W Class Miniature Steam Locomotives

2/7 Scale Fully Working Replica Steam Locomotives

McDowall Affleck

The Team

- Project Manager:
  - PHIL GIBBONS Industrial machinist, commercial miniature locomotive constructor, “Flying Scotsman” emergency repairs
- Engineers:
  - DAVID NAESER University of Cape Town: BSc(Mech Eng), MSc(Eng), South African Railways, Research Engineer UCT, Auto Industry, McDowell Affleck.
  - RICHARD STUART University of London: BSc(Eng), PhD , Offshore Oil & Gas Industry, RJS Dynamic Systems Pty Ltd.
- Manufacturer: KENTIN ENGINEERING
  - KEN AUSTIN, Managing Director
  - LES AUSTIN, Workshop Manager
  - MALCOLM AUSTIN, CNC Machining Specialist

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Previous Experience

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Design Brief

- To build a 12-inch gauge working steam railway
- Locomotives based on existing full size examples:
  - WAGR W Class, Built 1951, Beyer Peacock, Manchester, UK
  - Selective improvements, eg: larger tenders, increased boiler insulation thickness, modern bearing materials, free-flowing steam circuit, 10bar working pressure, superheated.
  - Emphasis on efficient performance as well as aesthetics.

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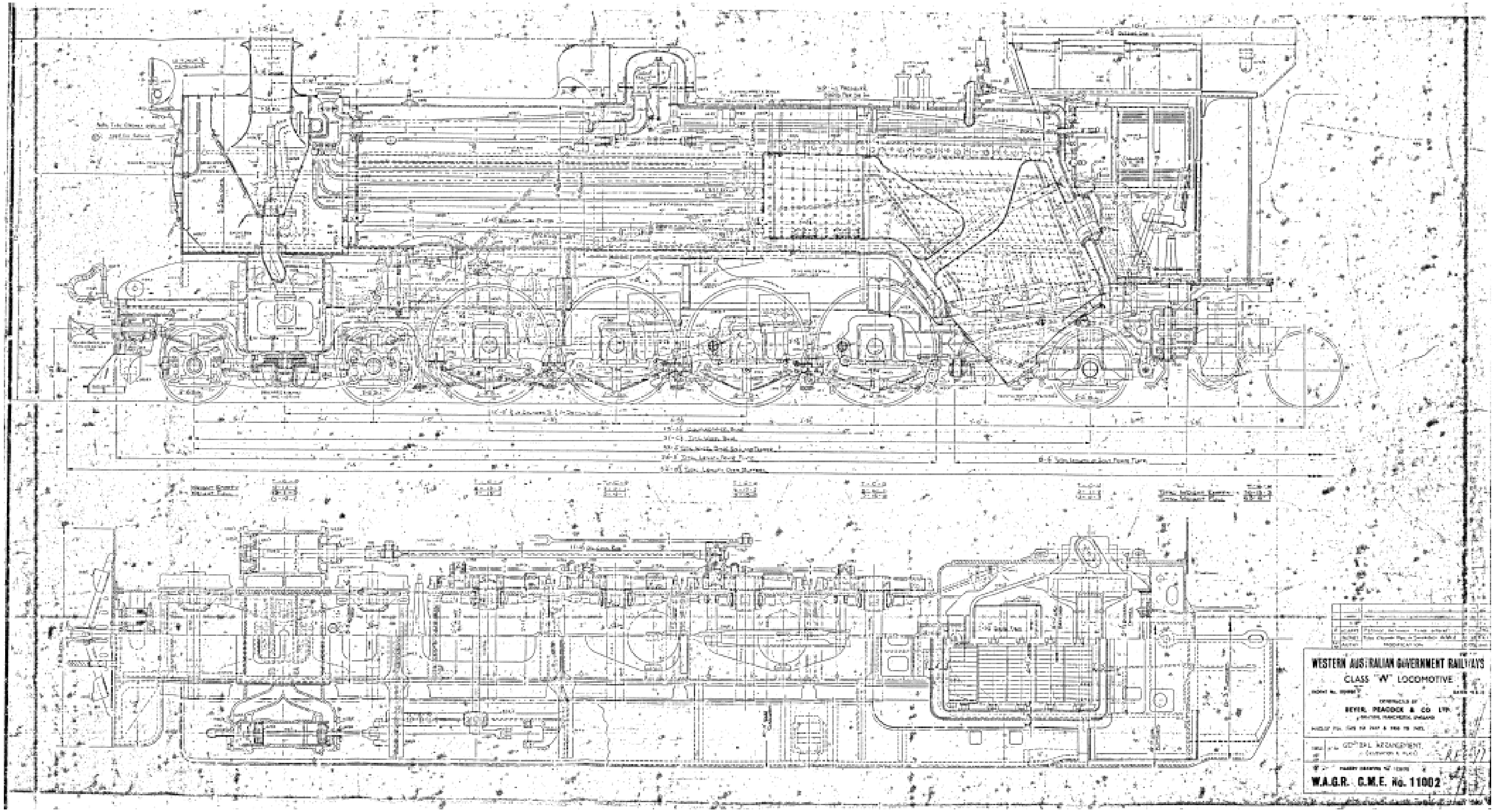
W-Class Locomotive –the design start



Manufacturer's Drawings- >200 sheets

Key dimensions decided

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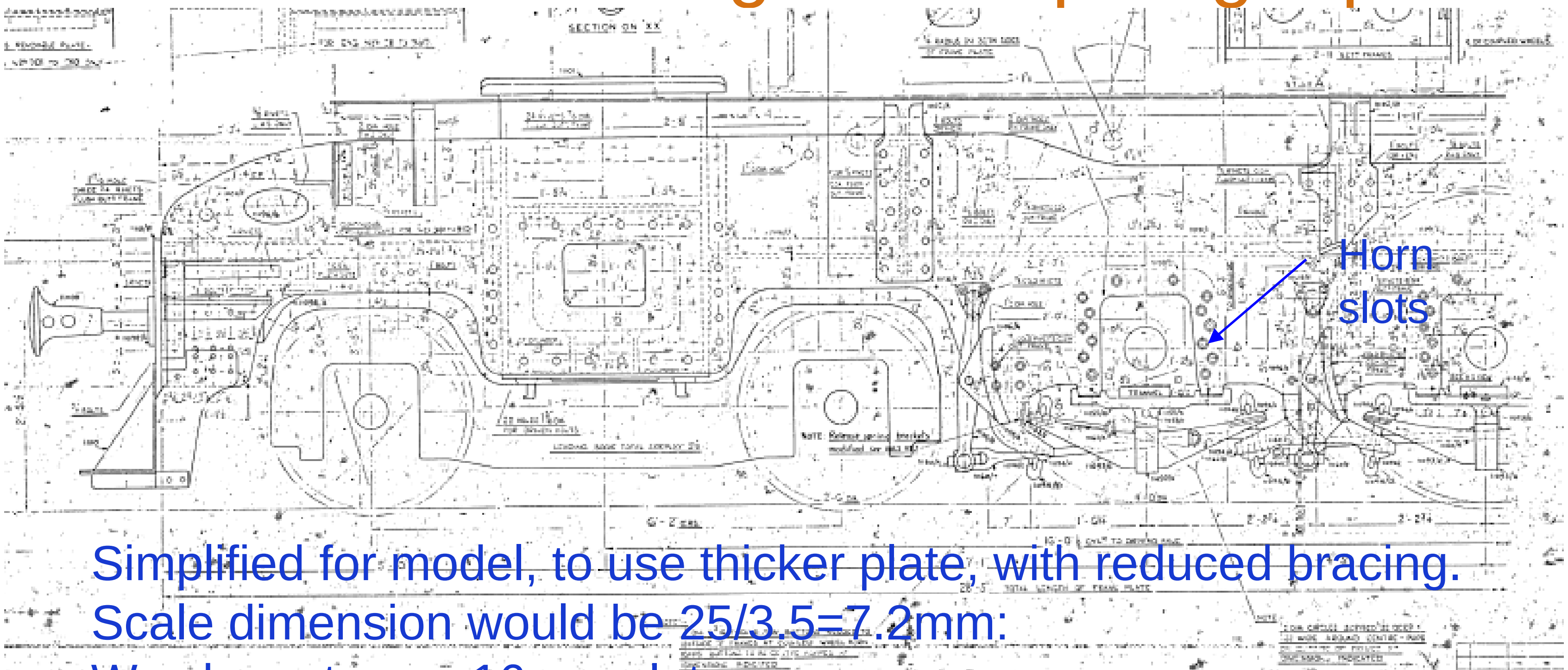
Major Components - Frame

- Original was 25mm plate frame with extensive stiffening and diaphragm plates



Simplified for model, to use thicker plate, with reduced bracing.
Scale dimension would be 25/3.5=7.2mm:
We chose to use 16mm plate.
- Easier to maintain flatness, simpler, stiffer, adds adhesive weight

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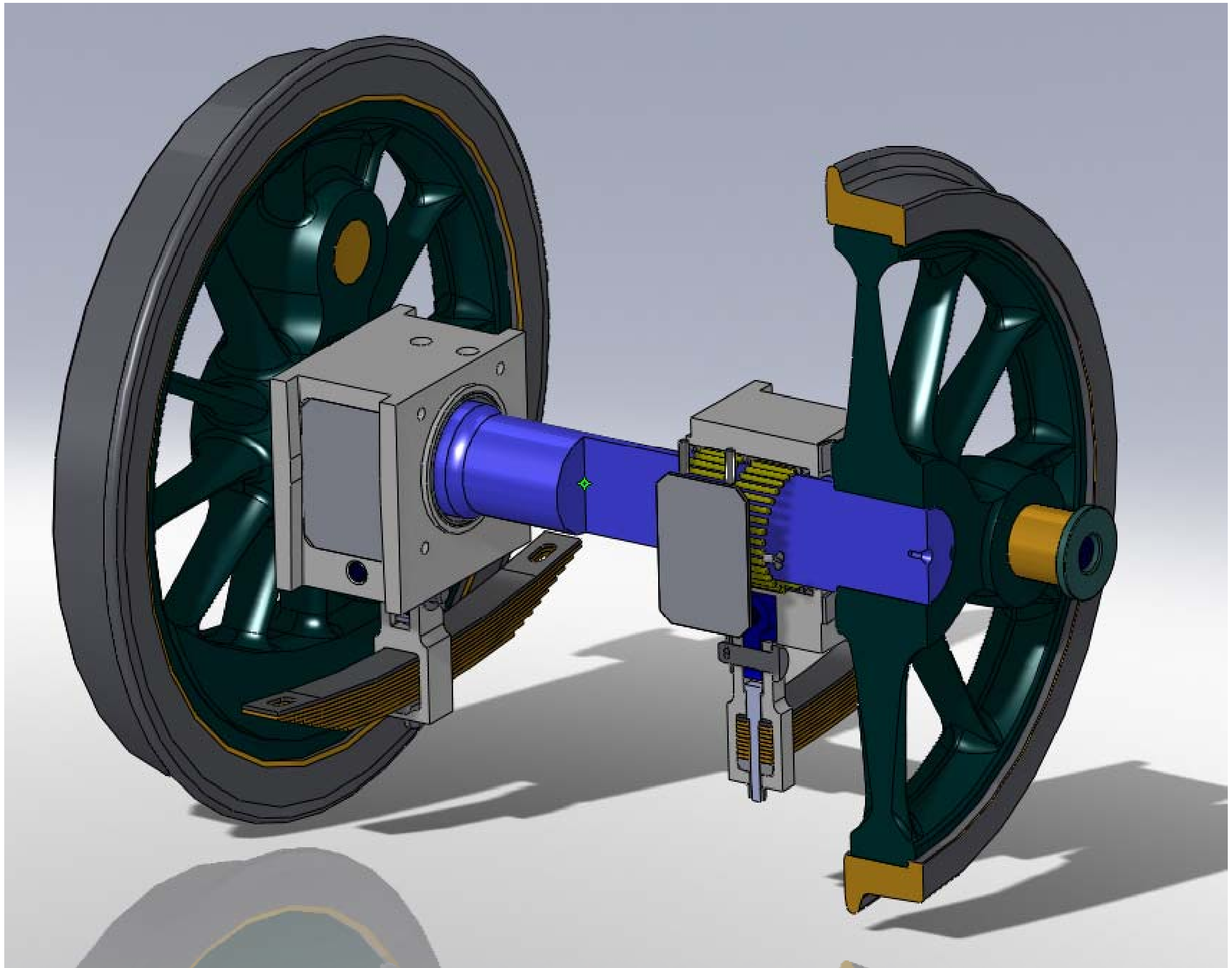
Major Components – Axle assy



Wheels – SG iron with Smorgen 147M tyres

Axles – AS 1444X4317 (DIN17CrNiMo6)

Bearings – sealed needle rollers, directly running on hardened axle

Axle boxes – steel with SKF PTFE wear strips

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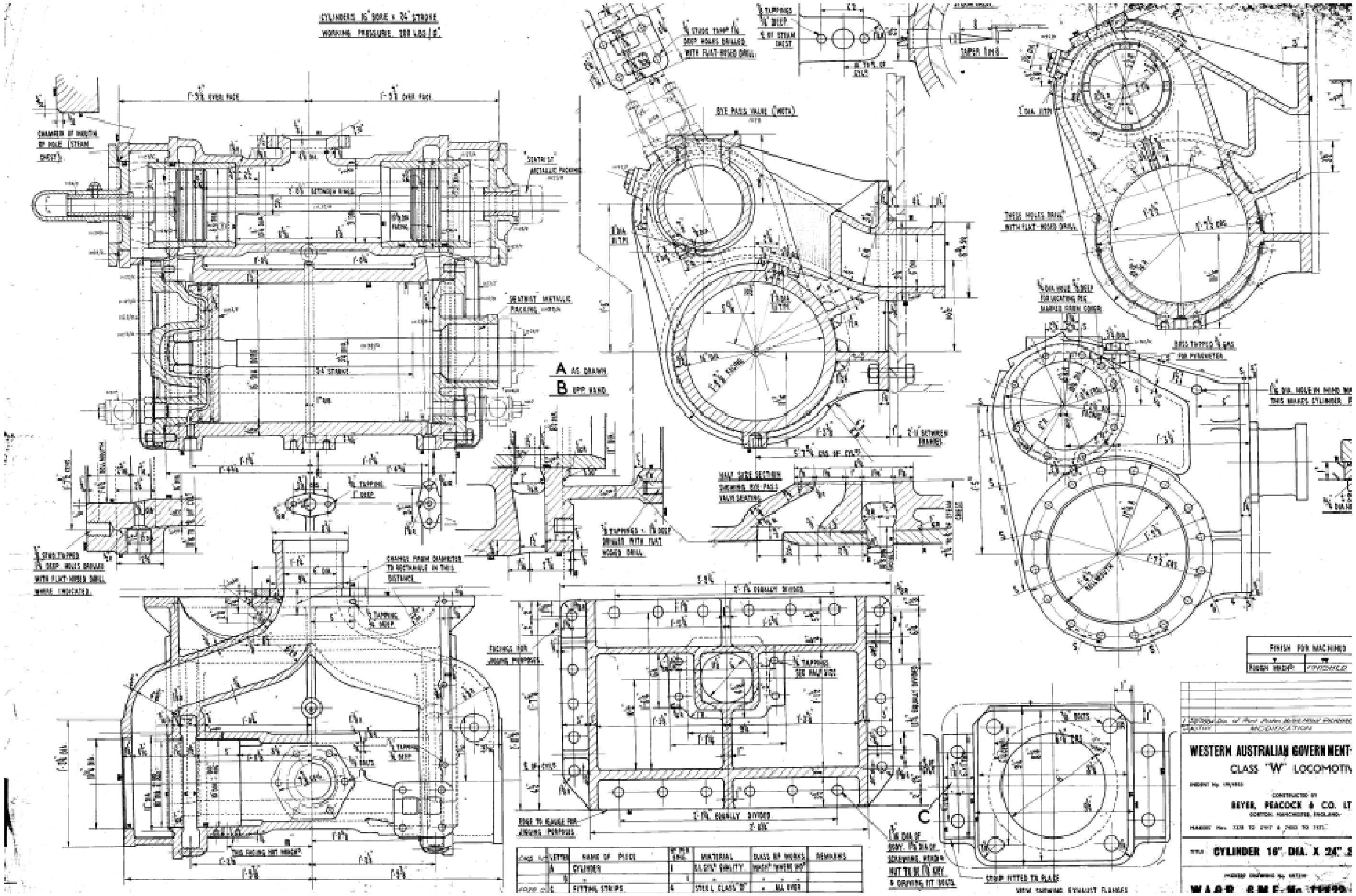
Major Components - Cylinders



- Full size was a complex casting
- Contains ports
- Piston Valve
- Steam entry and Exhaust passages with connections
- Pistons
- Mounting pad
- Covers and glands

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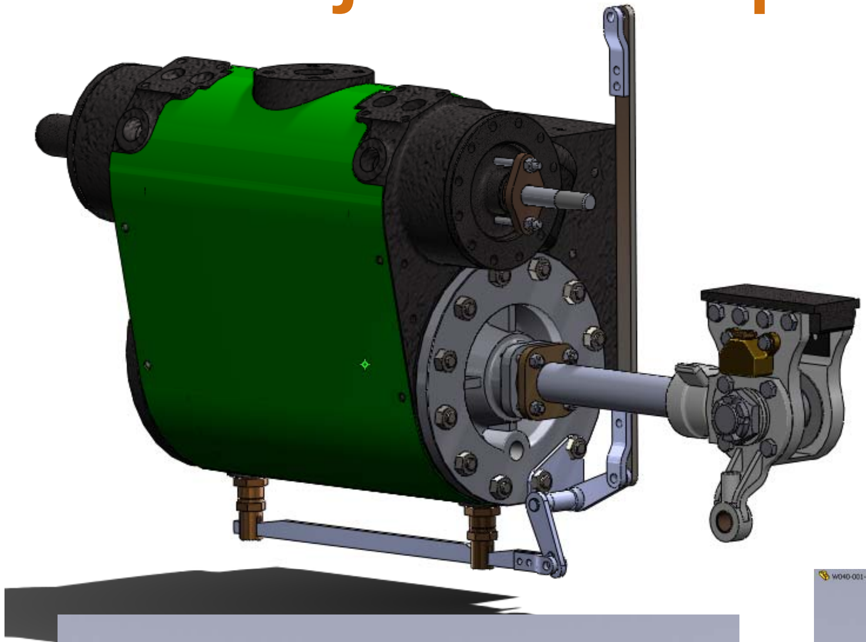
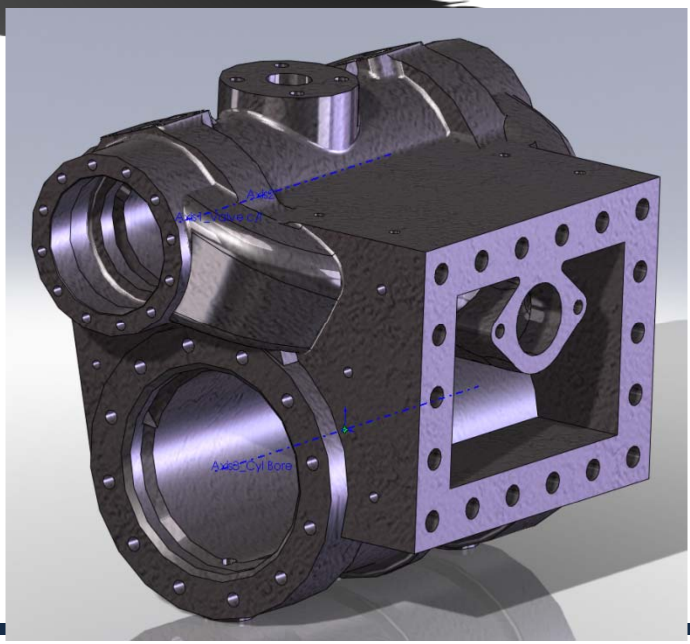
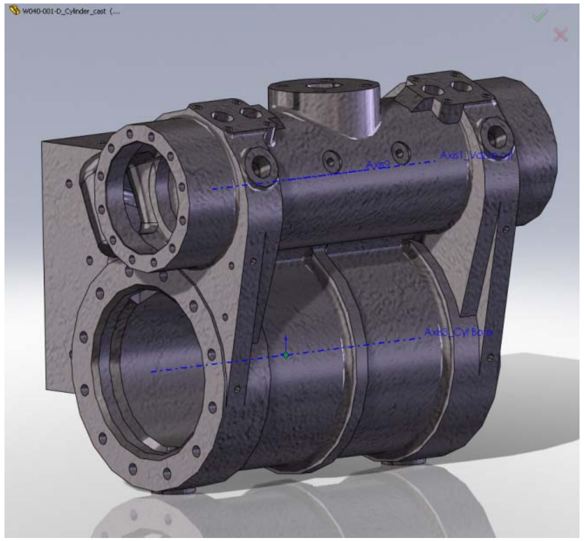
Major Components - Cylinders







For the model, also a casting, but simplified

Contains ports

Piston Valve chamber

Steam entry and Exhaust passages with connections

Mounting pad to frame

Various bosses for mounting of fittings

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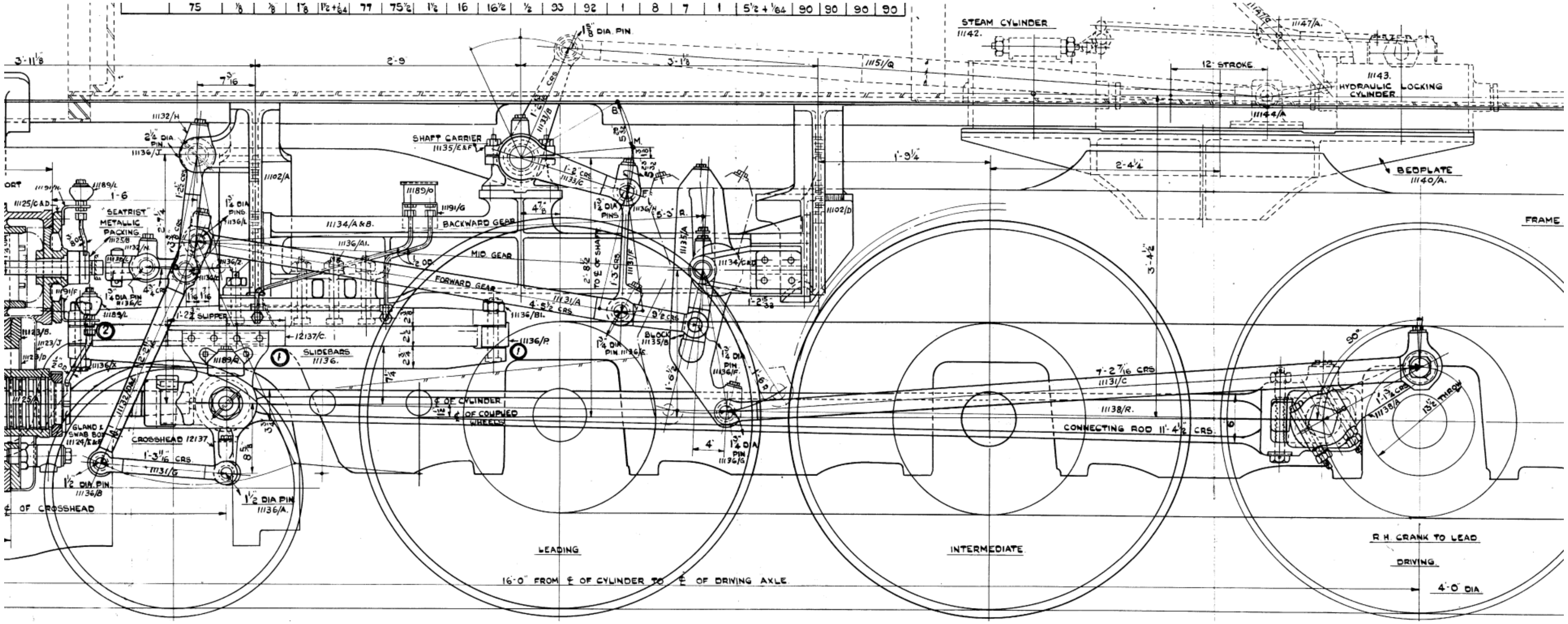
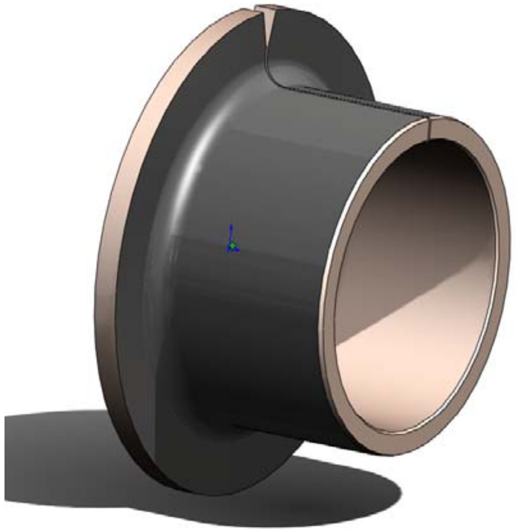
Major Components - Motion





Bearings used were SKF sintered bronze with PTFE on steel backing.

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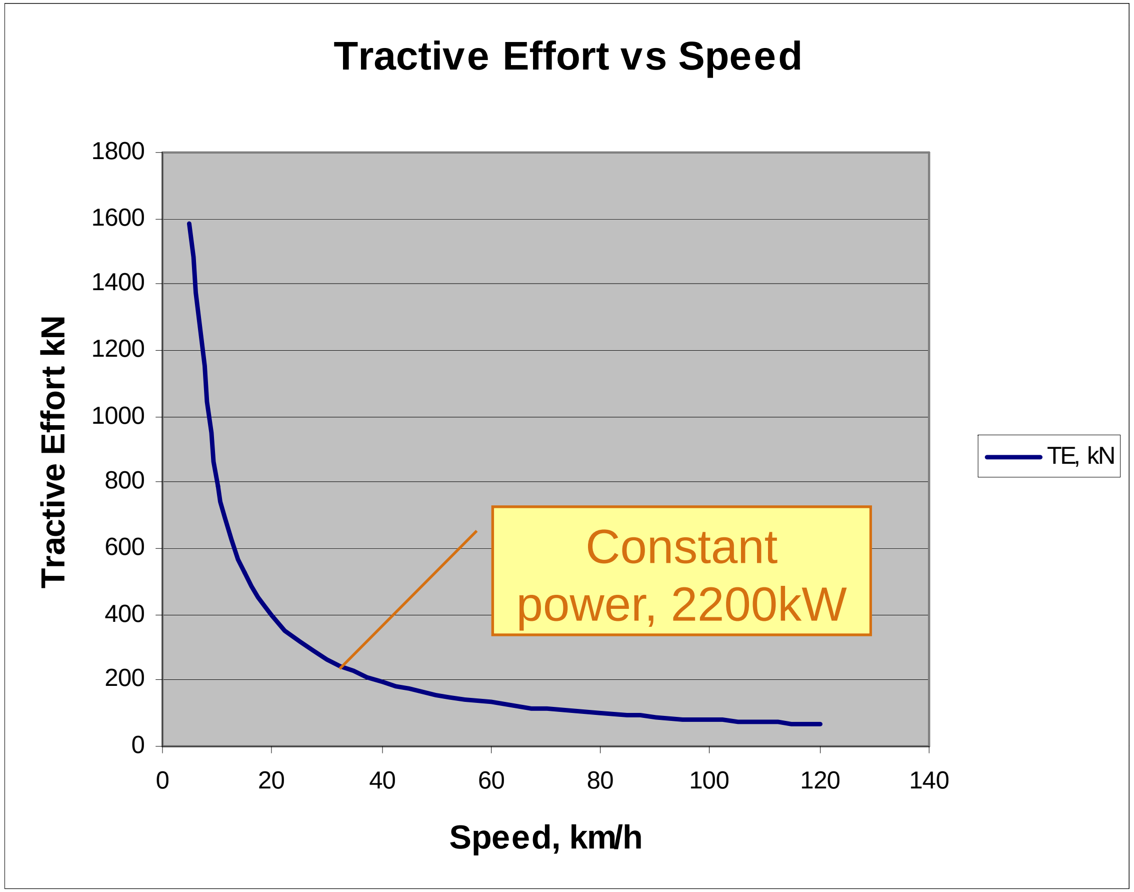
Locomotive Tractive Effort 1



- Diesel-Electric Locomotives are (simplistically speaking) constant power machines.
- Tractive effort is a function of power/speed

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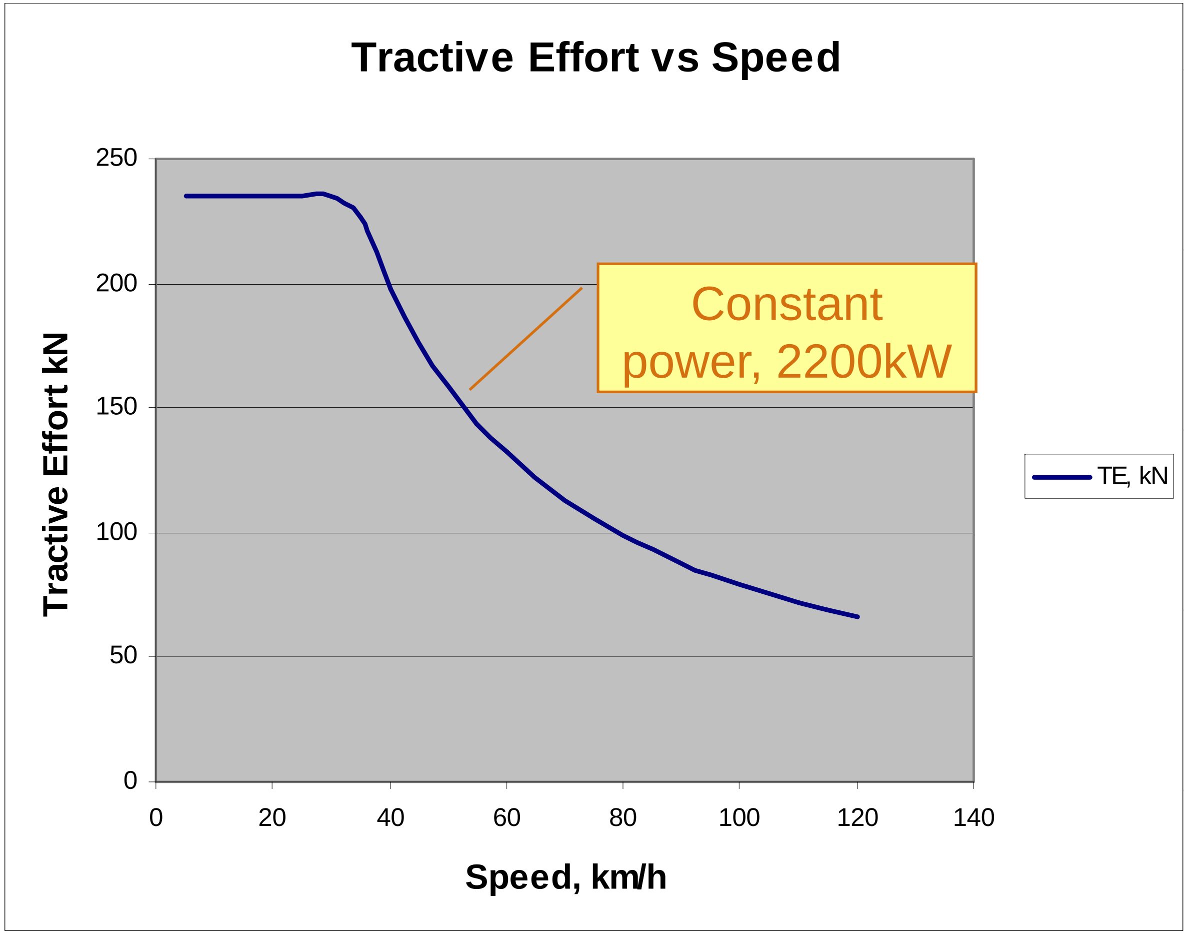
Locomotive Tractive Effort 2



- Tractive effort is limited at low speed by wheel/rail coefficient of friction and adhesive weight
- Coefficient of friction typically 20~25%.

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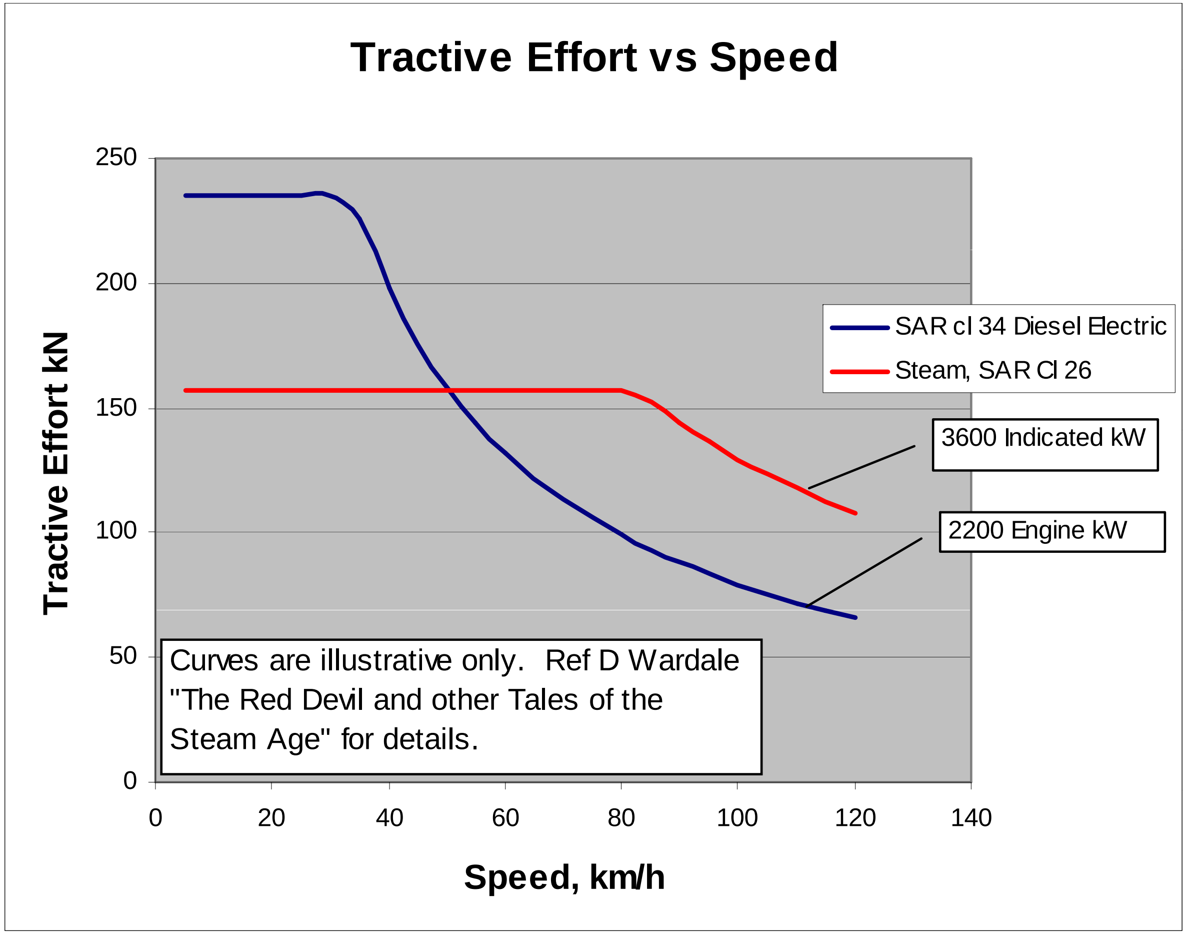
Locomotive Tractive Effort 3



Curves are simplified and ignore speed-dependant frictional and pumping losses for steam locomotives and generator, engine and traction motor matching for diesel-electric. See appendix 1 for some actual tractive effort curves and appendix 2 for power curves

- Tractive effort is limited at low speed by adhesion and adhesive mass
- Adhesive mass 120 000kg for Diesel-Electric
- Adhesive Mass 80 000kg for Steam locomotive
- Steam locomotive developed power increases with speed until the boiler limit is reached

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Locomotive Performance

- A major limitation to steam locomotive performance is adhesion, which affects the low speed operation, train starting etc
- This is worse for the case of scaled locomotives………
- A further difficulty is that the tractive effort varies over the wheel rotation, unlike a diesel-electric locomotive.

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Scale Effects

Locomotives generally designed such that the calculated tractive effort is matched to the available adhesion

- For the scaled locomotive, mass is proportional to $1/scale^3$
  - Thus adhesion too proportional to $1/scale^3$
  - But tractive effort depends on piston area, hence proportional to $1/scale^2$

So tractive effort exceed available adhesion by the scale factor, or 3.5 x the available adhesion in this case.

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Scale Effects

To reduce tractive effort to match the available adhesion:

- Boiler pressure needs to be reduced
- Or cylinder bore and stroke reduced
- Or mass increased

- All the above were done, within the limits of the client’s preferences

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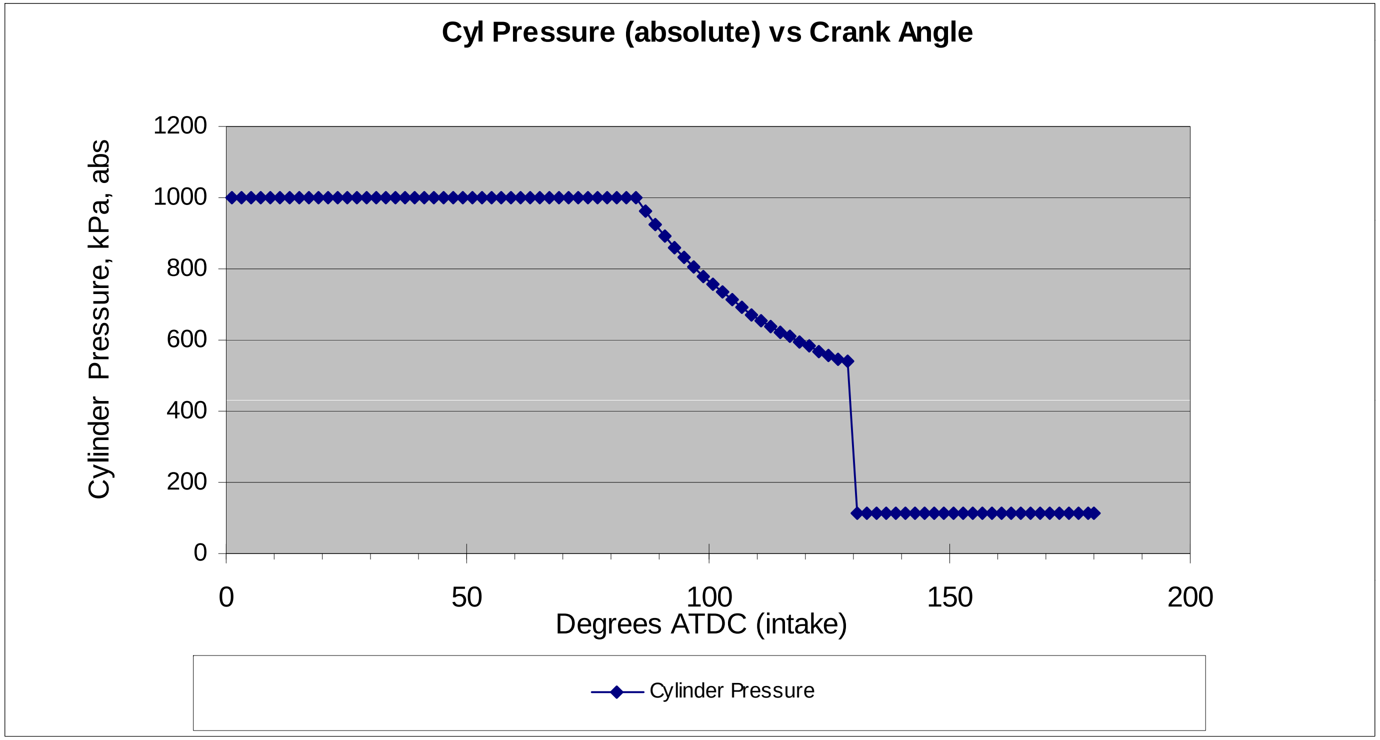
Piston Force

- Tractive effort was plotted over one stroke (180deg), to demonstrate this issue: From the cylinder pressure diagram of pressure vs crank angle at 50% admission of steam….



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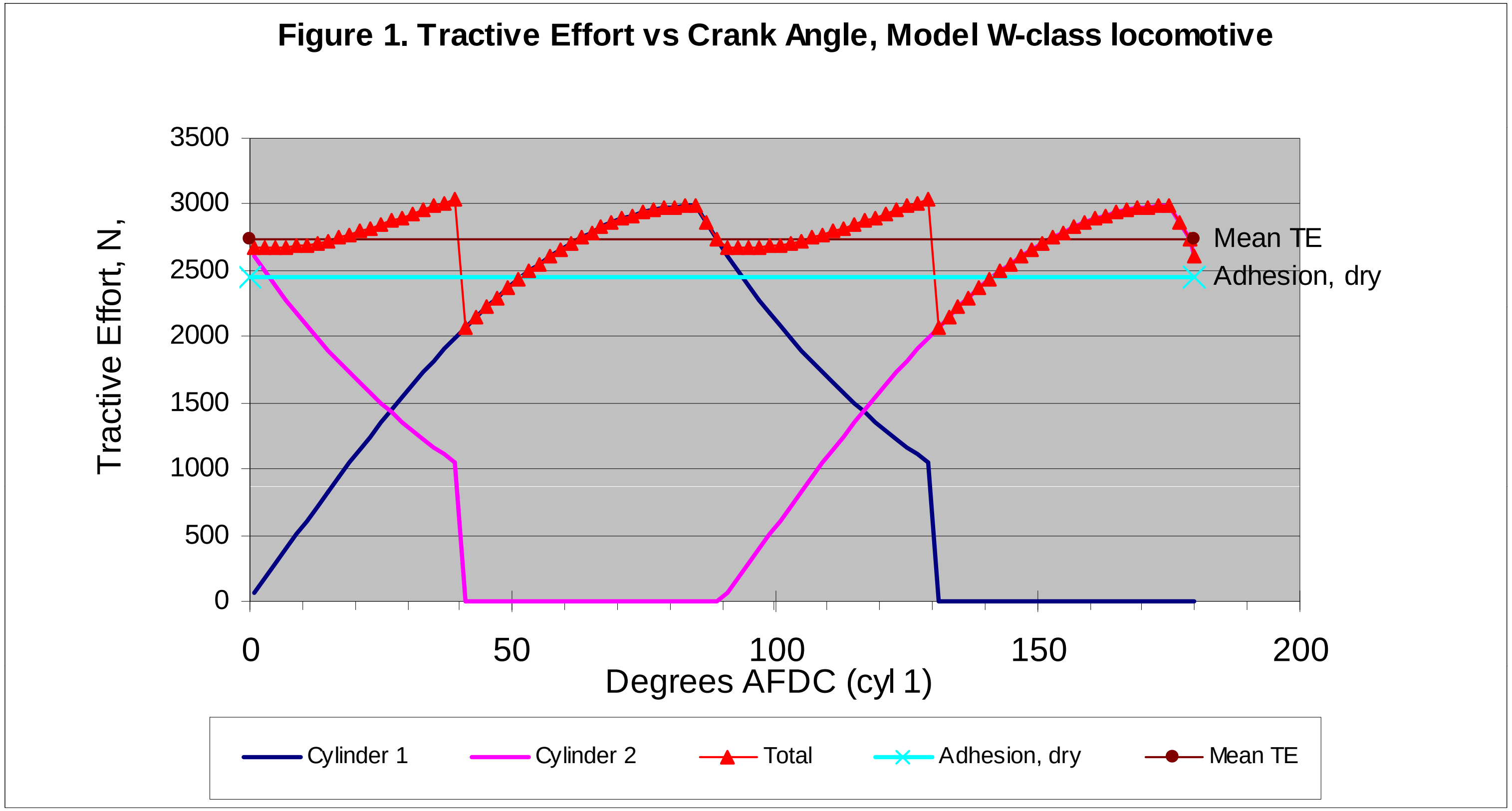
Piston Force

….the instantaneous tractive force at the wheel rim was obtained and summed over two strokes to give the average tractive effort over the wheel rotation:



- The cylinder bore and stroke were varied until the desired tractive effort was achieved.

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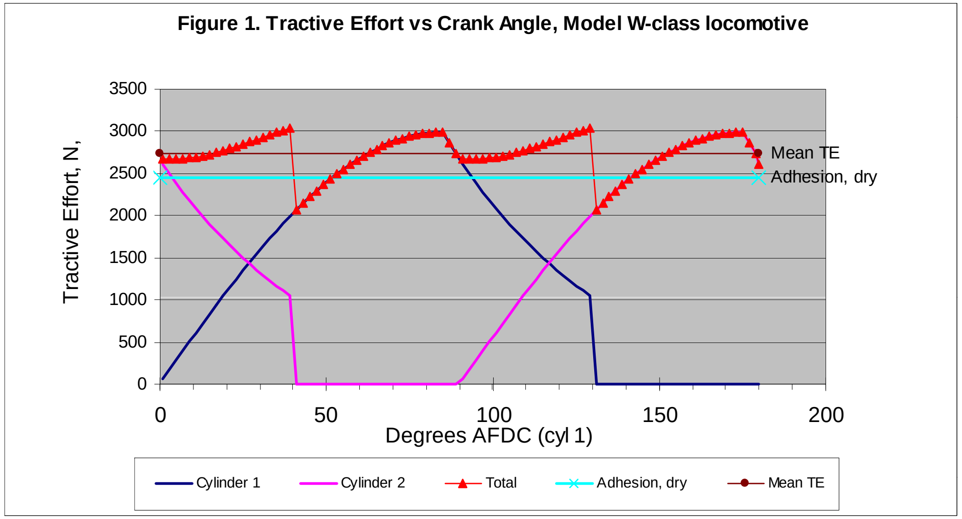
Steam Consumption

- Summed for two strokes per 180 degree wheel rotation:



From the steam flow rate, and using a typical value for boiler efficiency, the required coal combustion rate (and gas flow) could be estimated. These were inputs into the boiler thermal and fluid calculations.

Once cylinder dimensions were known, from the Tractive Effort Spread sheet, the volumetric steam flow rate could be obtained at the design speed of 20km/h.

Scale Effect:

Volumetric flow rate proportional to $1/\text{scale}^3$

Grate area is reduced by $1/\text{scale}^2$, so boiler grate loadings are considerably reduced compared to the full size locomotives.

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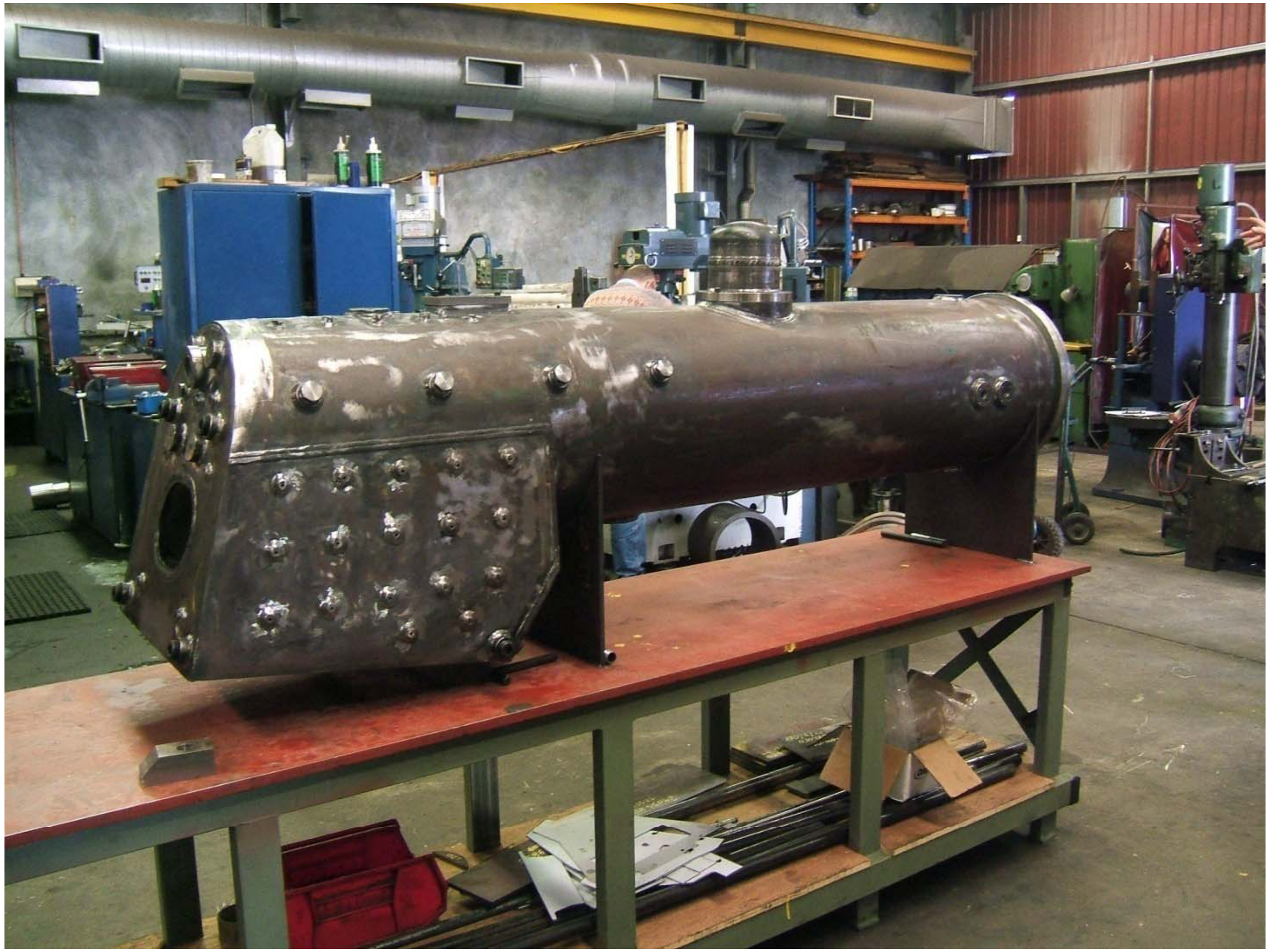
Boiler



Too large to be covered by the AMBSC code.

Not within WorkSafe jurisdiction for design registration.

(But we were warned of consequences of improper safety in design or construction!)

Too small for Rail Safety Authority.

Duty of care to ensure sound design and construction and compliance with most appropriate code.

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Boiler Mechanical Design

- Design Codes:
  - AS CB1 Pt III (1957), Locomotive Boilers for Railway Purposes (*Withdrawn*).
  - AS1228 (2006), Pressure Equipment - Boilers (*Re-introduces reference to locomotive boilers and CB1 code*).
  - Australian Miniature Boiler Safety Committee (AMBSC) Pt 2 1995, Steel Boilers (*Max internal volume 50 litres*)
  - McDowall Affleck, Rules for Small Locomotive Boilers for Railway purposes, 2007, by the late Gary Affleck. Key issues include tube pitch, inspection openings, water leg widths and inspection clearances.
  - Selected approach is to use AS1228, supplemented by McDowell Affleck design rules.
- Mechanical design by D Naeser, with independent design verification by McDowall Affleck.

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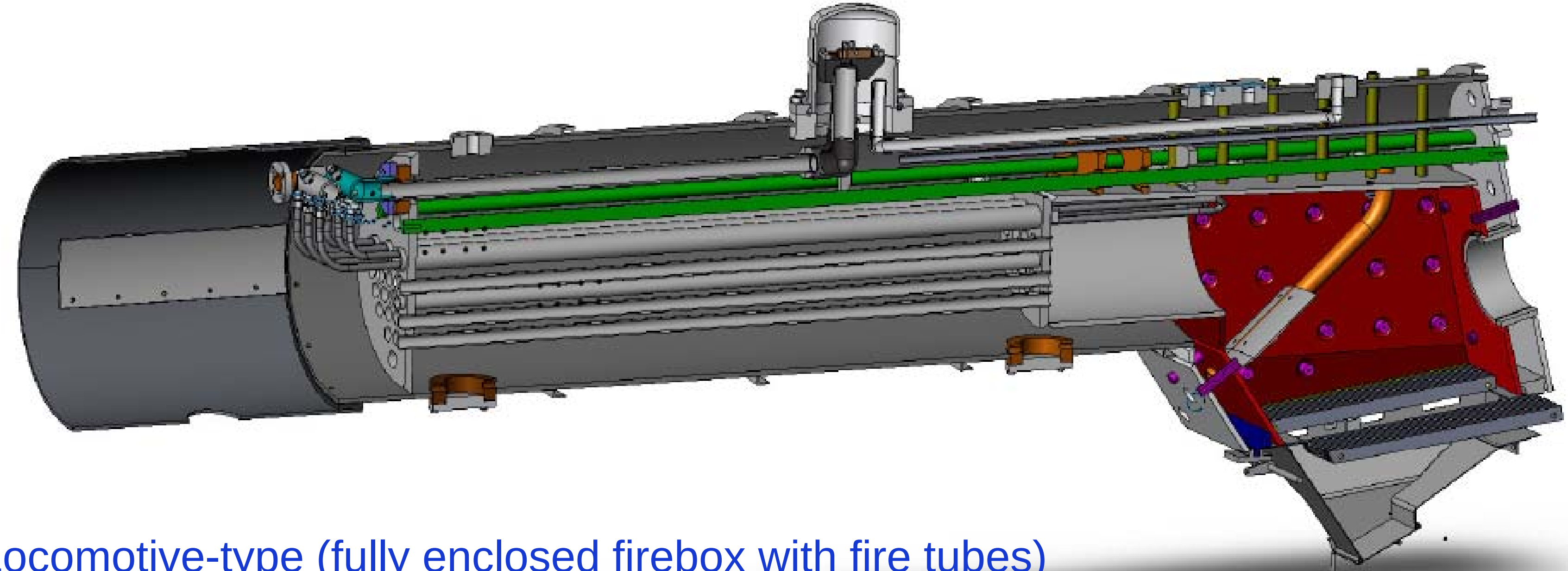
Boiler



Locomotive-type (fully enclosed firebox with fire tubes)

Combustion chamber

Arch tubes

Fully welded plates

Tubes welded to tube sheets

Simple construction – no flanged plates

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Thermodynamic Design

- Traditional thermodynamic design generally based on empirical practices and experimental work.
- Thermo-hydraulic characteristics of a steam locomotive are exceptionally complex.
- Very few attempts at rigorous thermodynamic analysis; Chapelon (1920s – 1950s), Porta (1940s – 2003), Wardale (1980s – ongoing).
- Steam locomotive industry wound down before the onset of the computer age.
- Opportunity to apply computer analysis to a traditional subject:
  - Thermo-hydraulic performance of the boiler
  - Exhaust system design, using programs developed by R Stuart
- Test boiler instrumented to measure performance.

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Boiler Testing

Testing to establish superheat temperatures, pressure drop over superheater, temperature gradient down tubes and combustion efficiency validated the design.

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Boiler Manufacture

- As pressure vessels, the boilers require stringent quality control.
- Manufacture to AS4458, Examination & Testing to AS4037, Welding & Welder Qualification to AS3992.
- Every piece of material recorded and certificated.
- Every weld recorded and subject to NDE and visual inspection.
- Pressure test by NATA certified agency.

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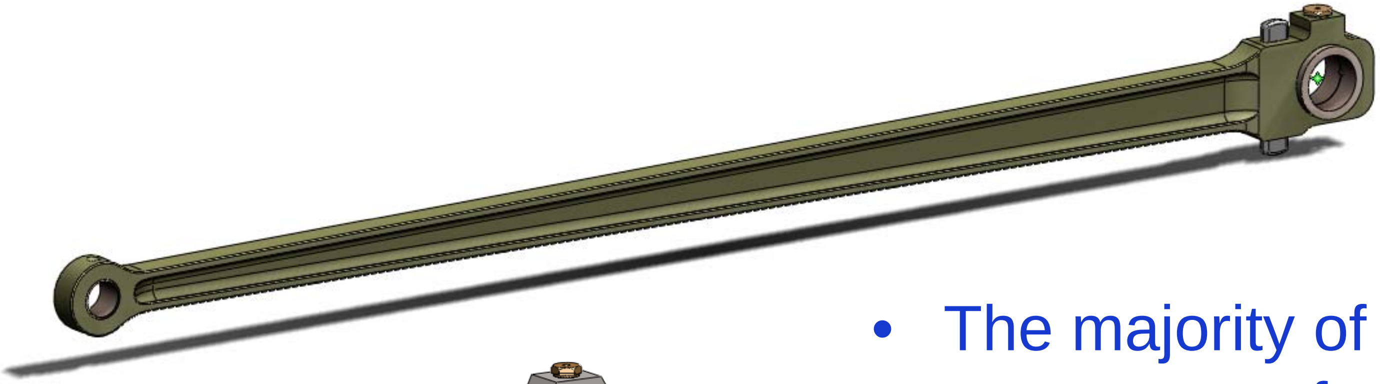
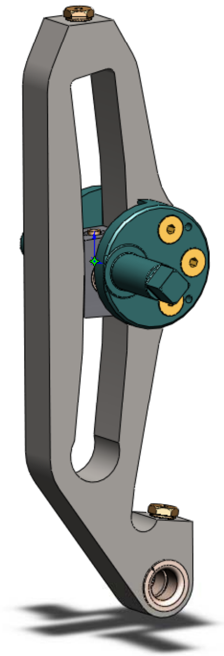
Manufacturing - CNC





- The majority of components for the motion were CNC machined directly from the 3-D STEP files
- Files fed into MasterCam, from which the cutter paths were generated.

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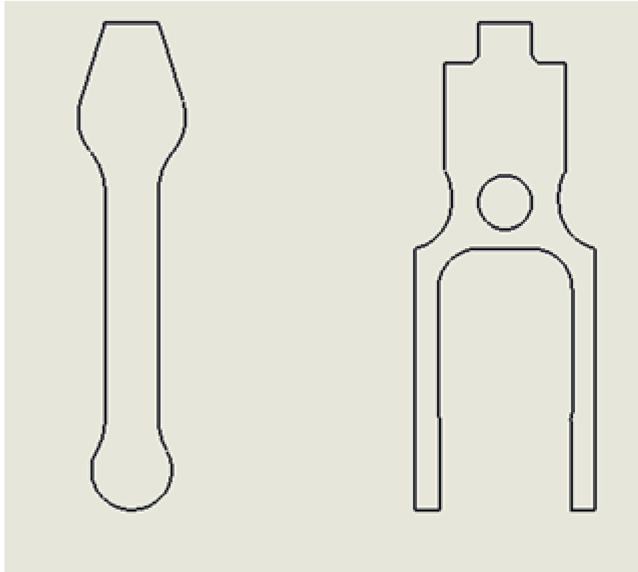
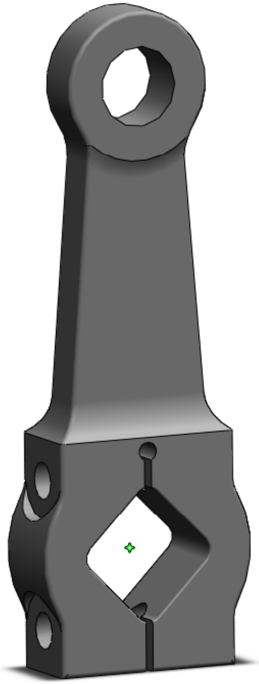
Manufacturing – Wire Cutting





- A number of components were wire cut using EDM machines.
- 2-D .dxf files used to generate the cutter paths in one or two planes.

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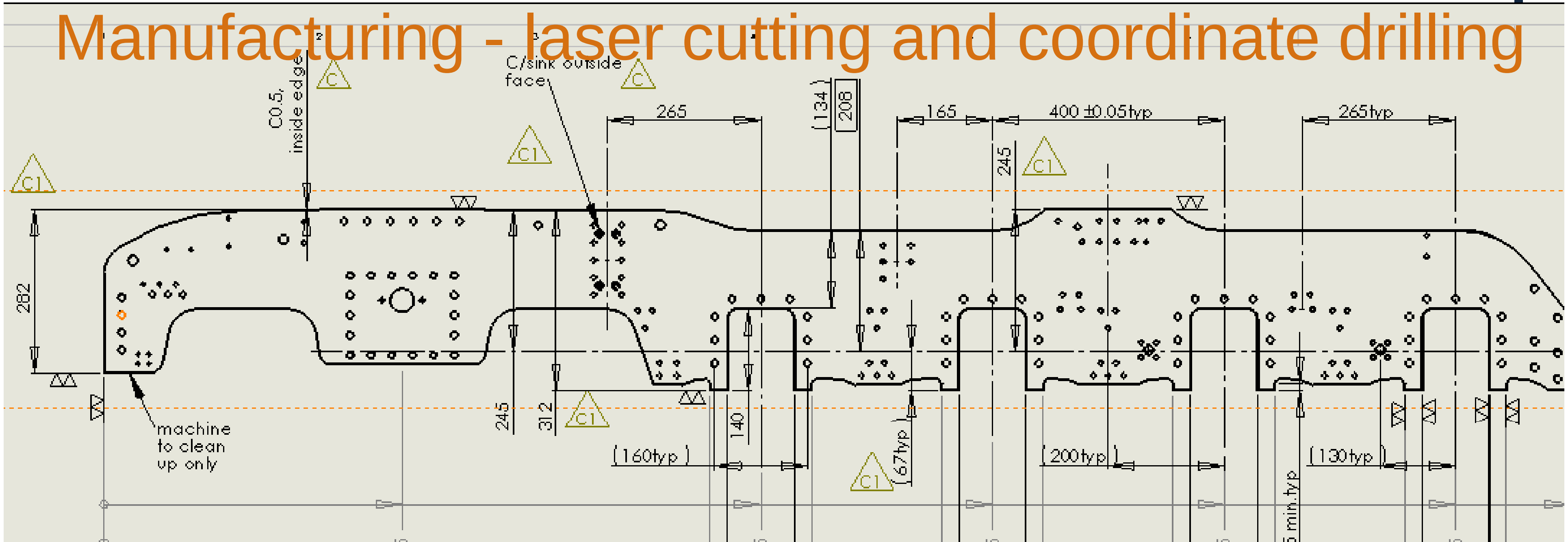
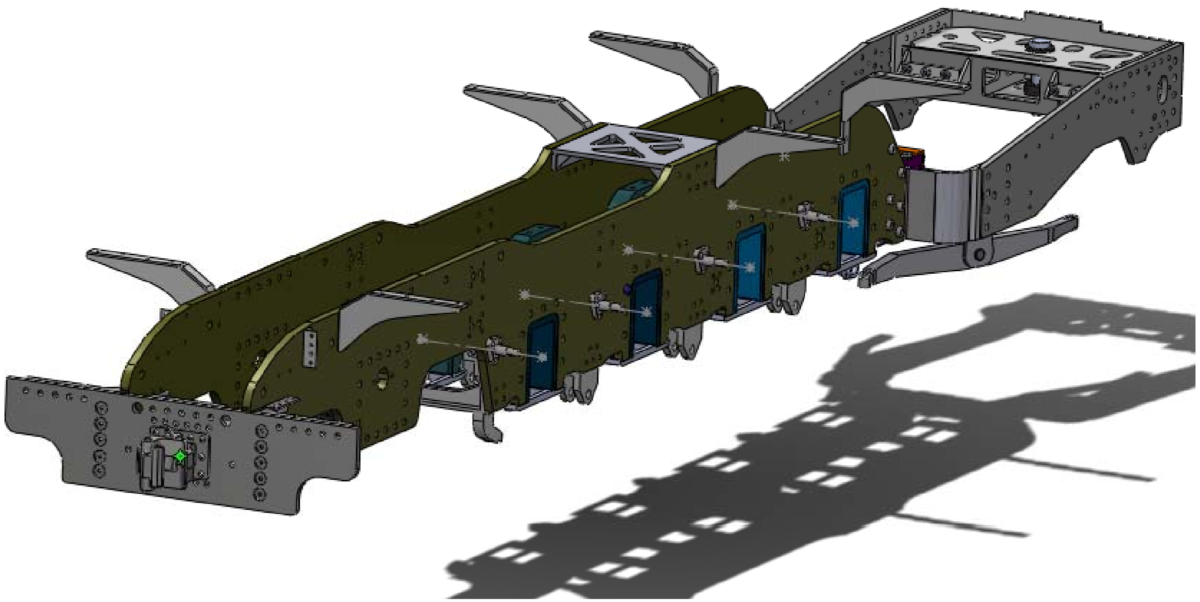
Manufacturing - laser cutting and coordinate drilling





- A number of parts were flame or laser cut from the 2-D dxf files.
- Frame was CNC drilled and machined on ref faces from CAD data.
- Accuracy ensured

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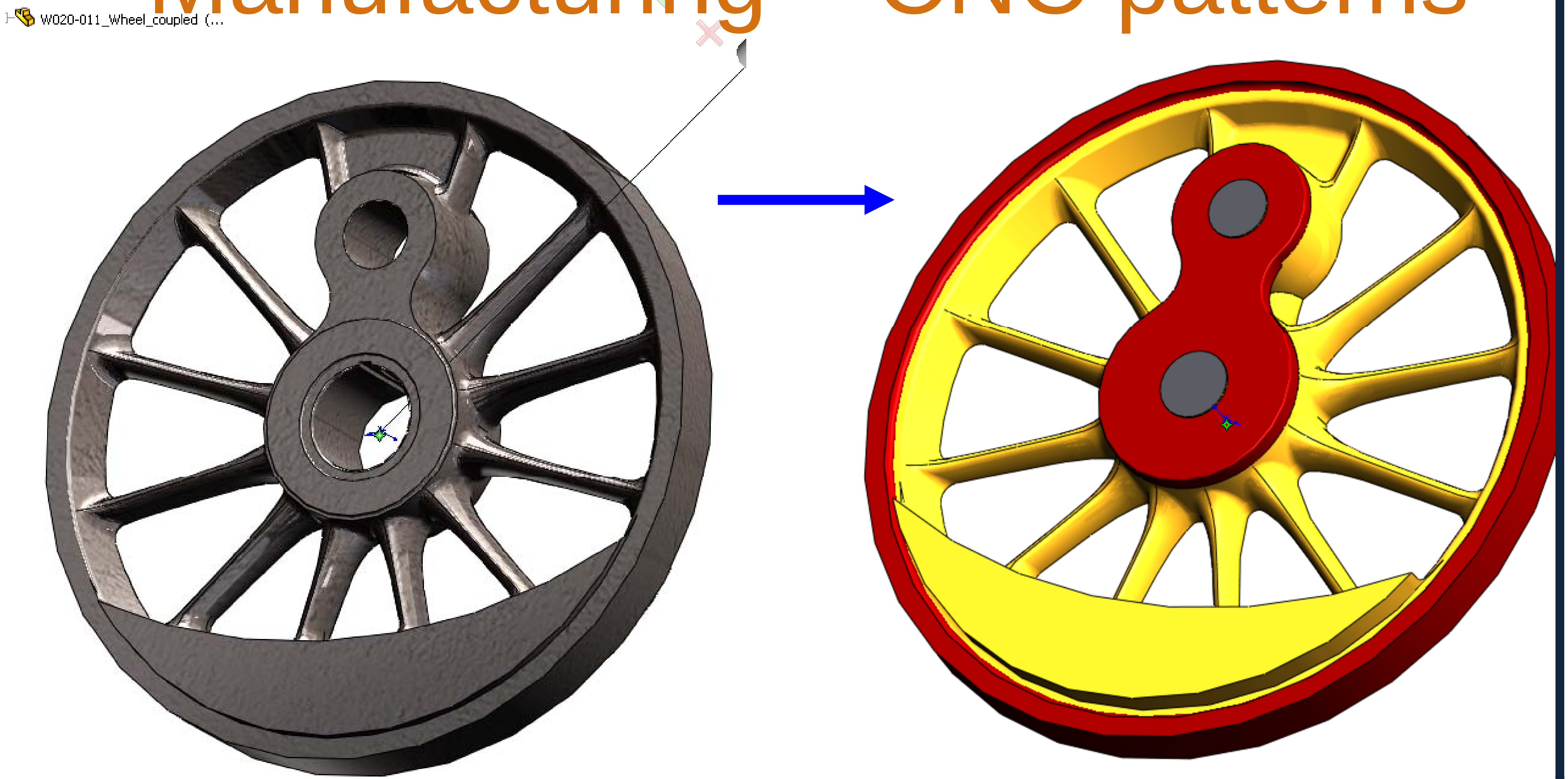
Manufacturing – CNC patterns



- **From the 3-D model file a variant for the pattern was generated.**
- **Contained shrinkage, draft and machining allowance**
- **From this the pattern was machined directly by CNC.**

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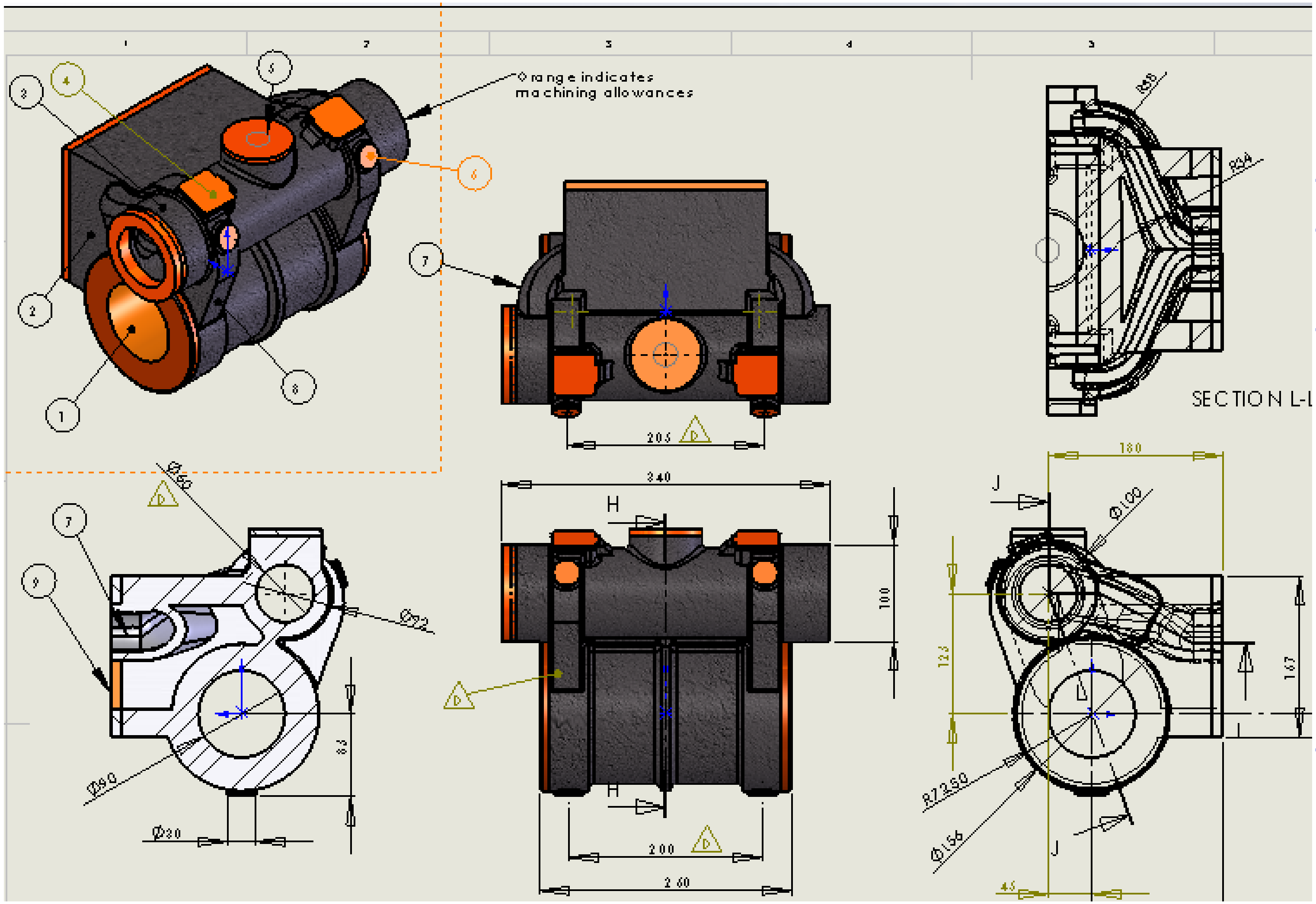
Traditional Pattern-Making



Some components did not lend themselves to CNC methods and traditional pattern making was required.

Luckily such skills could still be found!

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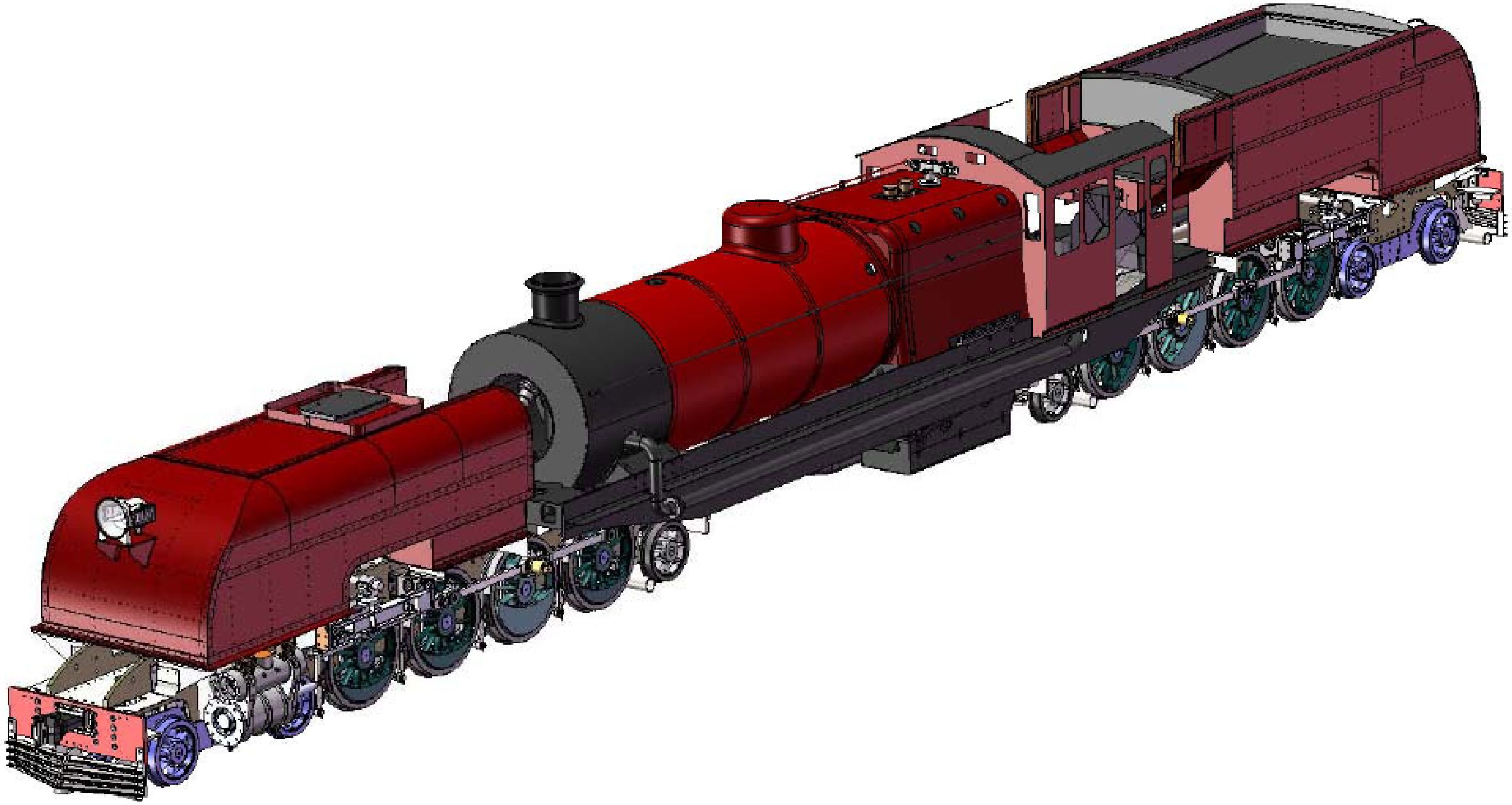
Future Development



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Modern Steam Links

- http://www.martynbane.co.uk/ Contains a summary of current modern steam developments around the world.
- http://www.a1steam.com/ A UK project which has successfully built, and now operates, a new full size main line steam locomotive
- http://www.5at.co.uk/ A UK based project to construct an advanced technology high speed main line steam locomotive.
- http://www.dlm-ag.ch/index.php A Swiss manufacturer of modern steam locomotives and marine steam equipment.

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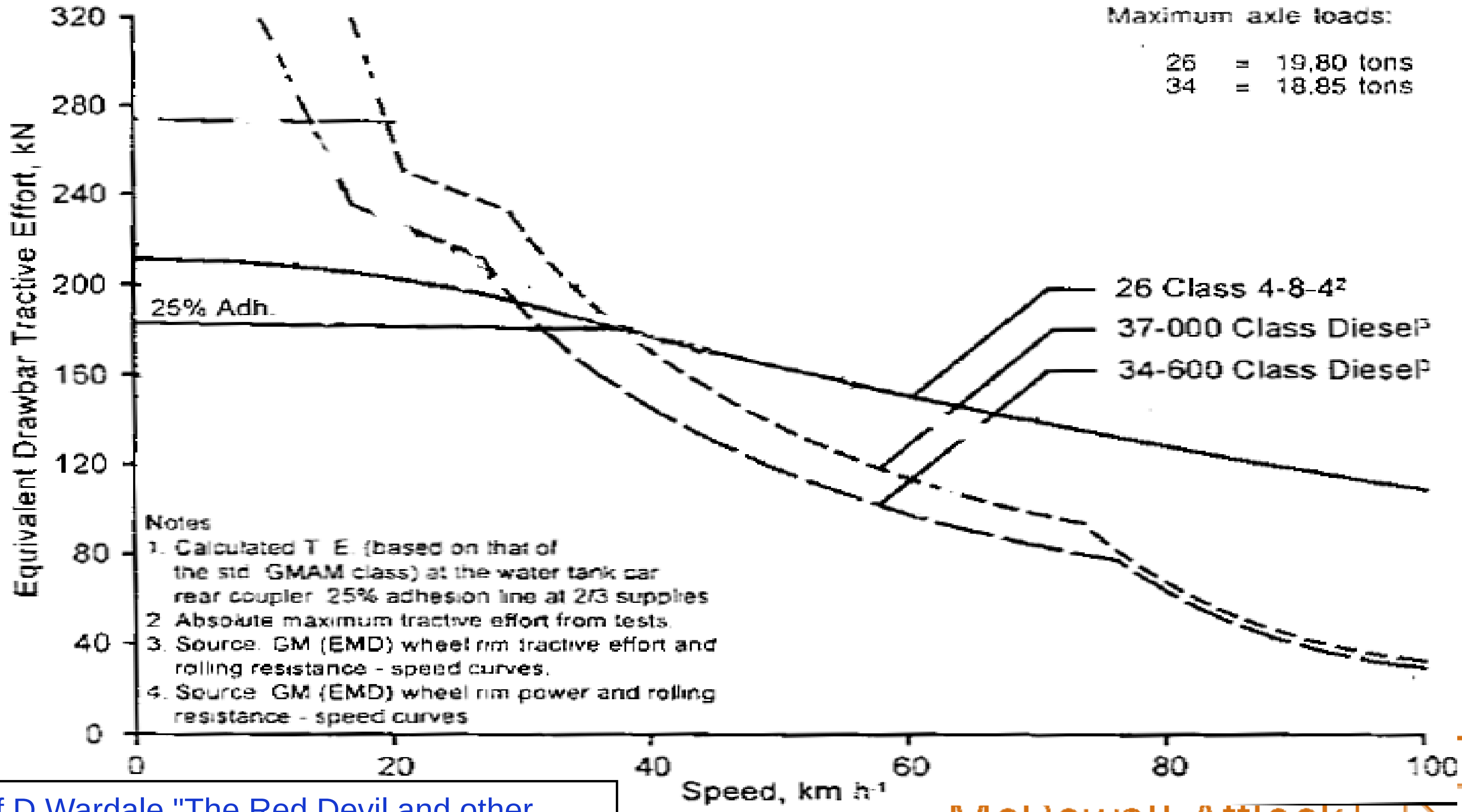
Appendix 1. Tractive Effort - Examples

Steam Tractive Effort, 4-8-4 South African Railways Class 26.

Diesel-Electric, Co-Co, South African Railways Classes 34 and 37



Ref D Wardale "The Red Devil and other Tales of the Steam Age".

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Appendix 2. Steam Locomotive Power - Two examples

Pennsylvania Railroad K4, 4250 draw bar horse power (3145kW). Ref. Andre Chapelon, Giant of Steam. English translation, Camden Miniature Steam Service

268 *The Red Devil and Other Tales from the Age of Steam*

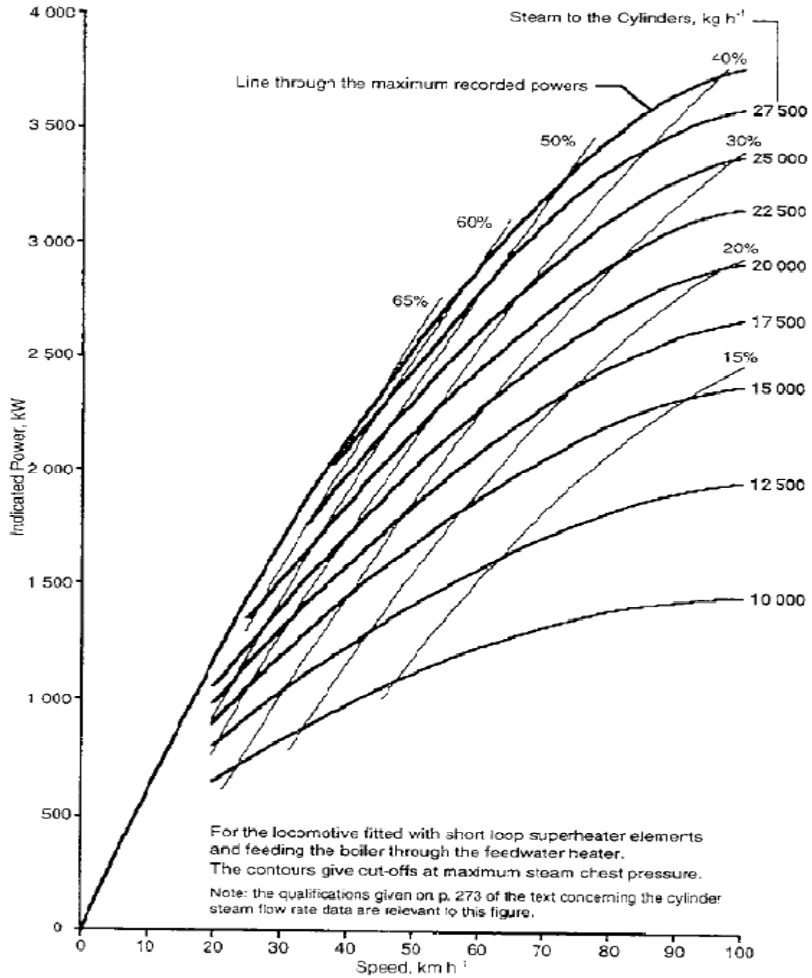
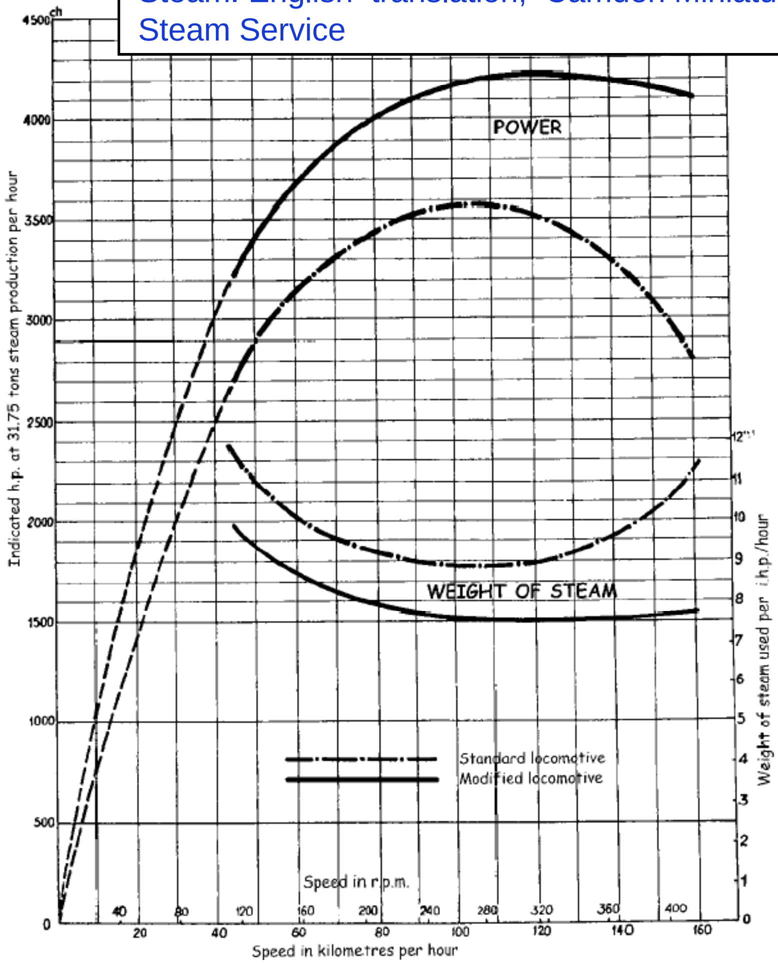


Fig. 83

SAR 26 Class 4-8-4 No. 3450: Indicated Power versus Speed



SAR class 26, Power vs speed 3600 indicated kW. Ref D Wardale "The Red Devil and other Tales of the Steam Age"

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