Why Did BR Give Up On Steam ?
– And Could It Have Been Avoided

Part 2 – Solutions

Andrew Hartland
18th September 2021

Objective

- This presentation seeks to answer two questions:

1. What were the reasons given at the time for the perceived superiority of diesel over steam traction ?
2. Would it have been possible for different designs of steam locomotive to the BR Standards actually built to have addressed these perceived weaknesses ?

Contents – Part 2

1. Requirements Recap
   - Benefits of Diesel Over Steam
   - Perceived Steam Shortcomings
2. Previously Proposed Solutions
   - BR Standards
   - Bulleid
   - US Proposals
   - Chapelon
3. New Solutions
   - Technologies
   - Availability & Utilisation
   - Design
     - Worked Examples – Express Passenger

Requirements For Steam to Compete With Diesel

- Less Old Fashioned
- Cleaner
  - ➔ Less Pollution
  - ➔ Better combustion (with lower quality coal)
- Less Manual Labour
  - Cleaning/Servicing
  - Firing
  - ➔ machine washing, stoker firing & reduced service reqmts
- Higher Low Speed Performance
    - ➔ Better Acceleration & Hill Climbing
    - ➔ consistent higher power outputs (Kiefer Rule) ➔ mech. firing
    - ➔ better use of locomotive weight for adhesion
- Reduced OPEX
  - Reduce Fuel costs to Diesel levels ➔ Higher Efficiency
- Higher Availability/Utilisation ➔ match diesels
  - Increased Operating Range w/o refuelling/water/ash removal
  - Reduced terminal time (turn, water, coal, ash)
  - Reduced servicing
  - Increased major repair intervals

Previous Solutions

BR Standard Design Philosophy – Cox/Bond/Riddles

- Plateau in steam locomotive performance reached world-wide
  - approx. 13 lb steam/ihp hr for simples, 10% less for compounds
- No significant reduction in sfc possible without adding unacceptable complication
- Simplicity (min. number of cylinders) preferred
- Good accessibility for regular maintenance
- Reduced repair & servicing time
- Large grates, high superheat and long travel valves ➔ good economy
- 3000 lb/hr max. sustained coal rate
- Designs deliberately front-end limited in an attempt to limit degradation of boiler performance at high specific firing rates

Bulleid's Desiderata (1947)

1) To be able to run over the majority of the company's lines.

(2) To be capable of working all classes of trains up to speeds of 90mph

(3) To have its whole weight available for braking and the highest possible percentage thereof for adhesion

(4) To be equally suitable for running in both directions without turning, with unobstructed look-out.

(5) To be ready for service at short notice.

(6) To be almost continuously available.

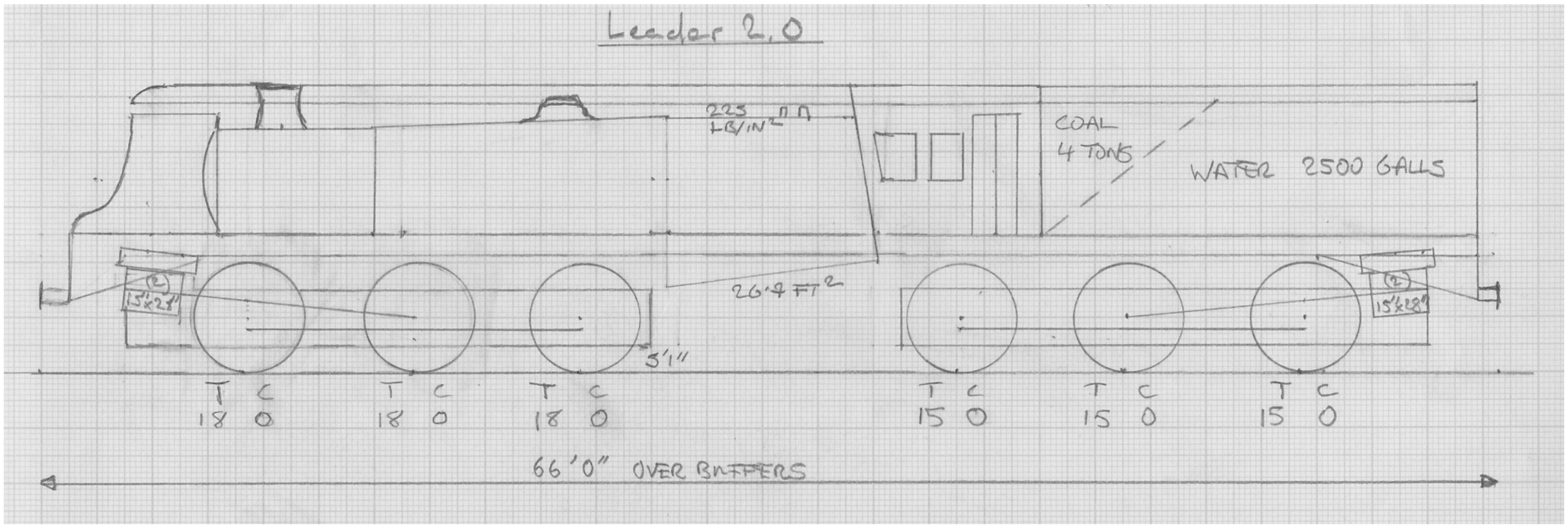
(7) To be suitable for complete "common use".

(8) To run not less than 100,000 miles between general overhauls with little or no attention at the running sheds.

(9) To cause minimum wear and tear to the track.

(10) To use substantially less fuel and water per drawbar horse-power developed.

Leader 2.0

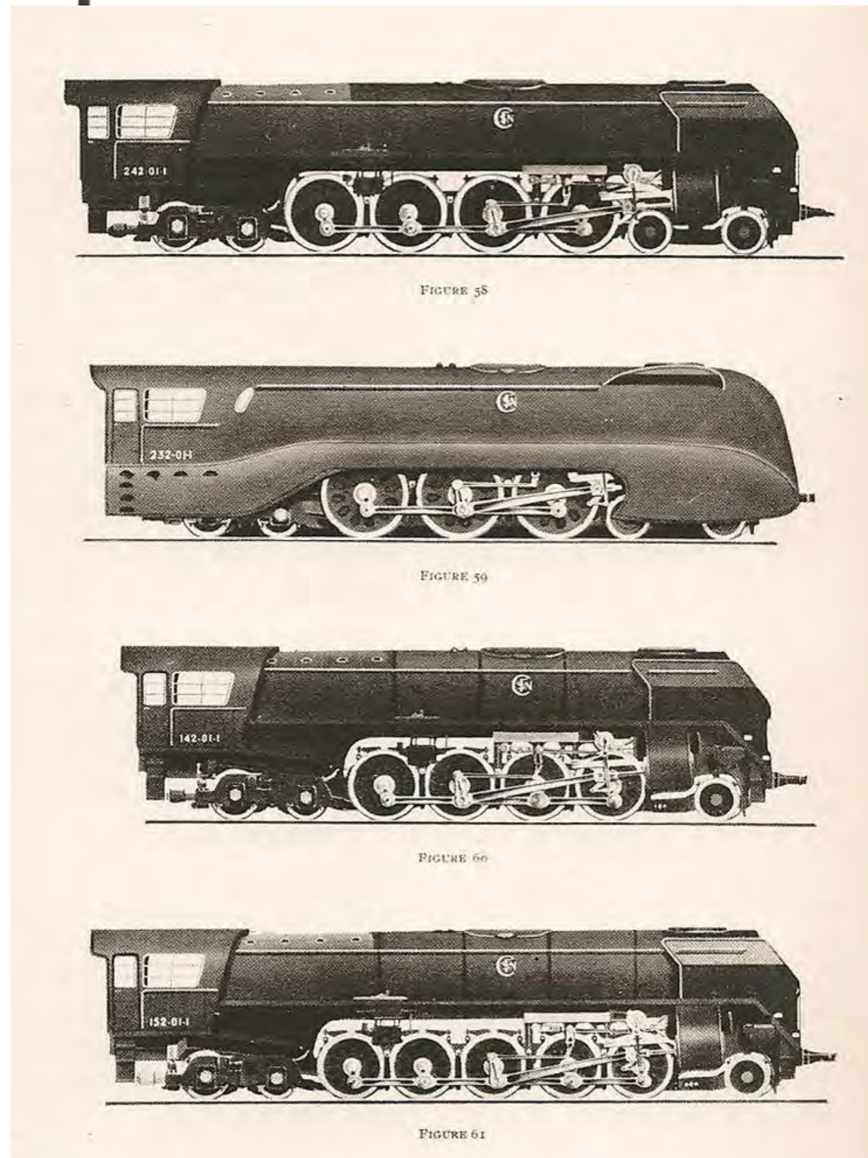


Driver Dia	Cyl Dia x Stroke (in)	Tractive Effort (lbf)
5'1"	15" x 20"	28,844
4'4"	15" x18"	30,453

- Q1 based
  - Q1 230 psi boiler
  - Conventional 0-6-0 design for each power bogie
  - Stephenson valve gear
  - Central cab
  - No boiler offset

Chapelon 1943 Proposals for SNCF

- Standard range of locomotives intended to meet SNCF traffic requirements from 1950 to 1970
- 23t axle loading
- 5000 ihp sustained, 6000 ihp max
- common 22 atm (320psi) boiler
- 6m2 grate, HT1 mech.stoker
- 30t/hr max evaporation
- 425 deg C steam temp
- 3 cyl compound
- Roller bearings throughout
- Welded 1 piece frame
- Spring controlled lateral displacement coupled axleboxes
- Franklin self-adjusting axlebox wedges



New Solutions

Target Specifications

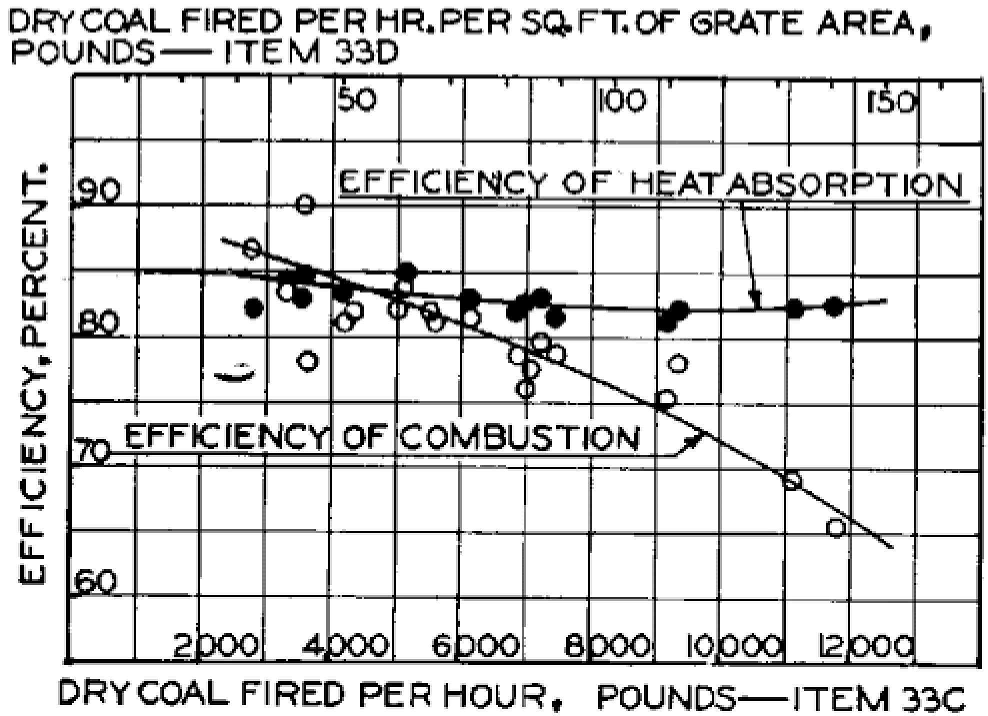
								KX- Edinburgh	
		DE Equiv	Steam	Av DBHP Reqd (400t trailing load)			Max Speed	Av.Speed	Time
		hp	ihp	Level	Level+50%	Up 1:200	mph	mph	hr
1GS	Class 40	2000	3000	830	1245	1610	90	67	6
2GS	Deltic	3300	4950	1004	1506	1855	105	73	5.5
3GS	HST	4500	6750	1583	2374	2622	125	89	4.5
4GS	Class 91	6300	9450	2087	3130	3256	140	100	4

- Kings X – Edinburgh non-stop used as reference “mission”
- Av & Max Speeds taken from contemporary schedules / diesel performance

Technologies

Efficiencies

	High	Low
	%	%
Simple	85	80
Compound		
HP	91	85
LP	85	80
Combustion	85	50
Condensing	+40	



- The big opportunities are:
  - improved combustion efficiency
    - Performance
    - Environmental
  - Vacuum condensing

Pulverised Coal Firing (1)

- 6 German locos converted to Stug system of pulverised coal firing (plus 4 AEG system) from 1928
- For 3 years 1933-1936 50,000 km/loco per year
- Converted G12 class locos in service at least 1931 -1944
- 1st Australian Coal Dust experiments 1923
- 1948 one X class 2-8-2 converted to Stug system

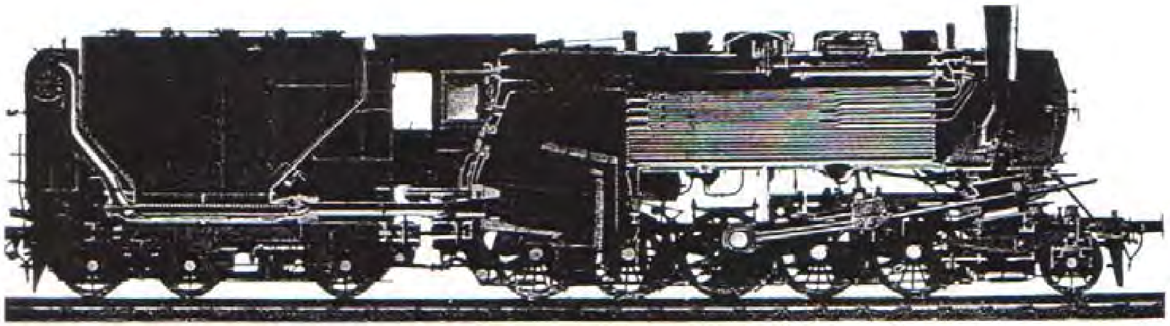


FIG. 507. Longitudinal section view of a German locomotive with Stug equipment for coal dust firing.

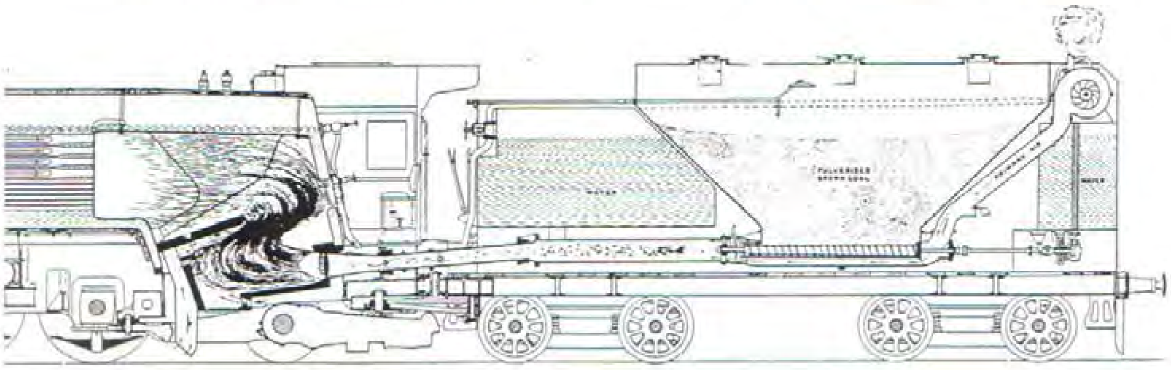


FIG. 508. General arrangement of brown coal dust fired locomotive and tender of the Victorian State Railways, 1950.

Pulverised Coal Firing (2)

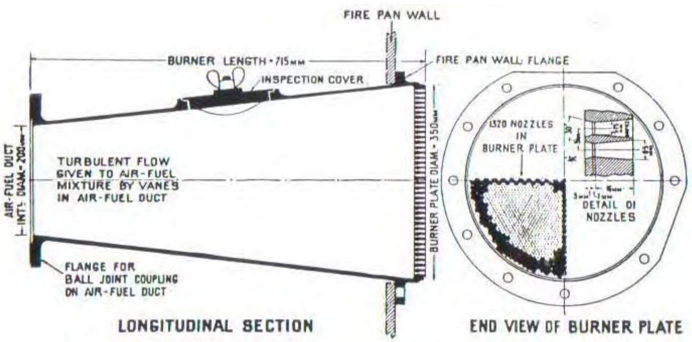
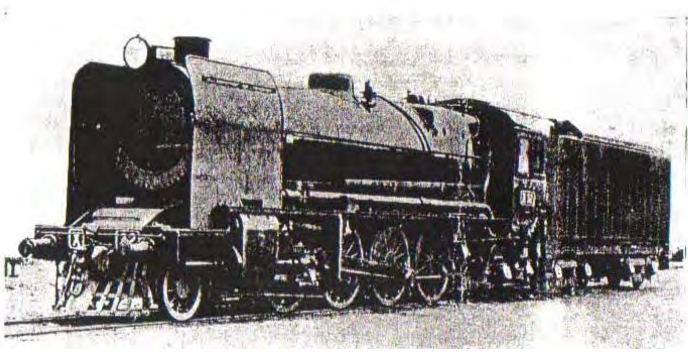


FIG. 511. The Stug burner as used on Victorian locomotive X32.



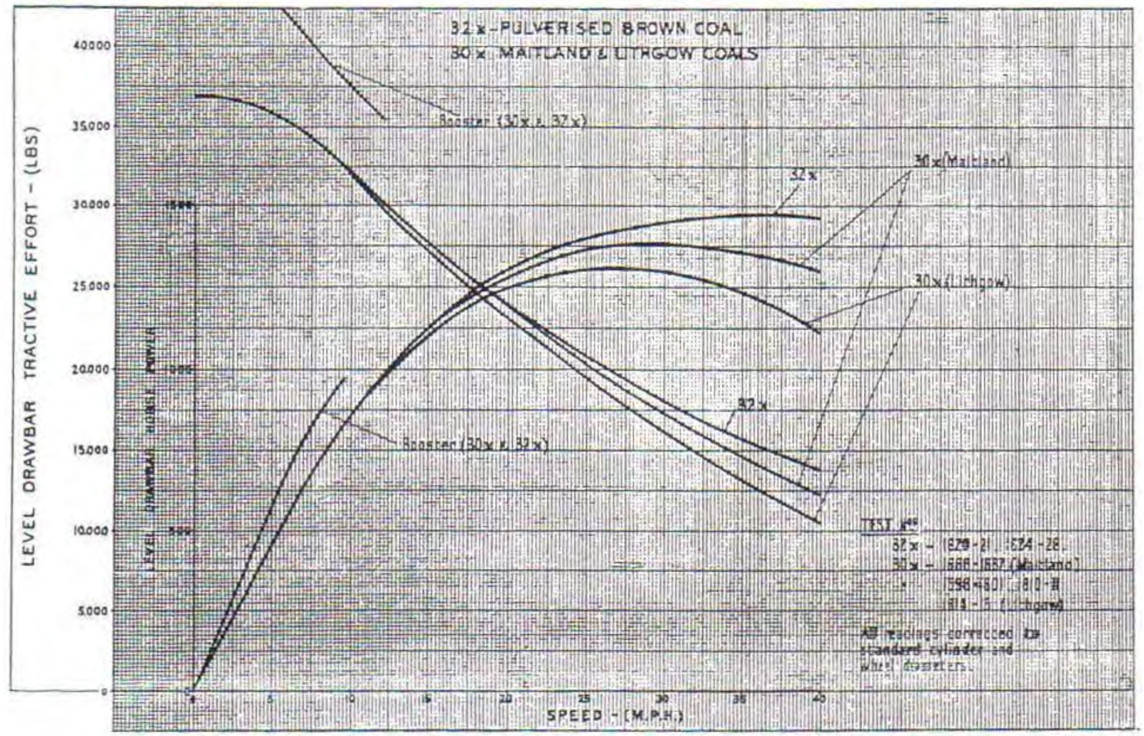


FIG. 514. Dynamometer car tests on Victorian brown coal dust locomotive X32 compared with tests on an X class locomotive burning lump black coal from Maitland and Lithgow, New South Wales.

		Yallourn Dust	Maitland	Lithgow
GCV	Btu/lb	10.540	13,510	11,200
Moisture	%	5.48	2.4	3.7
Volatiles	%	46.9	36.0	27.4
Carbon	%	45.9	53.7	48.9
Ash	%	1.7	7.8	20.0

- Pulverised Coal Loco had higher performance than Standard Loco burning Lump Coal
- PC Boiler Efficiency 75% cf. 65% for Lump Coal
- Concerns about storage of “Coal Dust” proved unfounded

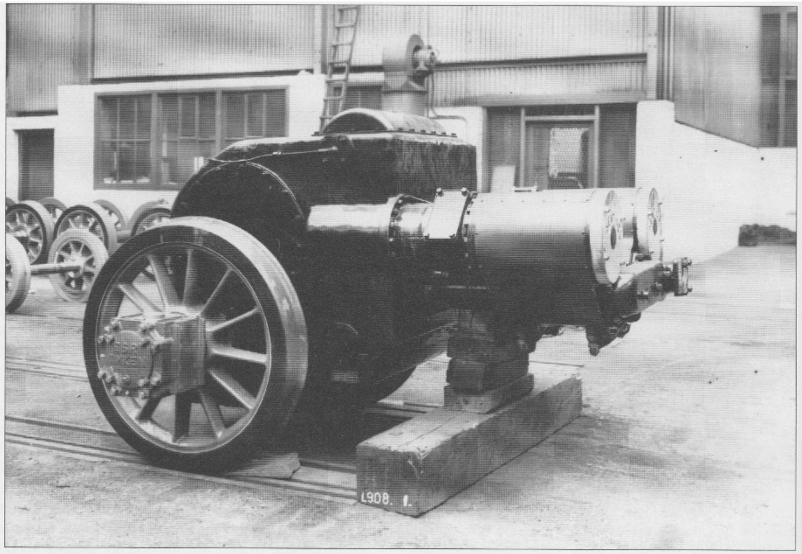
Condensing (1)

- Many attempts to introduce condensing: 2 types
  - Atmospheric – water conservation
  - Vacuum– performance improvement
- All attempts to use sub-atmospheric condensers on locomotives have struggled to maintain design condenser vacuum (i.e. air leaked in)
- Atmospheric condensing locos used successfully in Germany (167 Class 52 KON), Russia (4,200 Class SO^k) and South Africa (90 Class 25C)
- Maintenance costs of 25C significantly higher than 25NC (Girdlestone)
  - Higher man hours to repair (more complex)
  - High cost of spare parts (bought in cf. in-house manuf.)
  - Major problem erosion of blower turbine vanes

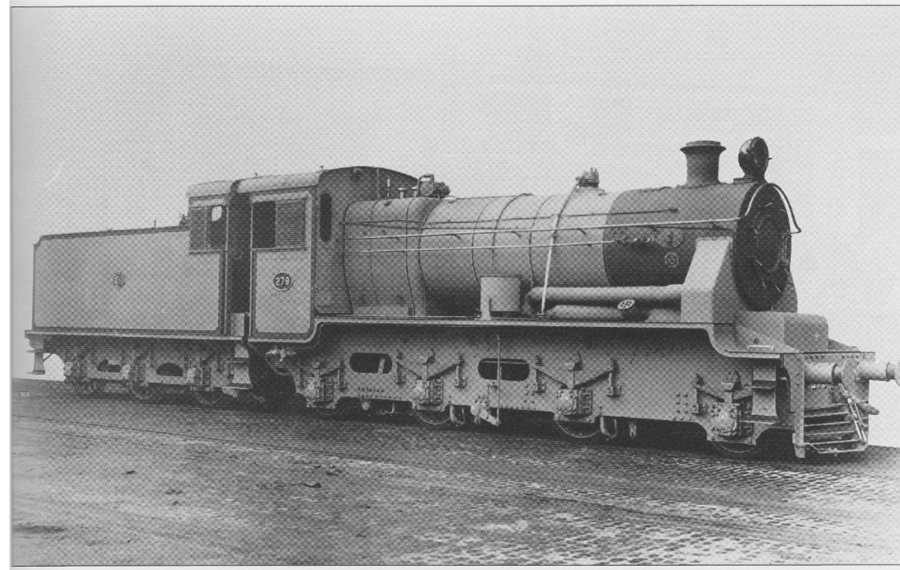
Condensing (2)

- Benefits
  - Greatly Extended Operating Range
    - Elimination of water stops/ pickup
  - Improved performance
    - 9%–16% on SAR Class 20A test
    - Attributed to more even draught
  - Possible to increase adhesive weight
- Drawbacks
  - Cost (CAPEX & OPEX)
  - Complication
  - Dirty (➔ poor combustion)

Alternative Cylinder/ Final Drive Configs.



A Complete Sentinel engine unit for the Egyptian locomotives awaits fitting in the North British Locomotive Company's Workshops in Glasgow. (Author's collection)



Job Number 9299 as completed by the North British Locomotive Company for Egypt. (Author's collection)

- Sentinel Enclosed Engine Unit
  - Fitted to 8 locos & 16 railcars
- Sentinel 6 Cylinder Single Acting Engine
  - Fitted to 163 railcars (52 LNER)

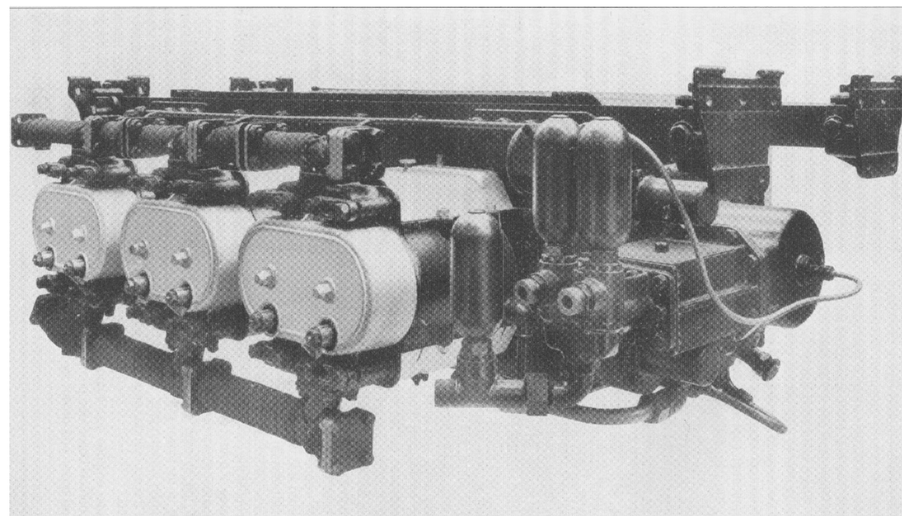
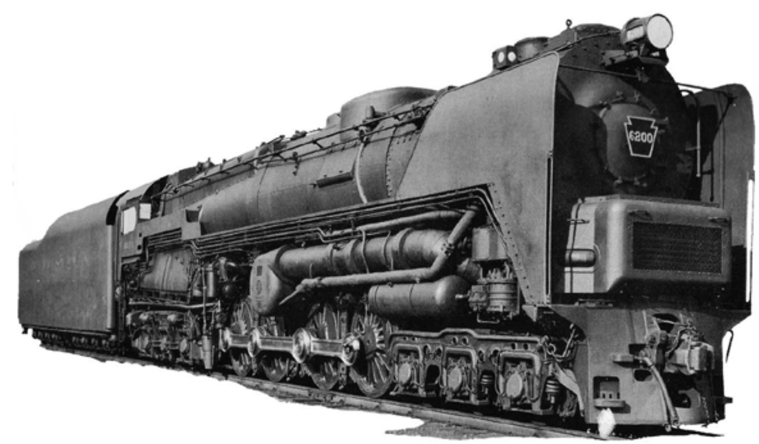


Figure 17: *The six-cylinder Mark I engine from the cylinder side.*

4GS Candidate Advanced Technologies

- Higher Boiler Pressures & Temperatures
  - Chapelon – Triple Expansion, 40 bar
  - Porta – Triple Expansion, 60 bar
- Water Tube Boilers
- Turbine Drive
- Electric Transmission

- Turbocharging
  (“Mechanical Resuperheat”)
  - Sharpe 1982
- Vacuum Condensing



Availability & Utilisation

Top Shed Pacifics 1956

	Sun	Mon	Tues	Wed	Thur	Fri	Sat
60028	X	3.50	Up	3.50	Up	3.50	Up
		4/45		4/45		4/45	
60017	12/18	Up	X	Up	3.50	Up	3.50
			4/45		4/45		W.O.
60025		5.50	5.15	X	5.15	5.15	5.15
		5/0	5/0	5/0	5/0	5/0	5/0
60007	W.O.	Up		Up	X	Up	
	6/0	7/21	5/30	7/21	5/30	7/21	5/30
60022	Up	W.O.	Up		Up	X	Up
		5/30	8/20	5/30	8/20	5/30	8/20
60003	X	10.40	10.40	10.40	10.40	10.40	10.40
		10/45	10/45	10/45	10/45	W.O.	11/0
60014		2.15	2.15	2.15	X	2.15	2.15
		2/0	2/0	2/0		2/0	2/0
60015	W.O.	10.20	10.20	10.20	10.20	X	10.20
		10/35	10/35	10/35	10/35	10/35	10/35
60006	12/18	12/18	12/18	12/18	12/18	12/18	12/18
	W.O.	11/00	11/00	11/00			
60030		9.10	9.10	9.10	9.10	9.10	X

Depot Targets	%
Target Availability	85
Repairs	10
Works	5
	100

		%
Diagrammed	10	48
Spare	8	38
Works	3	14
Allocated	21	100

Diagrammed Locos		
Traffic Days	55	79%
X	9	13%
Washout	3	4%
Idle	3	4%
Total Days	70	100%

- Availability of Diag. Locos < Overall Target
- Utilisation of Diag. Locos 33% max. (8 hrs/24)
- Figures for Spare Locos likely to be worse

Uncomfortable Questions

- Is the boiler the achilles heel of the steam locomotive ?
  - Inspection requirements – safety
  - Maintenance costs
  - ➔ Low Availability ?

  - Frequent Servicing Required
    - Water, Ash, Fuel
    - ➔ Low Utilisation ?

- Does direct side-rod drive inevitably mean low annual mileages ?
  - Fluctuating, asymmetric loads imposed on frames, axleboxes etc.
  - Mitigations – Tandem coupling rods, Franklin Wedges etc.

Design

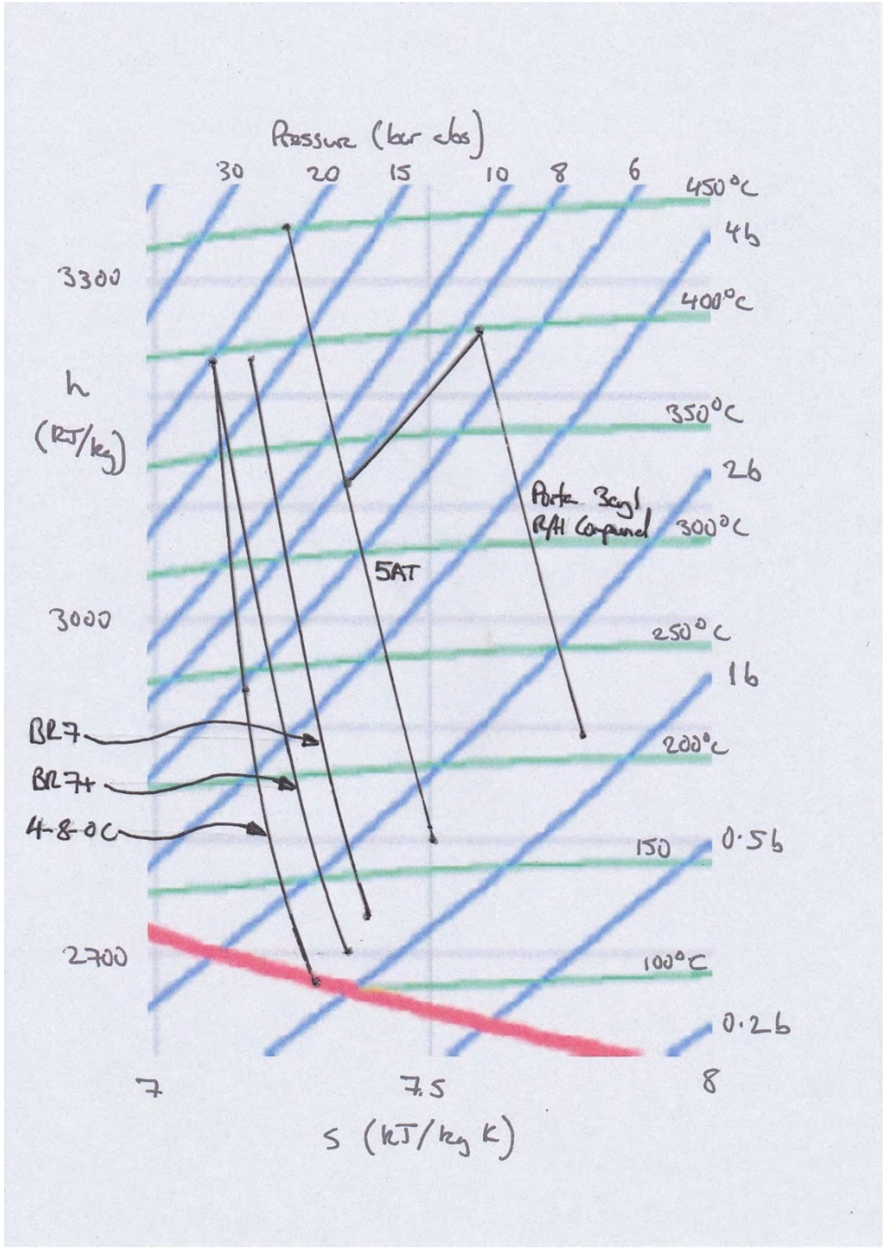
Parametric Design

- Performance estimates largely scaled from 5AT FDC + Roosen for Condensers
  - Major Exception LR
    - N/ton approach not valid for Aerodynamic Drag

  ➔ David Pawson formula used for LR
- Weight Estimates derived from 5AT/ Girdlestone/ Durrant, factored for cycle efficiency
- Deviate as little as possible from traditional Stephenson form to minimise risk
- Introduce new technologies only when absolutely necessary to address shortfalls in traditional Stephenson designs cf. diesels

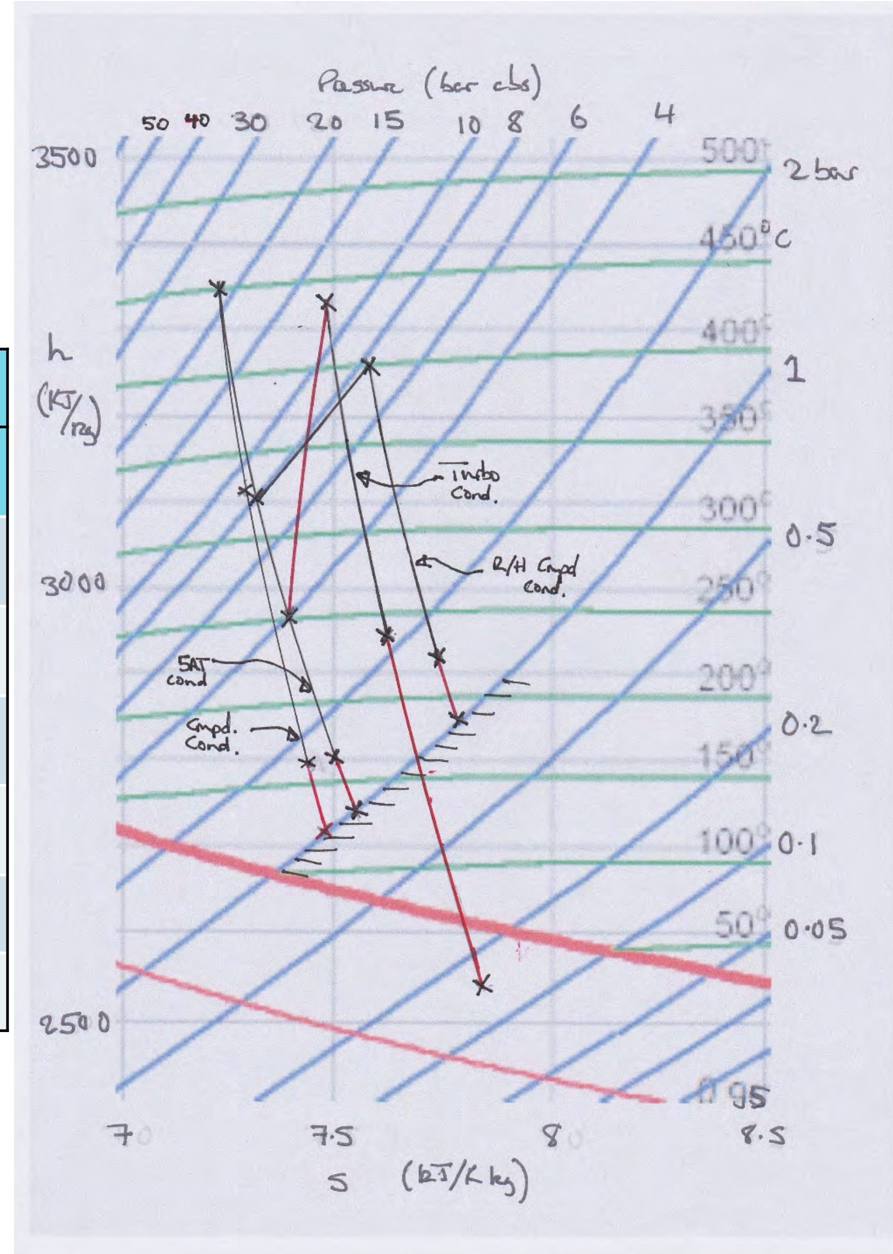
hs Diagram – 1GS & 2GS

@ 70 mph	Evap. (lb/hr)	Pressure (psig)	Temp (deg C)	Delta h (KJ/kg)	Isen. Effy (%)
1GS					
BR7	24,000	250	393	496	86.9
	32,000	250	402	458	86.0
BR7+	24,000	290	393	527	85.0
	40,000	290	410	481	82.8
Chapelon 4-8-0	24,000	290	393	549	91.0
	40,000	290	410	524	89.5
2GS					
5AT	37.789	290	450	550	81.0
Porta 3 cyl compound		290	450	609	83.0



hs Diagram – Condensing Cycles

			Delta h (KJ/kg)		
	Pressure (psig)	Temp (deg C)	Cyls	Turbo	Isen. Effy (%)
3GS					
5AT 1b Cond	290	450	551	73	85
Porta 1b Cond.	290	450	562	75	88
Porta R/H 1b Cond.	290	450	595	74	83
4GS					
Turbo Cond.	290	450	766	403	85



Boiler (1)

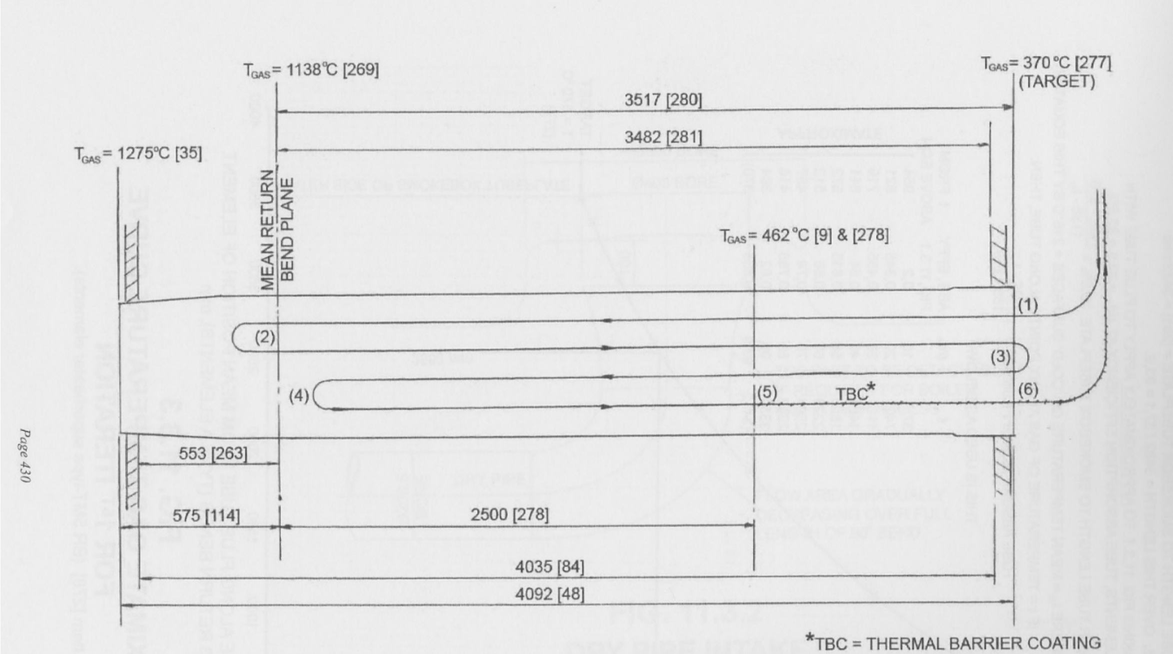
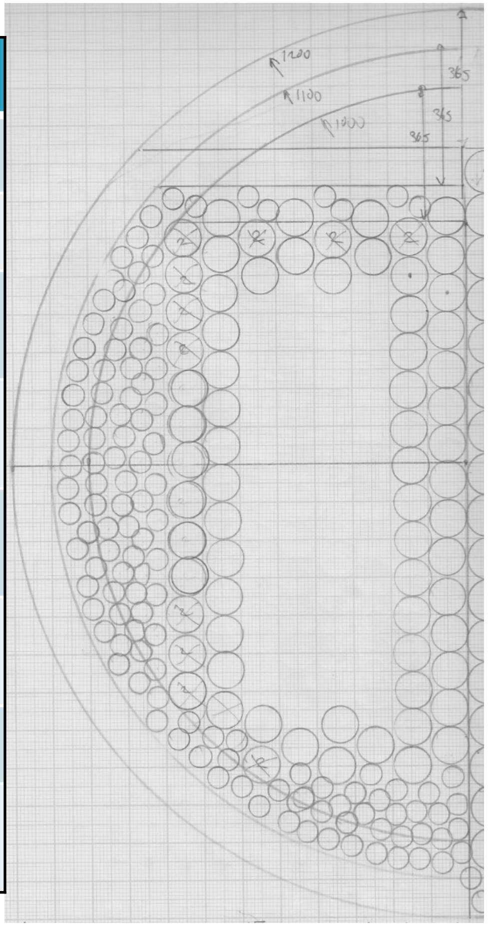


FIG. 11.3.4.
FLUE TUBE-SUPERHEATER ELEMENT ARRANGEMENT
DIAGRAMMATIC AND NOT TO SCALE. FOR ITEM [283].

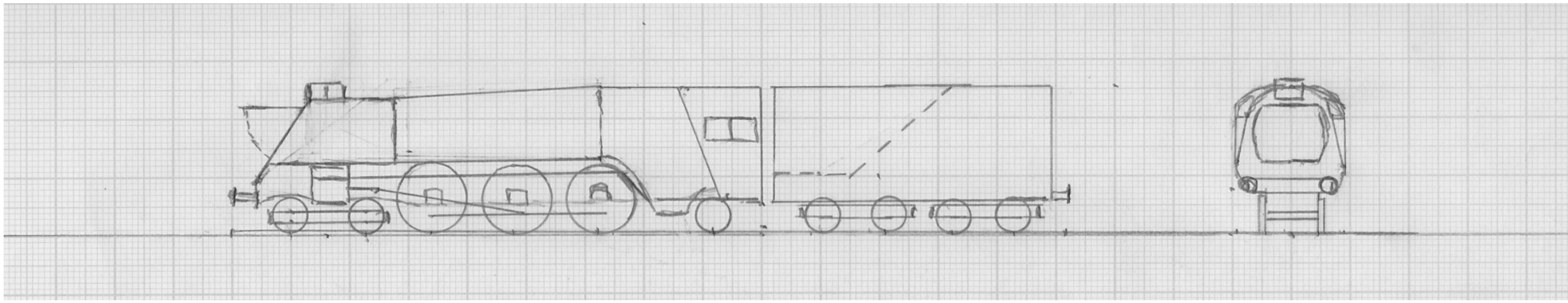
- 5AT Target Steam Temp = 463 degC (450 deg C in cyl)
- ➔ Flue gases cool SH steam once gas temp drops below 463 deg C
- ➔ TBC rqd for final SH element beyond 2.5m
- Tube Length kept constant for 2GS/3GS/4GS designs

Boiler (2)

		5AT	1GS	2GS	3GS	4GS
Max Evap	Kg/hr	17,141	18,611	24,012	36,190	36,429
SH Type		E	A	E	E	E
N Lg tubes		96	90	134	203	204
N small tubes		70	66	102	148	149
R tube bundle	mm	700	819	828	1017	1020
Tube Lgth	mm	4049	5185	4049	4049	4049
Max Dia	mm	1740	1968	1997	2374	2381
Grate Area	m2	2.67	3.90	3.74	5.64	5.67



1GS – 2000hp DE Equivalent



1GS			KX_Edinburgh			
Config.	4-6-2	Steam	Time	Av.Speed	Max Speed	DB Effy
DE Equiv	hp	ihp	hr	mph	mph	%
Class 40	2000	3000	6	67	90	5.6

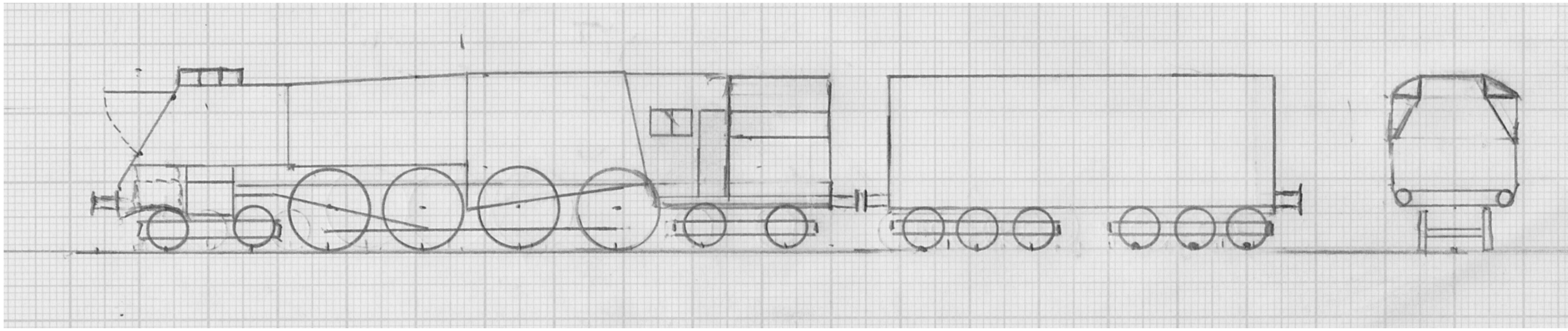
Cylinders		HP	LP
number		2	0
dia	in.	20	
stroke	in.	28	

Weights	Full	Coal	Water
	ton	ton	gall
Loco	98	0	0
Tender	62	10	5,000
Total	160	10	5,000
Max Axle Load	21.5		
Adhesion	64		

Thermodynamics	BR7+	
Max Boiler Pressure	psig	290
Cyl Steam Temp	deg C	410
Max Evap	lb/hr	41,030
Max Coal	lb/hr	6,969
Grate Area	ft2	41.9
N Large Tubes		90
N small tubes		66
Tot. delta h	KJ/kg	433

Starting T.E.	lbf	39,173
Driver Diam.	ft	6.2
Max Boiler Diam.	ft	6.45
Length Overall	ft	71.1

2GS – 3300hp Deltic Equivalent



2GS			KX_Edinburgh				
Config.	4-8-4B	Steam	Time	Av. Speed	Max Speed	DB Effy (%) @ Max Pwr&Speed	
DE Equiv	hp	ihp	hr	mph	mph	Cmpd	Simple
Deltic	3300	4950	6	73	105	9.2	8.6

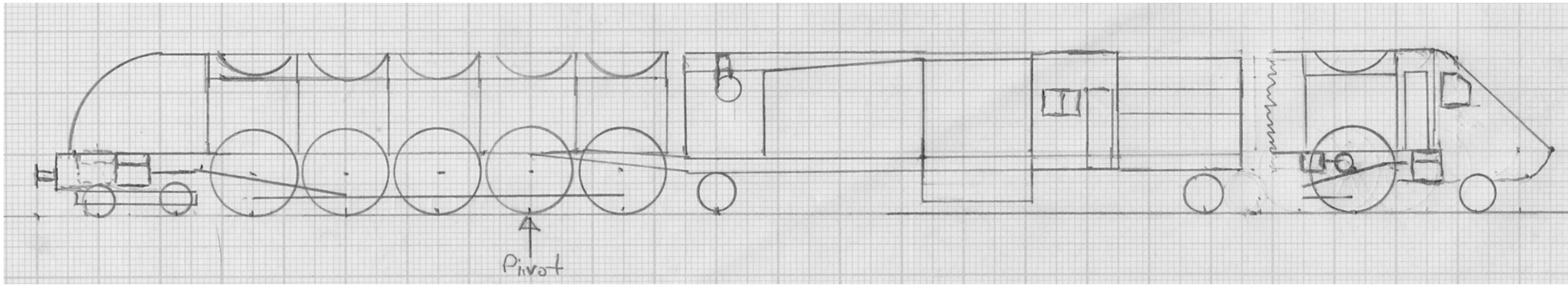
Cyls		HP	LP	S
no.		1	2	3
dia	in.	20.1	24.8	17.0
str	in.	31.5	31.5	31.5

Weights	Full	Coal	Water
	ton	ton	gall
Loco	119	9	
Tender	88		13,200
Total	207	9	13,200
Max Axle Load	20		
Adhesion	80		

Thermodynamics	Porta R/H Cmpd	
Max Boiler Pressure	psig	305
Cyl Steam Temp	deg C	450
Max Evap	lb/hr	52,630
Max Coal	lb/hr	6,465
Grate Area	ft2	40.2
N Large Tubes		134
N small tubes		102
Tot. delta h	KJ/kg	582

Starting T.E.	lbf	50,252
Driver Diam.	ft	5.84
Max Boiler Diam.	ft	6.55
Length Overall	ft	82.5

3GS – 4500hp HST Equivalent



3GS			KX_Edinburgh				
Config.	4-10-2+ 2-10-4	Steam	Time	Av. Speed	Max Speed	DB Effy (%) @ Max Pwr&Speed	
DE Equiv	hp	ihp	hr	mph	mph	Cond	NC
HST	4500	6750	5	89	125	7.3	7.3

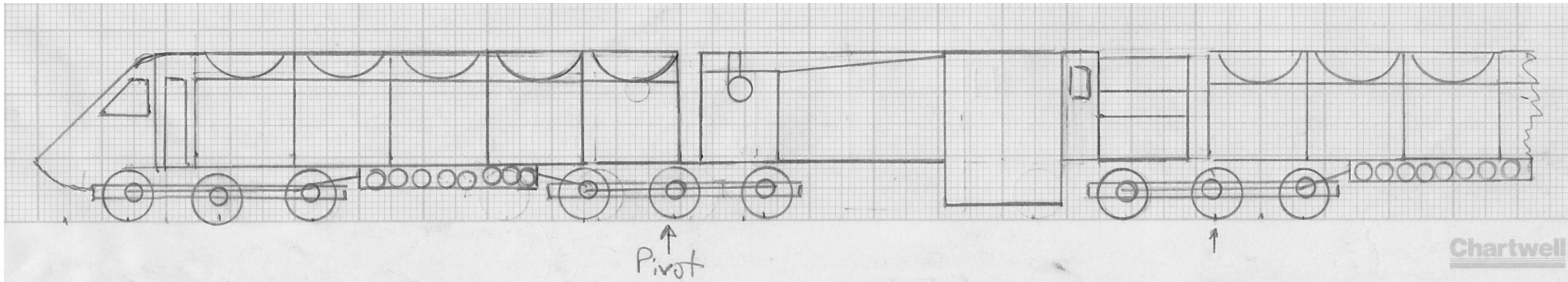
Thermodynamics	5AT Cond.	
Max Boiler Pressure	psig	305
Cyl Steam Temp	deg C	450
Max Evap	lb/hr	79,784
Max Coal	lb/hr	10,915
Grate Area	ft2	60.6
N Large Tubes		203
N small tubes		148
Tot. delta h	KJ/kg	523

Cylinders		Trad.	Encl.
number		6	20
dia	in.	21.0	15.0
stroke	in.	31.5	18.0

Weights	Full	Coal	Water
	ton	ton	gall
Loco (Cond.)	280	15	1,500
Loco + Tender (NC)	373	15	24,000
Max Axle Load	20		
Adhesion	200		

Starting T.E.	lbf	129,135
Driver Diam.	ft	6.95
Max Boiler Diam.	ft	7.78
Length Overall	ft	148.2

4GS – 6000hp Electric Equivalent



4GS			KX_Edinburgh			
Config.	Co-Co+ Co-Co	Steam	Time	Av. Speed	Max Speed	DB Effy @ Max Pwr&Speed
DE Equiv	hp	ihp	hr	mph	mph	%
Class 91	6300	9450	4	100	140	10.9

Cylinders		HP	LP
number		16	16
dia	in.	13.8	18.1
stroke	in.	19.7	19.7

Weights	Full	Coal	Water
	ton	ton	gall
Loco	227	10	1,000
Tender			
Total	227	10	1000
Max Axle Load	19		
Adhesion	227		

Thermodynamics	Turbo Single Act.	
Max Boiler Pressure	psig	305
Cyl Steam Temp	deg C	450
Max Evap	lb/hr	80,311
Max Coal	lb/hr	7,889
Grate Area	ft2	61.0
N Large Tubes		204
N small tubes		149
Tot. delta h	KJ/kg	728

Starting T.E.	lbf	131,766
Driver Diam.	ft	3.93
Max Boiler Diam.	ft	7.81
Length Overall	ft	142.0

Assessment

	Diesel Equiv.	Assessment
1GS	Class 40	Steam cheaper, much lower risk
2GS	Deltic	Technology to match Deltic performance with steam available in 1950s
3GS	HST	Reaching limits of 5AT technology
4GS	Class 91	Further improvements possible if greater complexity accepted

Requirements Steam vs. Diesel	1GS	2GS	3GS	4GS
Modern Looking	X	X	X	X
Cleaner		X	X	X
Less Manual Labour	X	X	X	X
Low Speed Performance	X	X	X	X
Reduced OPEX		X	X	X
Increased Operating Range			X	X
Reduced terminal time		X	X	X
Reduced servicing				X
Increased major repair intervals				X

Conclusions

- Yes, BR could have done something different
- Proven technologies were available
- Performance is the easiest issue to address once manual firing limit removed
- Competitiveness of steam dependent on price ratio of coal/oil (and environmental acceptability)
- Availability & Utilisation constraints of steam may be limiting factors, not performance

- Still To Come:
  - Freight Locos
  - Shunters
  - Multiple Units

End of Part 2
Presentation

Main References

- Performance
  - 5AT FDCs, Wardale & Newman, ASTT, 2015
  - “Selection of papers by L.D.Porta Vol 2”,ASTT
  - “La Locomotive a Vapeur”, Chapelon/Carpenter, Camden, 2006
  - “The Benefits of Compounding”, Pawson,
  - “Coal Burning Locomotives for the 1990s”, Sharpe, 1981
  - Locomotive Panorama Vol 1 & 2, Cox, Ian Allan, 1965
  - Bulleid IMechE Presidential Address,1947
- Pulverised Coal Burning
  - “Brown Coal” ,H. Herman, State Electricity Commission of Victoria, 1952
- Condensing
  - “Camels & Cadillacs”. Phil Girdlestone, Stenvalls 2014
  - “Condensing Locomotives”, Lomonossoff & Lomonossoff, IMechE paper 1945
  - “Class 25 Condensing Locomotives on SAR – Design & Operating Experiences”, Roosen, IMechE paper 1960
- Other
  - “Sentinel Locomotives & Sentinel-Cammell Railcars”, Hutchings, IRS, 2020
  - “Garratt Locomotives of the World”,Durrant, David & Charles, 1981
  - “Top Shed”, Townend, Ian Allan, 1975