The 5AT Project: The End of the Line
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The artist's final impression of the 5AT and how it would look running on the national network. Note the 'air dam' below buffer level. The front brake hoses and retractable coupling gear are pocketed when not in use. ROBIN BARNES

The 5AT proposal is a high-performance 'second generation' steam locomotive of classical format for main line special train service on Network Rail tracks. First described in any detail in 2000, the rationale behind the idea was given in *Steam Railway* No 272 (June-July 2002) and the design was described in *Steam Railway* No. 273 (July-August 2002). But it has now been decided to stop work on the 5AT and the Project Group will concentrate on technically less ambitious but more realisable goals. This article describes what has been achieved with the 5AT, why it is being halted, and what will replace it as the Group's objective.

Firstly, it is emphasised that the 5AT was proposed to ensure as far as possible that main line steam continues into the indefinite future by producing a locomotive that more closely matches the operating pattern of a modem railway than heritage steam (original or replica) is able to, by virtue of higher speed capability, longer range between supplies replenishment, and (crucially) better reliability. It was not intended to be a competitor to modem traction, nor a template for a truly 'high tech' steam design for modem railways, which, if it ever were to be thought necessary, would take quite a different form from that of the Stephensonian locomotive. Its sole purpose was to keep alive the spectacle of main line steam, an aesthetic experience for which adherence to the format of the steam locomotive as we know it is a condition *sine qua non.*

The design that satisfied this aim was the result of the present writer's experience, particularly (i) that a much higher power/weight ratio than given by 'first generation' steam is possible and (ii) that this can be achieved by the 2-cylinder simple format that (for good reason) became almost a world-wide standard. A consequence of (i) meant that quite a small locomotive could deliver sufficient power, which gave the advantage of allowing a large tender - for long range - without overall length exceeding that of the largest heritage locomotives. Both (i) and (ii) allowed the overall size and format of the engine (excluding tender) to be the same as that of the BR 5MT 4-6-0, thereby, it was hoped, reducing vehicle acceptance difficulties as the 'dynamic envelope' would be the same as that of an existing design. It was from this that the 5AT gained its designation, '5' from the BR 5 and 'AT' for 'Advanced Technology'.

5AT load-speed-gradient curves and tractive effort / power-speed characteristics were given in *Steam Railway* No. 273, resulting in some disbelief amongst those who were apparently unaware of the performance achieved by the South African Railways 26 Class 4-8-4, from which 5AT output was predicted with appropriate allowances for differences in the two designs. One of the reasons for the 5AT Fundamental Design Calculations (FDCs), sponsored by a project member (who has also created and maintained the project website at www.5at.co.uk) and undertaken by the present writer, was to determine engineering features of the locomotive necessary to deliver this level of performance. It is these FDCs, which include such items as construction methods and materials that define critical features of the 5AT. Some of their results are given in the Table, where 5AT and BR 5MT data are compared, showing how much performance can be improved for a given amount of hardware and giving some of the engineering changes that achieve this.

The 2-cylinder 5AT has been designed for a top speed of 125 mph, and the FDCs needed to show that at this speed dynamic augment ('hammer blow') due to the balancing of reciprocating masses would be acceptable. Critical to this is the mass of the reciprocating parts, and these have been specified in some detail. Using mostly weldable alloy steel of high fatigue strength, the total reciprocating mass per side for balancing purposes (which includes a piston tail rod) is calculated to be 260 kg versus 375 kg for the BR 5MT, a reduction of 30%. This, together with the use of a large tender and suitable engine/tender buffer and drawgear, would allow AAR criteria for the allowable unbalanced reciprocating mass per side to be met with zero reciprocating balance added to the coupled wheels, i.e. zero hammer-blow. In the event, sufficient balance would be used so that the 5AT hammer blow at 125 mph (by whichever criterion this is measured - per wheel, per axle, per rail or per locomotive) would not exceed that of the BR 5MT at its currently allowed speed of 75 mph. Two cylinders are thus no barrier to high-speed operation, as demonstrated over 70 years ago by the fastest steam trains of all time, the Milwaukee Road 'Hiawathas' hauled by 2-cylinder locomotives with 100+ mph running needed to maintain their schedules. This has an important by-product as it is much easier to demonstrate by calculation that crankpins and straight axles are safe when generating high power at 125 mph than to do the same thing for a crank axle, a potential structural weak-point.

The FDCs have been arranged in the style the late L. D. Porta used for his calculations, and thus another of their functions has been to document for posterity Porta's calculating method. With very few exceptions they have been made using engineering knowledge and techniques that would have been available to steam engineers in the 1950s. By showing how much better the BR 5MT - and therefore contemporary steam in general - could have been if engineered to the standard that was then possible, Porta's contention that steam engineers "gave the knife by the handle" to the diesel interests is amply demonstrated.

The FDCs refined the 5AT's original specification, resulting in some changes being made to the locomotive's appearance, amongst them (i) the use of two surface-type feedwater heaters placed behind the smokebox in French fashion in place of one ahead of the chimneys, found necessary to give the required heat transfer area (and, incidentally, removing a possible source of disturbance to exhaust lifting from the chimneys), (ii) substituting 'crocodile' slidebars for the original multiple-bearing type, so that the crosshead reaction always puts the aluminium alloy crosshead slippers in (fatigue-free) compression, and (iii) valve gear alterations, including using a 'double-hanger' link instead of the usual valve crosshead and slidebars to support each combination lever. This gives an elegant solution for driving the two spindles of the double piston valves used on each cylinder, the small vertical movement imparted to the spindles being accommodated by floating packings.

The use of Walschaerts valve gear and piston valves instead of British Caprotti valves caused some controversy. However the valve gear (all pivots on roller bearings and with mechanical lubrication of the die blocks), and especially the piston valves, are of much superior design to those formerly used, and would be expected to give cylinder efficiency that is at least as good as with Caprotti gear. The aesthetic factor favours Walschaerts gear and Caprotti valves arranged to provide a full by-pass when drifting are absolutely unacceptable as cushioning steam is mandatory to prevent excessive crankpin loads when drifting at high speed.

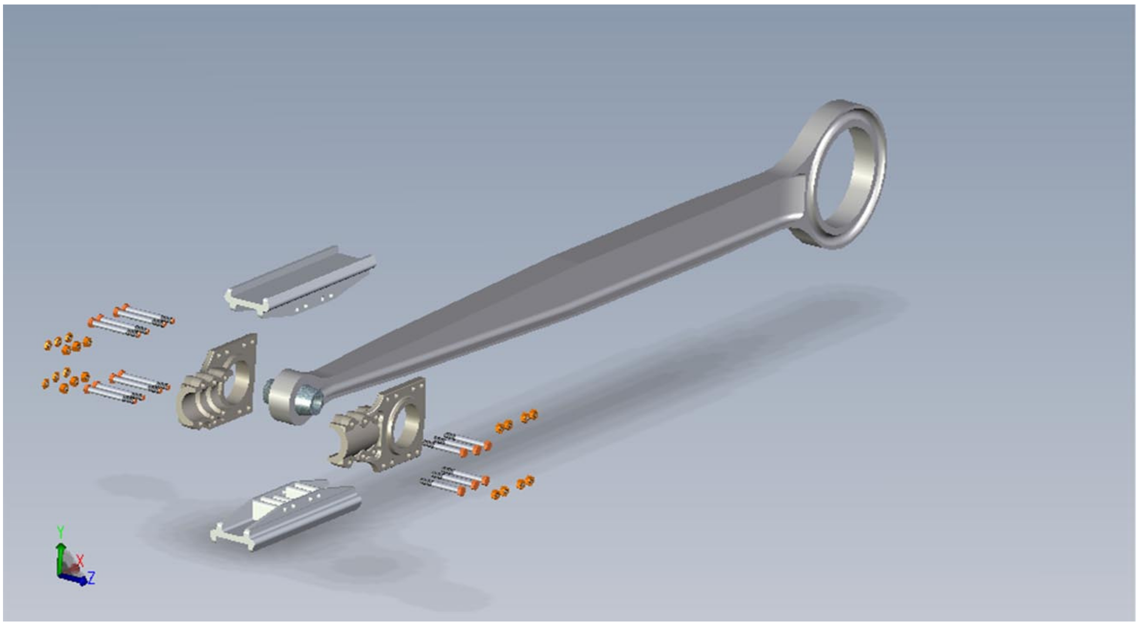
The specified coupled wheels have changed from Boxpok to Scullin to BFB. American Scullin wheels are preferred for minimising 'fan effect' air resistance, but as they were in the developmental stage when steam finished in America it was thought vehicle acceptance would be simplified by using BFB wheels, which have a proven UK track record.

The final change in appearance has been to consider extending the frontal streamlining downwards closer to rail level, something important for minimising air resistance but which also has to comply with current Railway Group Standards.

As part of the FDCs an elementary vehicular stability analysis was made (excluding the tender). This predicted stable running on tangent track (no flange contact) up to 102 mph, but because of simplifications in the mathematical model this is thought to err on the low side. This factor would need thorough investigation by modem computer techniques to ascertain what, if any, chassis refinement would be needed to ensure stability at maximum speed, and is just one of the areas for which R & D would be required as an integral part of the design process. Other areas include firebox expansions and stay stresses (stays must not fracture), and combustion equipment.

The preferred fuel is diesel oil, and whilst FDCs have shown that with this fuel virtually complete combustion at maximum evaporation within the confines of the firebox is in principle possible, developing a burner to actually achieve this remains to be done. Coal firing, with mandatory use of the gas producer combustion system, could achieve the required evaporation but at lower combustion efficiency than with oil, and would require R & D for the gas producer system itself and for the (obligatory) mechanical firing and spark arresting / self cleaning smokebox, none of which at the present state of the art is suitable for second generation steam.

The late Prof. W. Hall's *Perwal* computer program was used to predict a maximum sustainable indicated power-speed curve based on the design parameters calculated by the FDCs. The result is given in the graph, together with the original relationship estimated from experience. It is seen that *Perwal* predicts a slightly lower maximum indicated power (up to 3% less) between about 70 and 120 mph (although at 125 mph the *Perwal* curve is still rising), and higher power outside this zone, considerably higher over the 20 - 50 mph range. The small high-speed discrepancy is within the calculating accuracy of both methods and is not significant, whilst were there to be higher power at lower speeds it would be welcome for higher acceleration if adhesion allowed, which would be problematical with less than ideal rail conditions (the design would be better as a 4-8-0 except for the consequent reduction in tender capacity if overall length were unchanged, but this would be expected to significantly complicate vehicle acceptance.) The FDCs were calculated specifically to give the originally estimated maximum equivalent drawbar power, occurring at 71 mph, and at this speed the two curves agree to within 0.4%.



Above: Computer Aided Design drawing of the 5AT's roller bearing connecting rod and some elements of the Timken-type split roller-bearing crosshead with aluminium alloy slippers. RICHARD COLEBY

To summarise, the FDCs have confirmed that the 5AT concept is technically sound for achieving the target performance or, as in the case of vehicular stability and oil combustion, have given reasonable indication that it should be with the necessary R & D. Nevertheless, it has been decided to halt work on the project as there does not appear to be any realistic chance of it being brought to a successful conclusion, which may be defined as the locomotive operating profitably on Network Rail at its designed capability, in terms of speed, load haulage and unlimited annual mileage. There are various reasons for this, which are, to a greater or lesser degree, interlinked. Firstly, there is the question of funding - an estimated £10 million of it (including a 25% contingency) to get the first 5AT on the rails. Where is a sum of this magnitude to be found? Then, if it were obtained, the 5AT would have to be designed. The nature of the FDCs is to prove the concept's engineering viability whereas design means producing manufacturing drawings and data down to the last nut and bolt. Porta's definition of second generation steam is that which uses state-of-the-art steam technology requiring little or no further research. Some research is therefore allowed within this definition, and features of the 5AT, being at the cutting edge of second generation steam, would require R & D, as indicated earlier. This leads to the question of who could make the design. Porta's definition implies using a design team thoroughly familiar with world-wide state-of-the-art first generation steam practice, from which the 5AT would be a natural development. Such a team does not exist anywhere, including the UK, where main line steam design was abandoned over 50 years ago and where very little of it could latterly be regarded as state-of-the-art. The handful of engineers world-wide with some working knowledge of advanced steam technology would not give a team of the required size or breadth of experience to design the 5AT, and would have to be augmented by specialists with specific engineering expertise, including in aspects of modern railway vehicle design. Even if recruiting such a team of the required calibre for a 'one-off' project were possible - which is questionable - its lack of working knowledge of all aspects of state-of-the-art steam practice, which realistically cannot be corrected, would be a major drawback, a critical factor given the vital importance of detail design to proper functioning and especially reliability. Designing the 5AT so that it fully realised its potential in practice would be a most difficult exercise, especially as the option of a second locomotive to 'get it right' - often an engineering necessity - would be an unlikely luxury. If it were to be attempted, those involved would bear the responsibility to ensure that the locomotive would not be let down by its details, which is always a great risk, especially if, as is likely, design were to be made under pressure of time.

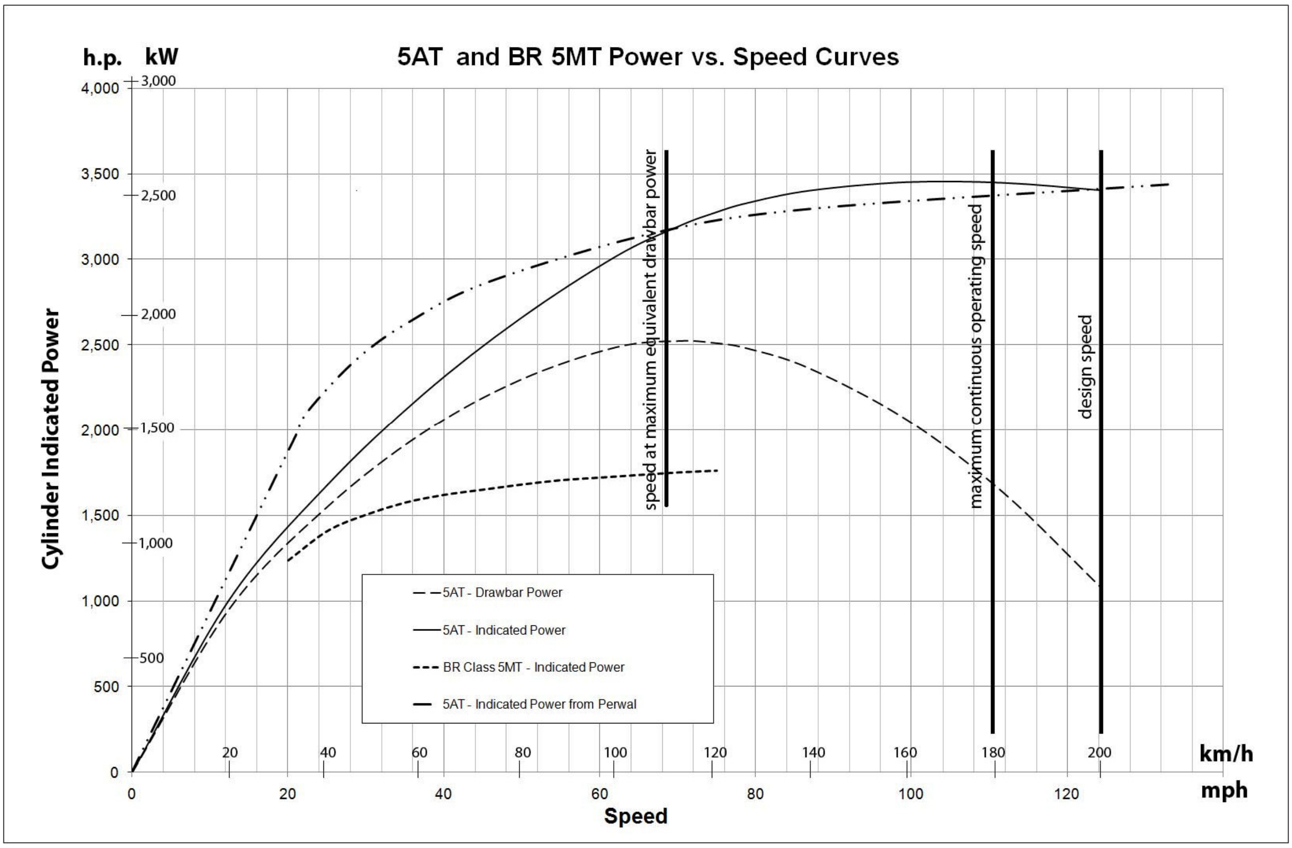
If it were successfully designed, manufacturing should present no problem other than considerable expense. But vehicle acceptance for running at up to 125 mph and unlimited annual mileage would be a major hurdle. Only exploratory contact was made with Railtrack at the start of the project. There was no point in pursuing it further when there was nothing substantive to discuss. It is thought that acceptance by the same route and with the same restrictions that apply to heritage steam would be relatively straightforward, but these restrictions are a consequence of the extent of steam's noncompliance with the full Railway Group Standards and the various derogations it therefore requires. The only realistic route to obtaining derogation from these restrictions - if at all possible - would be for them to be relaxed little by little as operating experience grew, which, supplemented as necessary by testing and rigorous engineering proof of component reliability at high speed, might eventually result in the locomotive being allowed to operate at its full potential. But there is so much inherent uncertainty in this that it would be hard to justify the expense and effort of producing the 5AT merely in the hope that it would happen.

Even supposing it did happen*,* what would the 5AT be used for? It would need to be used much more intensively than just in occasional charter service. One possibility is for an 'English Heritage Express' run to a regular schedule linking tourist centres, such as Bristol - Bath - Salisbury - Oxford - Warwick (connecting bus to Stratford-on-Avon) - Birmingham - Nottingham - Lincoln - York - Durham - Newcastle, a route with engine turning possibilities at each end, Birmingham and Lincoln, to be served by outlying stations to avoid reversals. This could be a normal service that anyone could use between any points, running in each direction every other day (or every day with two train sets, one of which could, at least initially, be diesel), say Mondays - Saturdays from March to October, minor maintenance to be carried out on Sundays and major over the winter. Such a service would give suitably intensive utilisation, requiring second generation steam reliability. But however attractive it would be to the steam enthusiast or general tourist, getting it up and running would no doubt be highly problematical. And whether it could make financial sense is another matter, as analysis has shown no service that would allow the 5AT's total (design + manufacture + acceptance) capital expenditure to be recouped within a reasonable time.

So, there would be serious obstacles facing the 5AT and it is being terminated, or rather put into a state of indefinite abeyance, until such time as success in all aspects of the project can realistically be expected, which, unless the adverse factors described above change dramatically, amounts to the same thing. And there is something else influencing this decision that would need to change - the level of demand for the 5AT. If something is not wanted, or not shown to be wanted, it will not happen. There would need to be widespread and vociferous support clamouring for the 5AT for the project to have any chance of attracting the required investment to start with and the necessary cooperation and goodwill of the railway industry down the line. Such support has not materialized. The 5AT was, from its inception, promoted as main line steam suitable for a future when heritage steam might be crowded out of heavily trafficked routes, or perhaps even banned altogether if Network Rail, which has the power to do so, decided it could no longer allow it to ran. Perhaps the proposal's fundamental problem is being in limbo between a future scenario that is uncertain and practical steam expertise at the required level that is forever receding into the past.

Finally, the 5AT has attracted a core group of people with various skills who share the fundamental philosophy that steam will have to develop if it is to survive in the long term, even in heritage service. The construction of replicas is one way to put new locomotives on the rails, but being replicas they will perpetuate all the weaknesses of first generation steam, weaknesses that make it so expensive and unreliable (in the truest sense) to operate. The new aim of the group, building on the experience gained with the 5AT, is to bring a more forward-looking approach to the question of new steam, yet not making its proposals as ambitious as the 5AT and therefore more realisable, e.g. requiring fewer knowledge resources for design. The question of locomotives suitable for heritage railways is being addressed first. To this end, a market survey of UK heritage lines is being made to assess all factors relevant to their motive power needs, and it is hoped that this consultation will allow the group to decide what, if any, locomotive proposals will have the broadest appeal for heritage railway operation.

The 5AT has now been abandoned, although the group hopes that many of the innovations developed for the locomotive can be employed in certain existing locomotives. ROBIN BARNES



Performance graph illustrating the power-speed ratio of the 5AT compared to the Riddles 5MT. DAVID WARDALE

Table - The 5AT and BR 5MT Compared

Item	Unit	5AT design values from the FDCs	BR 5MT
Wheel arrangement	-	4-6-0	4-6-0
Maximum axle load	tonnes	20	20
Adhesive weight (full boiler)	tonnes	60	59
Total engine weight (full boiler)	tonnes	80	77.2
Tender type	-	double bogie	3-axle BR1 type
Fuel	-	diesel oil	good coal
Fuel capacity	tonnes	7 (oil)	7 (coal)
Water capacity	tonnes	46.3	19.3
Tender weight (full supplies)	tonnes	80	49.9
Nominal maximum wheel rim tractive effort	kN	146	116
Nominal coefficient of adhesion at max. T.E.	-	0.248	0.20
Maximum sustainable cylinder (indicated) power	kW	2580 (at ≈ 105 mph)	1312
Maximum sustainable equivalent drawbar power	kW	1890 (at ≈ 71 mph)	1060
Overall thermal efficiency at max drawbar power	%	11.4	6.8
Design speed	mph	125	-
Maximum boiler pressure	kPa	2130 (2100 normal max. operating pressure)	1551
Coupled wheel diameter	mm	1880	1880
Number of cylinders	-	2	2
Cylinder bore diameter	mm	450	483
Piston stroke	mm	800	711
Cylinder clearance volume, % of piston swept volume	%	10.6	11.3
Number of piston valves per cylinder	-	2	1
Piston valve diameter	mm	175	279
Piston valve steam lap	mm	65	43
Piston valve exhaust lap	mm	18	0
Mean (front & back port) maximum cut-off	%	75	78
Lead	mm	7	6.35
Valve travel at 20% cut-off	mm	153	103
Valve opening to inlet steam (average of front & back ports) at 20% cut-off	mm	11.5	8.5
No. of valves per cylinder x valve diameter x valve opening to inlet steam at 20% cut-off	cm^2	40.3	23.7
Valve opening to exhaust steam (average of front & back ports) at 20% cut-off	mm	58.5	51.4
No. of valves per cylinder x valve diameter x valve opening to exhaust steam at 20% cut-off	cm^2	204.8	143.4

Maximum rated evaporation (superheated + saturated)	kg/h	17000	11930
Cylinder inlet steam temperature at maximum evaporation	°C	450 (cooled valve liners)	375 (with final blast nozzle)
Feedwater temperature at maximum evaporation	°C	105 (typical value)	≈ 80 (exhaust injector)
Combustion air temperature at maximum, evaporation	°C	100	ambient
Boiler: number of small tubes	-	70	151
Boiler: outside diameter of small tubes	mm	44.5	47.63
Boiler: number of large tubes	-	96	28
Boiler: outside diameter of large tubes	mm	88.9	130.18
Total tube water-side evaporative heating surface area	m^2	147.7	137.4
Firebox heating surface area	m^2	≈ 15.9	15.9
Total boiler evaporative heating surface area	m^2	163.6	153.3
Total boiler tube mean free area	m^2	0.403	0.423
Fraction of tube mean free gas area through large tubes	%	79	51
Type of superheater element	-	E (finned)	A
Number of superheater elements	-	48	28
Total superheater gas-side heating surface area	m^2	130.3 (incl. fins)	44.0
Total steam flow area through superheater elements	m^2	0.0306	0.0177
Exhaust system type	-	double modified Lempor	single, plain
Total blast nozzle tip area	cm^2	165.4	120.4 (final blast nozzle)
Total chimney mixing chamber / choke area	m^2	0.114	0.103
Total chimney exit area	m^2	0.390	0.134
Type of brake system	-	Knorr-Bremse Kss high-speed air brake	engine = steam tender=vacuum
Number of wheels braked	-	all	coupled and tender wheels
Brake force on the wheel rims as a fraction of locomotive weight for speeds < 60 km/h (38 mph)	%	73.6	60.7
Brake force on the wheel rims as a fraction of locomotive weight from 60 - 200 km/h (38 - 125 mph)	%	up to 181.0	60.7
Coupled wheel brake rigging	-	compensated	uncompensated
Engine suspension system	-	3-point, compensated	uncompensated

Main frame:	5AT: welded plate frame with welded-on cylinder block. BR 5MT: built-up plate frame with bolted-on cylinders
Leading bogie:	5AT: cast or welded frame, geared roller centring BR 5MT: plate frame, spring centring