BOILER RESISTANCE: THE WAY OUT

Back pressure behind balancing heat transfer and engine efficiency

Hendrik Kaptein, for ASTT 2025 Darlington conference

1. **Overview**. Given a certain firing rate more heating surface is good for boiler output and efficiency. Within steam locomotive space and weight limitations heating surface mostly consists of relatively narrow tubes and flues, causing serious combustion gas flow resistance. Ejector back pressure needed to overcome this impedes engine output and efficiency.

So – and given the best possible exhaust system – the TRADE-OFF is BOILER V. ENGINE PERFORMANCE, once again demonstrating the need for integral design.

2. **Methodology**. Simplified QUALITATIVE APPROACH (thus containing little quantification apart from a couple of important relationships) concluding with some general guidelines for future steam boiler design within heritage limits: "NO CALCULATION WITHOUT KNOWLEDGE OF WHAT IS TO BE CALCULATED AND WHY". Example of "the steam locomotive as an organic whole": *La bête locomotive* ...

3. **History**. No that much discussion on this up to now (as far as known to the present author). Mentioned by Chapelon (1938, in terms of *tempérament* or freedom of combustion gas flow) but no elaboration (Chapelon going for high output / weight ratios anyway). ... Latest (?) contribution by Adrian Tester (ASTT 2022 presentation and book, 2024), including historical overview of boiler resistance theory, experiment & experience. – Here no more than marginal elaboration of their fundamental findings.

4. **Neglect explained (?)**. Locomotive boiler designs since Henry Booth (realised by Stephenson) more or less successful. But then ENGINE EFFICIENCY LEFT OUT of the whole story ....

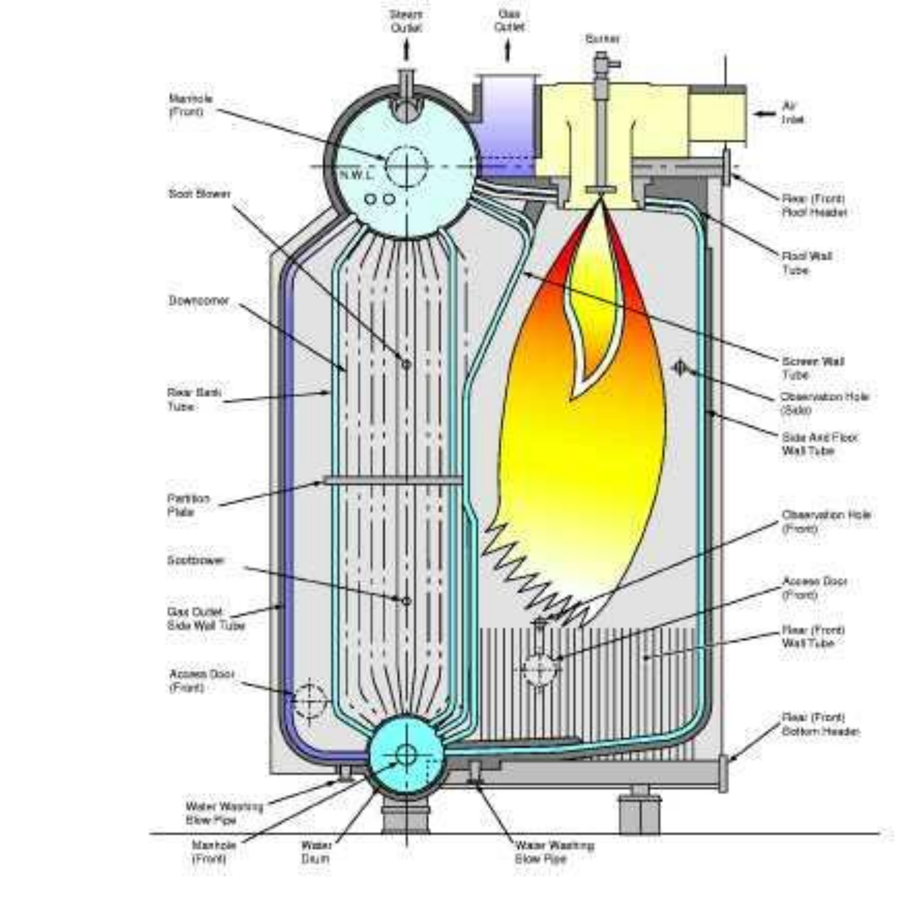
(+ tendency to "isolate" design issues from each other.)

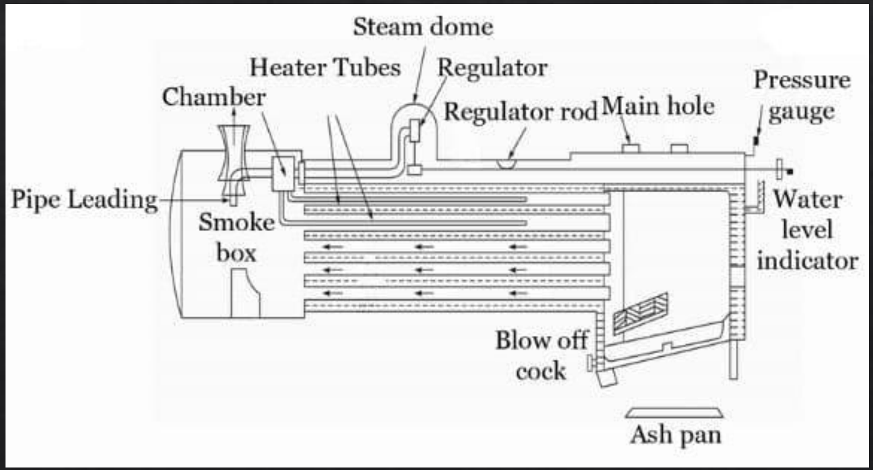
5. **Limitations of applied thermodynamics v**. Up to now combination of general thermodynamics & test results in order to inductively reach general results.

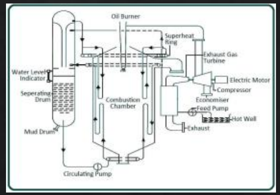
Still steam loco boilers, engines. exhausts etc. seem relatively simple things but then calculating, comparing, weighing etc. combustion gas (& steam) flows, heat transfer etc. is quite another & rather complex matter indeed.

Computer modelling may bring progress here (as with stationary boilers).

6. **The problem visualised**: +/- equivalent boilers in terms of output: stationary, locomotive, Velox (not exactly up to scale …)







7. **Small is not so beautiful?** The "compression" issue: three boilers (scaling +/-, not important given major differences in size and weight), with +/- identical output (say 10 t / hr) & efficiency (up to 90% at lower loads, decreasing at higher loads (though large stationary boilers may reach full load total efficiencies up to almost 100%). – WHY ARE LOCOMOTIVE BOILERS SO SMALL? Obvious answer but still …

8. **Size issues**. A. The smaller the equivalent boiler, the higher its combustion gas flow resistance. B. For the same amount of combustion gas to be moved more energy is needed to overcome this resistance in a smaller boiler.

+ smaller "equivalent" boiler operates at higher combustion gas speeds & pressures, increasing heat transfer (again: Velox boiler the extreme case in this respect as well).

9. **Draught power consumption**. Stationary: "for free": natural draught up long chimneys guiding hot & thus light gases upwards. Loco boiler: exhaust ejector consuming part of total engine power. ("Extreme" Velox: exhaust gas turbine driving combustion air compressor.)

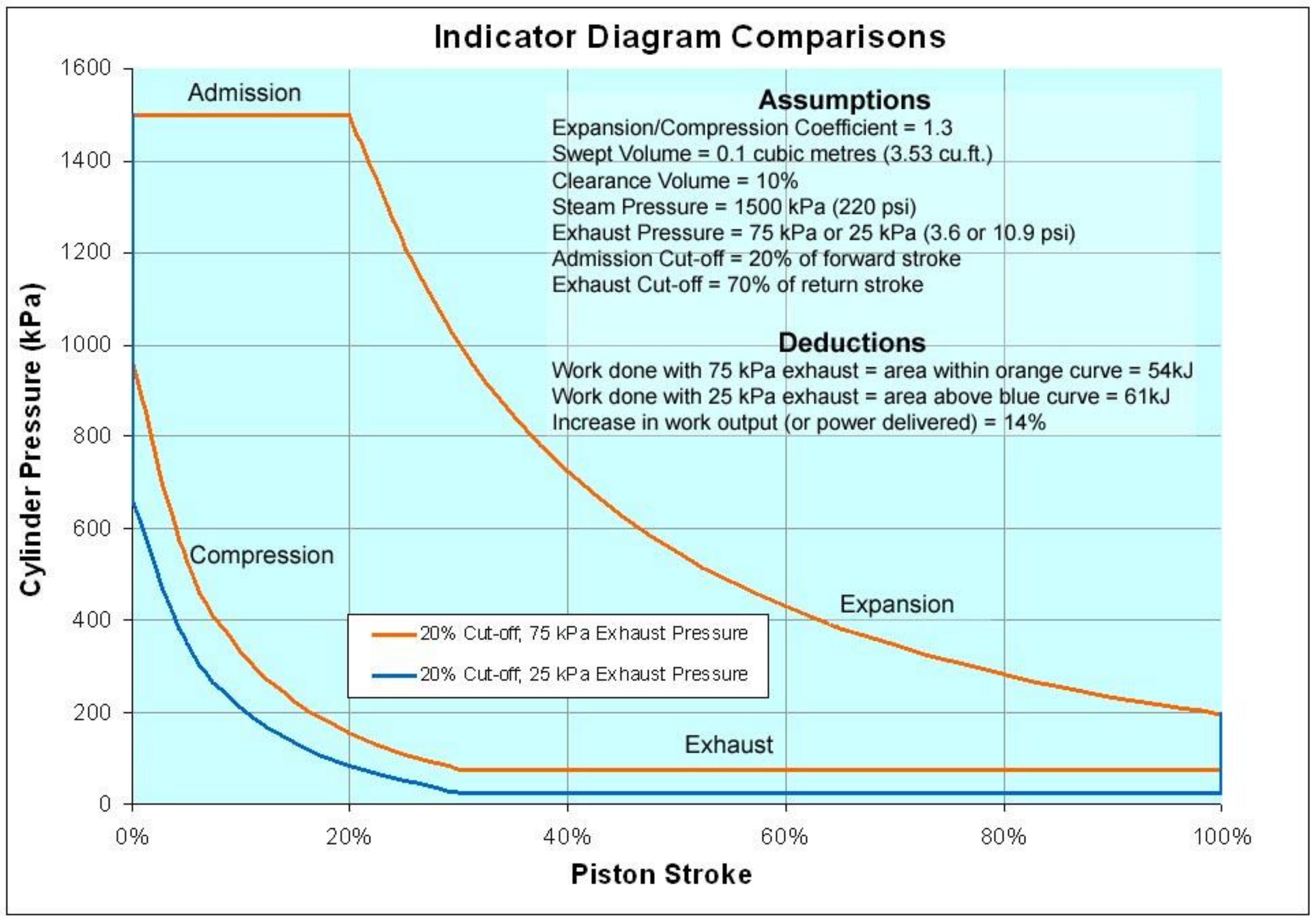
So the LOCO BOILER is a SPECIAL CASE in one more respect: both stationary & Velox draughted by combustion gases themselves, loco boiler DRAUGHTED BY ITS PRODUCT: "fundamental handicap".

10. **Locomotive boiler resistance factors**. (Evidently:) air inlet under (or in) firebox, grate, firebed (if any), brick arch, tube plate, tubes & flues, superheater, (combustion gas feedwater heater,) smokebox, spark arrester / self cleaning devices and their dimensions. (Strahl [early 20th century]: "normal" flue and tube resistance making up for +/- 50% of total boiler resistance.)

Here mainly discussion of TUBE / FLUE SIZES & RELATIONSHIPS, given the relative "constancy" of other factors.

11. **The problem**. Boilers may not be shrunk "for free", as the same heating surface within a smaller boiler increases combustion gas flow resistance: overall efficiency is determined by energy needed for combustion gas flow as well => back pressure …

"Coughing out impediments:"



Indicator Diagram Comparisons
Cylinder Pressure (kPa)
1600
1400
1200
1000
800
600
400
200
0
0%
20%
40%
60%
80%
100%
Piston Stroke
Admission
Compression
Expansion
Exhaust
Assumptions
Expansion/Compression Coefficient = 1.3
Swept Volume = 0.1 cubic metres (3.53 cu.ft.)
Clearance Volume = 10%
Steam Pressure = 1500 kPa (220 psi)
Exhaust Pressure = 75 kPa or 25 kPa (3.6 or 10.9 psi)
Admission Cut-off = 20% of forward stroke
Exhaust Cut-off = 70% of return stroke
Deductions
Work done with 75 kPa exhaust = area within orange curve = 54kJ
Work done with 25 kPa exhaust = area above blue curve = 61kJ
Increase in work output (or power delivered) = 14%
20% Cut-off, 75 kPa Exhaust Pressure
20% Cut-off, 25 kPa Exhaust Pressure

13. **Expansion.** This is the simple(r) part of the story: increase in engine efficiency is a matter of more work done by the same amount of steam, amount of which is to be derived from comparing indicator diagrams depicting degrees of expansion.

Engine design itself no main issue here. Still lower back pressures change compression. This may necessitate smaller clearance volumes / marginal changes in valve events in order to prevent curtailing of inlet steam flow.

(This relates to the much greater importance of avoiding exhaust choking compared to inlet throttle losses.)

14. **Expansion f.** Some more interesting relationships (again as explained by Chapelon):

Doubling back pressure => output goes down by 25% (other things equal).

Longer cut-off needed for the same ihp, e.g. from 15% to 22% => 14% increase in fuel consumption.

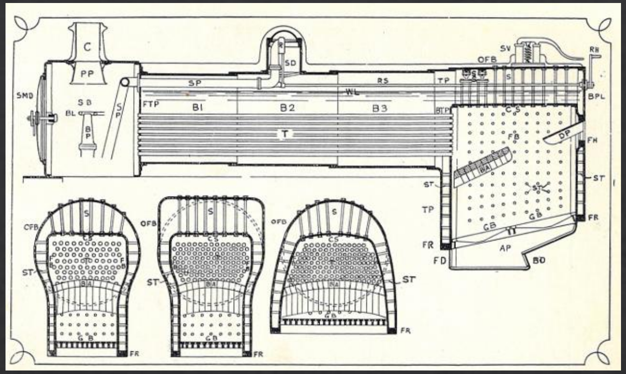
15. **Expansion f.** Not really the subject here but still:
NONLINEAR RELATIONSHIP OF DRAUGHT AND BACK PRESSURE
=> "small" increase in draught comes with "large" increase in back pressure:

E.g. "35% more fuel burned => 90% smokebox vacuum increase with 130% back pressure increase …" (From Chapelon's complex theory of the "automatic" relationship of load and draught, much simplified here indeed.)

16. **The issue clarified**: Back to boiler design: what is the OPTIMAL BALANCE of the conflicting factors of BOILER RESISTANCE and ENGINE BACK PRESSURE (in specific circumstances)? Looks simple but actually is rather complex …

17. **Optimally efficient exhaust the one and only constant design factor** (!). Always go for the the specific setup offering optimal relationships between back pressure and smokebox vacuum for relevant steaming conditions & ranges. (Wardale: EXHAUST is the BEAST'S beating HEART.)

(Still under development: see Jos Koopmans' work & other sources, conflicting at times).



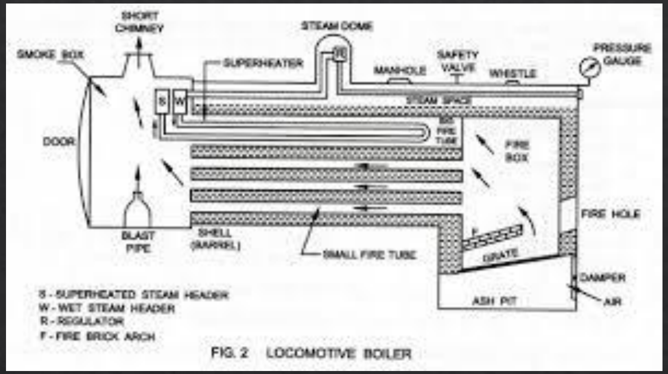
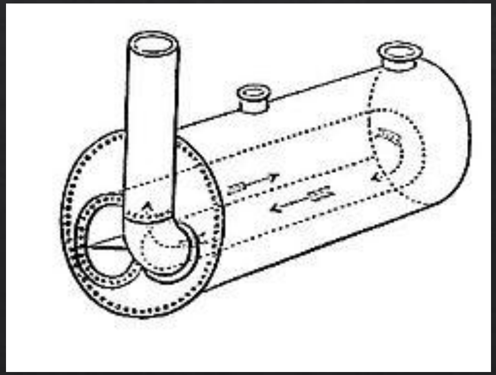


FIG. 2 LOCOMOTIVE BOILER

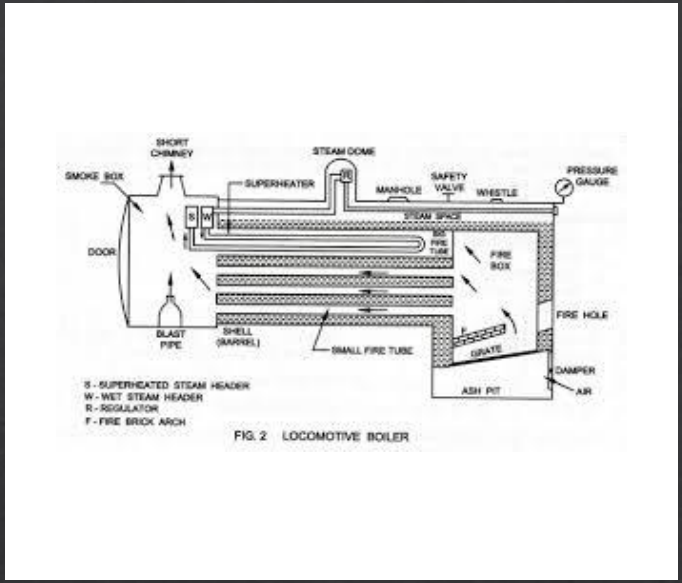


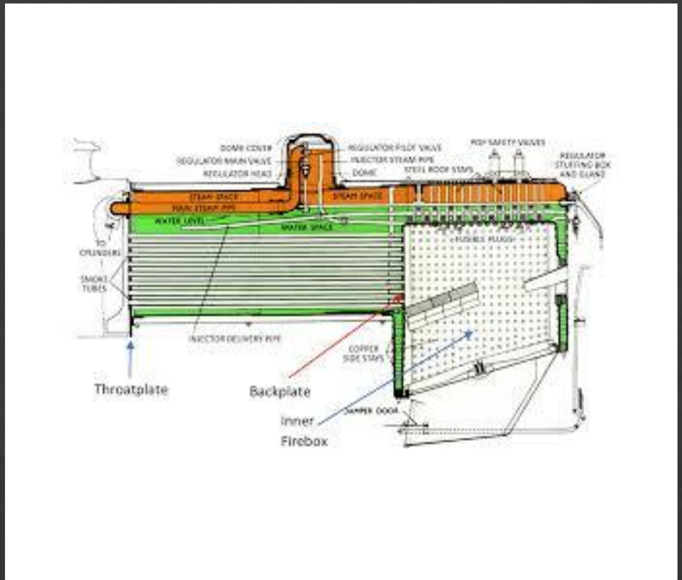
18. **Boiler resistance: high, low & somewhere in between.**

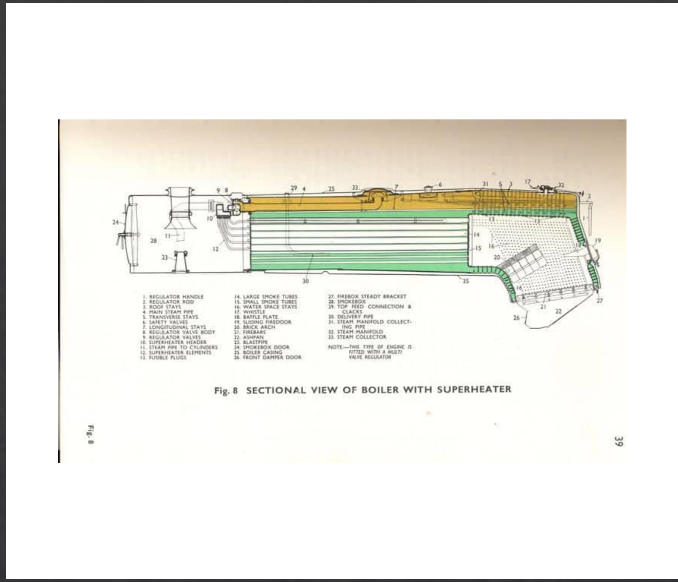
This time of +/- identical size and weight:

Single tube / normal / small diameter tubes / flues.

19. **Different relationships**. Low back pressure => high engine efficiency / low boiler output at acceptable efficiencies, or “normal” back pressure at higher boiler output with acceptable boiler efficiency => “normal” engine efficiency, high back pressure, high boiler output + efficiency => high back pressure as well & thus low engine efficiency.





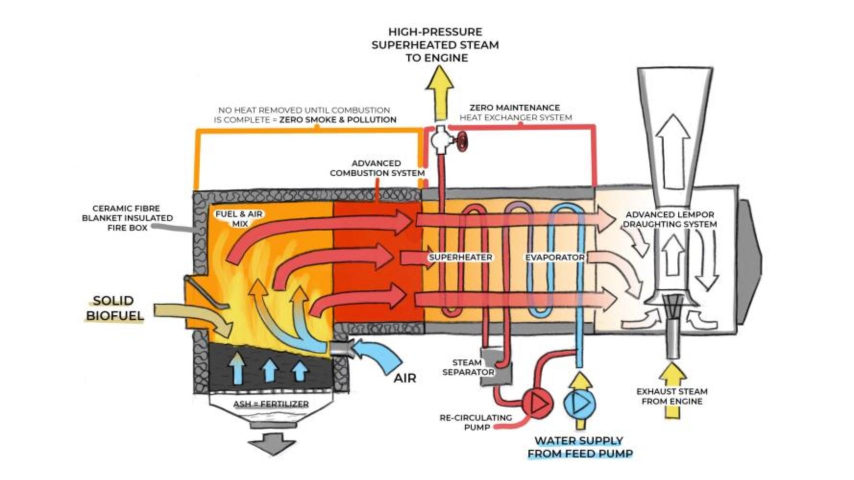


20. Three more pictures, with “normal” tubes and flues but with different firebox sizes / tube lengths. **Same story**: “More “choked” boiler => less powerful engine” or INVERSE RELATIONSHIP OF BOILER V. ENGINE OUTPUT / EFFICIENCY

21. **Direct v. indirect heating surface**. First hunch: go for relatively more direct heating surface, thus reducing harmful back pressure. Related to boiler loading: more output => relatively more tube & flue contribution: "heat transmission moved forward into the boiler".

(x like graph)

22. **The other way round (extreme case)**: Verderber's ["destroyer's"] DRY FIREBOX, Hungary, late 19th century: good for combustion, no brick arch adding to boiler resistance, overall efficiency comparable to normal firebox (!), reiterated by Mackwell, see picture, still under development.) Not to be further discussed here.



23. **Caveat**: HEAT TRANSMISSION BY RADIATION NOT DEPENDENT ON FIREBOX AREA. Still with relatively larger firebox area less thermal stress, better flame formation in relatively larger firebox, etc.

(Fry, referring to earlier tests: more heat transfer in bigger firebox.)

24. **Tube & flue resistance relationships.** TUBE RESISTANCE is PROPORTIONAL TO LENGTH (thus length halved => half of the original resistance, etc.), and INVERSELY PROPORTIONAL TO DIAMETER

With laminar flow to the fourth power (doubling the diameter => 1/16 of original resistance). Tube resistance more or less proportional to diameter with turbulent flow (simplifications).

25. **Standard ratios**. Diameter / Length 1:100 = Area / Surface 1:400, tube / flue free area / grate area 15%

Products of long time TRIAL & ERROR, given “adequate” exhausts but with no attention to boiler v. engine efficiency at different loads & with different boiler sizes.

26. **Relationships**. Pressure drop in tubes &c. more rapid than gain in heat transfer.

Tube diameter given a certain free gas area + l / d ratio makes little difference.

E.g. ¼ more tube length => ¼ more resistance but ¼ more tubes / flues => +/- 1/3 less resistance.

27. **The core issue.** Long story cut short: LONGER & NARROWER TUBES AND FLUES GREATLY INCREASE BOILER RESISTANCE BUT DO NOT GREATLY IMPROVE HEAT TRANSMISSION. Or: both surface area and resistance do not make major differences for steam production.

=> "Garratt" like boiler: Heat transferred per hp of gas pumping highest in a boiler with a large number of short tubes of small diameter (already suggested by D.K. Clark).

(Detailed by both Chapelon & Tester.)

28. **Provisional simplification**. "... almost any combination of tube number, diameter and length will result in a satisfactory value for the absorption efficiency – once the amount of tubular surface provided exceeded a surprisingly small minimum."

So just a bit of indirect heated surface will do …

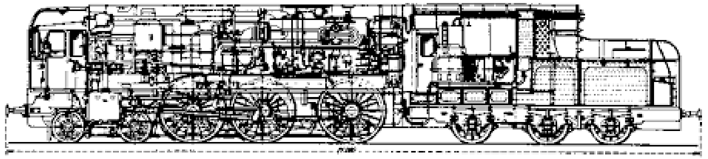
29. **Educated guess** or at least hunch: even the latest “STANDARD” LOCOMOTIVE BOILERS ERR ON THE "RESISTANT” SIDE, in the interest of adequate output at acceptable efficiency but at the cost of engine performance, the more so given primitively inefficient ejectors generally used to the very end of regular steam.

30. **Still more variables.** The SAME BOILER may be pushed more or less hard: MORE OUTPUT or MORE EFFICIENCY. (Lower steaming rates lead to less smokebox vacuum & the other way round.) Also less resistant & thus bigger boilers for a given steam rate may be less advantageous with frequent starts and stops and / or on uphill track, etc.: lots of conditions to be reckoned with.

31. + e.g. relatively less draught at higher loads (no strictly proportional relationship) => lower loaded boilers may do better (standard designs generally producing too much excess air at low loads indeed). Etc. etc.

32. **More radical solutions**. Why not tackle the core issue, e.g. by turbocharging with MECHANICAL EJECTORS? Exhaust steam turbines / pumps rather more efficient than ejectors (e.g. DR condensing loco's, DB 01 177 experiment) but then expensive, complex and prone to wear as well.

33. **Next step: doing away with the whole back pressure issue?** By forcing combustion gases out in another fashion: e.g. Anderson recompression / passive CONDENSING: LESS THAN ATMOSPHERIC BACK PRESSURE, with live steam engines / turbines driving exhaust pumps, etc.: still some or other exhausting energy needed (+ no longer direct coupling with load, to be catered for).



34. **Still more radical solutions**. Why not go the whole way, toward atmospheric back pressure with radical size & weight reduction (good for mobile applications anyway) as well? Back to the VELOX boiler: combustion gas turbine driving air compressor.

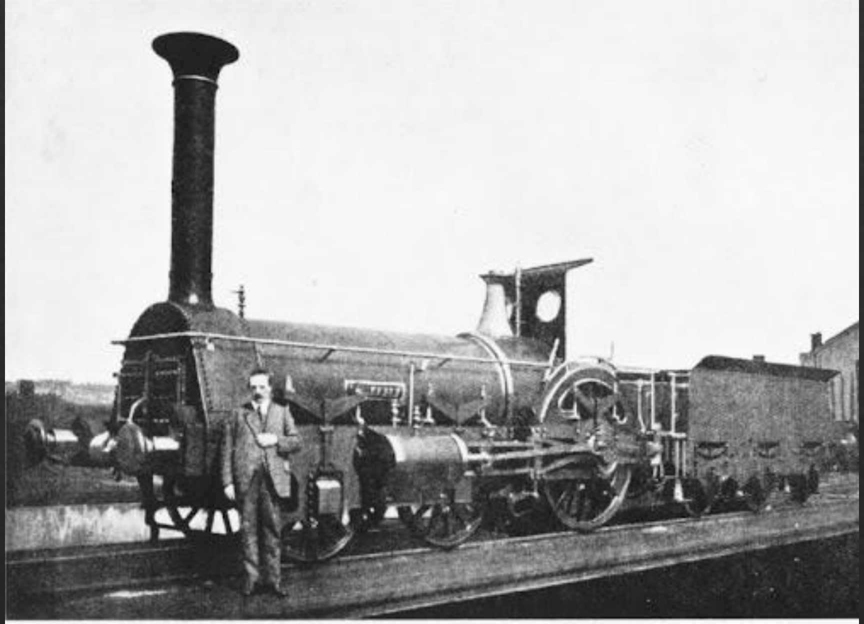


Plate 37 Reconstructed Crampton express locomotive No. 28 *Die Pfalz*, Palatine Railways, which has been placed in the railway collection at the Nuremberg Museum.

35. **Or the other way round** towards the natural draught "ideal" of stationary boilers: exhaust gases driving out themselves ("passive Velox"). Not that practicable? Stationary boilers "on the road" even less so ...

36. **Or move the boiler away, to some or other stationary position**, feeding FIRELESS LOCOMOTIVES. Then highest efficiency boilers (up to almost 100%) including feed water heaters, economisers etc. may do the work, fired by environmentally friendly heat sources (e.g. scrap iron from discarded boilers replaced by duly optimalised versions => no CO_2 emission at all).

37. **These stationary loco boilers** may drive simple, safe & one person operated fireless locomotives with ATMOSPHERIC BACK PRESSURE, + FREE SUPERHEATING w/o superheating elements (up to 320° C) if fed by high pressure steam delivered by superheated low pressure stationary boilers and reduced on board to normal working pressures (as explained in earlier contribution).

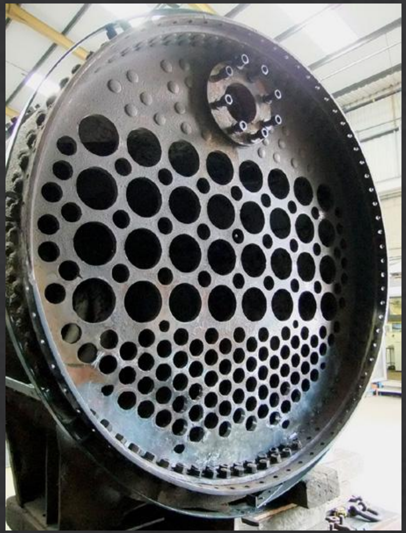
38. **Too impractical for now?** Back to the future of "low load" heritage service: go for LESS RESISTANT BOILERS => given size and weight slightly less steam produced but with considerably LOWER BACK PRESSURE. May lead to easier steaming as well. So still: "Get it more stationary boiler like".

Or "light" heritage service may better served by "low load" low resistance boilers.

39. **Exhaust** (*bis*): "The heart of the matter" is THE ONE CONSTANT FACTOR: to be devised for optimal efficiency indeed (no balancing against other factors, like other boiler dimensions).

So GO FOR THE MOST EFFICIENT EXHAUST SYSTEM from the start, for a designed range of steam production. (Don't go the other way round: first designing a boiler & next experimenting with different exhaust systems as was once suggested for *Revolution.*)

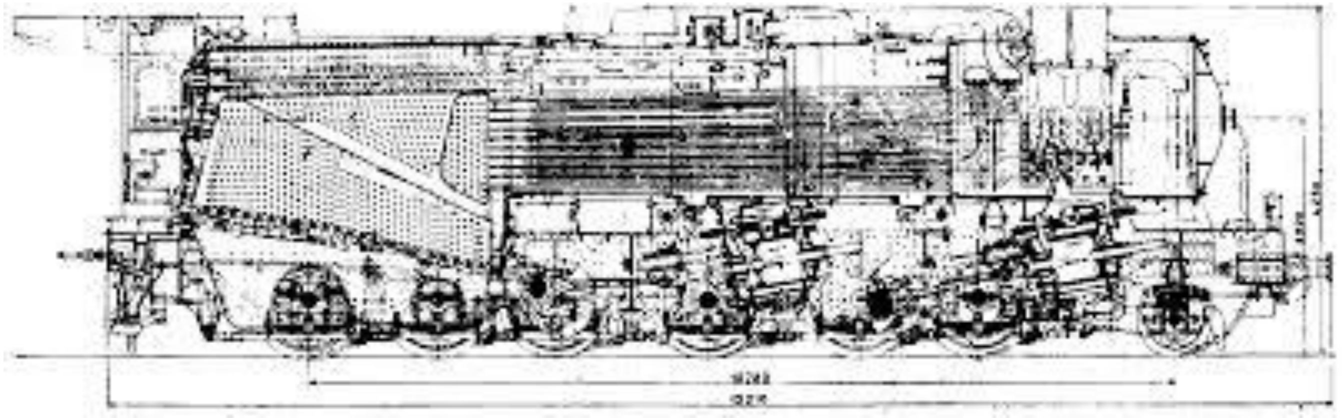
40. **Example.** *Revolution* like boiler may well be scaled up after all ...



41. **Mechanical advantages**. Boiler simplified => lower first costs, more rugged construction => easier cleaning & maintenance.

+ relatively more direct heating surface => less thermal stress on sensitive firebox tubeplate connections, &c.

42. **Additional measures**. Replace the front part of the boiler by a feed water heater or "simplified Crosti" (cf. 160A1): marginal gain (by greater temperature difference) but also less boiler stress caused by feed water temperature differences. (+ corrosion issues?)



43. **Additional measures f**. Steam feed water heaters reduce draught, lower superheat temperatures, etc. (Steam air preheating may be a better idea.) (GPCS? Increasing boiler resistance?) Still all such appliances may be MORE ATTRACTIVE to the degree BOILER DRAUGHT becomes LESS IMPORTANT, potentially relegating exhaust steam to other duties.

No superheating (steam jackets instead) => less resistant and also more efficient boiler, oil / gas firing => no grate resistance, no self cleaning smokeboxes, ..., …

44. **Implementation.** Set up a (complex) model for predicting boiler behaviour in all relevant respects as explained above (already done for stationary boilers), & apply it to a test project.

Revolution: err on the "temperamental" side i.e. less boiler resistance (unless there is time & resources for specific calculations), then you end up with a simpler & stronger boiler as well. (+ see earlier ideas on ample water spaces around the firebox etc.)

45. **Practice**. Even without any boiler adaptation unnecessary boiler resistance may be reduced: go for free air intakes, thin fires, keep everything as clean as possible, (remove self cleaning elements / spark arrestors wherever feasible), etc.

Promotion may appeal to improved energy efficiency: "less coal / sustainable fuel used for the same amount of work done". (But then again: newly built & less resistant boiler is cheaper as well.)