From "Red Devil and Other Tales from the Age of Steam" by David Wardale pages 160 to 162

5. Superheating *[relating to modifications made in the development of "The Red Devil"]*

The fundamental laws of thermodynamics dictate that for the maximum thermal efficiency from any heat engine the working fluid must commence its expansion from the highest possible temperature. In a steam locomotive this was accomplished by superheating the steam. Superheating not only improved the ideal cycle efficiency but also gave a number of very important practical benefits not connected with the second law such as reduced heat transfer losses to the cylinder walls, reduced steam flow pressure drop for a given volumetric flow rate, and reduced water consumption. Such was the benefit of the Schmidt type superheater realized in actual service that it must rank as the twentieth century's most important single contribution to the art of steam locomotive design. Yet as with the exhaust system and feedwater heating, superheating was rarely fully exploited. The superheat temperature should have been the maximum possible - full stop - and this should have been all the motivation that was needed to improve the factors such as valve and cylinder lubrication which were said to be limiting it. However all too often the reverse attitude seems to have been taken, these factors being seen as rigid barriers to higher temperatures and lower-than-possible ones being consequently accepted as the highest that could be allowed - or simply 'good enough'. This was certainly the case on, for example, the SAR, where it was thought that steam temperatures of the order of 380°C as transitory values were all that were possible due to the lubrication issue. Worse still, the myth that high superheat merely wasted energy in the exhaust steam was believed by not a few engineers right down to recent times. On the other hand both Germany and France pursued means to allow the use of high steam temperatures: 400°C was normal in Germany on the standard designs first introduced in 1925 whilst Chapelon's locomotives recorded temperatures as high as 425°C. In Argentina the Rio Turbio Railway 2-10-2's had a peak steam temperature of 420°C.

The need to increase the superheat on the modified 25NC was clear: not only was the existing steam temperature too low but the use of a feedwater heater always decreased the superheat and this factor had to be compensated for[1]. The only practical way then known to do this was to increase the size of the superheater, essentially to increase the number of elements and the fraction of the gas-carried heat entering the tube bank which swept the superheater surface. This required new tubeplates, with more large tubes and fewer small tubes, and a larger superheater header, all of which would normally have been expensive to manufacture and install and, in the

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[1] In a letter to Chris Newman dated 9thMarch 2011, Wardale explained this point as follows: "Consider a boiler + superheater with no feedwater heater. To generate and superheat to temperature 't' at a given steam flow, let the required fuel heat release rate be m, and let (for example) 0.7m of this go towards evaporation and 0.3m to superheating. Suppose the feed is now preheated in a feedwater heater. The amount of energy required to evaporate the same amount of water as before is now reduced, say by 10% so the heat release rate for the evaporation becomes 0.7 x 0.9 = 0.63. But the split between the total heat release rate to boiler and superheater is fixed by the boiler design and does not change, so the ratio of heat release rate for evaporation : superheating is the same as before, and the heat release rate for superheating is therefore (0.3/0.7) x 0.63 = 0.27, i.e. 10% less than before. But the steam flow through the superheater is unchanged, therefore the superheat temperature will come down. This is essentially because the feedwater heater reduces the evaporative load on the boiler for a given evaporation, but not the superheat load for a given temperature, and without altering the boiler's evaporative : superheating heat transfer ratio (e.g. by enlarging the superheater) the split of the (now reduced) heat release rate will not be changed. This is no mere theory, it is what actually happens. (Note: the 5AT has been calculated from the start with feedwater heating)."

A simpler explanation is that since less heat needs to be generated in the firebox to boil preheated water, then there'll be less heat available for superheating the steam that is generated.

case of the header, required much design effort. However two circumstances made enlarging the superheater feasible.

i) It was mandatory to replace the combustion chamber tubeplate on all 25 class locomotives during heavy repair due to thinning of the plate in service. As the cost of an altered tubeplate would be almost the same as that of a standard one the debit to the modification work of the tubeplate alterations would virtually be confined to the changing of the smokebox tubeplate. It was found just possible to accommodate one extra row of ten large tubes, bringing the total to 50 in place of the standard 40, without reducing the tubeplate bridges to an unacceptable size. The effects of this on various boiler parameters are given in Table 30, the most significant being the increase from 49.4% to 63% in the fraction of the total tube bundle mean gas flow area provided by the large tubes.

ii) 50-element superheater headers were fitted to the GMAM class Garratts and some of them were of fabricated steel construction which could be made to fit the modified 25NC class boiler by cutting off the steam pipe flanges and welding on new cast steel ones. Spare headers of this type were available and the time and expense of designing and manufacturing an entirely new header were therefore obviated. The headers in question had been manufactured in Germany and were interesting in that the saturated and superheated compartments were entirely separate pieces which minimized unwanted heat transfer through the header walls. They incorporated a five main valve throttle as against four valves in the standard 25 class header, an incidental but important advantage of the larger superheater being the 25% increase in steam flow area it gave. On the negative side a superheater header did not lend itself to fabricated construction and the interior was full of sharp edges to disturb the steam flow. The two parts of the header were also difficult to align, good alignment being essential for the element - header joints. But the worst was that none of the spare headers was in good condition. Having ascertained that some were in stock I did not think to examine them personally and this problem was discovered too late, during assembly. A particular defect was that many of the welded-on mild steel seats for the element clamp bolts had yielded and were deformed. This was certainly a weak point of the header design but in the circumstances we just had to fit the equipment as it was and hope that the seats did not yield any further.

The standard 25NC class superheater elements were of a shortened Robinson loop type which concentrated the superheater heat transfer surface towards the back of the boiler. As obtaining extra superheater surface area by lengthening the element loops could have been counterproductive, because it would have increased the gas flow resistance through the large tubes and hence forced a higher fraction of the gas-carried heat through the small tubes, the element design was left unaltered. The first four rows of elements were completely standard and the fifth row differed only in having a longer riser section. Approximate calculations predicted that this arrangement would give the design steam temperature of 450°C, equal to the maximum on Porta's experimental 4-8-0 (on the modified 25NC this referred to the steam leaving the superheater: after mixing with the valve liner cooling steam in the steam chests the temperature of the steam entering the cylinders was calculated to be 440°C). To reliably generate and use steam at such a temperature the following factors required attention: lubrication, stresses in the high temperature metal of the superheater header and steam pipes and joints, burning of the superheater element ends nearest to the firebox, and the reliability of the element - header joints. In a letter Porta considered each one of these in turn. Because the valve liners would be cooled lubrication was no longer expected to be the limiting factor, despite lubrication difficulties roughly doubling for every 15 degrees C rise in temperature above 400°C. However the other components involved were based on practice that had been successful only below 400°C: no special creep-resistant steels were employed and the various bolted connections were suspect in view of the higher expansions which would occur. Porta therefore recommended 440°C as the maximum, which was close to the figure I had set. A higher temperature would have required improving the mechanical design of the entire high pressure steam circuit downstream of the dry pipe and this was something which, although desirable, could not be done with the available resources.

To accommodate the larger header alterations were required to the smokebox shell, and new header supports and cover plates for the smokebox openings had to be designed. These were not all easy to fit in and involved design work that was rather time-consuming for such mundane details. The throttle linkage also had to be altered.

The manufacturing work for the superheater alterations was divided between Salt River, Beaconsfield and Koedoespoort workshops (Pretoria). Koedoespoort made the elements as it was the concentration centre for superheater element manufacture for the entire railway.

A tube baffle manufactured at Beaconsfield was positioned in front of the smokebox tubeplate, covering all 69 small tubes below the bottom row of large tubes. The idea behind such a 'superheat booster' has been explained on p. 98. Although fitted to 19D No. 2644 no steam temperature measurements had been made on that locomotive and the effectiveness of the device remained unknown. Tests had however been made on 2644 to determine the relationship between the baffle movement and the smokebox tubeplate vacuum. This had been done by welding an extension to the baffle pivot, the extension passing through a rivet hole in the tubeplate flange and boiler barrel. A pointer fixed to the extension ran over a scale graduated in degrees and the angular movement - tubeplate vacuum relationship had been measured during stationary tests made with the cylinder by-pass valves removed. These tests had shown that the baffle needed to be weighted to prevent excessive movement and the baffle for the 25NC class was designed with a steel block welded to the bottom for this purpose, an opening of about 50° at maximum vacuum being aimed for. Plate 21 shows the smokebox tubeplate with the 50-element superheater and superheat booster in position.