Stavanger was only 2500; by 1855 it was 12,000, and by 1875 20,350.

STAVROPOL, a government of Northern Caucasia, Russia, having an area of 26,530 square miles, and a population (rapidly increasing by Russian immigration) last returned at 637,893. It is bounded by Astrakhan and the province of the Don Cossacks on the N., Kubañ on the W., Terek on the S., and the Caspian Sea on the E., occupying the eastern part of the broad plains and steppes which fringe the main chain of CAUCASUS (*q.v.*) on the north. In the western part of the government a broad undulating swelling, ranging from 1500 to 2000 feet above sea-level, extends northwards from the central mountain chain; in the southern part of this swelling, in the vicinity of Pyatigorsk, there is a group of sixteen mountains, 2800 to 4600 feet in height—the Beshtau,—which, as shown by Abich, ought to be considered as a porphyritic upheaval which took place at a point where the two predominant directions in Caucasus (south-west to north-east and south-east to north-west) meet. Northward and eastward of the above plateau are extensive steppes, from 400 to 200 feet above the sea, having gentle slopes both to the north (to the depression of the Manytch) and to the east (towards the low and dry steppes of the Caspian littoral). The geological structure of Stavropol is most interesting. The mountains in the southern parts of Pyatigorsk consist of trachytic porphyries and volcanic rocks. Numberless hot mineral springs (see PYATIGORSK) occur in this group, and earthquakes are most common in the region. A broad belt of Miocene deposits, represented by the "steppe limestone" with *Mactra podolica*, girdles the hilly tracts, attaining a breadth of 40 miles or rather more; while the remainder of the steppes, which gently slope towards the Manytch and the Caspian, are occupied by the Post-Tertiary Caspian formation (loess).

Stavropol is chiefly watered by the Kuma and its tributaries (Podkumok, Karamyk, Buivola, &c.), its basin being the most fertile part of the province, but the evaporation is so great that the Kuma never reaches the Caspian except in spring. The Manytch is less a river than a series of lakes occupying a depression which formerly was a connecting channel between the Black Sea and the Caspian. This channel has two slopes, the eastern sometimes discharging its scanty water-supply into the Kuma, while on the western slope the elongated lakes which fill up the depression drain into the Don, reaching it, however, only during spring. Two Yegorlyks (Great and Middle), the Kalaus, and the Tchogra (temporary tributaries of the Manytch) water the west part of Stavropol; while the Yeya and the Barsukly—a tributary of the Kubañ—rise in the district of Pyatigorsk. On the whole, irrigation is scanty, and in the eastern steppes water is supplied only by cisterns. Besides the few lakes of the Manytch depression, there are many smaller salt lakes around the Caspian. Timber is scarce, even in the hilly tracts.

The climate is severe. Although Stavropol and Pyatigorsk both have an average yearly temperature of 48° Fahr., frosts of -22° Fahr. are not uncommon, and the average winter temperature is only 28°·7 at Stavropol (January, 25°; July, 71°). Yellow and other endemic fevers, sometimes very severe, are common on the low banks of the Kuma and Manytch.

The region is traversed by both the great highways along the western shore of the Caspian (the Vladikavkaz and the Derbent routes), and accordingly several nations in their migrations have left stragglers on the steppes of Stavropol. Thus we now find in these steppes Lamaite Kalmucks (about 10,000), Mohammedan Turcomans and Nogais (together about 60,000), as well as less considerable remains of several other tribes. On the other hand, immigrants from Great and Little Russia, Poles, Germans, Esthonians, Greeks, and even a few Scots (in a colony close to Pyatigorsk) have settled in the most fertile and best watered parts of Stavropol in the course of the present century. The Russian population is growing very rapidly, and already numbers upwards of 500,000.

There are three administrative districts, the chief towns of which are Stavropol (35,470 inhabitants in 1884), Pyatigorsk (11,115), and Alexandrovskaya (8710), and a territory of nomad natives which occupies more than two-fifths of the entire area of the government.

The educational returns for 1883 show 7 gymnasiums and "real schools," with 1081 boys and 491 girls, and 139 elementary schools, with only 5310 boys and 1034 girls.

Agriculture is the chief occupation of the settled population, and so large is the harvest that no less than 16,000 labourers, attracted by high wages, come annually from European Russia to assist in gathering in the crops. Large amounts of corn are exported both to the mountainous districts of Caucasus and to Russia (Rostoff-on-the-Don). Cattle-breeding is engaged in very largely, not only by the Kalmucks, Turcomans, and Nogais, but also by the Russians. In 1884 Stavropol had 154,000 horses, 808,500 cattle, 2,540,000 sheep, 45,000 goats, 75,000 pigs, and 7500 camels. Cattle and horses, as also wool, hair, hides, and sheepskins, are exported in considerable quantities. A remarkable feature of Stavropol is the rapid growth among the Russian peasant population of a great variety of domestic trades both for local supply and for exportation. Silk wares are now woven in the villages to such an extent as to become an important article of export to Russia. Many other petty trades have also grown up of late, such as various kinds of cotton-weaving, the manufacture of leather wares, small metallic wares, and so on. Manufactures proper (chiefly distillation) employed some 1000 persons in 1870, and their produce was estimated at about £140,000 per annum. Since that time they have slowly expanded. A brisk trade is carried on in the above-mentioned articles of export, and twenty-nine village fairs show an aggregate annual return of nearly £300,000.

History.—The northern slopes of Caucasus began to be colonized by Russians at a very early period, and as early as the 11th century part of the territory now occupied by Stavropol was known to Russian annalists as the Tmutarakañ principality, which had Russian princes. A new attempt to colonize North Caucasus was made in the 16th century, under Ivan the Terrible, who married a Kabardian princess. This was again unsuccessful, and it was not till 1711 that Russia began regularly to colonize the territory by Cossack settlements. The military colonization was continued during the whole of last century; Kizlar was founded in 1736, Stavropol in 1776 or 1777. Immense tracts were given by Catherine II. to her courtiers, who began to people them with serfs brought from Russia. The flow of immigrants rapidly increased as soon as peace was firmly established, and it is still on the increase, especially since the emancipation of the serfs, so that Stavropol is rapidly becoming a Russian province, with a comparatively limited number of natives in the steppes of its eastern part.

STAVROPOL, capital of the above province, is situated on a plateau 2000 feet above the sea, on the northern slope of the Caucasus, 360 miles to the north-west of Tiflis and 914 miles from Moscow. It is connected by rail with Rostoff-on-the-Don. Although founded only in 1776 for military purposes, it has rapidly grown, and has now a population of 35,500, while it is one of the best built provincial towns of the Russian empire. It has wide streets, and its houses are mostly of stone; large gardens surround the houses; and numerous farms and gardens occupy the territory (nearly 50,000 acres) belonging to the town. It is well provided with educational institutions, there being four gymnasia for boys and girls and several primary schools. Nearly all the manufactures of the province are concentrated in Stavropol. The trade is considerable, large numbers of cattle (more than 35,000 head annually) being sent to Moscow and St Petersburg, while tallow and more than 15,000 sheepskins are exported *via* Rostoff to Russia. Corn is also exported to the value of nearly £300,000, while manufactured wares are imported to the value of nearly £150,000. Armenian, Georgian, and Persian merchants carry on a lively trade in local wares.

STEAM-ENGINES AND OTHER HEAT-ENGINES

Definition of heat-engines

A HEAT-ENGINE is a machine in which heat is employed to do mechanical work. In all practical heat-engines, work is done through the expansion by heat of a fluid which overcomes resistance as it expands—in steam-engines by the expansion of water and water-vapour, in air-engines by the expansion of hot air, in gas-engines by the expansion of a burnt mixture of air and gas. One of the most simple and historically one of the oldest types of heat-engines are guns, in which heat, generated by the combustion of an explosive, does work in giving energy of motion to a projectile. But guns differ so widely from all other types, both in their purpose and in their development, that it is convenient to leave them out of account in treating of engines which may serve as prime movers to other mechanism

I. EARLY HISTORY OF THE STEAM-ENGINE.

2. The earliest notices of heat-engines are found in the *Pneumatica* of Hero of Alexandria (*c.* 130 B.C.). Two contrivances described there deserve mention. One is the æolipile, a steam reaction-turbine consisting of a spherical vessel pivoted on a central axis and supplied with steam through one of the pivots. The steam escapes by bent pipes facing tangentially in opposite directions, at opposite ends of a diameter perpendicular to the axis. The globe revolves by reaction from the escaping steam, just as a Barker's mill is driven by escaping water. Another apparatus described by Hero (fig. 1)[1] is interesting as the prototype of a class of engines which long afterwards became practically important. A hollow altar containing air is heated by a fire kindled on it; the air in expanding drives some of the water contained in a spherical vessel beneath the altar into a bucket, which descends and opens the temple doors above by pulling round a pair of vertical posts to which the doors are fixed. When the fire is extinguished the air cools, the water leaves the bucket, and the doors close. In another device a jet of water driven out by expanding air is turned to account as a fountain.

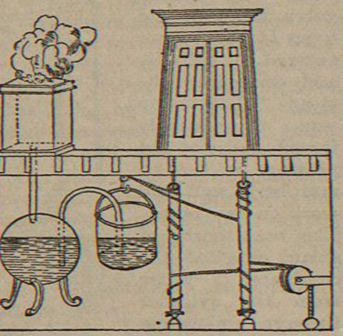

FIG. 1.—Hero's Apparatus, 130 B.C.

3. From the time of Hero to the 17th century there is no progress to record, though here and there we find evidence that appliances like those described by Hero were used for trivial purposes, such as organ-blowing and the turning of spits. The next distinct step was the publication in 1601 of a treatise on pneumatics by Giovanni Battista della Porta, in which he shows an apparatus similar to Hero's fountain, but with steam instead of air as the displacing fluid. Steam generated in a separate vessel passes into a closed chamber containing water, from which a pipe (open under the water) leads out. He also points out that the condensation of steam in the closed chamber may be used to produce a vacuum and suck up water from a lower level. In fact, his suggestions anticipate very fully the engine which a century later became in the hands of Savery the earliest commercially successful steam-engine. In 1615 Solomon de Caus gives a plan of forcing up water by a steam fountain which differs from Della Porta's only in having one vessel serve both as boiler and as displacement-chamber, the hot water being itself raised.

4. Another line of invention was taken by Giovanni Branca (1629), who designed an engine shaped like a water-wheel, to be driven by the impact of a jet of steam on its vanes, and, in its turn, to drive other mechanism for various useful purposes. But Branca's suggestion was unproductive, and we find the course of invention revert to the line followed by Della Porta and De Caus.

5. The next contributor is one whose place is not easily assigned. To Edward Somerset, second marquis of Worcester, appears to be due the credit of making the first useful steam-engine. Its object was to raise water, and it worked probably like Della Porta's model, but with a pair of displacement-chambers, from each of which alternately water was forced by steam from an independent boiler, or perhaps by applying heat to the chamber itself, while the other vessel was allowed to refill. Lord Worcester's description of the engine in his *Century of Inventions* (1663) is obscure, and no drawings are extant. It is therefore difficult to say whether there were any distinctly novel features except the double action; in particular it is not clear whether the suction of a vacuum was used to raise water as well as the direct pressure of steam. An engine of about two horse-power was in use at Vauxhall in 1656, and the walls of Raglan Castle contain traces of another, but neither Worcester's efforts nor those of his widow were successful in securing the commercial success of his engine.

6. This success was reserved for Thomas Savery, who in 1698 obtained a patent for a water-raising engine, shown in fig. 2. Steam is admitted to one of the oval vessels A, displacing water, which it drives up through the check-valve B. When the vessel A is emptied of water, the supply of steam is stopped, and the steam already there is condensed by allowing a jet of cold water from a cistern above to stream over the outer surface of the vessel. This produces a vacuum and causes water to be sucked up through the pipe C and the valve D. Meanwhile, steam has been displacing water from the other vessel, and is ready to be condensed there. The valves B and D open only upwards. The supplementary boiler and furnace E are for feeding water to the main boiler; E is filled while cold and a fire is lighted under it; it then acts like the vessel of De Caus in forcing a supply of feed-water into the main boiler F. The gauge-cocks G, G are an interesting feature of detail. Another form of Savery's engine had only one displacement-chamber and worked intermittently. In the use of artificial means to condense the steam, and in the application Savery 1698.

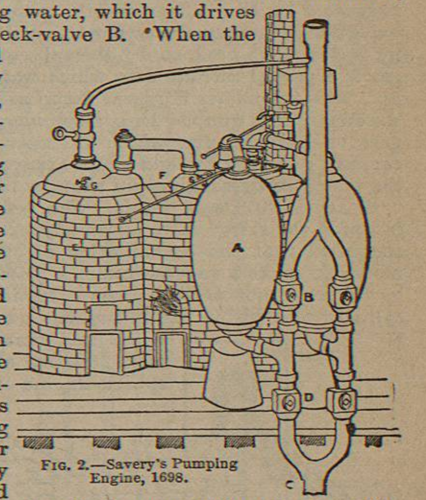

FIG. 2.—Savery's Pumping Engine, 1698.

[1] From Greenwood's translation of Hero's *Pneumatica*.

of the vacuum so formed to raise water by suction from a level lower than that of the engine, Savery's engine was probably an improvement on Worcester's; in any case it found what Worcester's engine had failed to find,—considerable employment in pumping mines and in raising water to supply houses and towns. and even to drive water-wheels. A serious difficulty which prevented its general use in mines was the fact that the height through which it would lift water was limited by the pressure the boiler and vessels could bear. Pressures as high as 8 or 10 atmospheres were employed—and that, too, without a safety-valve—but Savery found it no easy matter to deal with high-pressure steam: he complains that it melted his common solder, and forced him, as Desaguliers tells us, "to be at the pains and charge to have all his joints soldered with spelter." Apart from this drawback the waste of fuel was enormous, from the condensation of steam which took place on the surface of the water and on the sides of the displacement-chamber at each stroke; the consumption of coal, was, in proportion to the work done, some twenty times greater than in a good modern steam-engine. In a tract called *The Miner's Friend*, Savery alludes thus to the alternate heating and cooling of the water-vessel: "On the outside of the vessel you may see how the water goes out as well as if the vessel were transparent, for so far as the steam continues within the vessel so far is the vessel dry without, and so very hot as scarce to endure the least touch of the hand. But as far as the water is, the said vessel will be cold and wet where any water has fallen on it; which cold and moisture vanishes as fast as the steam in its descent takes place of the water." Before Savery's engine was entirely displaced by its successor, Newcomen's, it was improved by Desaguliers, who applied to it the safety valve (invented by Papin), and substituted condensation by a jet of cold water within the vessel for the surface condensation used by Savery.

Cylinder and piston engine. 7. So early as 1678 the use of a piston and cylinder (long before known as applied to pumps) in a heat-engine had been suggested by Jean Heautefeuille, who proposed to use the explosion of gunpowder either to raise a piston or to force up water, or to produce, by the subsequent cooling of the gases, a partial vacuum into which water might be sucked up. Two years later Huygens described an engine in which the explosion of gunpowder in a cylinder expelled part of the gaseous contents, after which the cooling of the remainder caused a piston to descend under atmospheric pressure, and the piston in descending did work by raising a weight.

8. In 1690 Denis Papin, who ten years before had invented the safety-valve as an adjunct to his "digester," suggested that the condensation of steam should be employed to make a vacuum under a piston previously raised by the expansion of the steam. Papin's was the earliest cylinder and piston steam-engine, and his plan of using steam was that which afterwards took practical shape in the atmospheric engine of Newcomen. But

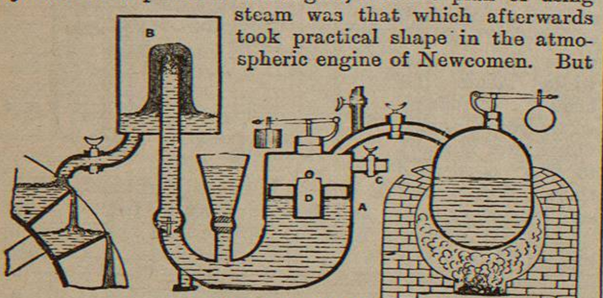

FIG. 3.—Papin, 1705

his scheme was made unworkable by the fact that he proposed to use but one vessel as both boiler and cylinder. A small quantity of water was placed at the bottom of a cylinder and heat was applied. When the piston had risen the fire was removed, the steam was allowed to cool, and the piston did work in its down-stroke under the pressure of the atmosphere. After hearing of Savery's engine in 1705 Papin turned his attention to improving it, and devised a modified form. shown in fig. 3, in which the displacement-chamber A was a cylinder, with a floating diaphragm or piston on the top of the water to keep the water and steam from direct contact with one another. The water was delivered into a closed air-vessel B, from which it issued in a continuous stream against the vanes of a water-wheel. After the steam had done its work in the displacement-chamber it was allowed to escape by the stop-cock C instead of being condensed. Papin's engine was in fact a non-condensing single-acting steam pump, with steam-cylinder and pump-cylinder in one. A curious feature of it was the heater D, a hot mass of metal placed in the diaphragm for the purpose of keeping the steam dry. Among the many inventions of Papin was a boiler with an internal fire-box,—the earliest example of a construction that is now almost universal.[1]

9. While Papin was thus going back from his first notion of a piston-engine to Savery's cruder type, a new inventor had appeared who made the piston-engine a practical success by separating the boiler from the cylinder and by using (as Savery had done) artificial means to condense the steam. This was Newcomen, who in 1705, with his assistant Cawley, gave the steam-engine the form shown in fig. 4. Steam admitted from the boiler to the cylinder allowed the piston to be raised by a heavy counterpoise on the other side of the beam. Then the steam-valve was shut and a jet of cold water entered the cylinder and condensed the steam. The piston was consequently forced down by the pressure of the atmosphere and did work on the pump. The next entry of steam expelled the condensed water from the cylinder through an escape valve. The piston was kept tight by a layer of water on its upper surface. Condensation was at first effected by cooling the outside of the cylinder, but the accidental leakage of the packing water past the piston showed the advantage of condensing by a jet of injection water, and this plan took the place of surface condensation. The engine used steam whose pressure was little if at all greater than that of the atmosphere; sometimes indeed it was worked with the manhole lid off the boiler. Newcomen's atmospheric engine, 1705

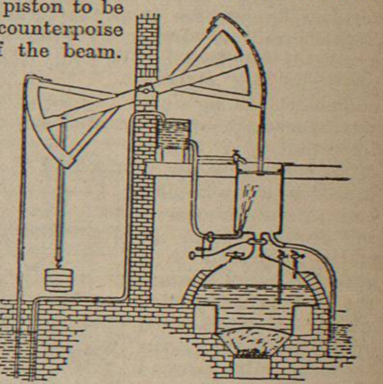
FIG. 4.—Newcomen's Atmospheric Engine, 1705.

10. About 1711 Newcomen's engine began to be introduced for pumping mines; and in 1713 a boy named Humphrey Potter, whose duty it was to open and shut the valves of an engine he attended, made the engine self-acting by causing the beam itself to open and close the valves by suitable cords and catches. Potter's rude device was simplified in 1718 by Henry Beighton, who suspended from the beam a rod called the plug-tree, which worked the valves by means of tappets. By 1725 the engine was in common use in collieries, and it held its place without material change for about three-quarters of a century in

[1] For an account of Papin's inventions, see his *Life and Letters*, by Dr E. Gerland, Berlin, 1881.

all. Near the close of its career the atmospheric engine was much improved in its mechanical details by Smeaton, who built many large engines of this type about the year 1770, just after the great step which was to make Newcomen's engine obsolete had been taken by James Watt.

Compared with Savery's engine, Newcomen's had (as a pumping-engine) the great advantage that the intensity of pressure in the pumps was not in any way limited by the pressure of the steam. It shared with Savery's, in a scarcely less degree, the defect already pointed out, that steam was wasted by the alternate heating and cooling of the vessel into which it was led. Though obviously capable of more extended uses, it was in fact almost exclusively employed to raise water,—in some instances for the purpose of turning water-wheels to drive other machinery. Even contemporary writers complain of its "vast consumption of fuel," which appears to have been scarcely smaller than that of the engine of Savery.

Watt, 1763. 11. In 1763 James Watt, an instrument maker in Glasgow, while engaged by the university in repairing a model of Newcomen's engine, was struck with the waste of steam to which the alternate chilling and heating of the cylinder gave rise. He saw that the remedy, in his own words, would lie in keeping the cylinder as hot as the steam that entered it. With this view he added to the engine a new organ—an empty vessel separate from the cylinder, into which the steam should be allowed to escape from the cylinder, to be condensed there by the application of cold water either outside or as a jet. To preserve the vacuum in his condenser he added a pump called the air-pump, whose function was to pump from it the condensed steam and water of condensation, as well as the air which would otherwise accumulate by leakage or by being brought in with the steam or with the injection water. Then as the cylinder was no longer used as a condenser he was able to keep it hot by clothing it with non-conducting bodies, and in particular by the use of a *steam-jacket*, or layer of hot steam between the cylinder and an external casing. Further, and still with the same object, he covered in the top of the cylinder, taking the piston-rod out through a steam-tight stuffing-box, and allowed steam instead of air to press upon the piston's upper surface. The idea of using a separate condenser had no sooner occurred to Watt than he put it to the test by constructing the apparatus shown in fig. 5. There A is the cylinder, B a surface condenser, and C the air-pump. The cylinder was filled with steam above the piston, and a vacuum was formed in the surface condenser B. On opening the stop-cock D the steam rushed over from the cylinder and was condensed, while the piston rose and lifted a weight. After several trials Watt patented his improvements in 1769; they are described in his specification in the following words, which, apart from their immense historical interest, deserve careful study as a statement of principles which to this day guide the scientific development of the steam-engine:—

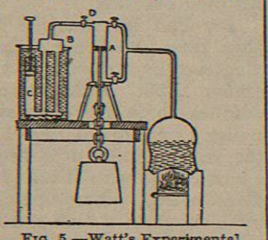

FIG. 5.—Watt's Experimental Apparatus.

"My method of lessening the consumption of steam, and consequently fuel, in fire-engines, consists of the following principles:—

"*First*, That vessel in which the powers of steam are to be employed to work the engine, which is called the cylinder in common fire-engines, and which I call the steam-vessel, must, during the whole time the engine is at work, be kept as hot as the steam that enters it; first by enclosing it in a case of wood, or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and, thirdly, by suffering neither water nor any other substance colder than the steam to enter or touch it during that time.

"*Secondly*, In engines that are to be worked wholly or partially by condensation of steam, the steam is to be condensed in vessels distinct from the steam-vessels or cylinders, although occasionally communicating with them; these vessels I call condensers; and, whilst the engines are working, these condensers ought at least to be kept as cold as the air in the neighbourhood of the engines, by application of water or other cold bodies.

"*Thirdly*, Whatever air or other elastic vapour is not condensed by the cold of the condenser, and may impede the working of the engine, is to be drawn out of the steam-vessels or condensers by means of pumps, wrought by the engines themselves, or otherwise.

"*Fourthly*, I intend in many cases to employ the expansive force of steam to press on the pistons, or whatever may be used instead of them, in the same manner in which the pressure of the atmosphere is now employed in common fire-engines. In cases where cold water cannot be had in plenty, the engines may be wrought by this force of steam only, by discharging the steam into the air after it has done its office. . . .

"*Sixthly*, I intend in some cases to apply a degree of cold not capable of reducing the steam to water, but of contracting it considerably, so that the engines shall be worked by the alternate expansion and contraction of the steam.

"*Lastly*, Instead of using water to render the pistons and other parts of the engine air and steam tight, I employ oils, wax, resinous bodies, fat of animals, quicksilver and other metals in their fluid state."

The fifth claim was for a rotary engine, and need not be quoted here.

The "common fire-engine" alluded to was the steam-engine, or, as it was more generally called, the "atmospheric" engine of Newcomen. Enormously important as Watt's first patent was, it resulted for a time in the production of nothing more than a greatly improved engine of the Newcomen type, much less wasteful of fuel, able to make faster strokes, but still only suitable for pumping, still single-acting, with steam admitted during the whole stroke, the piston, as before, pulling the beam by a chain working on a circular arc. The condenser was generally worked by injection, but Watt has left a model of a surface condenser made up of small tubes, in every essential respect like the condensers now used in marine engines.

12. Fig. 6 is an example of the Watt pumping-engine of this period. It should be noticed that, although the top of the cylinder is closed and steam has access to the upper side of the piston, this is done only to keep the cylinder and piston warm. The engine is still single-acting; the steam in the upper side merely plays the part which was played in Newcomen's engine by the atmosphere; and it is the lower end of the cylinder alone that is ever put in communication with the condenser. There are three valves, — the "steam" valve a, the "equilibrium" valve b, and the "exhaust" valve c. At the beginning of the down-stroke c is opened to produce a vacuum below the piston and a is Watt's pumping engine, 1769.

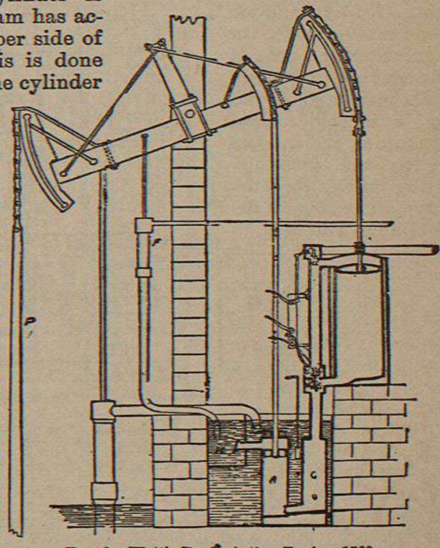

FIG. 6.—Watt's Single-Acting Engine, 1769.

opened to admit steam above it. At the end of the down-stroke *a* and *c* are shut and *b* is opened. This puts the two sides in equilibrium, and allows the piston to be pulled up by the pump-rod P, which is heavy enough to serve as a counterpoise. C is the condenser, and A the air-pump, which discharges into the hot well H, whence the supply of the feed-pump F is drawn.

13. In a second patent (1781) Watt describes the "sun-and-planet" wheels and other methods of making the engine give continuous revolving motion to a shaft provided with a fly-wheel. He had invented the crank and connecting-rod for this purpose, but it had meanwhile been patented by one Pickard, and Watt, rather than make terms with Pickard, whom he regarded as a plagiarist of his own ideas, made use of his sun-and-planet motion until the patent on the crank expired. The reciprocating motion of earlier forms had served only for pumping; by this invention Watt opened up for the steam-engine a thousand other channels of usefulness. The engine was still single-acting; the connecting rod was attached to the far end of the beam, and that carried a counterpoise which served to raise the piston when steam was admitted below it.

14. In 1782 Watt patented two further improvements of the first importance, both of which he had invented some years before. One was the use of double action, that is to say, the application of steam and vacuum to each side of the piston alternately. The other (invented as early as 1769) was the use of steam expansively, in other words the plan (now used in all engines that aim at economy of fuel) of stopping the admission of steam when the piston had made only a part of its stroke, and allowing the rest of the stroke to be performed by the expansion of the steam already in the cylinder. To let the piston push as well as pull the end of the beam Watt devised his so-called parallel motion, an arrangement of links connecting the piston-rod head with the beam in such a way as to guide the rod to move in a very nearly straight line. He further added the throttle-valve, for regulating the rate of admission of steam, and the centrifugal governor, a double conical pendulum, which controlled the speed by acting on the throttle-valve. The stage of development reached at this time is illustrated by the engine of fig. 7 (from Stuart's *History of the Steam-Engine*), which shows the parallel motion *pp*, the governor *g*, the throttle-valve *t*, and a pair of steam and exhaust valves at each end of the cylinder. Among other inventions of Watt were the "indicator," by which diagrams showing the relation of the steam-pressure in the cylinder to the movement of the piston are automatically drawn: a steam tilt-hammer; and also a steam locomotive for ordinary roads,—but this invention was not prosecuted.

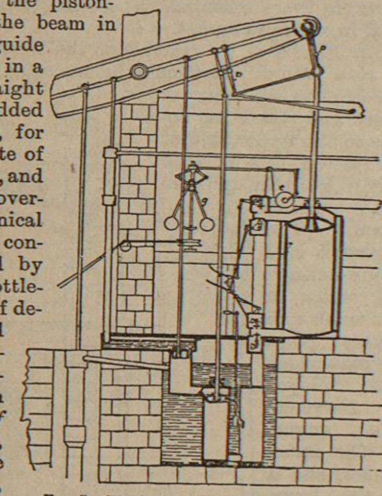

Fig. 7.—Watt's Double-Acting Engine. 1782.

In partnership with Matthew Boulton, Watt carried on in Birmingham the manufacture and sale of his engines with the utmost success, and held the field against all rivals in spite of severe assaults on the validity of his patents. Notwithstanding his accurate knowledge of the advantage to be gained by using steam expansively he continued to employ only low pressures—seldom more than 7 lb per square inch over that of the atmosphere. His boilers were fed, as Newcomen's had been, through an open pipe which rose high enough to let the column of water in it balance the pressure of the steam. He introduced the term "horse-power" as a mode of rating engines, defining one horse-power as the rate at which work is done when 33,000 lb are raised one foot in one minute. This estimate was based on trials of the work done by horses; it is excessive as a statement of what an average horse can do, but Watt purposely made it so in order that his customers might have no reason to complain on this score.

Non-condensing engine.

15. In the fourth claim in Watt's first patent, the second sentence describes a non-condensing engine, which would have required steam of a higher pressure. This, however, was a line of invention which Watt did not follow up, perhaps because so early as 1725 a non-condensing engine had been described by Leupold in his *Theatrum Machinarum*. Leupold's proposed engine is shown in fig. 8, which makes its action sufficiently clear. Watt's aversion to high-pressure steam was strong, and its influence on steam-engine practice long survived the expiry of his patents. So much indeed was this the case that the terms "high-pressure" and "non-condensing" were for many years synonymous, in contradistinction to the "low-pressure" or condensing engines of Watt. This nomenclature no longer holds; in modern practice many condensing engines use as high pressures as non-condensing engines, and by doing so are able to take advantage of Watt's great invention of expansive working to a degree which was impossible in his own practice.

Leupold, 1725.

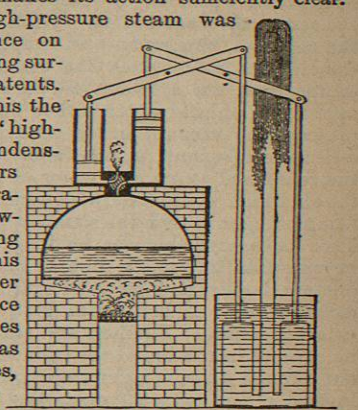

Fig. 8.—Leupold's Non-Condensing Engine, 1725.

High-pressure steam: Trevithick and Evans.

16. The introduction of the non-condensing and, at that time, relatively high-pressure engine, was effected in England by Trevithick and in America by Oliver Evans about 1800. Both Evans and Trevithick applied their engines to propel carriages on roads, and both used for boiler a cylindrical vessel with a cylindrical flue inside—the construction now known as the Cornish boiler. In partnership with Bull, Trevithick had previously made direct-acting pumping-engines, with an inverted cylinder set over and in line with the pump-rod, thus dispensing with the beam that had been a feature in all earlier forms. But in these "Bull" engines, as they were called, a condenser was used, or, rather, the steam was condensed by a jet of cold water in the exhaust-pipe, and Boulton and Watt successfully opposed them as infringing Watt's patents. To Trevithick belongs the distinguished honour of being the first to use a steam-carriage on a railway; in 1804 he built a locomotive in the modern sense, to run on what had formerly been a horse-tramway in Wales, and it is noteworthy that the exhaust steam was discharged into the funnel to force the furnace draught, a device which, 25 years later, in the hands of George Stephenson, went far to make the locomotive what it is to-day. In this connexion it may be added that as early as 1769 a steam-

carriage for roads had been built by Cugnot in France, who used a pair of single-acting high-pressure cylinders to turn a driving axle step by step by means of pawls and ratchet-wheels. To the initiative of Evans may be ascribed the early general use of high-pressure steam in the United States, a feature which for many years distinguished American from English practice.

17. Amongst the contemporaries of Watt one name deserves special mention. In 1781 Jonathan Hornblower constructed and patented what would now be called a compound engine, with two cylinders of different sizes. Steam was first admitted into the smaller cylinder, and then passed over into the larger, doing work against a piston in each. In Hornblower's engine the two cylinders were placed side by side, and both pistons worked on the same end of a beam overhead. This was an instance of the use of steam expansively, and as such was earlier than the patent, though not earlier than the invention, of expansive working by Watt. Hornblower was crushed by the Birmingham firm for infringing their patent in the use of a separate condenser and air-pump. The compound engine

Woolf, 1804.

was revived in 1804 by Woolf, with whose name it is often associated. Using steam of fairly high pressure, and cutting off the supply before the end of the stroke in the small cylinder, Woolf expanded the steam to several times its original volume. Mechanically the double-cylinder compound engine has this advantage over an engine in which the same amount of expansion is performed in a single cylinder, that the sum of the forces exerted by the two pistons in the compound engine varies less throughout the action than the force exerted by the piston of the single-cylinder engine. This advantage may have been clear to Hornblower and Woolf, and to other early users of compound expansion. But another and probably a more important merit of the system lies in a fact of which neither they nor for many years their followers in the use of compound engines were aware—the fact that by dividing the whole range of expansion into two parts the cylinders in which these are separately performed are subject to a reduced range of fluctuation in their temperature. This, as will be afterwards pointed out, limits to a great extent a source of waste which is present in all steam-engines, the waste which results from the heating and cooling of the metal by its alternate contact with hot and cooler steam. The system of compound expansion is now used in nearly all large engines that pretend to economy. Its introduction forms the only great improvement which the steam-engine has undergone since the time of Watt; and we are able to recognize it as a very important step in the direction set forth in his "first principle," that the cylinder should be kept as hot as the steam that enters it.

Cornish engine.

18. Woolf introduced the compound engine somewhat widely about 1814, as a pumping engine in the mines of Cornwall. But here it met a strong competitor in the high-pressure single-cylinder engine of Trevithick, which had the advantage of greater simplicity in construction. Woolf's engine fell into comparative disuse, and the single-cylinder type took a form which, under the name of the Cornish pumping engine, was for many years famous for its great economy of fuel. In this engine the cylinder was set under one end of a beam, from the other end of which hung a heavy rod which operated a pump at the foot of the shaft. Steam was admitted above the piston for a short portion of the stroke, thereby raising the pump-rod, and was allowed to expand for the remainder. Then an equilibrium valve, connecting the space above and below the piston, as in fig. 6, was opened, and the pump-rod descended, doing work in the pump and raising the engine piston. The large mass which had to be started and stopped at each stroke served by its inertia to counterbalance the unequal pressure of the steam, for the ascending rods stored up energy of motion in the early part of the stroke, when the steam pressure was greatest, and gave out energy in the later part, when expansion had greatly lowered the pressure. The frequency of the stroke was controlled by a device called a cataract, consisting of a small plunger pump, in which the plunger, raised at each stroke by the engine, was allowed to descend more or less slowly by the escape of fluid below it through an adjustable orifice, and in its descent liberated catches which held the steam and exhaust valves from opening. A similar device controlled the equilibrium valve, and could be set to give a pause at the end of the piston's down-stroke, so that the pump cylinder might have time to become completely filled. The Cornish engine is interesting as the earliest form which achieved an efficiency comparable with that of good modern engines. For many years monthly reports were published of the "duty" of these engines, the "duty" being the number of foot-pounds of work done per bushel or (in some cases) per cwt. of coal. The average duty of engines in the Cornwall district rose from about 18 millions of foot-pounds per cwt. of coal in 1813 to 68 millions in 1844, after which less effort seems to have been made to maintain a high efficiency.[1] In individual cases much higher results were reported, as in the Fowey Consols engine, which in 1835 was stated to have a duty of 125 millions. This (to use a more modern mode of reckoning) is equivalent to the consumption of only a little more than $1\frac{3}{4}$ lb of coal per horse-power per hour—a result surpassed by very few engines in even the best recent practice. It is difficult to credit figures which, even in exceptional instances, place the Cornish engine of that period on a level with the most efficient modern engines—in which compound expansion and higher pressure combine to make a much more perfect thermodynamic machine; and apart from this there is room to question the accuracy of the Cornish reports. They played, however, a useful part in the process of steam-engine development by directing attention to the question of efficiency, and by demonstrating the advantage to be gained by high pressure and expansive working, at a time when the theory of the steam-engine had not yet taken shape.

Compound engine.

19. The final revival of the compound engine did not occur until about the middle of the century, and then several agencies combined to effect it. In 1845 M'Naught introduced a plan of improving beam engines of the original Watt type, by adding a high-pressure cylinder whose piston acted on the beam between the centre and the fly-wheel end. Steam of higher pressure than had formerly been used, after doing work in the new cylinder, passed into the old or low-pressure cylinder, where it was further expanded. Many engines whose power was proving insufficient for the extended machinery they had to drive were "M'Naughted" in this way, and after conversion were found not only to yield more power but to show a marked economy of fuel. The compound form was selected by Mr Pole for the pumping engines of Lambeth and other waterworks about 1850; in 1854 John Elder began to use it in marine engines; in 1857 Mr Cowper added a steam-jacketed intermediate reservoir for steam between the high and low pressure cylinders, which made it unnecessary for the low-pressure piston to be just beginning when the other piston was just ending its stroke. As facilities increased for the use of high-pressure steam, compound expansion became more and more general, its advantage becoming more conspicuous with every

[1] *Min. Proc. Inst. C.E.*, vol. xxiii., 1863.