Compound Locomotives

The usual arrangement on a compound engine is that the steam is first expanded in one or two high-pressure (HP) cylinder(s), then having given up heat and losing pressure, it exhausts into a larger volume low-pressure (LP) cylinder, (or two, - or more), thus extending the cycle. Thus the cylinders can be said to work in "series" as opposed to the normal arrangement of a simple-expansion locomotive where they work in "parallel", the steam being expanded just once in any one cylinder. In order to balance piston thrusts of a compound, the HP:LP cylinder volume ratio has to be carefully determined, usually by increasing the LP cylinder diameter and/or by lengthening the stroke. In non-condensing engines, the HP:LP volume ratio is usually 1:2¼. On geared locomotives, cylinder volumes can be kept more or less identical by increasing LP piston speed. Strictly speaking compound only stands for double-expansion, but the term is loosely applied to any multiple-expansion engine. The instances where railway locomotives have employed triple-expansion with steam going from high pressure (HP) cylinder, to medium pressure (MP) cylinder and finally to a low pressure (LP) one are rare, but triple expansion engines were very common in steamships in the late 19th/early 20th centuries.

For railway locomotive applications the main benefit sought from compounding is economy in fuel and water consumption plus high power/weight ratio due to temperature and pressure drop taking place over a longer cycle, this resulting in increased efficiency; additional perceived advantages include more even torque and in many cases, superior riding qualities with consequent less wear on the track. In situations where heavy grades and low axle loads were combined, the ordinary compound locomotive was often deemed to be the most viable solution. However, in the past, optimum performance demanded constant attention and expert handling, which usually made single-manning advisable, thus reducing a locomotive's availability. At the end of the steam age, this particular problem was being addressed by Andre Chapelon and Livio Dante Porta also actively pursued this line of research. Successful design of a compound locomotive demands a firm grasp of thermo- and fluid dynamics; that such has frequently not been the case is why many productions in the past have been far from optimal. This is especially true of locomotives built in the early years of the 20th Century. The problem not only affected compounds, but was dramatic in their case due to the long steam cycle which made them particularly sensitive to temperature-drop and condensation of the steam during its lengthy passage. In rebuilding older locomotives from 1929 onwards, Chapelon was able to inexpensively obtain what seemed almost "magical" improvements in power and economy by improving flow through the steam circuit, at the same time putting in a larger superheater in order to increase the initial steam temperature so that cooling took longer. Subsequently, in order to maintain a more constant temperature throughout the cycle, Chapelon successfully applied re-superheating between HP and LP stages plus steam-jacketed cylinders to an a "test-bed" freight locomotive, 160 A1 (tested 1948-51). Resuperheating was also a feature of L.D. Porta's prototype 4-8-0 rebuild: 'Presidente Peron'/'Argentina' (tested around the same time in Argentina from 1949). Proponents of simple expansion argue that use of early cut-off in the cylinder thus expanding small quantities of steam at each piston stroke obviates the need for the complication and initial expense of compounding and indeed multi-cylinder single expansion - this is an on-going debate.

There are many compound systems and configurations, but we can define two basic types, according to how HP and LP piston strokes are phased and hence whether the HP exhaust is able to pass directly from HP to LP (Woolf compounds) or whether pressure fluctuation necessitates an intermediate "buffer" space in the form of a steam chest or pipe known as a receiver (receiver compounds).

The eternal problem with compounds is starting: for all cylinders to take their weight, it is advisable to have some way of short-circuiting the HP cylinders and getting steam at a reduced pressure directly to the LP cylinder(s); hence many of the patented compound systems are associated with particular starting arrangements. The de Glehn 4-cylinder system is probably still the most sophisticated of all with independent HP & LP cut-off and a rotary valve, called a lanterne allowing independent working or combinations of HP and LP groups. Most other systems employ starting valves of various kinds. Another criterion is whether the valve gears of the two groups are wholly independent or linked together in some way.

Configurations

Two cylinder compound

- 2 cylinders, alternating high and low pressure - "continuous expansion locomotive"
  (Samuel/Nicholson)
- 1 high pressure, 1 low pressure
  (Mallet-1; Vauclain; Von Borries-1; Lindner; Golsdorf-1; Herdner)

Three cylinder compound

- 2 high pressure, 1 low pressure
  (Francis William Webb)
- 1 high pressure, 2 low pressure
  (Sauvage; Klose; Weyermann; Walter Mackersie Smith; Samuel W. Johnson; Richard Deeley; André Chapelon, Livio Dante Porta)

Three cylinder triple expansion

- 1 high pressure, one medium pressure, 1 low pressure
  (Livio Dante Porta)

Four cylinder triple expansion compound

- 1 high pressure, 1 intermediate pressure, 2 low pressure
  (LF Loree)

Four cylinder compound

- 2 high pressure, 2 low pressure
  (de Glehn; Barbier; Von Borries-2; Golsdorf-2; Vauclain-1&2, Mallet articulated locomotives)

Six cylinder compound

- 2 high pressure, 4 low pressure
  (Chapelon)

These can be staggered with drive to more than one axle, in line concentrated on one axle or in tandem with HP and LP driving a common crank, the latter system being much employed in the U.S.A in the early years of the 20th Century, notably on the Santa Fe.

In 1850 United Kingdom Patent number 13029 was awarded to James Samuel, the engineer of the Eastern Counties Railway, for a "continuous expansion locomotive", a method of steam locomotive compounding, although the idea appears to have come from one John Nicholson, a driver on the line. In this system, the two cylinders alternated as high and low pressure, with the change-over occurring half way through each stroke. Two locomotives, one passenger and one goods, were converted to the system but no further examples followed.

Whether the above locomotive is strictly-speaking a compound is subject to debate: the first recognisable compound application to a locomotive was on Erie Railway's No 122, an ordinary American type fitted in 1867 with tandem compound cylinders following J.F. Lay's patent no. 70341. Nothing is known of this locomotive's subsequent career and it does not appear to have been reproduced.

Mallet

Apart from this isolated case, the first known commercial application of compounding to locomotives was due to Anatole Mallet who introduced in 1876 a series of small 2-cylinder compound 0-4-2 tank locomotives for the Bayonne-Anglet-Biarritz Railway. These were entirely successful and worked for many years. Mallet also worked out schemes for compounds with independent divided drive for HP and LP, some with a single rigid chassis that were never built, others with a rigid rear chassis on which the HP cylinders were mounted and an articulated LP front engine unit. The latter arrangement was adopted worldwide. The first application was a series of 600 mm gauge locomotives specially built by the Decauville Company for the Paris Exposition of 1889. Of course the arrangement entailed articulated steam piping which might be liable to leak which is why the LP cylinders were located on the front engine unit, an advantage to some extent offset by the great length of the steam pipes, causing a tendency to temperature drop and condensation, especially in cold weather: one of the main reasons why simple expansion "Mallets" became more prevalent in the U.S.A. in later years.

Webb

Mallet's aforementioned rigid wheelbase divided-drive schemes, although never actually applied, may have inspired Francis Webb in Britain. After trials with an old single-driver converted into a 2-cylinder compound in 1878, he introduced in 1882 his first Experiment class with similar divided-drive: 3-cylinder compounds with uncoupled driving wheels in which two small outside high-pressure cylinders exhausted into one large low-pressure one between the frames. Other similar classes followed, progressively enlarged.

Wheel arrangements varied: 2-2-2-0, 2-2-2-2, 2-2-2-2T, 2-2-4-0T and 0-8-0; the last were freight locomotives and the only ones of this type to have all wheels coupled. Webb's next stage consisted of two classes of 4-cylinder compound 4-4-0s one 4-6-0 type and finally more 0-8-0s The latter are considered to have been the most successful Webb compounds and some lasted in their original condition into the 1920s.

Europe and USA

The compound principle became popular for railway locomotives from the early 1880s and by the 1890s were all the rage. Large numbers were constructed, mostly two and four cylinder compounds, were developed in France, Germany, Austria, Hungary, and in the case of the U.S.A, down to the early years of the 20th Century after which they were generally abandoned. Maintenance costs were greater than expected, and superheating provided similar efficiencies at lower cost. Nonetheless, compound Mallets were built by the Norfolk and Western Railway right down to 1952.

Vauclain

In 1889 Samuel M. Vauclain of the Baldwin Locomotive Works devised the Vauclain compound locomotive. This design used a double-expansion engine fitted into the space occupied by a conventional single-expansion engine on the locomotive, using a single piston valve with conventional gear to control both the high- and low-pressure cylinders. Substantial fuel efficiencies were achieved, but maintenance difficulties doomed the type. Most were converted to conventional engines.

De Glehn

type long-familiar on French railways was the 4-cylinder de Glehn compound. The prototype was a 2-2-2-0 designed by Alfred de Glehn, an engineer at the Société Alsacienne de Constructions Mécaniques (SACM). It had a 4-cylinder layout with the driving wheels uncoupled and bore a superficial resemblance to a Webb compound, except that inside HP cylinders drove the leading driving axle whilst the LP cylinders were outside driving the trailing axle. In 1891 two production locomotives were placed in service with the cylinder positions inversed, that is outside HP and inside LP, one of which initially had uncoupled driving axles as before but this arrangement proved inferior to the coupled version.

As such the de Glehn type was built in large numbers in France in various wheel arrangements for service at home and abroad; a number were also built in Germany and Belgium. Many gave long service: a 4-6-0 230D locomotive introduced 1909, stationed at Creil could often still be seen at the Gare du Nord, Paris in the late 1960s.

Three of the 4-4-2 type were purchased by the Great Western Railway, one in 1903 and two slightly larger ones in 1905 under its Locomotive Superintendent George Jackson Churchward for use in comparative trials and were tested against his own designs. For comparison with the later de Glehn compounds, the 4-cylinder simple 4-4-2 locomotive no 4000 North Star was specially built. Although a number of items of French practice were adopted by the Great Western as a result of these trials, the de Glehn compound system was not one of them.

Chapelon

André Chapelon's celebrated above mentioned rebuilds from 1929 onwards were mostly of de Glehn compounds. Chapelon, along with other French engineers such as Gaston du Bousquet, and Marc de Caso brought these locomotives to their highest pinnacles of performance.

Maffei in Munich also built a large proportion of the German 4-cylinder compounds, mostly on Von Borries' later system. In spite of a sweeping standardisation policy by the Reichsbahn imposing simple expansion, a small but consequent number of Maffei Pacifics of a design dating from 1908 were nevertheless considered indispensable for hilly routes with severe axle load limitations and were built new as late as 1931.

Chapelon's aborted post-war locomotive replacement programme included a whole range of 3-cylinder Sauvage compounds. The only one to come into existence was 242A 1, a 4-8-4 prototype rebuilt in 1946 from an unsuccessful 4-8-2 3-cylinder simple. 242A 1 was probably the most important compound locomotive of all time, capable of developing a remarkable 5,300 cylinder horsepower (4,000 kW) for an engine unit weighing just 145.6 metric tons. One of the most efficient steam locomotives ever built, coal consumption was just 850 g/hp (1.1 g/W) per hour and water consumption was 6.45 L/hp (8.6 mL/W) per hour at 3,000 hp (2,200 kW). A typical simple expansion locomotive could consume approximately double these amounts to generate the same output.

Porta

Livio Dante Porta in 1948 drew inspiration from Chapelon's 4700/240P rebuilds for "Argentina"; his first production, a 4-cylinder compound rebuilt from an old British-built metre-gauge Pacific into a futuristic 4-8-0.

A layout with more or less 120° crank setting (the final setting was to be empirically determined) with HP cylinder placed on the left-hand side was fully developed by L.D. Porta for new-built modern steam locomotives all of which would have used multiple expansion, some following this 3-cylinder compound system. These included locomotives of the 2-10-0 wheel arrangement, one of which was intended for fast freight work in the US, this being a high-pressure triple-expansion machine. Strange as this layout may seem, it had a number of advantages from the point of view of equalising piston thrusts and arrangement of steam passages. It was claimed that with proper maintenance and operating procedures, such locomotives could compete with modern forms of traction. Other projects were for small 2-cylinder compounds: notably a locomotive for sugar plantations in Cuba, burning bagasse.

Sauvage

Another historically important, albeit less numerous configuration also had its origins in France: the three-cylinder compound with two outside LP set at 90° fed by one HP cylinder between the frames with the crank set 135° from the others. It was first incorporated into a prototype for the French Nord Railway in 1887 to the design of Edouard Sauvage. This remained a solitary example but nonetheless put in 42 years' service.

Smith, Johnson, Deeley

On the British North Eastern Railway there appeared in 1898 a prototype 4-4-0 compound locomotive (NER Class 3CC) with this same layout to the design of Walter Mackersie Smith (this itself being a rebuilt from an earlier Wordsell/Von Borries 2-cylinder compound prototype). This formed the basis for an initial batch of five Midland Railway 1000 Class locomotives designed by Samuel W. Johnson for the Midland Railway. These were followed from 1905 onwards by 40 of an enlarged production version where all the Smith fittings were replaced by a simplified starting arrangement incorporated into the regulator; this to the design of Johnson's successor, Richard Deeley. The original Johnson locomotives were rebuilt as Deeley compounds from 1914 onwards and were superheated.

After the formation of the London, Midland and Scottish Railway in 1923, and after comparative trials against locomotives of the constituent companies, the Midland compound was deemed the best and adopted in a slightly modified version, the LMS Compound 4-4-0, from 1925 to 1932 as the LMS standard class 4 express locomotive reaching a final total of 245 locomotives. The LMS locomotives were not universally appreciated especially on the old LNWR section where they went hand in hand with operating methods imposed by the Midland Railway constituent but in Scotland they were received as the solution to serious endemic express locomotive problems and were generally well liked.

Five larger 3-cylinder locomotives were built to the same general pattern by Beyer, Peacock and Company to the design of G.T. Glover for the Great Northern Railway (Ireland) in 1932 for the Dublin-Belfast expresses. Preserved examples are the rebuilt prototype Midland Compound, 1000 (BR 41000), and GNR(I) no 87 Kestrel.

Weymann

From 1896, Weymann introduced a 3-cylinder 2-6-0 type with divided drive and cranks at 120° for service on the heavily graded Swiss Jura-Simplon routes; eventually they numbered 147 units.