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 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.

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 single­cylinder 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 foot­pounds 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 13/4 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.

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.B.,* vol. xxiii., 1863.