MINTEK

A global leader in mineral and metallurgical innovation

Computational modelling of furnace tapholes

a case study in life at the interface between academic and industrial research

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2030 NDP

INTRODUCTION | About Mintek

- **Mandate: conduct research and development of new technologies to support and enhance the metallurgical and minerals processing sector in South Africa**
- South African state-owned science council
- Established 1934 (82 years old)
- Permanent staff about 700 (300 professionals)
- Funding approximately R450M p/a
- 50/50 split between gov't and commercial income
- Multiple divisions focusing on different disciplines

INTRODUCTION | Pyrometallurgy

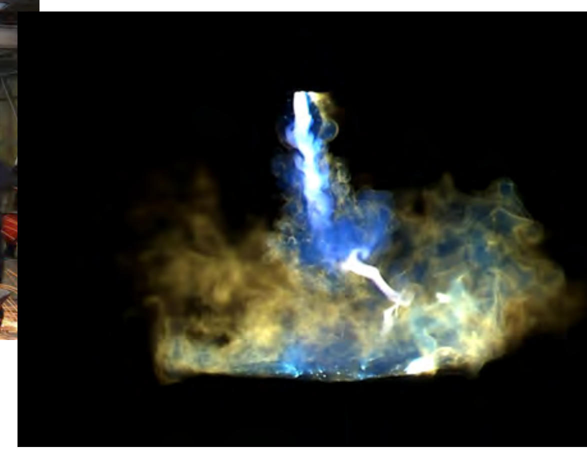
- **Pyrometallurgy**: the mineral processing discipline concerning the conversion of raw materials into valuable products using high temperatures
- Pyrometallurgical furnaces are grand challenge engineering unit operations – many complex phenomena occurring simultaneously

Thermal Stressing

Transsonic/Supersonic Flow

Particle-Fluid Coupling

Magnetohydrodynamics



Thermochemistry

Heat Transfer

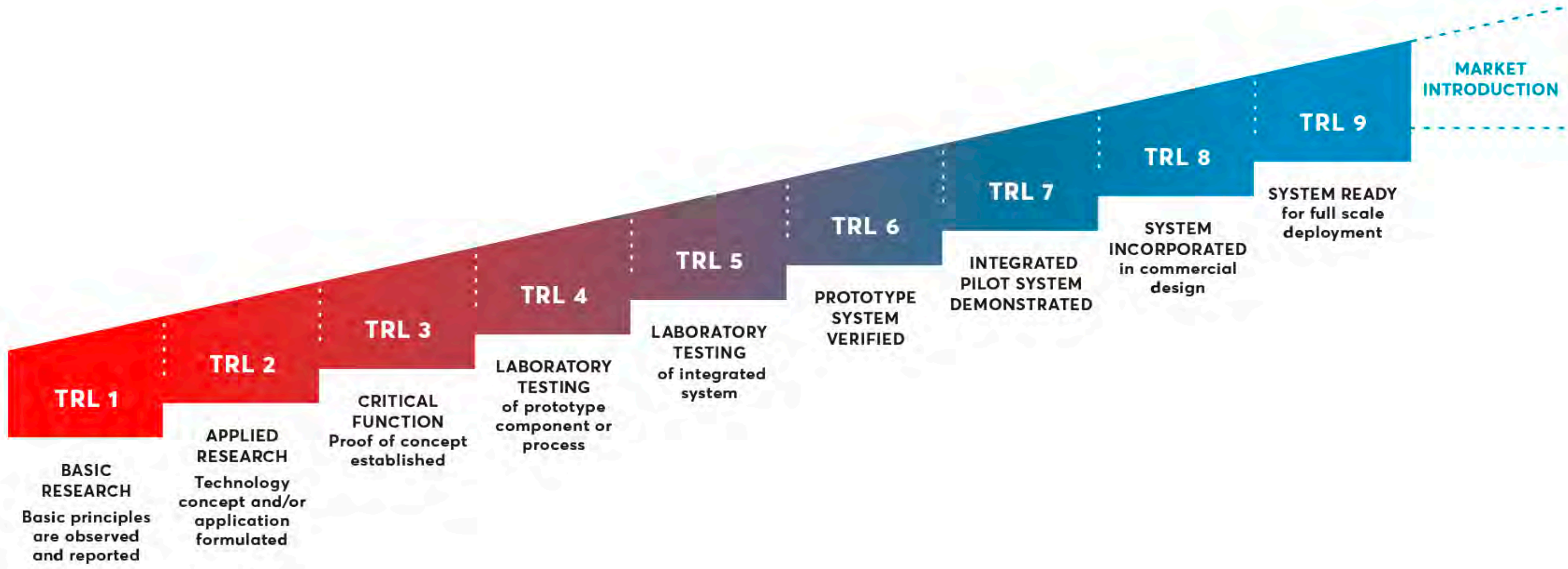
Phase Equilibria

Multiphase Flow

INTRODUCTION | Pyrometallurgy

- Pyrometallurgy is **expensive**
  - Greenfield plants can cost R bn's
  - Long-lifetime assets, typically 30+ years
  - Operating costs (electricity and/or raw materials) skyrocketing
  - Profits marginal, many commodity prices in prolonged recession
- Pyrometallurgy is **difficult** and **hazardous**
  - High temperature materials at 1500°C+
  - Electric smelters use high voltages, very high currents
  - Materials handling and transport challenging
  - New equipment and designs introduce new problems
- These combine to make the industry highly risk-averse
- Very long time frames, typically at least 20 years from concept to industrial adoption
- Industry push for technology improvements, but everyone wants to be "first to be second"

R&D PIPELINE | The good ol' yesterdays



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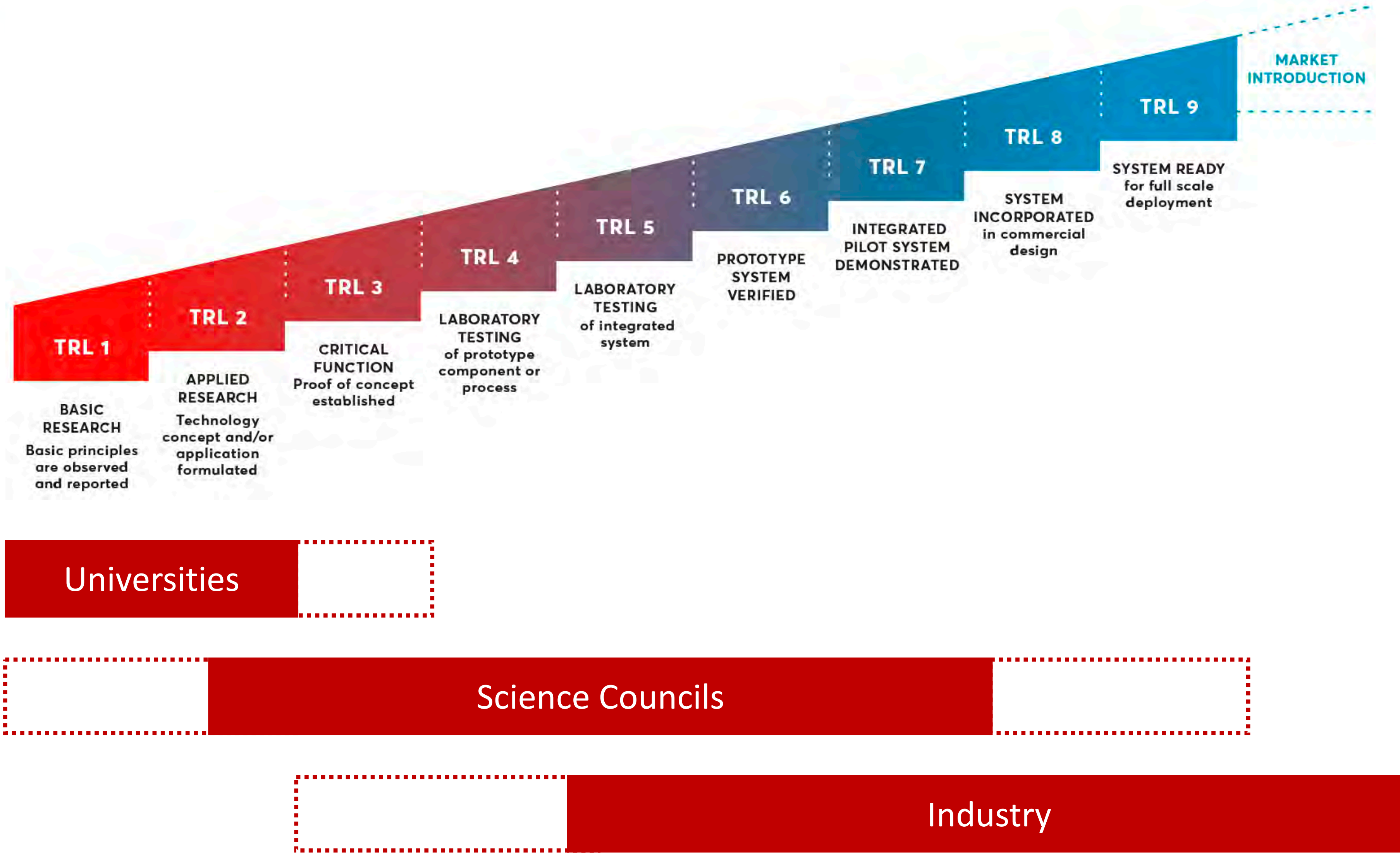
R&D PIPELINE | The good ol' yesterdays



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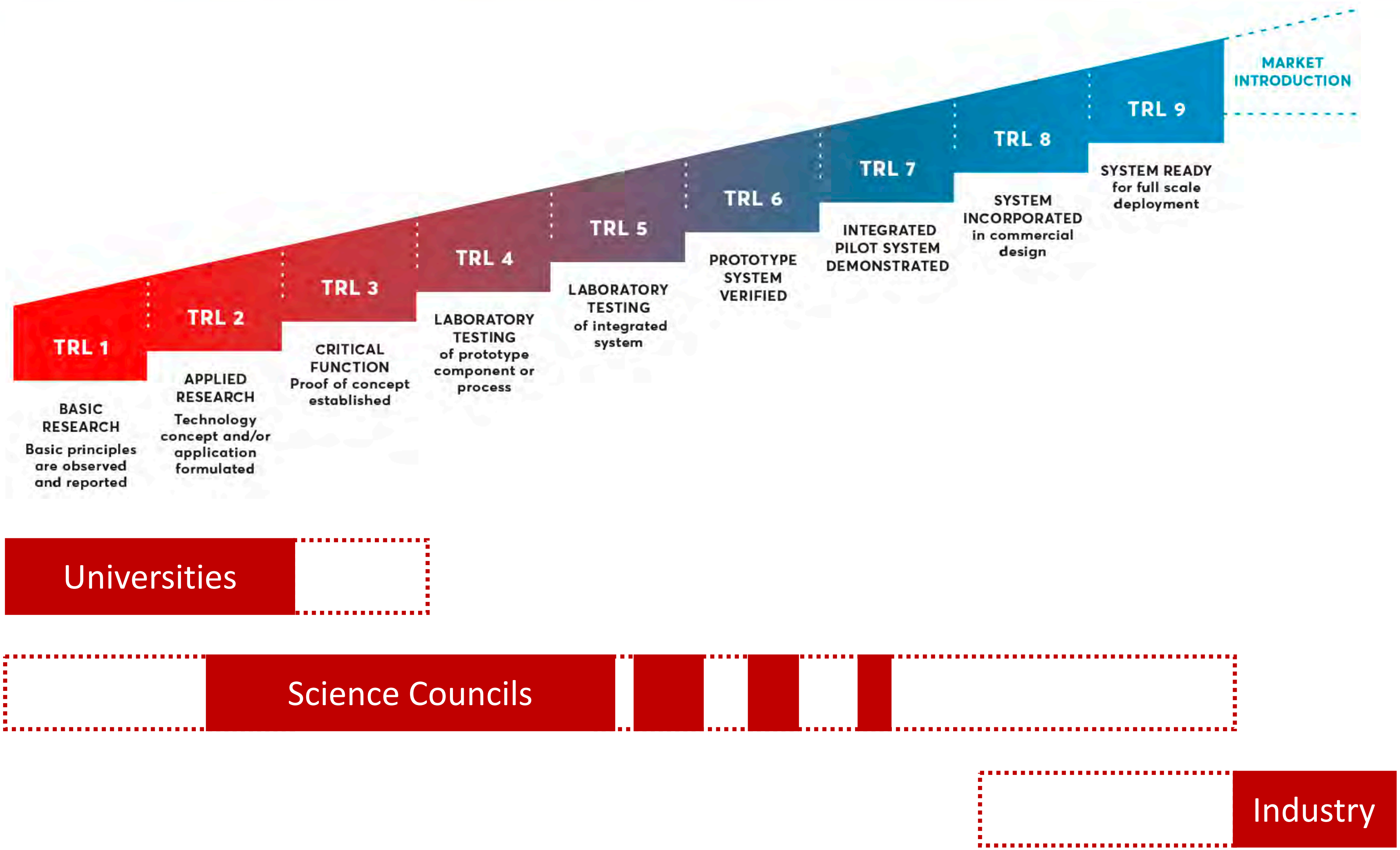
R&D PIPELINE | The bad ol' todays



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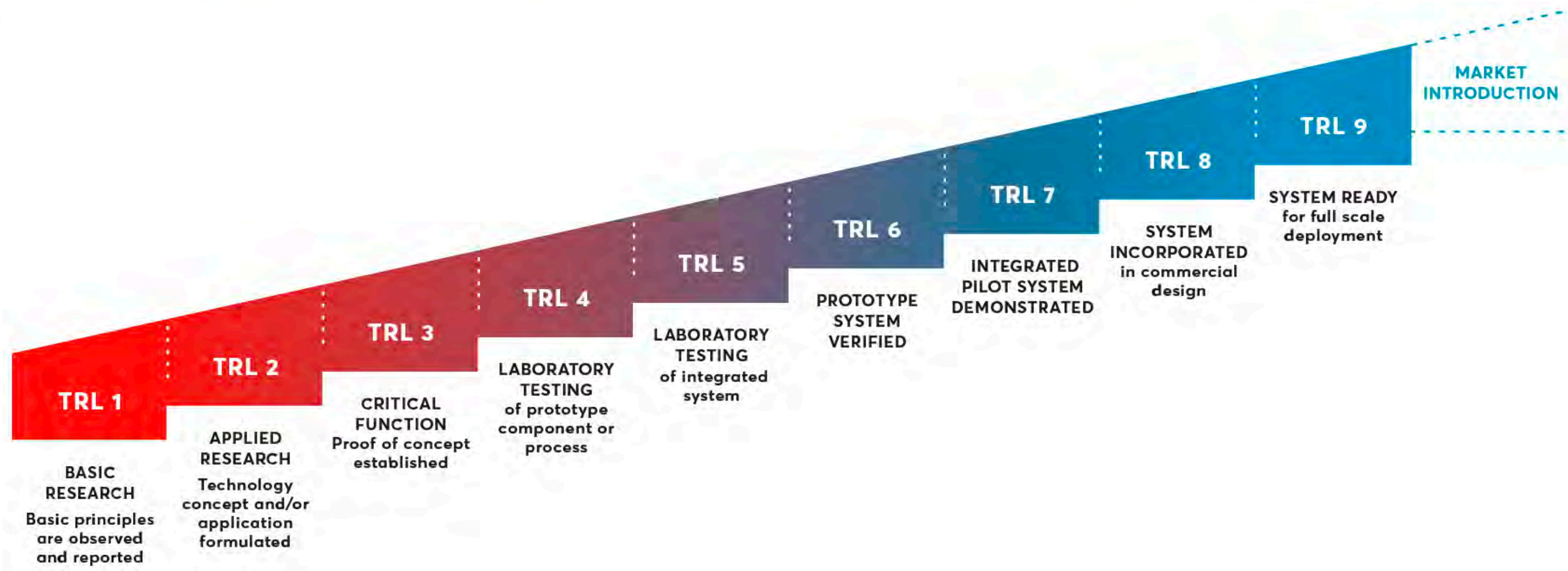
R&D PIPELINE | The bad ol' todays



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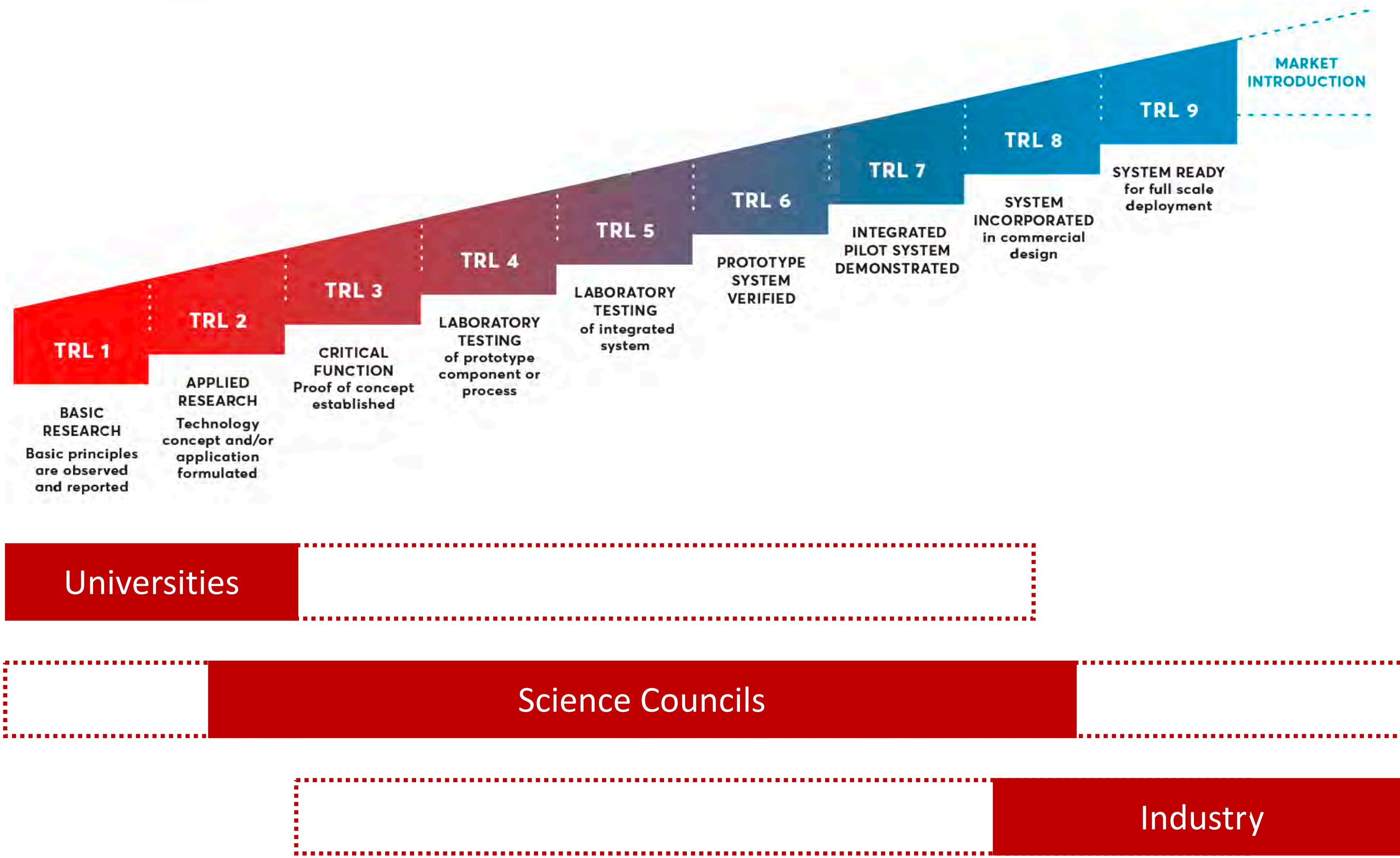
R&D PIPELINE | The (hopefully) better ol' tomorrows



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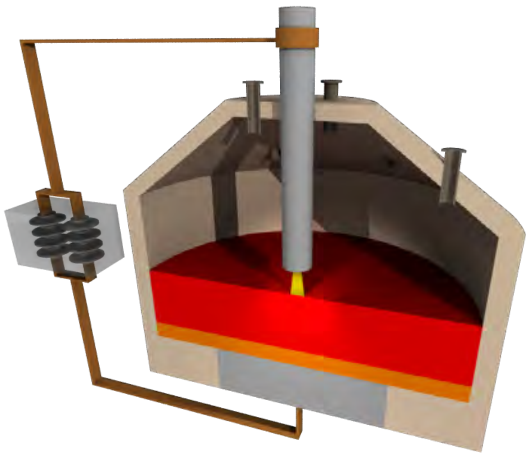
R&D PIPELINE | Modelling Technologies

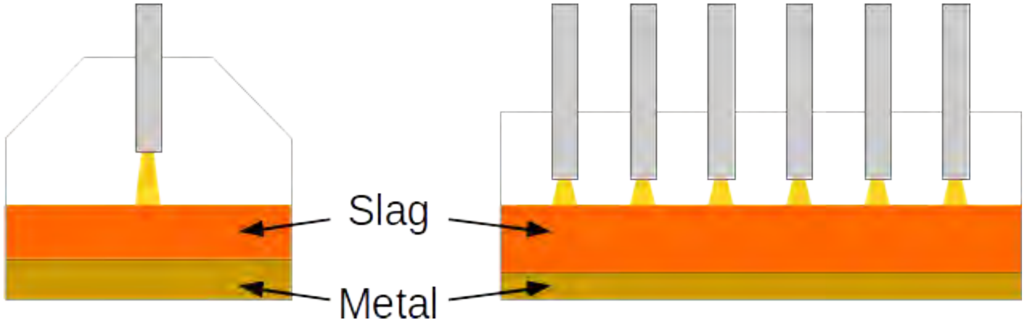
- Disruptive technologies such as computational modelling create opportunities to change how research is done in pyrometallurgy…
- "Blue sky" research
  - Previously untested or completely novel models and applications
  - Validation data limited or non-existent
  - Ideas and theory often originate from academic environments
  - Emphasises qualitative behaviour
- "Concept proving" research
  - Well-tested models, either internally or externally
  - Improved availability of validation data and test cases
  - Industry participation (but probably not funding ;-)
  - Emphasises quantitative accuracy
- *"Commercialised" research*
  - *Competent professional service providers*
  - *Tools fully validated and trusted by academic and industry partners*
  - *Production capable, industry funded*

Case Study:

Taphole Flow Modelling

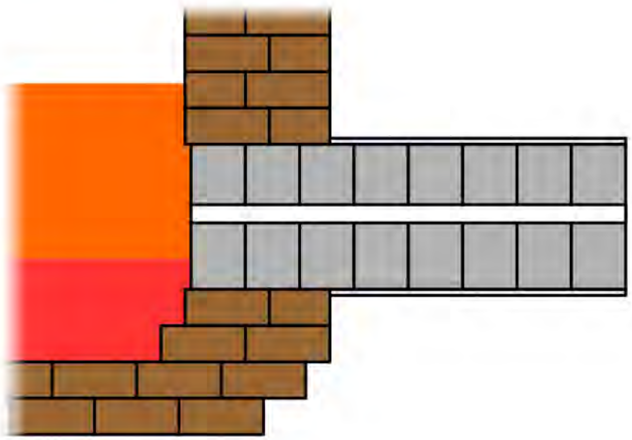
- Smelting furnaces typically contain two or more immiscible liquid phases when operating
  - Metal, metal oxides (slag), metal sulphides (matte)
  - Slag phase is lower density but higher viscosity
- Chemical reactions used to convert ores into valuable metals while in the molten state





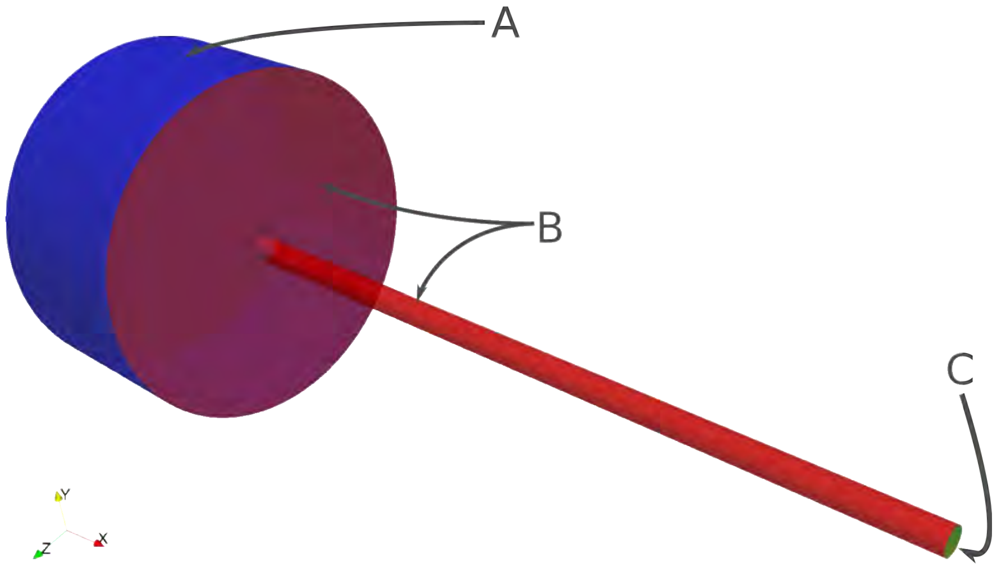
TAPHOLE MODELLING | Introduction

- Furnaces often use **tapholes**, special openings in the side walls, for removal of molten products and wastes from the vessel
- Taphole assembly consists of cylindrical or rectangular inserts made of graphite or refractory
- Tapholes are blocked with clay, and opened with drills or oxygen lances when tapping is required



- Computational fluid dynamic models implemented using OpenFOAM®
  - Dynamic time stepping based on local Courant number
  - LES to capture turbulent flow features (dynamic k-equation SGS model)
  - Matte taphole modelled as a single phase flow field, flow only, no heat transfer
- Geometries generated using Gmsh and cfMesh
  - "Generalised ideal taphole" used as starting point

- Inlet at boundary A, outlet at boundary C, solid walls at B
- Fixed pressure differential applied across region
- Mesh sizes ~2M, resolved boundary elements



Parameter	Slags	Mattes	Metals
Density ρ, kg/m^3	2500 – 4000	4200 – 4500	5500 – 7500
Viscosity μ, Pa.s	0.1 – 1.5	0.003 – 0.05	0.004 – 0.007
Pressure ΔP, kPa	5 – 40	15 – 100	20 – 120
Diameter D, m	0.04 – 0.1	0.04 – 0.1	0.04 – 0.07
Length L, m	< 1.3	1 – 1.5	1 – 1.5

$$N_{Re} = \frac{Du\rho}{\mu} \qquad N_T = \frac{D\sqrt{\rho\Delta P}}{\mu} \qquad N_L = \frac{L}{D}$$

$$\boldsymbol{N_{Re} = f(N_T, N_L)}$$

Parameter	Range
N_T	500 – 500000
N_L	10 – 50

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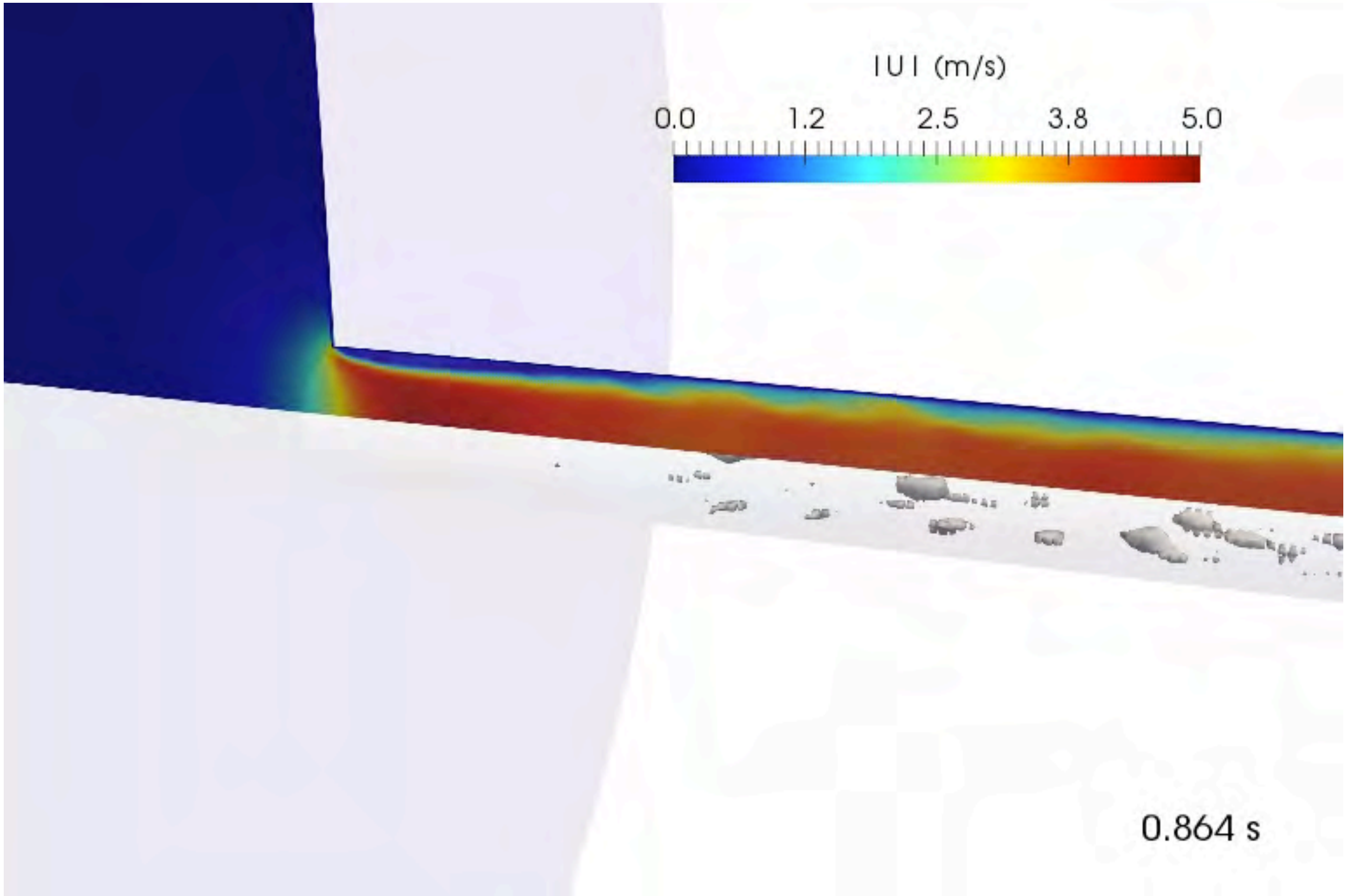
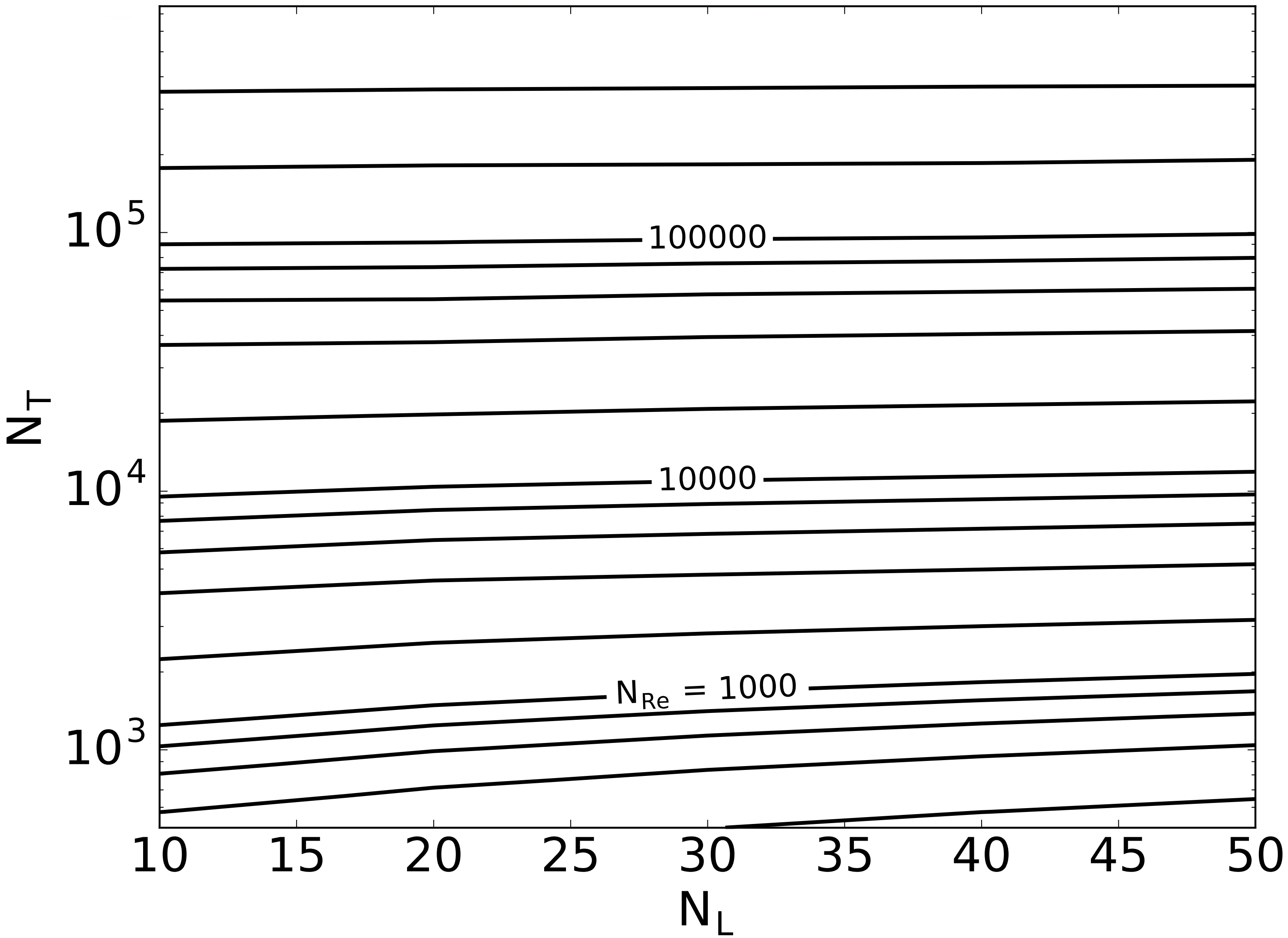
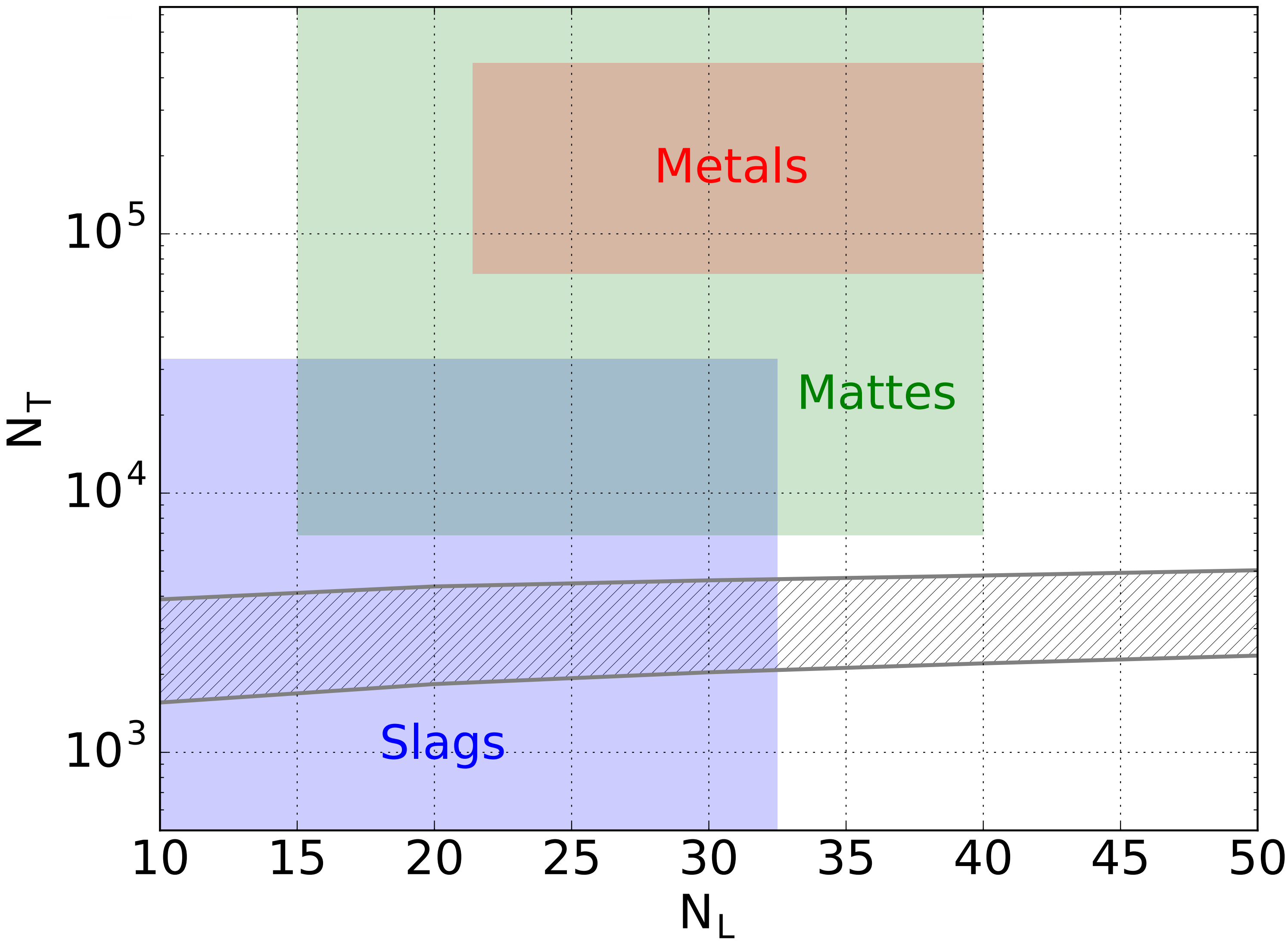


- $N_T = 5000$, $N_L = 30$
- Turbulent transition region (contour of turbulence energy k shown)

TAPHOLE MODELLING | Generalised tapholes

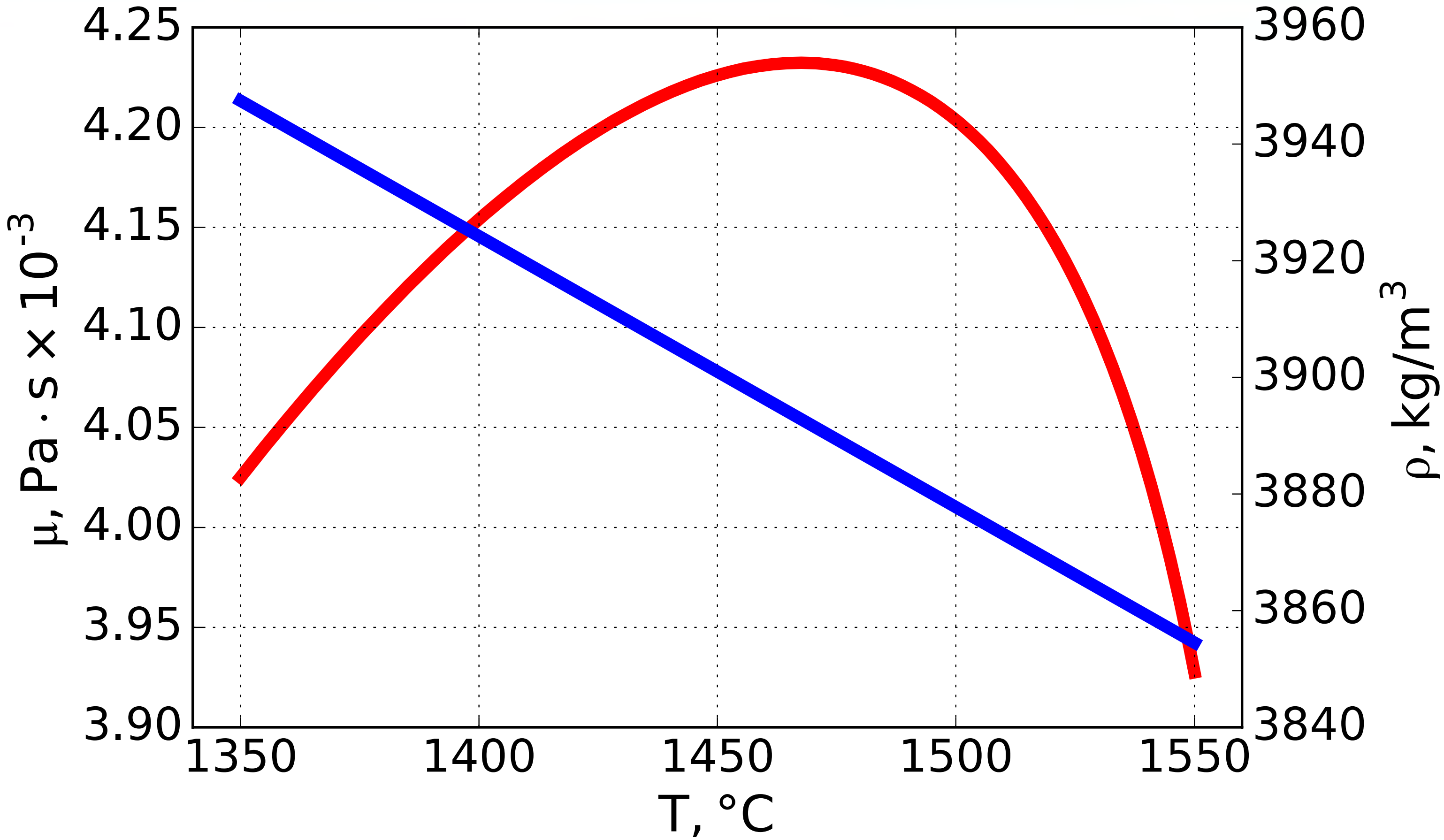


TAPHOLE MODELLING | Generalised tapholes



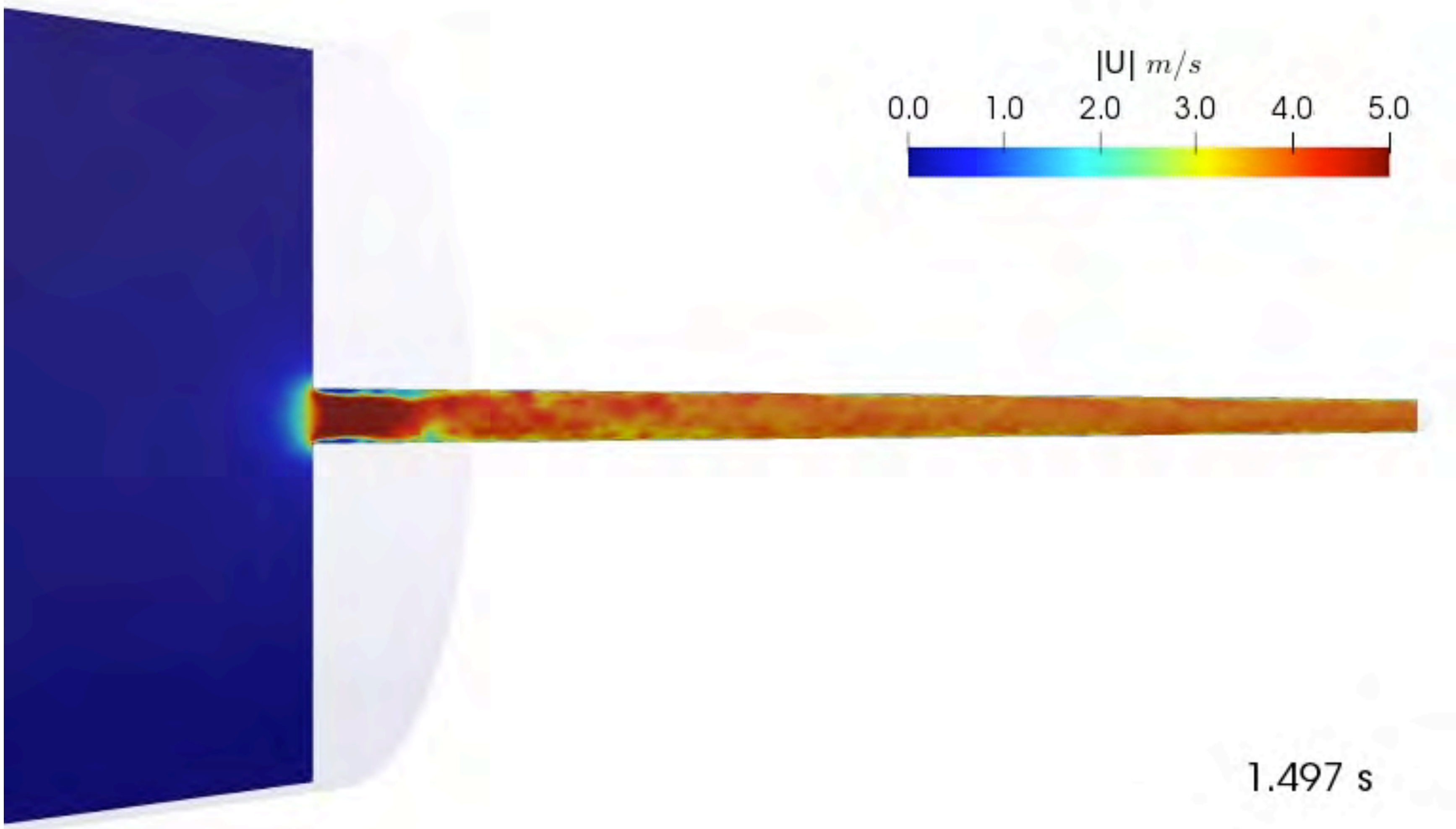
Parameter	New	Partial Repair	Worn
Matte T, °C	1350 – 1550	1350 – 1550	1350 – 1550
Head ΔP, kPa	27 – 63	27 – 63	27 – 63
Diameter, m	0.038	0.038 – 0.108	0.058 – 0.108
Length, m	1.314	1.314	1.314

- Parameters specific to matte taphole of an industrial PGM smelter
- Head pressure range determined from densities and operating heights (above taphole centreline) of matte, slag, and burden layers
- Taphole geometries obtained from taphole design dimensions and measurements during taphole dig-outs and repairs



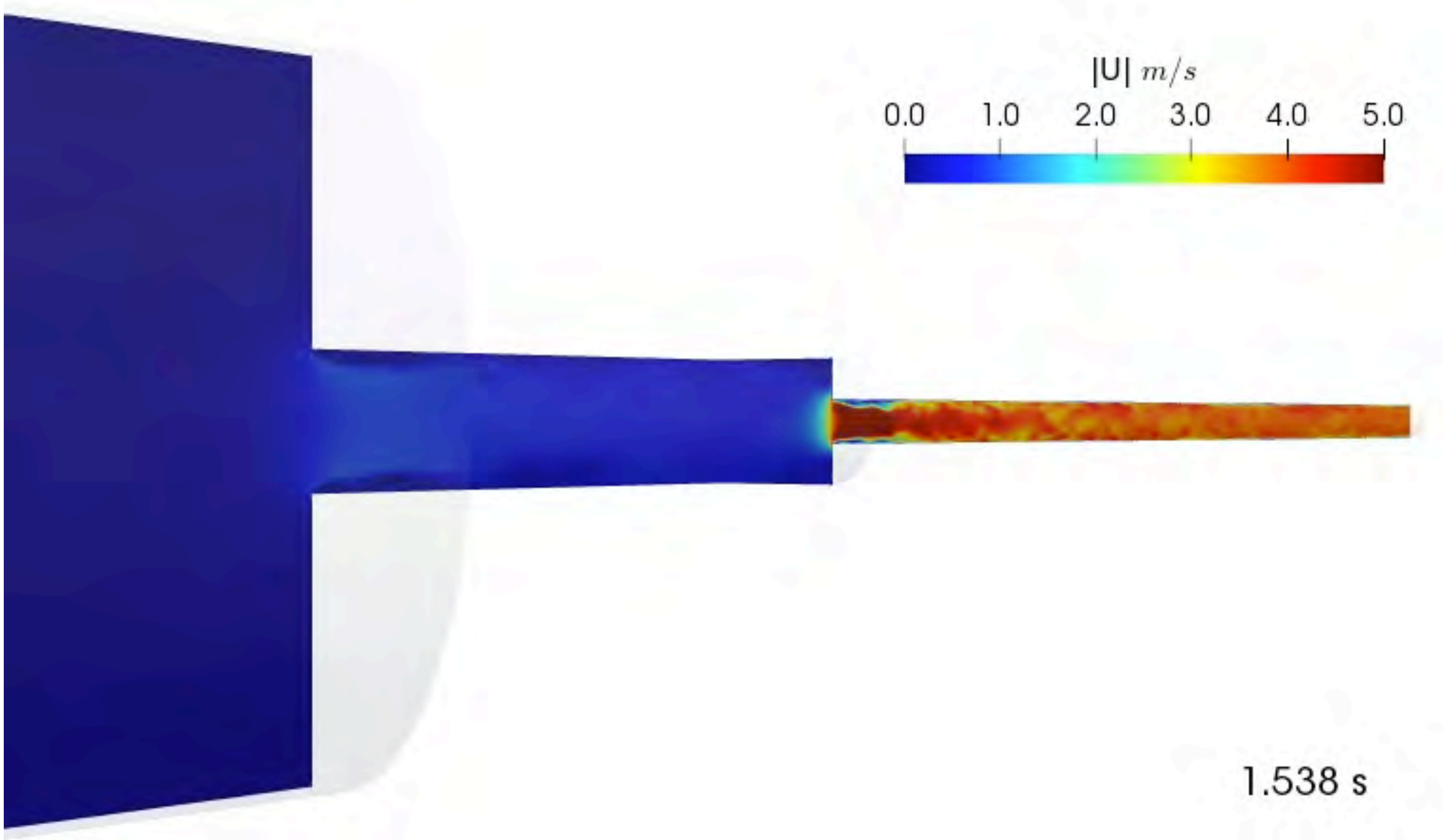
red = viscosity blue = density

64% FeS, 21% Ni_3S_2, 15% Cu_2S



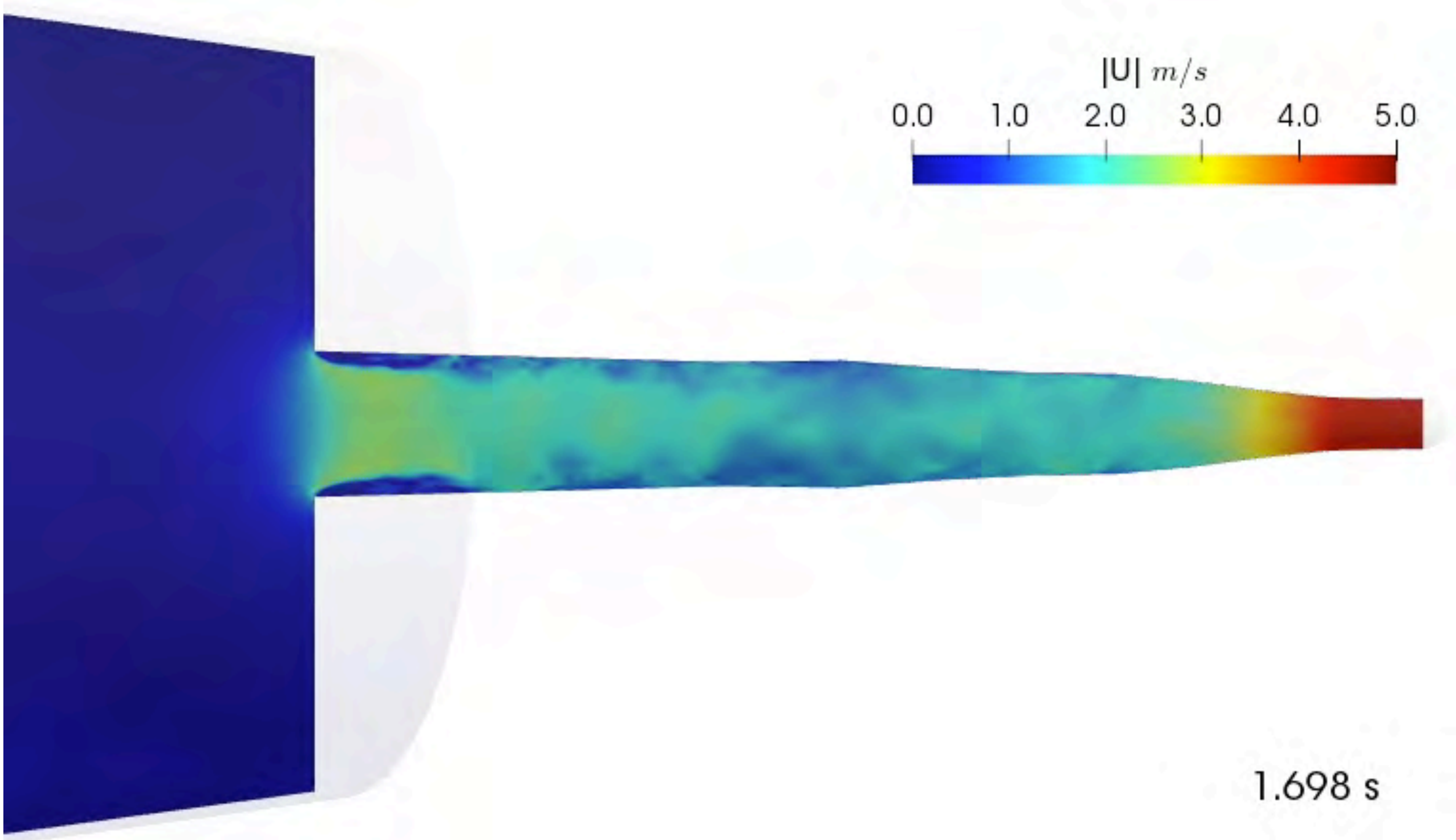
- New taphole geometry, matte velocity

TAPHOLE MODELLING | Real tapholes

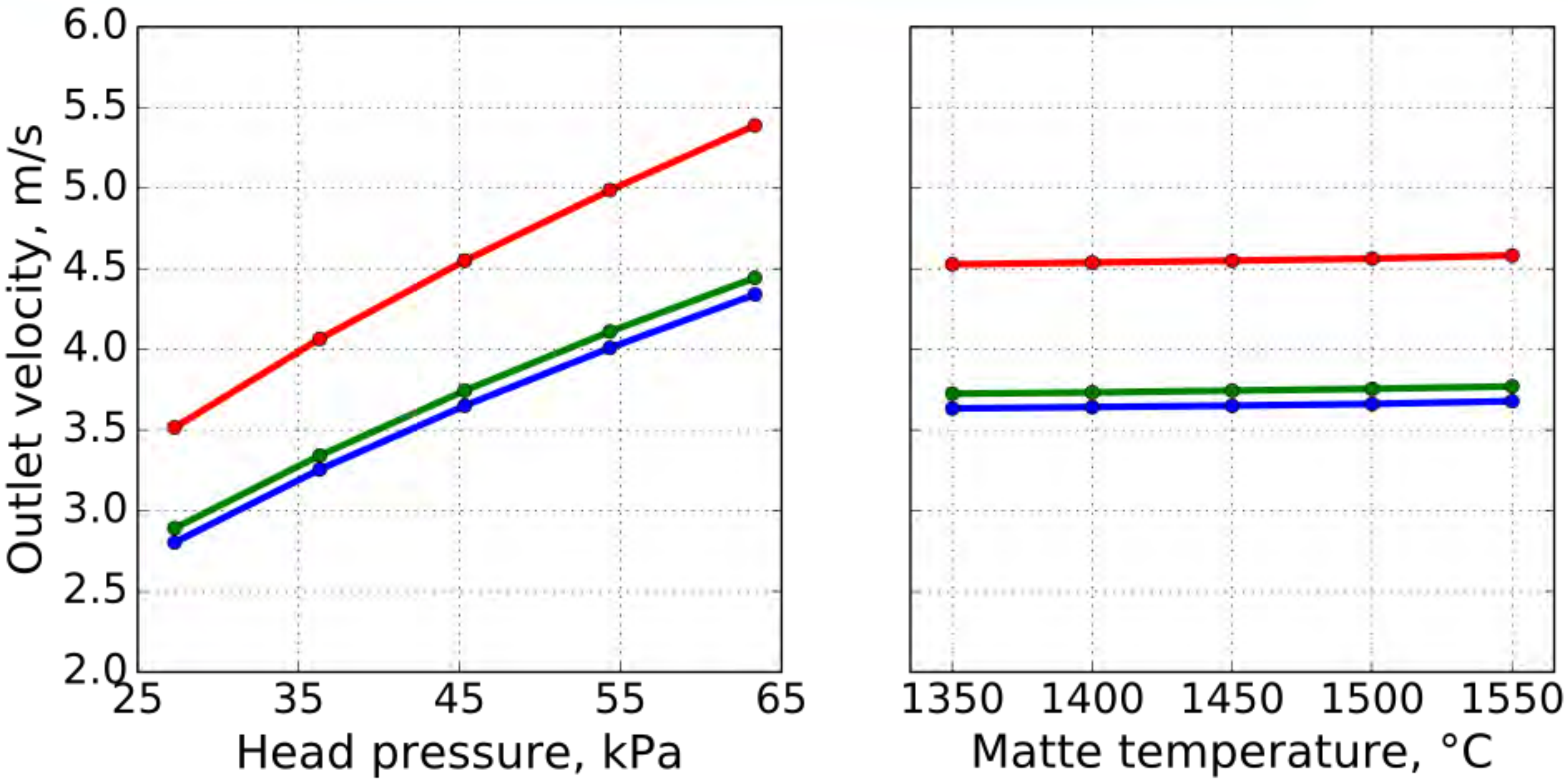


- Partially-repaired taphole geometry, matte velocity

TAPHOLE MODELLING | Real tapholes



- Worn taphole geometry, matte velocity



blue = new green = partial repair red = worn

Strong dependence on ΔP, very weak on T

- Limited industrial data on tapping flowrates available (generally only averages across whole taps, with multiple parameters varying)
- But – theory of turbulent fluid flow in pipes and channels is often used to estimate and predict taphole flow behaviour, so we can compare against that
- Bernoulli + Darcy-Weisbach:

$$\Delta P = \left(1 + K_L + \frac{f_D L}{D}\right)\frac{\rho u^2}{2}$$

- Irreversible (frictional) head loss accounted for by entrance coefficient K_L and friction factor f_D
  - $0 < K_L < 0.5$ for smooth (worn) to sharp-edged entrances
  - $0.01 < f_D < 0.02$ for circular pipe flow at Re ~ 10^5, with majority of pressure drop occurring only in narrowest sections of channel ($0 < L < 1.3$ m)

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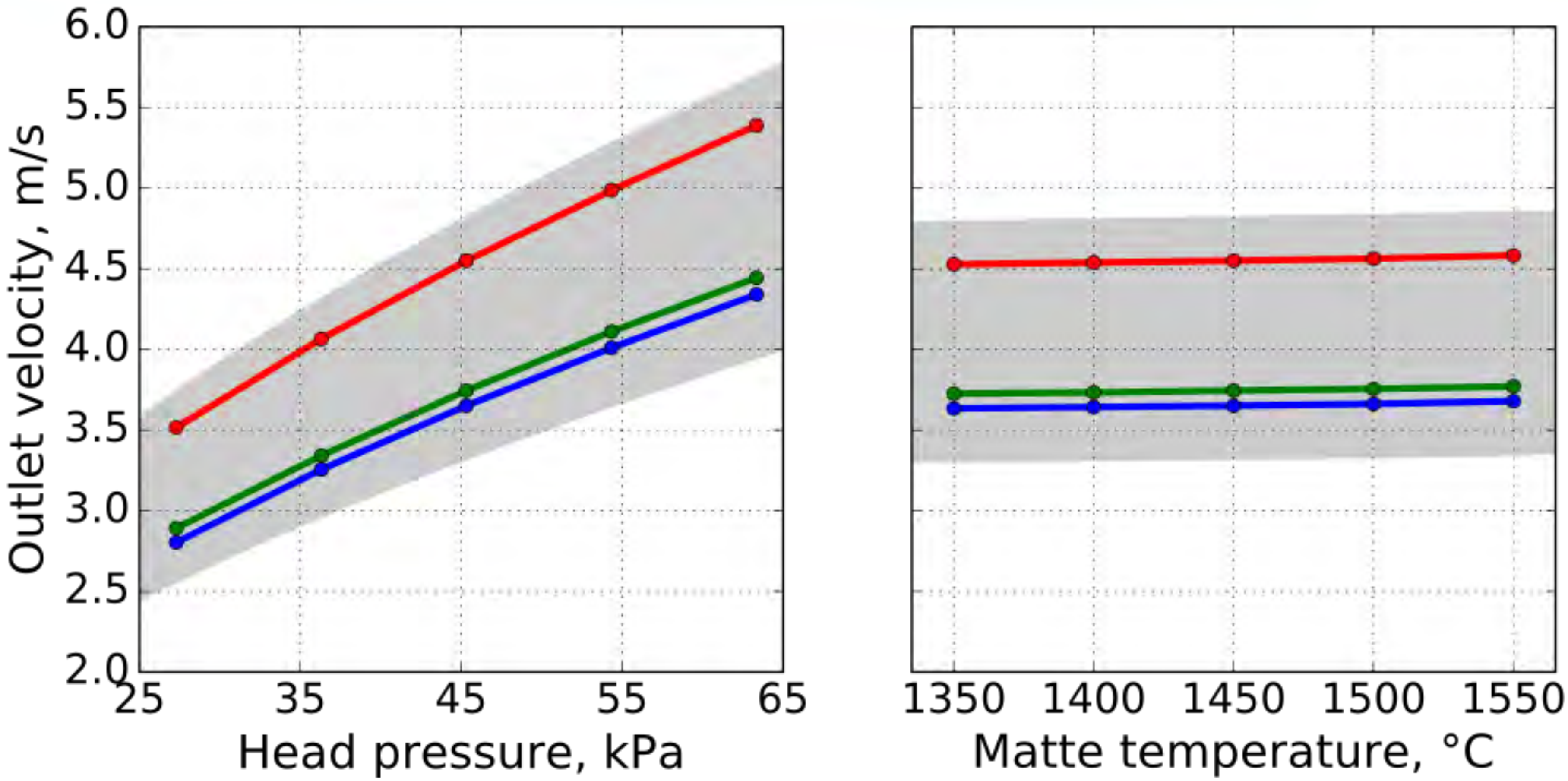

blue = new green = partial repair red = worn

Results track BDW equation ranges well

- Still in the "concept proving" phase for now, but industry interest is getting stronger…

- Active engagement in progress with multiple partners locally and internationally on data gathering and validation against a variety of taphole designs and operations
  - Accurate measurement of time-dependent tapping flowrates
  - Online and offline measurements of taphole shape and geometry, particularly wear patterns

- End result (hopefully) – evolution of the pyrometallurgy industry toward deep trust of taphole models
  - Job creation and income for computational modelling professionals
  - Better, faster, cheaper taphole designs, diagnostics, and predictive tools
  - Industry partners increasing safety and reliability, and saving $$$

CONCLUSIONS

- For highly risk-averse non-agile industries, technologies can take a very long time to be fully trusted and adopted (decades!)
  …and trust can be destroyed in an instant by over-selling and under-delivering

- You can beat the missing middle in the technology R&D pipeline if you leverage virtual design and engineering tools
  …but remember to make and work with partners in academia and industry

- Eat the elephant one bite at a time, and be clear at all times about which bite you're taking
  …if you're stuck with a complex industry problem like pyrometallurgy, don't try and solve it all in one grand unified model (yet)

- Keep your blue sky and concept proving research going
  …it will feed the commercialisation end of your pipeline when the time is right

ACKNOWLEDGEMENTS

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Thank you for your attention!

Questions?

http://www.mintek.co.za/Pyromet/Index.htm#TechnicalPapers

Reynolds, QG and Erwee, MW. Multiphase fluid flow modelling of furnace tapholes, *Proc. CFD 2017*, p 521

Reynolds, QG and Erwee, MW. Computational modelling of fluid flow through a PGM furnace matte taphole, *Platinum 2017*, (presentation only)

Reynolds, QG, Olsen, JE, Erwee, MW, and Oxtoby, OF. Phase effects in taphole flow – a computational modelling study, *Furnace Tapping 2018*, (in press)