increase in boiler pressure—until now there are few large land engines and scarcely any marine engines that do not employ it. In marine practice, where economy of fuel is a much more important factor in determining the design than it is on land, the principle of compound expansion has lately been greatly extended by the intro­duction of triple and even quadruple expansion engines, in which the steam is made to expand successively in three or in four cylinders. Even in the building of locomotive engines, where other considerations are of more moment than the saving of coal, the system of com­pound expansion is beginning to find a place.

The growth of compound expansion has been referred to at some length, because it forms the most distinctive improvement which the steam-engine has undergone since the time of Watt. For the rest, the progress of the steam- engine has consisted in its adaptation to particular uses, in the invention of features of mechanical detail, in the recognition and application of thermodynamical prin­ciples, and in improved methods of engineering construc­tion by which it has profited in common with all other machines. These have in particular made possible the use of steam of eight or ten times the pressure of that employed by Watt.

20. The adaptation of the steam-engine to railways, begun by Trevithick, became a success in the hands of George Stephenson, whose engine the “ Rocket,” when tried along with others on the Stockton and Darlington road in 1829, not only distanced its competitors but settled once and for all the question whether horse traction or steam traction was to be used on railways. The principal features of the “ Rocket ” were an improved steam-blast for urging the combustion of coal and a boiler (suggested by Booth, the secretary of the railway) in which a large heating surface was given by the use of many small tubes through which the hot gases passed. Further, the cylinders, instead of being vertical as in earlier locomotives, were set in at a slope, which was afterwards altered to a position more nearly horizontal. To these features there was added later the “ link motion,” a contrivance which enabled the engine to be easily reversed and the amount of expansion to be readily varied. In the hands of George Stephenson and his son Robert the locomotive took a form which has been in all essentials maintained by the far heavier locomotives of to-day.

21. The first practical steamboat was the tug “Char­lotte Dundas,” built by William Symmington, and tried in the Forth and Clyde Canal in 1802. A Watt double-acting condensing engine, placed horizontally, acted directly by a connecting-rod on the crank of a shaft at the stern, which carried a revolving paddle-wheel. The trial was successful, but steam towing was abandoned for fear of injuring the banks of the canal. Ten years later Henry Bell built the “ Comet,” with side paddle- wheels, which ran as a passenger steamer on the Clyde ; but an earlier inventor to follow up Symmington’s success was the American Robert Fulton, who, after unsuccessful experiments on the Seine, fitted a steamer on the Hudson in 1807 with engines made to his designs by Boulton and Watt, and brought steam navigation for the first time to commercial success.

22. The early inventors had little in the way of theory to guide them. Watt had the advantage, which he acknowledges, of a knowledge of Black’s doctrine of latent heat; but there was no philosophy of the relation of work to heat until long after the inventions of Watt were complete. The theory of the steam-engine as a heat-engine dates from 1824, when Carnot published his *Reflexions sur la Puissance Motrice du Feu,* and showed

that heat does work only by being let down from a higher to a lower temperature. But Carnot had no idea that any of the heat disappears in the process, and it was not until the doctrine of the conservation of energy was established in 1843 by the experiments of Joule that the theory of heat-engines began a vigorous growth. From 1849 onwards the science of thermodynamics was devel­oped with extraordinary rapidity by Clausius, Rankine, and Thomson, and was applied, especially by Rankine, to practical problems in the use of steam. The publication in 1859 of Rankine’s *Manual of the Steam Engine* formed an epoch in the history of the subject by giving inventors a new basis, outside of mere empiricism, from which they could push on the development of the steam-engine. Unfortunately, however, for its bearing on practice, the theory of the steam-engine was to a great extent founded on certain simplifying assumptions which experience has notv shown to be far from correct. It was assumed that the cylinder and piston might be treated as behaving to the steam like non-conducting bodies,—that the transfer of heat between the steam and the metal was negligibly small. Rankine’s calculations of steam-consumption, work, and thermodynamic efficiency involve this assumption, except in the case of steam-jacketed cylinders, where he estimates that the steam in its passage through the cylinder takes just enough heat from the jacket to prevent a small amount of condensation which would otherwise occur as the process of expansion goes on. If the transfer of heat from steam to metal could be overlooked, the steam which enters the cylinder would remain during admission as dry as it was before it entered, and the volume of steam consumed per stroke would correspond with the volume of the cylinder up to the point of cut-off. It is here that the actual behaviour of steam in the cylinder diverges most widely from the behaviour which the theory assumes. When steam enters the cylinder it finds the metal chilled by the previous exhaust, and a portion of it is at once condensed. This has the effect of increasing, often very largely, the volume of boiler steam required per stroke. As expansion goes on the water that was condensed during admission begins to be re-evaporated from the sides of the cylinder, and this action is often prolonged into the exhaust. In a later chapter the effect which this exchange of heat between the metal of the cylinder and the work­ing fluid produces on the economy of the engine will be discussed, and an account will be given of experimental means by which we may examine the amount of steam that is initially condensed and trace its subsequent re-evaporation. It is now recognized that any theory which fails to take account of these exchanges of heat fails also to yield even comparatively correct results in calculating the relative efficiency of various steam pressures or various ranges of expansion. But the exchanges of heat are so complex that there seems little prospect of submitting them to any comprehensive theoretical treatment, and we must rather look for help in the future development of engines to the scientific analysis of experiments with actual machines. Much careful work of this kind has already been done by Hirn and others, and there is room for much more. Questions relating to the influence (on heat-engine economy) of speed, of pressure, of ratio of expansion, of jacketing, of compound expansion, or of superheating must in the main be settled by an appeal to experiment,—experiment guided and interpreted at every step by reference to the principles of thermodynamics and the theory of steam.

*References.—*Stuart, *Descriptive History of the Steam-Engine,* 1825 ; Farey, *Treatise on the Steam-Engine,* 1827 ; Tredgold, *The Steam-Engine,* 1838 ; Muir- head's *Mechanical Inventions of James Watt,* and *Life of Watt;* Galloway, *The Steam-Engine and its Inventors* ; Thurston, *History of the Growth of the Steam- Engine;* Cowper on the Steam-Engine *{Heat Lectures Inst. C.E.,* 1884). Tait, *Sketch of Thermodynamics.*