# Improving Performance & Efficiency of 35011 *General Steam Navigation*


Dr Steve Rapley

Chief Mechanical Engineer

35011 General Steam Navigation Locomotive Restoration Society


16th October 2022

# Contents

1. Introduction
    1. Who I am
    2. Who GSNLRS are, & what our aims are
2. Issues with the original design & how we're addressing them
    1. Crank axle failure
    2. Drifting exhaust
    3. Low performance efficiency (including *How to perform locomotive exhaust CFD*)
3. Questions?

# About me

- Chartered Engineer, Member of the Institution of Mechanical Engineers, Professional Aerodynamicist
- BSc in Mathematics (with Study in Europe), MSc in Theoretical and Applied Fluid Mechanics, PhD from the School of Mechanical, Materials & Manufacturing Engineering at the University of Nottingham
- 15 years professional experience working for Rolls-Royce plc. & Bladon Micro Turbine
  - 6 years at Rolls-Royce Submarines
    - CFD of the PWR
    - CFD of the Steam Generator
  - 6 years at Rolls-Royce Fuel Cell Systems
    - heavily focused on CFD analysis of ejectors, building up a wealth of knowledge of how to analyse these
    - Predominantly single nozzle designs, though some work on multi-nozzle oblong ejectors
  - 3 years at Bladon Micro Turbine, Principal Aerodynamicist, leading the Aerothermal Team

# About me

- Life long interest in railways & steam locomotives
  - Earliest memory of a steam locomotive 34092 *City of Wells* on the K&WVR
  - Keen railway modeller, interested in the unusual.
- Various heritage railway volunteer roles & memberships over the years
  - Romsey Signal Box Project
  - Great Central Railway (Nottingham)
  - General Steam Navigation Locomotive Restoration Society
- Member of GSNLRS since 2017
  - Society put out an appeal for a CME in 2020
  - I applied and was appointed to the role in September 2020

# GSNCIC/GSNLRS Introduction


- General Steam Navigation CIC
  - Custodians of BR(S) Rebuilt Merchant Navy Pacific 35011 *General Steam Navigation* since 2016
  - Supported by General Steam Navigation Locomotive Restoration Society
- Aim of the project is to return 35011 to *original* design condition for mainline running
  - Removing the 3 sets of Walschaerts valve gear & the inside-admission middle cylinder
  - Refitting Bulleid's chain driven valve gear & steam reverser
  - Manufacturing a new middle cylinder to the original design with outside admission
  - Manufacturing a new crank axle (35011 lost its axle before arrival in the scrap yard)
  - Refitting the air-smoothed casing

# The life (so far) of 21c11…




Photos courtesy of A Cawston, Colour Rail, D Philips, D Beardmore &GSNCIC

# Restoration progress

- Moved locomotive from Sellindge to Blunsdon (Swindon & Cricklade Railway)
  - Provides a base that is on a railway and more centrally located
- Boiler lifted from frames and de-tubed
- Trailing truck sent to North Norfolk Railway Engineering for restoration
- Frames stripped of Walschaerts valve gear and other features added on rebuilding
- Building up inventory of parts for boiler backhead
- Purchased the vital steam reverser
- Completed design work of replacement frame stretchers and new crank axle
- Started design of new middle cylinder

# Engineering-implementing modern working practises & techniques

- Established Engineering Sub-committee to lead engineering efforts
- Brought in safer working practices, reflecting the need for competencies within the volunteer workforce
- Developing an electronic bill of materials, complete with drawings from the Bulleid Pacific Locomotives Association archive
- Using Computer Aided Engineering to resolve issues with the original design
- Founding member of *Main Line Steam Builders Group*

General Steam Navigation Locomotive Restoration Society

21c11 35011

# Issues with the 1944 Bulleid *Merchant Navy* design

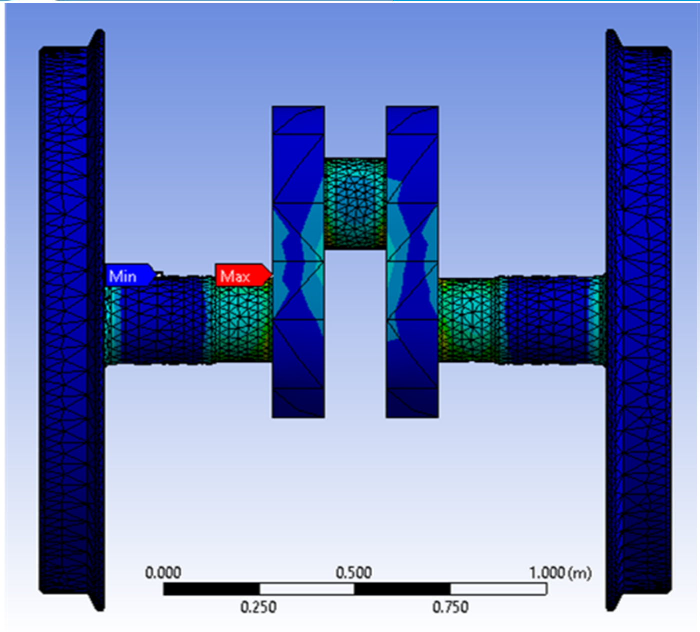
1. Unbalanced Crank axle
   - Spectacular failure of crank axle on 35020 *Bibby Line* at Crewkerne in 1953
2. Drifting exhaust
3. Poor fuel economy
   - Minimum specific steam consumption 15-20% higher than comparable designs
4. Myths?
   - Casing fires
   - Tendency to slip

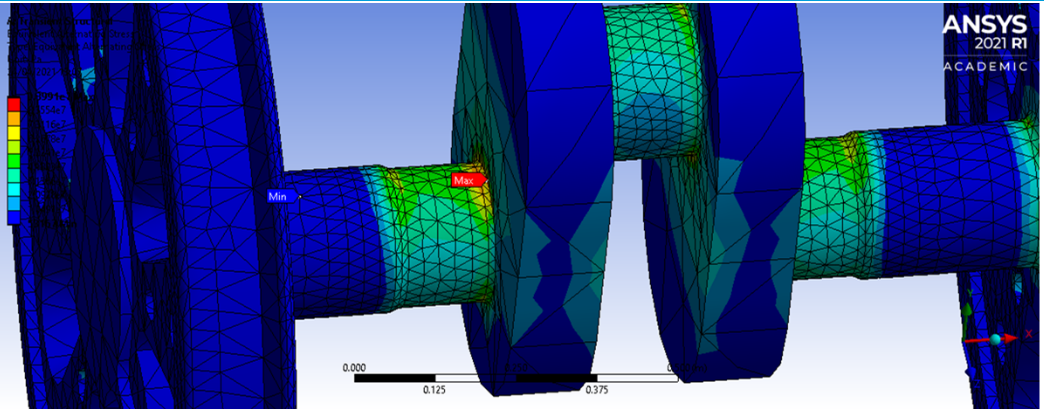
# Crank axle failure

AFTER COMING TO REST AT CREWKERNE
APRIL 24TH. 1953

- Crank axle on 35020 *Bibby Line* fractured at ~80MPH as the locomotive passed through Crewkerne station
  - No derailment, no reported injuries, no fatalities
- Entire *Merchant Navy* Class swiftly withdrawn for investigation
  - Subsequent investigations showed failure was likely to occur on 20 out of 30 class members soon
  - Light Pacifics showed no issues
- Failure due to high stress on axle at speed due to unbalanced design
- Axle initially redesigned to a larger diameter, unbalanced design, with onerous inspection regime, to return class to service
- Latter balanced arrangement designed, first 6 balanced axles were fitted to original Merchant Navy locomotives, including 35011
  - All rebuilt Bulleid pacifics received design on rebuilding.
  - No original Light Pacifics ever fitted with design

# Crank axle Finite Element Analysis (Original Design)



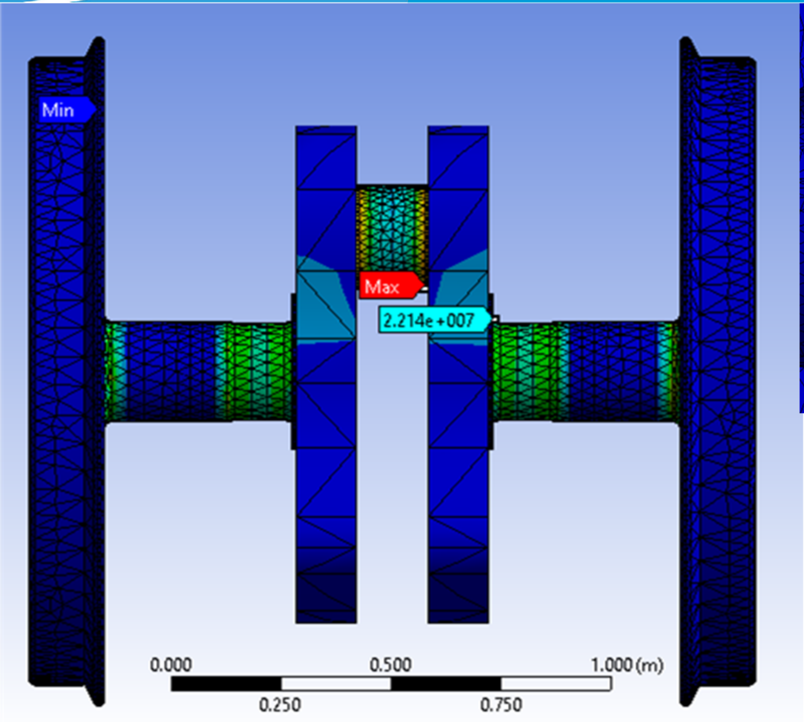



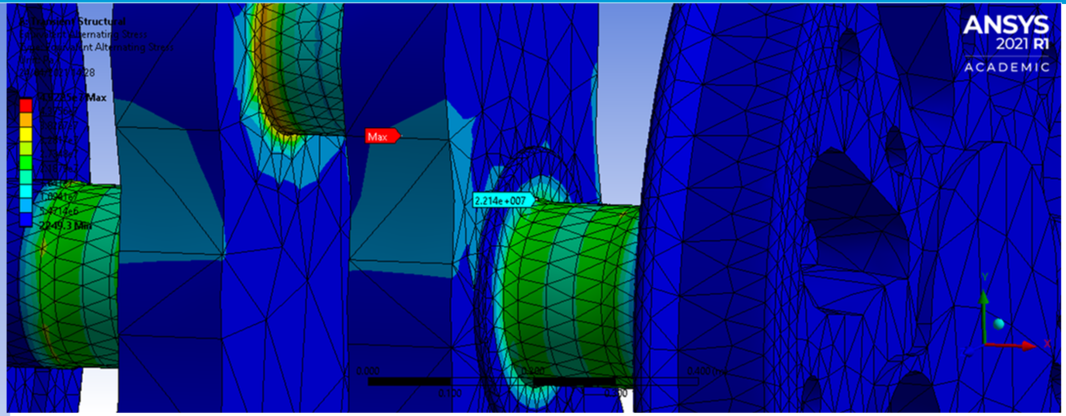

- Stress concentrations predictions on the original axle design
- localised large stress concentration on the top edge of the boundary between the crank web and the axle piece.
- High stress on the surrounding areas of both the axle piece and the crank web.
- Stress patterns non-uniform, spreading from the epicentre of the stress on the top of the axle piece, in line with the orientation of the crank web.
- Safety factor predictions indicate low safety factor at this location
- Very close match with where the failure on 35020 occured

General Steam Navigation Locomotive Restoration Society

21c11 MERCHANT GENERAL STEAM NAVIGATION NAVY CLASS 35011

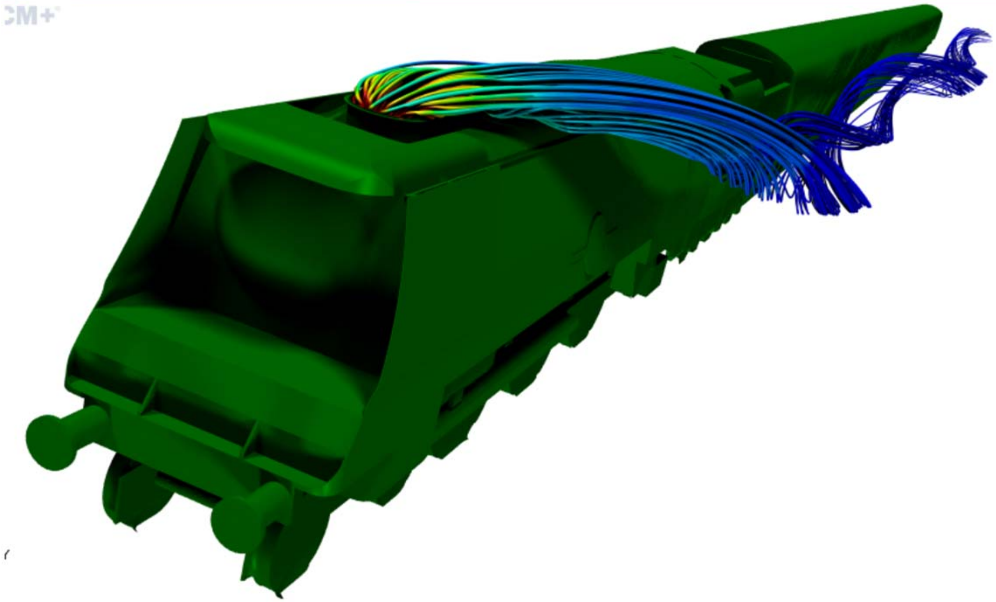
# Crank axle Finite Element Analysis (Balanced design)



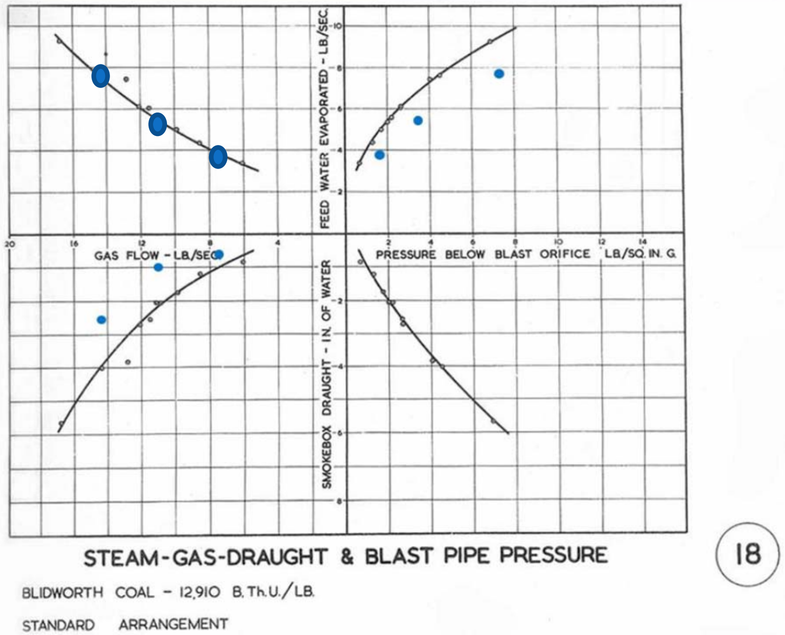

- Stress concentrations predictions on the balanced axle design
- Maximum stress is now found on central crank pin, rather than the axle piece.
- The area of peak stress from the original design now only feels a stress of 23.5% of the stress felt there in the original design.
- stress redistributed more evenly, resulting in consistent contours of stress around the circumference of the axle piece.
- Infinite life predicted with both 1956 material (modern equivalent 945m38) A4T

# Drifting exhaust: External aerodynamics CFD



- Industrial tutor for final year Mechanical Engineering students CFD project at Loughborough University
- Known issue with original Bulleid pacfic design regarding drifting exhaust obscuring crew forward visibility
- Study conducted to explore options for improving conditions via:
    - Extending duct around exhaust further back (10% improvement in visibility)
    - Modifications to exhaust design (up to 50% improvement (?!))

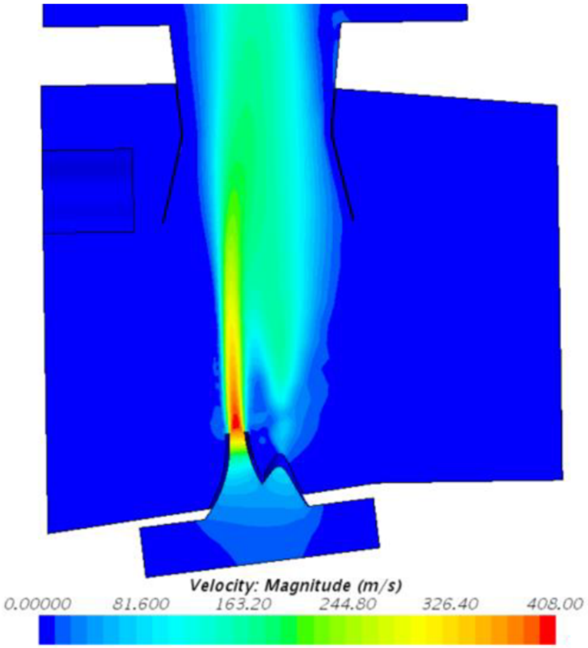
# Poor fuel economy: Internal Aerodynamics (H2 2020)




- Industrial tutor for final year Mechanical Engineering students CFD project at Loughborough University
- Projects split in to a group stage to develop methodology, then individual tasks
- First attempt at project
  - Error in geometry provided to students (smokebox oversized by about a foot)
  - Only found one data set for validation prior to starting project (BR Performance & Efficiency Bulletin 10)
  - Boundary conditions applied with hindsight not completely appropriate

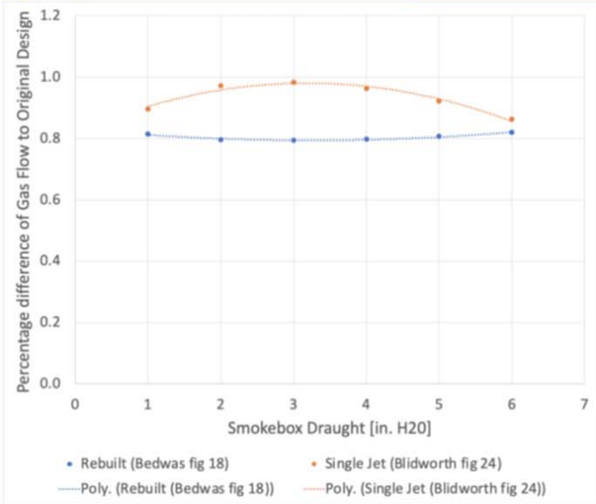


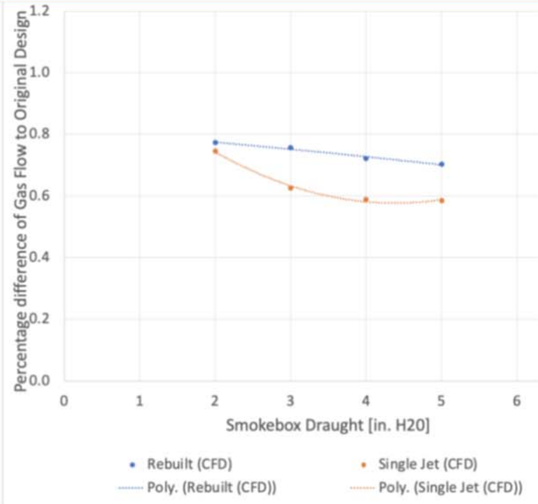
# Poor fuel economy: Internal Aerodynamics (H2 2020)




- Flow structures for Bulleid-Lemaitre design.
- Vast gap between nozzles and exhaust, compounded by geometrical error
- Diffuser not working well
- Incorrect boundary conditions make results from individual tasks not relevant for much read across

# Poor fuel economy: Internal Aerodynamics (H2 2021)




- Second attempt at project
  - Attempted validation against bulletin 10 & bulletin 20
  - Boundary conditions applied with hindsight not completely appropriate (still)
  - Key result is CFD is not far off in prediction of performance variation between designs
  - Results from individual tasks again not easy to read across due to incorrect boundary conditions

# Poor fuel economy: Ejector simulation & design experience from RRFCS

- At RRFCS most of our ejectors were single nozzle designs, based on the work of Kentfield & Barnes
- Lots of CFD performed upon them
- Two key takeaways:
  - Very good resolution of the boundary layer vital for accurate simulations-targeting single digit wall y+ values, ideally with a surface average below 3.
  - Vital to have good grid resolution along the primary flow path, using a separate domain/zone within the mesh to ensure this
    - Prevents artificial numerical mixing of the primary and secondary flows
- As our flow rates increased, we started looking at multiple ejectors in parallel, and then multi-nozzle ejector designs, inspired by steam locomotive exhaust designs (Giesl & Kylchap)
  - Oblong ejectors with multiple parallel nozzles work if the flow area per primary nozzle is maintained the same as the ideal single-nozzle ejector (squaring the circle)



# Locomotive Exhaust CFD

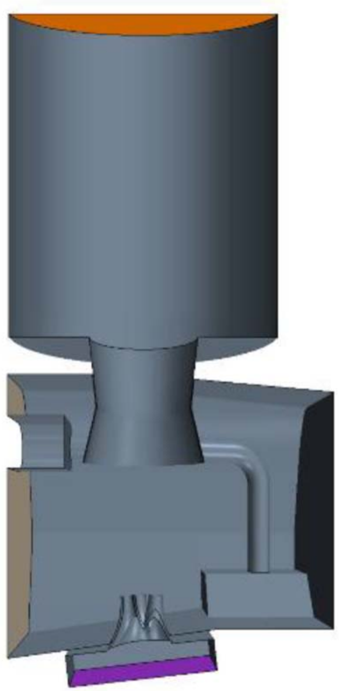
- How should we do CFD analysis of a locomotive exhaust? Lessons learnt from Loughborough students & my experience

# Validation *before* design

- Validate your CFD methodology against a comparable design with some good test data
  - BR Performance & Efficiency reports are a goldmine for this purpose
    - Bulletin 8 gives good data for a single nozzle design
    - Bulletins 10 & 20 give good data for multi-nozzle designs
    - Bulletin 18 gives good data for a Giesl ejector
  - Need good drawings of the components in question though-the less you know, the more errors you’re potentially introducing
- Consider the impact of different turbulence models & approaches
- A methodology that is consistent is a useful one. If it always underpredicts boiler airflow by 10%, for example, across multiple designs, you can have confidence that for any new design, the predicted airflow will be within 10% of reality. Or you can use it to rank designs

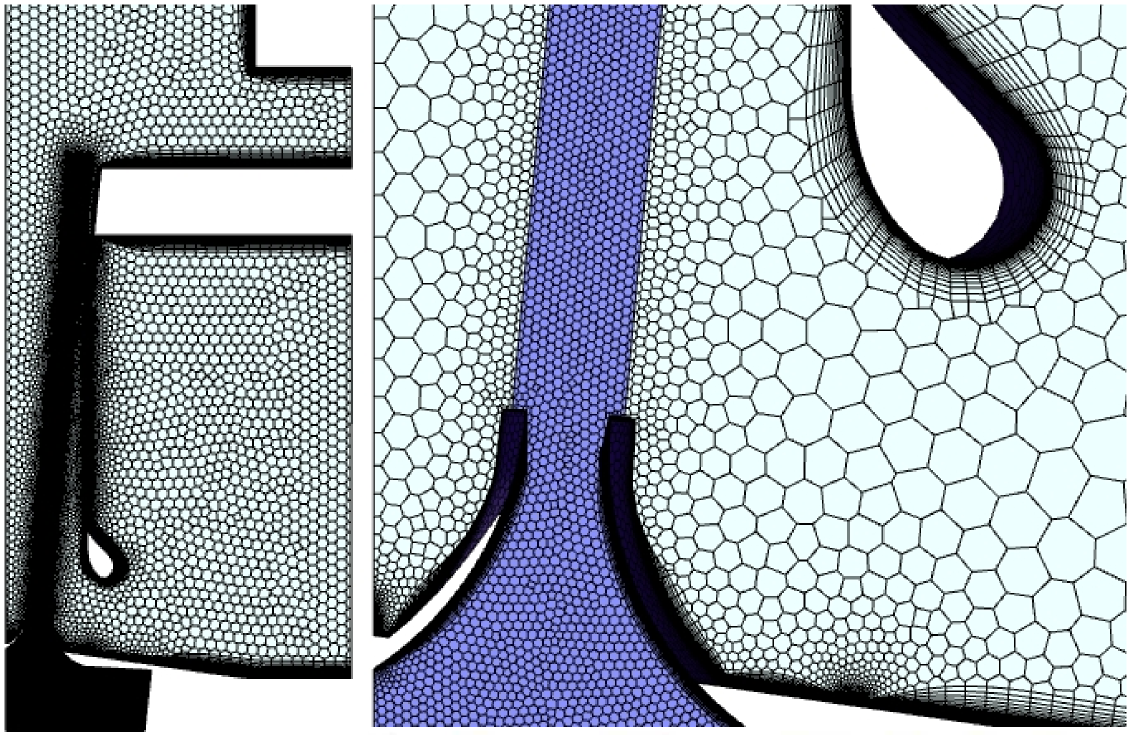


# CFD Domain



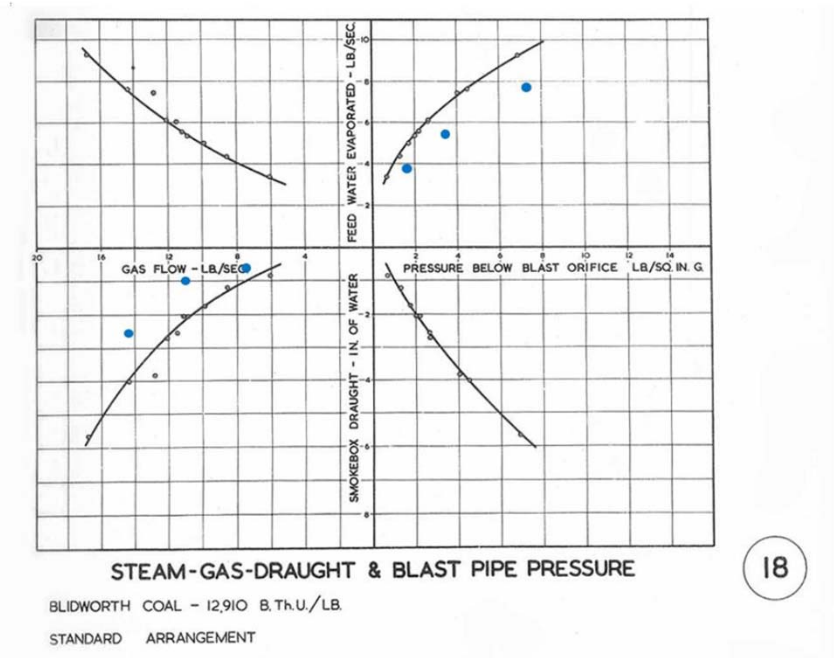
- Model air flow from exit of tubes to beyond the locomotive boundary
  - Important to allow exhaust to function "properly", terminating domain too soon will at best cause convergence issues, at worse artificially it will impact the predicted performance as the top of the exhaust won't function normally.
- Model steam flow from well upstream of nozzles
  - Helps with numerical convergence, especially if flow is choking
- Can you employ symmetry?
- If you're replicating a test, consider what parts of the test environment need including in your model

# Mesh design



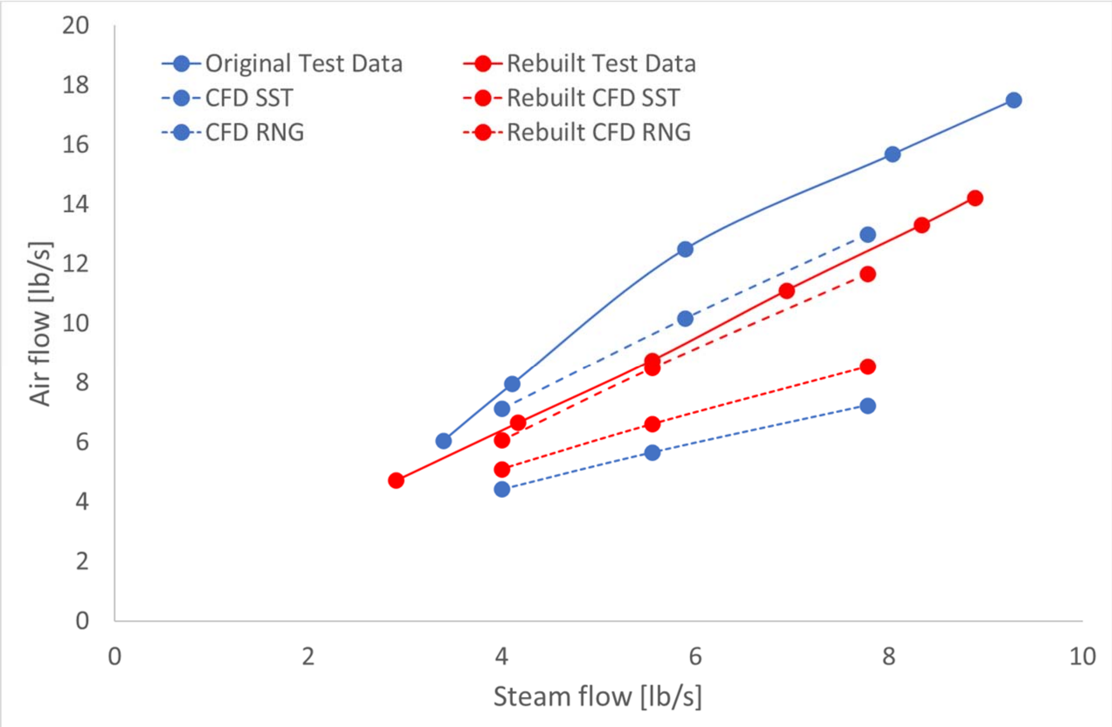
- Prism layers (and lots of them)
  - Vital for good resolution of near wall behaviours
  - Targeting single digit wall $y^+$ values
    - Enhanced wall treatment area-weighted average <1 with maximum below 3
    - SST k-ω target average of <5
- Divide/refine mesh by projecting cylinder from tip of blast nozzles to the top of the exhaust
  - Prevents growing mesh causing artificial mixing of steam and air too early
  - Beware of mesh collapse on corners/interfaces

# Boundary conditions



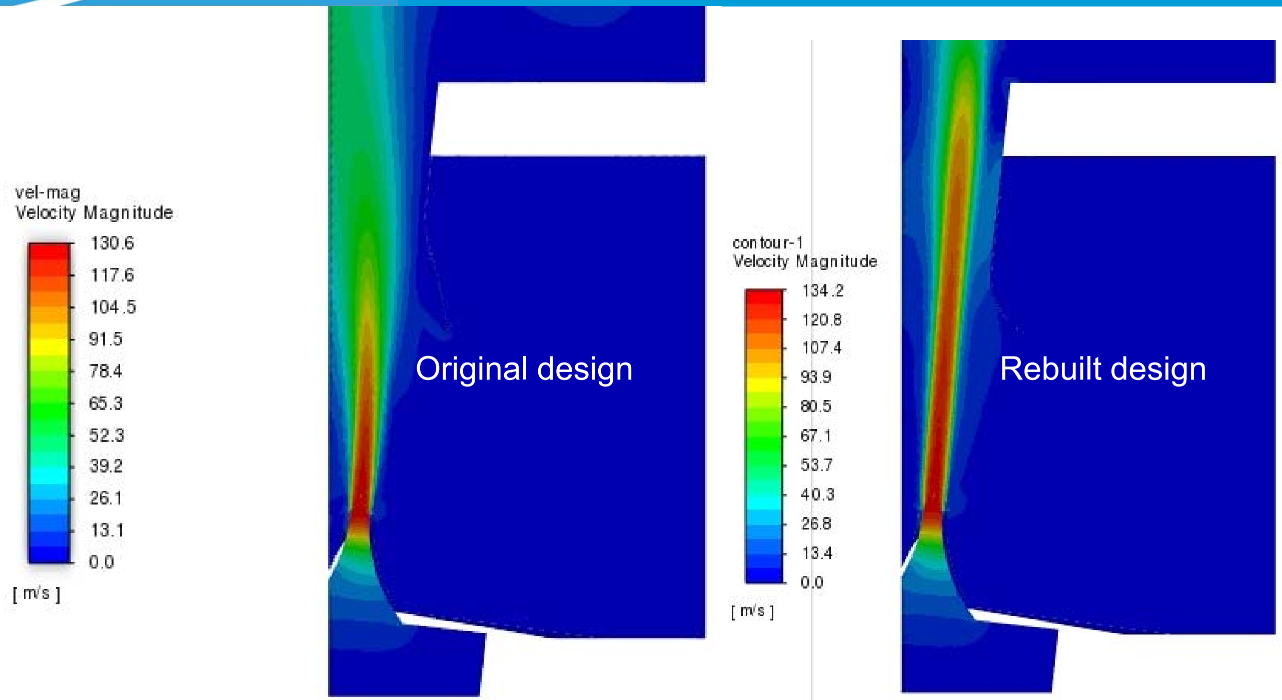

- All flow boundaries should be pressure boundaries
  - Helps with convergence, especially as steam flow will likely be choked.
  - Steam pressures from top right quadrant of graph
  - Gas inlet pressure (smokebox draught) should be negative, and should be adjusted until, when gas inlet pressure vs mass flow is plotted, it sits on the curve in lower left quadrant
  - Result you then compare against test data is in top left quadrant of graph
  - Apply turbulent boundary conditions instead of default
    - Turbulence intensity commonly defined as $0.16Re^{-0.125}$
    - Re used in intensity calculation should be based on local hydraulic diameter

# MN Exhaust: Turbulence model/Validation




- Simulations of original and rebuilt exhaust designs, using methodology of previous few slides
- Comparison between RNG k-ε and SST k-ω turbulence models
  - SST both closer to test data & predicting relative behaviour of two designs
  - SST used in design study presented later on
  - Depending on the solver you use & the data set you model, you may not get this result (CFD can be fickle)

# Steam jet dissipates sooner in original design

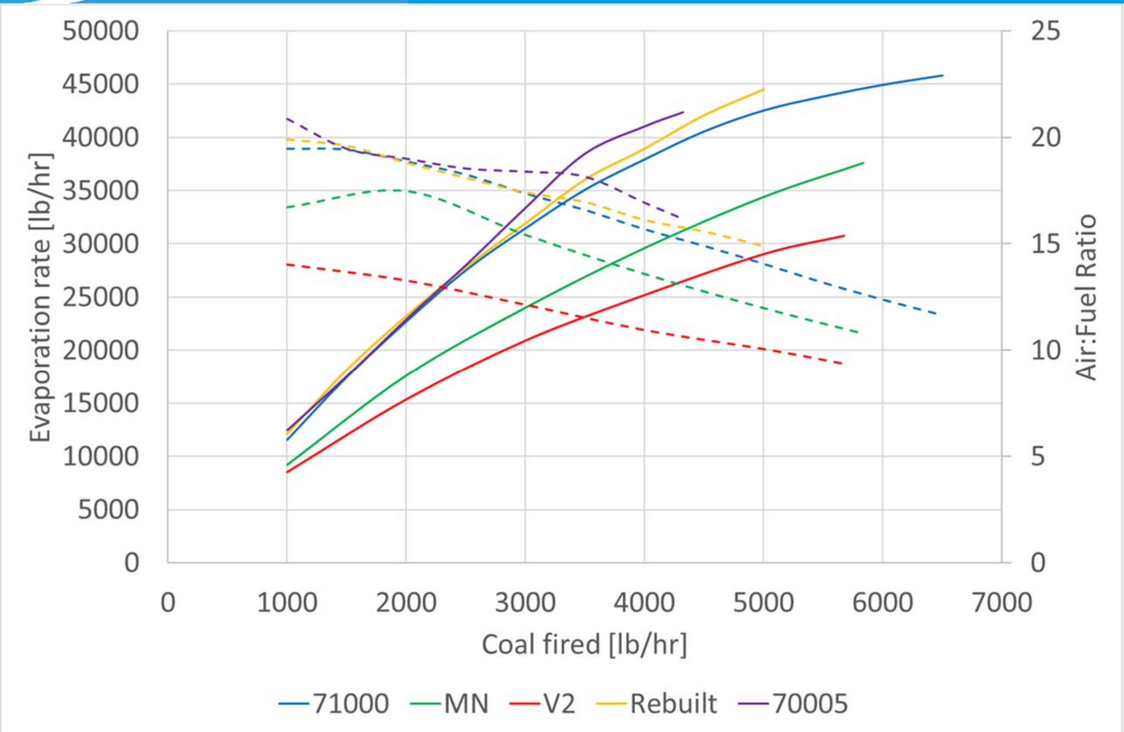



- Simulation of 1/10th of smokebox, assuming rotational periodicity can be applied
- Contours of velocity magnitude on symmetry plane
- Steam jet dissipating sooner in original design, hence reduced performance
  - Jet moving out of mesh refinement region, leading potentially to underprediction of entrainment, especially at higher flows

# Preparing for H2 2022 Projects

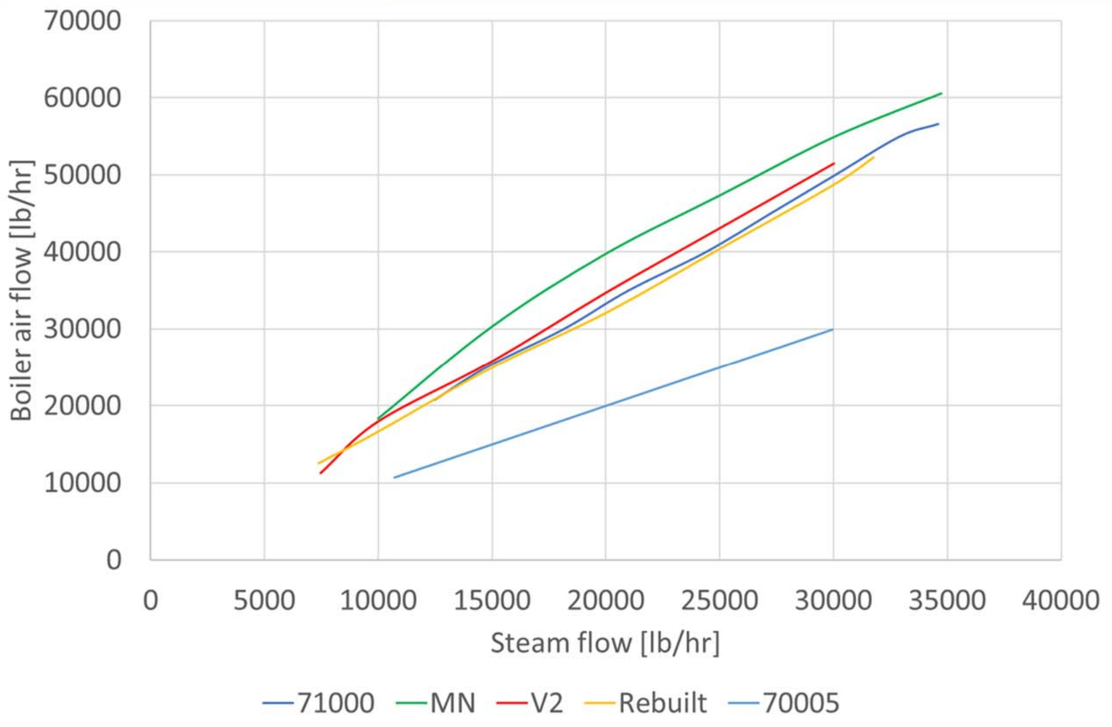
- Read some good books:
  - *The Red Devil and Other Tales from the Age of Steam* by David Wardale
  - *"The fire burns much better ..."*, the Ph. D. thesis by J.J.G. Koopmans
  - *Fundamental Design Calculations for the 5AT Locomotive*, as prepared by David Wardale
  - *La Locomotive a Vapeur*, by A Chapelon
  - …and numerous technical articles
- Had a good think about what we're trying to achieve with improving 21c11 (and what the rebuilt locomotives achieved)

# Merchant Navy Fuel economy poor



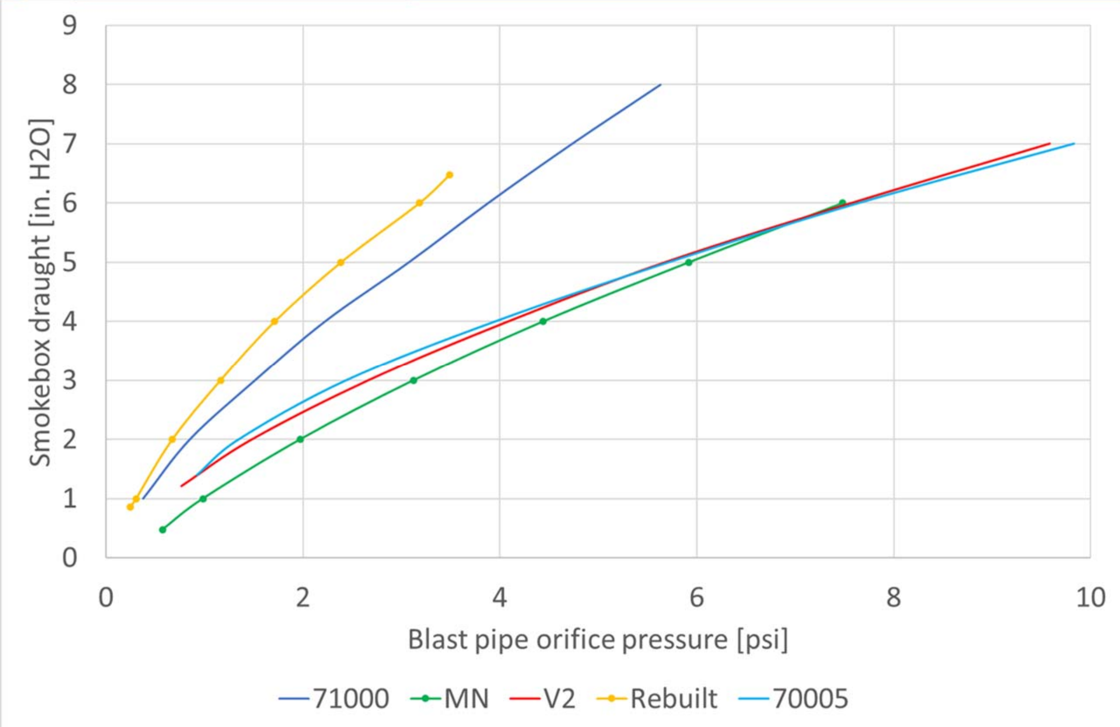

- Original Merchant Navy produces ~25% less steam per pound of coal than rebuilt MN or BR standard pacifics
  - AFR ~14% less on original design
- Rebuilt MN performance similar to 71000 prior to modifications to latter in preservation
- *Data from BR test bulletins 5 (Std 7), 8 (Single chimney V2), 10 (Merchant Navy), 15 (Std 8), 20 (Rebuilt MN)*

# Merchant Navy Boiler air flow high




- Original Merchant Navy has ~20% higher air flow than rebuilt design
  - …but AFR is low, suggesting poorer combustion conditions
- Rebuilt MN has very similar air flow as 71000 prior to modifications to latter in preservation
- *Data from BR test bulletins 5 (Std 7), 8 (Single chimney V2), 10 (Merchant Navy), 15 (Std 8), 20 (Rebuilt MN)*

# Smokebox draught on Original design low




- OVS Bulleid fitted Lemaître style exhausts to all his new locomotive designs
- Problems with original design
  - Same exhaust design fitted to the MN & Light Pacific designs, despite the different power levels of the two designs
  - Comparing Lemaitre's original drawing with those of the Bulleid design show the steam nozzles may be too far away from the chimney
  - Blast nozzle area roughly half that of contemporaneous designs
    - Low area will increase cylinder back pressure
- Original Merchant Navy smokebox draught relatively low
- Rebuilt MN has more than double the draught of original
- *Data from BR test bulletins 5 (Std 7), 8 (Single chimney V2), 10 (Merchant Navy), 15 (Std 8), 20 (Rebuilt MN)*



# Changes in gas circuit on rebuilding (MN class)

- Damper doors *were* fitted to original & rebuilt MN design
  - Flow area *halved* from 12.2 ft$^2$ to 6.1 ft$^2$ upon rebuilding
- Primary flow area reduced from 50% to 37.3% of grate upon rebuilding
  - Compare with LNER V2 36.6%, BR Std 7 37%, BR Std 8 43%
- Superheater surface area reduced 8% due to lack of space in new smokebox
- Exhaust modified from Bulleid-Lemaître to new design
  - 5 nozzle blast pipe retained, unaltered
  - Replacement exhaust with slightly lower diffuser angle (12.7 (original) vs. 12 (rebuilt)) & longer diffuser (18 ½ vs. 26 inch)
  - Exhaust length comparable
  - Geometric choke lower on rebuilt design



# Improvement goals

- Reduce cylinder back pressure by increasing effective blast nozzle area
- Improve performance & efficiency by increasing AFR (via increased boiler air flow)
  - Target is better air/steam ratio than rebuilt design; in simulations this is 1.513
- Stretch goal: to improve performance & efficiency further by adding tube-in-shell feedwater heater

# Options

1. Keep the original exhaust design
    - Known design
    - Fuel economy is poor, costing us money
2. Refit the rebuilt design
    - Some improvement on the original design, still poor
3. Fit a modern exhaust
    - New design, possibly unproven
    - Potential for performance improvements
    - Any exhaust changes shouldn’t change the aesthetic of the locomotive



# Alternative exhaust option

- British “best-practise” suggests fitting either double Kylchap or a Giesl
  - Doesn’t fit with requirement that any exhaust changes shouldn’t change the aesthetic of the locomotive
  - Giesl performance can be temperamental
- Double or triple Lempor
  - High levels of performance possible
  - Doesn’t fit with requirement that any exhaust changes shouldn’t change the aesthetic of the locomotive
- Single squat Lempor (or even Kylpor)
  - Possible compromise on performance
  - Fits with requirement that any exhaust changes shouldn’t change the aesthetic of the locomotive

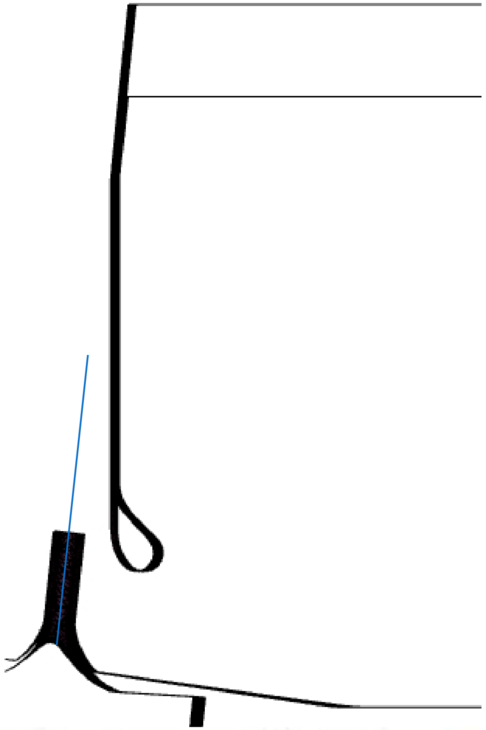

# New exhaust designs for original & rebuilt Bulleid locomotives

| | Lempor | Bulleid-Lemaître |
|---|---|---|
| Blast nozzle area ($cm^2$) | 205.7 | 174.6 |
| Blast nozzle diameter (mm) | 58 | 66.675 |
| Number of nozzles | 9 | 5 |
| Distance from nozzle tip to exhaust (mm) | -103 | 600 |
| Mixing chamber area ($m^2$) | 0.276 | 0.317 |
| Mixing chamber diameter (mm) | 593 | 635 |
| Mixing chamber length (m) | 0.9413 | 0 |
| Exhaust area ($m^2$) | 0.426 | 0.426 |

- Sized using D. Wardale's 5AT FDCs as a primer
  - Equations converted into excel spreadsheet
- Drawing on experience from RRFCS, assumed that a multi-nozzle ejector can be thought of as multiple triangular ejectors blended into one another
- Extrapolated sizing of 4 nozzle Lempor to a 9 nozzle design, compromising on diffuser length in order to fit aesthetic requirement of one single exhaust
  - Sized by designing for 2¼ exhausts on blast nozzle flow area, then combining mixing duct flow areas, maintaining duct length, and setting total diffuser outlet area to be the same as the original design (2'5" diameter)
- Differences between calculated design and model
  - Nozzle distance adjusted to give higher & more robust performance
  - Mixing chamber length increased to take up available height
- Numerous simulations conducted varying nozzle angle, position, length and diameter, to study impact on performance



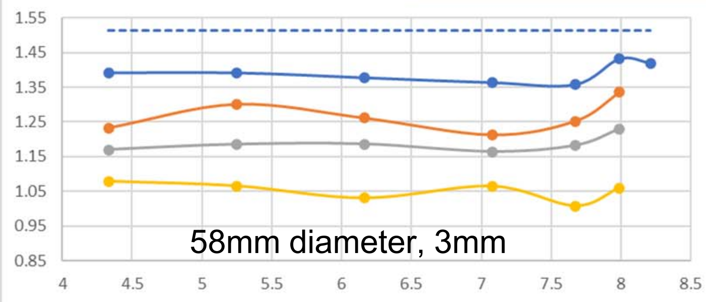
# Lempor geometry variation

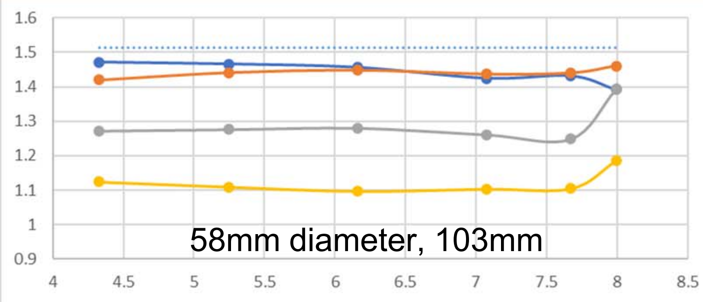


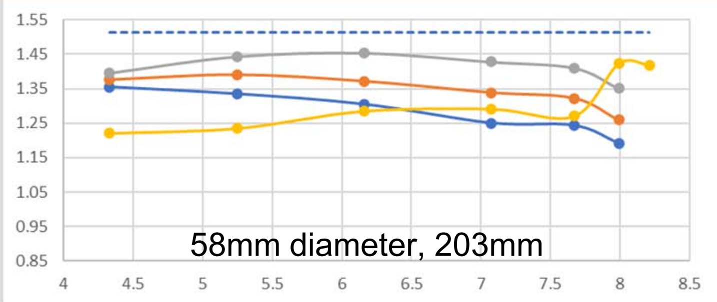
Parameters varied (and meaning of some values):

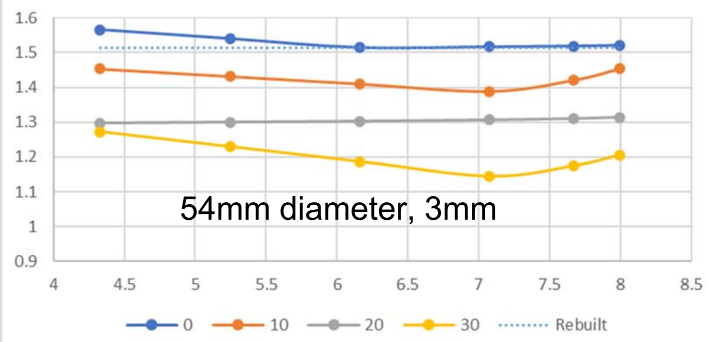
- Nozzle angle: image shows 6.16 degrees, matching diffuser angle. At radial location 0mm, angle 4.33 orients jet towards the centre of area of the 1/9th sector each nozzle feeds
- Radial location: at nozzle angle 6.16degrees, location 0mm has the nozzle axis and diffuser wall intersecting. Distances beyond this are towards the axis
- Nozzle diameters: 58mm, 54mm (& starting to work on 48mm)
- Nozzle length: 203mm (shown here) has nozzle tip in line with base of the mixing duct. Other lengths bring the nozzle tip towards the base of the smokebox (103mm is in line with the base of the bell mouth)

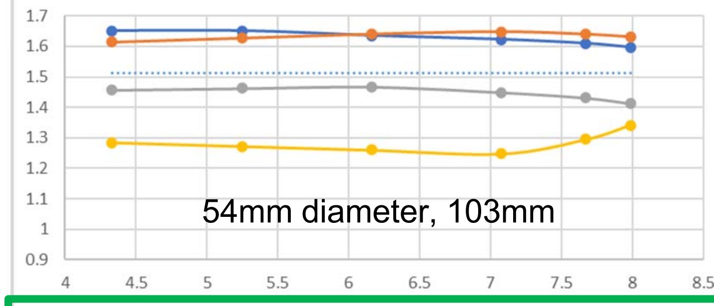
# Effect of nozzle variables on performance

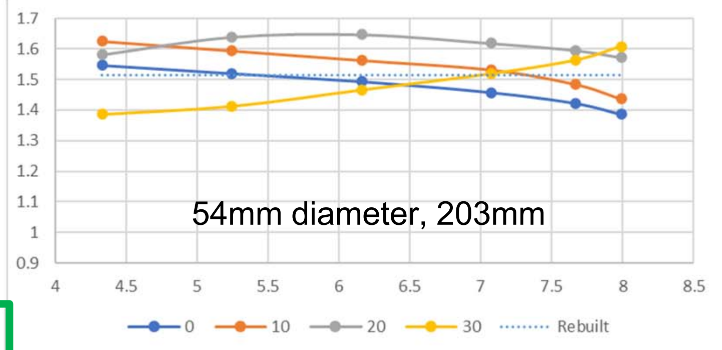


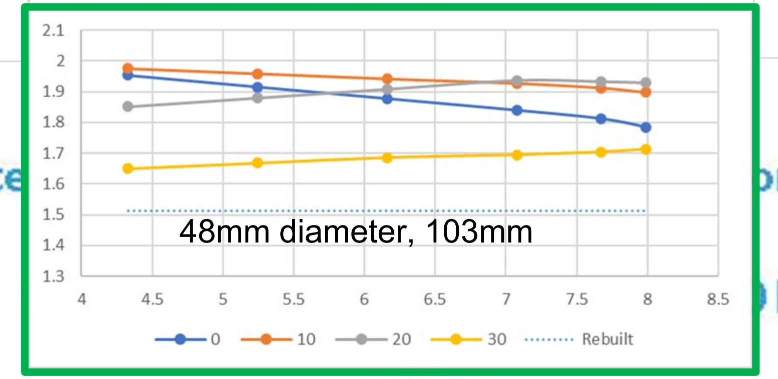



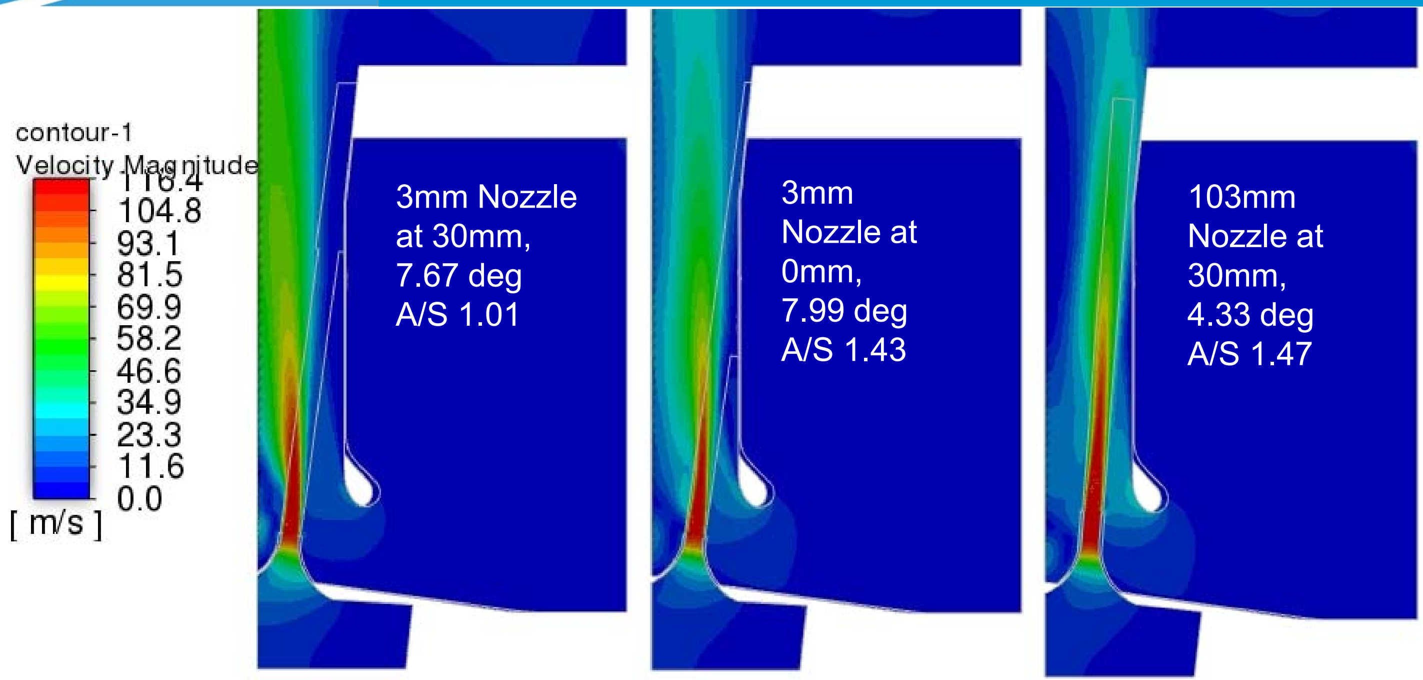




General Ste… …oration Society

# Flow visualization (58mm diameter)




- Simulation of 1/18th of smokebox, assuming rotational periodicity
- Contours of velocity magnitude on symmetry plane
- Steam jet being pulled towards axis in 30mm design, hence reduced performance (A/S ratio 1.01 vs 1.43)
  - Flow moving out of mesh refinement so A/S may be underpredicted
- More acceleration of secondary flow at exhaust entrance
- Flow staying attached to diffuser in 103/30/4.33 design, hence strong performance (A/S 1.47)



# Summary/Next steps with exhaust

- Best design, compared to rebuilt exhaust design, currently offers:
  - 31% increase in airflow
  - 30% decrease in steam pressure upstream of blast nozzle if running conjunction with FWH
- Confirm “spare-time” analysis with Loughborough analysis
- Finalise design for rebuilt MN
- Finalise design that has margin for supplying up to 20% steam to feedwater heater
  - 48mm diameter nozzle showing potential for much higher A/S ratio (~2)
  - If 20% steam flow passed to FWH, steam pressure in line with 54mm diameter designs



# Improve fuel efficiency through feedwater heating

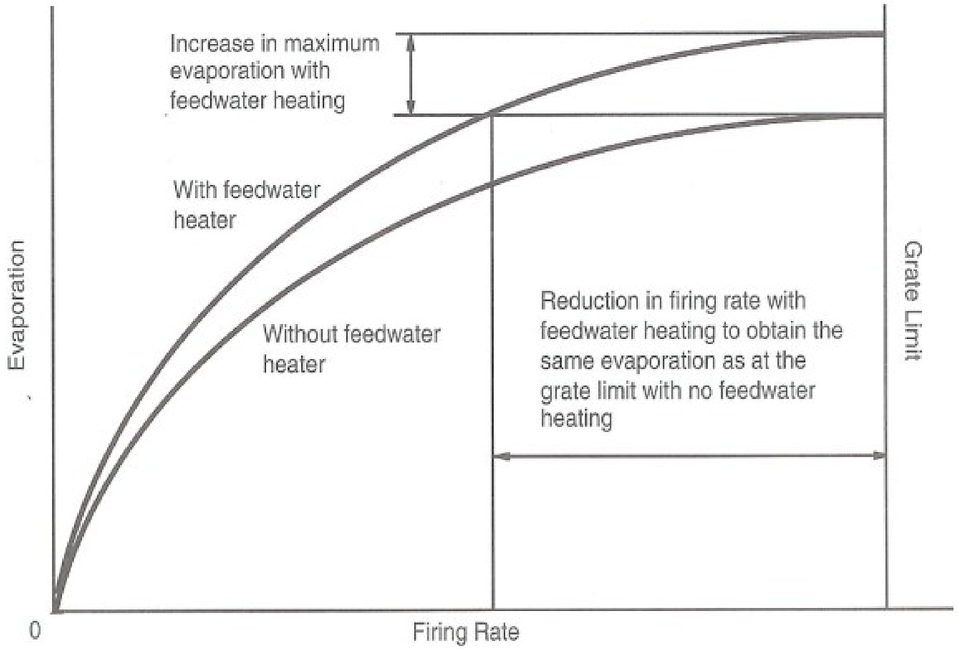



**Fig. 41**
**Qualitative Effect of Feedwater Heating on Boiler Output**

Most “modern” steam locomotives used steam injectors to transfer water into boiler

- Raise pressure from atmospheric to 250psi
- Raise temperature to ~70degC

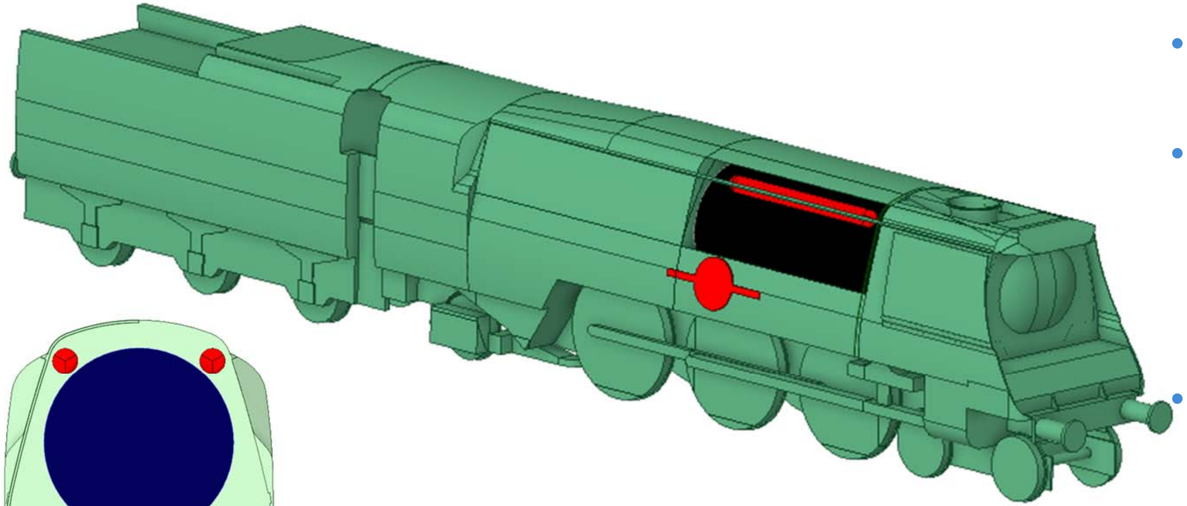
Using tube-in-shell feedwater heater (& pumps) increases feed temperature to ~110-140C

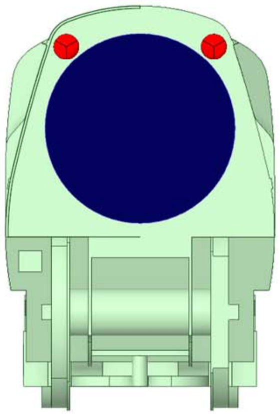
- Increase in maximum power available, & fuel savings available (15% water, 30% coal)

*Graph Fig.41 from The Red Devil and Other Tales from the Age of Steam 2nd edition by Wardale, David )*



# Fitting a feedwater heater to an original Bulleid





- Unusual for many British locomotives to have any apparatus on the boiler shell
- FWH can be hidden under Bulleid air smoothed casing
  - (Image shows where it would go)
  - Comprise on outer diameter, but significant length available
- Concept design
  - Two heaters
  - 2.7m long, 250mm OD
  - Single pass steam, 6-pass water
  - 15mm OD Copper Tubes
  - 15-21 tubes per pass (TBD)
  - HT area 16.7-23.4$m^2$ (5AT 18.3$m^2$, SAR26 13.3$m^2$)

# Improve fuel efficiency through feedwater heating

- Focus: improve utilization of fuel by pre-heating feedwater
- Internal aerodynamics/heat-transfer: tube in shell heat exchanger

Group tasks

- Study empirical design methods for heat exchangers (ESDU data items, heat transfer literature)
- Develop geometry models and simplifications to study different geometric arrangements of feedwater heater
- Develop boundary conditions for feedwater heater running at different engine power.
- Develop a CFD model of the feedwater heating and steam cooling.
- Decide validation strategy to build up the scientific credibility of your simulations.
- Develop post-processing tools for high-quality result visualisations.

Suggested individual tasks:

- Study the effect of mesh on predicted flows.
- Study the effect of turbulence model on predicted flows.
- Design explorations to improve heat transfer performance and/or reduce pressure drops across a range of operating conditions

General Steam Navigation Locomotive Restoration Society

21c11 — MERCHANT NAVY CLASS — GENERAL STEAM NAVIGATION — 35011

# Put the steam back in *General Steam Navigation*

- Visit our website (www.35011gsn.co.uk)
- Become a member (https://35011gsn.co.uk/membership.html)
- Become a volunteer (restoration, fundraising, engineering leadership (https://35011gsn.co.uk/about-us-1/working-weekends.html))
- Sponsor a component (https://35011gsn.co.uk/supporting-us/component-sponsorship.html)
- Become a shareholder-benefits can include seats on the first train hauled by 35011, footplate rides, and the chance to drive 35011, depending on the level of your shareholding (https://35011gsn.co.uk/shares.html)

# Any questions?

General Steam Navigation Locomotive Restoration Society

21c11 35011