Power and Economy

Developing the ZBs

Ian Gaylor

Steam Loco Design

More than doubling the power output of a steam locomotive while simultaneously cutting fuel consumption by 25% is the surprising achievement of one current steam development programme. This fascinating story and the background leading up to it is the topic of this article.

The need for more powerful locos

The railway in question is the nine mile long Bure Valley Railway running between the historic market town of Aylsham and Wroxham 'the Capital of the Broads'. This 15" narrow gauge line is a major tourist attraction carrying over 130,000 passengers a year and runs on the former Aylsham extension of the East Norfolk Railway. The track bed was originally laid as a standard gauge line in 1880 but after closure in 1982 was relaid as a 15" gauge tourist railway in 1990 at a cost of £2.5m.

As a volunteer engineman weaned on the continuous gradient of the Festiniog Railway in North Wales I was at first surprised to find that the line is very demanding for both locomotives and engine crew. However, all becomes clear when you assimilate three key points. Firstly, when the line was constructed the earthworks involved were kept to modest proportions and thus the line follows the gentle undulations of the landscape. This translates in railway terms to a series of switchback banks in the range 1 in 100 to 135 which are too long to rush giving little respite in either direction and with one short section of ¼ mile at 1 in 76.

Secondly, with a maximum line speed of 20 mph and a start to stop average of 12 mph involving three intermediate stations this is no stroll in the countryside. In fact it is more akin to a fast suburban service which demands rapid acceleration with top speeds close to the permitted maximum to maintain time. Thirdly, train loadings have been inexorably creeping upwards and the summer service regularly brings 12 bogie carriage plus brake van formations of around 40 Tonnes gross weight or four times the weight of the locomotive to put it in perspective.

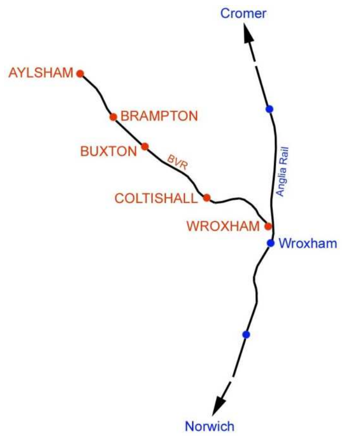


Figure 1. Map of the Bure Valley Railway which is laid on the trackbed of the former Aylsham extension of the East Norfolk Railway. The line was originally laid in 1880 and relaid as a 15" gauge line in 1990.

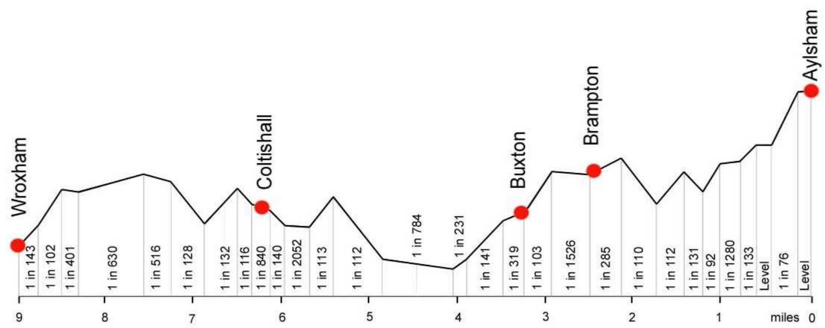


Figure 2. Gradient profile of the Bure Valley Railway. The limited earthworks of the original line have given rise to a switchback gradient profile with the steepest gradient being 1 in 76 and average gradients in the range 1 in 100-135.

Initially the line was operated by locomotives hired from the Romney, Hythe and Dymchurch Railway but as traffic grew it became clear that the greyhounds from the flat Romney Marshes were being asked to work outside their comfort zone and something larger was required.

The ZB is born

As a result the first two of the ZB class of locomotives, BVR Nos. 6 and 7, which are based loosely on the Indian Railway type, were designed and built very cost effectively by Winson Engineering in 1994. The class has become closely associated with the line and in service the new locomotives quickly established themselves as rugged and reliable performers. They have served the railway extremely well and with a maximum tractive effort of 3054 lbs are capable of starting the heaviest of trains even in adverse conditions. In traffic however, the fuel and water consumption was found to be high. Although initially this was not a serious issue, as passenger loadings continued to rise over a number of seasons it became apparent that the locomotives were slow to accelerate the increasingly heavy summer loads and could not maintain full line speed on gradients.

Figure 3. No. 7 'Spitfire' at Wroxham in original condition as manufactured by Winson Engineering Ltd. The loco weighs approximately 12 tonnes in full working order and high summer trains are frequently 12 coaches plus a brake van giving a gross weight of around 37 tonnes excluding the engine.

Photo Alan Richardson

Operating the locomotives at the edge of their performance envelope trip after trip was a challenge for crews especially if single manned. Every gradient had to be rushed at full line speed with as much water in the boiler as you could manage, the pressure on the red line and then with raucous roaring exhaust the speed would slowly and inexorably burn off despite your best efforts. With a heavy 12 coach train the speed would settle to around 12-15 mph at 50% cut-off and then all you could do was watch the water go down and hope the fire held out until the end of the climb as any attempt to fire while pulling would precipitate a disastrous loss of pressure. With the top of the climb behind you the cut-off could safely be shortened and with both injectors on to replace the water the train would be worked up to line speed again on the down grade. Getting a large round on the fire was the next essential item and as the doors opened an absolutely white incandescent fire would greet you. The trick was to keep it thin enough to burn really hot in the climb but not so thin it burnt right through to form a hole. Normally there would be some latitude in the optimum firebed thickness but at this level of evaporation there was only one option, perfect every time. Of course perfection is hard to achieve and there was no way to recover from errors of judgement, you just had to live with the consequences for the rest of the trip! Coal deliveries were serious events as each new batch had the potential to turn a difficult tour de force into impossibility. Only 'rocket fuel' was acceptable, loads of Welsh with hints of slate were sent away with baleful glares and any vestige of slack was shovelled to one side as it would simply be thrown out as red hot grit if you tried to fire it.

The voracious appetite for fuel of the ZB led to them being dubbed 'the miners friend', because you never stopped shovelling. Typically a 3 trip 54 mile day plus lighting up would require the tenders to be heaped up with up to 35 buckets of coal weighing approximately 410Kg. One enthusiastic driver was sure he had got this fuel economy thing licked and loading only 28 buckets at the end of the previous day resulted in an emergency call for coal to be despatched to meet him on route to enable him to get home!

The first BVR improvements

In 1997 2-6-2T BVR No. 8 entered service having been erected from a kit of parts supplied by Winson Engineering in the BVR workshop at Aylsham. Although this locomotive is styled to resemble a Vale of Rheidol Tank it is also a member of the ZB class sharing the same chassis, cylinders, running gear and boiler with only superstructure changes creating the visual transformation. One important difference was that unlike other members of the class it is oil fired which is useful in the dry summer periods if fire risk is high.

About three years after Nos. 6 & 7 entered service the BVR investigated the valve gear design and discovered that the piston valves had a massive 10mm of exhaust clearance which allowed the steam to be exhausted from the cylinders before it had expanded adequately. New valves were manufactured for No. 6 and as a result the locomotive performed better and coal consumption fell by 20%, typically to around 27 buckets of coal per day weighing approximately 320 Kg. Subsequently these improvements were also applied to Nos. 7 & 8 with some further small experimental differences between the three locomotives.

At first the reduction in fuel bills and the slight latitude created by the lower evaporation rates was reassuring. However, the need to still push the locomotives hard with no quarter given was exacting a toll as the high fire temperatures were shortening the life of the boilers and repair costs were rising seriously.

No. 9 'Mark Timothy' arrives

In 1999 the class expanded to a total of 4 with the arrival of 2-6-4T, 'Mark Timothy', BVR No. 9. It is named in memory of owner Alan Richardson's son and originally it was styled to resemble a County Donegal Class 5A locomotive.

When it was first delivered a number of serious problems were identified and the locomotive was returned for rectification. When it was redelivered, it was apparent that it was still unable to enter service, and shortly afterwards Winson Engineering closed down.

Rebuilding a brand new locomotive before it enters revenue-earning service is an unusual step to have to take but as there were a number of serious technical issues to be resolved Alan Richardson consulted locomotive builders Alan Keef Ltd, who undertook to rebuild the locomotive in 2001.

Figure 4. No. 9 'Mark Timothy' as originally built by Winson Engineering Ltd to resemble a County Donegal Class 5A tank locomotive. As delivered the locomotive had a number of serious problems making it unable to enter service.

Photo Alan Richardson

Figure 5. No. 9 'Mark Timothy' on test at the Perrygrove Railway with temporary firebars to enable a coal fire to be used as the original oil burner could not raise sufficient steam to enable testing to be undertaken.

Photo Alan Richardson

At this point the scope of the problems was rather daunting. An immediate issue was that the cab was too low to accommodate the locomotive crew as even the shortest engineman couldn't sit upright. There were also a large number of detailed mechanical problems with the frames and motion which would have prevented reliable regular use. The oil firing system was not functioning properly and indeed the trials at Perrygrove had to be undertaken with temporary firebars and a coal fire. Lastly there were a number of areas on the boiler which required remedial work to satisfy the boiler inspector before he would sanction use other than for test purposes.

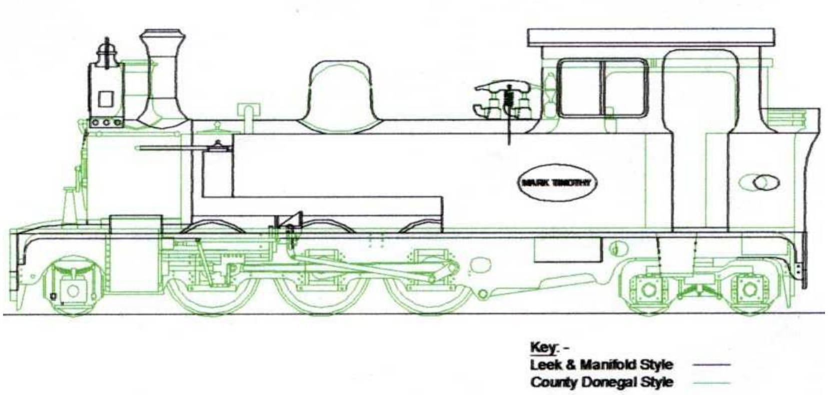
A key issue was to steam test the locomotive before stripping it and arrangements were made with Michael Crofts for these trials to be undertaken at his Perrygrove Railway when there was no passenger service running. These trials proved very useful and despite the problems, the locomotive was shown to have significant potential.

Remodelling the locomotive

The locomotive then moved to Keef's works at Lea Line near Ross-on-Wye and stripping of the locomotive commenced. In parallel a design study was carried out to look at the options to overcome the limited room available in the cab. It became rapidly apparent that the County Donegal prototype around which the external appearance of 'Mark Timothy' had been modelled was very restrictive and that the visual balance of the locomotive would be spoilt if an enlarged cab were to be fitted. As an alternative, discussions between Alan Richardson and Patrick and Alice Keef settled on the possibility of changing the appearance to match that of a Leek and Manifold locomotive.

Figure 6. The County Donegal and Leek and Manifold profiles overlaid showing the increased height necessary to create sufficient headroom in the cab. The original County Donegal profile is shown in green while the new Leek and Manifold one is in black.

Drawing Alan Keef Ltd



This had the benefit of providing a much larger cab but pushed the limits of the current BVR loading gauge especially in terms of clearance between both the cab roof and chimney and the top of the tunnel at Aylsham.

In conjunction with the BVR it was arranged to measure in detail the vertical clearances in the tunnel and also to check the effect on draughting of the fire with the top of the chimney close to the roof.

These tests were undertaken in April 2002 and with No. 7 sporting a temporary extension to the chimney several runs were made through the tunnel at a variety of power levels to see whether there was any tendency for the fire to blow back into the cab. The trials were a success and with all eyebrows still intact it was agreed that the revised overall height was practical.

With a major remodelling exercise to be undertaken it was also decided to change the locomotive from oil to coal firing. This would reduce both fuel costs and the ambient noise level for engine crew as oil firing tends to produce high levels of low frequency noise particularly when working hard.

Figure 7. Bure Valley Railway CME, Dave Phillips, checking the clearances with an increased chimney height in Aylsham Tunnel using No. 7 as a testbed.

Photo Alan Richardson

Redesigning the front end

As a Consultant Design Engineer by profession I had undertaken projects previously with the owner of BVR No. 9 'Mark Timothy', Alan Richardson, and he invited me to design a new front end for the locomotive to improve power output and fuel economy. Concurrent with the commencement of the rebuilding of No. 9 the BVR were rebuilding No. 6 and this led to the possibility of designing and building new cylinders and draughting arrangements for both locomotives unhampered by the legacy of the existing parts.

A project of this nature is always the subject of collaboration between the interested parties and I would like to especially mention the workshop teams of both the BVR and Alan Keef Ltd who contributed their expertise to the programme.

Designers like Chapelon, Porta and Wardale advocate that design must progress considering the locomotive as a whole and with a clear understanding of the thermodynamic implications so that the technical potential of improvements can be assessed. Whether a potential improvement is commercially worthwhile must then be judged in the context of total cost of ownership and with locomotives of this size the relative balance of the various contributions is different compared to say standard gauge locomotives with different usage patterns.

In this case, despite the thermal efficiency benefits obtainable by superheating, modification of the boilers was ruled out at this stage for financial reasons as it would have meant replacing large parts of sound boilers and the fuel saving could not justify the costs involved. However, consideration was given to possible fitment of superheated boilers at some point in the future when replacement was required. Similarly, to limit the impact of the work on the rest of the locomotive, the mainframes were not to be modified and the existing cylinder mounting bolt positions, exhaust passageway cut-outs and cylinder bore and stroke were retained.

Figure 8. The hollow bronze valve heads are mounted on stainless steel valve and tail rods which are through ported to improve exhaust release and relieve loads on the valve gear. Bronze was selected for the valve heads as it provides a good wear combination with the cast iron liner. Stainless steel was selected for the rods as it had a similar coefficient of thermal expansion as the valve head and therefore would not loosen in service while also providing excellent corrosion resistance when the locomotive is laid up over the winter period preventing damage to gland packing.

Photo Alan Keef Ltd

Accepting that it was to remain a saturated engine, the important point with the new front end design was still to get more useful work out of the steam before exhausting it. To do this required both expansion of the steam to the lowest pressure possible to maximise the useful work done and also minimising negative work in the form of back pressure, friction and avoidable leakage and condensation losses.

With this in mind I prepared an outline design scheme and, having obtained everyone's approval, undertook the necessary computer modelling, design calculations and drawings to enable manufacture of the parts for both locomotives.

Looking at the improvements in broad terms and working through the items in a logical sequence we start at the cylinder steam chests.

To meet the demand at speed when the valve opens during admission you need large steam chests so that sufficient steam is available. This ensures that steam pressure doesn't fall because it suddenly has to surge down the steam pipe from the boiler to get there. For this reason the steam chests were made as big as possible within the constraints of the loading gauge and while the volume is a little smaller than is ideal they are more than eight times larger than the originals.

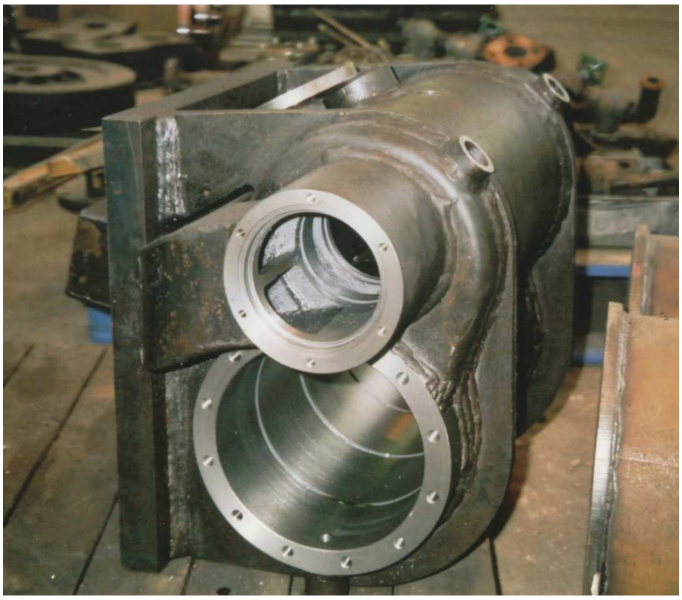


Figure 9. One of the new fabricated cylinders showing the large steam chest, exhaust ports and passageways prior to fitting the cast iron cylinder and valve liners. The grooves in the cylinder which take the Aflas O rings which prevent leakage between the cylinder liner and the fabrication can be clearly seen.

Photo Alan Richardson

The valves and ports are also important in controlling the steam flow to and from the cylinder and the transfer ports were designed with fewer but larger trapezoidal shaped ports to improve the available area during initial opening compared to the smaller but more numerous triangular form used previously. The use of narrow tapered lands on the admission and exhaust edges of the valve head enabled the valve events to be defined accurately by the valve rings under the control of the valve gear.

Table 1. Comparison of the original ZB cylinders with BVR valve modifications as fitted to No. 7 and the new cylinders for No. 9.

The new cylinders are designed to allow the locomotive to breath freely and this is assisted by the large steam chest volume, increased valve travel coupled with reduced full gear cut-off to improve valve events, increased lead steam coupled with larger steam and exhaust lap, and larger transfer ports and exhaust passageways to reduce back pressure.

Notes: [1] The original pipework in the smokebox is the limiting factor rather than this value which is given for completeness. [2] This is the area in one end of the valve liner plus (on No. 9 only) the area through the ports in the hollow valve head. [3] These figures are not known for No. 7.

Item Description	No. 7	No. 9
Bore, mm	176	176
Stroke, mm	280	280
Steam chest inlet passageway area [1], cm^2	19.64	19.64
Steam chest volume, cm^3	688.7	5886
As a % of swept volume of cylinder	10.1	86.4
Valve diameter, mm	88	88
Area of transfer port in valve liner, cm^2	38.9	36
Max. valve travel, mm @ % cut-off	64 @ 82%	74 @ 70%
Lead steam, mm	1	2
Steam lap, mm	13	19
Exhaust lap, mm	0	2
Min. area of transfer port in cylinder liner, cm^2	8.5	34.32
Area of exhaust port [2], cm^2	28.3	77.99
Min. area of exhaust passageway in cylinder, cm^2	45.37	99.36
Clearance volume [3], cm^3	-	752.7
As a % of swept volume of cylinder [3]	-	11.04
Maximum expansion ratio @ 15% cutoff [3]	-	4.26

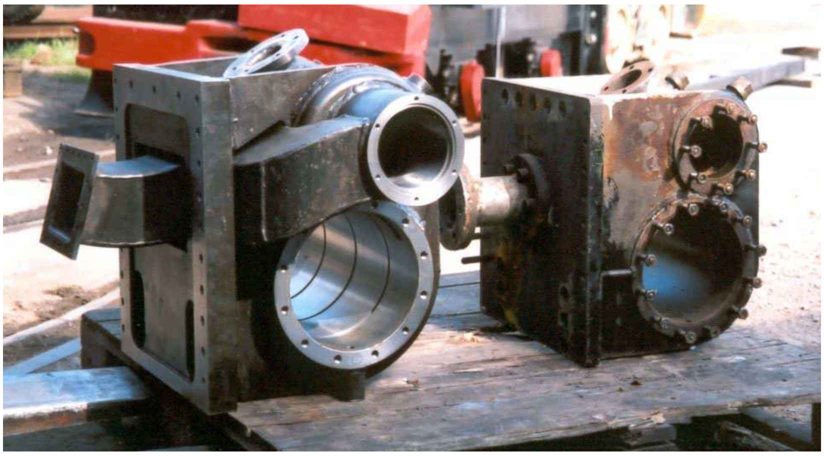


Figure 10. The new cylinder on the left shows the large inline transfer ports and exhaust passageways compared to the original cylinder on the right. The relief of the face which bolts to the locomotive mainframes can also be clearly seen and this reduces thermal conduction losses through the loco frames.

Photo Alan Keef Ltd

The valve gear was redesigned to improve the valve events by correcting geometry errors and limiting the full gear cut-off from 82% to 70% while also increasing the maximum valve travel by 10 mm to 74 mm. The overall effect is to make port openings larger for a given cut-off and is coupled with generous radii on the valve head which smooths the passage of the steam adjacent to the port.

Back pressure is minimised by allowing some of the exhaust steam to pass through the hollow valve head to make use of the other exhaust passageway branch. The combined effect of these changes is to promote good breathing while also reducing loads on the valve gear by lightening the valve head and balancing the load created by the exhaust back pressure.

The transfer passageways between the valve chest and cylinders and the exhaust passageways have also been carefully designed with rectangular sections to maximise the area for flow. They are as straight as possible but, where necessary, bends are flowing and even the valve chests and cylinders are smoothed internally. Compared to the original arrangement the passageways are enormous and one look at the illustration shows the difference in size between the original cylinders and the replacement units.

Sealing of the valves and piston has been improved by using Clupet rings which are shaped rather like a key ring and have no gap between the ring ends for steam to leak through. In addition the valve heads now have three rather than two ring grooves as the increase in lap has created enough space to fit them. The valve head is made of bronze giving good wear characteristics in combination with the cast iron valve liner and is supported by a tail rod to improve guidance.

Figure 11. One of the new split cast iron valve liners showing the trapezoidal transfer ports and large exhaust ports. Two liners are required per valve chest one being inserted from each end leaving a gap between them in the centre of the steam chest for passage of live steam to the valve head. As with the cylinder liners they are sealed to the cylinder fabrication using Aflas O rings and are clamped in position by the valve chest covers.

Photo Alan Keef Ltd

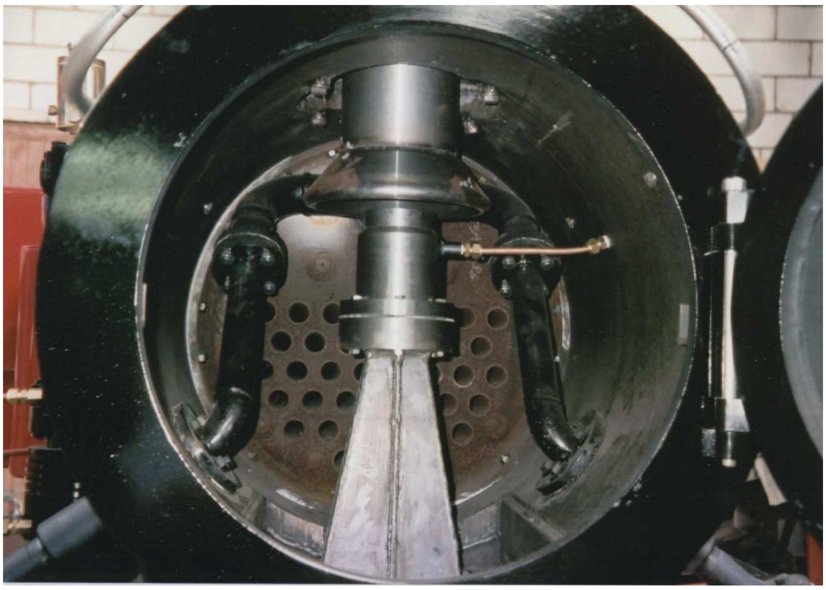


Figure 12. The new Lempor exhaust system installed in the smokebox showing the combined blast nozzle and blower assembly mounted on top of the tapering exhaust stand. The spark arrestor is not fitted and the copper pipe connecting to the right hand side is the blower supply.

Photo Alan Richardson

Table 2. Comparison of the original ZB stovepipe and single blast nozzle exhaust system as fitted to No. 7 and the new multiple blast nozzle Lempor system for No. 9.

The new exhaust system is designed to reduce back pressure and incorporates a Kordina in the blast pipe stand coupled with increases in both blast nozzle and chimney exit areas.

Item Description	No. 7	No. 9
Number of chimneys	1	1
Total blast nozzle tip area, cm²	15.91	20.91
Total chimney choke area, cm²	181.48	166.64
Ratio chimney choke area : blast nozzle tip area	11.4	8.0
Choke diameter, mm	152	146
Mixing chamber length, mm	N/A	291
Mixing chamber length : diameter ratio	N/A	2.0
Diffuser length, mm	N/A	452
Length of bellmouth, mm	0	47
Chimney length inc. bellmouth, mm	375	790
Total chimney exit area, cm²	181.48	404.81
Chimney exit diameter, mm	152	227
Diffuser included angle	0°	10.3°
Diffuser area ratio	1.0	2.43
Overall chimney length excluding bellmouth : mixing chamber dia ratio	N/A	5.10
Number of blast nozzles	1	4
Individual blast nozzle tip area, cm²	15.91	5.23
Blast nozzle exit dia, mm	45	25.8
Blast nozzle throat diameter, mm	N/A	23.9
Ratio of blast nozzle exit area : throat area	N/A	1.165
Kordina crossectional area, cm²	N/A	20.91

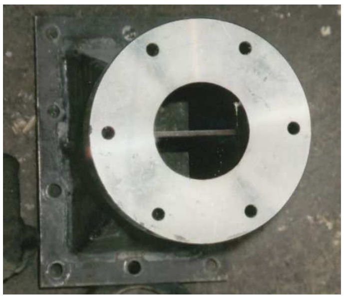


Figure 13. A view of the exhaust stand from above showing the divider of the Kordina immediately below the flange. The purpose of the Kordina is to reduce the negative effect on the other cylinder during an exhaust event by avoiding transfer of back-pressure. During the dynamometer trials which were carried out the benefits were shown to be significant.

Photo Alan Keef Ltd

Figure 14. The four nozzle blast cap with integral blower. The blast nozzles are of the convergent divergent type to maximise the coefficient of discharge and minimise the exhaust back pressure. The nozzles are also angled outwards to ensure that the blast fills the mixing chamber of the chimney evenly.

Photo Alan Keef Ltd

Avoidable heat loss has been lowered by the use of better and thicker ceramic insulation and reduction of contact area between the main frames and cylinders. Heat loss is further minimised by arranging for all coasting to be done in mid-gear as this prevents cooling of the cylinders by cold ambient air drawn in through the snifting valves. To enable mid gear coasting, without abrasive smokebox combustion gas and ash being drawn into the cylinders via the blast pipe, requires the provision of a small quantity of steam to the steam chest. By using this steam to atomise the cylinder lubricating oil as it enters the steam chest the lubrication of valves and pistons is also improved.

Better expansive use of the steam can now be made as a result of the improved valve events and with a small clearance volume a maximum expansion ratio of 4.26 is achievable at 15% cut-off.

The draughting arrangements in the smokebox were improved by the fitment of a multiple blast nozzle Lempor exhaust system which creates sufficient draught for efficient combustion with lower exhaust back pressure. A Kordina was also incorporated in the exhaust passageways from the two cylinders where they combine below the blast nozzles. This device prevents the exhaust release from one cylinder increasing the back pressure in the second cylinder.

The four nozzle blast cap is effectively 44.5% larger than the original single nozzle blast pipe taking into account the improved flow coefficients and has an integral four nozzle blower. This was machined rather than fabricated because of the small physical size and accuracy required which made this the easiest option. The Lempor mixing chamber and diffuser is concealed within a chimney of classical external shape but is larger in diameter as the exit area of the chimney was increased by 123% compared to the original. A further benefit is that the revised layout distributes the draught more evenly across the boiler tube plate and it is hoped that this will reduce the incidence of tube leakage in service from the upper rows of boiler tubes.

Rebuilding gets underway

During the later half of 2002 work got underway in earnest at Alan Keef's works. Under the supervision of works manager Phil Kent, the frames were lengthened and strengthened at the front and rear to suit the new design. During this period the pony truck and rear bogie were extensively rebuilt to provide adequate movement and side control. The successful 'shoe horning' of the alternator and rotary air compressor onto the rear bogie was particularly difficult with very limited space.

While the boiler was removed from the frames the opportunity was taken to carry out minor remedial work on it. The washout sockets, dome and one longitudinal stay which had curiously been found to be welded in position under compression all receiving attention.

Meanwhile, engineer Alice Keef had been looking at the typical weight distribution of the ZB design and confirmed that it was excessively back heavy. To correct the balance it was decided to fit a heavier front buffer beam and make the smokebox from 40 mm instead of the usual 6-10 mm thick plate. Alice is confident that this is one smokebox which is never going to rust through!

New coupling rods were designed by Alice to clear the lower running boards required by the new Leek and Manifold outline and Phil and his team in the works made these items along with replacement or remedial work on nearly every other item of the motion and valve gear.

As work on the chassis progressed, attention turned to the design and fabrication of the new tanks, bunker and cab. The tanks and bunker were fabricated first and then a wooden mock-up of the cab was prepared to check the sightlines and positions of controls and equipment before finalising the drawings for construction.

The new cab is extremely spacious and is fitted out to a very high standard internally with opening windows, a sunroof, and a wooden lining to the cab roof from which is suspended an instrument binnacle with integral LED spot lights for illumination of gauges. This is definitely the loco for winter nights on Santa trains!

Figure 15. One of the new cylinders in place with the steam pipe connected but without the lagging or end covers. The large rectangular exhaust passageway sweeping back from the front of the valve chest can be clearly seen.

Photo Alan Richardson

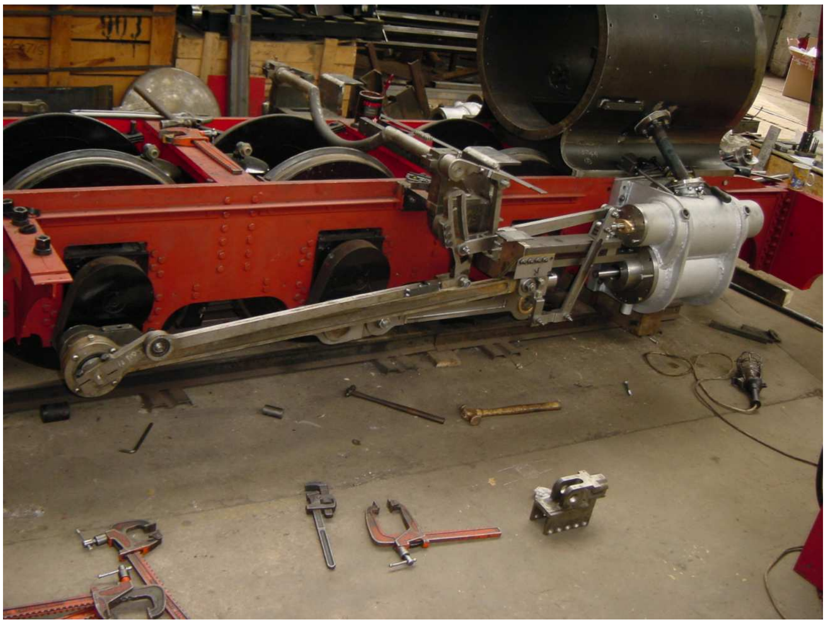


Figure 16. Setting the eccentric rod length during rebuilding of the redesigned valve gear which enabled the valve travel to be increased by 10 mm to 74 mm. The maximum full gear cut off was also reduced to 70% to improve the valve events. Note the thickness of the smokebox which was increased to 40 mm to improve the weight distribution of the locomotive which was rear heavy as originally built.

Photo Alan Richardson

Figure 17. The new cab layout showing the ergonomic positioning of controls which was the subject of favourable comment by the Railway Inspectorate during type approval trials. The use of LED illumination of gauges makes night time operation comfortable for crews and avoids reflected glare and the hassle associated with traditional oil lamps.

Photo Alan Richardson

The works steam test

The day of the first steam test dawned on Wednesday 23rd July 2003 and locomotive owner Alan Richardson and I set off early for Keef's works to witness the big event.

As we swung into the yard we were greeted by the sight of 'Mark Timothy' standing on 30-40 feet of jubilee track outside the erecting shop being swarmed over by boiler suited fitters all intent on adding the final parts before the fire was lit. Seeing the locomotive in its madder lake livery with cream lining was wonderful but climbing into the cab and seeing the comfort and ergonomic layout of the 'flight deck' was really impressive.

Soon a barrow of coal appeared next to the cab and the tell-tale signs of combustion wafted from the chimney. Whilst steam was raised the locomotive was greased and oiled ready to move and anyone who failed to look terribly busy at all times was co-opted to help prime the mechanical lubricator which feeds the cylinders.

Soon it was time to move the locomotive under its own power but with such a short length of track the steam brake was wisely warmed up very thoroughly beforehand. With Patrick Keef ready at the controls the yard rapidly filled with the team to witness the event, which was accomplished with much steam from drain cocks and cautious use of the brakes. Eventually the cylinders were warm enough to allow the drain cocks to be closed and we heard the first few audible beats from the chimney. With Alan on board, camcorder in hand, recording the scene and sounds Patrick then ran the locomotive forward as smartly as he dared followed by a swift brake application. After a large number of runs shuttling up and down, a list of all known minor leaks was made for correction and the safety valves finally set ready for the boiler inspector's visit on the Friday.

The boiler inspector's visit passed without event and with the minor items from the 'to do list' cleared up, the locomotive was duly loaded onto the lorry on Sunday to arrive at Aylsham Monday morning.

Commissioning trials at Aylsham

Monday arrived bright and sunny and when Alan and I arrived at Aylsham, unloading was well under way and 'Mark Timothy' was soon installed over the pit road.

The first task was to set the springs on the locomotive to obtain the correct ride height and weight distribution. Having achieved an adequate preliminary setting, initial running trials were held in the evening in the yard, which boded well for the following two days. There were no signs of hot bearings or other malfunctions and 'Mark Timothy' showed remarkable powers of acceleration even when hauling Nos. 1 and 8 dead as a test load.

Tuesday saw more activity over the pit and after lunch Alan fitted the spark arrestor without too much difficulty even avoiding the liberal dose of soot which is normally compulsory at these ceremonies!

Steam raising began mid afternoon and with myself driving and Patrick firing we were ready to move to train when the 5.15pm arrival pulled into Aylsham. The game plan was to first do a Brampton return, leaving Aylsham cab first to check the ride in reverse, and then set the atomising steam for the cylinder lubrication coming down the bank from Brampton towards Mermaid Bridge, followed by a Wroxham return to check line side clearances, performance and bearings.

With ten carriages and a brake van we set off, cautiously negotiating the tunnel without any nasty scraping noises and then listened delightedly as a light crisp exhaust beat developed at the chimney as we accelerated away from the tunnel in pilot valve with 10% cut-off. The first bit of serious climbing from Mermaid to Brampton was accomplished easily with the locomotive riding unbelievably smoothly. Mermaid was passed at about 16-18mph and with full regulator, 160 psi boiler pressure and 10% cut-off we started the climb. The exhaust beat was staccato and crisp and as the climb continued the cut-off was extended to only 25% by the top of the bank with a 2-3 mph drop in speed. Utterly effortless is the only way to describe it.

Figure 18. 'Mark Timothy' departs Aylsham during the commissioning trials with the author at the controls. The trials were the culmination of the project and were a very exciting three days for the whole team and in particular for locomotive owner, Alan Richardson.

Photo Alan Richardson

The return to Aylsham was uneventful and after running round at Aylsham we carefully coaled up to a known level and with a full tank of water set off back to Wroxham with the same train. During the journey it became clear that the locomotive steamed freely and required surprisingly little fuel to maintain full boiler pressure even with the dampers only moderately open. Wroxham was reached without incident and when we got to the water tower we realised we had only used just over 70 gallons compared to the 100+ gallons of No. 7. Apart from slightly warm coupling rod bearings on the front driving axle all was running smoothly and so the locomotive was given a reasonable amount of power on the climb out of Wroxham. In persistent rain once clear of the points the cut-off was set at 30% with full regulator. Acceleration was rapid and once clear of the trees part way up the bank the cut-off was advanced to 45% resulting in what I estimate to be 20 mph line speed well before reaching the top of the climb. The sound of the exhaust beat is very distinctive with every beat clearly separated and sounding more like a 'chunk' than a 'chuff'. If you have heard a Romney engine in full cry and can imagine that sound from a loco twice the size you've got it.

Figure 19. 'Mark Timothy' arrives at Wroxham with a thirteen coach test train. After running round this was subsequently increased to sixteen coaches plus brake van before making an impressive climb of Wroxham Bank accelerating the train to 20 mph from a standing start on the 1 in 102 gradient.

Photo Alan Richardson

Wednesday was the last day of the trials and there was much preparatory work to be done but at last we were ready. With myself and Patrick as crew we left with a 13 carriage plus brake van test train bound for Wroxham in dry conditions. A couple of photo run by stops were made on route and throughout the locomotive ran impeccably.

After a blow down at Wroxham it was decided to add a further three carriages bringing the total to 16 plus a brake van. With this load, which was an impressive 430 feet long, we commenced a full power climb of Wroxham bank and with a couple of minor slips on rails dampened by the drain cocks we got underway. Once clear of the points, cut-off was advanced to 52% with a wide-open regulator and a boiler pressure of initially 160 psi rising to 170 psi during the climb. The sound of the locomotive accelerating the train was amazing with the beat bouncing back from the cutting wall. Acceleration was rapid and once the rear of the train cleared the trees we were running at 18 mph and shortly after the cut-off could be reduced slightly to hold line speed while still on the bank. This was a real maximum effort attempt and on two occasions momentary disturbance in the beat indicated we were operating right on the adhesion limit of the locomotive. David Lowe who was our guard for the trip summed it up perfectly when he said afterwards "bank, what bank?"

Dave Phillips, the BVR's CME, then took over driving until Buxton and the excellent visibility afforded by the large headlamp and the internal cab lighting came into its own as the light faded. Dave, clearly having enjoyed the experience, said "I'd give it 11 or 12 out of 10". BVR Fitter/Driver, Bob King took her from Buxton to Aylsham and thought "He'd like to have two".

Dynamometer trials

After the commissioning of No. 9 it was felt that there was a lot to be gained by scientific testing of the improved locomotive and, by comparing it with Nos. 7 & 8, to see in detail what we had achieved and what could be improved further.

A group of engineers, John Scott, Julian Stow and Peter Mintoft, who are all volunteers on the Talyllyn Railway and had carried out instrumented trials there, kindly agreed to help us. During the spring of 2004, in two separate test sessions, they successfully recorded a mountain of data for which we are greatly indebted.

Figure 20. Test team Julian Stow, Peter Mintoft and John Scott worked in inhospitable winter conditions to record test data for 'Mark Timothy' and Nos. 7 & 8 and vast amounts of 'gaffer tape' were used to prevent the ingress of damp into sensitive electronic equipment and connectors.

Photo Alan Richardson

On the day of the first test it snowed, obliterating both the landscape and track which made conditions less than ideal for mounting sensitive electronic instrumentation on the locomotives! All the external electrical connectors had to be put in plastic bags and taped up to prevent short circuits and with leads held on by gaffer tape festooned everywhere, we prepared for the first trial. Pressure transducers were connected to the smokebox, to measure the vacuum, and sequentially to both the front and rear cylinder drain cock ports, to measure the cylinder pressure continuously. A linear transducer coupled to the crosshead, simultaneously recorded the cylinder position and a special coupling, containing a strain gauge, enabled us to record drawbar pull.

Figure 21. No. 9, festooned with cables and sensors and more than a little gaffer tape, about to depart from Aylsham during the dynamometer trials.

Photo Alan Richardson

The mass of data produced by these instruments had to be recorded and so the coach adjacent to the locomotive became the temporary dynamometer car for the test engineers with a data logger plus two computers to input run details and view the results. Power for this equipment was supplied by a portable generator further back down the train and the same 26 Tonnes set comprised of eleven carriages plus a generator car and a guards van was used for all the tests. Each locomotive was tested in turn with BVR chairman and driver Andy Barnes on the footplate assisted by Bob King and Patrick Keef acting as firemen. We used the nearest long bank close to Aylsham to provide something for the loco to work against and after accelerating the train down the bank from Burgh summit to a specified speed at the foot of the bank at Mermaid under bridge we then attempted to maintain a constant speed up the 1:110 bank towards Brampton. The locomotives were driven with a wide open regulator and the speed was controlled during the climb by adjusting the cut-off.

During the first series of tests each locomotive made numerous runs at different set speeds. Because we only had one high temperature pressure transducer, readings were taken of cylinder pressure at the front and rear drain cock ports on separate runs which meant that we had to do two trips to gather all the data.

The purpose of the trials was to establish a series of performance parameters which could be used to compare each of the locomotives. The tractive effort measured at the drawbar in kilonewtons (KN) at a measured speed enables the power output to be calculated in drawbar horse power (dhp). The indicator diagrams enable the cylinder efficiency in terms of extracting work from the steam to be compared. The cut-off setting from the diagram shows the amount of expansion of the steam occurring in the cylinder, the lower the % the greater the expansion. The exhaust backpressure is a measure of the negative work being done to force the steam from the cylinders via the valves and through the blast nozzle. The higher the back pressure in pounds per square inch (psi) the more wasted energy. The smokebox vacuum which is expressed in mm of mercury (Hg) determines the amount of draught available to burn the fuel. An efficient exhaust system creates enough draught to burn sufficient fuel for the steam required but does so at the lowest possible back pressure.

Trial results

The first locomotive to be tested was No. 7, the second of the ZB class of locomotives, built in 1994 and subsequently modified by the BVR to include improved valves. With the exhaust sounding as impressive as ever, the locomotive achieved a maximum power of 35.6 dhp at a steady speed of 11.9 mph generating a drawbar pull of 5 KN (1123 lbs) at between 55-60% cut-off. The smokebox vacuum was -11 mm Hg but the average backpressure at the cylinder was a woeful 65 psi, more than 43% of the boiler pressure of 150 psi and clearly one of the reasons for the deafening exhaust roar. The cylinder indicator diagrams show a severe lack of lead steam probably due to port and passageway restrictions which meant that steam had difficulty filling the cylinder adequately at the start of each stroke.

Next up was No. 8, the third member of the ZB class which entered service in 1997 and is mechanically similar to No. 7 though it is styled to resemble a Vale of Rheidol tank locomotive and is oil rather than coal fired. Despite generating insufficient steam to maintain boiler pressure which fell from 165 to 140 psi during the test a peak power output of 40.1 dhp was recorded. This was achieved at 55% cut-off at 13.4 mph generating a drawbar pull of 5 KN (1123 lbs), exactly the same as No.7. However, the average back pressure was lower at 43.5 psi or around 28% of the boiler pressure. This better result is probably due to the slightly larger passageway sizes in the cylinders and this seemed to be confirmed by the indicator diagrams which show an improved but still poor lead steam event. Given the reluctant steaming of this loco it is possibly significant that the smokebox vacuum was lower than No. 7 at -7mm Hg. However, it may be limited by the oil burner output as it is not possible to generate even a hint of grey in the exhaust at maximum evaporation rates which suggests that more fuel could be usefully burnt in the available air.

Figure 22. The first tests with No. 9 showed that the initial estimates for valve spindle thermal expansion were incorrect by approximately 0.5mm resulting in inadequate lead steam at one end of the cylinders and corresponding over compression at the other. This was corrected by resetting the valves during the second series of tests and the author is pictured making adjustments near Brampton.

Photo Alan Richardson

Finally it was the turn of No. 9 and with the significant improvements that had been made to the cylinders, valve gear and draughting we awaited what we hoped to be an interesting result with considerable excitement. With everyone on board we set off down hill accelerating towards test speed with Patrick Keef reporting on a two way radio the boiler pressure, steam chest pressure and cut-off at frequent intervals. At first all was going well and with speed picking up fast we all confidently expected an outstanding performance during the climb from Mermaid. However, as Andy Barnes started lengthening the cut-off the eager faces leaning out of the windows were abruptly treated to a deluge of black rain as the boiler contents suddenly foamed. Andy immediately shut off, opened the drain cocks and tried opening up again gently but once again, as Andy demanded some serious work, the contents foamed violently. Even though we made several runs, we were unable to achieve anything like the maximum power output of the locomotive which was constrained by the maximum evaporation rate that could be achieved without foaming. Unfortunately, with our only blowdown pit at the far end of the line, we had to console ourselves with doing the best we could in the circumstances. Even though we couldn't make a maximum effort the result was an excellent 63.5 dhp while accelerating the train at 14.1 mph with a drawbar pull of 7.5 KN (1685 lbs) at 45% cut-off. The back pressure was significantly lower at 24 psi or 14.8% of the 162 psi boiler pressure and smokebox vacuum was higher at -15 mm Hg.

Examination of the indicator diagrams showed that our estimates for thermal expansion of the valves from cold were incorrect and although the discrepancy was small (less than 1 mm) one end of the cylinder was over compressing to more than twice the boiler pressure and the other end had insufficient lead steam. This demonstrated only too clearly that we needed to reset the valves with transducers coupled to both ends of the cylinders to monitor the effects simultaneously and then carry out a second test. Meanwhile, the blast nozzles on No.9 were increased by approximately 7% in area to their full design value as the draughting had been shown in service to be heavier than needed and the dampers were nearly closed much of the time. The revised nozzles produced adequate draught to ensure free steaming in traffic and will have reduced the backpressure further from the value recorded in the first test.

The second test was undertaken some weeks later to enable the valves to be set accurately from oscilloscope traces of the simultaneous pressure readings of both ends of the cylinders. This enabled accurate valve setting to be achieved and showed clearly the action of the Kordina in lowering the exhaust backpressure on the return stroke. Then came the opportunity for No. 9 to show what it could do and so despite sub-optimal rail conditions, which limited traction, we made an excellent 20 mph climb with only 35% indicated cut-off. We had insufficient data recording equipment available and so we could not use the drawbar with the strain gauge during this test. However assuming that, despite the higher speed, the drawbar pull registered in the first test was not exceeded then No. 9 developed an estimated 90 dhp or more than double the maximum power output when compared with the already improved Nos. 7 & 8, which achieved 35 and 40.1 dhp respectively.

Reading	No.7	No.8	No.9 Test 1	No.9 Test 2
Boiler pressure, bar	10.2	10.5	11.0	-
Cut-off, %	55-60	55	45	35
Average back pressure measured at the cylinder, bar	4.5	3.0	1.65	-
Smokebox vacuum, average mm Hg	-11	-7	-15	-
Steady speed, mph	11.9	13.4	14.1	20.0
Drawbar pull [1], average KN	5.0	5.0	7.5	7.5
Drawbar power [2], KW	26.58	29.9	47.37	67
Drawbar power [2], HP	35.6	40.1	63.5	90

Table 3. A summary of the major test results.

The increase in drawbar horse power of No. 9 compared to Nos. 7 & 8 can be clearly seen in the results from test 2 while the higher smokebox vacuum with reduced total backpressure measured at the cylinder which results from the improved draughting can be seen in the results from test 1.

Notes: [1] For test 2 with No. 9 the drawbar pull was not measured and is conservatively assumed to be the same as for test 1 despite the higher speed. [2] On 1:110 bank.

The valve adjustments were felt by the drivers, subsequent to the test, to have made the locomotive even livelier and from experience we know that there is more power available. In ideal conditions cut-offs as long as 50-55% have been achieved when accelerating with heavy trains of up to 16 carriages in a climb at 20 mph. Although we have as yet been unable to practically check it by testing, our design calculations suggest a probable maximum power output of 113 dhp and we anticipate that if we can repeat the tests with better rail conditions we will be able to show further improvement.

Table 4. Coal used per day for steam raising and 54 miles of running for No. 7 with the original BVR valve improvements and for the rebuilt No. 9. The weight in Kg is based on 11.8 Kg per bucket.

Locomotive	Buckets	Weight in Kg	% reduction
No. 7	27	319	
No. 9	20	236	25.8

Much to everyone's delight fuel economy is also dramatically improved which is reducing operating costs and the physical work load on the crew. Typical consumption for a days operation of 54 miles plus lighting up is 20 buckets of coal or 236 Kg or a 25% saving compared to No. 7.

Figure 23. The rebuilt No. 6 'Blickling Hall' enters service at Aylsham. No. 6 has the same cylinder and valve gear modifications as 'Mark Timothy'. The loco is also fitted with a Lempor exhaust system but retains the original chimney casting which has been extended within the smokebox to incorporate a mixing chamber.

Photo Brian Lowe

No. 9 clocks up 9,000 miles and No. 6 enters service

With the successful trials behind us and type approval from the Railway Inspectorate, No. 9 has now been in revenue earning service for over a year. It has successfully clocked up more than 9,000 miles and Bob King's wish to have two improved ZBs has also come true with No. 6 entering service in February 2005.

One interesting effect of having the extra power available is that for the driver and fireman it changes the nature of the challenge. It is no longer a question of can the trip be completed on time, but instead how little fuel can a skilful crew use in a locomotive which can be driven in a text book manner and does most of the work required of it between 10 - 30% cut-off. Just in case this sounds too restful it has to be said that at times when rail conditions are slippery extra vigilance has to be exercised as loss of adhesion with a loco that can breathe well is a teeth rattling experience if you don't intervene quickly.

From the railway's operating perspective, having two locomotives that can cope with whatever the traffic department throws at them is reassuring, and cutting the fuel bill has made the Chairman, Andy Barnes, smile. However, what will really delight everyone is if the lower fire temperatures that are now required reduce the boiler repair costs and workshop work load. Time will tell but it looks very hopeful.

Figure 24. No. 8 in as built condition at Brampton shortly after assembly at Aylsham from a kit of parts supplied by Winson Engineering Ltd. No. 8 differs from the other locomotives in that it is oil fired and is likely to remain so for the immediate future as a precaution against possible high fire risk periods in the high summer.

Photo Alan Richardson

The potential for further improvement of the ZBs

Locomotive owner Alan Richardson was so fired with enthusiasm by the success of the modifications to No. 9 that he requested a design study from Alan Keef Ltd and myself to assess what improvements could be made from a visual, functional and performance perspective to the other ZB locomotive that he then owned, BVR No. 8.

No. 8, a 2-6-2T, entered service in 1997 and is styled to resemble a Vale of Rheidol tank. However, even at first sight it doesn't look quite right. The original Vale of Rheidol locomotives have a chunky charm and look as though they mean serious business while No. 8 just manages to look slab sided and plain.

Engineer Alice Keef investigated further and after visiting the sheds at Aberystwith and carefully measuring the real thing she prepared drawings of both locomotives and overlaid them. It became apparent that No. 8 was seriously out of proportion being too long, much narrower and a bit short of height. The extra width is definitely outside the loading gauge and would cause the locomotive to seriously overhang the platform edges so this was a definite no go zone. The additional length was also a problem. The boiler couldn't be moved forward as the firebox was already hard up against the rear driving wheels and the cab had already been lengthened by addition of a cranked back plate as engine crew were having to sit 'side saddle' to avoid toasted knees on the boiler backhead. The need for additional height was the one bit of good news. However, to completely avoid the current hunched driving stance, the cab needed to be raised further than was prototypical to the limit of the loading gauge established by No. 9.

Alice came to the conclusion that in any event the existing tanks and cabs would require replacement but, because of the constraints imposed by the BVR loading gauge, the non-scale engine crew and the current boiler and frames, it could never be made to be a good likeness. Alan was consulted about this dilemma and it was decided that the best way forward was to adopt the design philosophy of allowing form to follow function. In this way we could resolve the functional and performance issues and then consider how to make the locomotive visually attractive. As a Design Engineer I prefer this approach as otherwise the need to create a copy of a particular locomotive or type can add an additional set of constraints which may hamper achievement of the best technical outcome.

The ZB chassis and boiler arrangement is known to be rear end heavy and with the large overhang created by the firebox which is situated behind the rear drivers we knew that the weight distribution would require correction by addition of ballast at the front of the locomotive. The ride qualities of No. 8 were acceptable when running forward, which is almost always the case, but the ride in reverse was less comfortable and this was seen as an opportunity for improvement. Modification of the springing to include compensation and improvement of side control would not only improve the ride in both directions but also adhesion as the locomotive would be able to maintain traction better even on slightly uneven track. We knew from the experience with No. 9 that the additional power available meant that sanding gear was really essential and therefore it was decided to include air sanding gear for forward running.

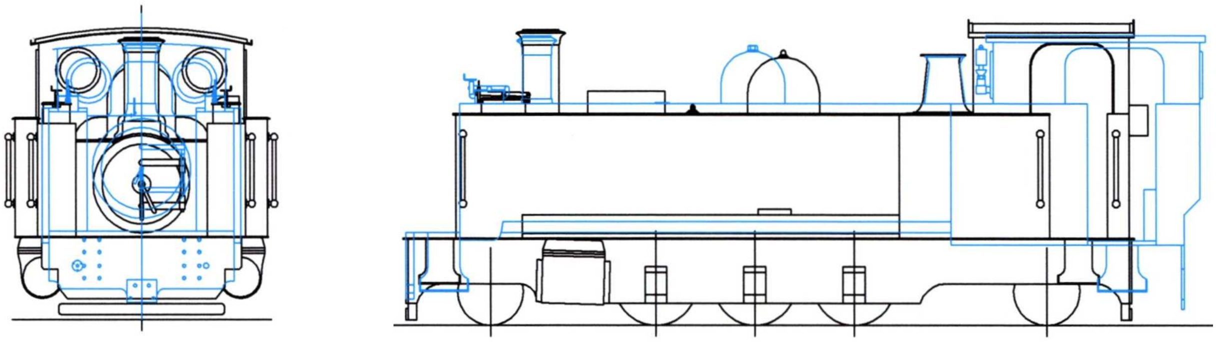


Figure 25. Front and side views of a Vale of Rheidol tank locomotive with the outline of No. 8 overlaid in blue. Alice Keef's drawing clearly shows the extent to which No. 8 diverges from the prototype in all three dimensions.
Drawing Alan Keef Ltd

The locomotive was constructed with oil firing because it was thought useful to have a locomotive available which would not present a fire hazard in the high summer. Originally it was supplied with a weir burner which creates a fan jet film of oil closely parallel to a similar thin but broad jet of steam which then entrains and atomises the oil. The burner was never satisfactory and after many sleeper fires with unburnt fuel flooding from the firepan the BVR developed its own design with technology similar to that used for industrial paint spray systems. In this arrangement the oil is atomised by steam as it passes through four identical nozzles which each incorporate swirl chambers. These create rotating hollow conical jets of oil which atomise as the film spreads and thins and are finally ruptured into a mass of tiny droplets. This system has proved excellent in service but is probably limiting the maximum power output of the locomotive as when it is climbing hard it tends to loose pressure and can become winded even with all four burners at maximum. In this situation the combustion is still very clean without a hint of grey and this suggests that it is running lean. Like all steam atomised systems, when the burners are at a high setting, the system generates a large quantity of very low frequency sound in the form of a continuous rumble. This has proved fatiguing for crew and can also detract from the passengers' experience in the first few coaches if sound is reflected back into the train in cuttings.

For these reasons a change in the current firing arrangements was considered desirable to make the locomotive capable of dual fuel operation, with the options of either conventional coal firing or oil firing using a surface combustion vapourising burner. Such a burner would have a firebed of refractory 'coals' supported on a system of vapourising tubes. The gas oil is vapourised within the tubes utilising heat absorbed from the hot refractory. The refractory acts as a catalyst at high temperatures and is heated to incandescence by the combustion of the gas oil vapour on its surface. The burner could be easily installed in the same position as firebars with an oil tank provided in the bunker space. Such an arrangement would offer an oil firing system which would be kind to the boiler, by mimicking the slower thermal response characteristics of a coal fire with high radiant heat output, and provide quiet clean combustion which would be ideal for one man operation. Change over between firing methods could be made in just a few hours and would offer flexibility to use whichever fuel suited the operating or commercial situation.

Reduction of the maintenance burden and daily crew workload was considered important. Measures to achieve this would include the fitting of roller bearings in those motion items with plain bearings, such as coupling rods and little ends, and improving horn guide lubrication to reduce wear.

No. 8 has never been a very comfortable or ergonomic environment for the engine crew. It is hot, cramped, noisy and control positioning is sub-optimal.

In addition it has a number of irritating quirks that can drive you crazy like the non-existent reverser scale, the lack of locker space and the rain water blowing off the top of the side tanks into the your lap!

Putting thought into cab layout and design really pays off and No. 8 would need some serious design input to bring it up to standard. No. 9 shows the way forward and is a tribute to Alice's design skills, in fact when the Railway Inspector rode with me as part of the type approval process he commented on the excellent control layout which minimised unnecessary movement and the superb visibility.

Last, but not least, was the need to improve power output and reduce fuel and water consumption. The first step needed would be to change the cylinders and draughting as we had done for No. 9 but the cylinder diameter would be reduced slightly to maintain the tractive effort of 12.7 KN (2855 lbs) with a small increase in boiler pressure. However, given the potential scale of the rebuild we also investigated additional improvements. Moderate superheating was a logical next step and modelling of the boiler showed that a five flue superheater could provide a modest average superheat of 88° C over the operating range. Ideally it would have been good to increase this further but the restricted firebox tubeplate area available for the tube bundle prevented this. While working so extensively on the boiler the opportunity to raise the boiler pressure from 180 psi to 200 psi seemed worthwhile, offering a slight increase in efficiency for little effort except paperwork with the insurers. Similarly, doubling the thickness of the boiler insulation to 50 mm and changing from fibreglass to ceramic material would cost very little but save fuel every hour the locomotive was in steam.

Item Description	No. 9	No. 8
Grate area, m²	0.37	0.37
Firebox heating surface, m²	2.105	2.105
Tube/flue heating surface, m²	13.064	9.15
Superheater heating surface, m²	N/A	3.45
Average superheat, °C	N/A	88
Boiler tube bundle mean gas free area [1], m²	0.039	0.045
Working pressure, bar (psi)	12.41 (180)	13.79 (200)

Table 5. Comparison of the new boiler for No. 8 with the ZB original as used on No. 9.

It was proposed to improve the thermal efficiency of No. 8 by a small increase in boiler pressure coupled with moderate superheat as part of a complete redesign package.

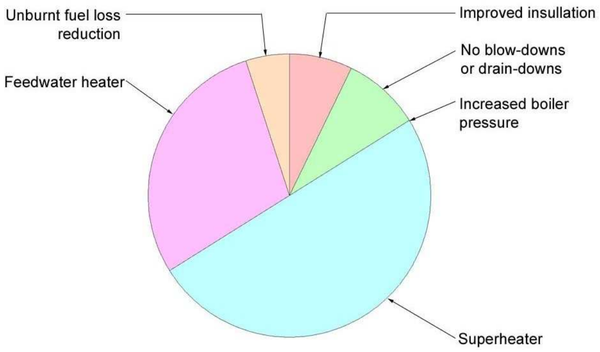
Note: [1] This is an estimated figure for No. 8.

Feedwater heating was also investigated. If the locomotive had been working continuously with an injector on, a straightforward option would have been to consider an exhaust steam injector. However, the switchback nature of the line means that to smooth out the demand on the boiler, most feedwater is fed when coasting down hill and so for simplicity an 'open' type feedwater heater with a hot well accumulation arrangement was considered the best option. With this system a gradually increasing reservoir of up to 16 gallons of water would be heated to 90° C while climbing. The heat required would be provided by condensing 14% of the exhaust steam from the cylinders in cold water drawn from the tanks. The resultant hot water could then be fed by an electric pump to the boiler under the control of the driver.

Use of the Porta Treatment system for boiler feedwater, which enables the locomotive to operate without blowdowns and very infrequent boiler washouts, was considered in detail. This process creates large quantities of suspended solids in the boiler water as a direct result of preventing scale formation. Normally this would result in foaming of the boiler water which could damage the cylinders and so the chemical treatment also includes powerful antifoaming agents to prevent water carry over. This treatment regime makes savings through extending boiler and tube life, reduces labour associated with washouts and reduces the heat losses caused by water discharge from the boiler.

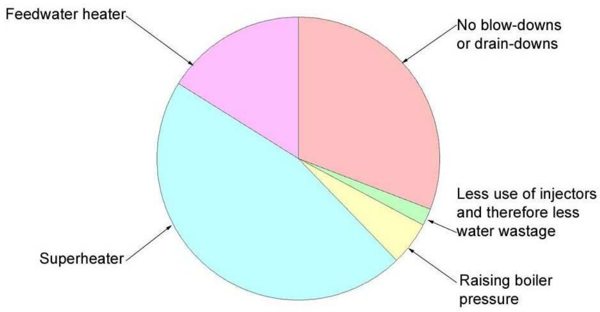
Compared to No. 9 this combination of improvements would produce further energy savings of 25% which equates to 60 Kg of coal or 46 litres (10 gallons) of gas oil and a reduction in water consumption of 46% or 922 Kg (203 gallons), broken down as shown in the charts.

Figure 26. Energy savings No. 8 compared to No. 9. Total energy saving 25%.



Considering the 25% energy savings first, the big win is the provision of a superheater which saves 12.3% and graphically demonstrates what we all know, that this is a must have item. The next largest contribution is from the feedwater heater at 7.2%. All the other items are relatively small. Avoidance of blowdowns or drain downs saves 2.2%, improved insulation a further 1.8%, the reduction in unburnt fuel losses from reducing the carry over of fuel particles in the draught on the fire saves 1.3% and the saving from raising the boiler pressure is just 0.06%.

Figure 27. Water savings No. 8 compared to No. 9. Total saving 46%.



The possible water savings of 46% are large and once again the superheater contributes most at 21.3%, followed by avoidance of blowdowns by using the Porta Treatment at 14.3% and the feedwater heater at 7.5%. There are small savings from raising the boiler pressure of 2.4% and reduced use of the injectors and therefore water wastage of 0.9%.

The study made it clear that to bring the locomotive up to the same standard as No. 9 would require very extensive rebuilding and that to improve the thermal efficiency further would at least involve adding superheating to a boiler not ideally suited for this purpose. The limited area at the firebox tubeplate available for the tube bundle including the superheater flues, would restrict the potential superheat temperature but still necessitate complete replacement of both the firebox and smokebox tubeplates. This really represents an over development of the original design and the old adage 'if you want to go there, don't start from here' summed up the situation.

The problems with the further development of No. 8 were discussed in detail with locomotive owner Alan Richardson. He felt that a more satisfactory approach would be to leave No. 8 as a working locomotive and to produce a new design tailored to the current and future operating needs of the BVR. He therefore ask Alan Keef Ltd and I to carry out a design study for the new locomotive and this is described below.

Figure 28. Proposed BVR No. 2, 2-8-0T 'Abigail', reproduced from the painting by Jonathan Clay. The locomotive is coal fired with moderate superheat and designed to deliver up to 140 drawbar horsepower. Intended to be capable of rapid acceleration of heavy trains not only in the high summer period but also in the adverse rail conditions which accompany winter 'Santa Specials' the locomotive is ideally suited to the future needs of the Bure Valley Railway.

The new design takes shape

Taking the performance of No. 9 as a baseline for reference, the philosophy behind this new design is to provide improvements in the operating characteristics to meet the BVR's current and future needs at the lowest total cost of ownership.

A number of areas were specifically targeted as priorities. Firstly, we wanted to provide a small increase in available power to facilitate the handling of heavy trains or the recovery of lost time by quick acceleration and also to increase the adhesion so that the extra power could be usefully applied to the rail. In conjunction with this we also wanted to improve the thermal efficiency and reduce operating costs by further reductions in fuel and water consumption in service. Secondly, the tasks of locomotive preparation, operation and disposal could be reduced by making items such as inspection, lubrication and cleaning as straightforward and easy as possible for the engine crew. Similarly availability could be increased and costs reduced by making routine maintenance and servicing as convenient as possible for the engineering staff and by using proprietary or stock items for consumable parts wherever possible. Lastly, we designed for ease of manufacture, to minimise the initial cost of construction, but without compromising the required operating characteristics.

A tank locomotive type was chosen as it is ideal for short haul work. There is sufficient space on the locomotive to carry the required fuel and water and these contribute to the available adhesive weight and avoidance of a tender maximises the power to weight ratio. For example No. 9, which is a tank locomotive, has a power to weight ratio of 11.3 drawbar hp/tonne but No. 6 which is identical, apart from having a tender, has a power to weight ratio of 9.41 drawbar hp/tonne. The new design will achieve a still higher power to weight ratio of 13.3 drawbar hp/tonne. Additionally, the capital cost of the locomotive is minimised as there is no tender to build and maintenance costs and overall availability are improved as there is less to maintain.

The 2-8-0 wheel arrangement was selected to enable a fourth driving axle to be used. This means that the maximum axle load of No. 9 is not exceeded, which will be kind to the track, while the adhesion factor in full operating condition is still improved from 4.1 for No. 9 to 5.8 despite an increase in power. Additionally, the absence of trailing non-coupled wheels avoids the transfer of weight from the driving wheels that occurs when pulling hard thus ensuring that the locomotive is less likely to slip. Lastly, the longer wheelbase compared to the overall length of the locomotive will give good longitudinal stability in the transverse plane which will be kind to the permanent way.

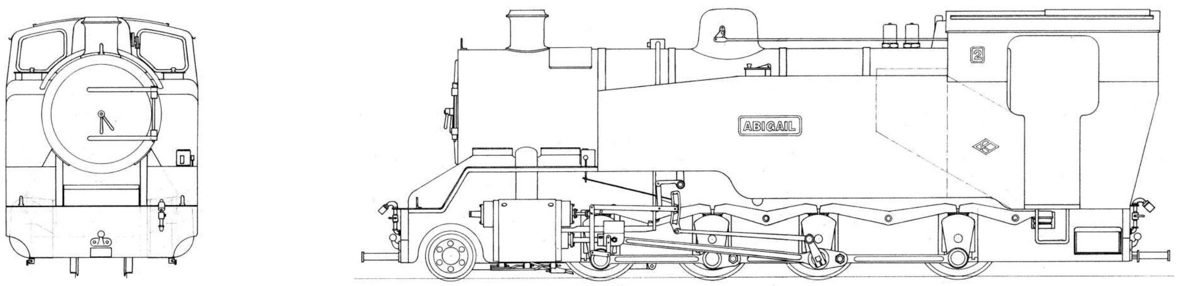


Figure 29. Side and end elevations of the proposed new locomotive. The tank locomotive type is ideal for short haul work, giving the maximum adhesive weight and maximising the power to weight ratio. The 2-8-0 wheel arrangement means that the maximum axle load is no greater than for No. 9 but the adhesion factor is improved from 4.1 to 5.8 despite the greater power of the new loco.

Drawing Steam Loco Design

Despite the stalwart efforts of the BVR permanent way department, the selection of round shingle rather than crushed granite as ballast by the original builders of the line makes it difficult to maintain alignment and levels. Sleepers sitting on 'ball bearing ballast' soon move with temperature changes and the passage of trains and therefore the design will feature fully compensated suspension to improve adhesion of the locomotive on areas of uneven track. Elastomeric springs made from moulded rubber will be utilised throughout to avoid the possibility of fatigue failures associated with the use of more vulnerable leaf springs and elastomeric bump stops will also be used to control the maximum travel of axleboxes. As an additional aid to stability and improved ride the leading pony truck is also coupled to the compensated suspension. In this arrangement, not only does the truck self-centre using roller followers acting on inclined planes, but as the axle is displaced laterally the locomotive will lean slightly into a bend.

Air operated sanding gear will be provided with the dry sand being stored in a box formed as part of the frames in the area of the apron plate. This position should ensure that, providing any spills are swept off, none should blow or fall into the motion. The sand will be applied ahead of the leading driving axle and provision will be made to ensure the sanders can be easily unblocked by the engine crew if the sand becomes damp.

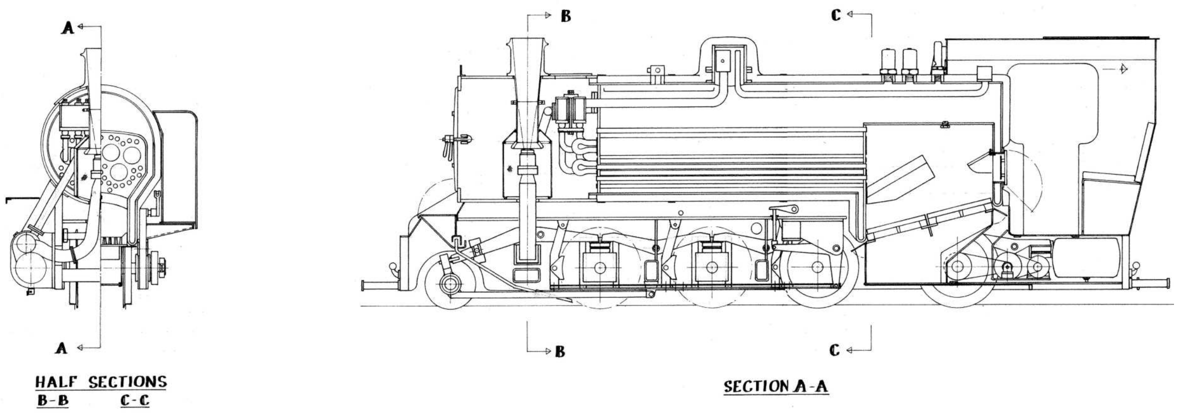


Figure 30. Sectional views of the proposed new locomotive showing the superheated boiler with Lempor exhaust system and stainless steel firebox arch and deflector plate. The fully compensated suspension with elastomeric springs can also be clearly seen.

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The boiler design will differ from the ZB arrangement in that the barrel will be 200 mm larger in diameter at 800mm and have a six flue superheater. Although the grate area will be the same at 0.37 sqm the firebox is of a narrow design with a sloping grate over the rear driving wheels. This will ensure that the boiler is well supported and the overhang at the rear of the engine is minimised giving good weight distribution and reducing the tendency to yaw laterally where rail joint alignment is poor.

The firebox arch will be made in two parts from stainless steel as it can be thinner than a cast refractory arch and this will provide additional height for coal on the grate at the front of the firebox. A stainless steel deflector plate and horizontally hinged mild steel fire door will optimise the admission of secondary air to aid good combustion. The locomotive will have a single chimney and a four nozzle Lempor exhaust system, similar to that used on No. 9, to keep exhaust back pressure to a minimum.

Item Description	No. 9	No. 2
Grate area, m^2	0.37	0.37
Firebox heating surface, m^2	2.105	2.7
Tube/flue heating surface, m^2	13.064	12.05
Superheater heating surface, m^2	N/A	4.24
Average superheat, °C	N/A	100
Boiler tube bundle mean gas free area, m^2	0.039	0.060
Working pressure, bar (psi)	12.41(180)	13.79 (200)
Area of transfer port in valve liner, cm^2	36	51.6
Lead steam, mm	2	2.5
Wheel arrangement	2-6-4T	2-8-0T
Driving wheel diameter, mm	610	550
Theoretical max. tractive effort on starting, KN (lbs)	12.7 (2855)	15.7 (3519)
Adhesion factor [1]	4.1	5.8
Service speed max, Km/hr (mph)	32.2 (20)	32.2 (20)
Max. est. indicated power [2], KW (hp)	99.2 (133)	122.3 (164)
Max. est. drawbar power [2], KW (hp)	84.3 (113)	104.4 (140)
Estimated max adhesive weight, Tonnes	5.4	9.3
Estimated total weight inc Fuel and water, Tonnes	10.0	10.5
Water capacity, litres	1710	950
Coal capacity, Kg	400	141
Rigid wheelbase max, mm	1524	2600

Table 6. Key parameters for the proposed 2-8-0T, BVR No. 2 compared with those for BVR No. 9. Only those cylinder dimensions which differ are included, the remainder can be found in Table 1 (page 6).

When comparing the proposed design of No. 2 with No. 9 the key points of interest are the modest weight increase of only 0.5 tonne coupled with large increases in power output, maximum tractive effort and adhesion factor which will ensure the locomotive will deliver significant performance benefits in traffic.

Notes: [1] Fully loaded with coal and water. [2] On level track at 32.2 Km/hr (20 mph).

Coal firing was chosen for reasons of lower capital and operating cost and with the reduced tendency to create sparks demonstrated by No. 9 it was felt unnecessary to consider oil firing. The coal bunker is integral with the rear of the water tank on the fireman's side, with a shovel plate at footplate level. The top of the bunker has a sealed lid to prevent dust being blown into the cab due to air flow through the fuel when running forward and the total coal capacity is approximately 140 Kg. Despite the slightly asymmetric transverse loading which occurs with this arrangement this was preferable to the overhung weight at the rear of the engine which occurs with a bunker of the type fitted to No. 9.

The high running plate was chosen to make access to the motion easy for maintenance and operating purposes. Optionally a rocking grate and hopper bottomed smokebox could be included to make preparation and disposal less labour intensive. All the motion and axlebox bearings are to be roller bearings as this not only makes lubrication a simple once a day activity but also reduces the internal resistance of the locomotive.

All rotating masses of the motion will be fully counterbalanced and reciprocating masses will be partially counterbalanced to approximately 33% of their mass to minimise longitudinal oscillations at the drawbar which currently can be a problem with the ZBs.

Thermal efficiency and power output will be increased by the use of thicker ceramic boiler insulation, moderate superheating to an average of 100° C over the operating range, a small increase in boiler pressure to 200 psi and a slight reduction in driving wheel diameter from 610 mm to 550 mm to increase piston speed.

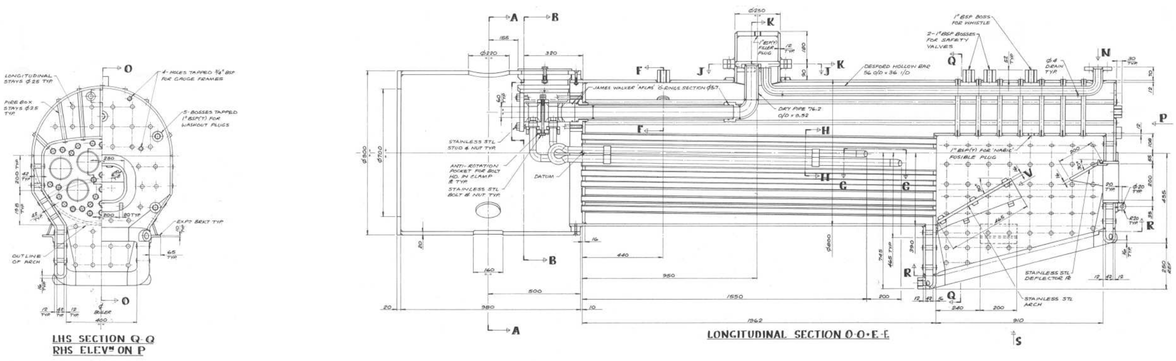

Figure 31. Sectional views of the boiler for the proposed new locomotive showing the narrow sloping grate arranged to fit over the rear driving wheels. The drawing also shows the forged foundation ring and firebox corners, included to eliminate stress cracking in service, and the six element twin pass superheater.

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The cylinders will be the proven design used on No. 9 with some small detail design changes to accommodate the increased power and superheating. The transfer ports in the valve liners will be lengthened to increase the area to allow for additional power output when using long cut-offs at maximum line speed and there will be a small increase in the lead steam to help cylinder filling at the slightly higher maximum revs required by the smaller driving wheels.

Our estimates indicate that the power output will be increased by approximately 24% compared with No. 9 for an equivalent quantity of fuel consumed and that the maximum drawbar horsepower available will be around 140 hp at 20 mph which should make for some exciting traction! Alternatively, if the power output is controlled in service to match that typically provided by No. 9, savings of approximately 20.4% in fuel and 23.5% in water will be made.

Computer modelling has been used to assess the key parameters and design layout drawings of both the locomotive and boiler have been prepared to ensure that reality will reflect our theories! The resulting design is a visually attractive modern locomotive, readily appreciated from the wonderful painting by transport artist, Jonathan Clay, prepared from the engineering drawings and reproduced above.

The design study has shown that this project for an attractive high performance 15" gauge locomotive is feasible and we are looking forward to the realisation of the proposal in the future.

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