (1846-1914). It enabled trains to be stopped in one-tenth of the distance possible formerly, and thus opened a new era of operating efficiency and safety in railroading.

The development of signalling devices has also played a great part in improving the efficiency and safety of the railroads. In 1794 the French Directory established a movable arm type of semaphore signal which was used for passing messages from hill to hill. Reizen suggested that an electric spark might be used for the purpose, and in 1798 Dr. Salva of Madrid actually constructed a telegraph based on Reizen's principle. These were not originally designed for railroad use, however, but were brought into the railroad field years later. The first fixed railway signal designed for the purpose was the cross-bar and lamp, introduced in England in 1834. Also English in origin was the ball signal of 1837, followed in 1841 by the semaphore--an adaptation of the eighteenth century French design. In 1839 the English produced a manual block system whereby trains could be identified as being in certain sections or "blocks" of track by an established system of signals--thus lowering the possibilities of rear-end collisions and speeding up trains travelling under low visibility conditions. An early type of manual block signal, the Banner Box Signal, was introduced in the United States in 1863, and eight years later the first electrically operated block signal, known as the "Banjo" Signal (U.S.) made its appearance. The automatic block invented by Dr. William Robinson came into use on American roads in 1872, followed by a controlled manual block in England in 1875. Four years after that the American Clockwork Signal appeared, being a mechanically operated automatic block signal with electric control. Further American development included the first power-operated semaphore, an electro-pneumatic type, in 1881; an electric semaphore, forerunner of the present electric motor semaphore signal, in 1893; and the color light in 1908, the position light in 1915, and the color-position light in 1921.

With the passage of years safety in other departments has also been stressed to the highest degree. Rolling stock, rails, roadbeds, terminals, bridges, tunnels, and crossings have all been improved to the point where accidents caused by their failure is almost negligible. For this, two main reasons may be cited: (1) that improved engineering techniques have led to better designed structures, and (2) that an enlightened maintenance policy has resulted in weeding out unsound elements. Generally speaking, the safety record of the twentieth century railroad has been most encouraging, but railroaders have not been lulled into a false sense of security by this fact; every year brings some new invention to the market designed to boost that record to even greater heights.

Railroads in Other Countries

FRANCE -- Although a tramway for use of the foundries of

Creusot went into operation at Mount Cenis in 1783, the horse-drawn line from St. Étienne to Andrézieux--opened throughout its entire length on October 1, 1828--is generally regarded as the first French railway.[21] The construction of this road was due largely to the efforts of the engineer Beaunier and several mining associates who had been influenced by the writings of de Gallois, based on his visit to Killingworth in 1818. In common with most roads of the time, it was single line with sidings at intervals for passing. Designed primarily for commercial use, it did not carry passengers until 1832. The next line, the 35-mile Lyons-St. Étienne Railroad, resulted from the concession given in 1826 to Marc Seguin, his two brothers, and Edouard Biot to connect the Loire and the Rhône. As a result of Seguin's visit to England during the latter part of 1827 and the early part of 1828, Robert Stephenson and Company delivered two locomotives to the French company in 1829, and regular operation commenced in 1831. This road, too, was designed primarily for industrial purposes, and it was not until 1837 that the first regular passenger line, the Paris-St. Germain, went into operation.

By 1842 the French railways had slowly increased their trackage to a total of 360 miles. In that year M. Thiers produced a scheme which has been the underlying principle on which France has since acted with regard to the railroads.[22] In brief the plan stated that (a) the State would construct the roadbed and lease it to companies; (b) the companies would supply the equipment and work the railroads; and (c) at the end of a specified period the whole system would revert to the State. Ten years later the mileage being operated had risen to 2185 miles, and by

1934 it had reached 33,282 miles. The amalgamations which had occurred in British and American practice in the latter part of the nineteenth century were evident in France as well, so that the early twentieth century found France with only seven great systems, the Nord, Est, Ouest, Paris-Lyon-Méditerranée, Paris-Orléans, Midi, and the State Railways.

THE LOW COUNTRIES -- Being a small country, Belgium was able to lay out a complete system at a relatively early stage in her railroad history. Initial studies were placed in the hands of the Belgian engineer, Albert Simons, and his associate, de Ritter, and in 1835 George Stephenson was called in by King Leopold to give further advice in the matter. British influence was particularly strong in these early years, for in addition to Stephenson's advice all of the original locomotives, other rolling stock, and rails were imported from England. The first section of line was put into operation from Brussels to Mechlin in 1835, construction having been started the year before, and the entire original system--laid down in the shape of an irregular cross, 350 miles in length--was completed by 1844. Initial progress in Holland was somewhat slower, however. The first railroad, built by Frederick W. Conrad between Amsterdam and Haarlem at the expense of the king, did not commence operations until 1839. Railroads in both countries soon reached the saturation point, so that in the twentieth century there has been relatively little new construction. While not nationalized in the strictest sense of the word, the almost wholly non-competitive state-controlled nature of their operation has made them State railways in practically all but name only.

GERMANY -- Railroading in Germany began at about the same time as it did in Belgium, with the opening in 1835 of the 4-mile standard gauge line connecting Nuremberg and Fürth in Bavaria. Engineer for this initial road was the Bavarian, Paul Camille von Denis, who had received his technical education in France. Less than two years later the Leipzig-Dresden Railroad, 70 miles in length, began operating, and by 1840 the first interstate line--from Magdeburg, Prussia, to Leipzig, Saxony--had been established. Like Belgium, Germany developed a systematic plan for expansion, due largely to the efforts of Friedrich List. Strict state control was exercised through the rapid construction period which commenced about 1846, private and public construction proceeding at about the same pace. The first State line had appeared in Brunswick in 1838, and by 1855 one-half of Germany's 5410 miles of track were owned by the State.

The Pruss°-Austrian War of 1866 and the Franco-Prussian War of 1870 strengthened state control, and by 1885 private railways in Prussia had become virtually non-existent. The same was true over most of the rest of Germany. Following the first World War the various State railways became the property of the Reich, but in 1924 their status was altered to that of a company basis in accordance with provisions of the Dawes Peace Plan. Regardless of what disposition is made of German railroads in the future, it is most likely that the two characteristics which have long been a part of the German tradition--the international character of the traffic and the high degree of State ownership and construction--will again manifest themselves strongly.

RUSSIA -- Russian interest in railroads was awakened as early as 1812 when Grand Duke Nicholas--later Czar--visited England. He admired Blenkinsop's locomotive so much that a model was later sent to him when he returned to Russia. The enthusiasm for the railroad which Nicholas had developed in England was translated into action when work was begun on the 14-mile 6-foot gauge private line from St. Petersburg to the country palace site at Pavlovsky in 1836. The project, directed by Franz A. von Gerstner of Prague, was completed in 1837. Again English influence was evident in that most of the material was imported from Britain, including three locomotives which came from three different British firms.

Shortly thereafter, work was begun by American engineers with American equipment on the 400-mile St. Petersburg to Moscow line. Construction was carried on from 1842 to 1851, resulting in a very direct and unnecessarily heavy line. It was a work particularly worth noting, for it represented the first successful attempt in Russia to establish a true railway system for the public good. Throughout the rest of the nineteenth century and into the twentieth, lines slowly reached out over the vast stretches of European and Asiatic Russia. Uppermost in many minds was the laying of a line clear across Siberia to the Pacific, a project which commenced with the government surveys of 1872-74. In January, 1903 the line between Moscow and Vladivostok, across Manchuria, was opened; Russian engineers had completed the monumental task of spanning a continent.

SWITZERLAND -- The extremely mountainous character of Switzerland has played a major part in the specialized development of the railroad in that country. Little in the nature of railroading was accomplished there until the latter part of the nineteenth century because of (1) the inability of early steam locomotives to negotiate the steep grades necessary in such rugged terrain, and (2) the difficulties encountered in punching tunnels through unscaleable mountains. Typical of Swiss railroads, early and modern, is the St. Gotthard Railway, proposed in the early fifties of the last century, but not a tangible possibility until the laborious hand-drilling of the Mount Cenis tunnel had been under way for some time, and rails had actually been laid across the Brenner. The St. Gotthard tunnel was pierced in 1880, and two years later the through service from Lucerne to Chiasso was inaugurated. In the 105½ miles from Lucerne to Bellinzona alone some eighty tunnels and three-hundred and twenty-four bridges and viaducts--all over 32 feet in span--were erected. When it was decided in 1913 to electrify the Federal Railway System gradually, the Erstfeld-Biasca mountain section of the Gotthard line was designated the starting point. Actual work was begun in 1916, and the entire 225 kilometers on the St. Gotthard road were electrified by 1922. Since that time the change-over from steam has continued steadily until today practically every part of the Swiss Federal Railway System is electrified.

Main lines were not alone in the extraordinary conditions overcome, for in their own way, small special lines have had their unique problems. One typical example is the rack-equipped, 2-foot 7½-inch gauge, funicular railway which climbs Pilatus near Lucerne. In 1885 Colonel E. Locher and E. Guyer-Freuler of

Zürich produced the Locker rack-rail system which made such a steep ascent possible. Construction of the line, which rises 5344 feet in 3 miles from Alpnachstad to Pilatus-kulm, was carried on from 1886 to 1888. The easiest grade on the line is 1 on 5, the average 1 on 2.8, and the maximum almost 1 on 2 (48%). One very interesting point about this railroad is the fact that its rolling stock is built out of plumb, so that passengers will enjoy a horizontal ride while travelling in an almost half vertical direction. The Pilatus line does not represent the ultimate in steepness, however. From the Ambri-Piotta power station on the St. Gotthard Railway a line ascends 2145 feet in 7/8 of a mile, with a maximum gradient of 87.8%.

OTHER EUROPEAN COUNTRIES -- The pattern of construction and operation of the railways in European countries other than those mentioned briefly above has been roughly the same. One particular line worth special note--because of its early appearance--was the 80-mile horse line in Austria, from Budweis on the Moldau to Linz on the Danube. Chartered in 1824, begun in 1825, and completed in 1832, the road was built by Franz von Gerstner with a gauge of 3 feet 6 inches and a maximum gradient of 1%. Its main business was to convey salt from a point near Salzburg to Hamburg, and to carry a few passengers as well.

In practically every European country some small private lines have existed from the early days of the railroad to the present, but the general tendency has been toward state control. Nationalization in most countries began at about the middle of the nineteenth century, occurring in the fourties in Russia, Italy, Switzerland, and Denmark, in the fifties in Sweden, Norway, and Portugal, and in the sixties in Turkey and Greece. In many places the lack of private capital made state owned and operated lines a necessity from the very beginning, this being particularly the case in countries such as Austria, Bulgaria, Czechoslovakia, Rumania, and Yugoslavia. By 1934 continental Europe, including Asiatic Russia, possessed some 235,719 miles of railroad, most of which now belong to the states through which they pass.

THE AMERICAS -- Most of North America's 332,233 miles of railroads tabulated in 1934 were located in the United States, with Canada and Mexico second and third respectively. Canadian construction followed a pattern similar to that of the United States in that the roads were gradually pushed to the west until the Pacific was reached. In 1836 the first railroad was established at St. John's, Quebec, and in the following year the horse on the road was replaced by a locomotive. Canada's "Railway Era" really began, however, in 1851, the year that the Act authorizing the Grand Trunk line was passed. Stretching from Montreal to Toronto, the Grand Trunk was completed in 1856, forming an important section of what later became--as the result of the amalgamations of several roads--the Canadian National, 23,750 miles in length, the second largest route mileage in the world. An American engineer, William C. Van Horn, was chosen in 1881 to push the first Canadian trans-continental line, the Canadian Pacific, to its completion. Many famous figures were connected with the gigantic enterprise, notable among whom were Lords

Strathcona, Mounstephen, and Shaughnessy. Finally the Rockies were conquered and the line from Montreal to Vancouver was opened for business in May, 1887. In Mexico, as in Canada and the United States, most of the main lines adhere to the standard gauge of 4 feet 8½ inches. However, the biggest system, the National Railway, includes considerable mileage of 3-foot lines. Like her northern neighbors, Mexico has succeeded in spanning the continent with the steel rail to form another great link between the Atlantic and Pacific Oceans.

The 1934 tabulation of railroads in South America listed a trackage of 66,603 miles, the most important portion of which belonged to Argentina. Her railways were built largely with private British capital and with British equipment. The main gauge adopted in this country has been 5 feet 6 inches, but standard and meter gauges are also in evidence. Brazil on the other hand, has adopted 5 feet 3 inches in the main, but possesses extensive mileage in the meter gauge as well. As in North America the general march of the railroads has been from the coast to the interior--generally speaking, on an east-west axis. Relatively little has been done in the way of north-south traffic, so it is questionable as to whether the variety of gauges which have sprung up in the various countries will ever seriously affect future traffic.

One particularly outstanding South American line which deserves comment[25] is the Peruvian Central Railway, originally known as the Callao, Lima, and Oroya. Begun in 1870 under Henry T. Meiggs of Philadelphia, the road was projected across the Andes at a summit level of 15,865 feet above sea level for the purpose of connecting the mines at Oroya with the sea at Callao, close to Lima. The work was halted at Chicla, 87 miles from the coast, in 1877 when Meiggs died. Two years later war broke out between Chile and Peru, discouraging any further progress for a time. After the works had been silent for eleven years, the Peruvian Corporation bought them and appointed William Thorndyke, another Philadelphian, to complete the job. In 1893 the road was completed--the highest standard gauge main line railroad in the world.

AFRICA, ASIA, AND AUSTRALASIA -- Most of Africa's 42,750 miles of track in 1934 were of the 3-foot 6-inch or meter gauge, although an early attempt was made to introduce the standard gauge of 4 feet 8½ inches. In 1860 a standard gauge road was opened in Natal, followed by a similar gauge between Cape Town and Wellington, but by 1870 less than 70 miles had been completed. By 1881 the gauge had been converted to 3½ feet. Northern lines in Morocco, Algeria, and Tunisia have, on the other hand, developed a considerable amount of standard gauge lines along with the meter gauge. The relative scarcity of population and commercial activity and the advent of the airplane have shared in reducing the demand for more trackage, but increased commerce in the future should go far towards creating a new demand for railroads on the "Dark Continent."

Railroads in Asia, as in Africa, got a relatively late start when compared with Europe and America, but construction proceeded at a rapid pace until there were--including European Russia--

133,862 miles of Asiatic roads tabulated in 1934. British India was in the forefront in Asia, developing an extensive system of 5½-foot and meter gauges. Here the earliest line of consequence was the East Indian, serving Calcutta, Allahabad, Agra, and Delhi, the first section of which was opened in 1854. Celon's system began operation in 1865, followed seven years later by that of Japan. Different gauges were developed in different countries, those predominating in Siberia being of 5 feet, in Japan 3½ feet, and in Siam the meter.

Most of the 31,958 miles of railroads (1934) in Australasia are, quite naturally, on the continent of Australia, and are, almost without exception, government owned. The first line built in Australia near Melbourne, Victoria, in 1854 was a product of private enterprise, but by 1878 almost all private lines in Victoria had been taken over by the government. The odd collection of main line gauges varying from 3½ to 5¼ feet render a future tying-in of connecting systems a difficult problem. It has been realized generally that one main gauge is what the country needs, but the economics involved have thus far prevented any extensive moves in that direction. As the country develops, standardization seems bound to come as it has on the older and larger systems of Europe and America.

Special Railway Types

AIR-PROPELLED LOCOMOTIVES -- Propelling locomotives by air has intrigued inventors ever since the time of Denis Papin (1688), but little of a practical nature has been accomplished in the commercial field. An early experimental road about a half a mile in length was set up in the outskirts of London by Samuel Clegg, whose patent was subsequently modified by Hallette and Hay. His ideas were similar to those of Medhurst, a Danish engineer living in London, who proposed in 1800 to propel carriages by compressed air from a reservoir. In 1810 Medhurst patented a pneumatic system, but there is no record of its practical application. For many years this indefatiguable inventor published treatises urging the use of air in some form or other for locomotion. His "Practicability of Conveying Goods and Letters by Air" (1812) formed the basis for a locomotive patent taken out by Valence in 1824. Three years later Medhurst produced another paper entitled, "A New System of Inland Conveyance for Goods and Passengers," which advocated an aerial tube and an air-tight carriage--something similar to the car driven in a tube by Beach at New York in 1869. A compressed-air locomotive was then patented and built in England by Bompass in 1828.

No practical application of the compressed-air locomotive seems to have taken place until 1873. In that year it was utilized[26] by the Plymouth Cordage Company of Plymouth, Massachusetts, and in the St. Gotthard tunneling operations. Three years later the first air-motor car was run in Paris, and it was soon followed by the compressed-air railway at Nantes. Berne, Switzerland, opened another such line, both suburban and city, in 1890. Generally speaking, however, the compressed-air locomotive found little use outside of relatively few mines. Lines operated on the vacuum principle were even less successful, though some, such as the London-Croydon line, were able to attain high speeds.

Some of the sections of line able to operate to a limited extent on the compressed air or vacuum scheme in some form have included the $1\frac{1}{2}$-mile Kingston and Dalky Railway (1843-55) near Dublin, 7 miles of the London and Croydon Railway, a number of miles on the South Devon Railway (1846-48) between Exeter and Plymouth, and the last steep $1\frac{1}{2}$ miles of the Paris-St. Germaine-en-Laye Railroad.

STREETCARS AND TRAMWAYS -- Brief mention should be given to the streetcars and tramways which have so long been a familiar part of the busy street scene in most of the larger cities of the world, but which now seem doomed to ultimate extinction by the advent of the subways, trackless trolleys, and motor buses. One of the earliest of the city horse-car lines was the New York and Harlem line, over 6 miles in length, opened in 1832. John Stephenson, an Irish-American, was the moving spirit in the enterprise, generally being regarded as the first to build a horse-car for this purpose. The company failed, however, for the heavy rails with their deep grooves were a menace to other carriages and had to be removed. In 1852 the line was rebuilt by the Franchman M. Lubat who, three years later, built Europe's first street tramway in Paris. The first street tramways in London were laid shortly thereafter--in 1857 or 58--by George F. Train, and at about the same time Henry Gore laid the first line in Valparaiso, Chile.

In cities with unusually steep hills cars drawn by cables have been in use for many years. San Francisco was in the forefront in the United States, inaugurating its continuous wire cable system in 1873, while the first such line in Europe was the one which went into operation in London on Highgate Hill in 1884. Though cable cars have tended to remain in use, another class of transport--the elevated--has slowly been going out with the surface streetcar. First of the roads which might be called elevated was the 4-mile London-Greenwich line dating from 1836. New York is usually credited with having the oldest elevated in the world though, it having been planned in 1835. The system began with an experimental section on the North Side and Yonkers Railway Company built by Charles T. Harvey along lower Greenwich Street. Liverpool, however, claimed the first electric elevated in the world when its system began operations in 1893. Though they served at first to eliminate congestion on the surface streets, elevated lines have been more than adequately replaced by the subway systems in most of the large cities, and there is very little evidence that they will ever return to the public favor they once held.

Summary

Several of the early mines in fifteenth century Germany and sixteenth century England were equipped with crude wooden rails to ease the way for their horse-drawn coal wagons. These "railroads" continued in much the same fashion until the latter part of the eighteenth century, when it was found that cast iron made a much more durable rail than wood. Use of the new material led to much experimentation with rail shapes, which took two basic forms, i.e., the "plate" rail and later, the "edge" rail.

Just as the edge rail was coming into popularity in the early decades of the nineteenth century, a new and revolutionary factor loomed large on the horizon--the steam locomotive.

Attempts at steam locomotion in the latter 1700's had been disappointing, and it was not until the brilliant Cornishman, Richard Trevithick, brought out his high-pressure steam locomotive in the first decade of the nineteenth century that the device began to show real possibilities. His work was soon followed by that of Blenkinsop, Hedley, and George Stephenson--all of whom were associated with British collieries in one capacity or another. Early experiments culminated in the Rainhill trials of 1829, where Stephenson's "Rocket" showed that the steam locomotive was now commercially feasible for other than colliery work. In the following year the "Railway Age" began, signalized by the opening of the Liverpool and Manchester Railway which carried both passengers and freight.

British development from this time to the middle of the nineteenth century was extremely rapid, and British influence in design and construction spread throughout the world. The introduction of the heavy locomotive brought an end to the fragile cast iron rails and brought malleable and wrought iron into favor. New methods of production permitted longer and heavier rails, while rolling stock increased in size accordingly. Dispute welled up in England over what future main line gauge or gauges should prevail, but a Parliamentary decision in 1846 determined that only one standard should remain--the 4-foot 8½-inch gauge. It was this gauge which came to be generally adopted in American and European practice, and which is now used on more than half the trackage of the whole world. American and European development closely followed that of England during the early years, but American construction continued at a terrific pace long after Europe had passed its peak.

New life was breathed into railroading in the 1860's with the introduction of the Bessemer steel rail. Once more much experimentation with size and shape was tried, resulting in heavier and stronger rails and heavier trains. Increased sizes meant increased speeds as well; higher speeds demanded greater safety precautions. As a consequence, great strides were made in the last half of the nineteenth century in the improvement of signalling devices, road beds, and rolling stock. The world was drawn closer, new lands were opened up, and colonial empires flourished as steel rails were pushed further and further into the wilderness. Not only were the frontiers rolled back by the railroad in North America, but great progress resulted in South America, Africa, Asia, and Australia in a similar manner. The period was characterized by the disappearance of the small privately owned roads and the emergence of a relatively few powerful amalgamations, which came eventually in most cases, into the hands of the State.

The full effect of the railroad on the social, political, and economic development of the world cannot yet, perhaps, be assessed in its true perspective, but most will agree that its influence has been profound. Centers of population have shifted, agricultural and manufactured products have found new markets, and vast new industries have sprung up largely as by-products of railroad development. Recent years have found trackage decreasing somewhat, as uneconomic lines--built during the flush of unrestricted competition--have been dropped, but part of this must also be attributed to the new competition from the highways and skyways. In some of the more developed countries it seems obvious that little additional trackage will be needed in the future, but in some of the more backward spots opportunity for additional construction abounds. It is not only in developing these new roads, however, that the engineer will be making his greatest contribution to society; the maintenance and continued improvement of existing installations is an ever-present challenge which must be met if our economy as set up at present is to continue.

FOOTNOTES

1. Jenkins, R., "The Collected Papers of Rhys Jenkins." pg. 36.
2. North, R., "Life of Francis North, Baron Guilford." pg. 281.
3. Walker, E., "An Account of the Stockton & Darlington Railway." pg. 4.
4. Francis, J., "A History of the English Railway." pg. 103.
5. Ellis, C.H., "Early Steam Coaches." in "Wonders of World Engineering," pg. 253.
6. Allen, C.J., "The Iron Road," Part II, pg. 3.
7. Dickinson, H.W. & Titley, A., "Richard Trevithick." pg. 64.
8. Warren, J.G.H., "A Century of Locomotive Building by Robert Stephenson and Co." pg. 15.
9. Smiles, S., "Lives of the Engineers," (George & Robert Stephenson), pg. 249.
10. Francis, J., op. cit., pg. 45.
11. "Penny Cyclopaedia." "Railway." pg. 245.
12. Francis, J., op. cit., pg. 246.
13. Kirkman, M.M., "Building & Repairing Railways." pg. 24.
14. Walker, E., "Cast Metal & Malleable Iron Railways." pg. 18.
15. "Penny Cyclopaedia." "Railway." pg. 255.
16. Sellew, W.H., "Steel Rails." pg. 366.
17. Cresy, E., "Encyclopaedia of Civil Engineering." pg. 302f.
18. Sellew, W.H., op. cit., pg. 90.
19. Williams, C.C., "The Design of Railway Location." pg. 12.
20. Ibid., pg. 22.
21. "Penny Cyclopaedia." "Railway." pg. 135.
22. Kirkaldy, A.W. & Evans, A.D., "The History and Economics of Transport." pg. 78.
23. Ellis, C.H., "The Trans-Siberian Route." in "Wonders of World Engineering." pg. 459.

24. Dean, F.E., "Stone and Steel on Pilatus." in "Wonders of World Engineering." pg. 207.

25. Ellis, C.H., "Across the Andes." in "Wonders of World Engineering." pg. 259.

26. Peele, R., "Compressed Air Plant." 4th ed., pg. 433.

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