Temperature Measurement for Better Processes to Create Better Products and Services

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Our businesses

Civil Aerospace

Defence Aerospace

Power Systems

Marine

Nuclear

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Importance of customer services

Align interests

For our customers,
their assets perform more efficiently for longer

For our business,
long-term visibility of income

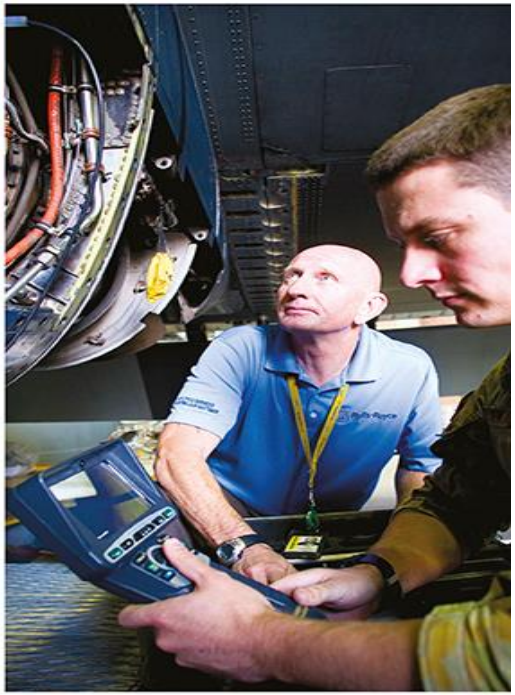
Growing installed engine base

Drives service revenues

Provides growth opportunity across the Group

Long-term service agreements

Create competitive advantage through deep connection to our customers



2016 financial data

total services revenue
£6.8bn

revenue by mix

Original equipment	Customer services
51%	49%

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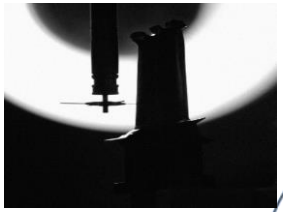
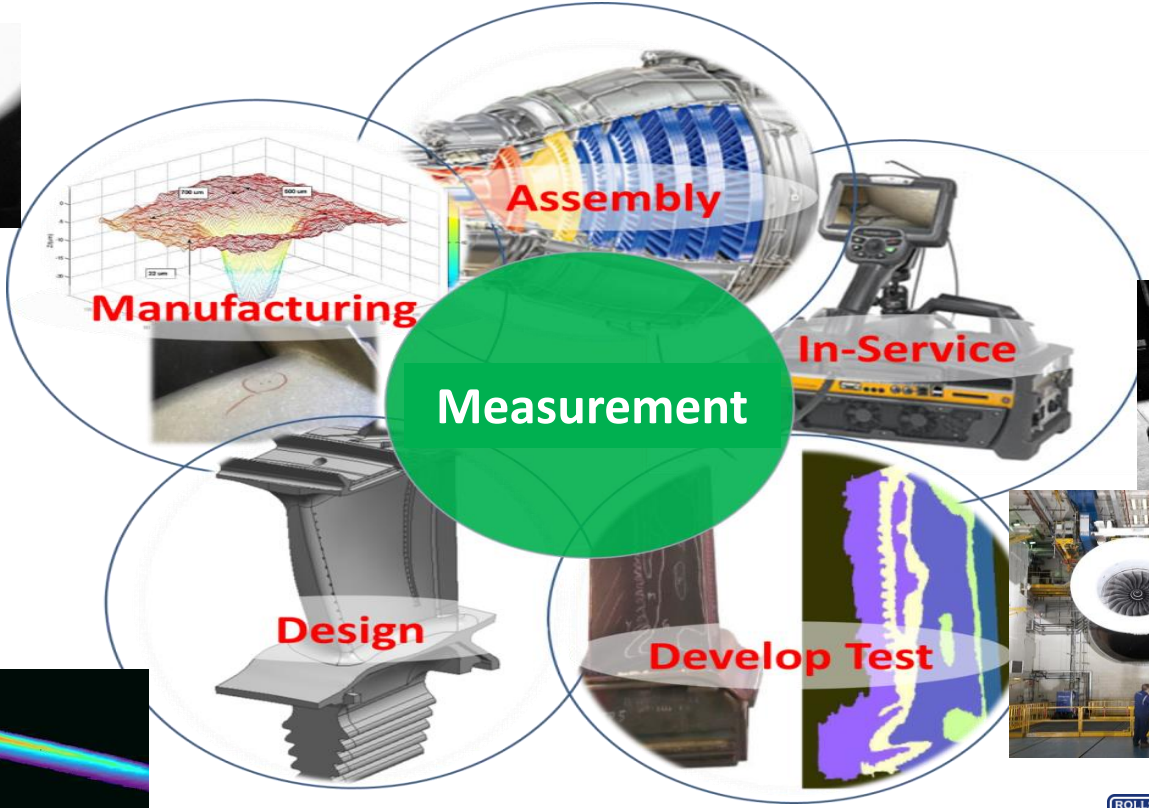
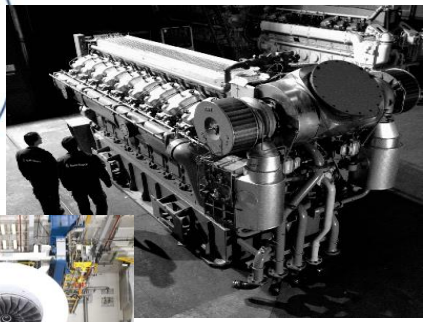
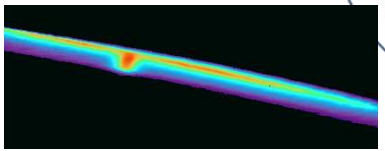
How Measurement is Used









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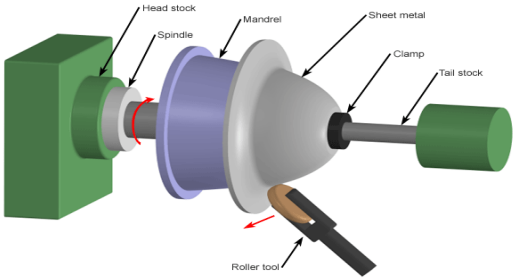
Net-Shape Cold Forming Example

Strategy and technologies

- **Near-net-shape manufacturing strategy in Rolls-Royce targeting**
  - improved buy-to-fly ratio
  - material property enhancements
- **Incremental forming technologies**
  - Typically **cold processing**
  - An optimised preform is **incrementally formed** with small contact between tooling and part
  - Large pressures at point location between tool and part generate **high localised pressure, allowing localised plasticity**
  - **Improved material properties** compared to conventional processing
- **Current technologies under development with the AFRC**
  - Cylindrical flow forming
  - Shear forming
  - Rotary Forging

Buy-to-fly drivers – improve material utilisation



Shear Forming – incremental forming

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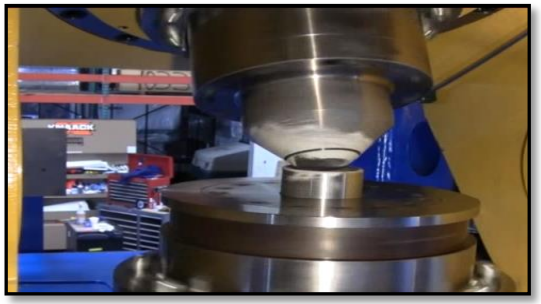
Net-Shape Cold Forming

Process advantages

- **Incremental forming technologies – advantages**
  - Force and power are a fraction of that for conventional forging
  - Uniform quality / reduced variability
  - Final product surface finish possible without machining
  - Improved properties from cold working
  - Close to size forming
  - Reduced processing noise and vibration

Flow Forming - cylindrical components

Shear forming - conical components



Rotary forging – flange and cones

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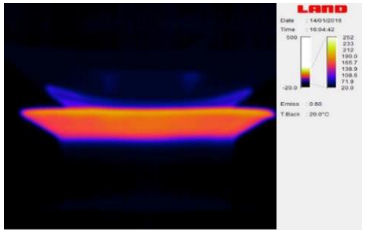
Net-Shape Cold Forming

Processing Challenges

- **Process Challenges**
  - Complex process mechanics
  - Localised metallurgical and mechanical properties
  - Residual stress control
  - Complex tooling and workpiece interactions
  - Very challenging to process model



- **Temperature measurement?**
  - Limited understanding of process temperature– rates and values
  - Line of sight access to tooling-part contact difficult
  - Multiple rotating parts and tooling hamper access
  - Typically forced coolant is used, blocking access to region of interest
  - Thermal cameras have been used - some success, but limited validation

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Net-Shape Cold Forming

Routes to market

- Industrial exploitation of these processes needs **improved understanding of product of process** against the design requirement

- **Validate near surface temperature measurement techniques are needed** to help with validation of our process models

- **Temperature of work-piece will be a key processing characteristic** – but very limited experience so far in detecting this

- **Final mechanical properties** for incremental formed parts likely to have **direct correlation with forming temperature**

Unlocking understanding of the near surface temperature for incremental technologies is an important characteristic of the process that will help with the **route to market for these technologies**

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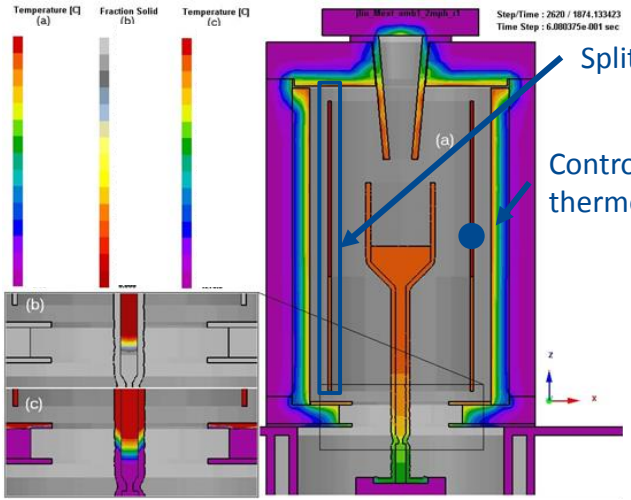
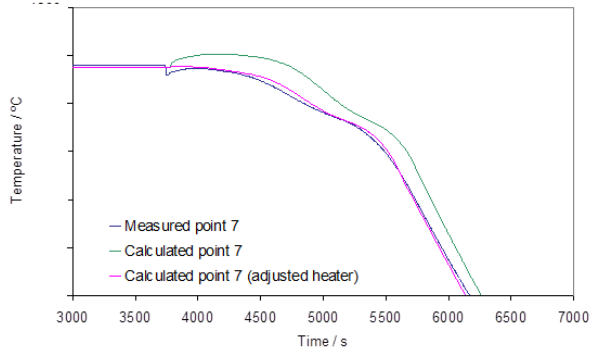
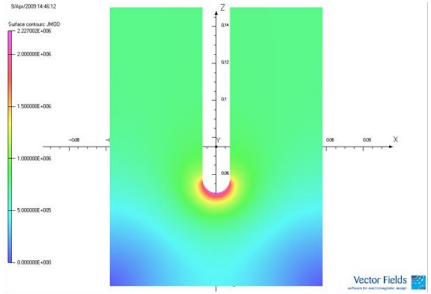
Casting Example



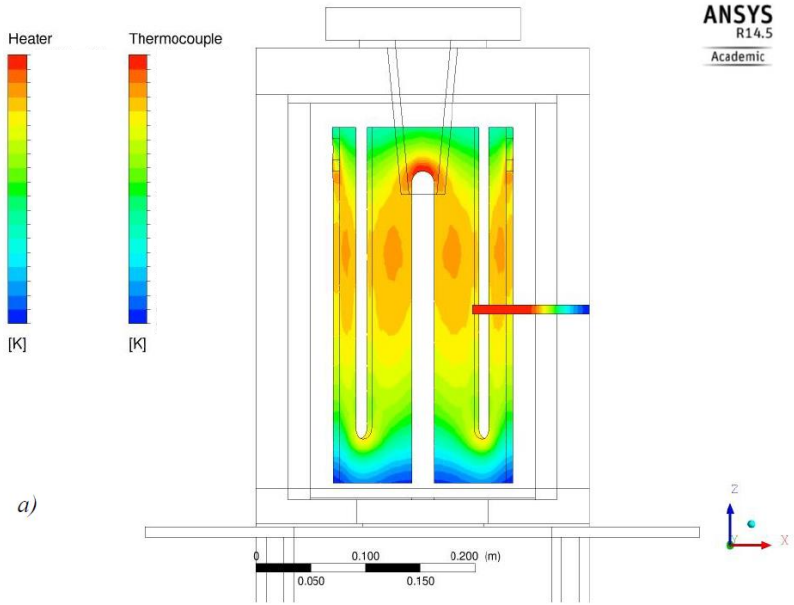


- Instrumentation can only show us so much of the condition of a physical system
A perfect sensor does not deliver a perfect measurement
-Setting the boundary conditions using the controlling thermocouple unsuccessful.
Revising the boundary condition gave good across many measurements
-The source of the error is the temperature distributions driven by heater non-uniform performance



Source: Newell M. 2009, The University of Birmingham

Set point 1923.15K



Set point 1823.15K

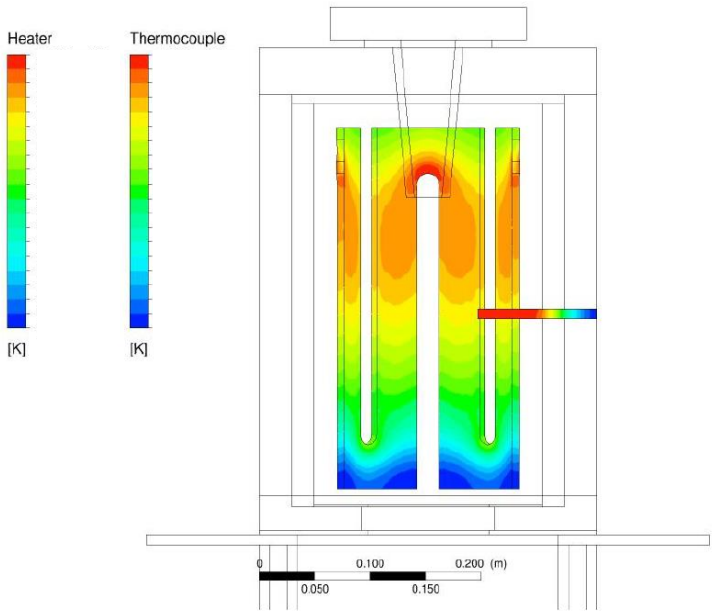


Figure 5-33: CFX model of Bridgman furnace incorporating single layer radiation baffle with 110 x 10^{-3} m diameter cut-out heated to a set hot zone temperature of 1823.15 K. Contour plots show heating element surface temperature and control thermocouple surface temperature.

Control thermocouple at set point the temperature
Distribution in resistance heater changed substantially between set-points.
By accurately measuring the potential across the heater the temperature field in the furnace was calculated

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Source: Dale S. 2014, The University of Birmingham

The next Paradigm Shift

Process Design:

- Deterministic Simulations
- Measurements for Boundary Conditions + Validate Key Process Parameters

Process Control:

- Direct measurement of Key Process Parameters + Control Laws

Process Design:

- Probabilistic Simulations
- Measurements of accessible parameters to reduce uncertainty

+ We always know what accuracy is worth!

Process Control:

- Simulation fed by optimised set of measured inputs

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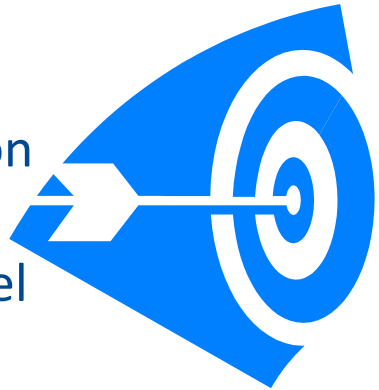
For Example

- Current flow or acoustic propagation through the Material during formation incorporated into simulation
- Attenuation / resistance/ dispersion / time of flight Across the path measured & compared with the model
- Iteration to achieve alignment.



Requires:

- Modellers
- Measurement Engineers
- Real Processes

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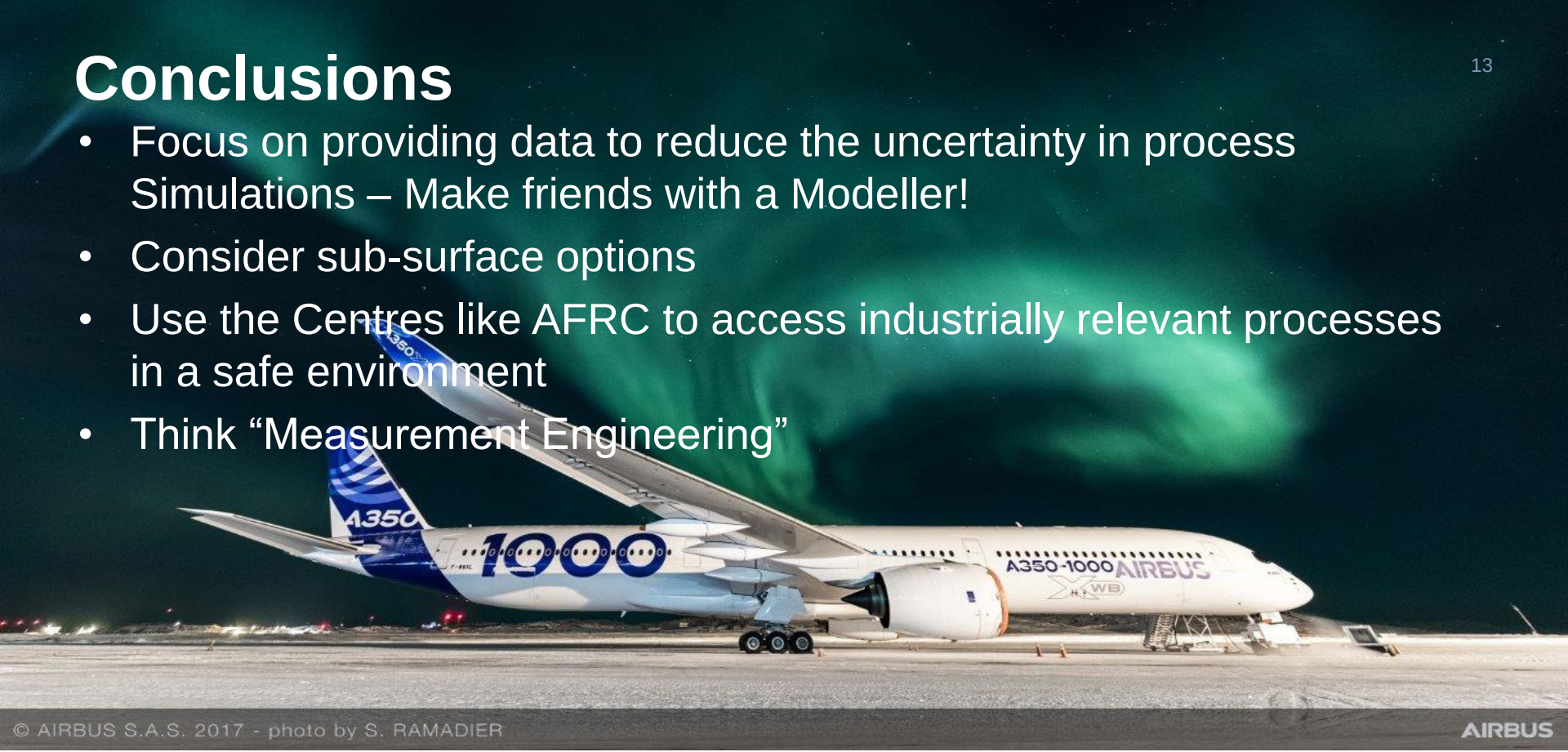
Conclusions

- Focus on providing data to reduce the uncertainty in process Simulations – Make friends with a Modeller!
- Consider sub-surface options
- Use the Centres like AFRC to access industrially relevant processes in a safe environment
- Think “Measurement Engineering”



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