The Benefits of Compounding

Hollingsworth and Cook, in their admirable survey of steam locomotives around the world put Andre Chapelon on the shortest of short lists for the greatest steam locomotive designer of all time, and few would disagree[1]. They also say that if one had to select one locomotive to represent the breed, then his 4-8-0 rebuilds of some ancient Paris Orleans (P-O) Compound Pacifics had good claim to be top of the list. The evidence is clear: the 2600 EDHP sustained by the first Chapelon 4-8-0 in 1932 was roughly twice anything that had been achieved in this country at that time. Later, an improved 4-8-0 sustained 3300EDHP from its 40.5 sqft grate, about 80 EDHP/sqft, and his 4-8-4 with a 54 sqft grate sustained 70 EDHP/sqft[1]. This compares with best sustained figures of around 55 EDHP/sqft in this country from simple engines, e.g. 2200 EDHP from an A4, this being similar to the best efforts of the French Compound Pacifics at 2600EDHP from 46 sqft. EDHP/sqft is a good measure of output in relation to size, and so in this respect the French Compounds set a very high bar.

Now such high powers require a high boiler output in relation to grate size, and efficient use of this steam in the cylinders. In Compounds, since all the steam needs to flow through two relatively small high pressure (HP) cylinders working at high backpressure, measures must also be taken to maximise the flow of steam into the cylinders; this is less of an issue in simples working at speed. So, Chapelon incorporated several ideas into his designs to allow the achievements above. However, the question of how much actual benefit Compounding brings to cylinder efficiency remains unclear. In the 1940s, RP Johnson, Chief Engineer at the Baldwin locomotive works in Philadelphia quotes Chapelon as saying that the benefit was ‘about 9%’.[2] He goes on to observe that American designers had by and large concluded that the complexities of Compound designs made them more trouble than the savings this brought were worth, a view *de facto* shared in most other countries of the world. In other words, when evaluating the operational and financial performance of locomotives, other factors than pure efficiency weighed more heavily. Indeed, even in France, it was the robust US built 2-8-2 simples that survived to the end of steam, not the more efficient 2-8-2 Compounds. On the other hand, Professor Tuplin wrote an article in the Engineer[3a] in the 1960s claiming a four cylinder simple 4-8-0 could have matched the 4-8-0, and that the efficiency benefits of compounding were negligible; the French 4-8-0 benefitted from high boiler efficiency he opined. There was a vigorous, lengthy riposte by Chapelon[4], a dismissive response from Tuplin[3b], and some support for Chapelon from George Carpenter[5]. As Bill Hall adduced[6], the problem even as late as the 1960s was that there was no robust quantitative framework against which the reliability of claims and test results could be judged, with the consequence that debates could be won through passion, or a good barrister!

In this article I will attempt to divine what the relative importance of the various contributory factors to French Compound outputs were, in the process putting a value on the benefit of compounding. My principal sources in this are Chapelon’s own accounts of his work[7,8], Baron Vuillet’s records of performance[9], which form the backbone of reports in the Railway Magazine in the 1930s and 40s, Revue Generale reports[10,11,12,13], Thierry Stora’s excellent website[14], and the Tuplin correspondence. The tools I will use are basically modern computational methods. These allow good assessments of running power needed using now well validated locomotive and coach resistance equations, the analysis of data with a speed and precision unthinkable in Chapelon’s day, and accurate programmes for both boiler and engine efficiency. On this latter point, the programme ***perform***[6,15,16] uses a computational fluid dynamics approach that is in my view the only satisfactory way to evaluate engine behaviour; steam age methods, based on inferences from thermodynamics are wholly supplanted, and indeed sometimes in error.

The Chapelon approach

Chapelon's work covered a range of classes. In the 1920s, most French Railways had four cylinder Pacifics of compound design dating from just before 1910 as their principal passenger type, themselves capable of a creditable 1500EDHP, but there was an increasing need to run heavier trains, which required more power. With electrification underway, steam's future was already looking bleak in France, so the approach taken was largely to upgrade these designs, rather than large scale new builds, and the clear goal was to try to demonstrate the highest possible power, with higher efficiency being one means to this end. There were eight key ideas in the plan:

- Increase superheater area and improve design to raise inlet steam from around 650°F, to peak values around 770°F, comparable with later best practice in the UK, e.g. on LNER Pacifics and the BR7, 8 and 9. In simples this would increase cylinder efficiency by about 5%, but for reasons I will come on to, the benefit could be greater in Compounds. Chapelon adopted a number of measures to achieve this, but modern computational fluid dynamics suggests that the one which had by far the largest effect was to bring the superheater elements closer to the firebox, increasing the radiative heat transfer. Others knew of this solution, but avoided it to minimise maintenance costs.

- Use ACFI feedwater heaters to recycle more of the exhaust steam to the boiler than possible with exhaust steam injectors (ESI). These latter typically recycle 6-7% of the exhaust steam; with feedwater heaters up to about 14% is theoretically possible. Curiously, Chapelon claims no more than about 8% for the ACFI equipment, but gives no indication as to how this figure was arrived at. My feeling is that it is a rather safe across the board assumption. So, a 5+% saving in coal might be expected relative to ESIs, or alternatively you would get about 5% more power at the boiler limit. ACFI feedwater heaters were tested extensively on the LNER, most notably on its B12 class 4-6-0s[17], but it was found that the maintenance costs were greater than the coal savings, in part because of the hard water in SE England.

- Retain the compounding principle, but seek to redesign so as to equalise the work between high and low pressure (HP and LP) cylinders. This could give improvements both to efficiency and maximum cylinder steam flow.

- Improve the draughting and reduce cylinder backpressure by better exhaust design. The best of many systems tried was the Kylchap, and it is clear that maximum feedwater evaporation rates of 1000+lbs/sqft grate/hr could be achieved with this, compared to the 800lbs/sqft/hr normally found with UK draughting systems, a 25+% increase in peak boiler output. The 4-8-0 Kylchap had a free nozzle area of about 31 sq ins, similar to later UK designs e.g. the Duchess and Kylchap LNER Pacifics, and this would give a several per cent improvement in engine efficiency over the narrower blastpipes of earlier designs. Note otherwise efficient BR designs were hobbled with primitive exhausts, e.g. the Britannia with a 22.7 sq in plain blastpipe, which didn't draught that well at high rates either.

- Increase working pressure from around 230 psig to up to 290 psig. This is the simplest way to improve the steam flow into the Compound HP cylinders, hence increase maximum power. On simples, maximum power at speed is usually limited by boiler output, not cylinder steam flow, so increased boiler pressure helps only by improving efficiency- it increases steam flow at a given cut off, so shorter, more efficient cut offs can be used to generate the same power. At low speed, high pressure also increases tractive effort hence starting power of both simples and Compounds, which may influence driver's perception of a locomotive's power, even though on simples at speed it is ultimately limited by boiler output/grate area.

- Generously proportioned steam circuits to reduce pressure drops to the steam chest; these will increase steam flow to the cylinders hence maximum power. The cross sections on the original Pacifics were quite restricted. Steam circuit pressure drops were not that great on latter day UK simples, and in any case they cause only a slight loss of efficiency at speed.

- Use poppet valves (which fell out of favour) or Willoteaux double piston valves to maximise steam flow to both HP and low pressure (LP) cylinders. This helps maximise cylinder steam flow, but for reasons given above, any benefits for this on simples would be small.

So, the maximum power of the Compounds was increased by boosting boiler output, coupled to a corresponding improvement to maximum HP cylinder steam flow through raising boiler pressure and modifying valve gear, and an improvement to engine efficiency through improved superheat and lower back pressure. On simples, increasing superheat and improving the draughting are the key steps form Chapelon's work, with lesser benefits from improving the steam flow to the cylinders. It is also worth noting that the outstanding French performances here reported were usually achieved with the benefit of coal with at least 5% higher in calorific value than the hard coals used on most lines in this country, either Welsh or indigenous Aniche coal. In fact, the fines in the coal, which would add to losses, were sieved out, and used to make briquettes which were sometimes used to supplement the raw coal, these factors together allowing a significant improvement in boiler output.

This improvement work was begun in the 1920s, but by 1931 the full flowering was achieved in Chapelon's work on rebuilding of the P-O's 3500 series 46 sqft grate Pacifics in line with his ideas. Given the success of this venture, he then rebuilt some 4500 Class P-O Pacifics, with slightly smaller driving wheels, into 4-8-0s, to tackle heavy trains on the ferocious gradients of the Brive-Montauban section of the line from Paris to Toulouse. This required a reduction in grate area from 46 to 40.5 sqft. Other railways upgraded their Pacifics on these lines- e.g. the PLM, whilst others introduced new build 4-8-2s, also of Compound design. The final flourish of these activities was the rebuilding of an unsuccessful 4-8-2 into a Compound 4-8-4 with 54 sqft grate, the most powerful European passenger locomotive by a long distance.

Performance of French Compounds.

Before discussing the benefits of compounding, we need to look at the substance of the French claims. Given that the whole objective of the improvement programmes was to maximise drawbar outputs, tests sought to establish the maximum output of the new designs, through road tests with a dynamometer car and either heavy main line trains, or several locomotives working in counter pressure mode on nearly level track at constant speed. Having reviewed all the above literature very carefully, and analysed running logs using standard resistance equations, it is clear that the drawbar powers quoted are generally sound. Some of the numbers quoted are transitory spikes on a dynamometer trace, but there are without doubt some quite spectacular sustained outputs.

Compound Pacifics. Road tests of the rebuilt P-O Pacifics took place over a number of years, the best early runs being of 3715 in 1933, which sustained about 2250 DBHP on test on the Nord Railway between Paris and Boulogne. Later P-O rebuild 231.726, fitted with poppet valves and slightly larger cylinders sustained 2550 EDHP on counterpressure road tests in 1935. The PLM upgraded their Class 231D Pacifics, which already had high superheat, in two stages[10]. Firstly, the 231Gs had a PLM version of the Kylchap double chimney, and improvements to the LP cylinder steam passages. The new draughting allowed an increase of 45% in the maximum steam rate, and this allowed sustained EDHP to increase to 2130 at 62 mph and 1960 at 75 mph. Secondly, the 231Hs had boiler pressure increased from 230 to 285psi, a Dabeg economiser, which increased temperature of the feed to the boiler, and a slightly higher superheat. A 231H sustained about 2500 EDHP on a constant speed road test at 62mph, as much as 2700EDHP for a 12 mile stretch.

These top outputs are of course measures of capability, not necessarily representative of daily work and indeed even in the 1930s, with an overall speed limit of 120km/hr, the logs show that power much over 2600 IHP/2000EDHP was rarely needed even with very heavy loads. There is a 1960s report of a late running Golden Arrow from Boulogne to Amiens with a rebuilt PLM Pacific[18]. The actual running rarely exceeded 1900IHP, more often about 1600IHP. This made up some, but not all the lost time, which would have been well within its capability. This is good 'Scot' level performance, and one wonders if the fireman was more interested in hanging out of the cab, enjoying the summer sea breezes, than shovelling hard to extract the full potential of his machine for the benefit of British tourists or 'La Gloire de la France'.

4-8-0 Compounds. The first rebuilt 4-8-0, 240.701, produced some astounding performances for its size. On counterpressure road tests, 3000 EDHP was sustained at 110km/hr. A later rebuild, 240.707, was sent to the Nord Railway for tests between Paris and Calais. Special dispensation was given to run at 140km/hr, and with a load of 650 tons, 240.707 produced performances which 'belong to the history of the steam locomotive' according to Vuillet. British recorder Brian Reed provided detailed logs, and on the return 240.707 certainly produced 2500-2600 EDHP for 20 minutes climbing from Amiens to Gannes, as Vuillet claimed, though Chapelon's peak of 3200dhp can only have been a transitory output. A similar peak value is claimed on an earlier run with 760 tons.

Later, some more 4-8-0s were rebuilt for work on the PLM mainline, with slightly larger cylinders, tenders and mechanical stokers. A series of tests were made on the climb to Blaisy-Bas summit, and on the 30th of April 1941 in the calm of Vichy France, three days after the Bismarck was sunk, 240P5 surmounted the 1/125 grade with 800tons at 60 mph, averaging an astounding 3300EDHP for about 17minutes, with a peak of about 3550 EDHP for the last 5 minutes. Remarkable indeed.

The problem with all these runs is the claimed IHPs. Chapelon believed that the difference between IHP and EDHP, Locomotive Resistance (LR) of the P-O 4-6-2s was of the order of 1000HP at 120km/hr, Likewise, he believed that LR of the 4-8-0s was 200, 400, 700, 1000 and 1200 HP at 50, 70, 90, 110 and 120km/hr respectively. However, these figures are physically unreasonable. The PLM knew better[10]. Tests on their 231G Pacifics suggested that LR was about 620HP and 750HP at 62 and

75mph respectively. Later tests on the Vitry test plant suggest that Machinery resistance (MR) was of the order of 100-300HP in this speed range. Now these figures are slightly on the high side based on current understanding (about 450 and 660HP for LR would be more likely), but well within the expected measurement error. The paper in fact reports that some tests on a 231D had given LR of 500 and 680 at the two speeds, in line with the models, suggesting that these lower values were attributable to indicators reading slightly low; more likely I think they were slightly high on the 231G.

Given what we now know, it is unlikely that LR for the 4-8-0 was more than 180, 280, 420, 630 and 760HP at the five speeds quoted, so Chapleon's values are up to 450HP too high. Since the reported EDHPs seem sound, this can only mean that all the quoted IHPs are high by up to this much. So, the claimed 4000IHP claimed for 3701 on counter pressure tests is more like 3650IHP, and the peak IHP on 240P5's climb to Blaisy Bas was about 4100, not the 4700 quoted by Stora, just as well but it is simply not possible to get enough steam into the HP cylinders to get 4700IHP! This means that some of the cylinder efficiencies are not as high as it might seem, and that the gap in cylinder performance between the Compounds and simples is not as large as the high claimed IHPs imply.

These are of course still quite remarkable efforts, but the task of explaining how it was possible is now significantly easier. Chapelon's lack of understanding of the factors involved in LR are revealed in a formula he proposed as late as 1952, which makes little sense from a theoretical perspective. Appendix 1 explores why his LR estimates will have seemed credible at the time in a bit more detail.

Performance of the 4-8-4 Compound.

Exactly the same problem dogs claims for Chapelon's final masterpiece, his 4-8-4[13]. A series of test runs with heavy trains was carried out in October 1948 climbing to 20 miles south to Blaisy Bas summit. Pretty similar efforts were recorded on four days. Up to 3500EDHP was developed on the easier grades on the lower 11 miles of the climb- more would have meant the 120km/hr speed limit would have been exceeded even with loads of 750-850tons! Once the 1/125 was reached, then an all out effort was made, with 4200-4300edhp at around 110km/hr, surely unequalled in Europe, and far better than was usually required of any US 4-8-4. However, Chapleon believed he was being conservative when adding the 4-8-0 LR figures to these EDHPs; this is what leads to claims of 5500IHP. In fact on the best runs, the peak short term IHP would have been around 5000IHP, with about 4500IHP sustained for the 15 minutes of the climb.

These tests are reported in the French Revue Generale, which was committed to highlighting the latest and best in French Railway practice. At the end of the article, there is a small photo of 242A1 hauling its mammoth test train, I suppose on the climb to Blaisy-Bas, vomiting a huge column of grubby exhaust over the coaches. It makes me wonder if the editor was subliminally saying 'Et voila, mes amis, that's why this is not the traction of the future.'

French reports on Compound Behaviour and efficiency.

The foregoing gives the bare bones of the capabilities French Compound designs, and this begs the question as to how this was possible. The most detailed report into the workings of the Compounds is found in two articles by Chapelon in the 1934 Revue Generale, on the tests of the 4-8-0s, running in total to 160 pages. I seized on these with great hope, only for this to be dashed by the reality. I am sorry to report that they are a remarkable example of how not to write a scientific report. Little or no raw data is quoted; how the tests were done is not stated; such results as are given are sometimes contradictory. For example, the indicator cards shown do not agree with the IHP versus cut off map produced and the reported temperatures and pressures at the inlet and outlet of the HP and LP cylinders often defy physics as we know it. It is not clear how cylinder flow with the feedwater heater in use has been estimated, and the tender feed rate one can infer from the coal and water/ihp-hr and dhp-hr figures quoted bear little relation those required by the cylinder heat drops which give cylinder efficiencies much better than those quoted on the efficiency maps. I could go on. Much of the report is Chapelon spinning his pet theories as to why the Compounds are so good, theories which with the benefit of 20/20 hindsight are not robust- he himself acknowledges that they are ideas, not definitive principles. The prose is flowery, and the whole thing is but a paean of praise to his own creations. No wonder Tuplin smelled a rat. The Parmentier report on the PLM 4-6-2s is better. Interestingly, Chapelon is barely mentioned (he had after all left the PLM for the P-O!), even though the work done closely followed what we think of as Chapelon's blueprint. One wonders if Parmentier knew some of Chapelon's claims were exaggerated, and some of his ideas not sound. The PLM chief's view was that 'Chapelon has done well, but my men have done better'. Some of the Vitry data on the Est 4-8-2 Compounds is clearly in error. The difference between IHP and wheel rim horsepower (MR) varies wildly from 285-557HP at 62 mph and 582-823HP at 75mph, clearly nonsensical. Quoted LRs for the 241 are about 900 and 1300 HP at these two speeds, quite wrong, but consistent with these MR values.

Table 1 shows some reported efficiency values. The EDHPs, hence drawbar efficiency measures are, I believe reasonably reliable. The calorific value of the coal is not given, but the quoted results imply it was at least 14500BthU/lb, consistent with reported values for Aniche coal, and this is the figure I have used. The cylinder results are shown on a 'for what it's worth' basis, bearing in mind that the IHPs and cylinder efficiencies of the 4-8-0 are very probably significantly too high. For the 4-8-0, I have used the diagrams on p287 and 314 of the Chapelon report, and it must also be borne in mind the IHPs here are not consistent with some of the other data reported.

Table 1. Reported Cylinder and drawbar efficiencies of French Compounds

Locomotive	Speed mph	Water rate, lbs/hr	Cylinder steam rate, lbs/hr	IHP	lb steam/ihp-hr	EDHP	Coal rate, lbs/hr	Lbs coal/ EDHP-hr	Approx drawbar thermal efficiency, %
4-8-0	43.5	30800	32900	2450	13.4	2050	4050	1.98	8.8
4-8-0	68.4	23100	25000	2190	11.4	1190	2700	2.46	7.7
4-8-0	68.4	27700	30700	2680	11.4	1590	3700	2.33	7.8
4-8-0	68.4	34400	36900	3190	11.6	2130	4840	2.33	7.7
4-8-0	68.4	40600	43700	3620	12.1	2570	6360	2.60	7.1
4-8-0	68.4	52400	57300	4410	13.0	3420	8640	2.53 (est)	6.9
PLM 231G	62.1	34900	37600	2800	13.7	2200	4700	2.14	8.0

	74.9	34300	37100	2700	13.7	2000	4840	2.42	7.0
Est 241	50.2	39100	42200(?)	3160	13.4	2800(?)	5480	1.96	8.7(?)

With respect to drawbar efficiencies, the figures of 2.3-2.5 lbs/EDHP-hr at 68-75mph are up to 20% better than the 2.8lb/ EDHP-hr obtained for the Duchess working at 38000lbs/hr with ESI and South Kirkby coal. The Compounds have overall drawbar thermal efficiency of 7-8%, at this speed. However, It is worth bearing in mind that if you plot drawbar efficiency versus steam rate and speed, there is a peak value around 40mph at intermediate steam rates- at higher speeds efficiency is depressed by the rising LR, at lower speeds/ steam rate engine efficiency falls. So, if you drop the speed to 45.5 mph, you can claim 9% for the 4-8-0, and indeed even the Britannia has a maximum over 9% if you choose the right operating conditions! So, beware vague drawbar efficiency claims when speed is not quoted. At a speed of 70 mph and steam rate of 31500lbs/hr, the Britannia's efficiency is about 6.9%, about 12% worse than the 4-8-0, though it is helped by its lower LR. With respect to cylinder efficiency, the high superheat 231G gives about 13.7lbs steam/ihp-ihr (probably reliable), only slightly better than a good simple under the condition quoted. The 4-8-0 appears substantially better than this, but as noted, it is highly likely that all the IHPs on which these estimates are made are very significantly overestimated. The Est 4-8-2 appears similar to the PLM 4-6-2- its IHPs looks reasonably sensible at high steam rates. However, at the low steam rates at which most of the tests were done-20-30000lbs/hr, inlet steam but 600-650^{0}F- possibly the normal working range- the cylinder efficiencies look quite poor, and worse than simples. (To be continued)

Appendix 1. French Locomotive Resistance

It is perhaps worth exploring why Chapelon's Locomotive Resistance (LR) values are so wildly out. Some years back, the editor published a short summary of a large amount of work done by myself and others to build sensible models of LR, such that the values for untested locomotives can now be predicted with reasonable, albeit not perfect accuracy[19]. The full text is available online. French locomotives are not that different to UK designs in size, and it is not unreasonable to apply these models to them. Much water has flowed under the bridge since then, but nothing has challenged the basic premise that LR is best thought of as the sum of the locomotive's vehicle resistance, given by the Davis equation, and its Machinery resistance (MR). I attributed this suggestion to John Knowles, but have since discovered this is exactly the approach advocated by RP Johnson, chief engineer at the Baldwin Locomotive Works[2]. Now Johnson states that the MR can be equated to 20T lbs, independent of speed, where T is the driver axle loading in US tons. I believe the origin of this figure is the PRR Altoona test plant whose reports include values for MR, the difference between IHP and WRHP on all their plant tests. If you look at the values for the K4 Pacific in 1914, the MR derived varies from 15-35T, mean about 23T. Other locomotives gave similar values, hence the Johnson value of 20T. It is clear from the PRR reports that their thinking on LR was not well developed at the time, and that they began to wonder about the MR values they were obtaining. By 1946, (after Johnson's book) they were quoting lower values than the K4 for the much larger T1 4-4-4-4. There are four basic reasons to believe the later values are better, and the original ones unreliable.

- There is enormous random scatter in the early MR values. This is particularly noticeable in the results for the K2 superheater tests, where MR apparently varies by a factor of 2 with the level of superheat! In fact, it is time dependence-the value depends on the month in which the test was done!

- 20T is quite incompatible with the Rugby test results, which latterly gave very self-consistent values for LR. 20T suggests that the MRHP for a BR5 is about 250HP at 70 mph. In fact it was more like 150.

- To assume MR is simply dependent on T is a gross oversimplification. Doug Landau has created a 'bottom up' model of LR from its various component parts, which turns out to support the Rugby values well[20]. MRHP is a multifactorial, at speed depending primarily on RPM cubed, with influence from many other factors e.g. axle load, piston and reciprocating masses, ITE. It is clear from this that if you were to try to relate everything to T, the coefficient would be higher for US locomotives than UK ones, but that even so, the Altoona MR values are likely significantly overstated.

- The underlying problem is that IHP measurements in the steam era were unreliable, particularly at short cut offs when the indicator diagrams were 'thin', suggesting there was a problem with measuring areas. In the UK, estimated IHPs in early Rugby tests came out too low, giving low or negative MR under these conditions; values were ok at high cut offs; analysis of the Altoona and Vitry data suggest the opposite problem namely that IHPs were overestimated at shorter cut offs.

The consequence of the widely reported MR Altoona values was, I believe, that in 1920s and 30s, these values were taken as correct, giving people permission to believe in high LR values: and indicator measurements that confirmed this would likely been seen as reliable ones. Chapelon himself published a formula for LR in 1952[21]. This is a very curious creation, depending only on the journal size and load, wheel diameter, number of axles and ITE. It does not depend on locomotive weight, the size of the tender, or the frontal area, which dominates resistance at high speeds. For what it's worth, it gives values of about 600HP at 62 mph and 850 HP at 75 mph and 3000IHP, not too far from the higher figures for the PLM 4-6-2.

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Part 2. Analysis of Compounds engine efficiency vs simples with perform

Where the 4-8-0 report is useful is that it shows the temperatures and pressures in the engine, so the set up can be analysed by the computer programme ***perform***. Table 2 shows calculations which define the efficiency benefits of compounding, and the benefits of full Chapelonisation of a simple. Three locomotives are compared: a Chapelon rebuilt 4-8-0; a BR Britannia, as is; and a BR Britannia 'Chapelonised' with 290 psi boiler pressure, and a Kylchap exhaust, to show what might have been achieved with the Britannia design using known technology- a 'Super Brit'. For all types I have assumed that there is neither condensation (mostly correct) nor leakage (incorrect) in the cylinders- a kind of 'pure' like with like comparison (I will return to the likely effects of leakage and condensation). The report shows that the pressure in the intermediate reservoir between the HP and LP cylinders was about 60psi at low steam rates, rising to 80 psi at high rates, when the locomotives were operated, as Chapelon intended with similar cut offs in HP and LP cylinders, so these are the conditions that need to be modelled. The comparison is made at equal steam rate, which at similar grate area likely corresponds to equal coal rate. Four cylinder steam rates are assessed, 24000lbs/hr- the typical maximum level in UK service, and quite possibly with hand firing in France too; 32000lbs/hr which is the maximum level it is reasonable to expect even a very hard working fireman to sustain, also something like the maximum possible with an 'as is' Britannia; 40000lbs/hr, to represent pretty extreme working, and 48000lbs/hr to represent ultimate capability given unlimited coal. The superheat for the Britannia is not dissimilar to the 4-8-0 at high rates, so I have assumed inlet steam temperatures of 393, 402, 410 and 415^{o} C respectively for all. The speed of 70 mph (112km/hr) represents express working, the 45mph calculations show the effect of speed.

Britannia vs Super Britannia. The Super Britannia is 6-7% more efficient than the actual Britannia at 24000lbs/hr, rising to 9% at 32000lbs, in roughly equal measure from the lower cut off the higher boiler pressure allows, and the benefit of reduced backpressure. On account of its better draughting, the Super Britannia could probably access much higher steam rates than can be dreamed of with an as is Britannia, and rates over 40000lbs/hr are not out of the question, even 48000lbs/hr. It might therefore have performed some jaw dropping 'all out power' stunts, over 3500IHP at speed. This is not to suggest that the Super Britannia would have been a stellar machine in BR days; the high boiler pressure would give a high tractive effort relative to adhesion weight, and hence it could be slippery, and since actual duties required no more than 24000lbs/hr, the efficiency benefit for higher pressure could have been lost if crews chose to work it in part regulator and longer cut off, as happened with the high pressure MNs. A Kylchap exhaust is however a no brainer- an all-round win.

4**-8-0 Compound vs Super Britannia.** Referenced to the 'Super Britannia' the 4-8-0 Compound has a 7-12% efficiency/power benefit. The benefit is slightly greater at lower speeds. Tens of similar calculations give exactly the same picture. To understand this, we need to delve into the murky

Table 2. The efficiency benefit of a 4-8-0 Compound vs Britannia and Super Brit.

Cut-off %	**Speed Mph**	**Steam consump-tion lb/hr**	**IHP**	**Back Pressure psig**	**Efficiency%**	**Inlet steam deg C**	**exhaust steam deg C**	**SSC, lbs/ihp-hr**	**Isentropic efficiency %**	**Ratio of Ihp: Super Brit**
Engine: Britannia										
26.4	70	24018	2013	6.12	15.5	393	134	11.93	86.90	0.94
34.5	70	31981	2485	12.25	14.3	402	163.5	12.87	86.00	0.91
Engine: Super Britannia										
21.6	70	23970	2144	3.00	16.6	393	115	11.18	85.00	1.00
28.6	70	32008	2723	5.82	15.7	402	138	11.75	83.20	1.00
35.4	70	39998	3254	9.89	14.9	410	158.5	12.29	82.80	
41.6	70	48017	3667	15.37	14	415	179.5	13.09	82.10	
Engine: 4-8-0										
32.7 HP	70	23987	1204	70.61	9.3	393	242	19.92	91.70	
42.7 LP	70	24012	1086	2.87	9.2	242	**Sat**	22.11	83.20	
Total			**2290**					**10.47**	***91.00***	1.07
39.4 HP	70	32021	1622	69.88	9.3	402	247.5	19.74	90.90	
52.2 LP	70	31980	1344	5.47	8.5	247.5	116	23.79	86.90	
Total			**2966**					**10.80**	**90.10**	1.09
47.3 HP	70	40023	1893	78.92	8.7	410	266.3	21.14	90.00	
57.5 LP	70	40011	1654	9.35	8.3	266.3	137.5	24.19	86.30	
Total			**3547**					**11.28**	**89.50**	1.09
54.1 HP	70	48035	2219	80.98	8.4	415	274.5	21.65	89.00	
64.6 LP	70	47952	1787	14.60	7.4	274.5	159	26.83	86.00	
Total			**4006**					**11.99**	**89.90**	1.09
Engine: Britannia										
33.2	45	24027	1906	6.35	14.7	393	147	12.61	82.60	0.93
43.4	45	31963	2318	12.72	13.4	402	179	13.79	80.60	0.91
Engine Super Britannia										
28.3	45	24018	2051	3.24	15.7	393	126.5	11.71	81.60	1.00
36.9	45	31960	2539	6.15	14.6	402	155	12.59	77.90	1.00
45.2	45	39988	2946	10.39	13.6	410	181	13.57	75.40	
53	45	48035	3261	15.94	12.5	415	203.5	14.73	73.40	
Engine: 4-8-0										
39.9 HP	45	24040	1215	68.87	9.4	393	238	19.79	91.50	
51.4 LP	45	24023	1049	2.93	8.9	238	Sat	22.90		
Total			**2264**					**10.62**	***90.00***	1.10
50.1 HP	45	31955	1566	68.54	9	402	252	20.41	86.94	
64.8 LP	45	32001	1259	5.76	8	252	128.5	25.42	82.10	
Total			**2825**					**11.31**	**86.30**	1.11
61.4 HP	45	40017	1758	79.79	8.1	410	275.5	22.76	84.50	
71.4 LP	45	39992	1534	9.95	7.6	275.5	156	26.07	82.50	
Total			**3292**					**12.16**	**85.30**	1.12
71 HP	45	48009	1982	80.16	7.5	415	288.5	24.22	78.80	
82.7 LP	45	47952	1570	15.77	6.5	288.5	187	30.54	76.10	
Total			**3552**					**13.52**	**79.70**	**1.09**

subject of isentropic (sometimes aka Rankine) cylinder efficiencies, a subject that was both misunderstood and abused in steam days. A full discussion of this is given in Appendix 2; here we need only note that since the isentropic efficiency of the Super Brit is in the range 82-85% at speed, the absolute maximum efficiency benefit for a Compound operating at the same inlet temperature and pressure is 20%, but only in the unlikely event of 100% isentropic efficiency being achieved.

As noted above these calculations assume that no condensation or leakage is taking place. If there are differences between Compounds and simples in these respects, this could shift the balance in either direction.

Condensation in Compounds. The superheat of the 4-8-0 was very high, remarkably so at low rates. The tests and calculations show that the exhaust temperature of the HP cylinder is well above the saturation temperature of the inlet steam, which means that, contrary to Chapelon's fear, there can be no losses from condensation on the HP cylinder walls. Likewise, the exhaust from the LP cylinder is superheated at all but the lowest steam rate, which means that at high rates it is very unlikely there is any condensation the LP cylinders either. However, the LP exhaust does become saturated at the lowest steam rate, and hence LP condensation occurs. This is a very important observation, for it occurs even with an exceptionally high inlet steam temperature of 393^{o}C degrees at this rate. With inlet steam temperatures even 20^{o}C lower- still high by normal standards- (as on the original French Compounds, and the best PLM figures), the LP exhaust would become saturated, leading to very significant condensation on the large surface area of the LP cylinders. In simples, once inlet steam is above about 330^{o}C, condensation is eliminated. This may point to the Achilles Heel of compounding- superheating has to be much higher than on simples to avoid low pressure cylinder condensation. The low reported efficiencies of the Est 4-8-2 at low superheat support this, as does the fact that the PLM 4-6-2 is probably a bit worse than the 4-8-0. The full package of 'Chapelonisation' addresses this, but with superheat at lower levels, as common right through the 1920s, it is likely that the efficiency benefits of compounding are much reduced.

Leakage in Compounds. An extensive study of published literature, and detailed analyses of the raw data from the Rugby test plant, leads to the conclusion that, even in pristine simple locomotives such as those tested at Rugby, there can be in aggregate leakage of between 500 and 1000lbs/hr per cylinder, at 20-25000lbs/hr steam[22]. Not all the leakage occurs in the cylinders themselves, but we are looking at say 5%-10% losses in two cylinder designs. In Compounds, leakage in the HP cylinders is not such a problem, for the steam finishes up in the LP cylinders, where it can do useful work; the important question is how much is lost in the LP cylinders and valves. Such understanding as we have suggests that valve chest leakage would be low even in simples, and piston ring leakage is the more important. The lower pressure of the LP cylinders compared to simples suggests that wasteful leakage there might be less, though one has too say that looking at Chapelon's data, it appears to be worse. Leakage from the steam circuit, e.g. from the boiler, could vary for other design reasons e.g. number of superheater elements, but may reasonably assumed to be similar in an ideal world. There may thus be a couple of percent advantage in leakage for Compounds, but overall it is too close to call. So, based on the above, cylinder efficiency related back to tender feed (the normal method) will in reality be up to 10% worse than the figures In Table 2. This would put the Compound's efficiency in the range 11.5-13 lbs/ihp-hr, compared to 12.3-14.3lbs/ihp-hr for the 'Super Brit'.

One point of interest is what the maximum starting tractive effort of the 4-8-0 was- it is not possible to calculate this easily, as one can for simples. Perform says it is about 36000lbs if operating in Compound mode, about A4 level. However, it was possible to feed live steam directly to the LP cylinders on starting, which would give a very beefy 50000lbs. Some of the very fast starts made by the 4-8-0 suggest a high fraction of starting TE was being applied-on UK simples it was rare for more than 60% TE being applied more than briefly- so this may be one practical benefit of Compounding.

Effect of altering HP/LP cut off settings on efficiency

The above calculations have been made with HP and LP cut offs being similar- Chapelon's preferred mode of operation. However, different combinations can be used- if LP cut off is lengthened, intermediate reservoir pressure falls, and HP cut off can be shortened. Table 3 shows how changing the ratio of HP/LP cut off influences efficiency at a steam rate of 36000lbs/hr for the 4-8-0, again assuming no leakage or condensation. As the LP cut off is shortened, and backpressure increases in the HP cylinders, this reduces the HP efficiency and increases the temperature and pressure of the HP exhaust. This allows the LP cylinders to become more efficient, and on balance there is a few per cent efficiency gain up to about 42/62 HP/LP. Shortening LP cut off beyond this brings little further benefit; this is in accord with Chapelon's own findings. It follows that if crews do not work as the cut off text book says, and use very long LP cut offs then up to half the potential benefit for compounding is lost. However, note also that the better efficiency of the more equal cut offs leads, as expected, to a reduction in LP exhaust temperature. This will increase the risk of LP condensation when superheat is not at exceptionally high levels. It may be that this explains why the original lower superheat compounds tended to be worked with relatively long LP cut offs. The basic point is that unless you have a fully optimised, high superheat Compound set up and you operate it correctly, much of the potential 10% efficiency gain could be lost for one reason or another.

Table 3. Effect of HP/LP cut off ratio on power and efficiency.

Engine: 240

Cut-off %	**Speed Mph**	**Steam rate, lbs/hr**	**IHP**	**Back pressure, psig**	**Efficiency %**	**Isentropic efficiency, %**	**Inlet temp deg C**	**Exit deg C**	**SSC lbs/ihp-hr**
38.5 HP	70	35976	2143	42.17	11	84.2	405	222	16.79
71.5 LP	70	35992	995	7.54	5.7	86	222	136	36.17
Total			3138			**88.1**			**11.46**
41.4 HP	70	36036	1972	58.47	10.1	89.1	405	237.5	18.27
61.8 LP	70	36037	1272	7.37	7.2	86.8	237.5	127	28.33
Total			3244			**89.6**			**11.11**
44.2 HP	70	36044	1697	80.02	8.7	91.8	405	261	21.24
52.8 LP	70	36025	1570	7.31	8.8	86.4	261	125	22.95
Total			3267			**90.1**			**11.03**
46.1 HP	70	35980	1523	94.34	7.8	92.2	405	276.5	23.62
48.2 LP	70	36005	1741	7.31	9.6	86.4	276.5	125.5	20.68
Total			3264			**90**			**11.02**

Calculated drawbar thermal efficiencies for a Compound 4-8-0.

Table 4. Calculated Cylinder and drawbar efficiencies.

Feed water Evaporation lbs/hr	Coal fired, lbs/hr	Cylinder feed, lbs/hr	Boiler efficiency	IHP	Cylinder efficiency	EDHP	Drawbar efficiency, lb coal/ edhp-hr	Drawbar Thermal efficiency, %	Drawbar efficiency: 4-8-0
45mph									
4-8-0C									
24000	**3117**	26400	81.20%	2264	12.75%	1974	1.58	11.12%	
32000	**4656**	35200	72.48%	2825	10.65%	2535	1.84	9.56%	
40000	**6499**	44000	64.90%	3292	8.89%	3002	2.16	8.11%	
48000	**8758**	52800	57.79%	3552	7.12%	3262	2.68	6.54%	
Super Brit									
24000	**3117**	26400	81.20%	2051	11.55%	1831	1.70	10.31%	1.08
32000	**4656**	35200	72.48%	2539	9.57%	2319	2.01	8.74%	1.09
40000	**6499**	44000	64.90%	2946	7.96%	2726	2.38	7.36%	1.10
48000	**8758**	52800	57.79%	3261	6.54%	3041	2.88	6.09%	1.07
Britannia									
24000	**3117**	25440	78.25%	1900	10.70%	1680	1.86	9.46%	1.18
32000	**4656**	33920	69.84%	2260	8.52%	2040	2.28	7.69%	1.24
70mph									
4-8-0C									
24000	**3117**	26400	81.20%	2290	12.90%	1640	1.90	9.24%	
32000	**4656**	35200	72.48%	2966	11.18%	2316	2.01	8.73%	
40000	**6499**	44000	64.90%	3547	9.58%	2897	2.24	7.82%	
48000	**8758**	52800	57.79%	4006	8.03%	3356	2.61	6.73%	
SuperBrit									
24000	**3117**	26400	81.20%	2144	12.07%	1614	1.70	9.09%	1.02
32000	**4656**	35200	72.48%	2723	10.27%	2193	2.01	8.27%	1.06
40000	**6499**	44000	64.90%	3254	8.79%	2724	2.38	7.36%	1.06
48000	**8758**	52800	57.79%	3667	7.35%	3137	2.88	6.29%	1.07
Britannia									
24000	**3117**	25440	78.25%	1990	11.21%	1480	1.70	8.33%	1.11
32000	**4656**	33920	69.84%	2440	9.20%	1930	2.01	7.28%	1.20

The calculations in Table 1 can be reworked to estimate the overall thermal efficiency of the 4-8-0, Super Brit and Britannia at water feeds of 24000-48000lbs/hr (Table 4). In these calculations I have assumed that overall there is steam leakage equivalent to 5% total feed/cylinder in the locomotives, that the 4-8-0 and super Brit are both fitted with feedwater heaters that recycle 10% of the exhaust steam, that best Welsh coal of 14500 BThu/lb is fired, and that this burns with slightly greater efficiency than hard coal, as demonstrated in Swindon testing. The LR of the 4-8-0 is assumed to be greater than the Britannia- a consequence of its higher frontal cross sectional area, (it would not fit the British loading gauge) and heavier machinery, which penalise it especially at lower powers.

At a typical normal UK service rate of 24000lbs/hr water, the 4-8-0 has only slightly higher drawbar efficiency than the Super Brit at 70mph, due to its higher LR. At higher rates, the drawbar efficiency advantage rises to about 7%. The estimated lb coal/edhp-hr figures for the 4-8-0 are slightly better than Chapelon reports, so these calculations in no way underestimate the efficiency of the 4-8-0. That they come so close to Chapelon's results shows there is nothing surprising about the 4-8-0's thermal efficiency - it conforms perfectly to modern day scientific models, and one can confidently map out its behaviour on this basis. There is no need to invoke ideas such as Tuplin's improved boiler efficiency. Maximum thermal efficiency at the drawbar is around 9% at 70mph, over 11% at 45mph. The super Brit is 10% more efficient at the drawbar than the as is Brit, thanks to higher engine efficiency and the feedwater heater. At a water rate of 32000lbs/hr, something like the maximum practicable in normal service with hand firing, the 4-8-0 is developing nearly 3000IHP, far more than was generally needed. This is 22% more than the actual Britannia, a 20% advantage at the drawbar, clearly in a different league, and a measure of the efficiency superiority of the 4-8-0 over something close to UK best practice. An A4 would do somewhat better on account of its streamlining and lower back pressure. Note that the decrease in thermal efficiency as firing rate increases is largely due to a fall in boiler efficiency, from ca. 80% to the mid-fifties at the highest rate.

The main point of Table 4 however is that the coaling rates required to deliver the extreme feats of the 4-8-0 are way beyond anything that is practicable or desirable. The 3650IHP sustained of 4701 would have required, conservatively, 6500lbs/hr firing- it was claimed on some test Fireman Marty shovelled as much as 9000lbs/hr! The 4000IHP of mechanically stoked 240P5 will have required even more than the 8800lbs/hr shown, for boiler efficiency suffers by about 15% with mechanical stoking. You can't get very far on a tender of coal if you are firing at over 5 tons/hr! So, the extreme outputs of the 4-8-0 often reported are about as relevant to daily running as Mallard's 126mph.

So why did no one else adopt compounding?

The 4-8-0s were a sensation in 1932. At that time, the most powerful locomotives in the UK were the Gresley A3s, (likely a bit less efficient than the Britannia), but the LNER was in such dire straits due to the depression that it was only running slow heavy trains that needed about 1600IHP to keep time. In the speed up that followed, they did on occasion sustain 1850IHP, say 1300 EDHP at 70 mph, this almost certainly limited by the poor draughting, with peak values around 1950 IHP. The low superheat Kings rarely sustained more than 1650IHP, though there are some extreme efforts approaching 1900IHP for a few minutes climbing Saunderton bank. (Claims of 2000 EDHP are just plain fantasy). Compare this with the Kylchap draughted Compounds that were able, at not unrealistic firing rates to produce nearly 3000IHP. No contest.

With such a remarkable advance, other engineers took note, and all of Chapelon's ideas, compounding apart, were tested in the UK in the 1920s and 30s, with Gresley taking the lead. The original 1934 P2, Cock O' the North, 2001, had poppet valves, Kylchap exhaust and an ACFI heater, as French as you could get. Boiler pressure was low (220psi) compared to French practice, but the large cylinders gave huge tractive effort, so this was not a problem. However, superheat, whilst good at high rates was only around 600^{o}F at normal rates- quite poor. This was a consequence of the low specific evaporation rates required from the 50 sqft grate, and the long tube plate distance. 2001 was by far the most powerful locomotive in the UK when tested in 1934, producing around 2600 IHP, but this was well short of the 4-8-0s, and 2001 was no more economical than an A3. The low superheat would have cost about 10% in efficiency relative to the Compounds, and with another 10% loss due to lack of compounding, 2001 could not hope to compete with the 4-8-0. The attempts to improve cylinder steam flow from poppet valves and reduction in steam chest pressure drops were actually pretty irrelevant in the UK context. So, in 1938 2001 it was rebuilt with piston valves, the boiler shortened, and the feedwater heater removed, and a few years later to a 4-6-2, since the high tractive effort the 2-8-2 arrangement allowed provided little practical benefit, even on the steep Edinburgh-Aberdeen road- the steep uphill stretches total not more than 25 miles. The Kylchap A4 had much better superheat, and this, along with the Peppercorn Pacifics is the nearest thing the UK had to a fully Chapleonised simple, not far short of the Super Brit in terms of efficiency.

A compound version of an A4 operating at the efficiency levels of the 4-8-0 is not possible within the British loading gauge- you can't get four cylinders of the requisite size abreast , but as Table 4 shows, the drawbar efficiency benefits would be pretty marginal at 24000lbs/hr feedwater anyway. Any attempt would have required a single inside cylinder, as on the Chapelon 4-8-4, and Midland and Webb Compounds. At higher rates of steaming, which could be and were sustained for short periods the efficiency benefit for such a locomotive might have exceeded 5%, if the engines were operated in the correct cut off ratio. It is difficult to see how this would have added up to much at the end of the steam era in Britain, either in terms of efficiency or slightly higher power at the same steam rate. Later French experience seems to confirm this. Critical to success would be high superheat, and this insight shows why the low superheat Midland Compounds broke no efficiency records, and why the saturated Webb compounds were such a disaster. So, compounding has considerable extra complexity for not much reward in the real UK operating environment, and a similar verdict probably applies to poppet valves, feedwater heaters and Chapelon's approach to high superheat. Low maintenance and better reliability always won out over marginal efficiency increases. In a world with no oil to bridge the gap between coal fired steam and electrification, these maintenance issues may have been resolved, but steam's days were already done.

If higher power is needed by the operators, as in the US, mechanical stoking is a must, but this immediately gives a 15% hit on boiler efficiency. If this is used to achieve higher specific evaporation rates, the like with like efficiency benefit for Compounding could widen to 8% at higher steaming rates. In the US, the choice between staying with two simple outside cylinders burning a bit more coal, and adopting a more complex design for an uncertain efficiency benefit was simply no contest. In France, Compounds existed, and the decision was taken to upgrade existing designs. Great things were achieved, but much to Chapelon's chagrin, one feels, no one followed suit; I think the foregoing explains why this was a perfectly rational position to take.

However, the frustration that the 'Ultimate' (reciprocating) steam locomotive has never been built, still lingers. As the Ultimate Steam page site[23] says: '*One thing a close study of the final steam efforts around the world shows: no steam locomotive yet built has included all the available proven techniques to maximize its performance in service'.* However the *'Maximise … performance in service*' goal - what Chapelon was trying to achieve - is, as I have shown, a somewhat spurious one since it can only be achieved with coaling rates that are astronomically high, and highly inefficient. A better target might be '*maximize efficiency in service'*. Since efficiency varies with operating condition, you then have to define what you want to achieve- how much power at what speed. If we consider only hand fired locomotives, and take it that the maximum practicable firing rate is 4500lbs/hr, say 32000lb/hr feedwater evaporation, - what changes might improve the 2900IHP/2300 EDHP the Chapelon 4-8-0 can deliver? The main target would have to be boiler efficiency, which was only just over 70% at this rate, even taking into account 10% steam recycle through the feedwater heater- unburned coal losses would be over 20%. Increasing grate area to the 54 sqft would almost halve these losses, allowing nearly 10% increase in steam at the same coal, though the lower specific evaporation rates this would lead to would reduce superheat. The much touted, though to my mind not fully proven GPCS could also help here. We might then get 35000lbs/hr water evaporated at this top coal rate, and with a better feedwater heater get 14% steam recycle, allowing a cylinder rate of 40000lbs/hr. With an exhaust that gave lower back pressure than the Kylchap, together these measures might then give another 400 IHP, and streamlining would get EDHP up to about 2750 at 70mph, so drawbar thermal efficiency improves from about 8.7 to 10.4%, about 20% better than the 4-8-0, 29% better than the Super Brit and fully 43% better than the actual Britannia. Reheating the steam between the HP and LP cylinders would give another few per cent. These improvements in boiler efficiency, feedwater heating, streamlining and backpressure could also be applied to simples.

Now the Ultimate steam page goes on to say '*This fact, (lack of fully optimised efficiency) more than any other factor, is what led to the downfall of world steam.'* Would then raising drawbar efficiency by 20% from steam age best practice have prevented steam's downfall? I don't think so. Steam's downfall was caused by a host of other social, economic and environmental factors that no efficiency improvement of this magnitude can hope to outweigh. I would like to see the ultimate steam locomotive built, but we should not burden it with unrealistic expectations about reviving steam traction. From a practical operating perspective, it would already be burdened with a host of devices not likely to improve operational reliability, which is what its operators would most desire.

Summary.

1. In the 1920s and 30s, the French were able to dramatically increase the peak outputs of 10-20 year old compound designs through a range of improvements to cylinder efficiency, boiler output and maximum cylinder steam flow. This latter point is critical in Compounds because all the steam has to pass through two relatively small cylinders working at high backpressure and maximum flow can limit power output. On most simples, particularly in the UK, les so in the US, maximum cylinder flow at speed is not an issue- the boiler limit always kicks in first, so these kind of improvements are less relevant.

2. Compounding can give efficiency benefits of up to 10% over simples. However, it is likely that this full amount can only be achieved at very high superheat (>750°F) as on the 4-8-0. At intermediate superheats (650-750°F), the advantage relative to simples will be reduced because of condensation in the LP cylinders. There is no condensation in the cylinders of simples at these inlet temperatures. For this reason, the efficiency benefits of many Compound designs, including French ones would be much reduced, particularly bearing in mind that typical maximum specific evaporation rates would relatively low- 600-700lbs/sqft/hr, this being some way below the level needed for highest superheat. Given this, it is not surprising that, outside France, steam engineers were never convinced of the benefits of compounding.

3. The very high drawbar outputs of the French Compounds were possible because the improved draughting allowed feedwater evaporation rates in excess of 1050lbs/sqft/hr to be achieved. With the benefit of 10% recycle from the feedwater heater, and an engine efficiency of around 12-13lbs steam/ihp-hr thanks to optimised compounding, this allowed maximum cylinder horsepowers around 4000IHP with the 4-8-0, around 100ihp/sqft grate, 30% better than best British efforts. Higher IHP claims are in error.

4. However, these extreme feats required absurdly high coaling rates that would never be used in practice. At a realistic maximum coal rate of about 4500lbs/hr, around 3000IHP could be sustained with top quality coal, far more than normally needed, and still significantly better than an optimised simple, thanks principally to higher engine efficiency. In addition, the high boiler pressure allowed high steam flow and power at lower engine speeds than other compound designs, ideal for the steeply graded Montauban-Brive line.

5. The French Compound 4-6-2s mostly operated at lower boiler pressure than the 4-8-0, hence the maximum cylinder steam flow and power were less, despite them having larger grates which would in principle allow them to produce more steam. They also operated at lower superheat, and in their normal working range would be only slightly more efficient than the equivalent simple. This, their feedwater heater and the use of high calorific value coal allowed them to sustain somewhat more power than the equivalent UK simples.

6. Some of the measures applied to the Compounds are also applicable to simples. The LNER under Gresley did its best to follow suit, most notably on the poppet valve, ACFI feedwater heater and Kylchap fitted P2 Cock O' the North. The ACFI heater was more trouble than it was worth, and the poppet valves gave no efficiency benefit on the simple, and the superheat was low at the low specific evaporation rates at which it was normally worked. The high tractive effort was not really needed, so 2001 was rebuilt not once, but twice. The nearest things to a full Chapelon simple in the UK were the Kylchap A4 and the Peppercorn A1 and A2, lacking only feedwater heaters. The BR standard designs were also good apart from their primitive LMS/GW exhausts.

7. Chapelon's work has led many to believe that extracting far more power at greater efficiency is possible for most steam age reciprocating simples. The truth is rather more prosaic. Taking the Britannia working at 70mph as the start point, a gain of about 14% drawbar efficiency is possible at typical maximum UK steam rates simply by dint of higher boiler pressure and better exhaust design. A further 15% might be possible by going to feedwater heating, GPCS firing, streamlining and further optimisation of the exhaust. These measures would make a huge difference to the maximum power that a Britannia could deliver, but as in France, this could only be achieved at impractically high hand firing rates. (The now moribund 5AT project could claim higher efficiency improvements because the superheat and draughting of the BR5 were inferior to the Britannia. The high increase in power also assumed that maximum evaporation rate would go up from about 800 to about 1150lbs/sqft/hr, fuel economy at this rate not known). A further 10% improvement from an optimised compound system would allow around 10.5% drawbar efficiency at 70 mph, magnificent, but not enough to resurrect steam.

Appendix 2. Cylinder efficiency

Overall cylinder thermal efficiency is the product of two things: the inherent or isentropic efficiency of a particular cylinder design, and the operating conditions used, inlet temperature and pressure and exhaust pressure. Both need to be optimised for maximum efficiency. Table 5 shows powers obtained by perfect cylinders operating at 100% isentropic efficiency at different operating conditions at a steam flow of 25000lbs/hr. Nature allows no more power or efficiency than this.

Table 5 Efficiency and Power from perfect cylinders at 25000lbs/hr steam flow, 100% isentropic efficiency

	Inlet temperature, deg F	Inlet pressure, psig	Exhaust pressure, psig	IHP	Overall thermal efficiency %	Lbs steam/ihp-hr
a	550	240	3	2154.5	16.99%	11.60
b	600	240	3	2245.8	17.34%	11.13
c	650	240	3	2342.9	17.73%	10.67
d	700	240	3	2445.5	18.16%	10.22
e	750	240	3	2553.9	18.61%	9.79
f	650	240	10	2108.7	15.96%	11.86
g	650	170	3	2128.8	16.07%	11.74

Note that in these perfect cylinders, the power obtained, and the overall thermal efficiency and power increases as inlet temperature increases (Rows a-e). This is basic thermodynamics; the hotter the working fluid in a heat engine, the more efficient it is. As exhaust pressure increases (Row f), or inlet pressure decreases (Row g) power and efficiency goes down. So engineers aiming for high thermal efficiency should firstly increase inlet temperature and pressure and decrease backpressure.

Engineers then need to design a cylinder set that operates at the highest possible isentropic efficiency. 100% isentropic efficiency means that the steam's entropy (the disorder in the system) does not increase during the expansion process, the ideal. If this could be achieved, it would be possible to recompress the steam back to its exact starting temperature and pressure. However, entropy or disorder in a system has a natural tendency to increase. Nature applies the entropy tax pretty ruthlessly, so the 'isentropic efficiency' always less than 100%, and in real life the overall efficiency figures in Table 2 will be reduced.

Note that it is perfectly possible for a set up with high isentropic efficiency to deliver lower overall thermal efficiency than one with lower isentropic efficiency, if it is fed for example with low temperature steam. This was not fully grasped in steam days. Some, particularly in the West Country, believed that high isentropic efficiency was an end in itself. It is in fact one means to the end of high overall thermal efficiency, but it is always better to also increase inlet temperature and pressure and reduce exhaust pressure. Numerical values for isentropic efficiency can only be usefully compared for engines working at the same inlet and exhaust conditions.

The challenge then is to design cylinders that achieve the highest possible isentropic efficiency under all working conditions, which is what Compounding seeks to do, so the question is what influences isentropic efficiency- where does nature extract its taxes? The first point to note from Table 1 (in main text) is that the common or garden Walschaerts leakage free cylinders of the Super Britannia are delivering 82-85% isentropic efficiency, increasing with decreasing cut off, so they are actually doing a pretty good job. The maximum possible increase in efficiency from improved cylinder design, e.g. Compounding is therefore about 20%.

Underlying the improvement in efficiency as cut off is reduced is the improvement in expansion ratio of the steam (Volume of steam at exhaust opening: Volume of steam at cut off, taking into account clearance volume (CV) effects). Any measure that allows you to keep expansion ratio high by getting more steam into the cylinders at a given cut off (e.g. increasing pressure, steam lap, valve size, but not clearance volume, which reduces efficiency for reasons I will return to) is therefore a good thing. In the steam age debate about compounding, proponents pointed to the very high expansion ratios achieved by Compounds; detractors pointed to their very high CVs. The proponents were misguided, because the overall expansion process in Compound cylinders is not isentropic, so the expansion ratio argument does not apply. Nature is not easily fooled, and extracts its taxes even from charming, urbane Frenchmen. The detractors did not understand that the loss of efficiency from high CV is not that great at high speeds.

Ideal cylinders would allow steam to expand from steam chest pressure at the point of cut off down to exhaust pressure at exhaust port opening. This expansion part of the process is isentropic, i.e. ideal, and it’s what happens elsewhere that’s the problem. Where then does nature extract its taxes? In general, entropy increases when steam flows through a valve opening, with an associated pressure drop. There are three main events to consider.

(a) **Filling the cylinders up to inlet pressure when the inlet ports open.** In an ideal world, engines would be designed so that the returning piston compresses the residual steam left in the cylinders when the exhaust ports close exactly to steam chest pressure when the inlet ports open i.e. compression pressure equals steam chest pressure; in practice, this may be possible under one operating condition, but certainly not all! Factors which tend to decrease compression pressure are low exhaust pressure, late closure of exhaust valves, (as in high cut off working), high CV, and early opening of the inlet valve through longer lead. The greater the difference between the steam chest pressure and the compression pressure, the greater the entropy gain at this point and efficiency loss at this point. The role of CV was not fully understood in steam days. It was clear that, at low engine speeds and high cut off, increasing CV increased steam flow to the cylinders. The net increase in power was however zero (i.e. the effective tractive effort did not go up), and so cylinder efficiency went down. For this reason, phrases such as ‘dead space’ were used to describe CV. What was happening was that the lower compression pressure caused by the increase in clearance volume was leading to increased entropy losses, and in effect the additional admitted steam was doing no useful work. Hence a fetish for low CVs. What seems not to have been appreciated is that at higher speeds when compression pressure tends to be higher, the entropy gain at higher CV is less, so the additional steam does some useful work, and gives a boost to power. For this reason, the Duchess (12% CV) produces more power at a given cut off than locomotives of similar nominal tractive effort but lower clearance volume, e.g. the A2 at 8% and King at 6%. So from a driver’s perspective, the Duchess has more ‘grunt’ than the other two; the fact that it loses a couple of percentage points efficiency in achieving this is barely noticeable. The other point to bear in mind is that whilst the low CV fetish works well for engines designed to trundle along at low speeds (the majority of locomotives, 0-6-0s, 2-8-0s and the like), for higher speed mixed traffic and express types, low CV can become a positive disadvantage, since it can lead to over compression at high engine speeds, which reduces steam flow to the cylinders, and can also lead to loss of steam through cylinder relief valves.

Overall, the entropy gain associated with this first process is the smallest of the three being considered.

(b) **Maintaining cylinder pressure at steam chest pressure during admission.** When engines are in long cut offs, (for simples, usually at low speeds) valve openings are large, and the flow of steam through the ports is sufficiently rapid relative to piston speed to maintain cylinder pressure more or less at steam chest pressure up to cut off. In this situation, the gain in entropy, hence loss of efficiency is quite small. As cut off is shortened as engine speed increases, the narrower valve opening and faster piston speed mean that the flow of steam into the cylinder is no longer able to maintain steam chest pressure up to cut off- the 'wiredrawing' effect. The pressure differential leads to an entropy gain and loss of efficiency.

(c) **Drop in pressure as incompletely expanded steam escapes through the exhaust ports.** The higher the pressure in the cylinder as the exhaust ports open the greater the entropy gain and efficiency loss. In low speed high cut off working the exhaust ports open when pressure is still high, so losses are large. In high speed short cut off working, the exhaust ports open quite late, and pressure is already quite low, so losses are not that great. Indeed, because the piston is moving quite fast and the pressure is low, not all the steam in the cylinder has time to escape, and some of the residual steam continues to expand down to exhaust pressure, as it should in an ideal world. (Simple expansion ratio considerations do not take this into account).

To summarise, in simples working at high speed the major efficiency loss is due to entropy gain during the cylinder admission phase. At lower speeds there are major losses at the exhaust ports, also at inlet if the CV is not filled; losses during admission are relatively small. From Table 2 it can be seen that at 70 mph, the Britannia can achieve 82-85% isentropic efficiency, falling to 73-82% at 45mph, so the losses from incomplete expansion at longer cut offs are generally greater than the losses during admission at shorter cut offs.

(d) **Application to Compound engines**. The relatively small size of Compound HP cylinders, coupled to the fact that they are working at higher backpressure means that they have to be worked in very long cut offs-60+% even at speed. These large port openings allow cylinder pressure to remain close to steam chest pressure during admission, so entropy gain is small. Further, because backpressure is high, steam is pretty much expanded down to exhaust pressure when the exhaust ports open, so entropy gain is small here too. Thus as Table 2 shows, the HP cylinders operate at isentropic efficiencies of 90% or more at high speed. The absolute efficiency is low because of the high back pressure, but the most of the energy in the steam not yet converted into useful work lives to fight another day. The French data show there is little pressure drop between the HP exhaust and LP steam chest, so no losses here. Table 2 shows the LP cylinders operate at similar isentropic efficiencies to simples- 83-86%. Despite the fact that the LP cylinders are worked in long cut offs and wide valve openings, because inlet pressure is relatively low, cylinder pressure cannot be maintained at steam chest pressure during admission, so there is a significant entropy gain. This is the ‘hidden’ tax between HP cut off ad LP exhaust on Compounds. The pressure at exhaust opening may be slightly lower at speed than simples, but for reasons given above this is a small benefit.

To summarise, the lower losses at Compound HP admission bring a significant advantage over simples. However this is to a significant degree offset by losses at LP admission. The net is that overall isentropic efficiencies for the Compound in Table 1 is about 90% at 70 mph, 80-90% at 45mph, leading to an inherent efficiency advantage of up to 10% for Compounds.

Shortening the cut off of the LP cylinder raises the LP cylinder pressure, and this brings two benefits (a) backpressure in the HP cylinder is higher, so losses at exhaust are less and (b) the higher pressure is better able to maintain pressure up to cut off in the LP cylinders. On the 4-8-0, changing the HP/LP cut off from 38.5/71.5 to 46.1/48.2 (this maintains the same steam flow) increases efficiency by 4% at 70 mph (Table 4). The Compound efficiencies in Table 2 are already at an optimised HP/LP cut off ratio, which means that if the Compounds are not operated correctly, a significant proportion of the 10% efficiency gain could be lost.

These calculations do not take into account the effects of condensation and leakage. As discussed in the main text, Compounds may have a couple of per cent efficiency advantage over simples due to lower leakage. However, unless superheat is very high (>750^{0}F) it is likely that LP cylinder condensation will eliminate this benefit, and quite possibly eat into the inherent advantage.

Two general conclusions follow. Firstly, only when Compounds are operated at very high superheat, and in the correct manner (as the 4-8-0s on test) is there likely to be a significant (>5%) cylinder efficiency advantage for Compounding. Small wonder they were not hugely successful elsewhere. Secondly, the above discussion of isentropic efficiencies, based on classical thermodynamics- the tool available in the steam age- is not of itself a quantitative one; the factors influencing isentropic efficiencies can be identified, but not quantified. Only by using the power of computational fluid dynamics, not available in the steam age can quantification be achieved. Small wonder then that in the steam age, in the absence of testing methods of sufficient precision, discussion of the benefits of Compounding on the basis of theory did not lead to a satisfactory resolution.

References (continued)

22. DP leakage unpublished

23. TUSP site