The Physiology of the Locomotive Boiler

- Another Peep!

ASTT Conference, Doncaster

Adrian Tester - 16th October 2022

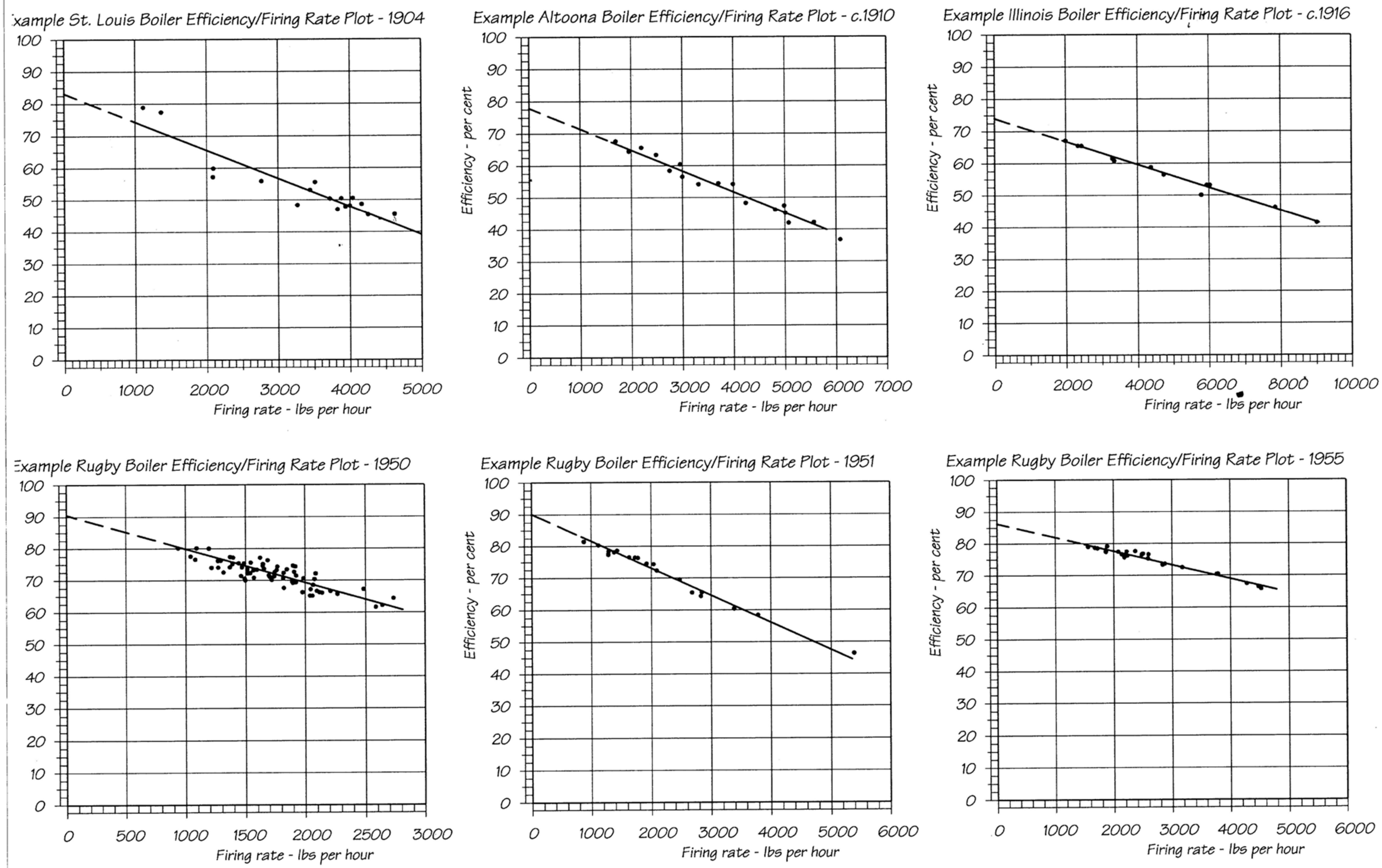


Fig. II.5 - The improvement in the accuracy of boiler efficiency tests with experience

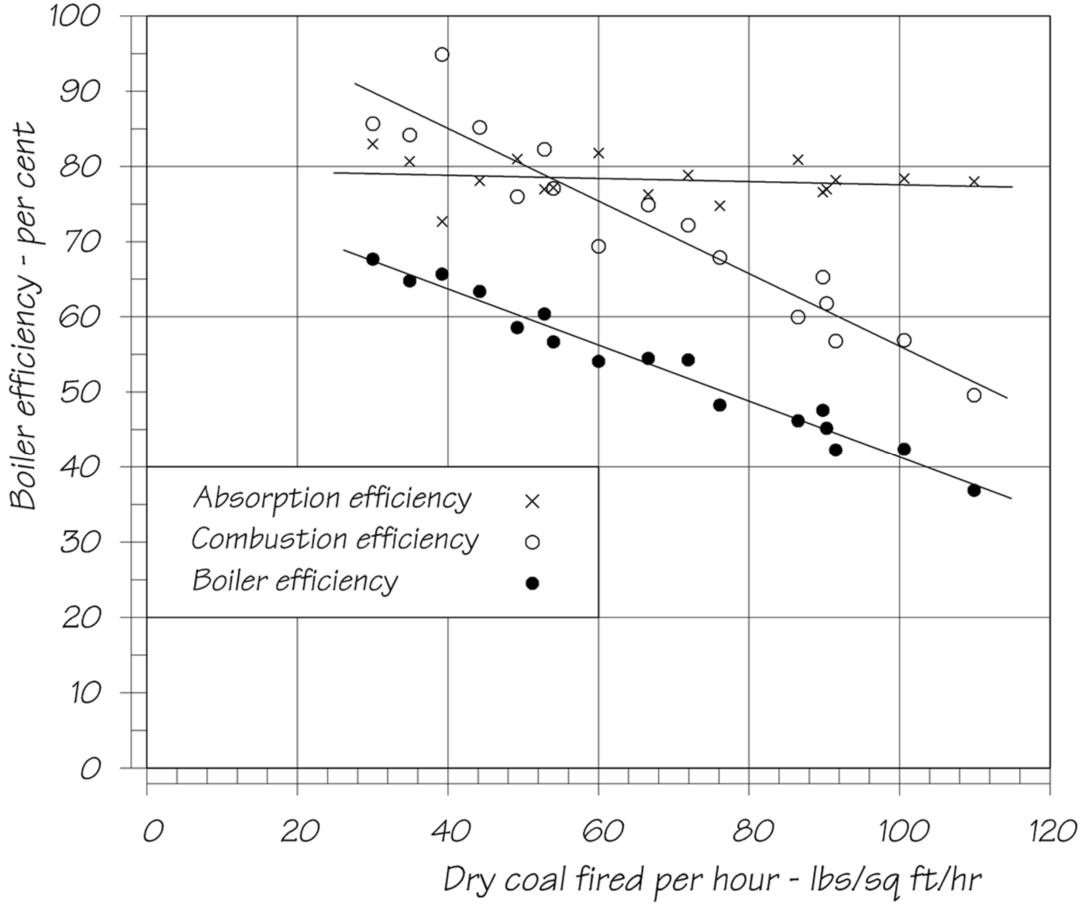
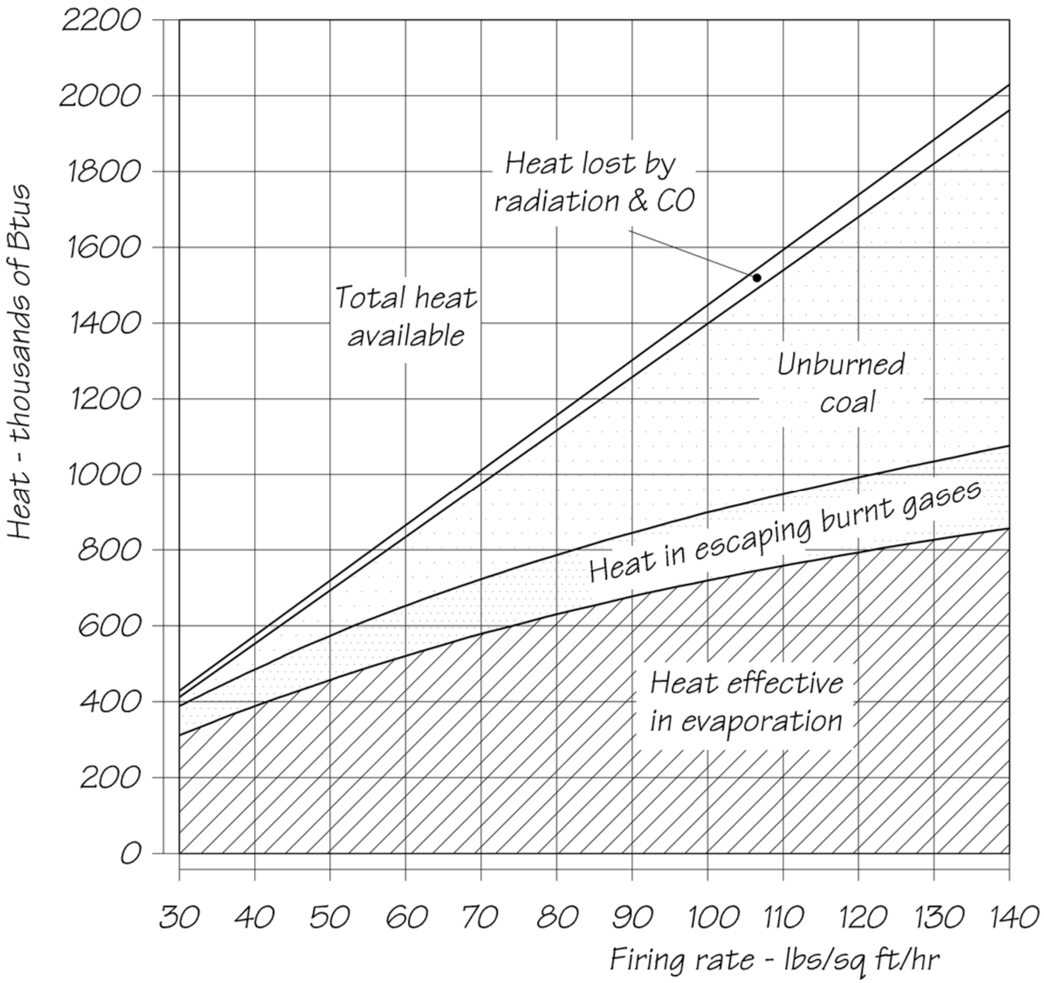


Fig. II.4 – Boiler efficiency curves for Pennsylvania Railroad E2a 4-4-2 N° 5266 tested at Altoona in 1905 – analysis by Lawford Fry



This figure is a way of demonstrating the heat balance, but serving to emphasize the losses and the useful heat absorbed in evaporation relative to the heat in the fuel fired. The first appearance of this format seems to have been in the paper *Some Effects of Superheating and Feed-Water Heating on Locomotive Working* by Messrs Trevithick and Cowan in 1913, which in a slightly modified form appears here. The heat input, represented by the specific firing rate follows a simple linear relationship formed from the product of firing rate and calorific value. The second linear curve represents the available heat after the reduction for the standing loss. It also includes the carbon monoxide loss. The proportion of the total heat utilized in steam production is seen to fall as the rate of firing increased. Due to the remaining two curves being parabolas, the proportion of the total heat in the coal fired which escaped unburned increased ever more rapidly until the grate limit was reached. This prompted consternation and disbelief amongst some of the engineers present - as doubtless was intended. William Rowland thought the diagrams unreliable and the unburned loss could not be anything like what was being suggested - a point taken up by George Churchward.......

Fig. IV.10 - Approximate heat utilized and lost per square foot of grate per hour at different firing rates - St Louis Test Series 200 - Lake Shore & Michigan Southern Railway 2-8-0 N º 734

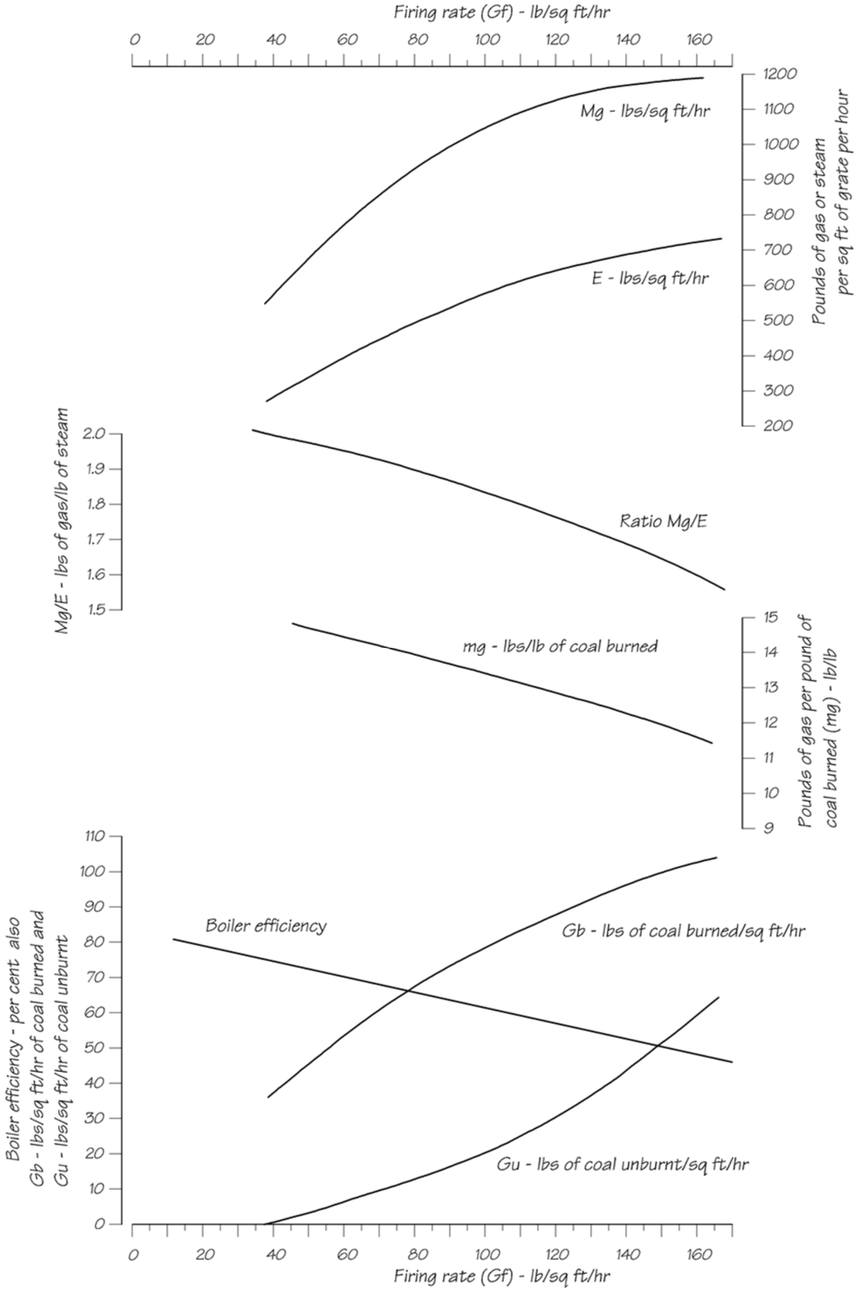


Fig IV.24 - Boiler performance chart for unidentified SAR locomotive - Dr M M Loubser's paper ***Some Aspects of Railway Mechanical Engineering***

The bottom pair *Gb* and *Gu* record the coal burned as opposed to the coal escaping unburned when plotted against the specific firing rate *Gf* – lbs/sq ft/hr of grate.

The diagram shews another way of displaying boiler performance as opposed say the the BR four-quadrant version used in Bulletins. Boiler efficiency follows the familiar linear relationship against firing rate. The topmost pair of curves, approximating to the anticipated parabolic, describe the evaporation and the flue gas produced per square foot of grate. The middle two curves both exhibit distinct curvature, though this is less pronounced in the case of specific gas production *mg* per pound of coal fired compared to the ratio *Mg/E* pounds of gas per pound of steam. Lawford Fry considered the first relationship to be linear, giving several examples in ***A Study of the Locomotive Boiler*** with engines draughted nearly to the grate limit. Mr Ell advised when the flue gas *Mg* is plotted against steam production *E* the resulting curve is linear but plotting against firing rate results in a curve.

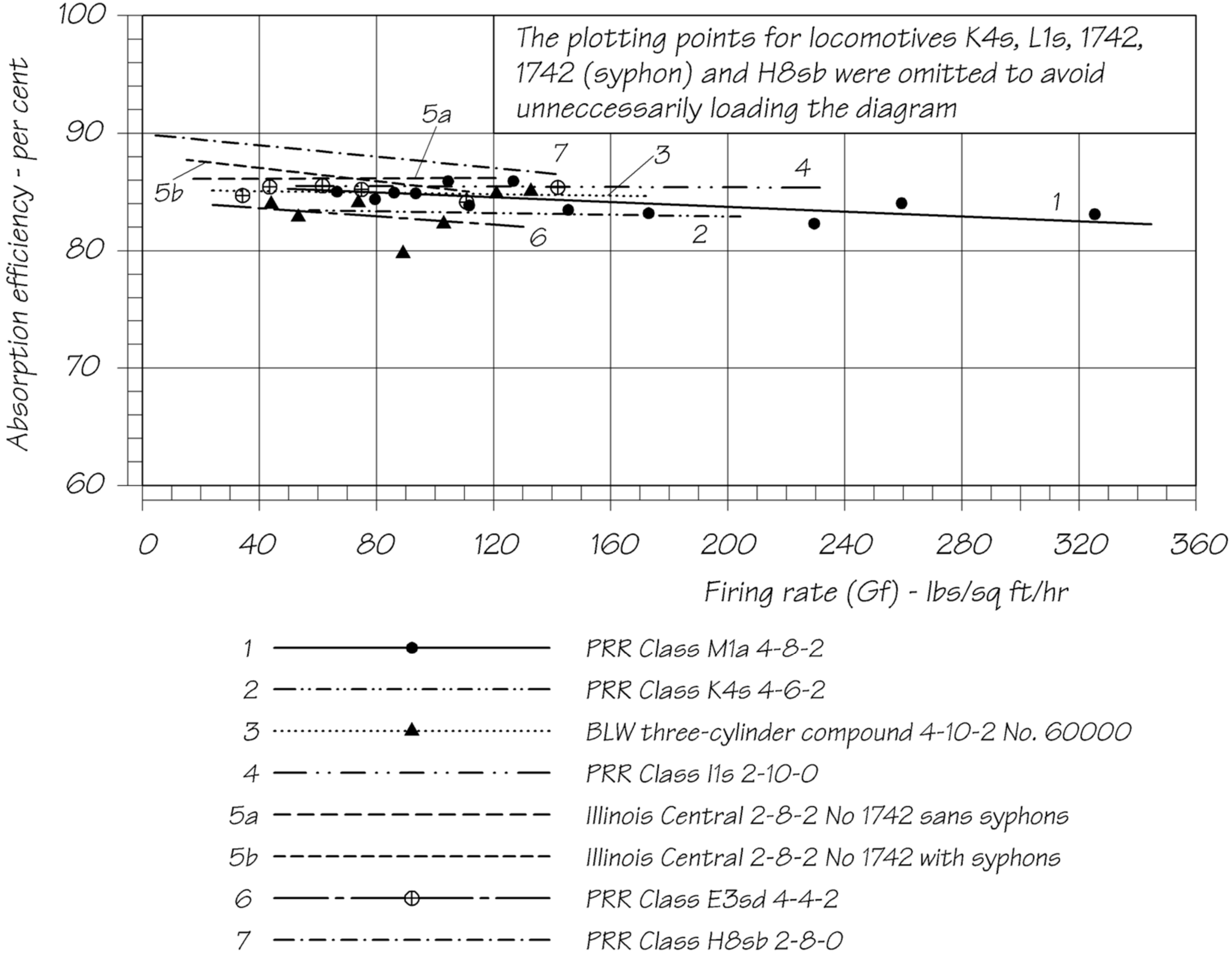
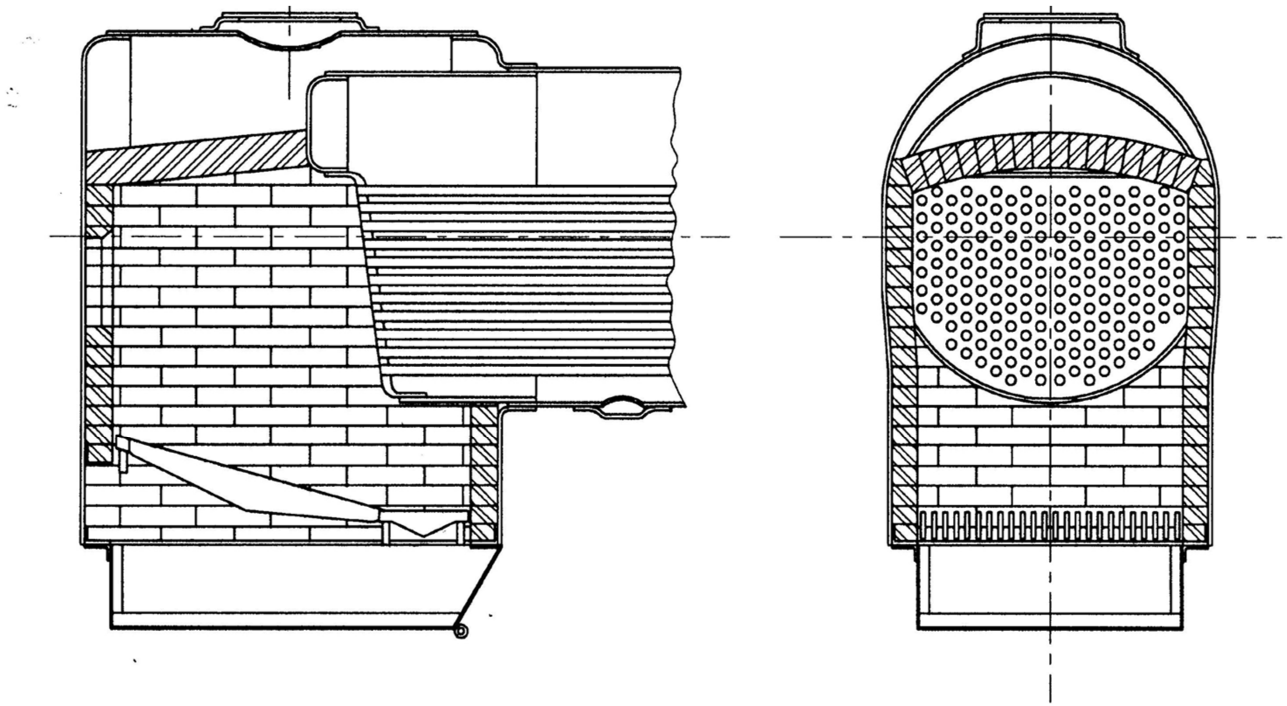


Fig. III.18 – Comparison in the absorption efficiency for a selection of American boilers – A Chapelon La Locomotive à Vapeur



Locomotive	Line	Distance - km	Load - tons	Ton-km	Coal consumption		Water consumption	
					Total - kg	per ton-km	Total - kg	kg/kg
19	Budapest - S Tarjau	123.4	380.0	46892	2,471	0.0527	11,550	4.67
104	- do -	123.4	352.8	435.4	2,425	0.0557	11,490	4.73
19	Budapest - Miskolcz	182.6	301.8	550.0	3,360	0.0611	15,410	4.59
104	- do -	182.6	292.5	534.4	3,428	0.0641	15,140	4.41
19	**Averaged results of the above**	**153.0**	**340.9**	**521.6**	**2,916**	**0.0559**	**13,380**	**4.62**
104	**- do -**	**153.0**	**322.7**	**493.7**	**2,927**	**0.0593**	**13,320**	**4.55**

Fuel - brown coal from S. Tarjau mines

Six-coupled goods engine No 19 was fitted with an ordinary firebox, No 104 was fitted with a Verderber firebox - both engines were class III.

Fig. VI.29 - Boiler having no direct heating surface - Verderber boiler Hungarian State Railways

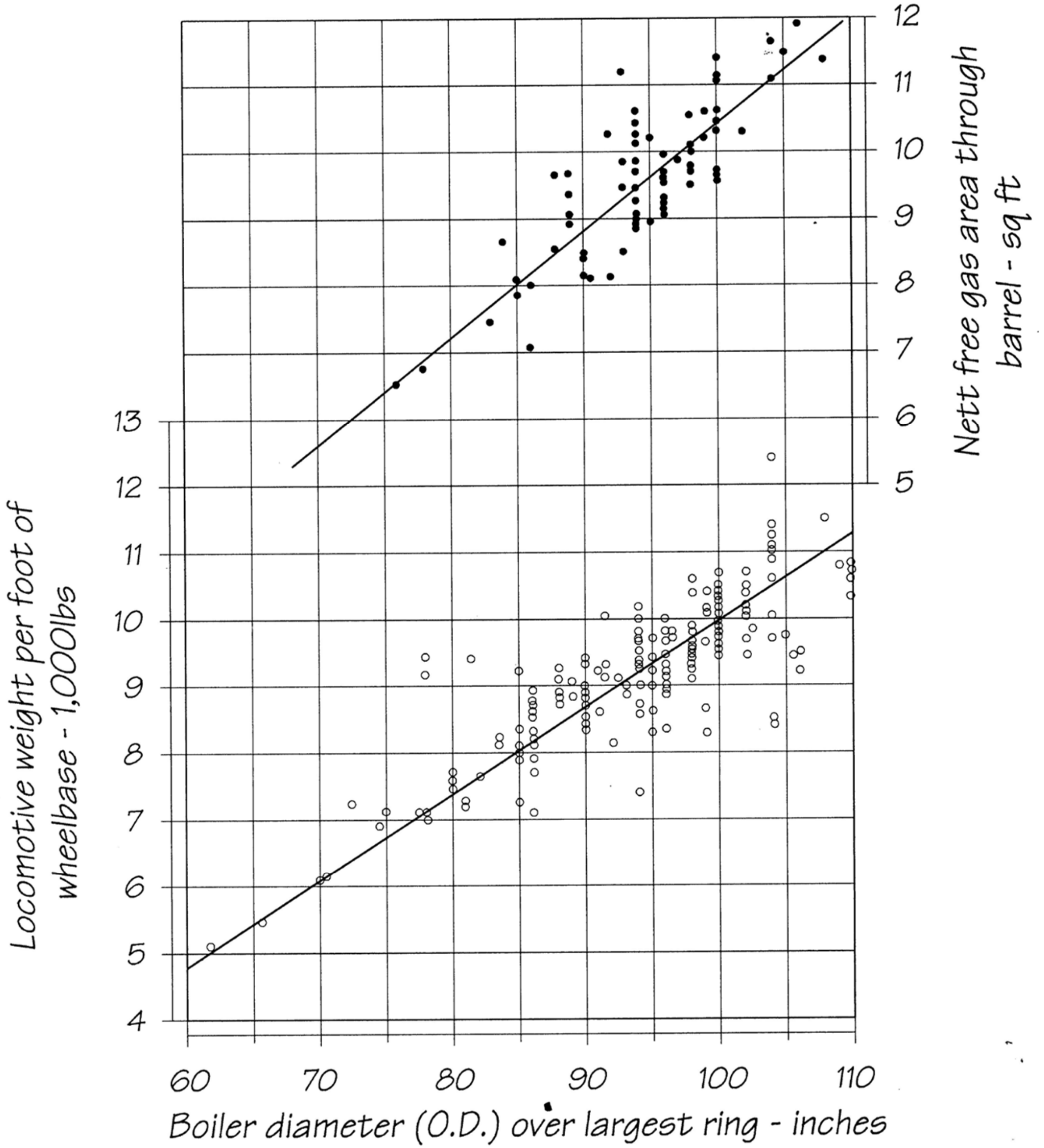
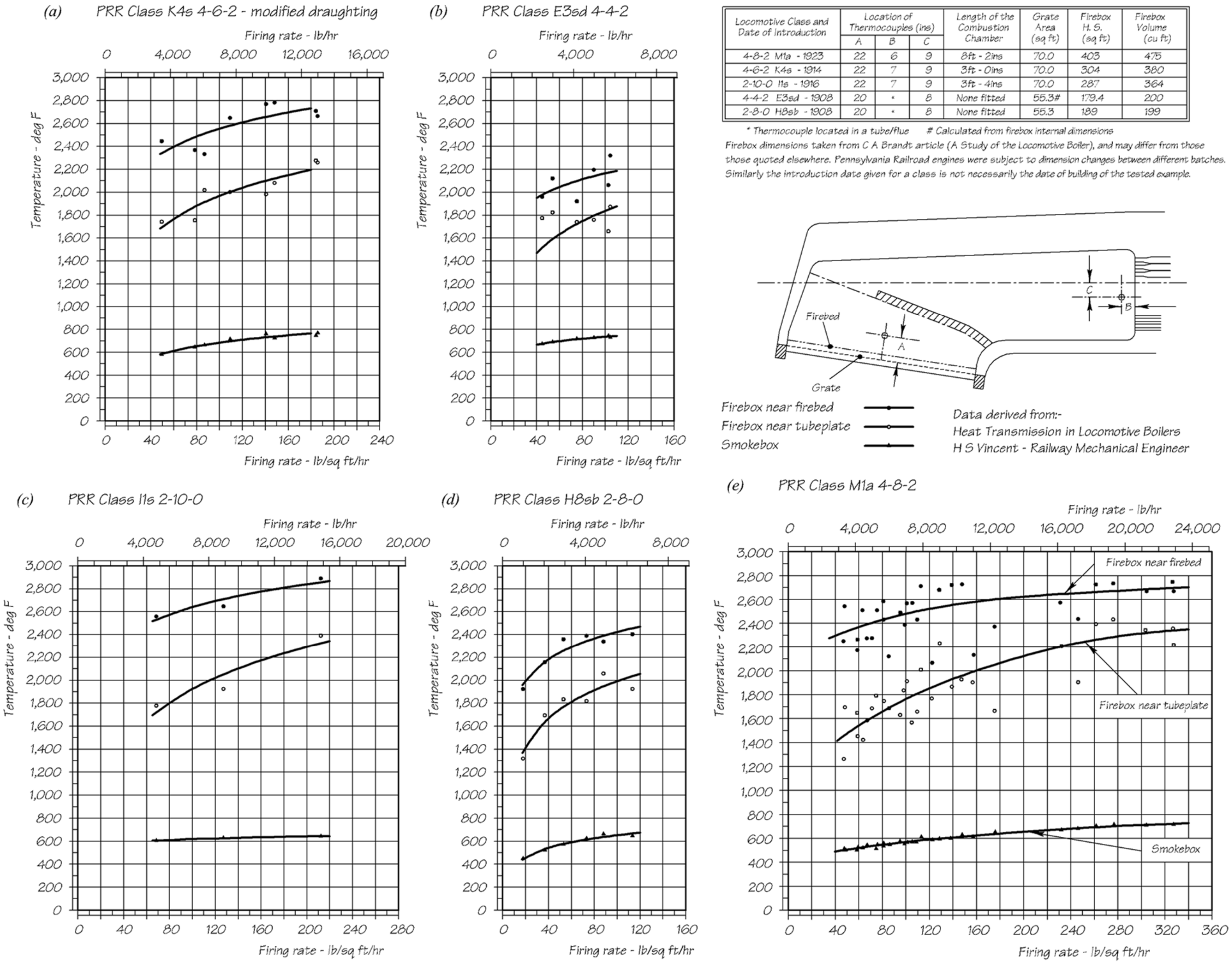


Fig IV.27 - Relation of boiler diameter to total weight of locomotive per foot run of wheelbase and also the available free gas area provided



Locomotive Class and Date of Introduction	Location of Thermocouples (ins)			Length of the Combustion Chamber	Grate Area (sq ft)	Firebox H. S. (sq ft)	Firebox Volume (cu ft)
	A	B	C				
4-8-2 M1a - 1923	22	6	9	8ft - 2ins	70.0	403	475
4-6-2 K4s - 1914	22	7	9	3ft - 0ins	70.0	304	380
2-10-0 I1s - 1916	22	7	9	3ft - 4ins	70.0	287	364
4-4-2 E3sd - 1908	20	*	8	None fitted	55.3#	179.4	200
2-8-0 H8sb - 1908	20	*	8	None fitted	55.3	189	199

* Thermocouple located in a tube/flue # Calculated from firebox internal dimensions

Firebox dimensions taken from C A Brandt article (A Study of the Locomotive Boiler), and may differ from those those quoted elsewhere. Pennsylvania Railroad engines were subject to dimension changes between different batches. Similarly the introduction date given for a class is not necessarily the date of building of the tested example.

Fig. IV.1 – Example firebox and smokebox temperatures recorded in PRR classes tested at Altoona

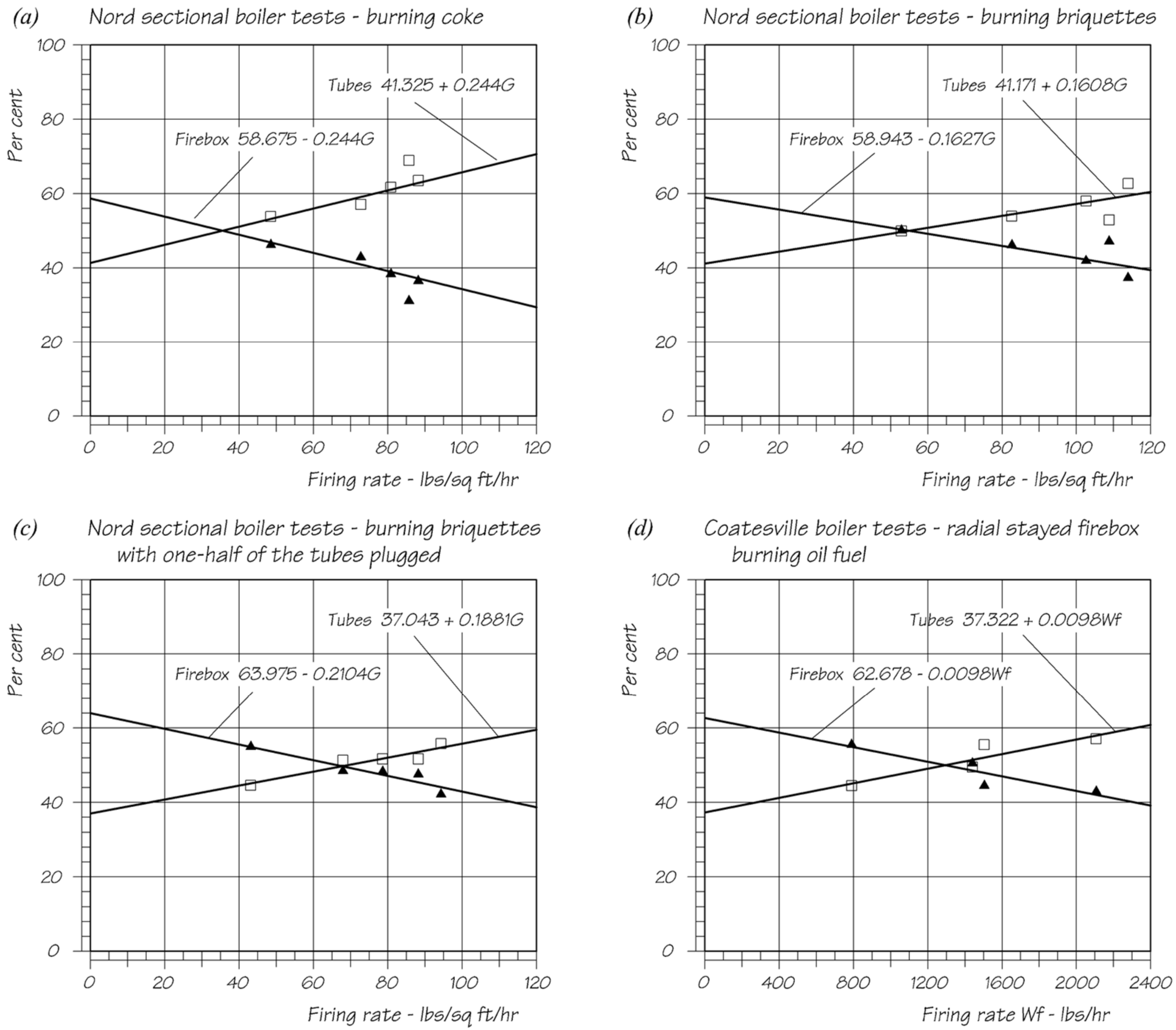
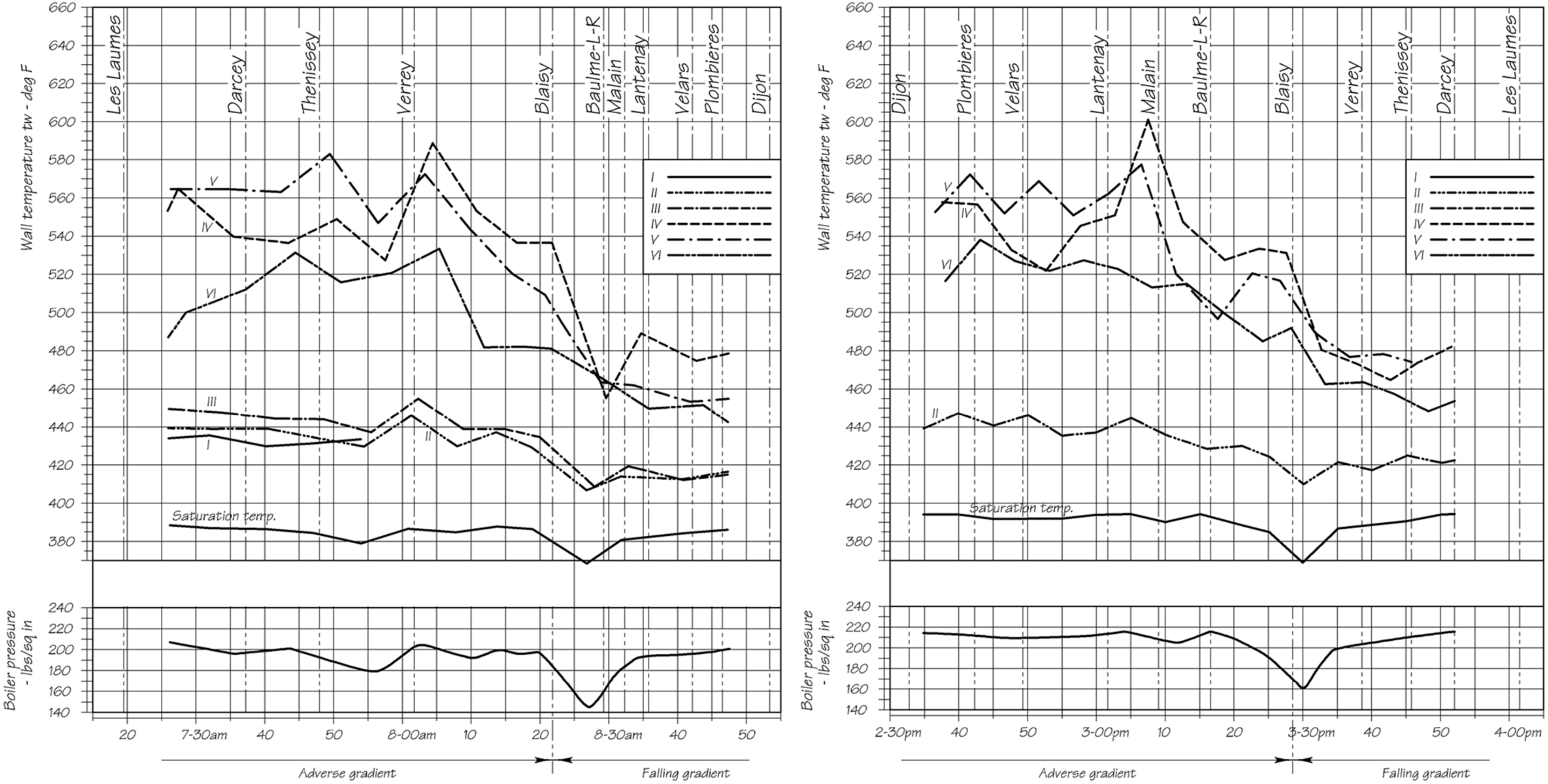


Fig. IV.3 – Observed change in heat apportionment between direct and indirect surfaces with rise in steam output – Nord and Coatesville boiler tests



Copper firebox - locomotive No. 141-C-448; left hand diagram running from Les Laumes to Dijon hauling train M.15 (902 tons) on 29th February 1940; right hand diagram running from Dijon to Les Laumes hauling train M.52 (894 tons) on 1st March 1940.

Fig. VII.30 - Comparison in wall temperatures in copper and steel fireboxes - South-western region of the SNCF 1940

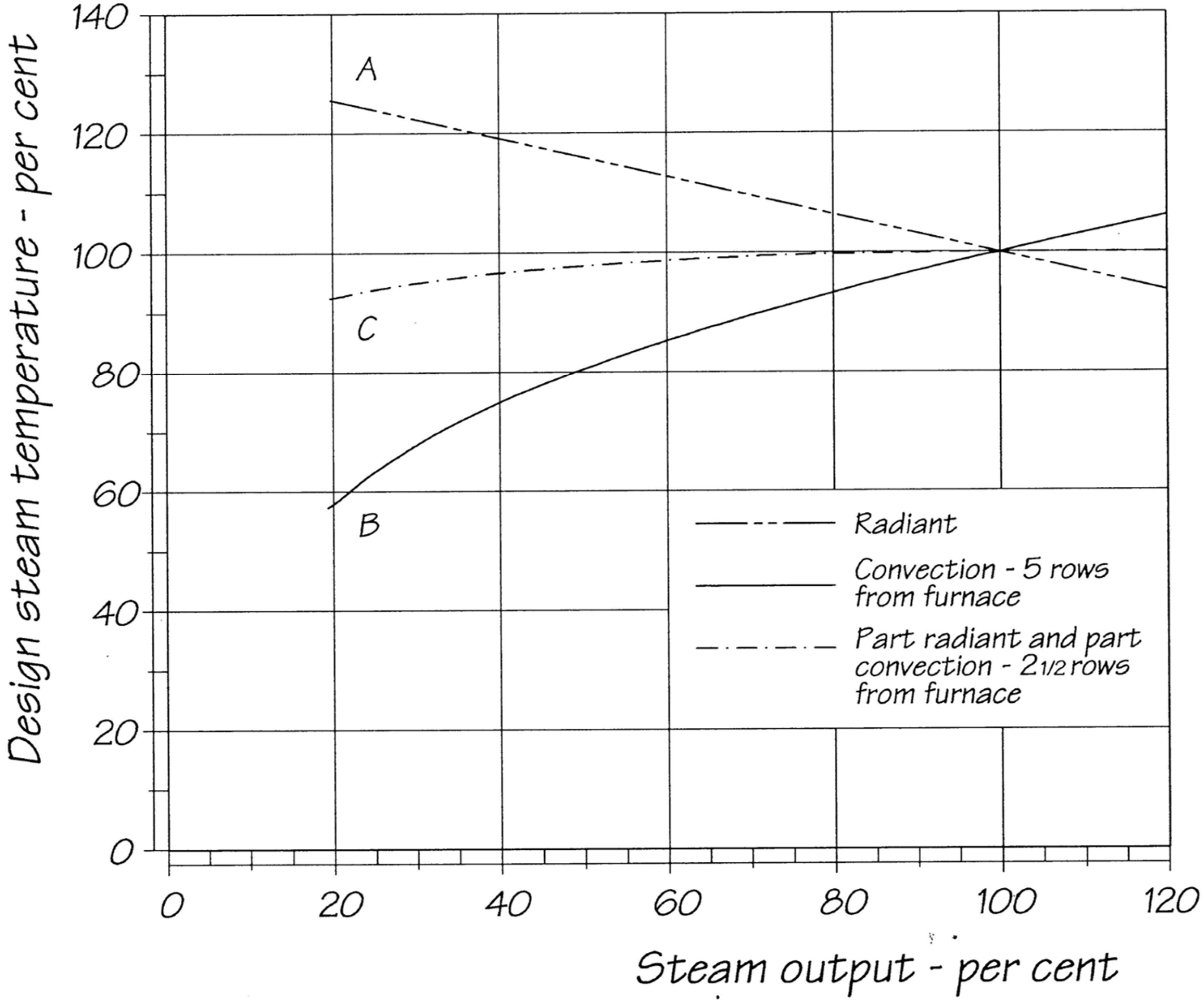
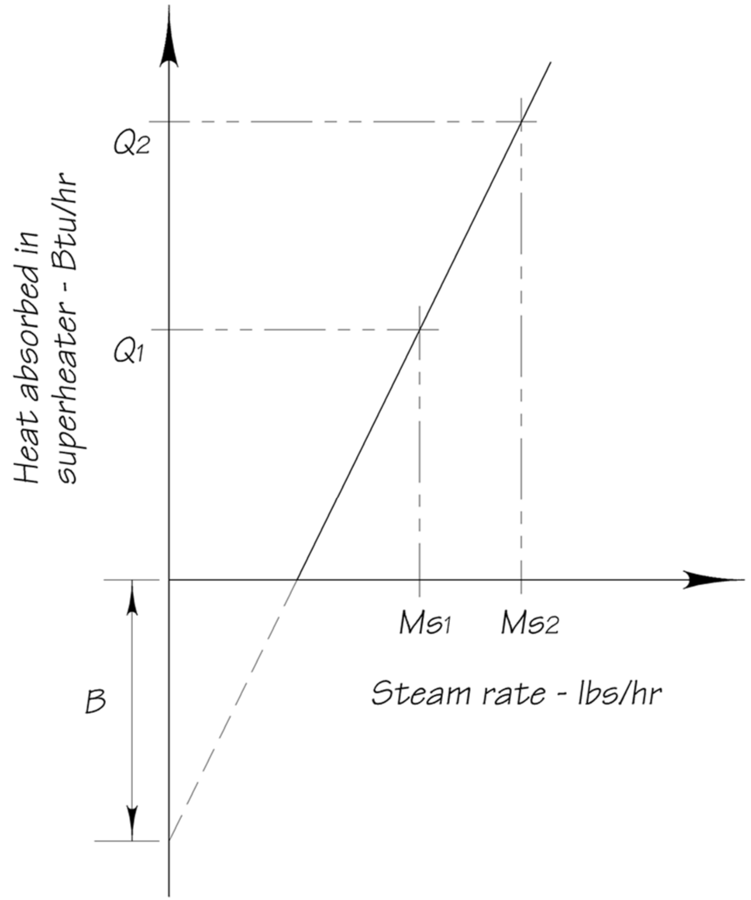


Fig. IX.4 - Superheater characteristics or the differences between radiant and convective superheaters



	A	B	R^2
LMS Class 4 2-6-0	208	478,530	0.9998
BR Class 4 4-6-0	188.95	606,204	0.9999

Fig. IX.30 – Linear relationship describing the heat absorbed in the superheater

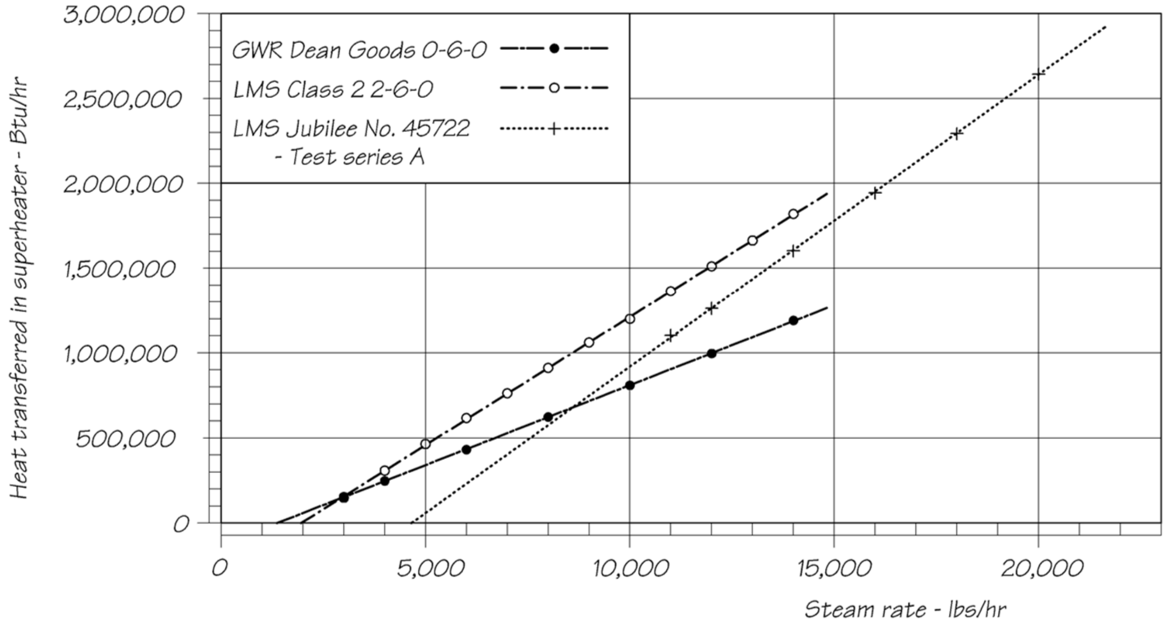
Usually appearing in locomotive test data is a curve or table recording the steam temperature obtained at certain steam rates. By assuming a constant dryness fraction and boiler pressure we may *estimate* the *amount* of heat the steam absorbed during its passage through the elements. When a series of these heat absorptions is plotted against steam rate they will be found to lie very close to a straight line. This linear curve is of the form:-

$$Q = (A \times Ms) - B$$

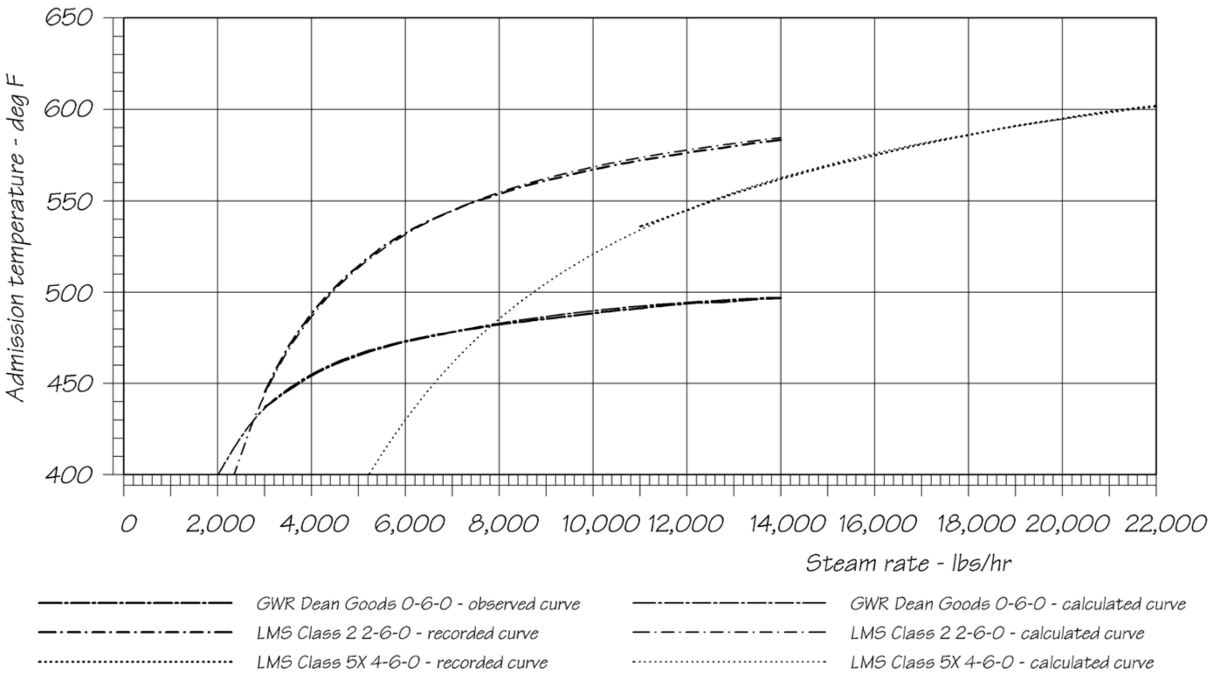
In this relationship *A* is the gradient of the curve obtained from:-

$$A = \frac{Q2 - Q1}{Ms2 - Ms1}$$

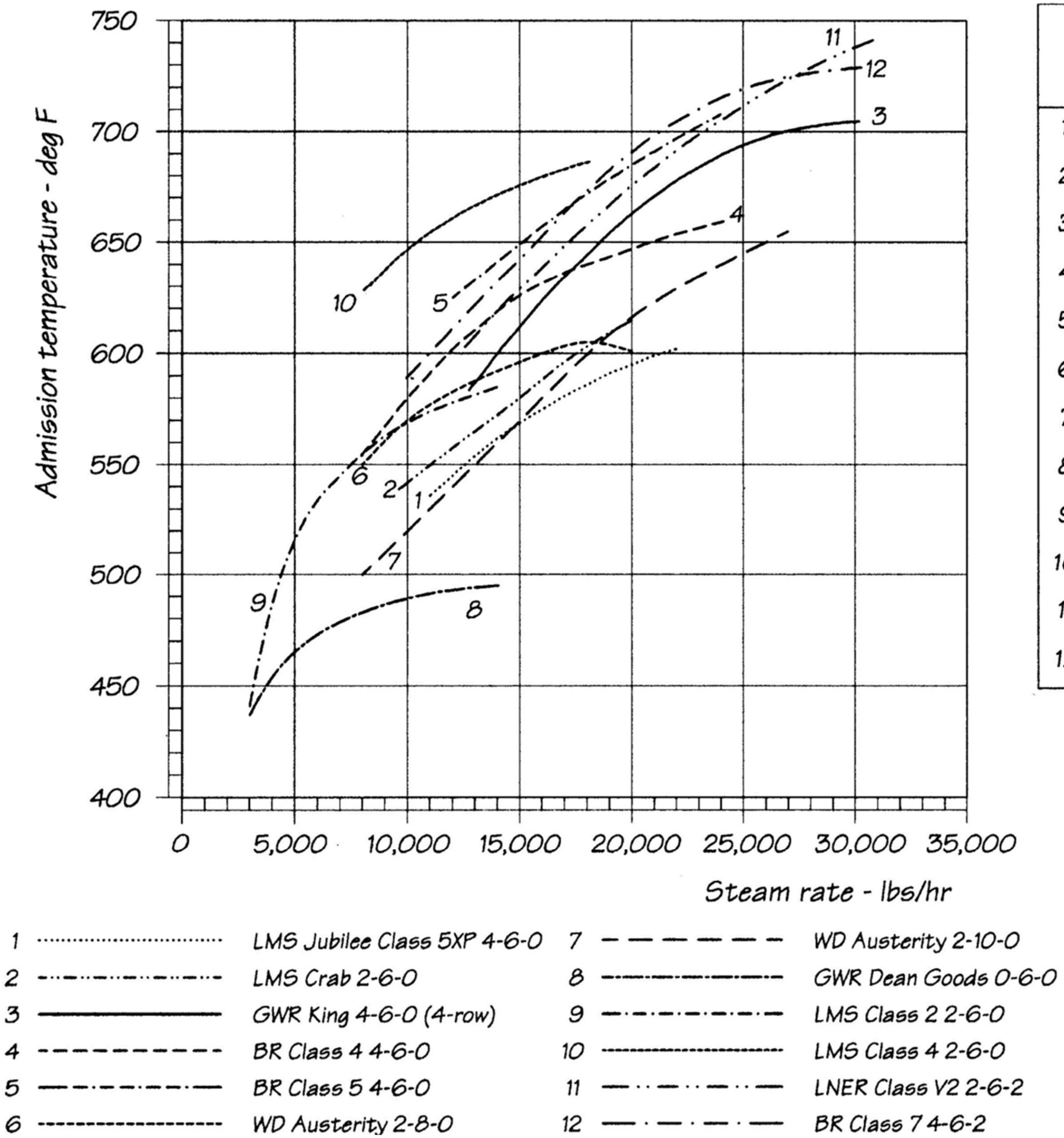
It indicates the rate at which the superheater is absorbing heat per pound of steam passing through it. From this we may appreciate the larger the value assumed by constant *A*, the steeper the curve and therefore the hotter the steam for any selected steam rate. Conversely, constant *B* tells us when superheat will start to appear. This is as soon as *Q* zero is value. Dividing *B* by *A* gives us the steam rate that has to be passing through the engine before any superheat starts to appear. This rate is influenced by several factors but the two most influential ones are the size of the firebox and the relative gas-side resistances of the flues and tubes. Large direct surfaces depress the firebox gas exit temperature while if the flues present a higher resistance than the tubes then the gas will favour the latter. The entering dryness fraction of the steam has often been held to be a cause of delayed or low superheat but test plant evidence, supported by calculations confirm the water content of the steam was consistently very low in well managed boilers.



Upper – ***Fig. IX.34 – Rate of heat absorption in three superheater designs assuming a constant saturated steam inlet condition of 0.98 dry***



Lower – ***Fig. IX.35 – Comparison between the recorded steam temperature and its calculated value for the same three engines based on a constant saturated steam inlet condition (0.98 dry)***



	Locomotive Class	S/A Ratio - tubes	S/A ratio - flues
1	LMS Jubilee Class 5XP 4-6-0	392	378
2	LMS Crab 2-6-0		
3	GWR King 4-6-0 (4-row)		
4	BR Class 4 4-6-0	405	368
5	BR Class 5 4-6-0	392	383
6	WD Austerity 2-8-0		
7	WD Austerity 2-10-0		
8	GWR Dean Goods 0-6-0		
9	LMS Class 2 2-6-0	374	303
10	LMS Class 4 2-6-0	374	301
11	LNER V2 2-6-2	417	439
12	BR Class 7 4-6-2	435	420

NB:- Curves largely taken from diagram appearing the paper on the British Standard classes presented by E S Cox to the I Loco E. It is known that in some instances the curves he presented differed from the equivalent ones appearing in the relevant Bulletin.

Fig. IX.2 - Admission temperatures and S/A ratios for a selection of British locomotives