The Development of the Bure Valley Railway ZB Class

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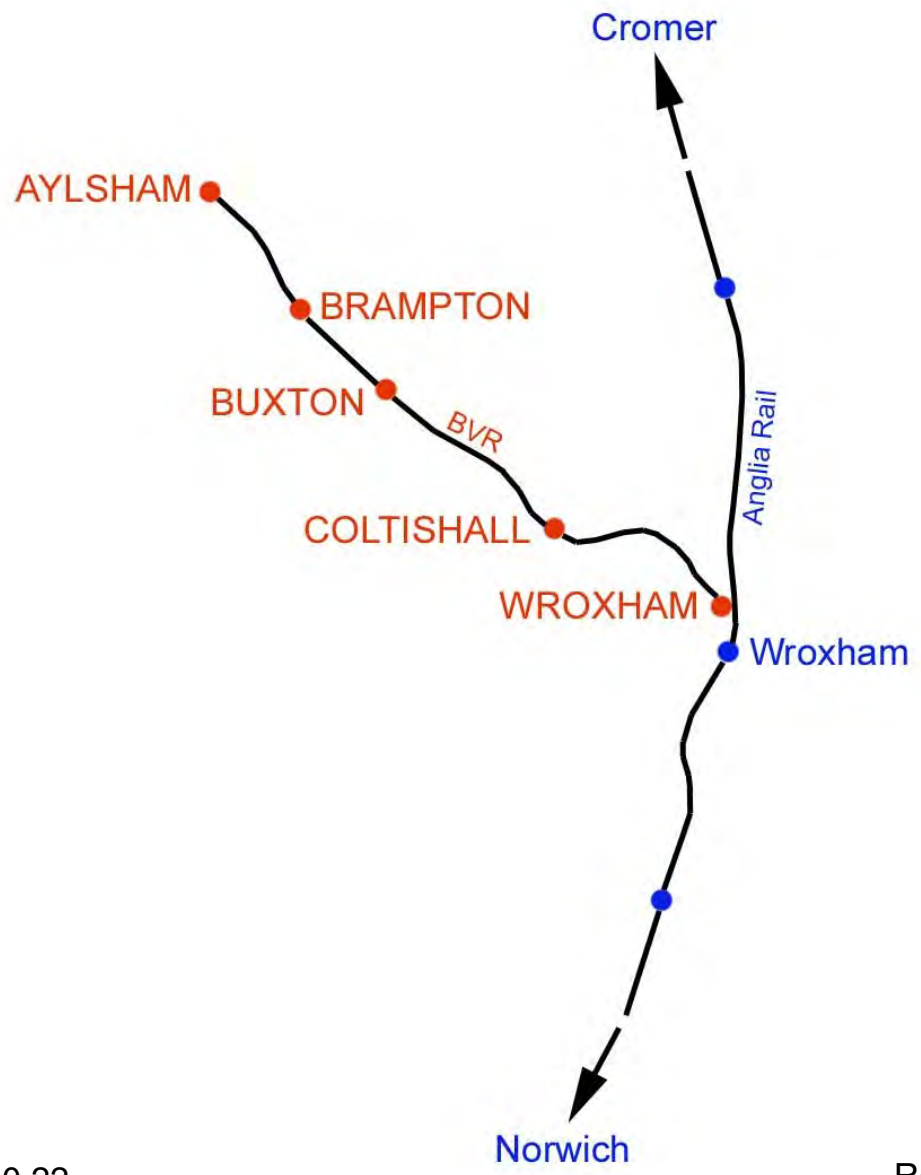
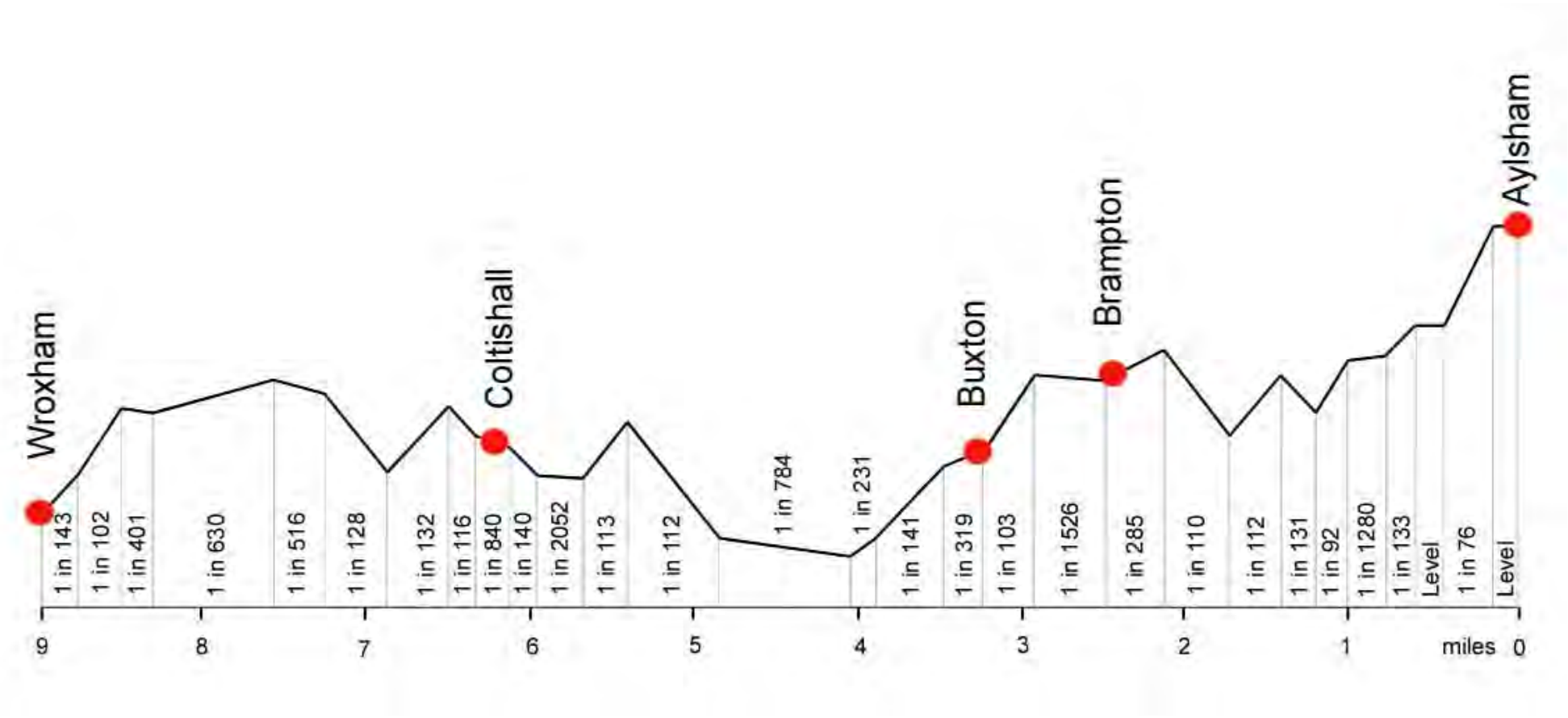
Rev.1
Date 4.10.22.

A brief history and route of the Bure Valley Railway



- Originally the Aylsham extension of the East Norfolk Railway line laid in 1880
- 9 miles long
- Passenger services ceased in 1952, goods traffic in 1981 and the track was lifted in 1984
- Broadland district council purchased the line and decided to divide the trackbed into a footpath and narrow gauge railway
- The 15” gauge line reopened in 1990 at a cost of £2.5m
- The railway had a turbulent commercial start but has enjoyed stability and growth under the current management since 2001
- 130,000 + passengers per year

Gradient Profile



More haulage capacity was required as the line grows in popularity

RH&DR No.9 Winston Churchill

Sian

No.24 Sandy River and Rangeley Lakes R.R

- The BVR was constructed to enable trains of up to 12 coaches with a capacity of 240 passengers to operate
- For financial reasons when the line initially opened motive power was hired in from the RH&DR
- Initially this worked well but as passenger numbers rose the 8 coach haulage limit of the RH&DR locos and the additional motive power available to the Railway became an issue from a commercial perspective
- Something bigger was required and Winson Engineering designed and supplied two approximately half scale locomotives based on the Indian 2’-6” gauge ZB

The inspiration for the Winson Engineering ZB

Western Railway of India: Class ZB no 69

- The 2’-6” gauge ZB class were built to Indian Railway standards with a 2-6-2 wheel arrangement and a 6- ton axle load
- They were supplied by a variety of overseas manufacturers including Bagnall, Corpet Louvet, Duro Dakovic, Krauss Maffei and Hanomag and several examples from the 1950s are preserved
- Initially as supplied the Bure Valley ZBs Nos 6 and 7 featured cow catchers, bases for flag mounting on the apron plates, shutters on the cab openings and a tender half cab. However they were rapidly anglicised by the removal of these features to the form with which we are now familiar.

The first two ZBs arrive from Winson Engineering in 1994

No.6 Blickling Hall

No.7 Spitfire

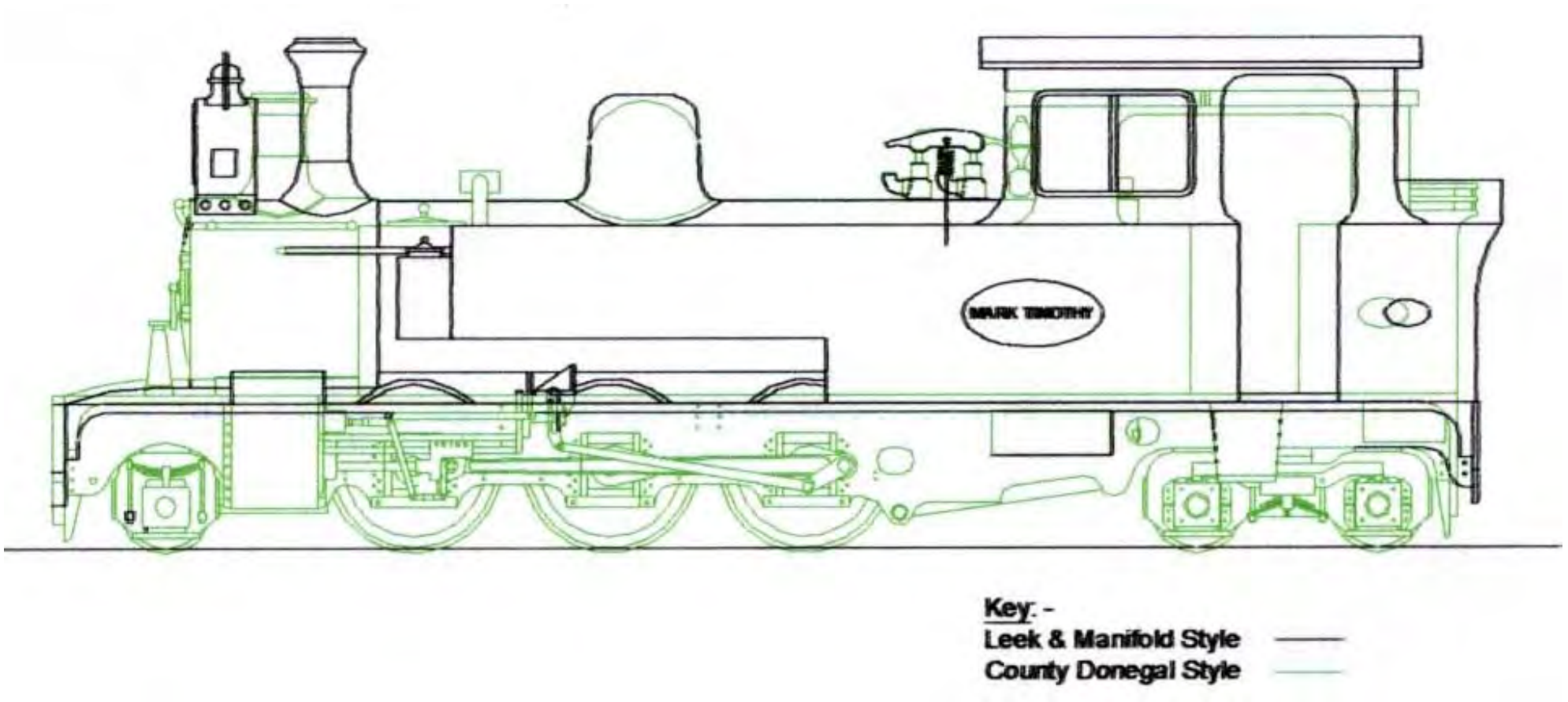
Technical specification as built	
Item Description	**No.6 and 7**
Boiler	
Grate Area	0.37 sqm (4.0 sqft)
Firebox Heating Surface	2.105 sqm
Tube Heating Surface	13.064 sqm
Boiler Tube Bundle Mean Gas Free Area	0.039 sqm
Working Pressure	12.41 bar 180 psi
2 x Piston Valve Cylinders	
Bore	176mm, 6.93”
Stroke	280mm, 11”
Valve Diameter	88 mm, 3.47”
Wheel Arrangement	2-6-2
Driving Wheel Diameter	610 mm, 24”
Power and speed	
Theoretical Max. Tractive Effort on Starting	13.6KN, 3054 lbs
Adhesion Factor fully loaded with coal and water	3.7
Service Speed Max.	32.2 Km/hr, 20 mph
Weights	
Estimated Total Weight inc Fuel and water	13.0 Tonnes
Water Capacity	2029 litres
Coal Capacity	400Kg
Wheelbase	
Rigid wheelbase max.	1524 mm

The broad evolution of the ZB Class

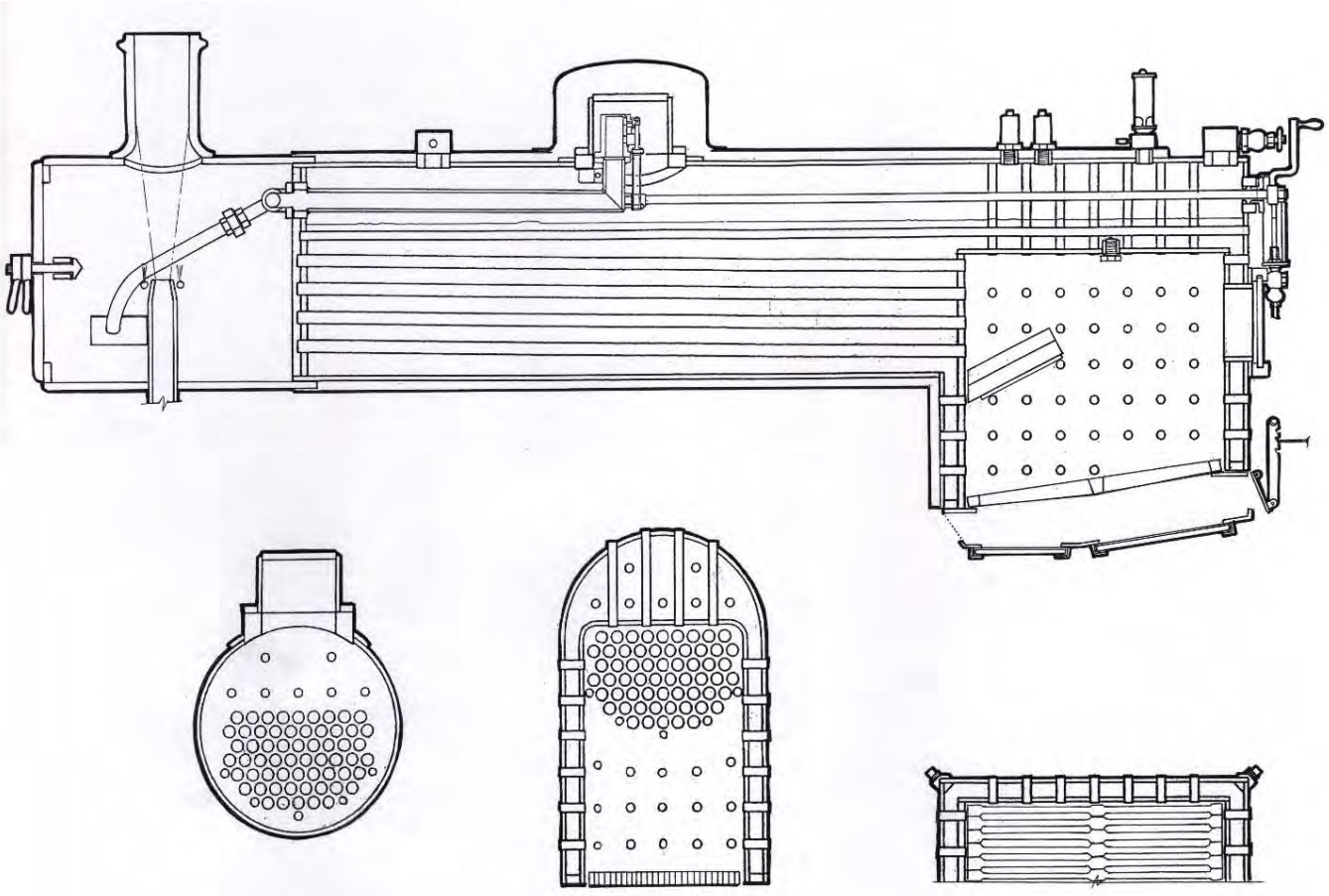
Locomotive appearance as built	BVR Loco No.	Date Built	Fuel as built	Rebuild details	Current fuel	As built buckets of coal/3 trip day	New solid valve head buckets of coal/3 trip day	As rebuilt buckets of coal/3 trip day	Locomotive appearance as rebuilt
	6	1994	Coal	BVR New valve head BVR/Keef Lempor exhaust Valve gear upgrade New cylinders	Coal	37	27	20	
	7	1994	Coal	BVR New valve head Lempor exhaust Valve gear upgrade Modified original cylinders	Coal	37	27	20	
	8	1997	Oil	BVR New valve head Revised oil firing Conversion to coal firing Lempor exhaust Valve gear upgrade Modified original cylinders	Coal	N/A	N/A	20	
	9	1999	Oil	Keef Conversion to coal firing Lempor exhaust Valve gear upgrade New cylinders Re-model locomotive	Coal	N/A	N/A	20	

No.9 ‘Mark Timothy’ as built under test at the Perrygrove railway

The Leek and Manifold outline enables the cab size to be increased

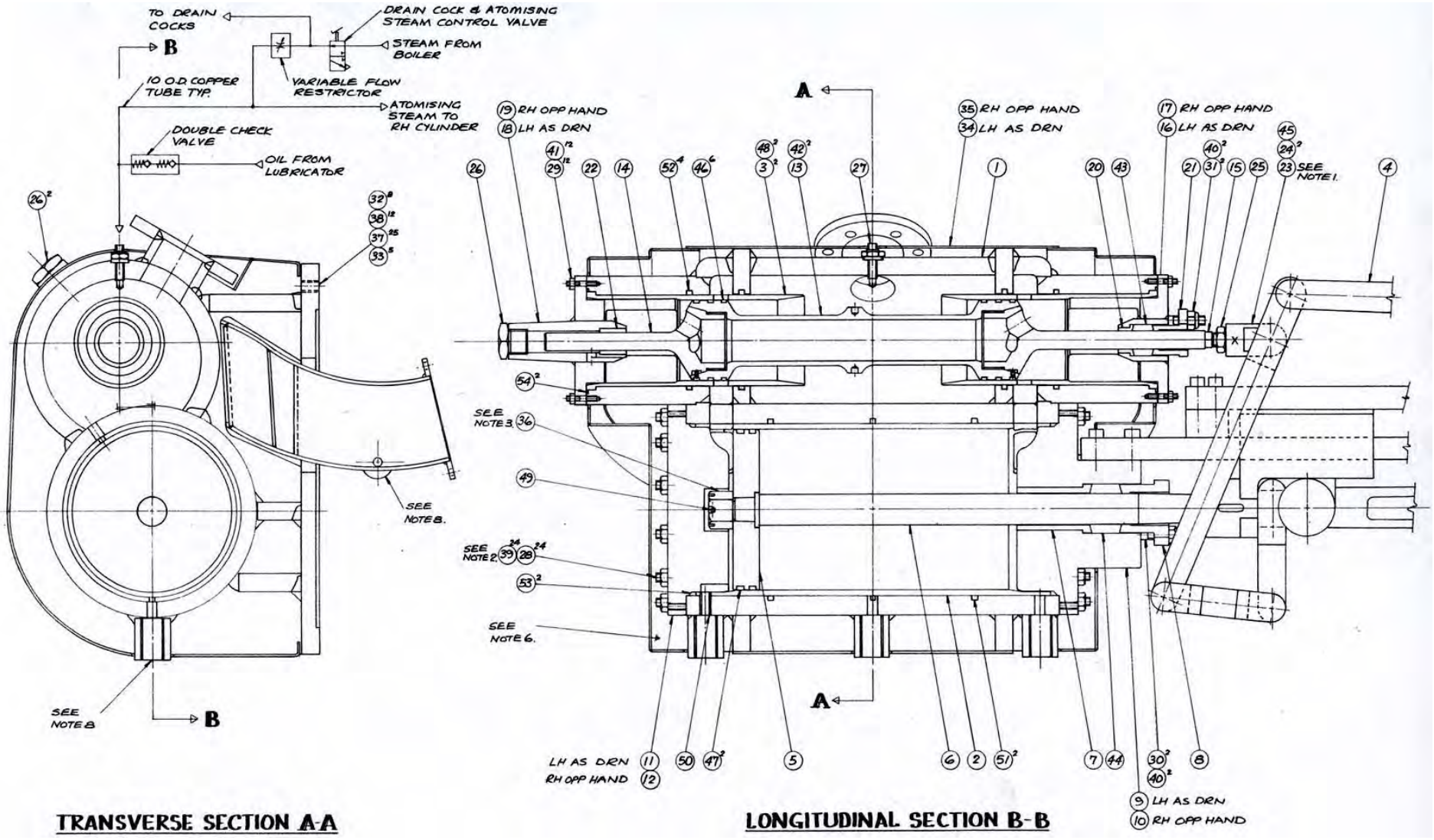


Sketch of ZB boiler as built

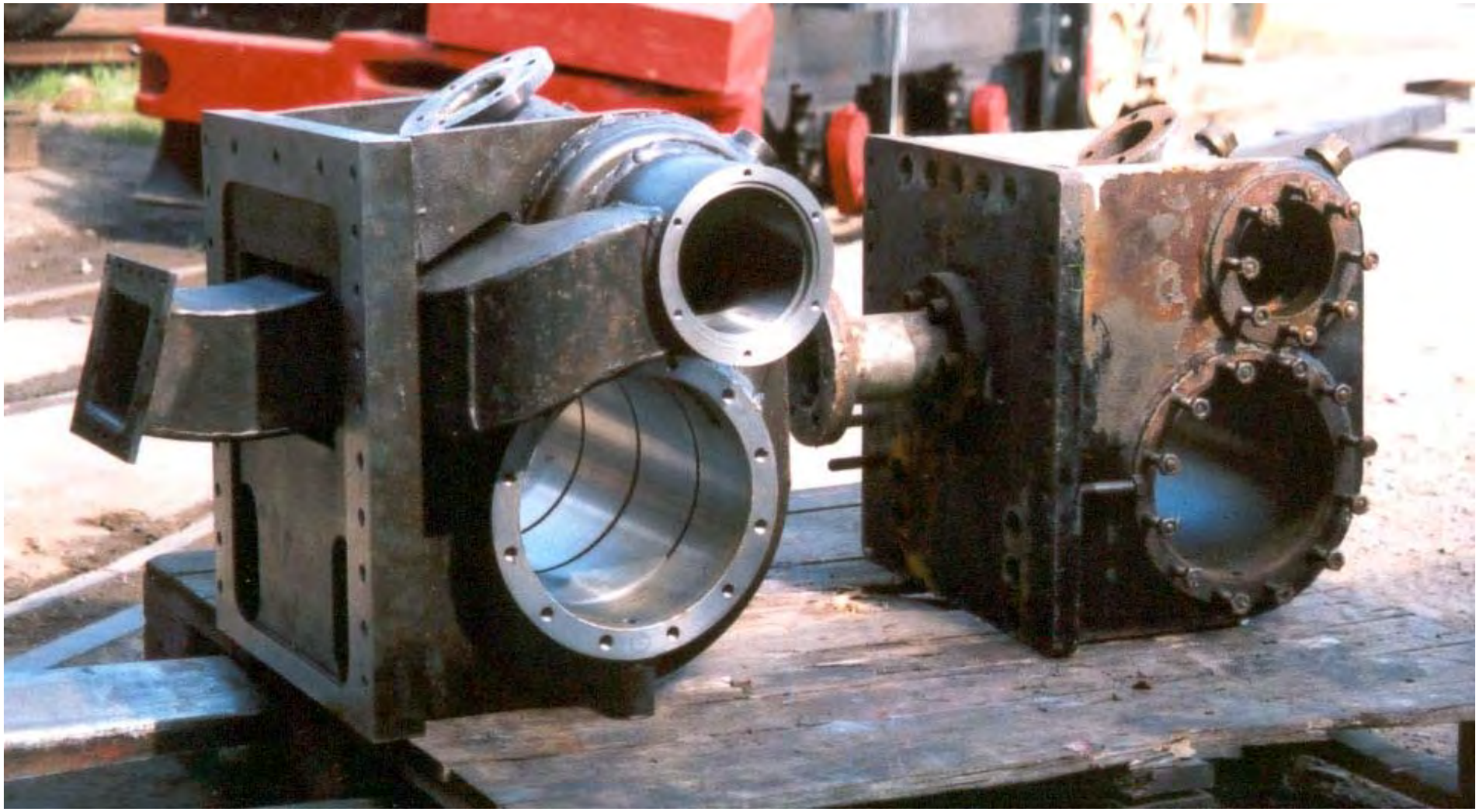


- The ZB boiler has proved to be very free steaming
- Some early problems were experienced with the firebox and in particular the tubeplate due to high evaporation rates and poor water quality.
- To overcome this the throat plate thickness was reduced from 20mm to 13mm to make it more flexible
- As a result of their early life the boilers of Nos. 6 & 7 have been replaced whilst that of No.9 remains in good condition

The new cylinder design takes shape



Comparison of new and original cylinders



The size of the passageways on the new cylinders is apparent

Split valve liner and hollow bronze valve head with stainless steel valve rod

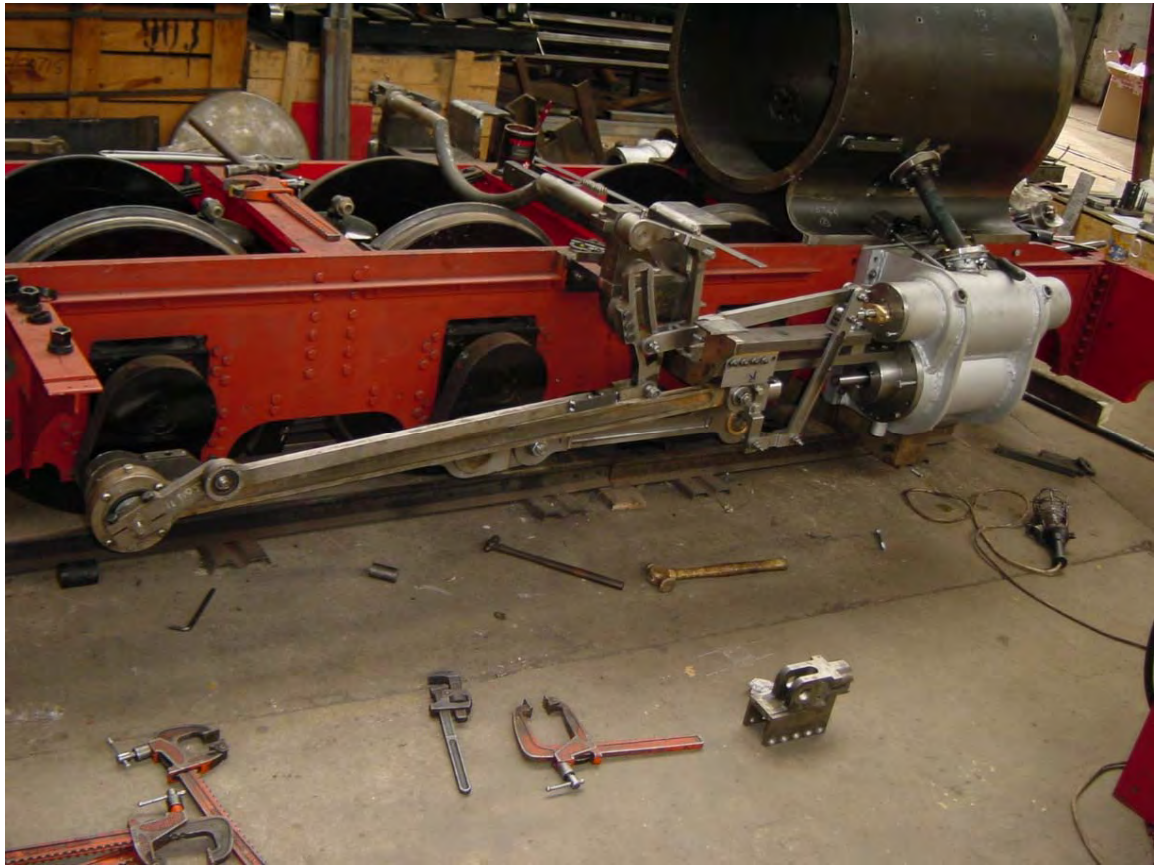
Comparison of cylinders of No.6 as initially modified and No.9 as rebuilt

Item Description	No. 6	No. 9
Bore, mm	176	176
Stroke, mm	280	280
Steam chest inlet passageway area 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%

Comparison of cylinders of No.6 as initially modified and No.9 as rebuilt

Item Description	No. 6	No. 9
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, cm^2	28.3	77.99
Min. area of exhaust passageway in cylinder, cm^2	45.37	99.36
Clearance volume, cm^3	-	752.7
As a % of swept volume of cylinder	-	11.04
Maximum expansion ratio @ 15% cutoff	-	4.26

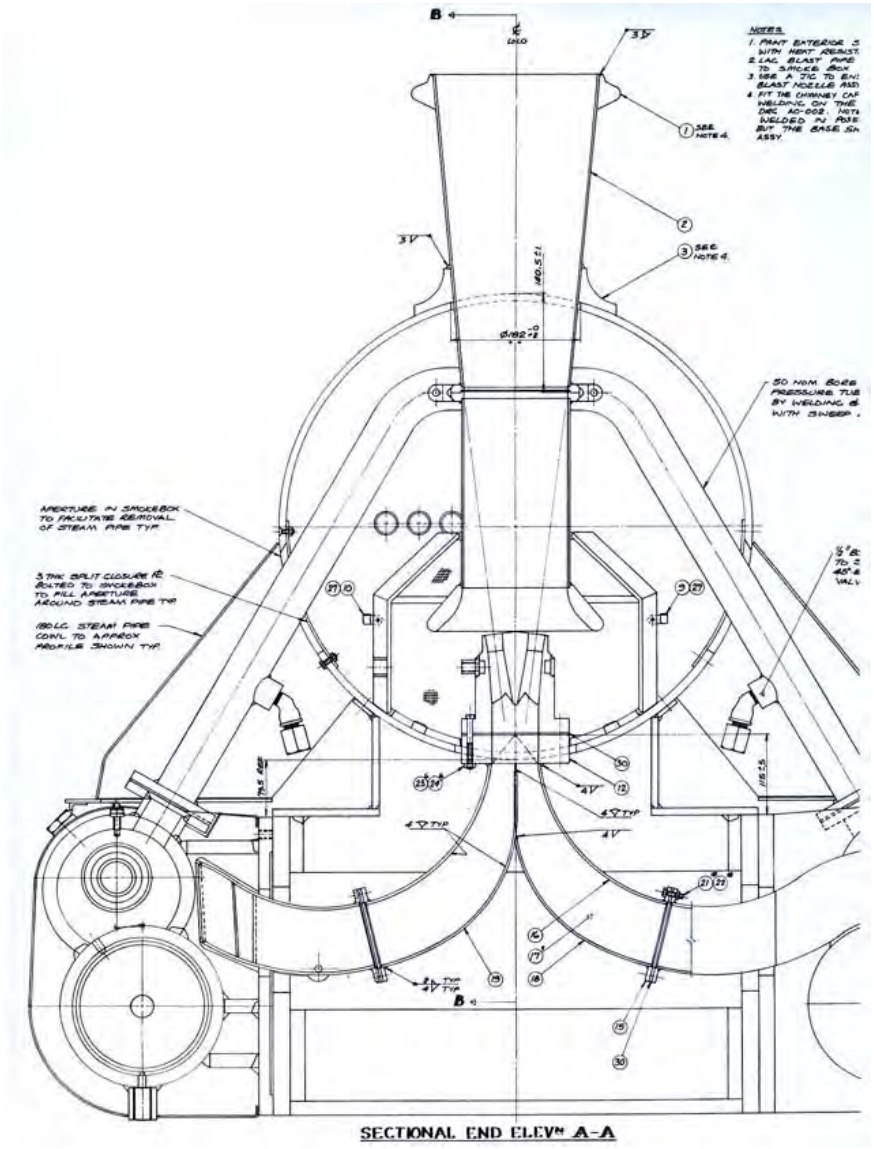
Construction of No.9



Failure of cylinder liner ‘O’ ring seals

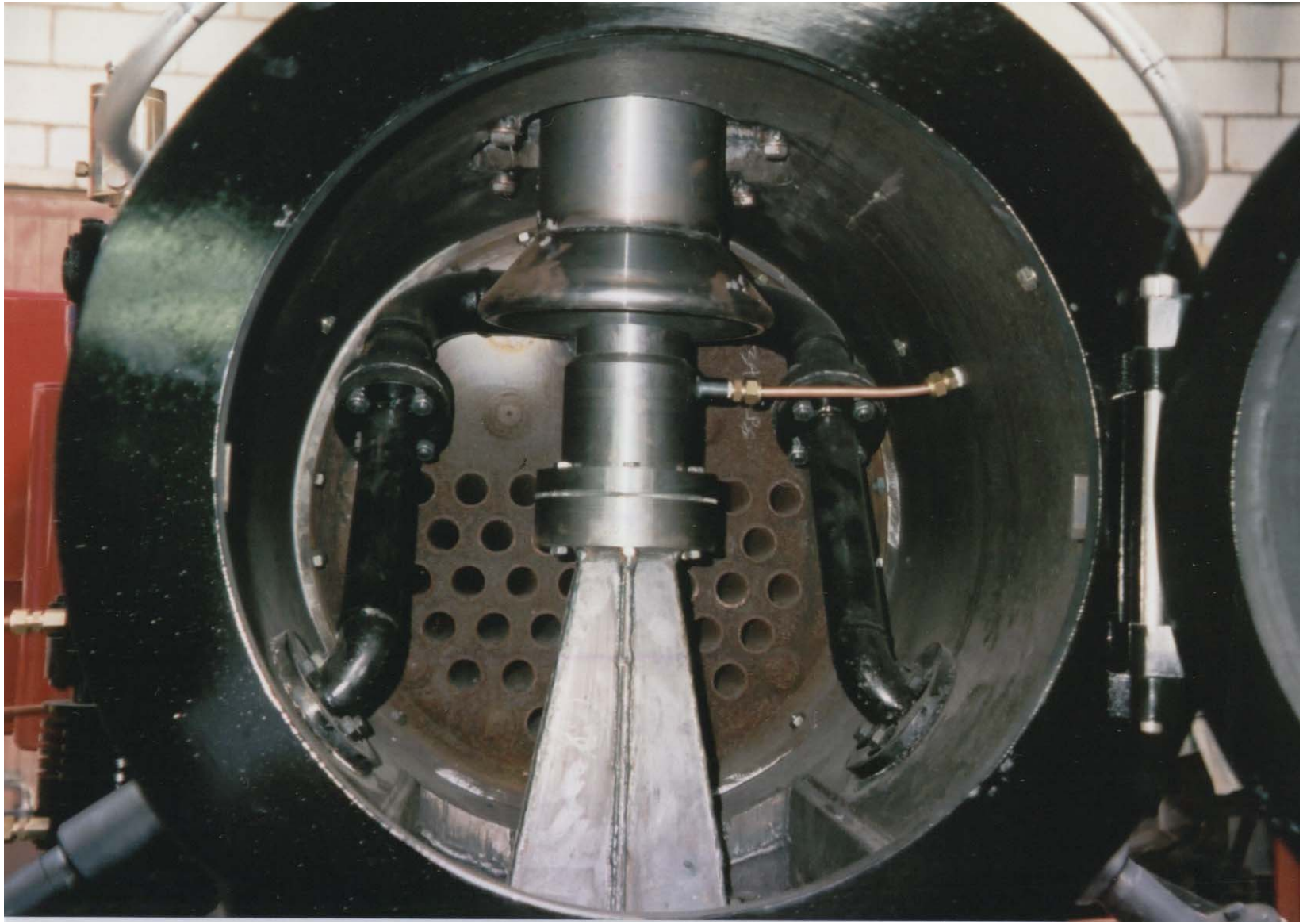
- After over 20,000 miles of operation the ‘Aflas’ ‘O’ rings on both Nos. 6 & 9 which sealed the cylinder covers to the cylinder liner and the bore of the cylinder fabrication failed.
- After examining the ‘O’ rings it was concluded that the most likely cause of this failure was explosive decompression due to the ring surface breaking down as absorbed steam/water was violently released from within the body of the ring
- Failure of the rings then enabled the liner to move due to the alternating pressure and the load on the anti-rotation spirol pin caused the edge of the liner to fail in shear
- Subsequently the liners were refitted and a gasket based repair was designed by the workshop which has been proved to be effective in service

The Lempor exhaust system for No.6 and the first blast nozzle prior to installation



The exhaust stand for No.9 showing the Kordina

The Lempor system installed in No.9



Comparison of draughting of No.6 as initially modified and No.9 as rebuilt

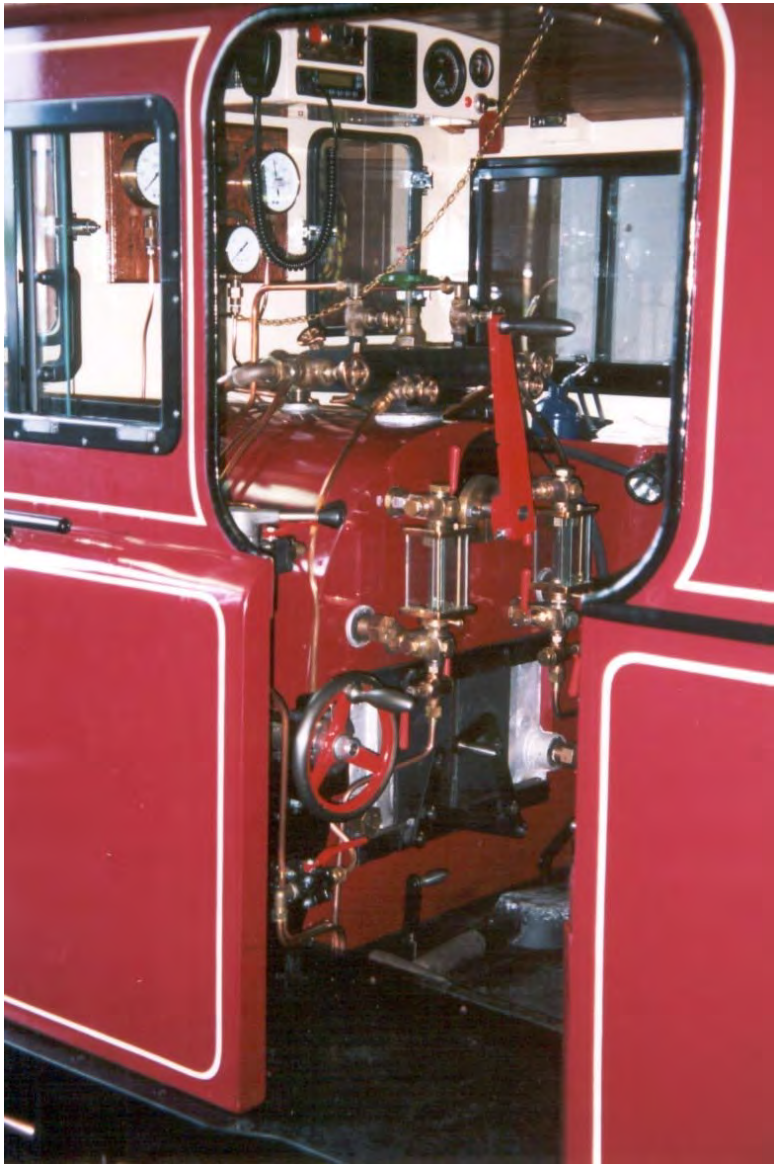
Item Description	No. 6	No. 9
Total chimney exit area, cm²	181.48	404.81
Chimney exit diameter, mm	152	227
Diffuser included angle	0°	10.3°
Diffuser area ratio	1.0	2.43
Overall chimney length excluding bellmouth : mixing chamber dia. ratio	N/A	5.10
Number of blast nozzles	1	4
Total blast nozzle tip area, cm²	15.91	20.92
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

No.9 in rebuilt condition at Wroxham

No.6 in ex works rebuilt condition

Artist Jonathan Clay captures the appearance of a proposed new 2-8-0T locomotive ‘Abigail’ which utilises ZB cylinders and valve gear

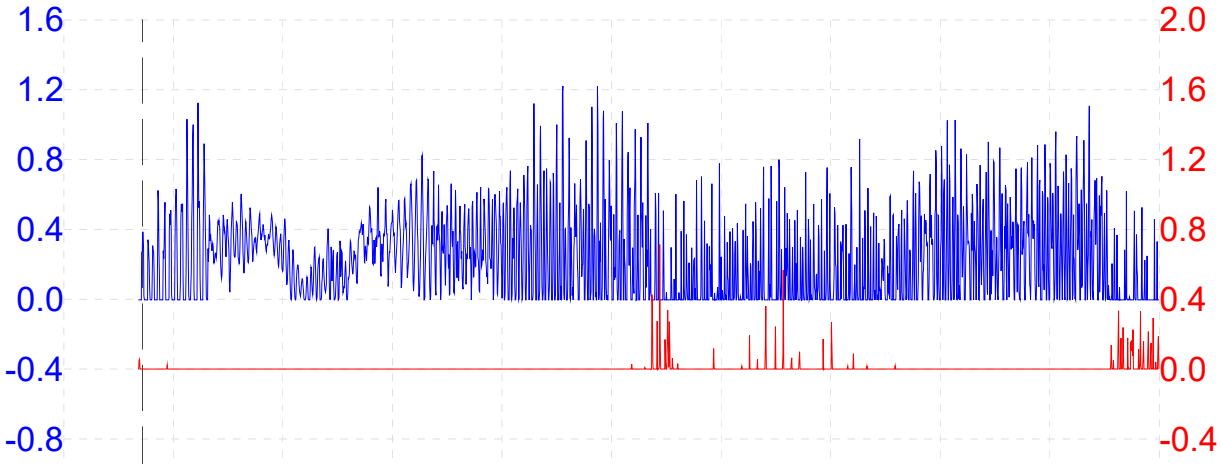
The ergonomics of the cab layout of No.9 was commended by HMRI



Considerable thought was given to the layout of the cab during the rebuild of No.9 to ensure crew comfort including: -

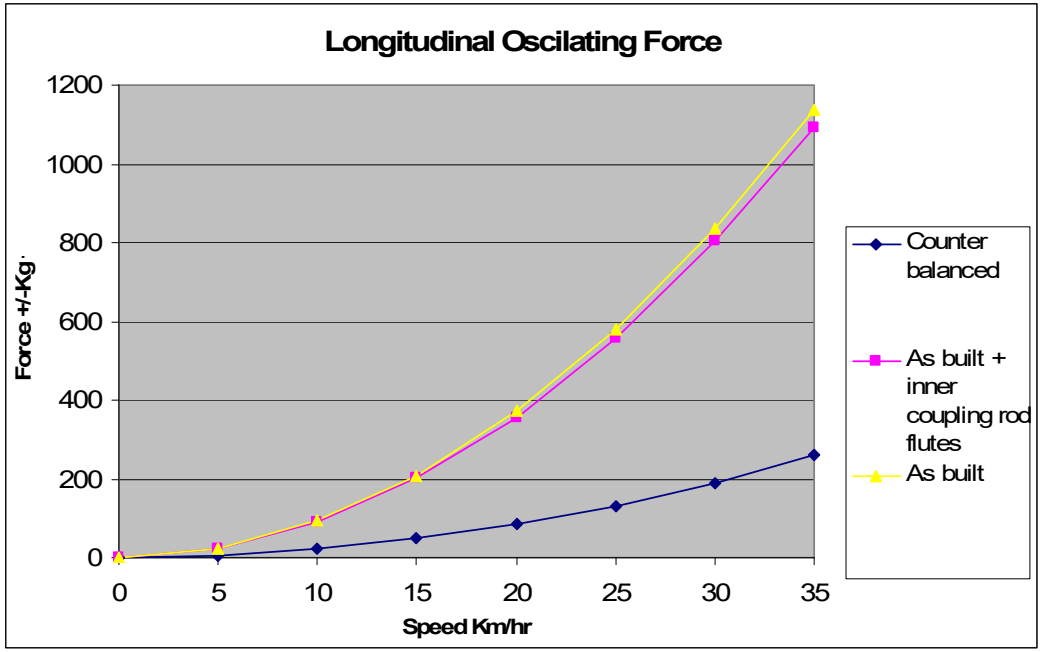
- Placing all controls within easy reach of the driver so that they can remain seated in one position
- Electric illumination of all pressure gauges and boiler water gauge (instead of using oil lamps)
- Powerful electric headlamp for night running
- Opening windows and ‘sun roof’ to enable crew to keep cool in the summer
- Provision of adequate locker space beneath the seat
- Easy access to coal which feeds from the bunker under the seat to the shovelling plate on the cab floor

Longitudinal resonance of train – ‘Shuttling’



- There was a long-term problem associated with the ZB locomotives which create longitudinal ‘shuttling’ of the coaches within the train when the set is excited at a resonant frequency typically at around 12-15 mph.
- This is both unpleasant for passengers and has also led to fatigue failures in the ball hitches of the coupling system
- The Coupling loads were measured by experimental testing and the trace shows resonance approaching Burgh summit with a 6 coach train.
  - The blue trace is tension and the red trace is compression.
  - The vertical axes show the load in tonnes force.
  - Surging can be seen where the coach is overrunning the coupling.

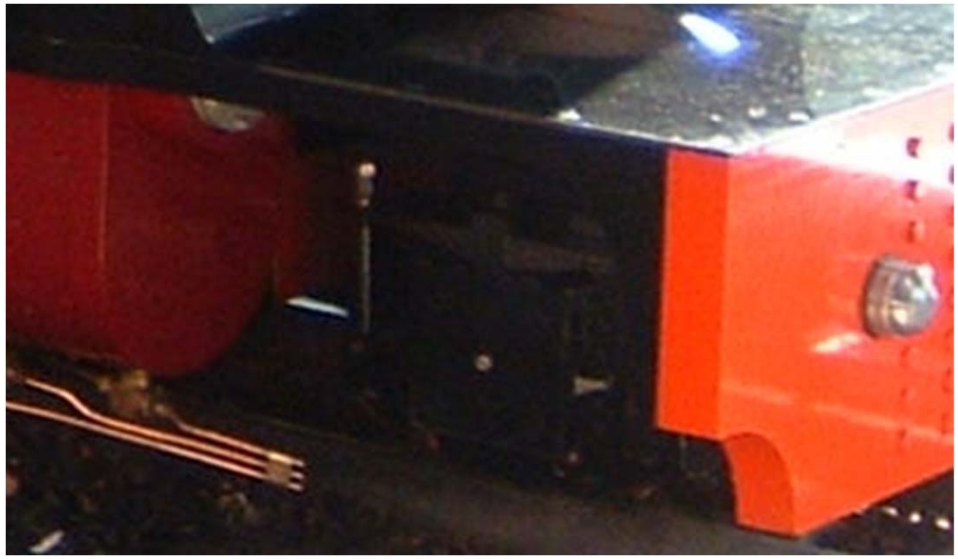
Longitudinal resonance of train – ‘Shuttling’



The ZBs were significantly unbalanced with only small counterweights on the wheels:-

- The reciprocating masses were completely unbalanced
- A significant proportion of the rotating masses were unbalanced
- As built the longitudinal disturbing force at 32.3 km/hr, 20 mph was ± 936 kg
- Counterbalancing all the rotating masses and 55% of the reciprocating masses reduced the magnitude of the pulsations by 77.3% giving a longitudinal disturbing force of ±219 kg which has significantly improved the passenger experience

Improvements to front pony truck springing on No.9

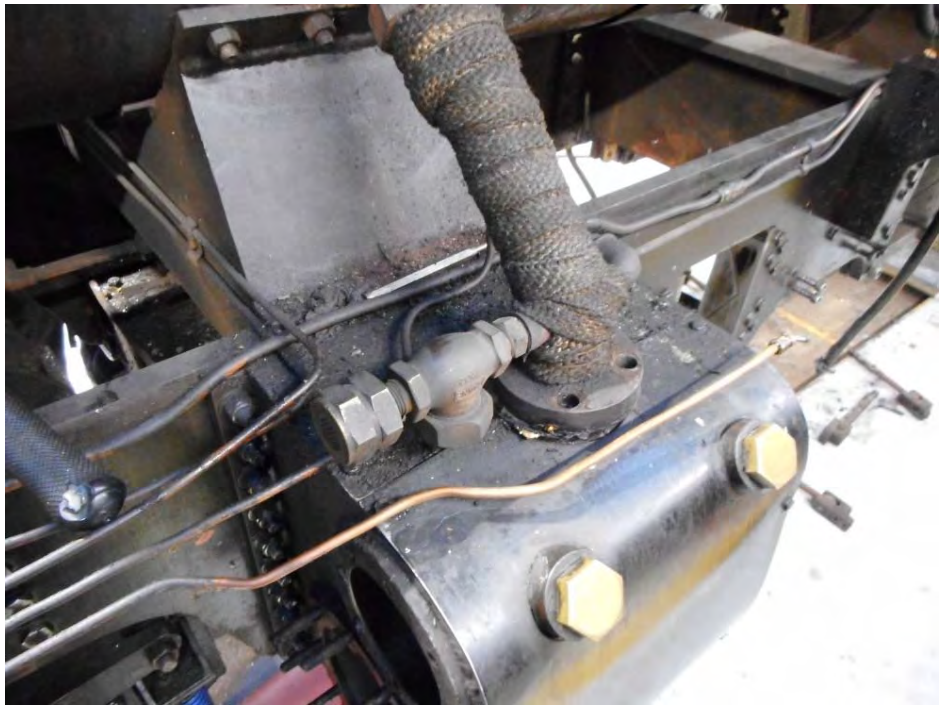


- The original leaf springs had few leaves making them too stiff and overstressed
- This was changed to a more compliant design with a greater number of thinner leaves but the fatigue life was limited due to space constraints (see photo)
- As the locomotives are always running in the forward direction the leading truck suspension takes a pounding from the track
- The final solution was to substitute the leaf spring with a solid beam and provide a pair of die springs with the identical rate but greater fatigue life (see photo)

The oil firing of No.8 is improved but is finally converted to coal firing

- To reduce fire risk No.8 was built with a Weir type burner below the front throat plate firing backwards
- Steaming was poor and the Weir burner was replaced with a row of 4 burner nozzles based on industrial paint sprayer technology
- The 4 nozzles fired towards the underside of an auxiliary brickarch situated below the fire door
- Steaming was better but limited the performance of locomotive + exhaust fumes and burner ‘rumble’ were unpleasant for crew and passengers
- Periodically soot required cleaning from boiler surfaces
- The rising cost of fuel and the need for improved performance resulted in a conversion to coal firing
- A bunker was constructed in the former oil tank and part of water tank space
- At the same time the cab enlarged with cranked back sheet and raised roof for crew comfort

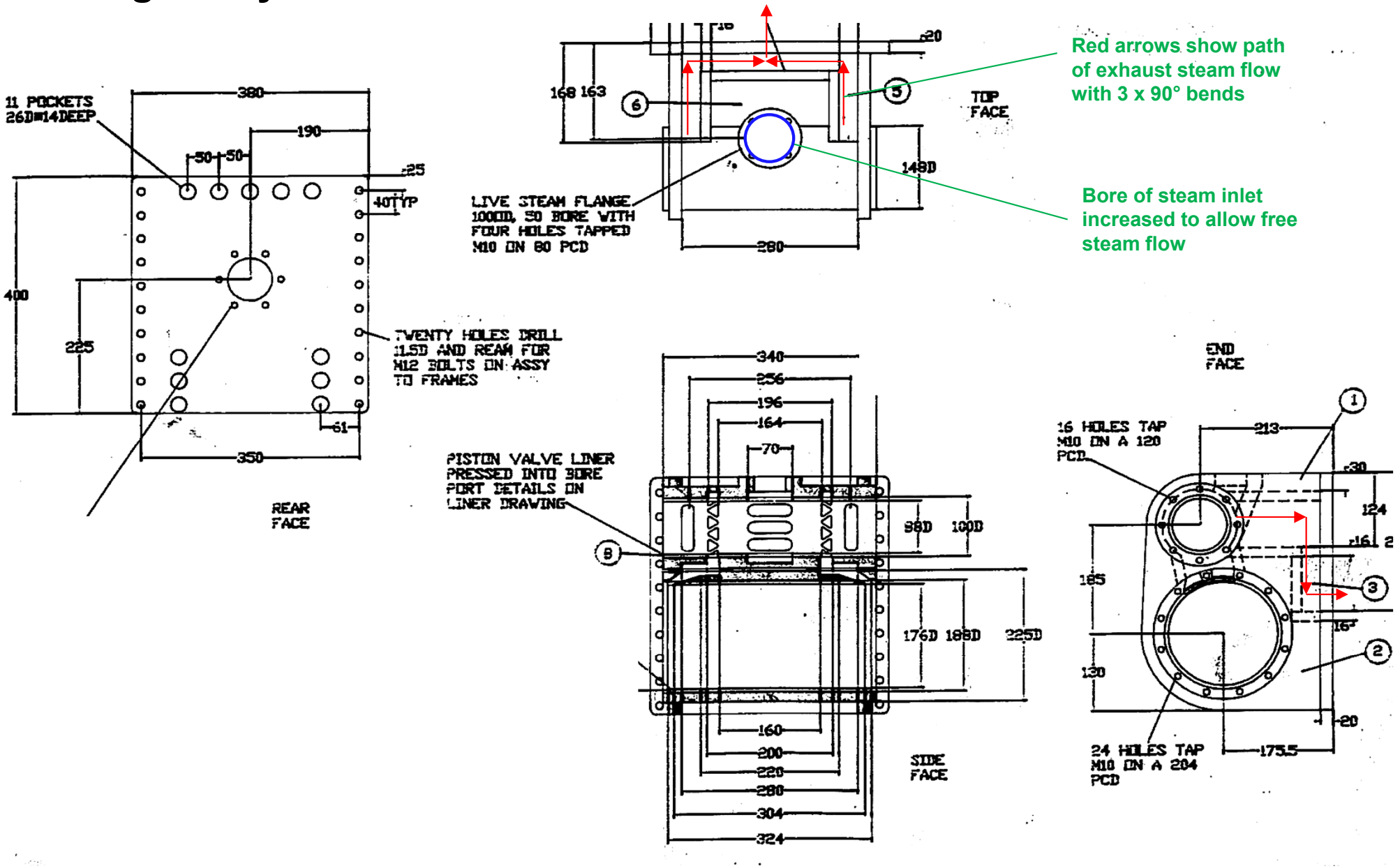
The original cylinders on Nos. 7 & 8 restricted the steam flow



As constructed: -

- The steam chest inlet, transfer ports and exhaust ports were restricted
- Steam chest volume was only 10.1% of cylinder swept volume

The original cylinders on Nos. 7 & 8 restricted the steam flow



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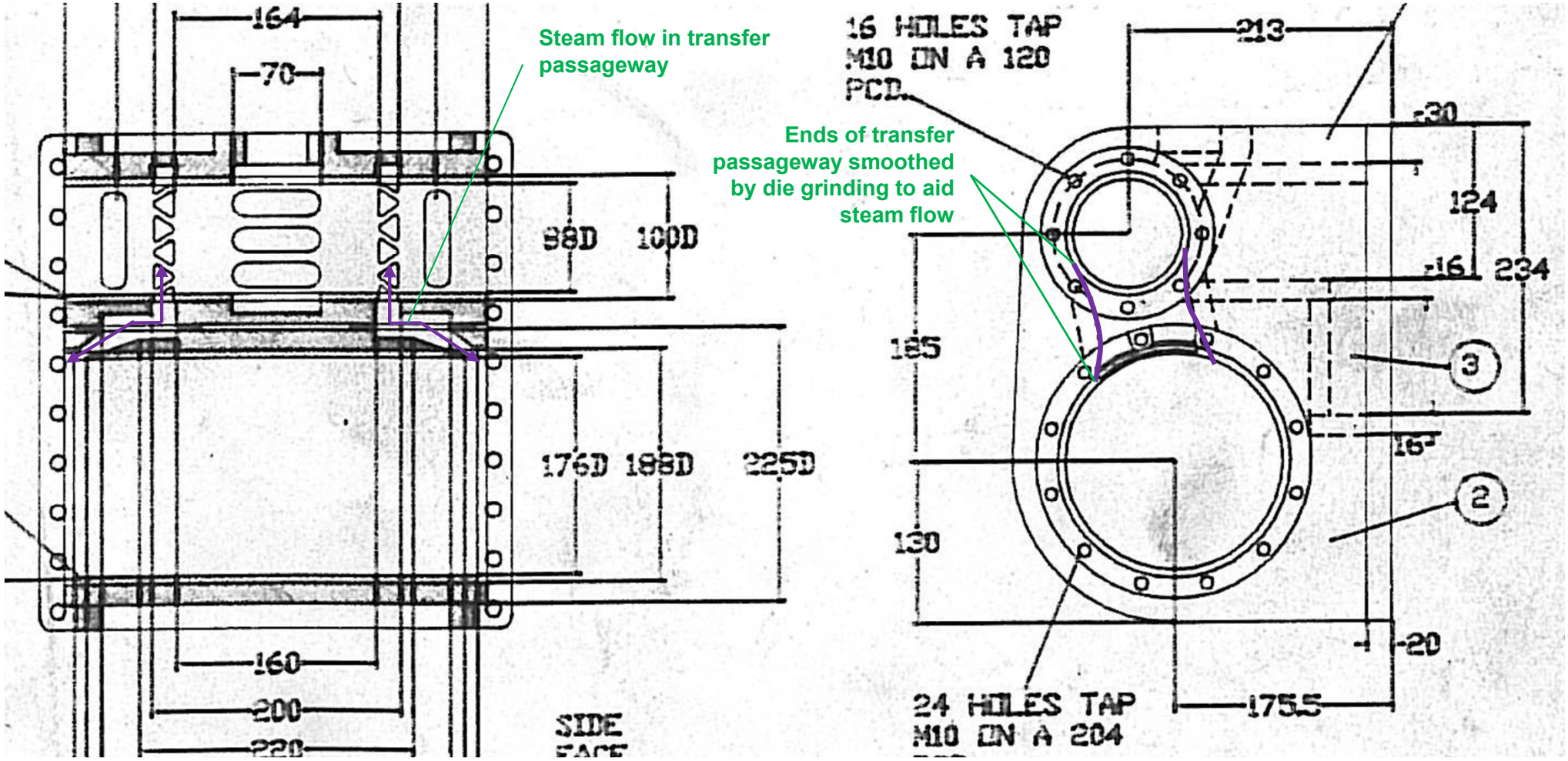

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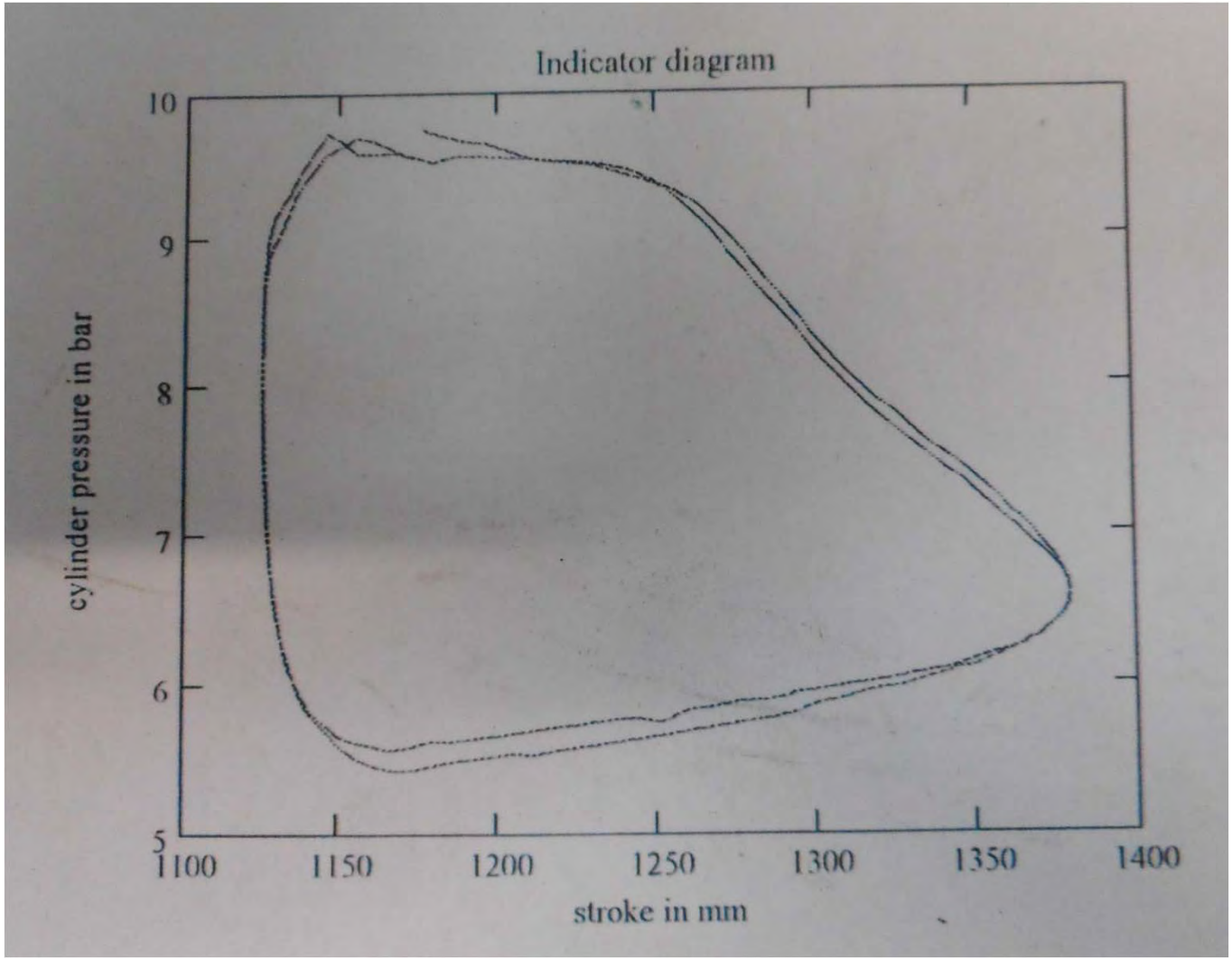
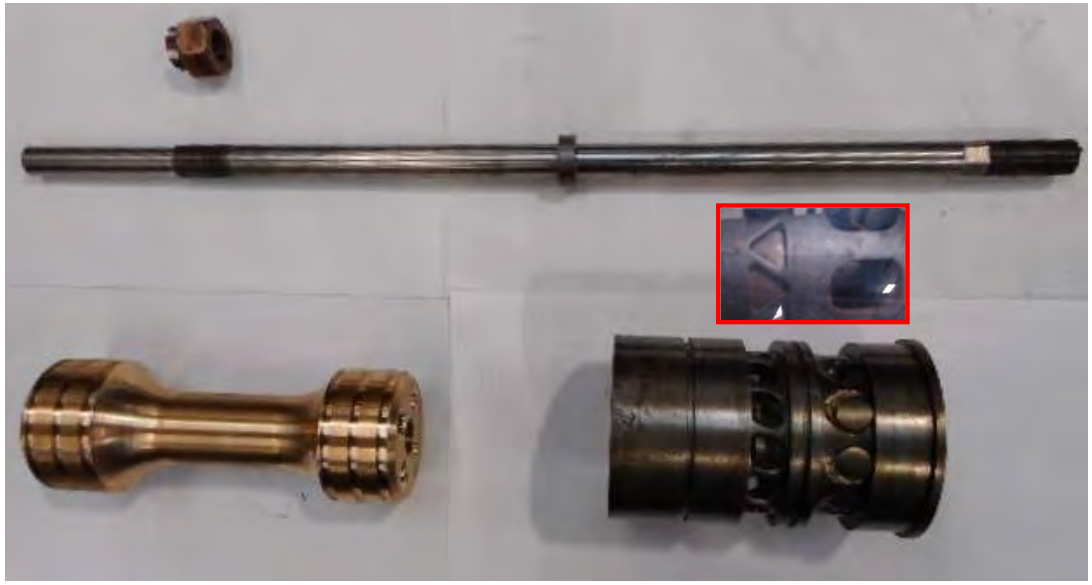


- Indicator diagram of cylinders as built (with early initial solid BVR valves)
- Boiler pressure 165 psig, 55% cutoff, speed 13.4 mph
- Note the exceptionally high back pressure

The original cylinders on Nos. 7 & 8 were improved

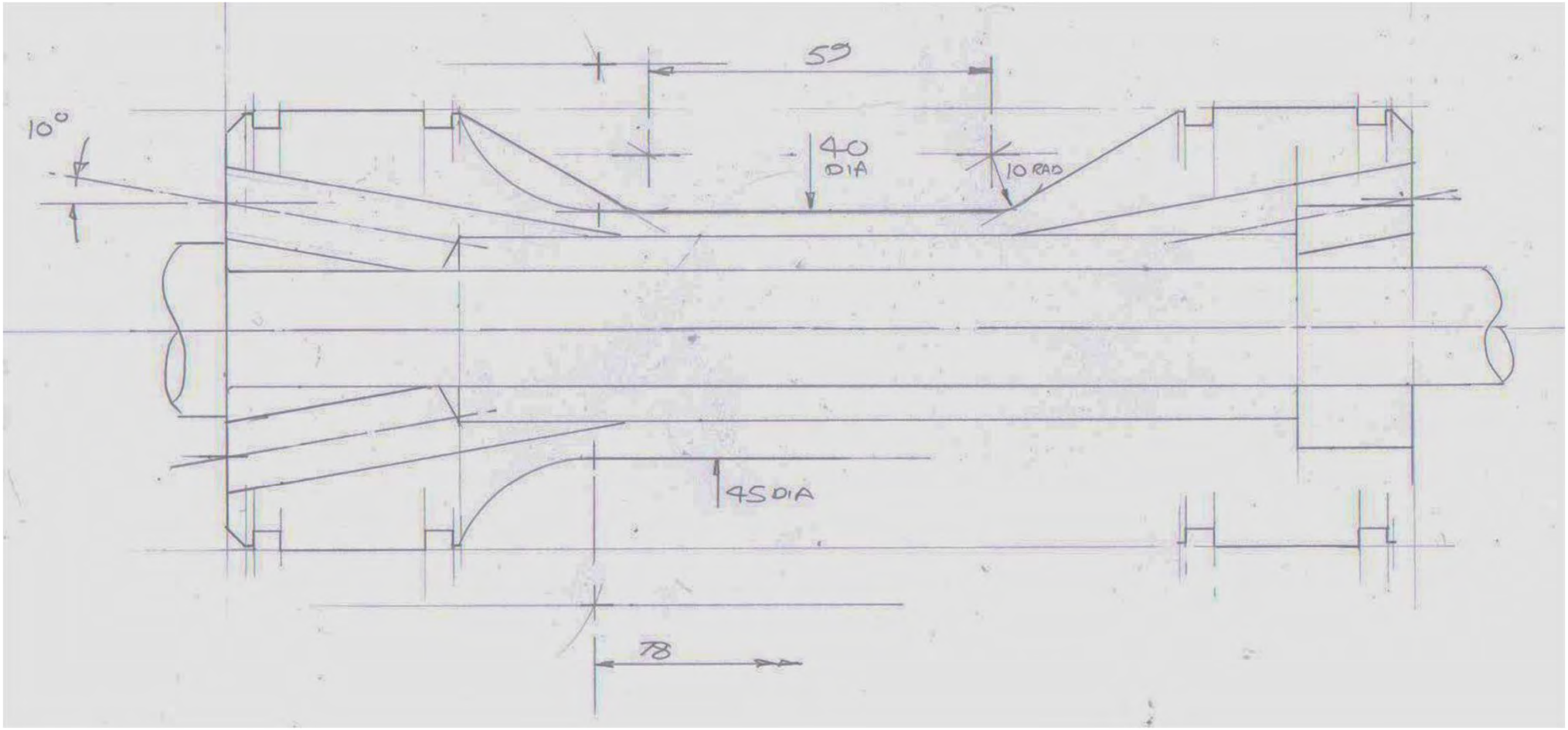
- The cylinders were probably designed for ease of manufacture and steam flow has not been optimised
- The cylinders were not stress relieved before machining when manufactured and are therefore prone to distortion (see joint with mainframe)
- Steam chest inlet and transfer ports were opened up by die grinding to increase steam flow however the transfer passageways remain 'Z' shaped
- Steam chest volume was increased by welding on large diameter pipe fittings in order to ensure a full indicator diagram at speed
- The exhaust ports remain restricted as the steam has to pass around 3 x 90° bends before reaching the pipe to the exhaust stand

New valves and liners were fitted to the improved cylinders



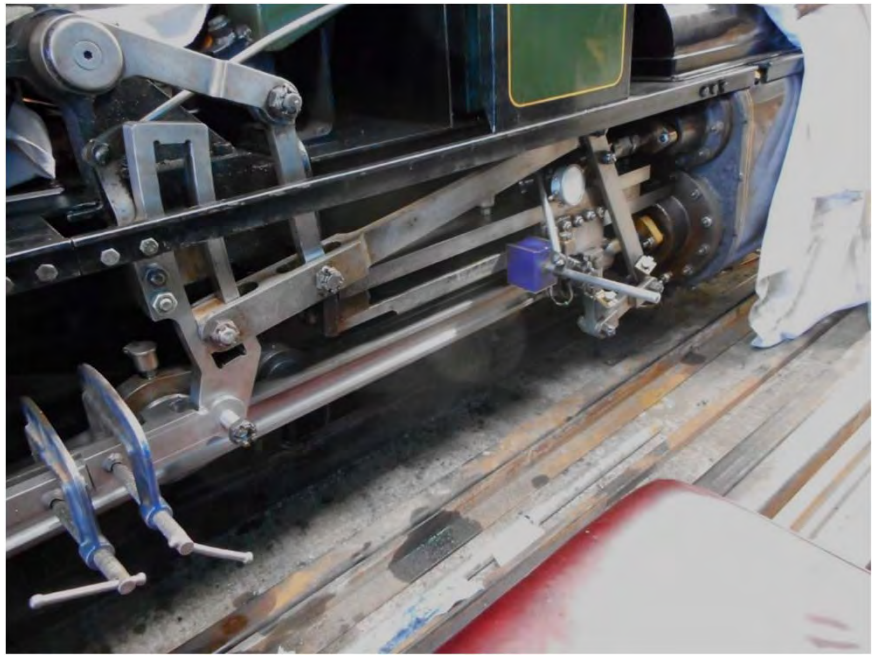
- New split cast iron valve liners have been manufactured with a bore of 76mm, 3”.
- Annular recesses are provided on the outside of the liner to enable the ports in the fabrication to; -
  - Align with the exhaust ports which have been moved outwards to accommodate the increased valve lap
  - Ensure that the transfer ports better connect with the transfer passageways
- Port areas have been increased and transfer port shape is improved for better admission at short cut offs
- A hollow bronze valve for improved exhaust flow features increased steam and exhaust laps with 3 x Clupet rings on each head
- A cylinder liner of 165mm, 6.5” bore is provided to reflect the reduced valve diameter

New valves were fitted to the improved cylinders



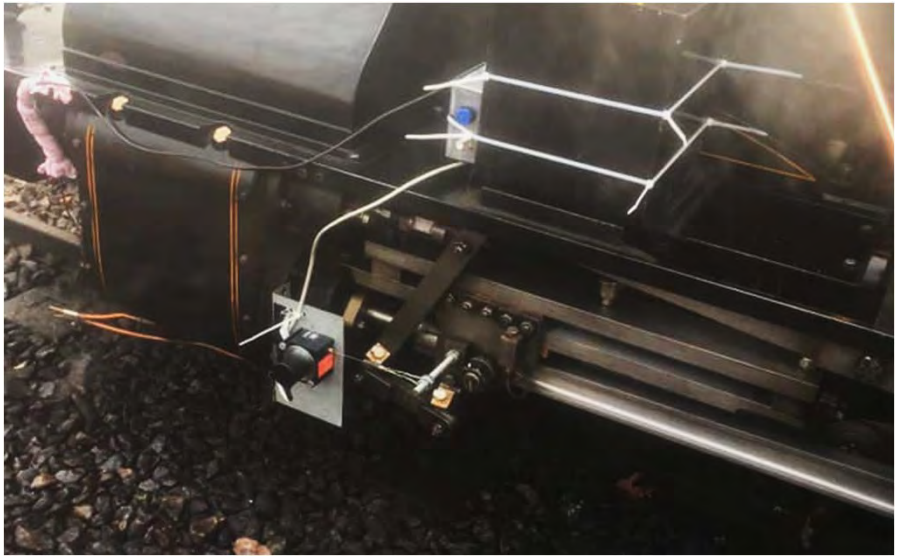
Design scheme showing longitudinal crossection of bronze valve with internal porting

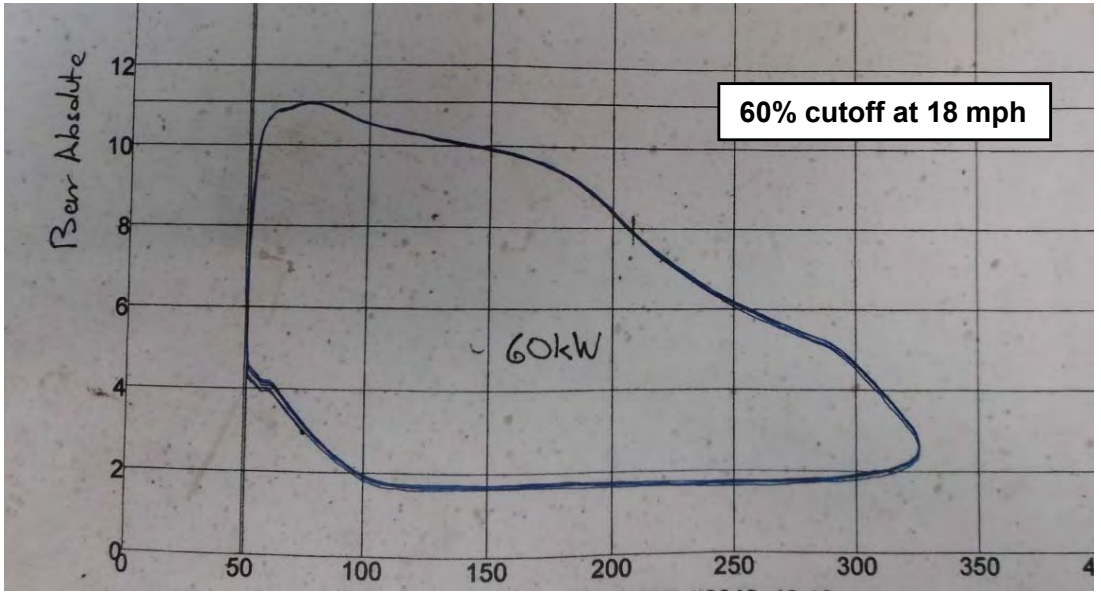
Valve gear improvements were made to Nos. 7 & 8

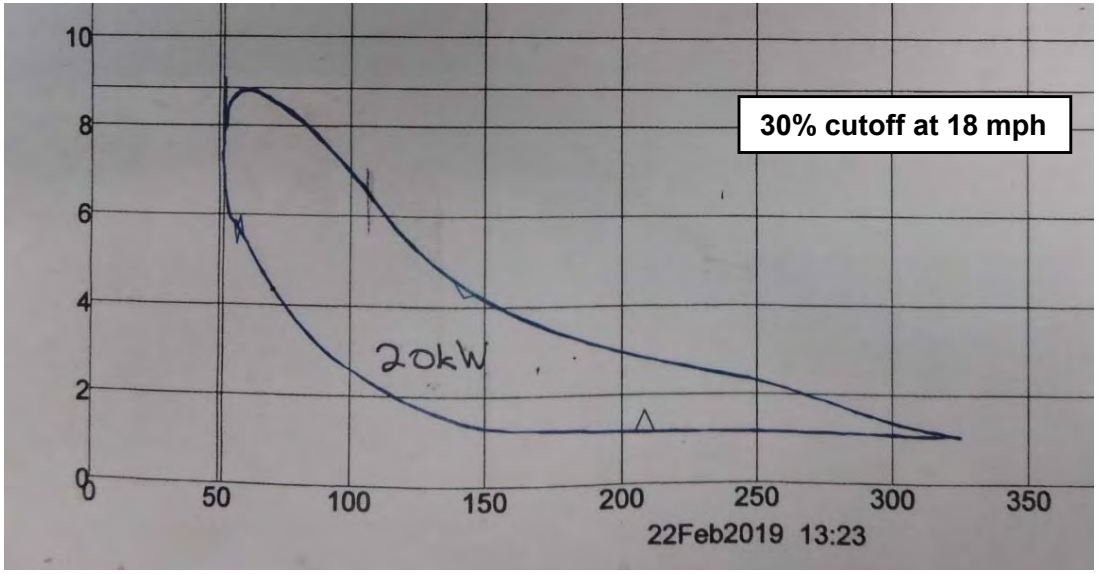


- The valve gear was redesigned to increase valve travel and therefore port openings for better steam flow which entailed:-
  - New expansion links with longer die block slots and shorter drop arms
  - New combination levers
  - Modifying the length of the eccentric rods to suit the new geometry (as shown in the photo)
  - Recalibration of the reverser scale to suit

Prior to increasing the steam chest volume indicator diagrams were prepared

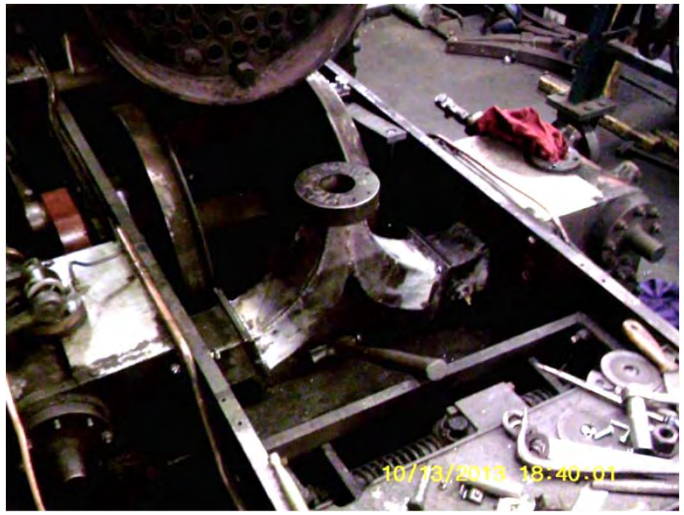






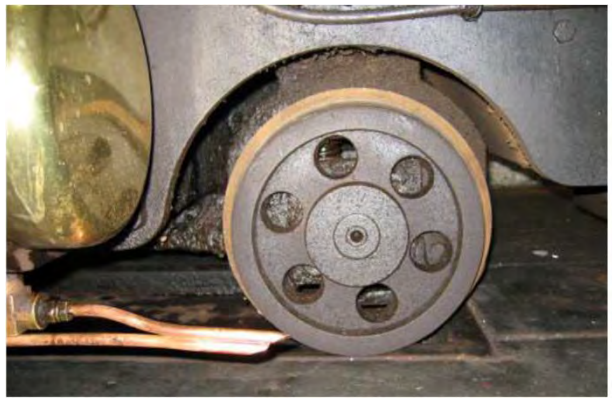
- Indicator diagrams were recorded digitally using pressure transducers and a liner transducer to measure crosshead position
- Poor filling of the cylinder during admission is thought to be due to lack of steam chest volume
- Subsequent increase in the steam chest volume has significantly increased power and it is planned to record fresh indicator diagrams

Revised exhaust systems were fitted to Nos. 7 & 8



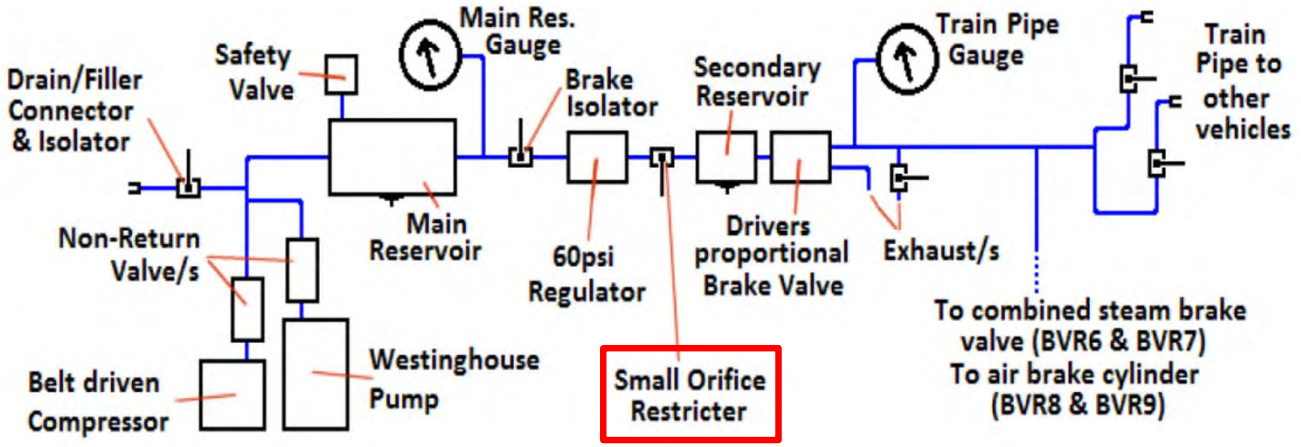
- A petticoat pipe was fitted to improve gas flow but the original chimneys were retained for appearance sake
- Installation of Lempor exhaust is on an extended circular exhaust stand as shown
- Basket type mesh spark arrestors are fitted to reduce spark throwing in the summer (but are omitted in the photo)
- The exhaust system below the smokebox is similar to that fitted to Nos. 6 & 9 and includes a Kordina for back pressure reduction (see photo)
- Drains are provided in the underside of the exhaust system to prevent the build up of condensate on shed

Suspension improvements



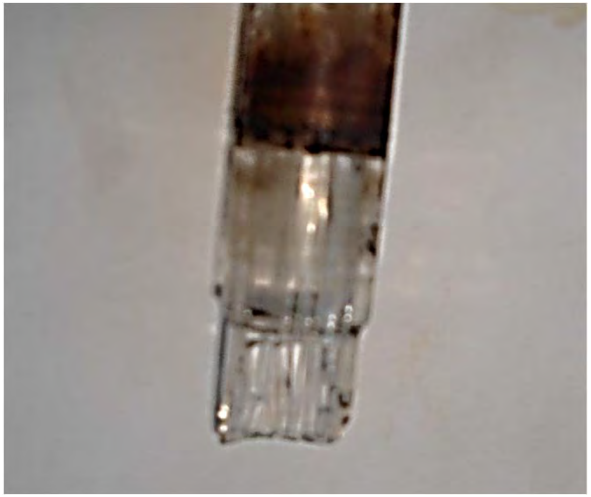
- The front pony trucks on Nos 6,7,and 8 were originally of inside frame design supported on twin die springs (see photo)
- The design was hard to inspect and maintain compared to the final outside frame arrangement provided on No.9
- A transition to outside frames is being implemented at heavy overhauls requiring extensive rebuilding of the pony truck and some main frame modification to provide clearance (see photo)
- Main spring design has been improved and a ‘Universal’ spring pack utilising a larger number of thinner leaves to maintain the spring rate but increase fatigue life is used for all locos

Braking installation on locomotives



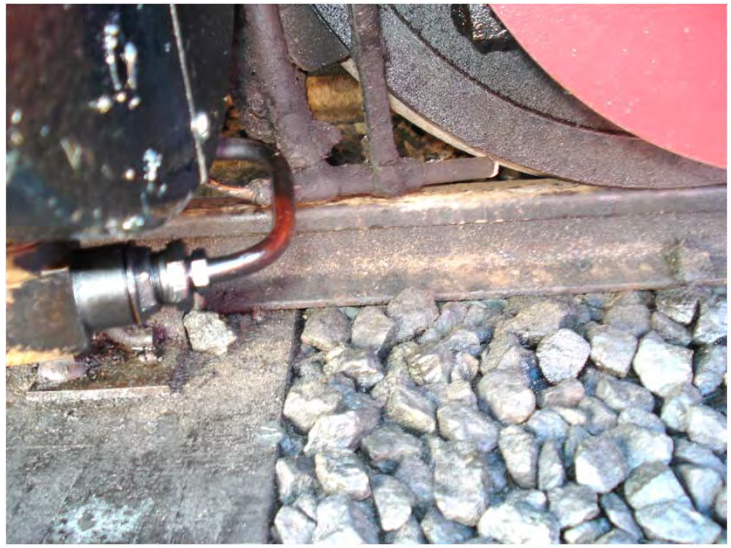
- The locomotives all have steam brakes operating on the driving wheels and Westinghouse style automatic single line air brakes which act on the driving wheels for the tank locomotives and the tender wheels for Nos 6 & 7
- Functional improvements to the double acting Westinghouse pumps were made and applied to all the locomotives (see photo)
- Concerns about braking performance and efficacy of the Guards' emergency brake led to a number of upgrades in conjunction with HMRI: -
  - A small orifice restrictor (highlighted in red on the diagram above) was added to prevent the air stored in the locomotive main reservoir overcoming the Guards' emergency brake or failure of the train pipe
  - The hysteresis of the triple valves was reduced to increase the maximum brake pressure applied by the cylinders
  - A drivers' steam brake valve was fitted to Nos. 6 & 7 which was also actuated by train pipe pressure to increase braking in order to compensate for the high locomotive weight (see photo)

Improvements in water treatment has reduced boiler maintenance

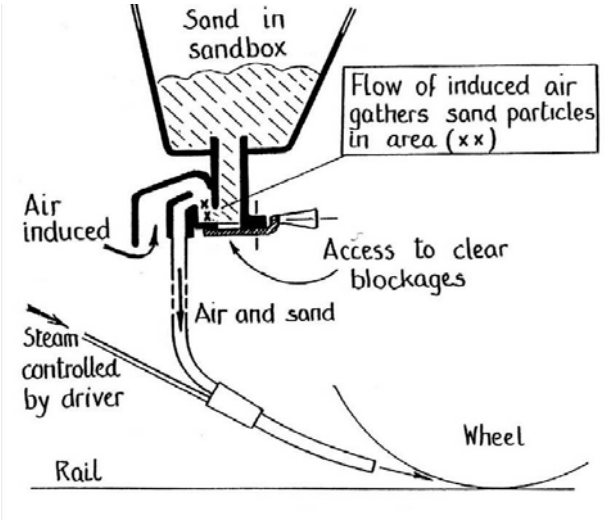


- During the early years build up of scale and high fire temperatures led to high boiler costs: -
  - Routine washouts were frequent and foaming was endemic
  - Acid washouts were needed at intervals to remove scale
  - Fire tube life was typically only 1-2 seasons with cracks developing in both firebox tubeplate ligaments and tubes
- Changing the boiler treatment to a regime similar to that recommended by Porta has transformed the situation: -
  - Boilers remain clean internally (see view inside boiler of No.7)
  - Washouts are typically every 90 days
  - Tube life is extended enormously (No.9 has the original tubes after 20+ years
  - However, the high ph of the boiler water does require regular changing of gauge glasses at 30 day intervals due to wasting (see photo) and inspection of the condition of threaded boiler fittings

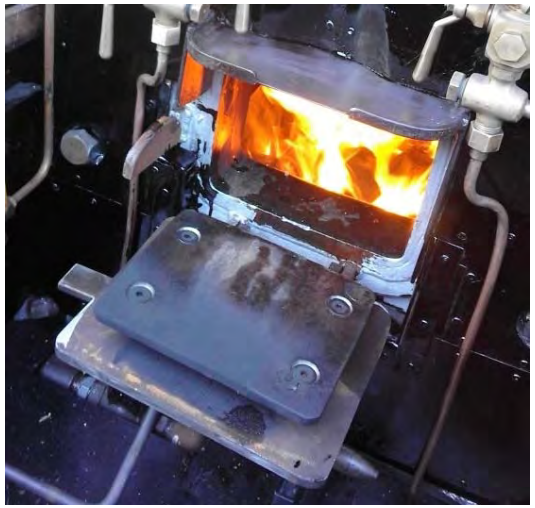
Addition of steam sanders



- Originally the locomotives had no sanding equipment leading to double heading or delays during adverse weather conditions
- Steam sanders working on the principle illustrated below were added to all the locomotives with sand boxes located in convenient positions close to the boiler where possible (see photos)
- Rubber hose is used for the connection between the box and sander to enable blockages to be dislodged by flexing the pipe

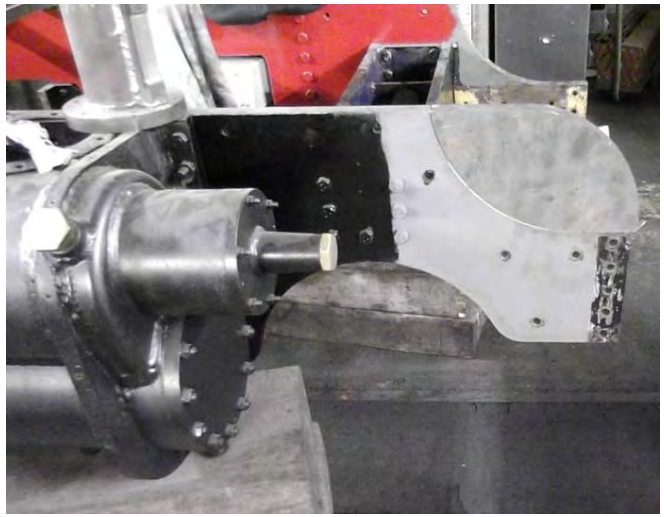


Fire doors and deflector plates



- The locomotives were fitted with brick arches cast in refractory concrete from new
- Subsequently deflector plates were added to enable the admission of a small amount of secondary air to reduce smoke in stations and when coasting without risk of damaging the tubes
- The original sliding fire doors ‘clank’ under the pulsations of the Lempor exhaust which is irritating for crew and gapping the door to control smoke creates an airflow direction which is sub-optimal
- The progressive change to drop down doors stops ‘clanking’ when pulling and when opened on the catch to admit secondary air the deflector plate and internal door baffle guide the air down towards the fire

Frame strengthening and weight distribution improvement

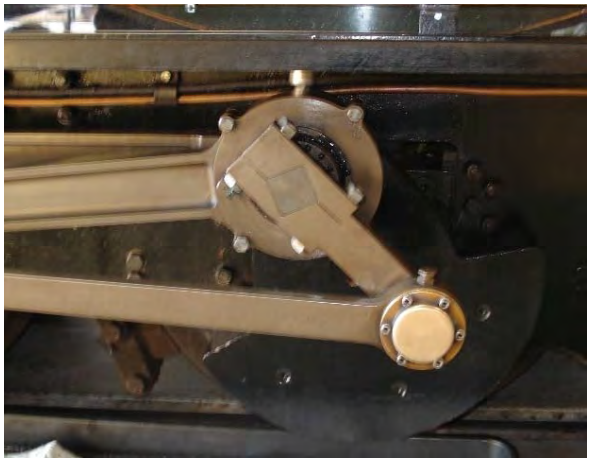


- Strengthening and alteration of the front and rear of the frames has been undertaken where required for a number of reasons including: -
  - Weakness at washout plug access holes which were too close to frame edge
  - Repositioning of washout plug access holes
  - Reprofiling of cutout for front pony trucks when converting from inside to outside axle box design
  - Addition of weight to the front end of locomotive to improve weight distribution on the driving wheels e.g. thick buffer beams, thick smokeboxes, smoke deflector plates etc.

Improving crew safety on Nos 6 and 7

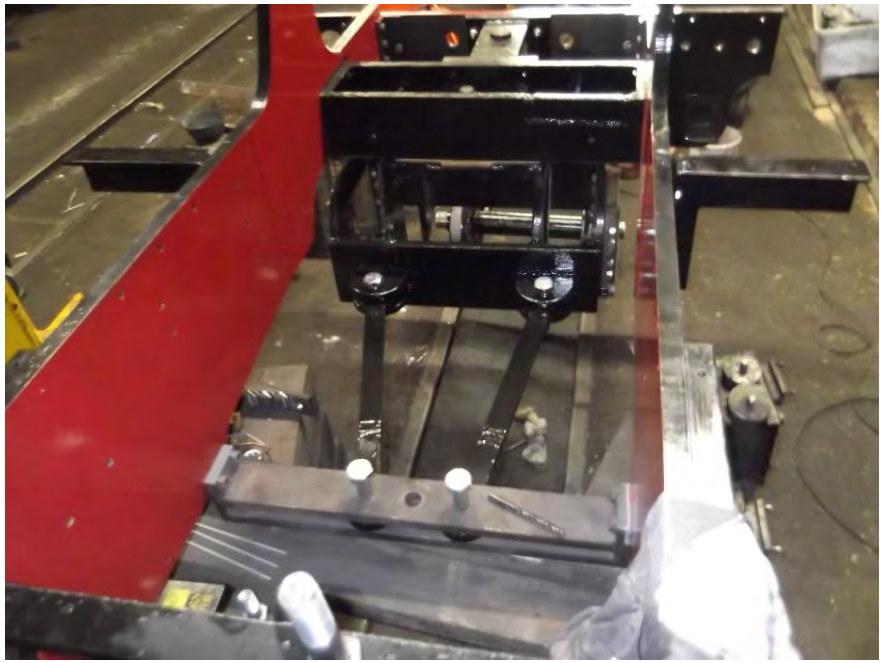
- The coupling between the loco and tender presented a hazard for crew in the event of failure
- To reduce this risk: -
  - The primary coupling was replaced with a better engineered unit having ball joints at each end
  - Twin emergency couplings with springs to absorb snatch if the main coupling fails are provided on either side
  - The fall plate mounting has now been moved from the loco to the tender to maintain a foot support for the crew at all times. In addition it is provided with supports to stop it falling down in the event that the main coupling has failed and the locomotive separates slightly

Redesign of the connecting rods and crossheads



- The original connecting rods and crossheads were unsatisfactory: -
  - The screw holes for the bearing clamp plates in the wall of the big end eye caused unacceptable stress raisers
  - The little end eye was overstressed and too narrow resulting in overloading and premature failure of the little end bush
- New connecting rods were designed in high tensile RQT701 with clamp screws outside the big end eye and wider little end eyes
- New wider crossheads were designed to suit the rods and improved securing of the little end pin with a taper collet was provided

Geometry of pivot points of front and rear pony trucks corrected



- Excessive tyre wear on the front and rear pony trucks was found to have been caused by the pivot point being too close to the truck axle
- Revised pivot point positions were calculated and corrections made to the geometry as follows: -
  - The front trucks had the ‘A’ frame cut and extended and a new pivot was located on a new member spanning between the frame stretchers below the front driving axle
  - The rear trucks had the ‘A’ frame removed and were supported on two inclined swing links attached to the original pivot stretcher such that the centre lines passed through the virtual pivot point. This corrected the geometry while avoiding the boiler firebox

No.7 Rebuilt in ex works condition

No.8 Rebuilt in ex works condition