The 5AT project:

Design and development of a "second generation" Advanced Technology Steam Locomotive

- Alan Fozard - Project Coordinator
- John Hind B.Sc, C.Eng, MIMechE
  - Chairman Engineering Planning Working Party

Notable steam loco design engineers active post - 1960

Andre Chapelon (France) 1892 – 1978

Livio Dante Porta (Argentina) 1922 – 2003

- Approached steam locomotive design on a much more scientific basis than hitherto particularly by using thermodynamic methods to optimise locomotive performance.
- Porta evolved a highly structured methodology for optimising the design of new steam locos.

1952 Comparison of drawbar thermal efficiencies and fuel costs of various types of rail traction*

	Dbte	Fuel cost per mile
Steam: Castle Class 4-6-0	5.5%	5.25p
Diesel Electric: 1Co-Co1 1750 hp	18.8%	5.33p
Gas Turbine: A1A+A1A No. 18000	6.6%	11.5p
Electric: Co-Co No. 20003	11.5%	9.6p

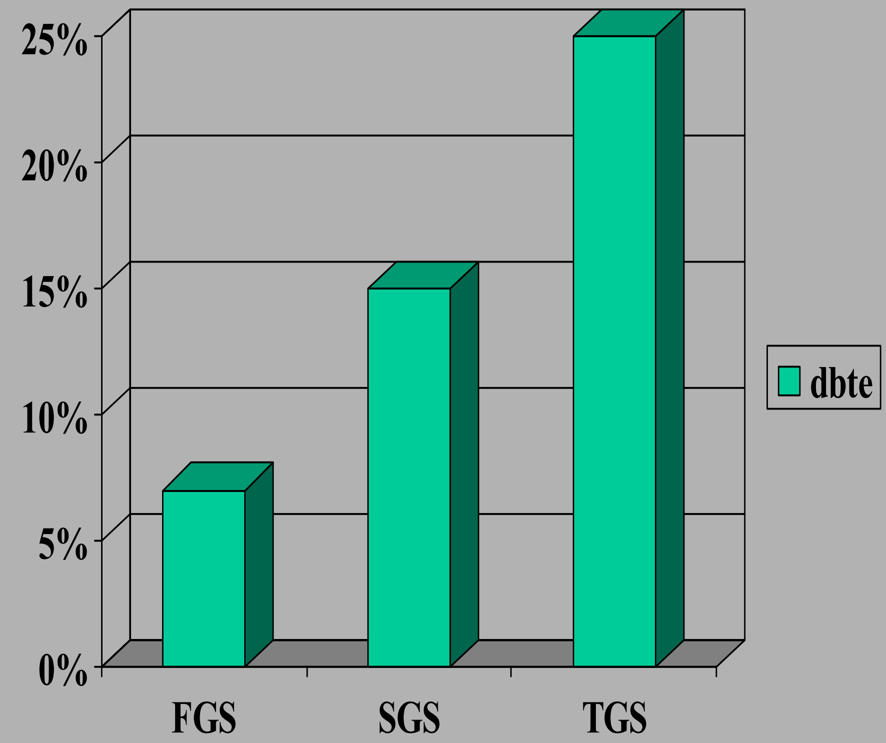
*** Reference: "Dropping the Fire" by Phillip Atkins, NRM, page 46.**

What is Advanced Steam?

First, Second & Third Generation Steam

(Porta's definitions)

- **FGS** practically all existing designs (typical drawbar thermal efficiency [dbte] -7%)
- **SGS** - new designs which can be built using best existing technology but need no further research. (dbte – 15%)
- **TGS** – designs which would require a significant amount of r & d. (dbte - condensing TGS - 25%).

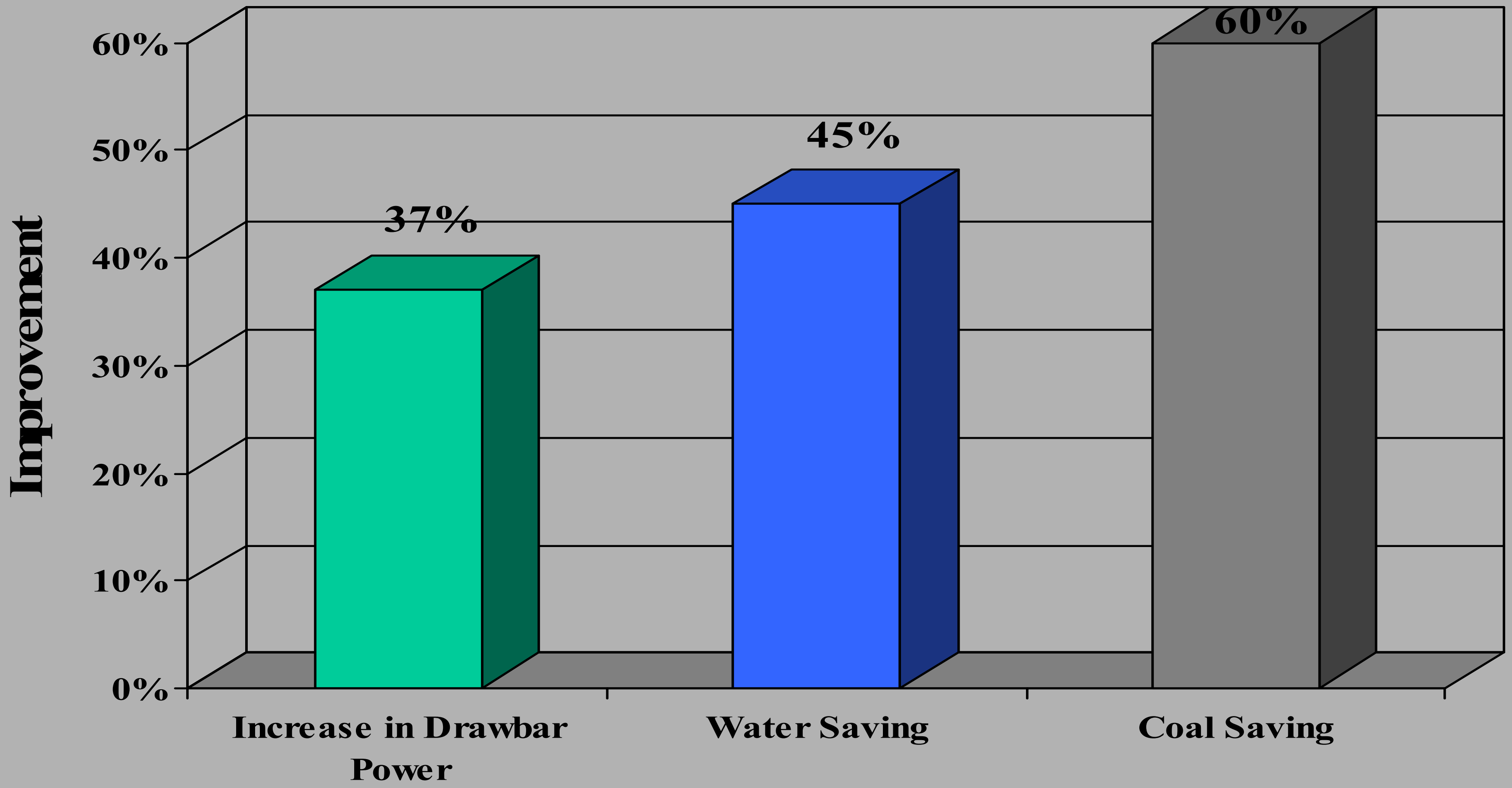


Advanced steam rebuilds

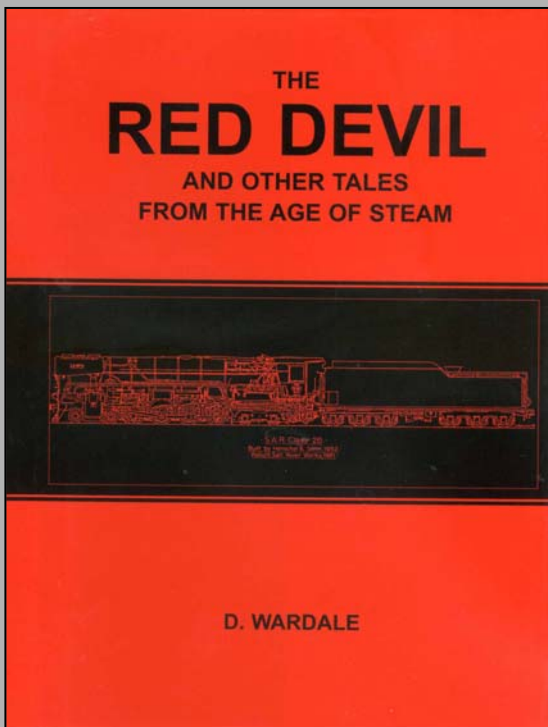
"La Argentina" by Porta
3 cylinder 4-8-0 compound
Dbte 11.9%

SAR Class 26
D.Wardale's "Red Devil"
2 cylinder 4-8-4 simple
Indicted te 13%

Class 26 Performance Improvements



Origin of the Project



David Wardale suggests a "super class 5" locomotive would have delivered outstanding performance.

2000 – refines the concept by calculating "Basic Performance Figures" for the locomotive.

Reasons behind the 5AT Project

- To build a fully optimised Second Generation Steam (SGS) locomotive for hauling excursion and cruise trains.
- To demonstrate the capabilities, reliability and profit making potential of SGS locomotives on the main line.
- To ensure that steam locomotive development continues and that steam remains operational on the main line in the long term.

5AT Project Status

- The 5AT Project is still at the Feasibility Stage
- Considerable work has been done and is still underway.
- Classic ‘fuzzy front end’ of a project,
- We do not have all the answers.
- Tonight is the 1st Public Viewing of some of the 5AT features.

5AT Design Principles

- Maximise Boiler Pressure
- Maximize Steam Temperature
- Maximize Feedwater Temperature
- Minimize Boiler – Steam Chest Pressure Drop
- Minimize the Steam Chest – Cylinder Pressure Drop
- Minimise Exhaust Steam Back Pressure
- Ensure that Draughting & Combustion Systems Guarantee Good Steaming

Fundamental Design Calculations (FDC's)

- 18 Subject Areas
- 356 pages of calculations
  - Over 6000 lines of calculations
  - Over 100 diagrams
- Defines Characteristics of the Main Components

FDC's

- Pistons
- Crossheads & Slidebars
- Connecting Rods
- Crankpins
- Coupling Rods
- Driving & Coupled Axles
- Piston Valves

FDC’s

- Boiler
- Exhaust System
- Valve Gear
- Cylinders & Cylinder Liners
- Mainframes
- Springs & Spring Rigging
- Brakegear
- Leading Bogie & Engine Stability
- Auxiliaries

FDC's

- Tractive Effort v Speed
- Horsepower v Speed
- Load, Gradient v Speed
- Expected Indicator Diagrams
- Efficiency

FDC's

Item No.	Item	Unit	Amount
91	Using the notation of Ref. [9], let common radial pressure at the pin / rod interface = p_o. In the pin: $p_o = (-a + b/[69]^2)$, $0 = (-a + b/[90]^2)$[10] from which: a = -1,29 p_o, b = -3 233 p_o. In the rod: $p_o = (-a? + b?/[69]^2)$, $0 = (-a? + b?/[79]^2)$[10] from which: a?= 0,56 p_o, b?= 17 227 p_o. Hoop stress at the gudgeon pin o/d $\sigma_1 = (a + b/[69]^2) = (-1{,}29\ p_o - 3\ 233\ p_o/[69]^2) = -1{,}58\ p_o$.[10] Hoop stress at the small-end bore σ? = $(a? + b?/[69]^2) = (0{,}56\ p_o + 17\ 227\ p_o/[69]^2) = 2{,}12\ p_o$.[10]		
92	Δd = (|σ_1| + σ?) x d ÷ E[9]. E = [2.1.(373)]:	N/mm^2	206 000
93	Substituting data into eq. [92]: [86]=(1,58p_o + 2,12p_o) x [69] ÷ [92] i.e. p_o =	N/mm^2	63,6
94	Hoop stress at small-end bore σ? = 2,12 p_o = 2,12 x [93] =	N/mm^2	135
95	Hoop stress at small-end o/d = $(0{,}56\ p_o + 17\ 227\ p_o/[79]^2)$ = 1,12 x [93] =	N/mm^2	71
96	Hoop stress at gudgeon pin o/d σ_1 = -1,58 p_o = -1,58 x [93] =	N/mm^2	-100
97	Hoop stress at gudgeon pin bore $(-1{,}29\ p_o - 3\ 233\ p_o/[90]^2)$ = -2,58 x [93] =	N/mm^2	-164
98	The mean interference fit hoop stress σ_m over the whole rod end section F-F must be found. It is given by: σ_m x ([79]/2 – [69]/2) = ?[69]/2 [79]/2 (a?+ (b?/(2r)^2)).dr where r = radius from gudgeon pin centre line. Solving gives σ_m = 1,5 x p_o = 1,5 x [93] =	N/mm^2	95
99	The maximum externally applied tensile load is taken under overload conditions: maximum P = [2.1.(395)] =	kN	402,5
100	Maximum direct stress F-F = [99] ÷ [75] =	N/mm^2	72

FDC's

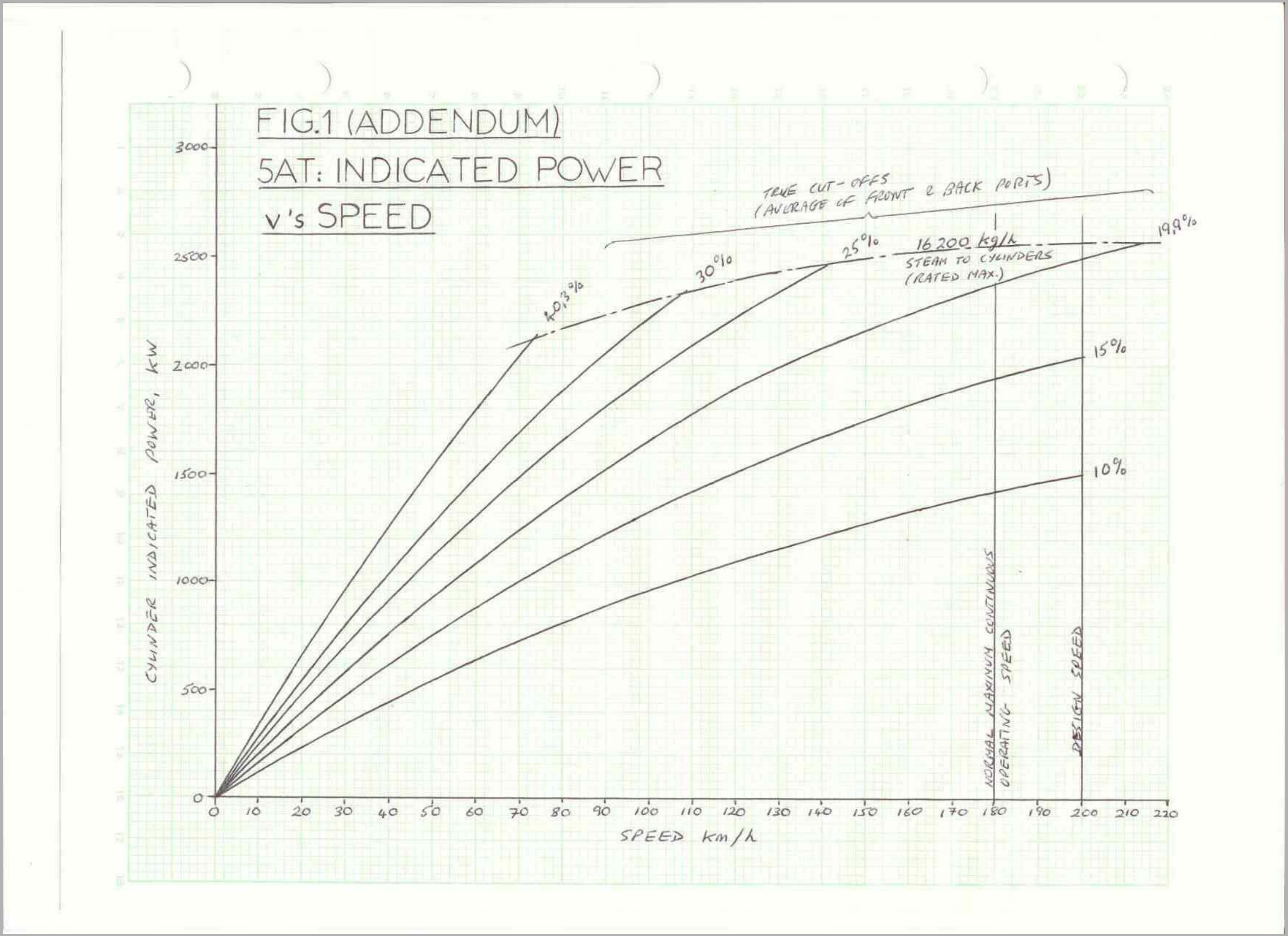


FIG.1 (ADDENDUM)
5AT: INDICATED POWER
v's SPEED
TRUE CUT-OFFS
(AVERAGE OF FRONT & BACK PORTS)
40,3%
30%
25%
19,9%
15%
10%
16 200 kg/h
STEAM TO CYLINDERS
(RATED MAX.)
NORMAL MAXIMUM CONTINUOUS OPERATING SPEED
DESIGN SPEED
CYLINDER INDICATED POWER, kW
SPEED km/h
0
500
1000
1500
2000
2500
3000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220

FDC's

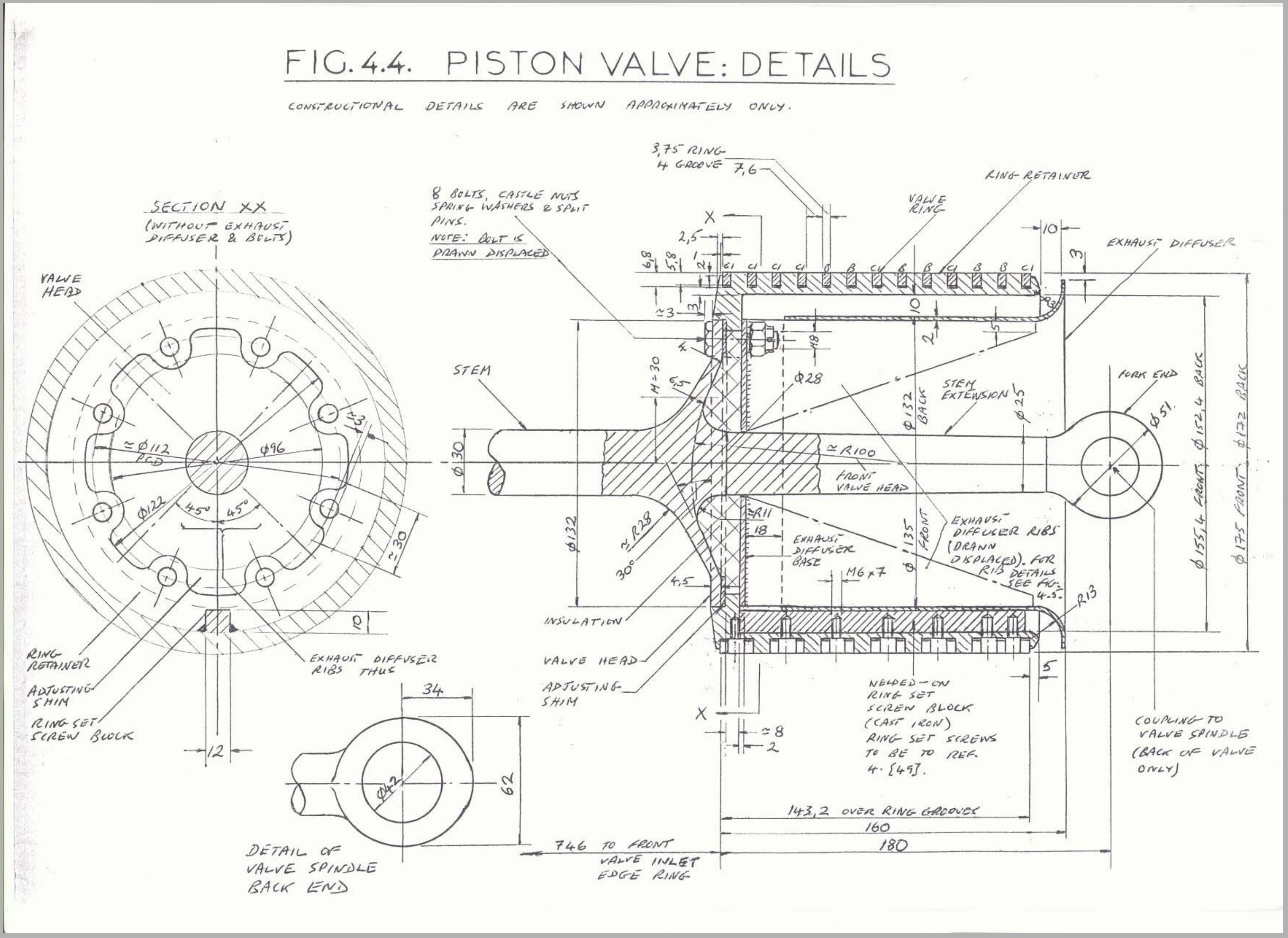


FIG. 4.4. PISTON VALVE: DETAILS
CONSTRUCTIONAL DETAILS ARE SHOWN APPROXIMATELY ONLY.
SECTION XX
(WITHOUT EXHAUST DIFFUSER & BOLTS)
VALVE HEAD
RING RETAINER
ADJUSTING SHIM
RING SET SCREW BLOCK
EXHAUST DIFFUSER RIBS THUS
DETAIL OF VALVE SPINDLE BACK END
8 BOLTS, CASTLE NUTS SPRING WASHERS & SPLIT PINS.
NOTE: BOLT IS DRAWN DISPLACED
3,75 RING 4 GROOVE
VALVE RING
EXHAUST DIFFUSER
STEM
STEM EXTENSION
FORK END
FRONT VALVE HEAD
EXHAUST DIFFUSER BASE
EXHAUST DIFFUSER RIBS (DRAWN DISPLACED). FOR RIB DETAILS SEE FIG. 4.5.
INSULATION
WELDED-ON RING SET SCREW BLOCK (CAST IRON) RING SET SCREWS TO BE TO REF. 4. [49].
COUPLING TO VALVE SPINDLE (BACK OF VALVE ONLY)
143,2 OVER RING GROOVES
746 TO FRONT VALVE INLET EDGE RING
160
180

5AT Specification

- Size & Format of BR Standard Class 5
  - 4-6-0
  - Maximum axle load 20 metric tons
- Coupled Wheel Diameter 1880 mm
- Continuous Drawbar Power
    - 1890 kW (2535 hp) at 113 km/h (71 mph)
- Maximum Sustainable Cylinder Power
    - 2580 kW (3460 hp) at 170 km/h (106 mph)

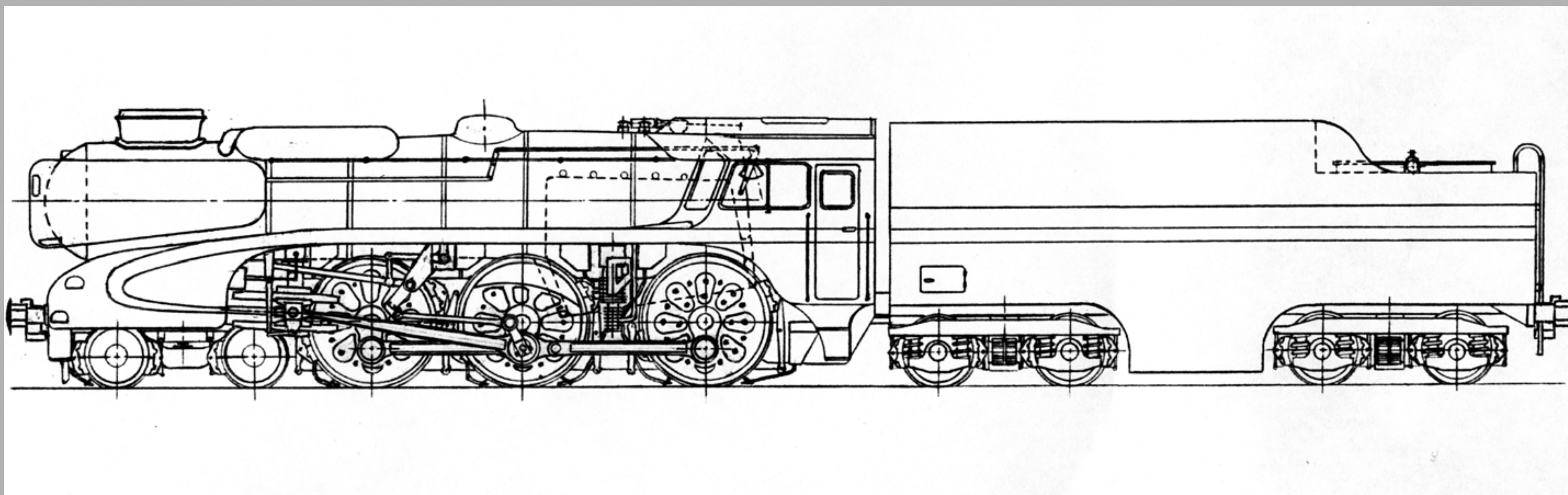
5AT – Design Performance

- Range (fuel light oil/diesel):

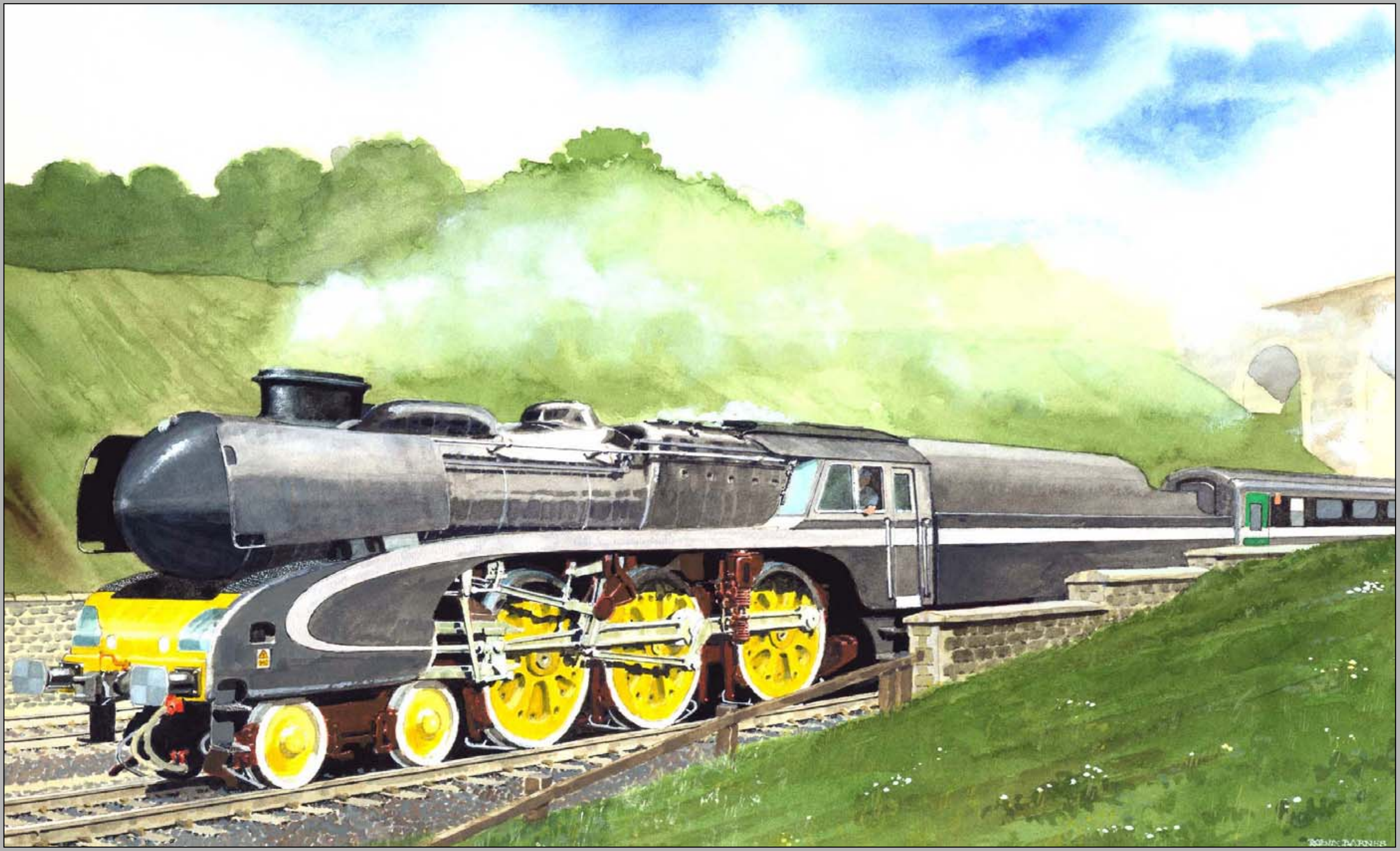
  - 920 km (780m.) fuel,

  - 620 km (380m.) water.
- Designed for operation at up to 180km/h (113mph).
- Maximum design speed 200km/h (125mph)

The 5AT



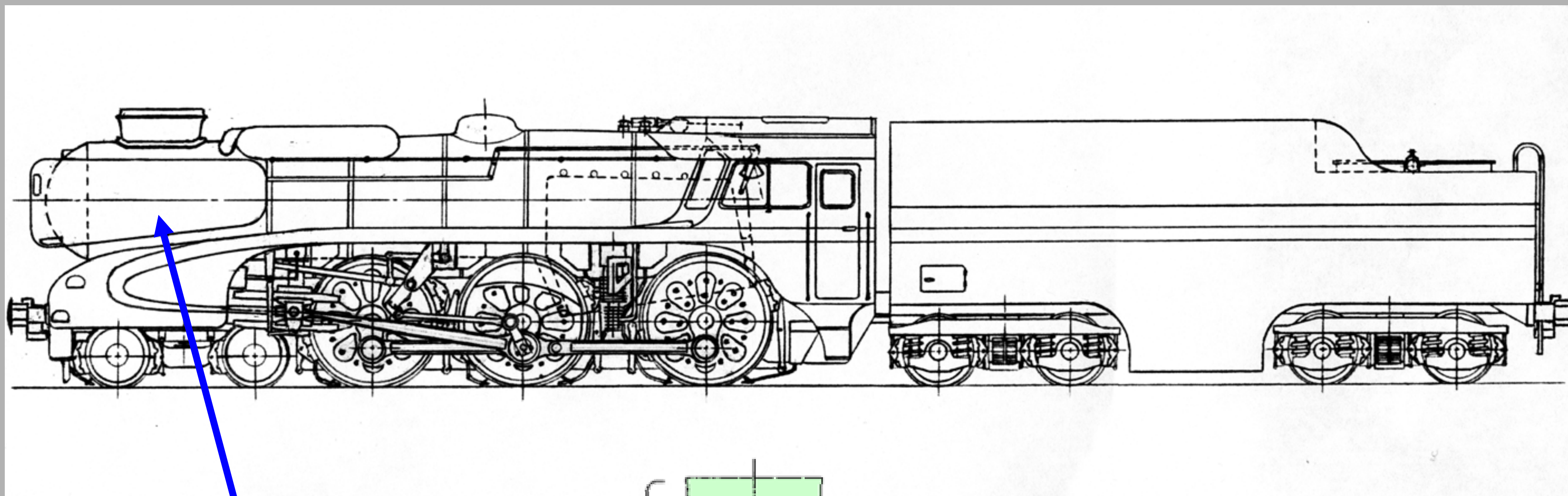
The 5AT as currently defined



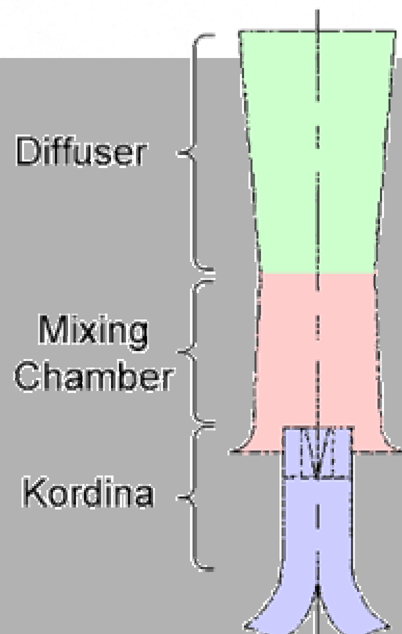
5AT improvements over 5MT

- Lempor Exhaust
- Higher Superheat
- Feedwater Heater
- Economiser
- Combustion Air Preheater
- New Pattern Twin Piston Valves
- Cooled Piston Valve Liners
- Lightweight Reciprocating Components
- Improved insulation

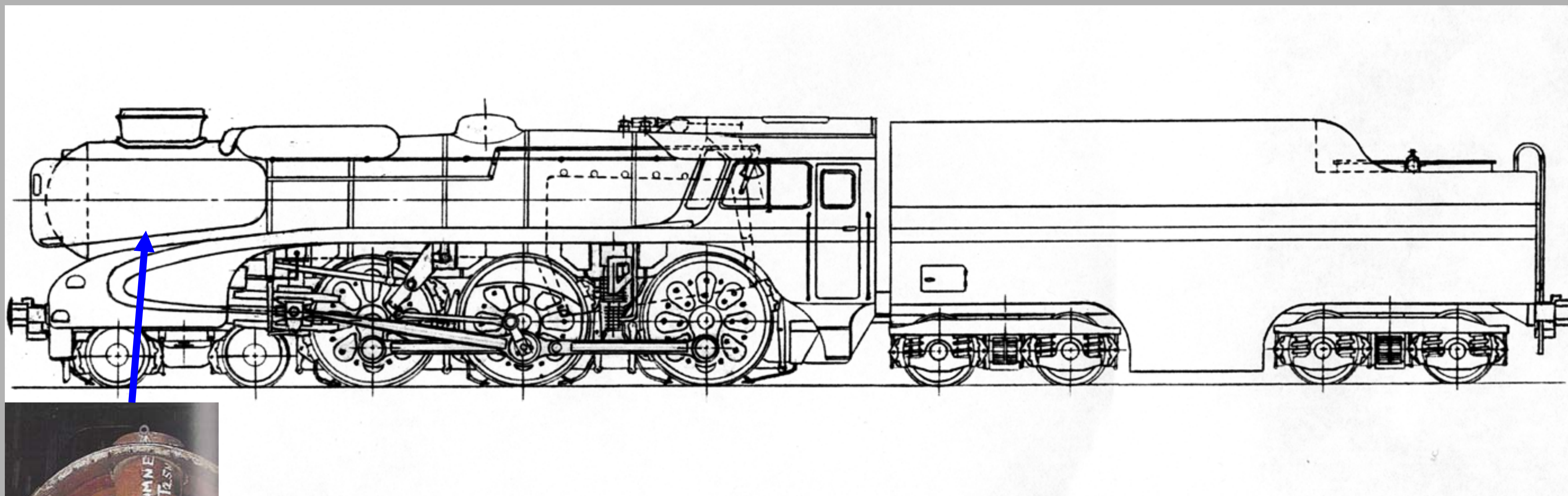
Lempor Exhaust



Lempor
Exhaust



Lempor Exhaust

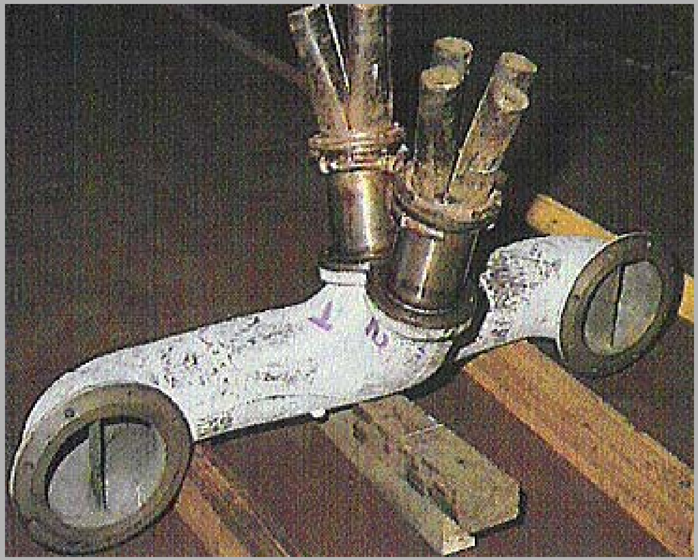


Lempor
Exhaust

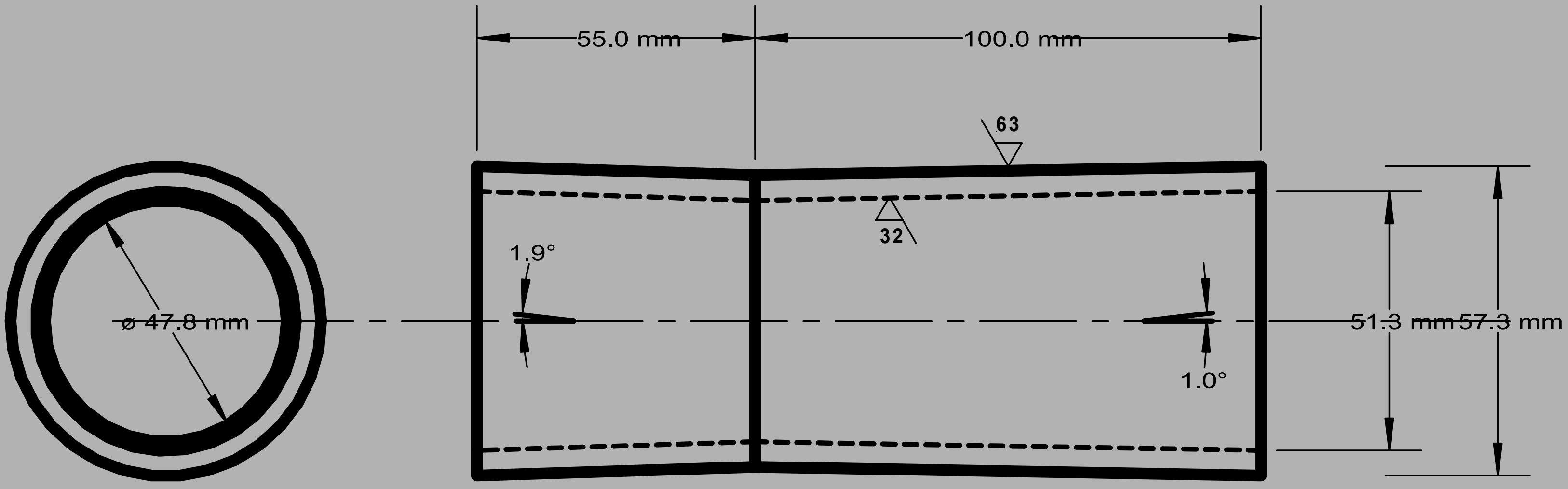
Blast
Nozzles

Kordina

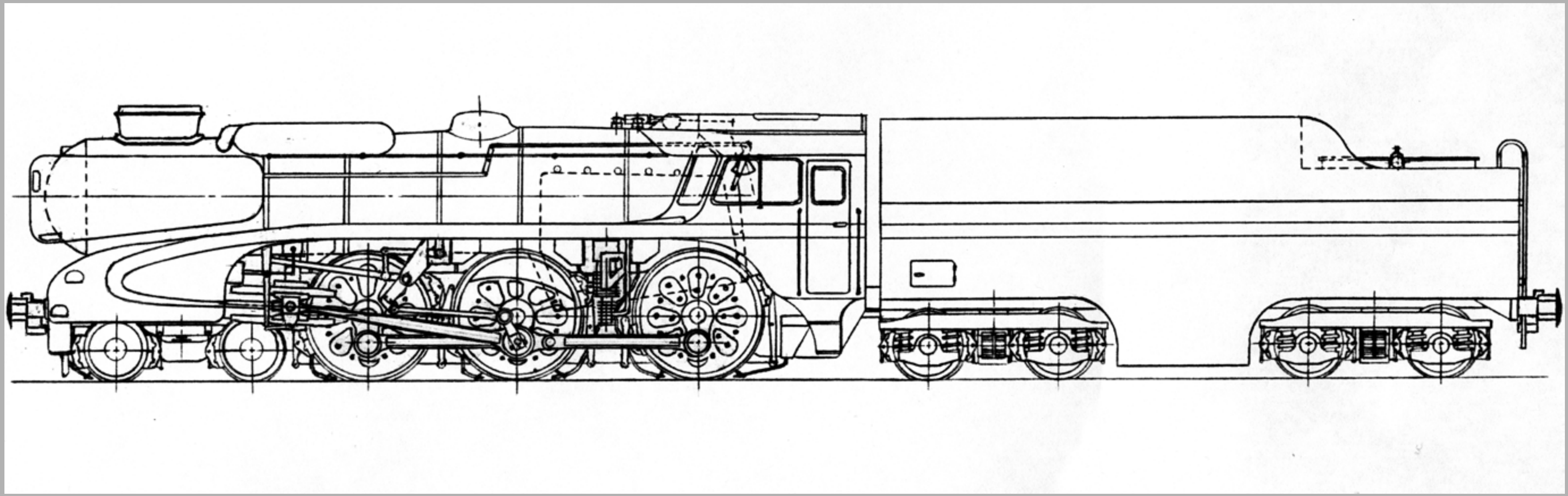
Lempor Exhaust



Blast
Nozzles



5AT – Boiler

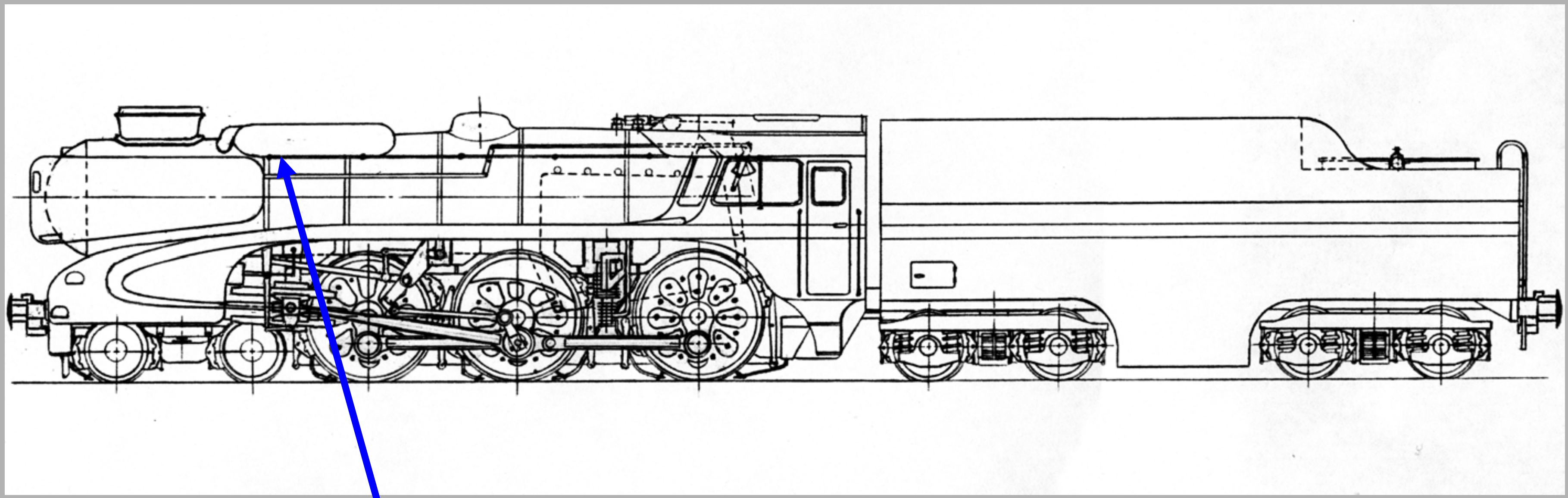


- All steel welded construction
- Belpaire firebox
- Oil fired
- Type E Superheater
- 96 Large Tubes
- 76 Small Tubes
- Steam Driven Feedpump
- Live Steam Injector
- Current generation insulation materials

5AT – Boiler

- Performance
  - Working pressure - 2100kpa (305psi)
  - Steam temperature at cylinders – 450^0 C
  - Evaporation – 17,000 kg/h (35,000 lb/hr)
- Principal dimensions as 5MT
- Designed to current Boiler Codes
- Will use Porta water treatment.

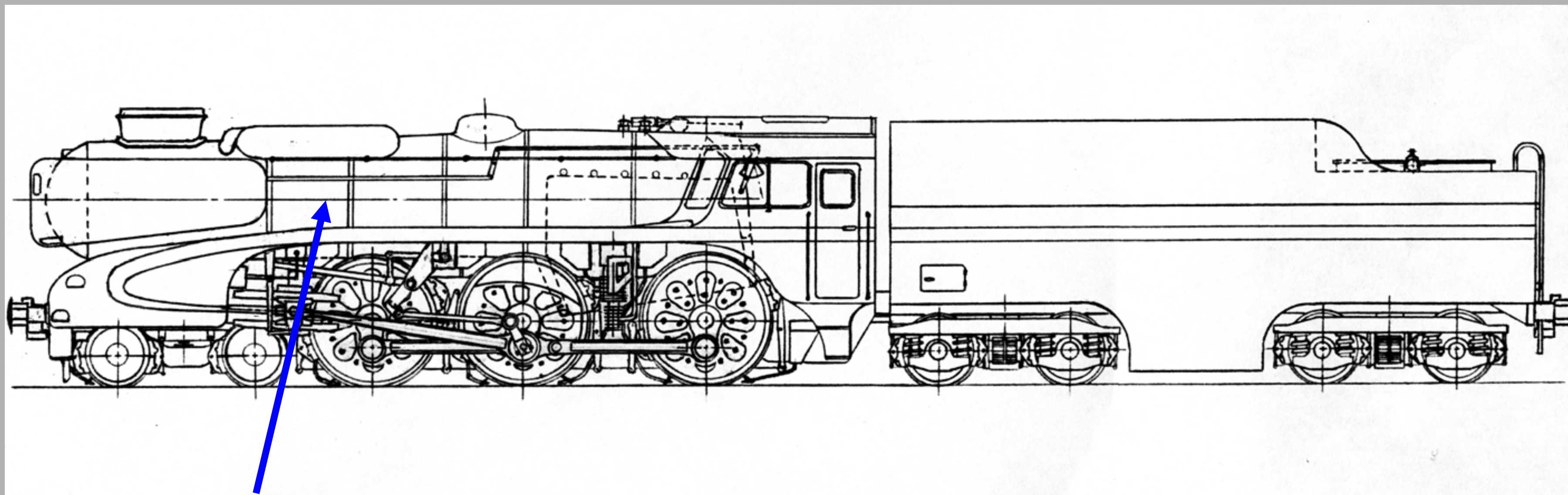
Feedwater Heater



2 Feedwater Heaters

- Shell & Tube Type
- Fed by Exhaust Steam
- Exhausts to Hot Well in the Tender
- Raises Water Temperature by 110 ^{o}C

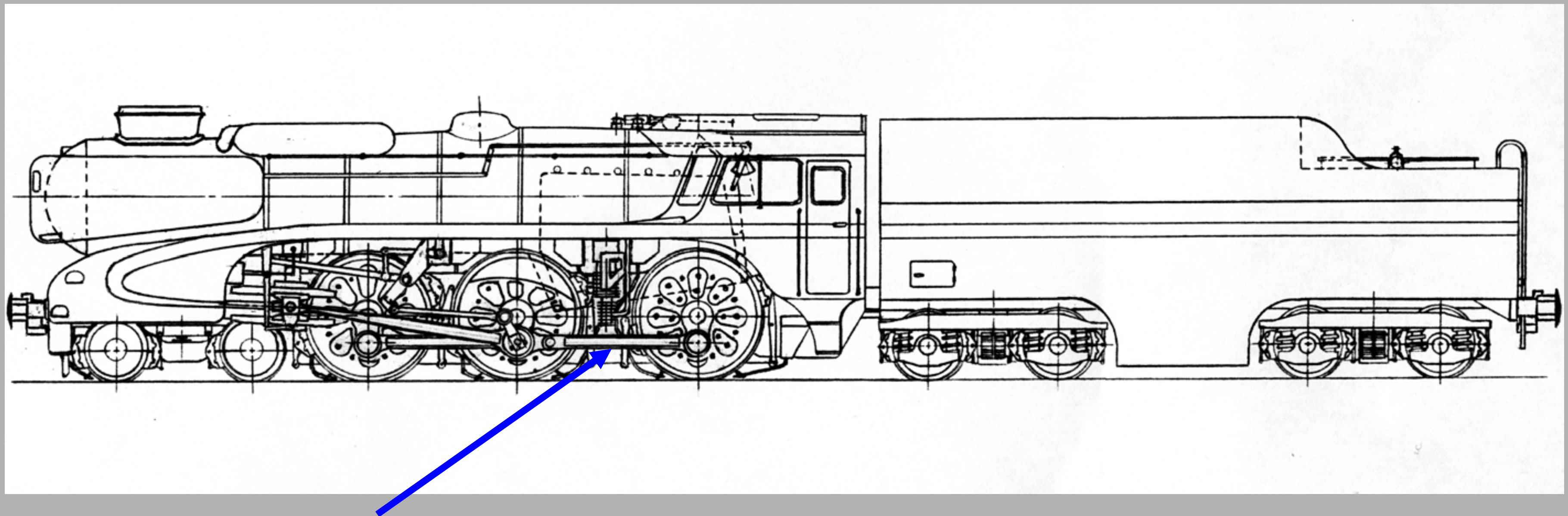
Economiser



Chapelon Type Economiser

- 1st 1.4m as economiser
  - Separated from rest of boiler by intermediate tubeplate
- Makes use of Flue Gases after they have passed over the Superheater
- Average Temperature in Economiser 161^{o} C

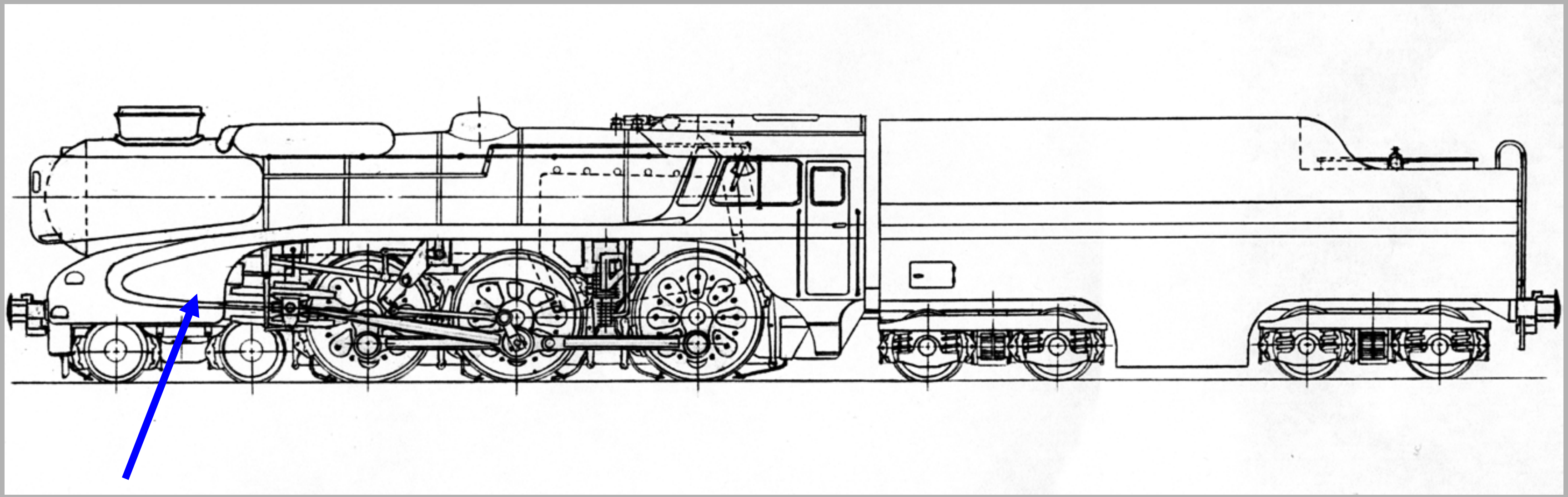
Combustion Air Preheater



Combustion Air Preheater

- To improve Boiler Efficiency
- Uses Exhaust Steam
- Pre-heats air to 100^0C

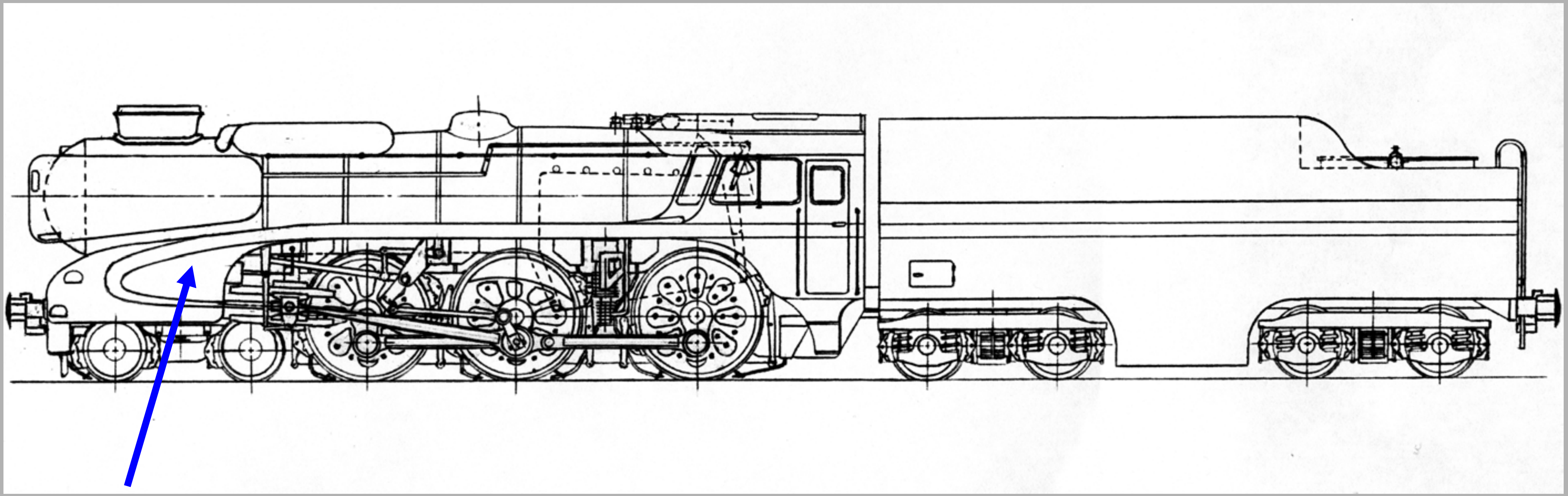
Pistons



Piston

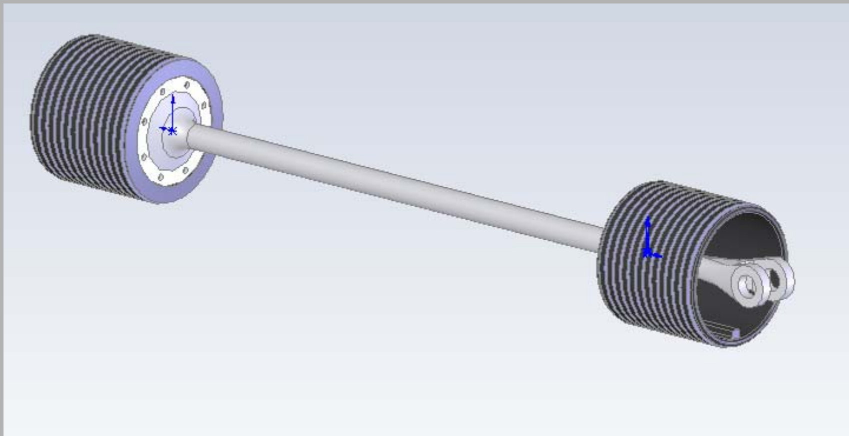
- Lightweight Piston
  - 450mm bore x 800 mm stroke
- 6 Piston Rings
  - 4 Cast Iron, 2 High Strength Bronze Rings
- Hollow Piston & Rod

Piston Valves

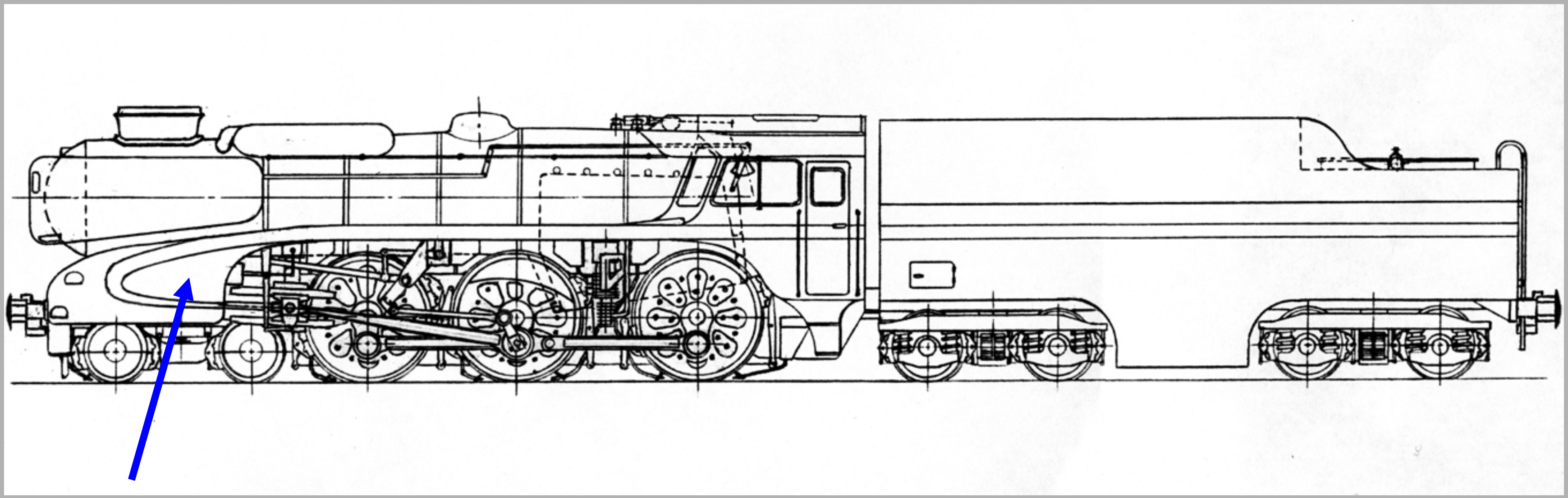


Piston Valve

- Lightweight Twin 175mm Dia Piston Valves per Cylinder
- 12 rings per head
  - 6 Cast Iron, 6 High Strength Bronze
- Low Friction ,Wear & Inertia

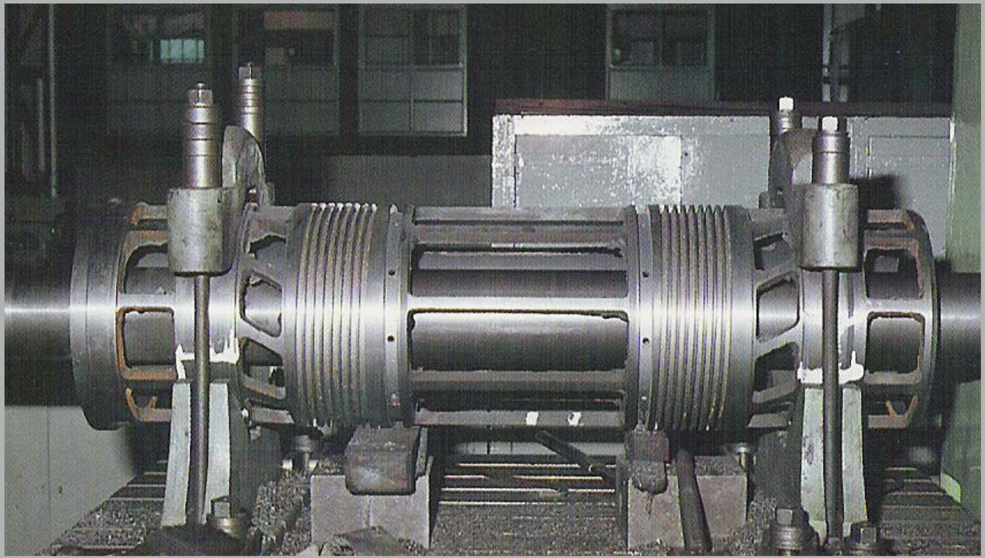


Piston Valves Liners

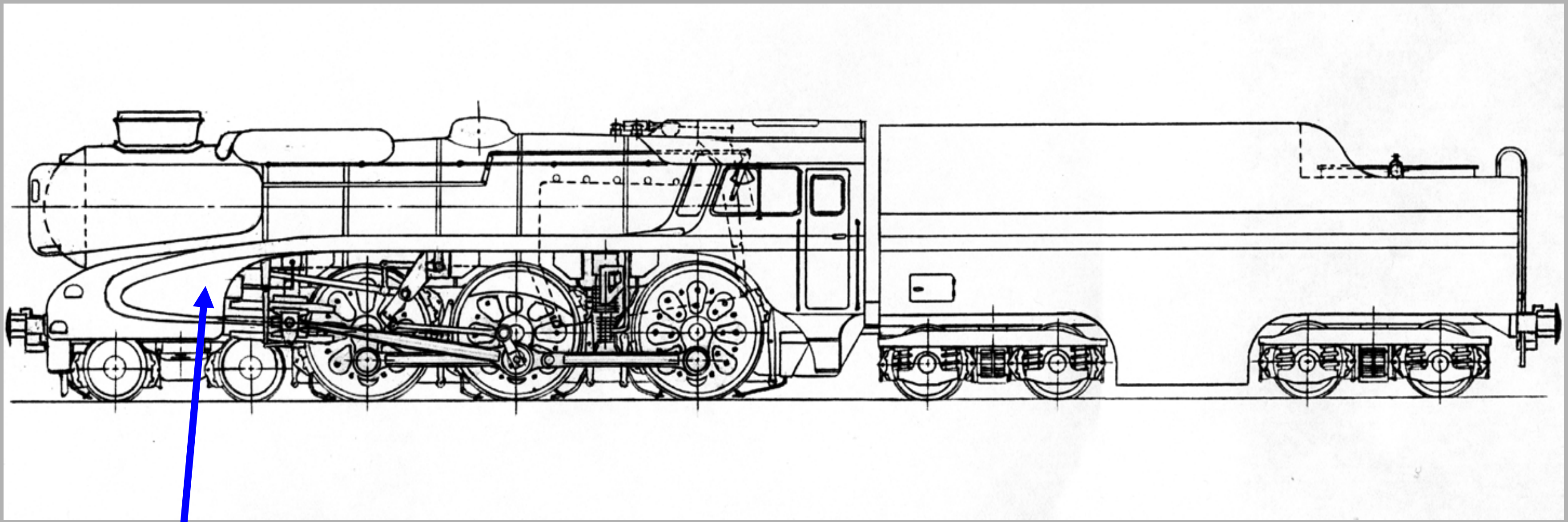


Piston Valve Liners

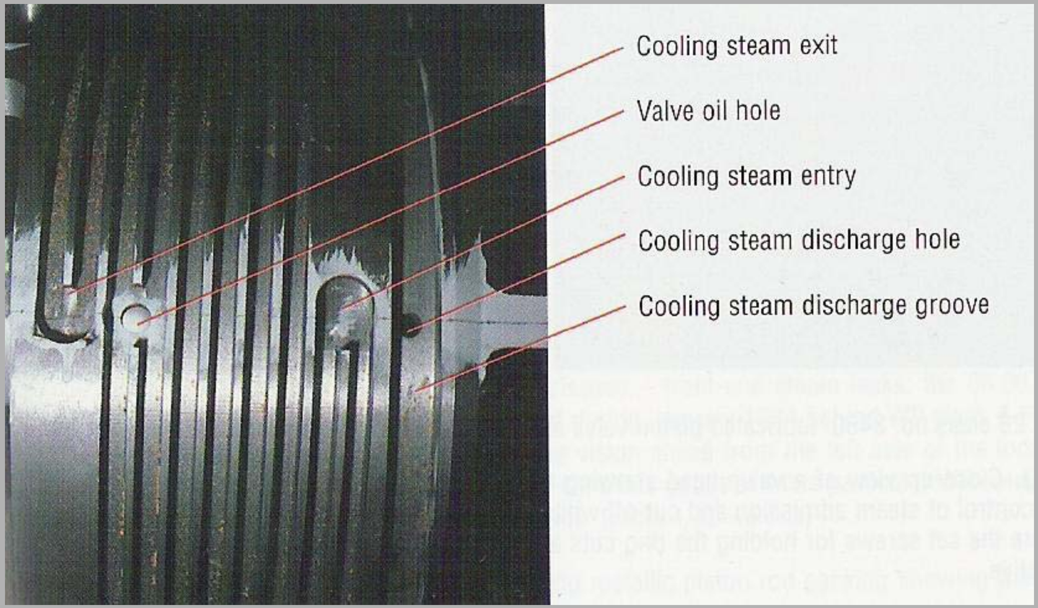
- Steam Cooled Piston Valve Liners
- Saturated Steam Cools Rubbing Surfaces to 300^0C



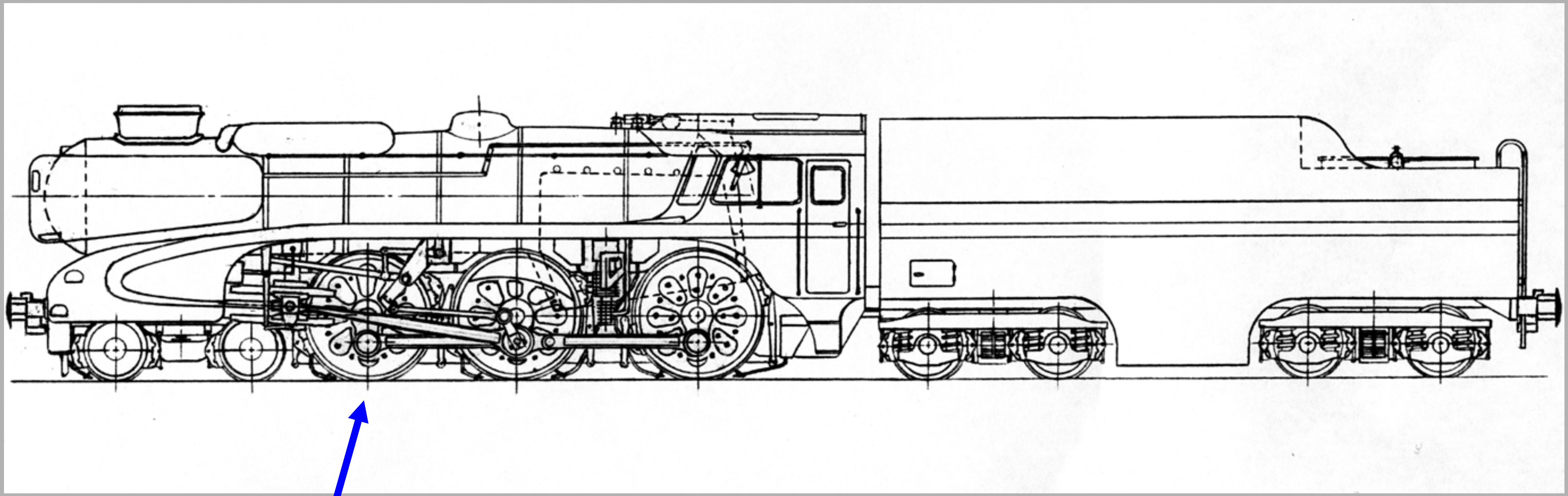
Piston Valves Liners



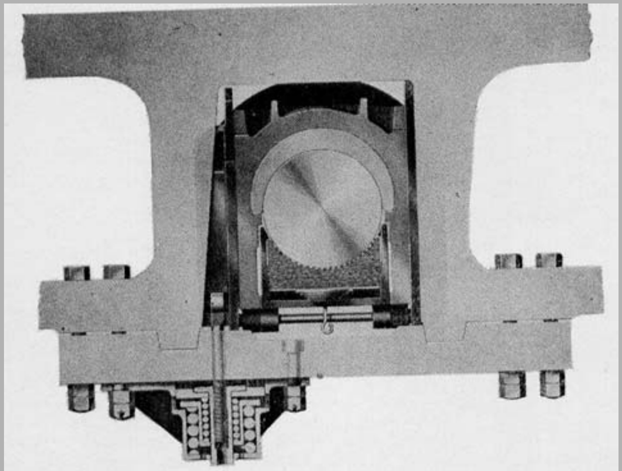
Piston Valve Liners



Frame

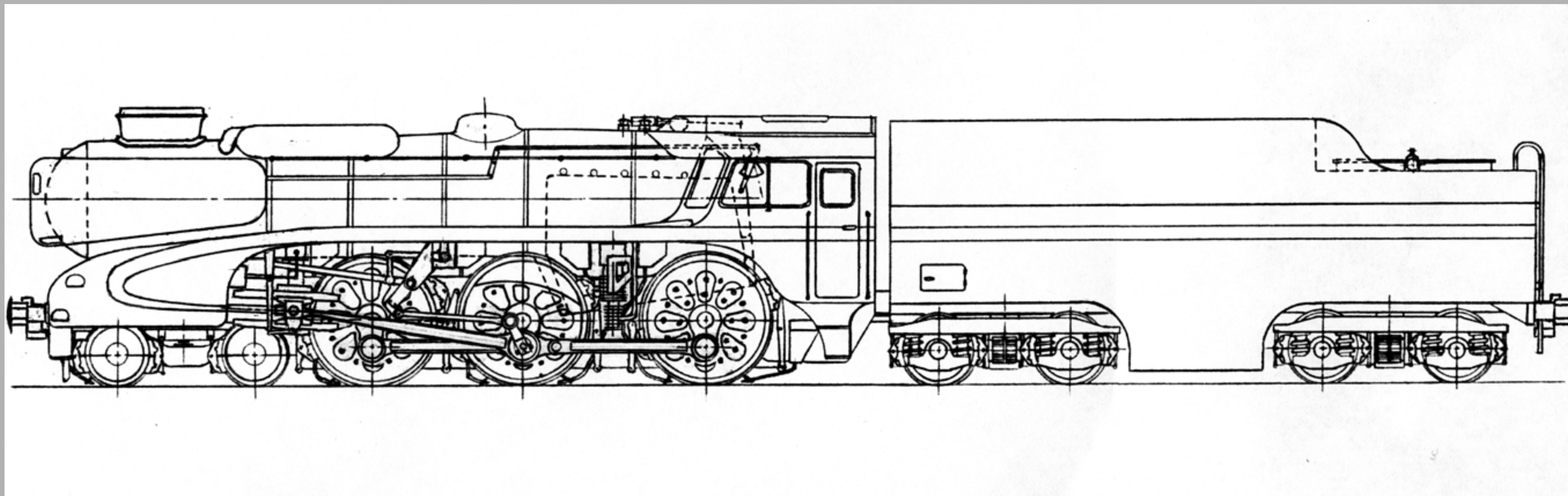


Franklin Spring Loaded Wedges



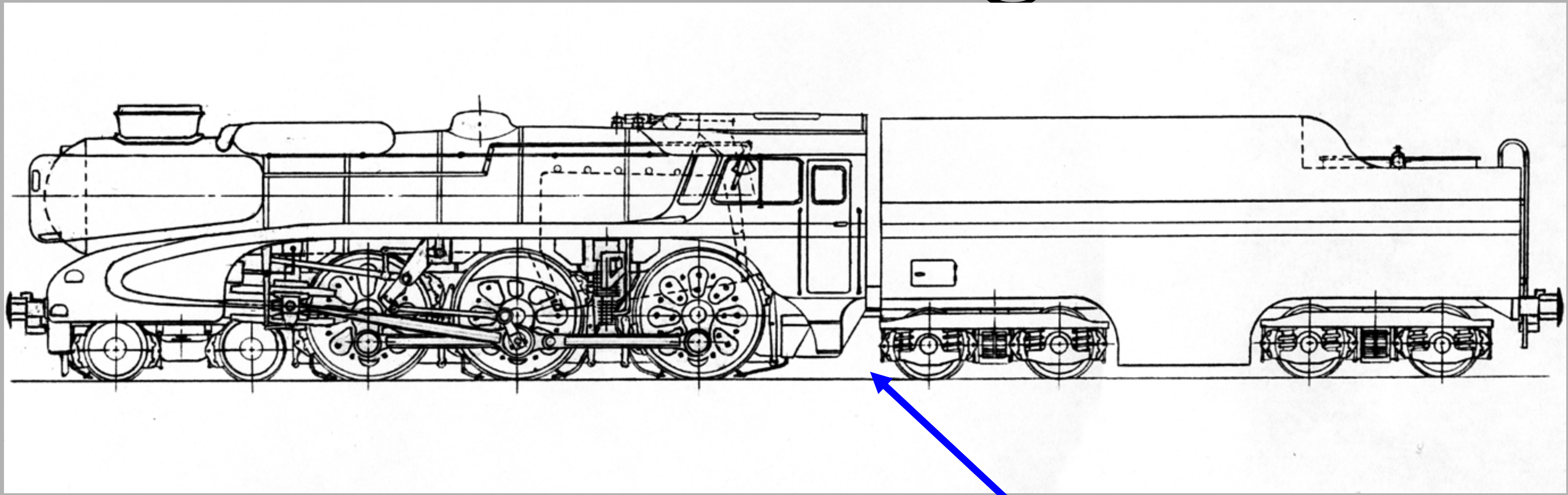
- Welded Plate Frames
- Well braced vertical & horizontal cross-members
- Follows post 1950 German practice

Adhesion

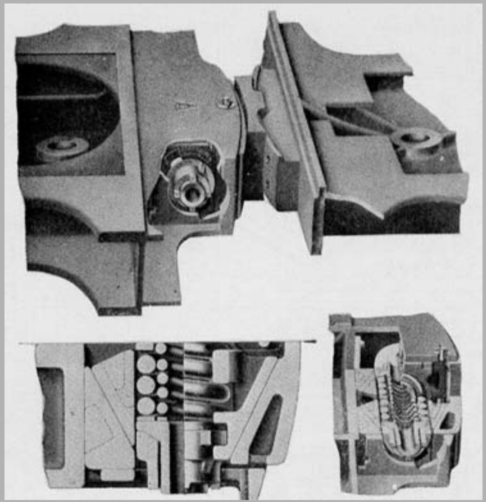


- Foot Pedal Operated Air Sanding
- Forwards – All Coupled Wheels
- Reverse – Trailing & Coupled
- Light Sanding Ahead of the bogie

Balancing



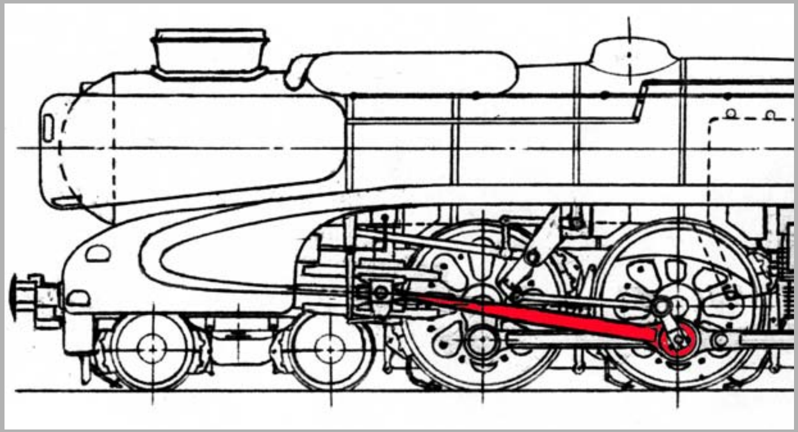
Franklin Radial Buffer



•Dynamic Augment no worse than a 5MT at 75mph

•To resist fore& aft vibrations Engine & Tender coupled together by solid unsprung coupling

Connecting Rod Design



- As light as possible
  - Reduces the need for reciprocating balance
- Minimum Maintenance
  - Roller Bearings
- Layout requirements
  - Clearance to Coupling Rod
  - Clearance to Expansion Link
  - Centre Distance
  - Loading Gauge

Connecting Rod Design

- Stress Analysis
  - Designed according to Association of American Railroads Rules
    - Proved successful on US High Speed Locomotives
  - Small End & Big End
    - Direct, Bending & Hoop Stresses
  - Shank
    - Buckling
    - Direct & Bending Stresses
- Fatigue Limits Checked
- Checked for Harmonics

Connecting Rod – 2 D Sketch

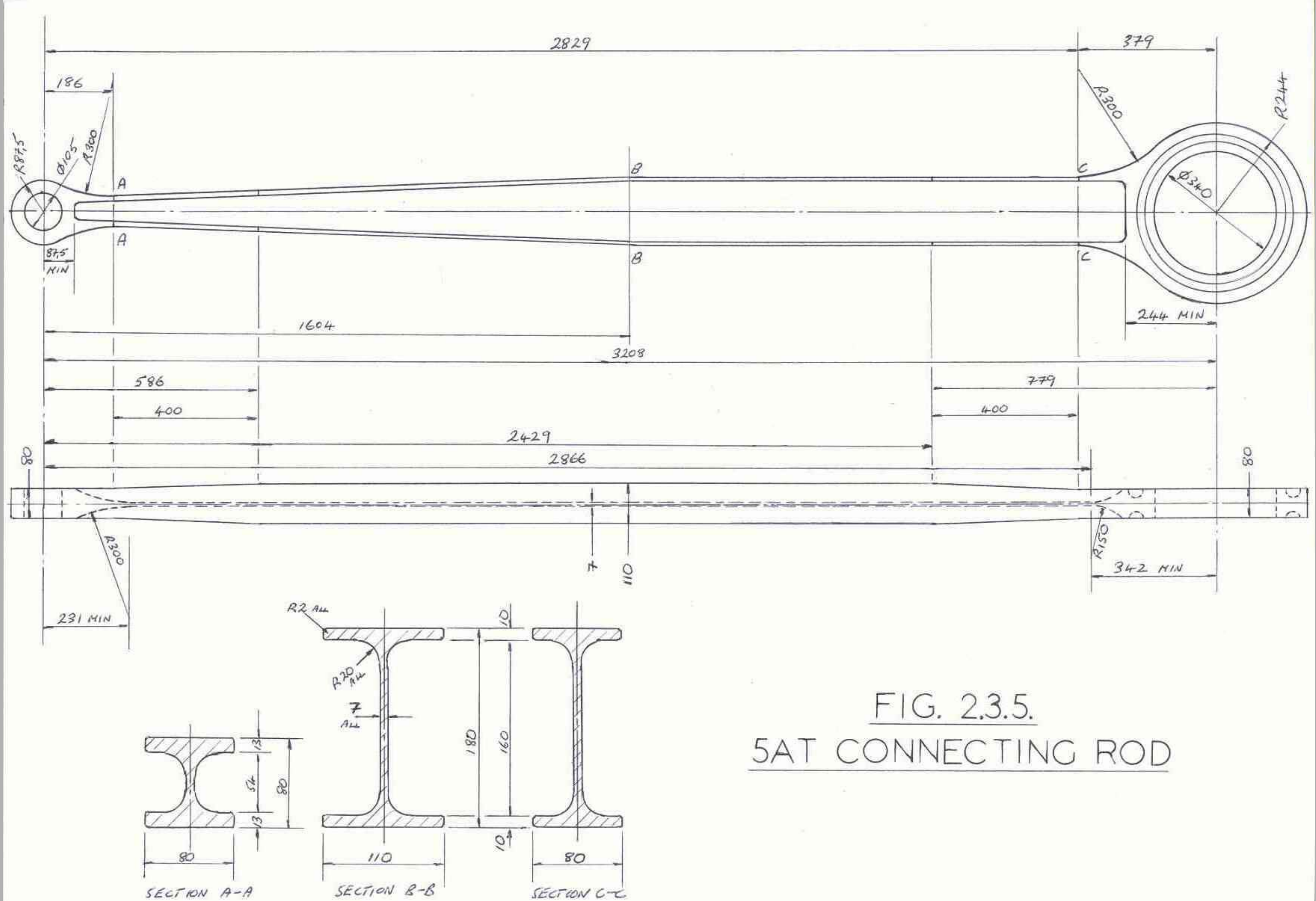
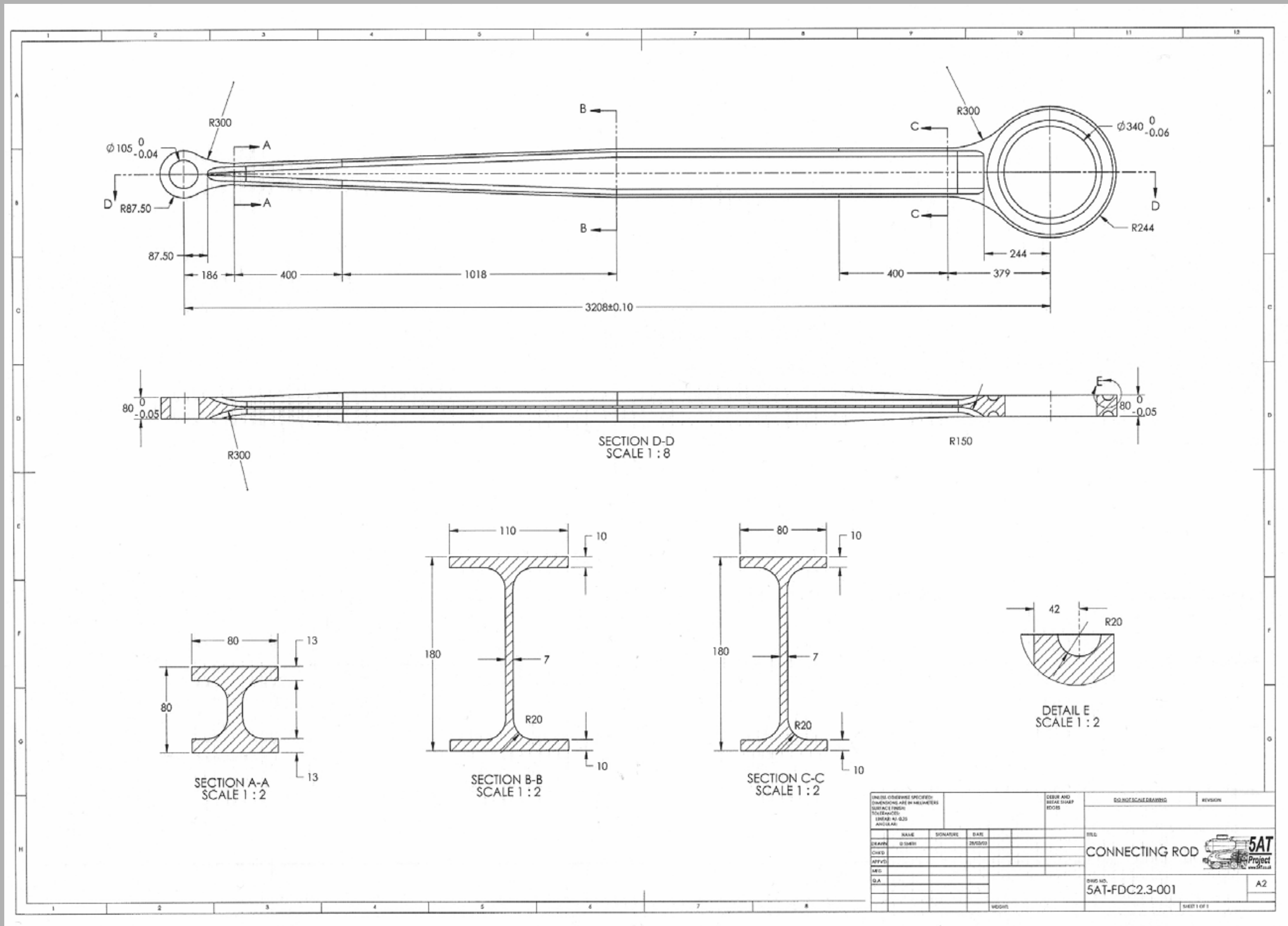


FIG. 2.3.5.
5AT CONNECTING ROD

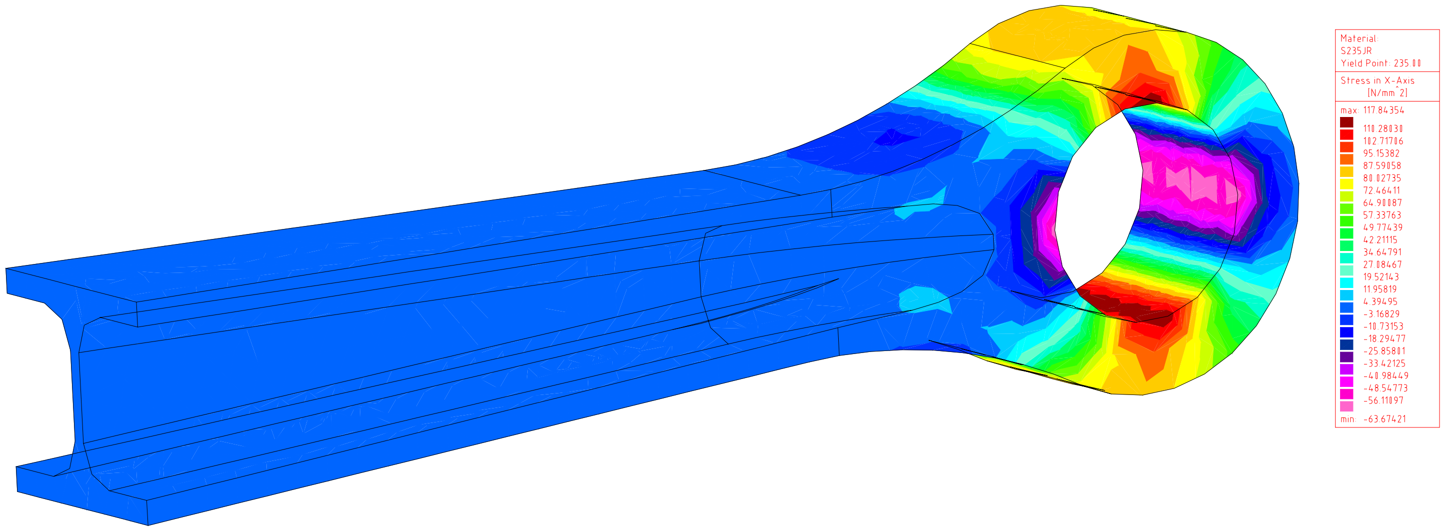
Connecting Rod - 3D Model

Connecting Rod – 2 D Drawing



Connecting Rod - FEA

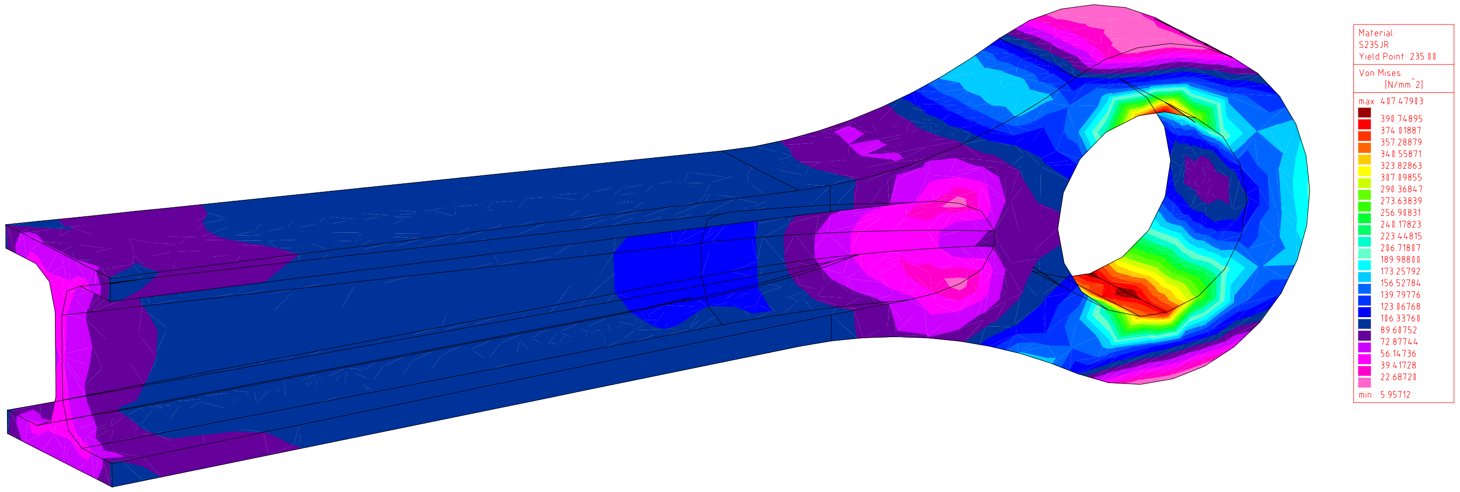
Little End - Press Fit



FLUID POWER DESIGN

Connecting Rod - FEA

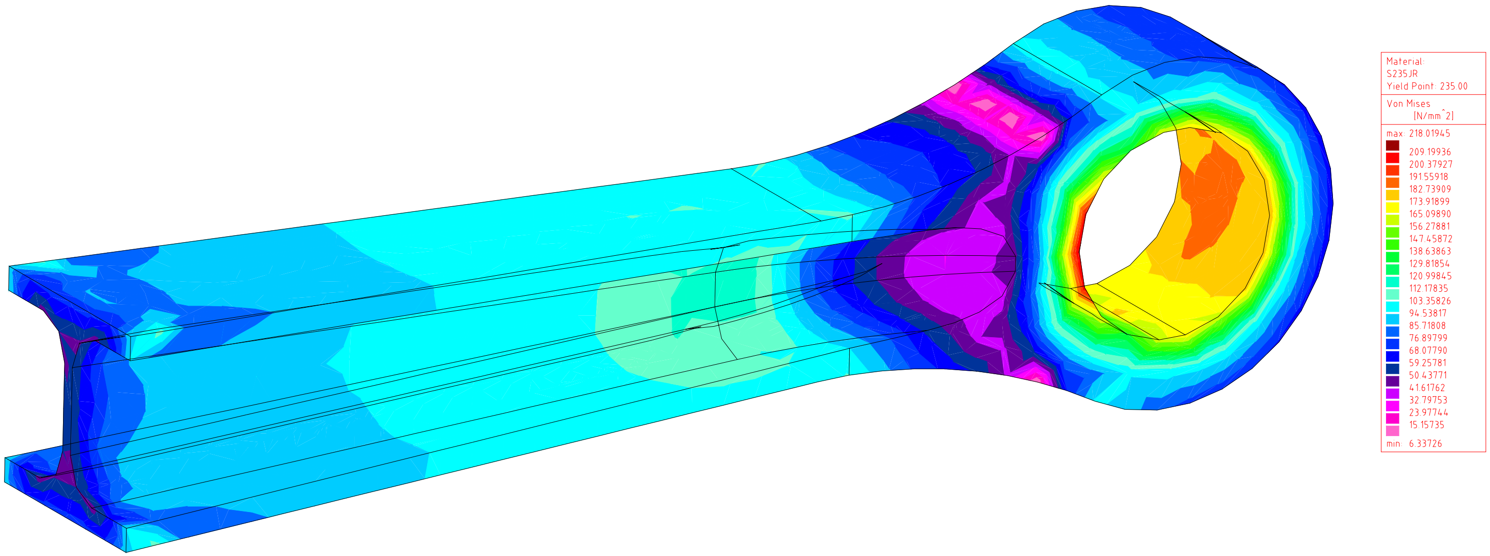
Little End – Press Fit + 320 kN Tension



FLUID POWER DESIGN

Connecting Rod - FEA

Little End – Press Fit + 320 kN Compression



FLUID POWER DESIGN

Connecting Rod - Material

- SAE 4340
- Properties
  - .4% C - .9% Mn - .35% Si
  - .95% Cr - 2.0% Ni -.35% Mo
  - Oil Quenched from 845^{0}C
  - Tempered at 642^{0}C
  - UTS - 1035 Mpa
  - Yield - 880 Mpa
- BS EN 10027-2 Steel No 1.6582
- BS 970 Pt1 817M40
  - UTS - 75 tons/in^2
  - Yield - 64 tons/in^2

EN 24

Connecting Rod
US High Speed Locomotives

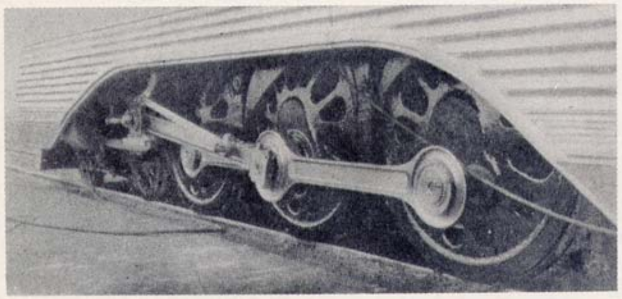


Fig. 8—(Left) Existing Burlington Type 4-6-4 locomotive modernized with Timken light-weight rods and reciprocating parts, reducing dynamic augment 75 per cent. The pistons, piston rods, crossheads, main rods, side rods, and all crank pins are made of Timken High Dynamic Steel. All crank pins, crossheads and axles are equipped with Timken Bearings. Driving axle and trailer truck applications fit into existing frame openings. The use of Timken Bearings and Timken High Dynamic Steel made possible a 52 per cent reduction in reciprocating weights. The Burlington operates 68 Timken Bearing Equipped steam locomotives

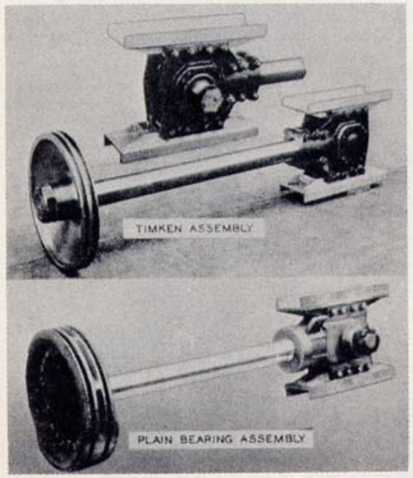


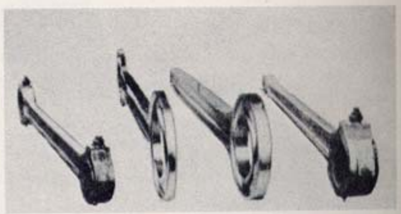
Fig. 10 (Right)

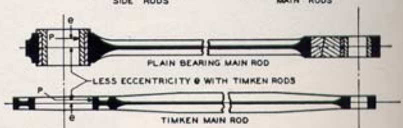
COMPARISON OF RECIPROCATING WEIGHTS, LBS.	PLAIN BRG	TIMKEN
CROSSHEAD ASSEMBLY	754	367
PISTON, PISTON ROD & PARTS	765	350
FRONT END OF MAIN ROD	422	210
UNION LINK AND BUSHING	30	17
TOTAL	1971	944
PERCENT	100	48

Fig. 12 (Above)

Fig. 11 (Right)

Fig. 9—(Left) Comparison of Timken designed reciprocating parts with conventional design for 4-6-4 high speed passenger locomotive. Note reduction in weights

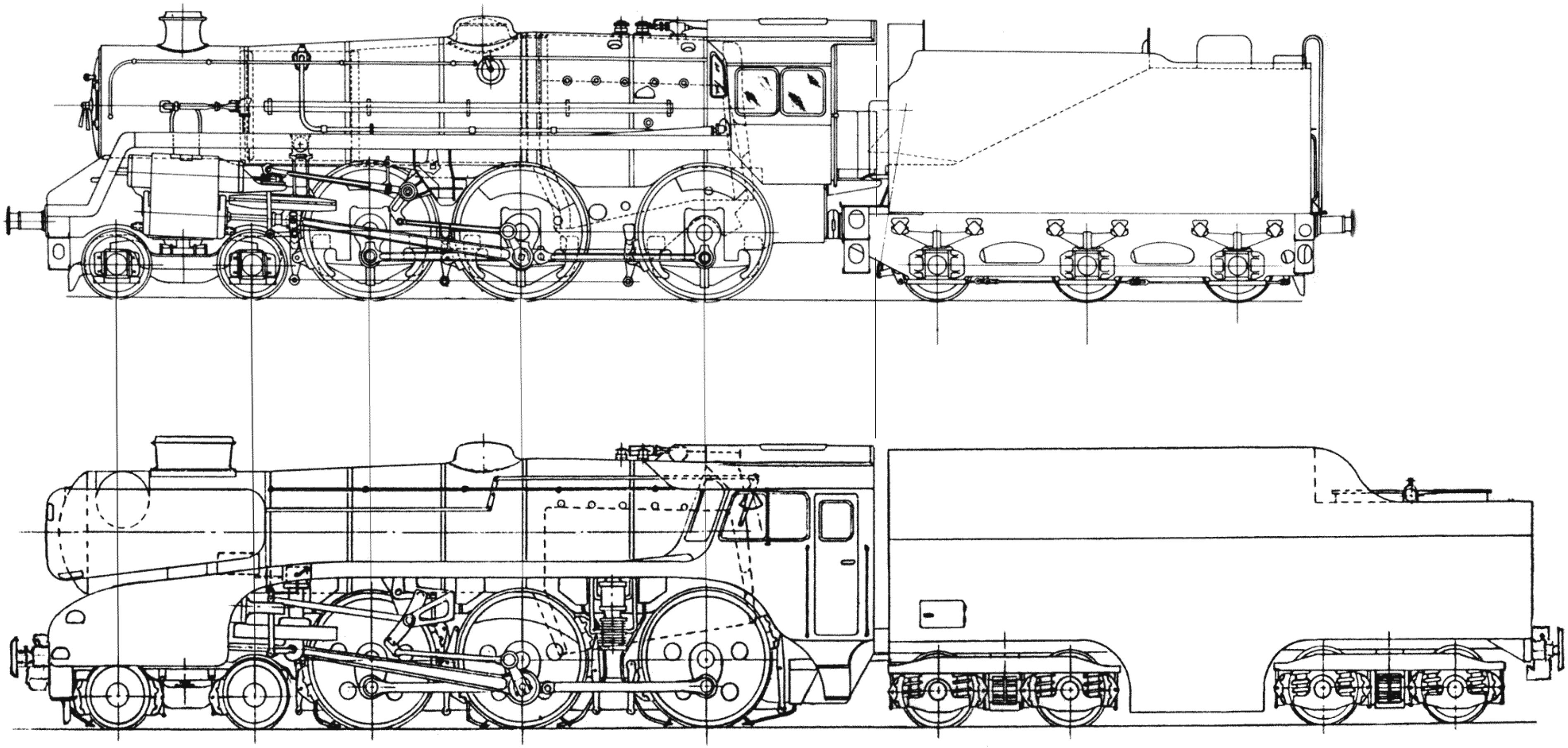




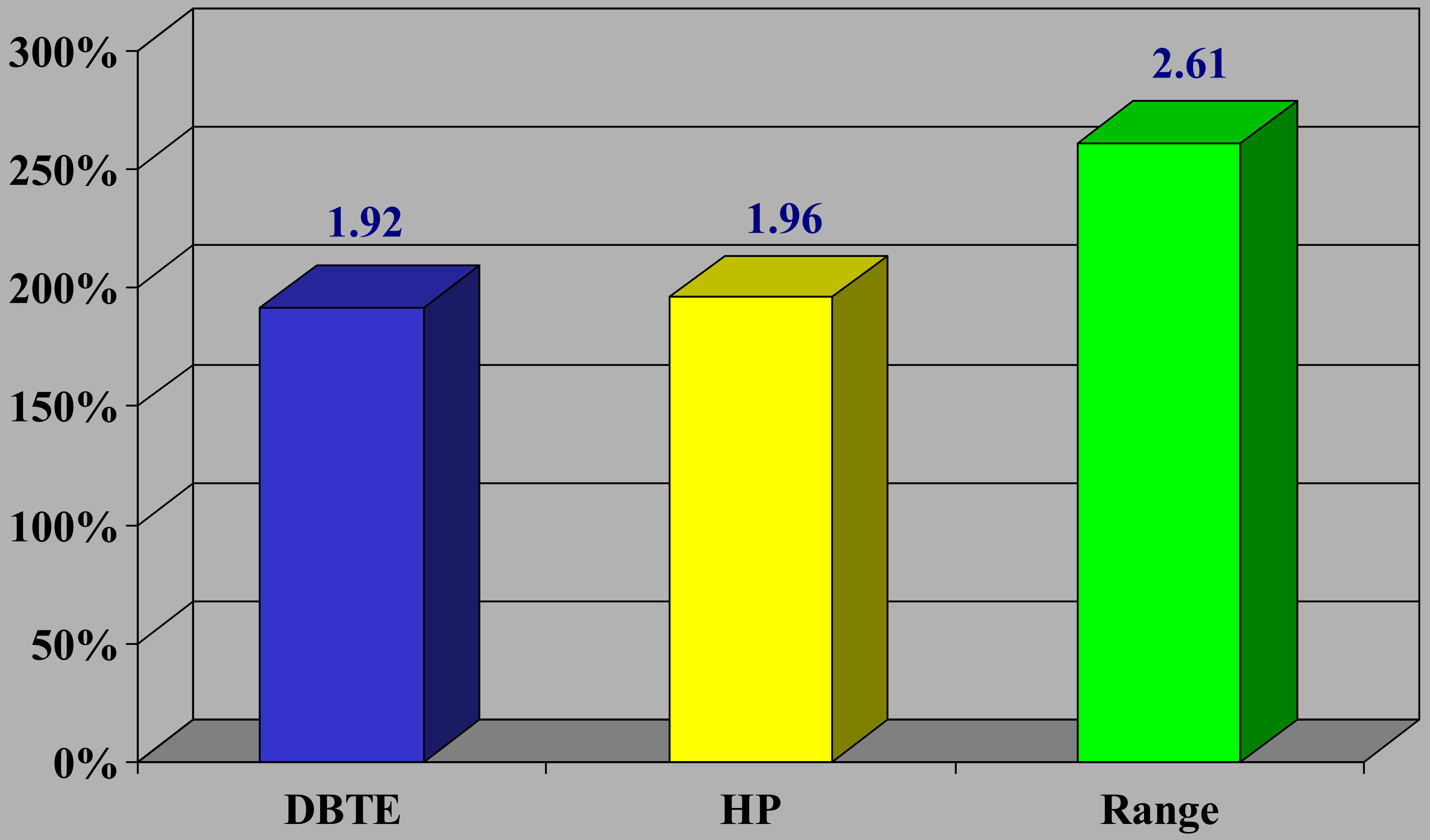
COMPARISON OF ROD WEIGHTS, LBS.	SIDE RODS		MAIN ROD	
	PLAIN BRG.	TIMKEN	PLAIN BRG.	TIMKEN
WT. ON MAIN PIN	556	338	581	319
WT. ON FRONT PIN	190	150		
WT. ON REAR PIN	178	150		
WT. ON X-HEAD PIN			422	210
TOTAL	922	638	1003	529

THE TIMKEN ROLLER BEARING CO., CANTON, OHIO

5MT and 5AT Compared

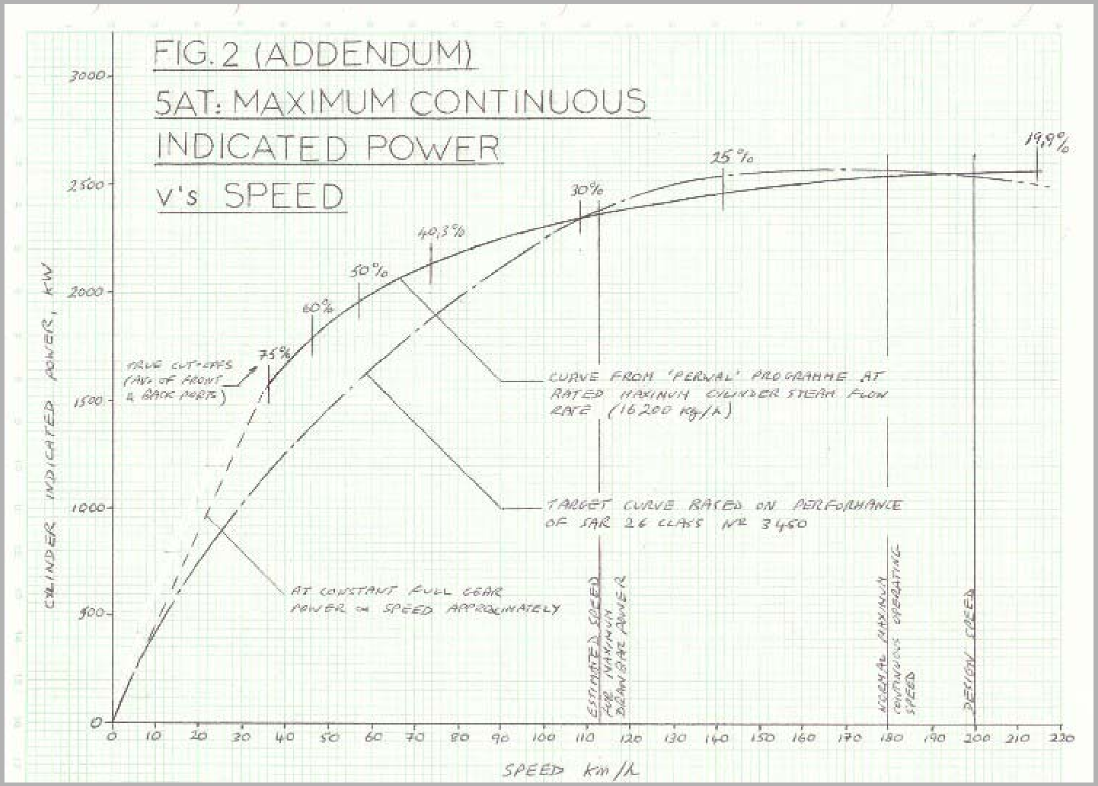


5MT & 5AT Performance

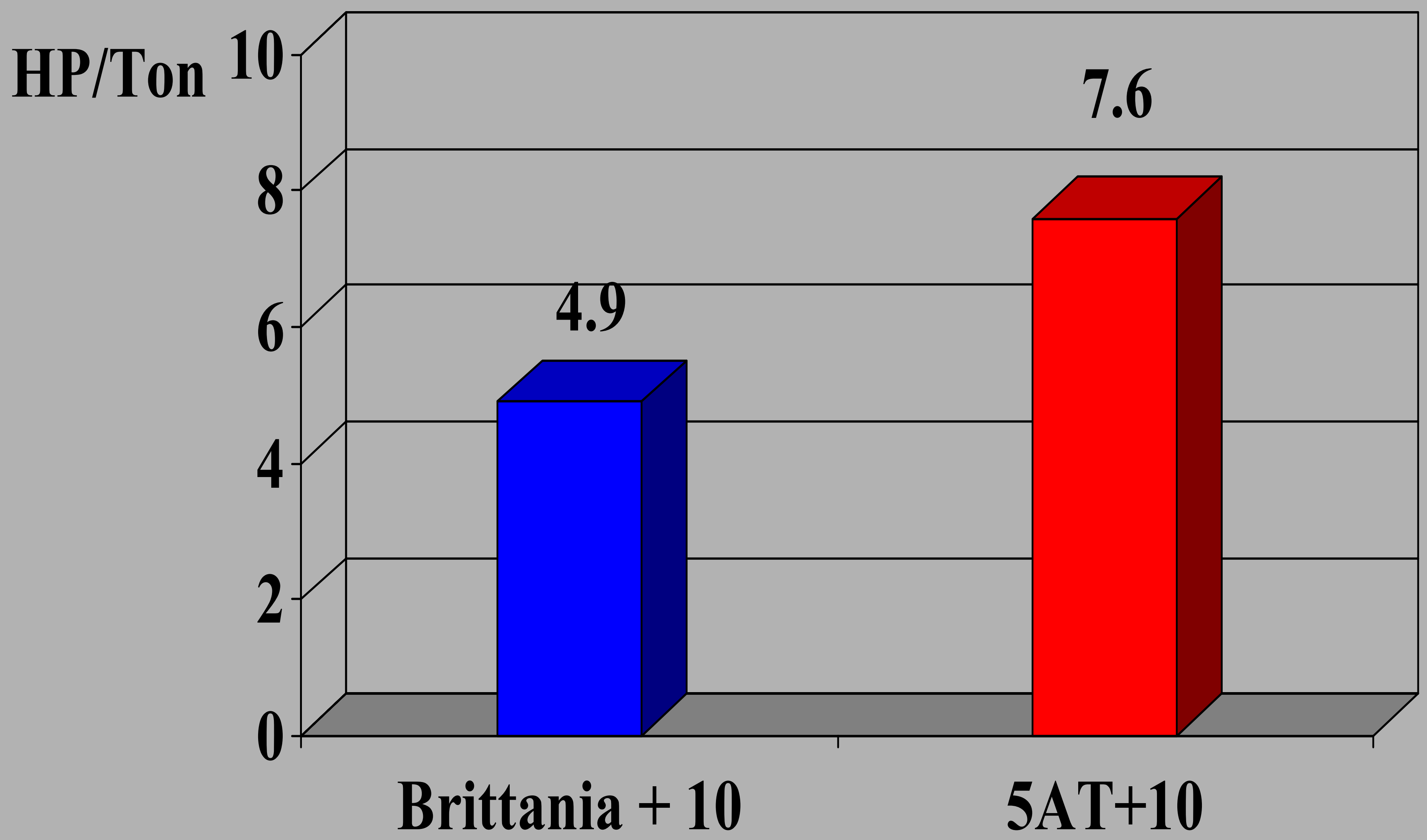


Performance Predictions

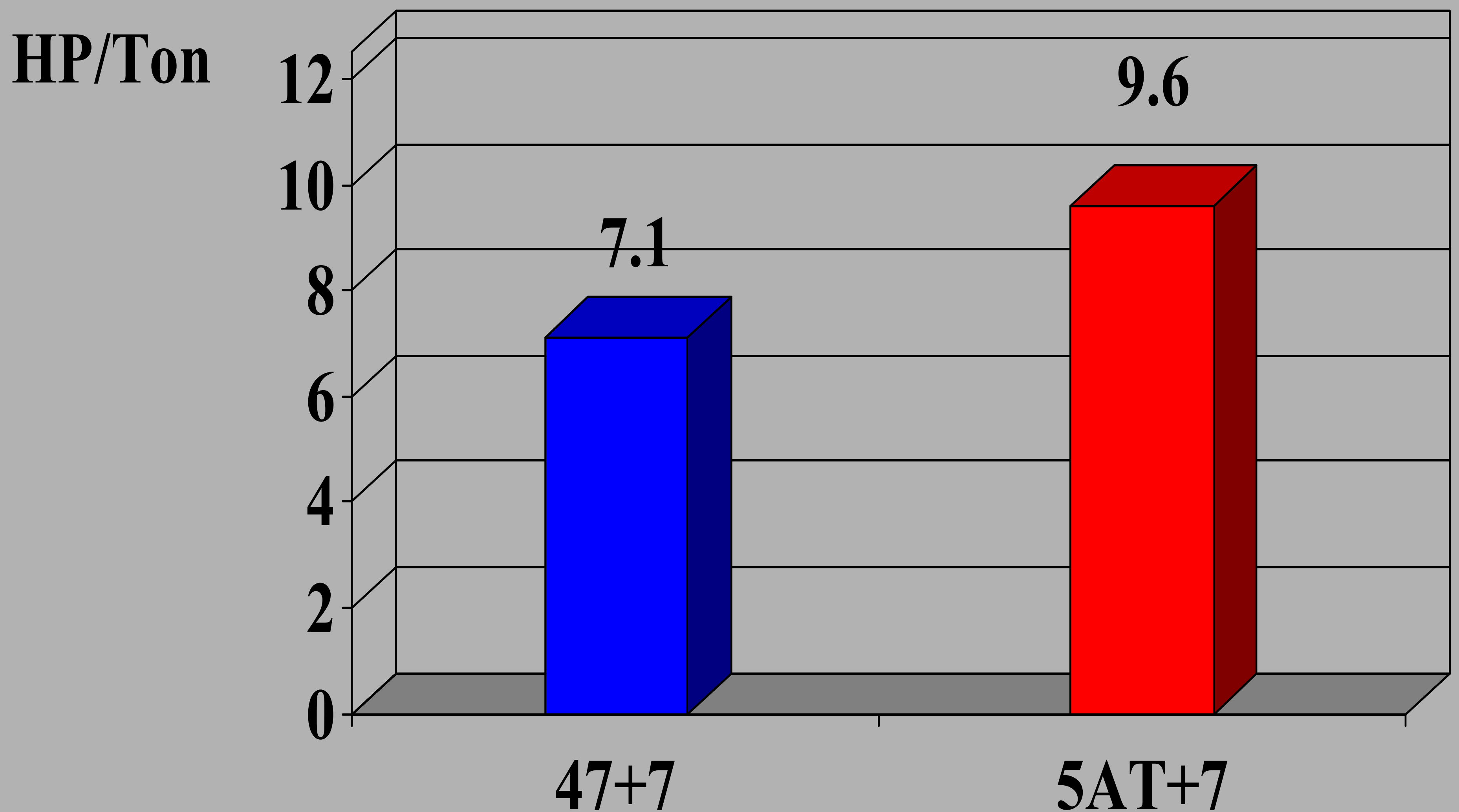
- Performance predictions in FDC's validated with Perwal
- Perwal is software programme for predicting steam locomotive performance
- Confirms maximum power above 100km/hr
- Predicts more power below 100 km/hr



5AT & FGS



5AT & Modern Traction



Feasibility Study

- Design
  - Tools & Techniques
  - Skills
  - Organisation
- Manufacture
- Acceptance
  - Engineering Acceptance
  - Network Rail
  - HMRI

5AT Acceptance

- Outline Proposals submitted to HMRI
  - Deemed acceptable in principle
- Reviewed by predecessor to NRAB
  - Recommended that 5AT Project reviews locomotive against Railway Group Standards
- Review against RGS underway

RGS Review

- Started in April 2005
- Not Yet Complete
- Carried out by a Network of Engineers
- RGS's subject to change over next 2 years
  - Have to start somewhere
  - Same situation as Bombardier or an ALSTOM

RGS Issues

- Shows a number can be met
- Shows a number that will require further work to prove compliance
  - GM/RT2100-Structural requirements for Railway Vehicles
  - GM/RT2160 - Ride Vibration and Noise Environment Inside Railway Vehicles
  - GM/RT2466 - Railway Wheelsets

RGS Issues

- GM/RT2161 - Requirements for Driving Cabs of Railway Vehicles
- GM/RT2190 - Requirements for Rail Vehicle Mechanical and Electrical Coupling Systems
- GM/RT2260 - Design for Recovery of Rail Vehicles
- GM/TT0088 - Permissible Track Forces for Railway Vehicles

RGS Design Dilemmas

- RGS RT2045 – Railway Braking Principles
  - Clause 7.2.5 states that ‘Either a full service or emergency brake application shall automatically inhibit or interrupt traction power’
  - Clause 7.2.6 states that ‘there shall be a system of interlocks between the traction control system and the brake control system that prevents traction power being applied until sufficient energy for the automatic brake system has been proved to be available to provide at least an emergency brake application’

RGS Design Dilemmas

- Could be met
  - Air Operated Regulator
  - At expense of
    - Additional complexity
    - Development cost & time
  - Goes against the basic simplicity of the Steam Locomotive

RGS Design Opportunity

- Offers New Opportunities
  - With & Air Operated Regulator & Air Motor Operated Reverser
  - Possibility TDM type of operation from a DVT
  - Backing out of terminal stations
    - Saving in operating costs

Opportunities with New Build

- Design Out Known Problems & Attention to Detail Design
  - Eliminate pipe joints over rails
  - Improve pipe supports & joints
  - Better gland packing
  - Pay attention to lubrication
  - Welded boiler stays
  - Etc, etc

Opportunities with New Build

- Use ‘off shelf’ proven components
  - Steam Valves
  - Air Brake Fittings
  - Roller Bearings for rod ends
- Design in Quality
  - Advances in engineering knowledge
  - Materials of known specifications
  - Features proven on today’s railway
    - Air sanding

Opportunities with New Build

- Any colour you like

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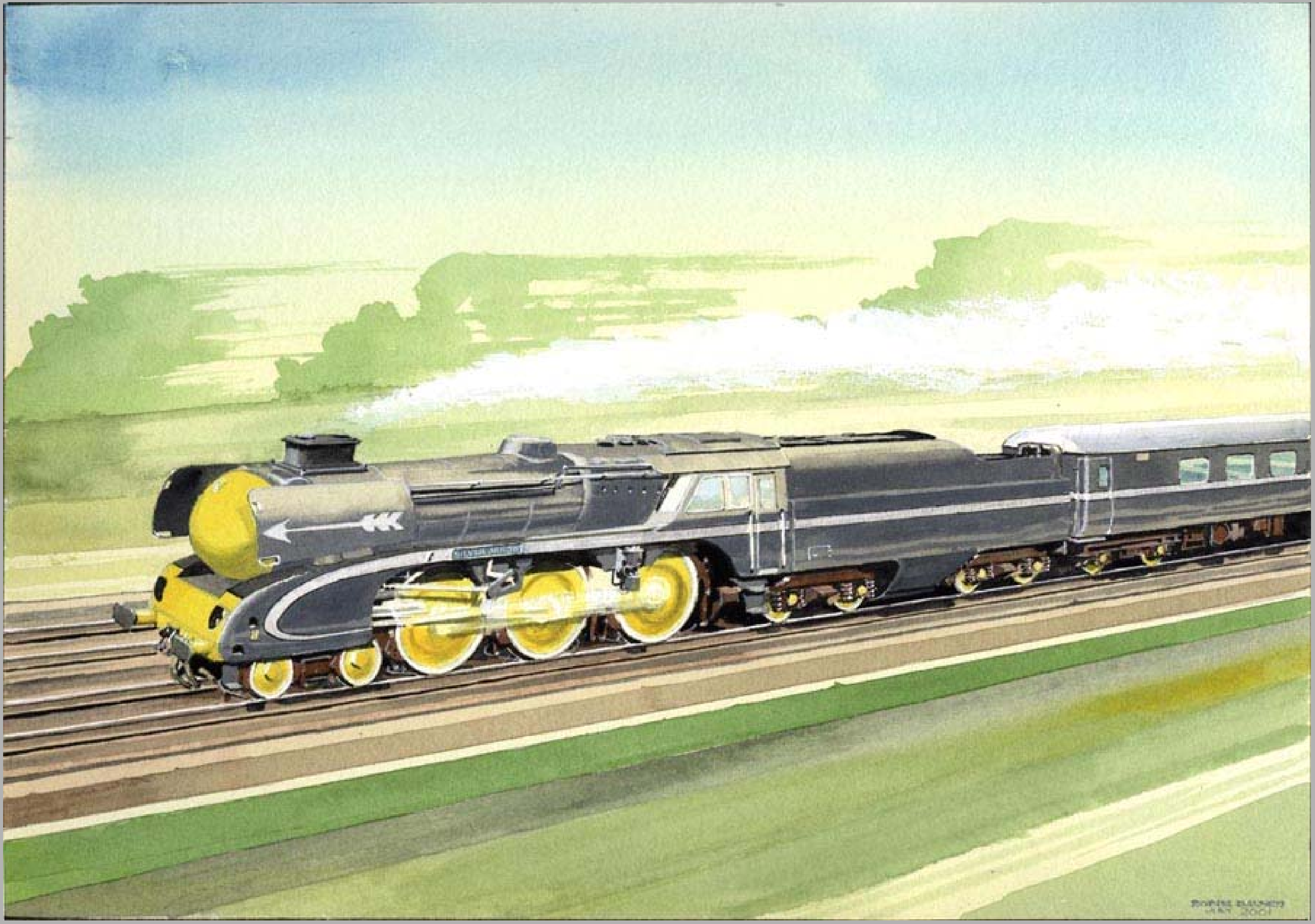
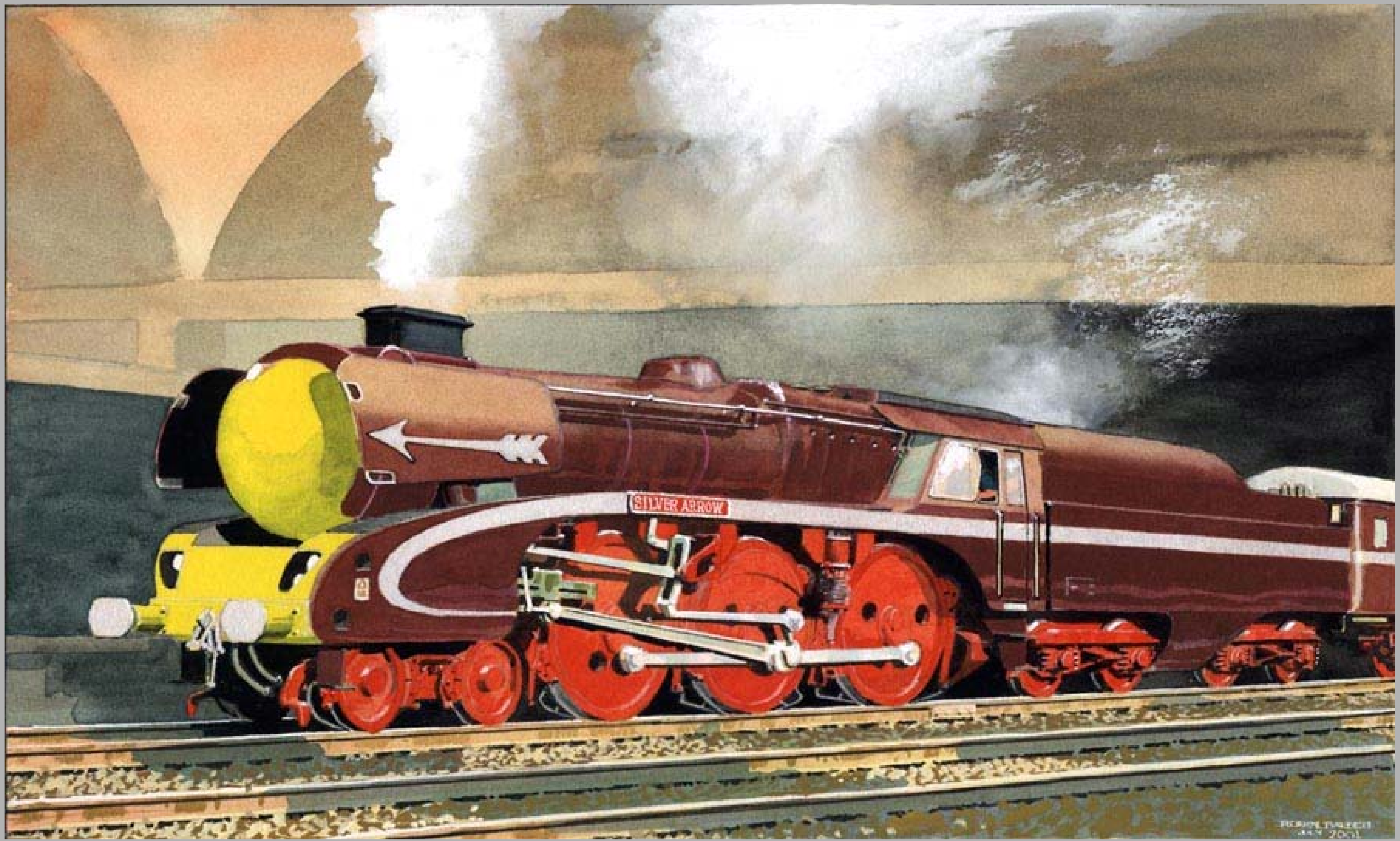
- Any colour you like



Opportunities with New Build

- Any colour you like



Opportunities with New Build

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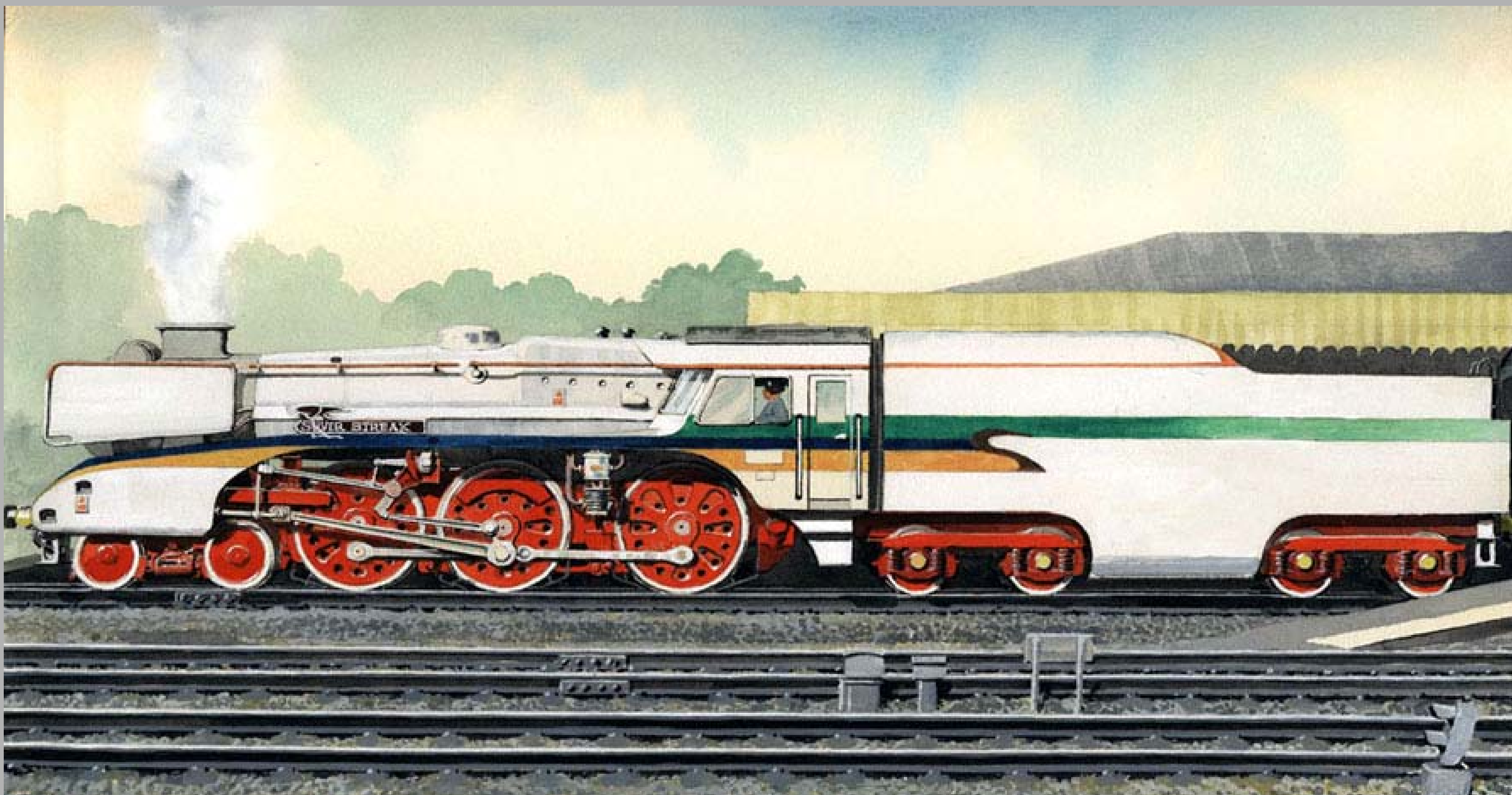
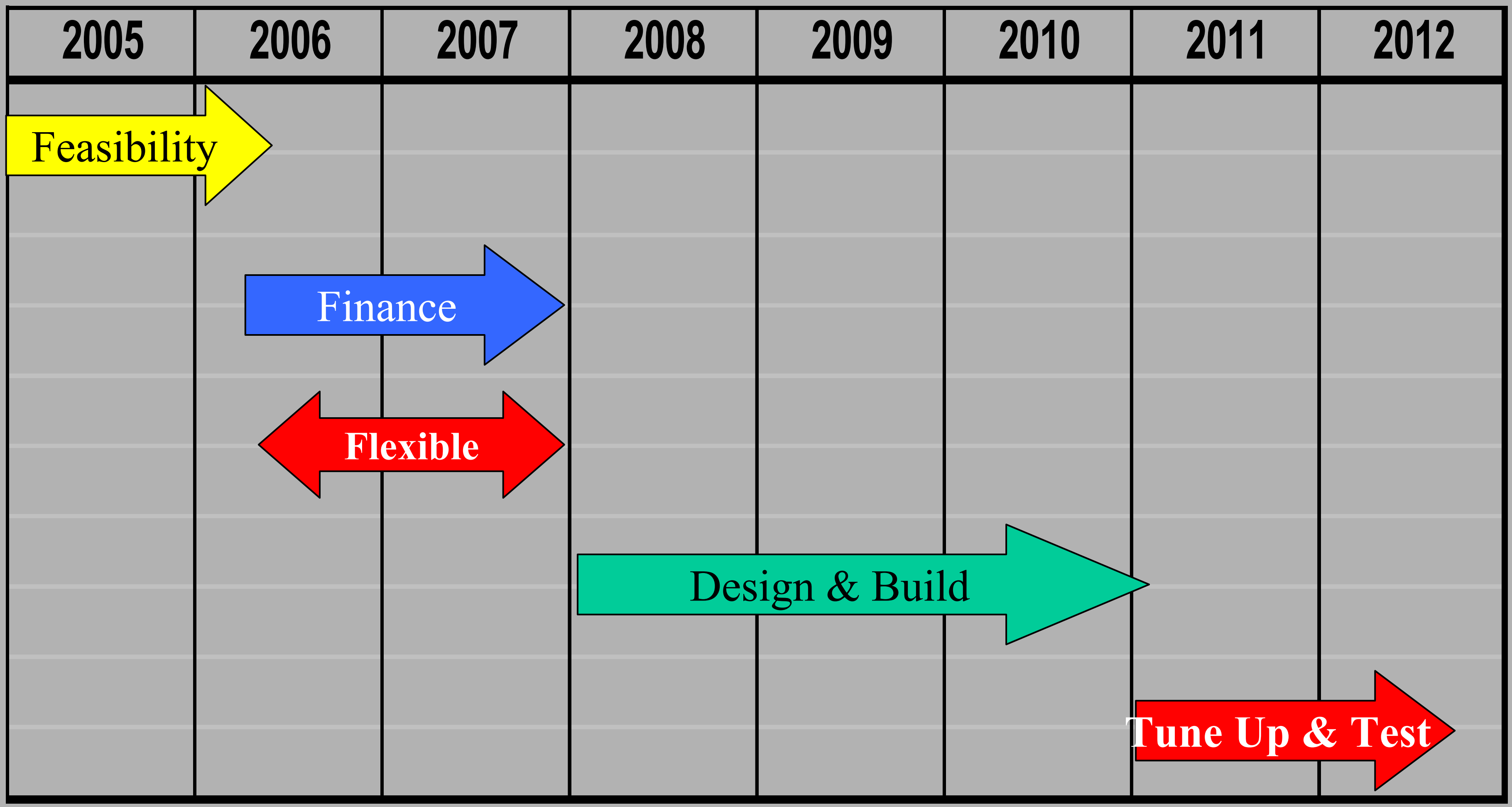


The Team

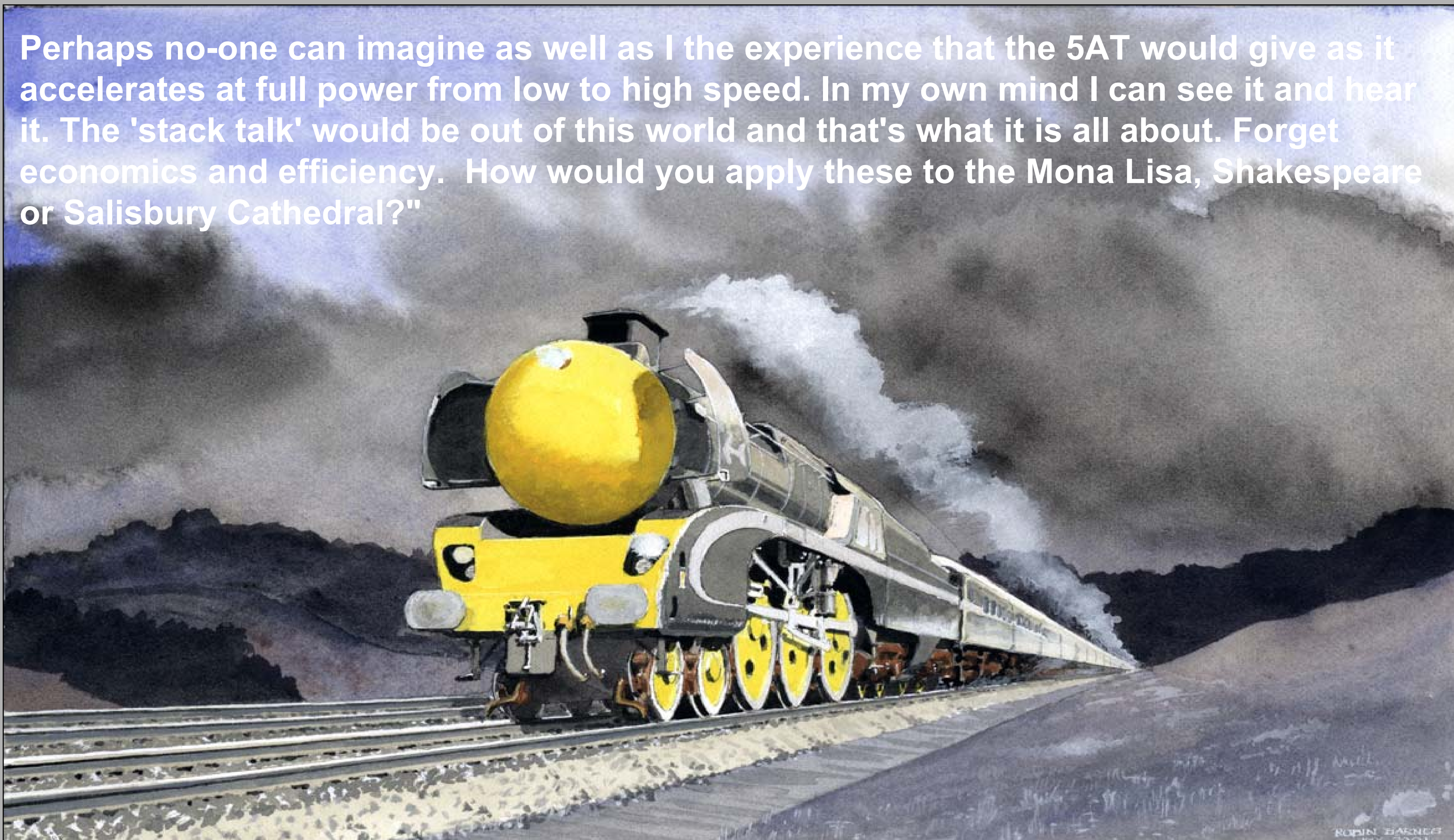
- Design of the 5MT completed by 1951
- Need to Create a Team
  - With a range of skills and knowledge
    - Today's Railway
    - Knowledge of Steam
    - Mechanical Design
    - Electrical Design
    - Project Management
    - Quality Assurance
- Team needs to respect each others' knowledge & experience

Current Estimate of Project Timescale…



The 5AT – Modern Steam for Modern Rail

The 5AT – Modern Steam for Modern Rail



Perhaps no-one can imagine as well as I the experience that the 5AT would give as it accelerates at full power from low to high speed. In my own mind I can see it and hear it. The 'stack talk' would be out of this world and that's what it is all about. Forget economics and efficiency. How would you apply these to the Mona Lisa, Shakespeare or Salisbury Cathedral?"

Current plan:

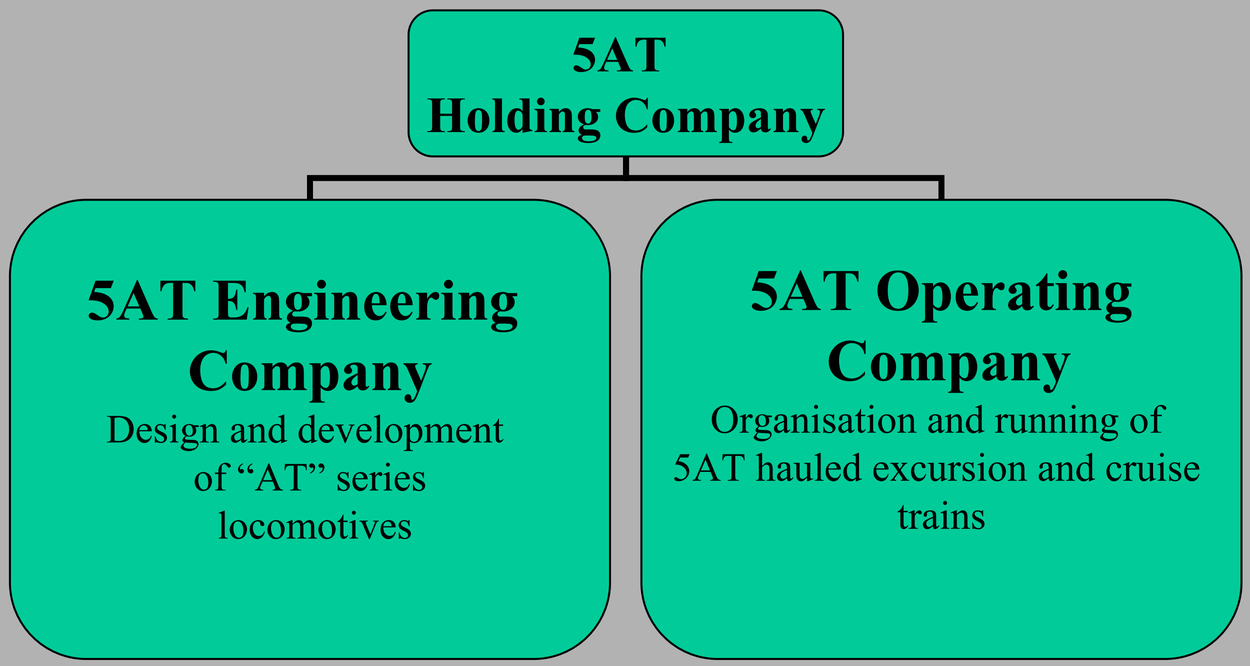
- Finalise cost estimates and complete the feasibility study by end Spring 2006
- Presentation of the project to rail and leisure travel industries Autumn 2006.
- Seek/gain finance for project by end 2007.

Commercial Implications

- To be a profitable investment the 5AT has to be used much more intensively than existing heritage steam locomotives.
- Ultimately profit levels depend on attracting sufficient numbers of passengers to travel behind a 5AT. Attractive new opportunities for running 5AT hauled trains need to be explored.

5AT – modern steam for modern rail

Possible 5AT organisation



"It is not true that the steam locomotive reached the pinnacle of its development" –

[L.D.Porta 1998]

5AT

Project

www.5AT.co.uk

The 5AT