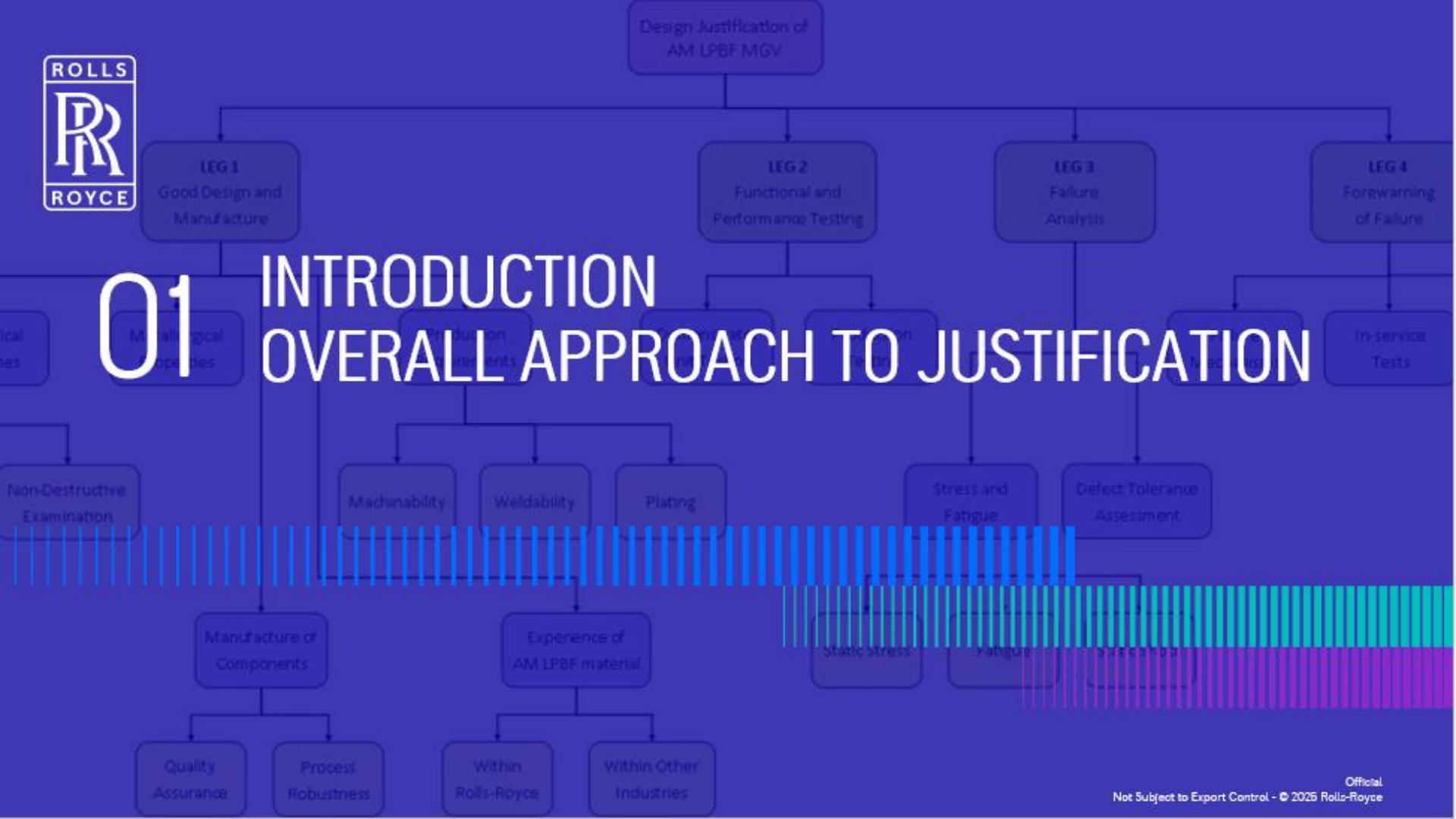
JUSTIFICATION APPROACH AND CODIFICATION OF ADVANCED MANUFACTURING TECHNIQUES FOR NUCLEAR FISSION PLANT COMPONENTS

(IAEA TECHNICAL MEETING ON EXPERIENCES IN CODES AND STANDARDS FOR FUSION TECHNOLOGY – VIENNA 18TH-21ST NOVEMBER 2025)

CONTENT

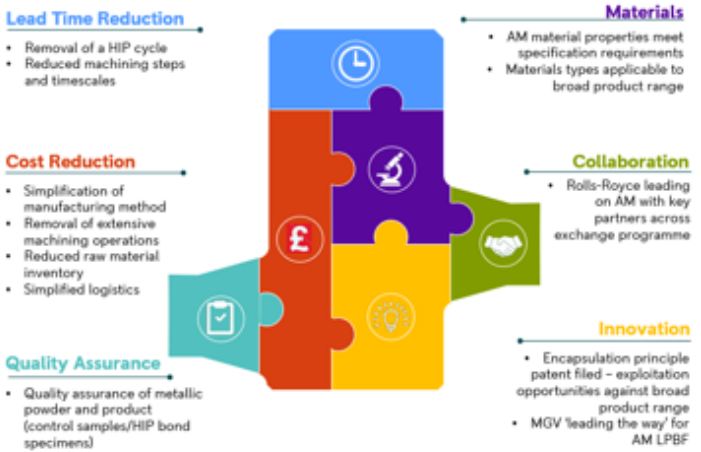


01 INTRODUCTION
OVERALL APPROACH TO JUSTIFICATION

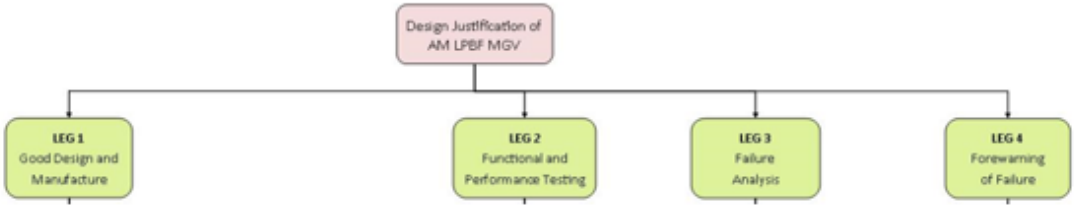
- When Rolls-Royce was looking to introduce new manufacturing technologies of Hot Isostatic Pressing (HIP) and AM Laser Powder Bed Fusion, there were no specific nuclear codes and standards for these technologies.

- There is the need to meet the requirement of '***Proven Technology***' in the nuclear industry.

How do you justify the application of a new manufacturing technology in the Nuclear Industry?



- Rolls-Royce used the UK TAGSI **4 Legged** approach, primarily developed for providing a **Structural Integrity (SI)** justification for '***Incredibility of Failure (IOF)***' components, i.e. the need to demonstrate an extremely high level of reliability, e.g. components such as the RPV.



- The approach isn't just for providing a SI justification of IOF components (TAGSI recognises that). It can be used for lower classification components.

- Although developed for providing a SI justification, i.e. not specifically developed to justify new manufacturing processes, Rolls-Royce considered it to provide a usable framework.

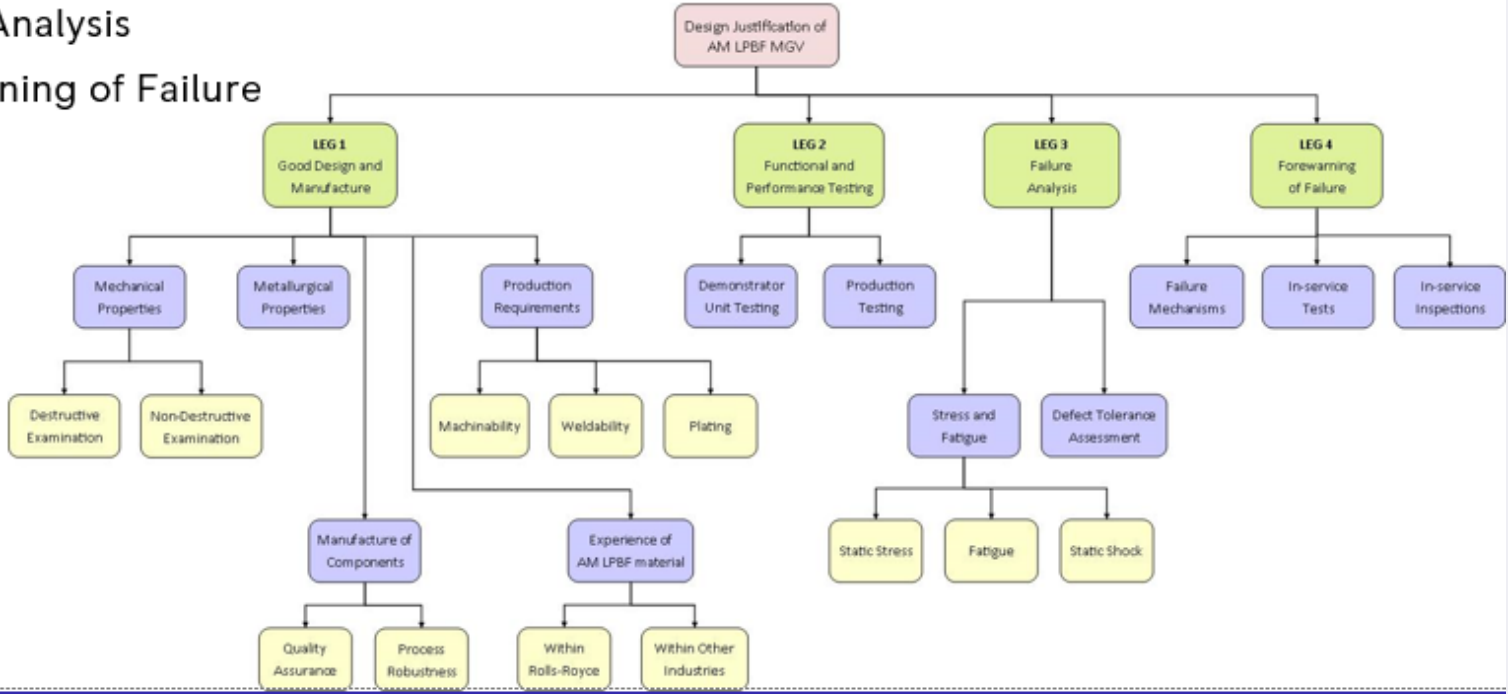
- Four independent legs:

  Leg 1 – Good Design & Manufacture

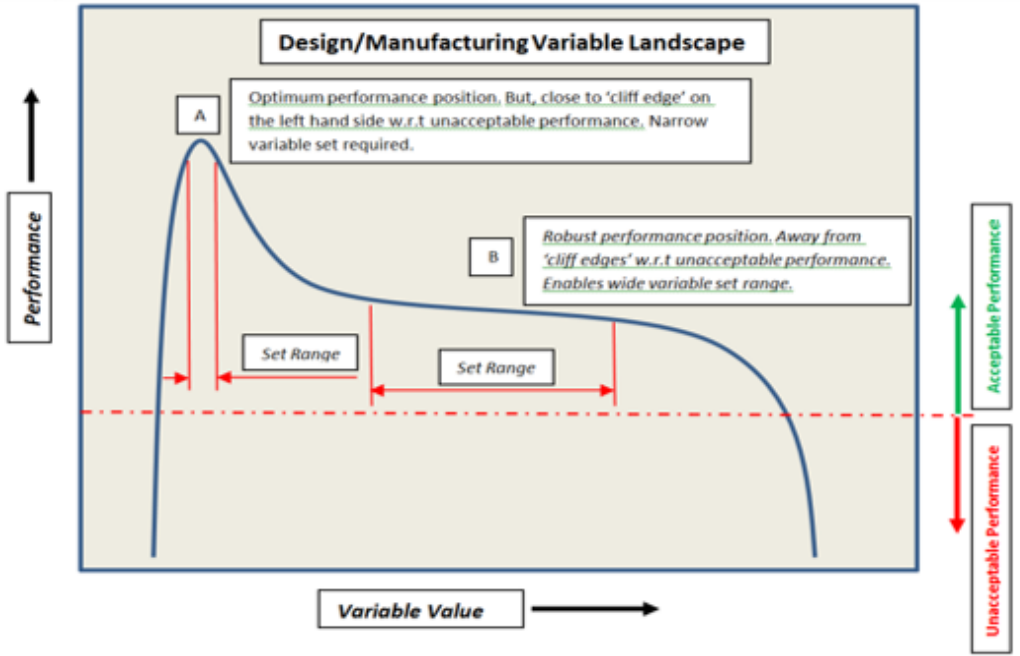
  Leg 2 – Functional & Performance Testing

  Leg 3 – Failure Analysis

  Leg 4 – Forewarning of Failure



- Overall objective is to establish a **'Robust'** Method of Manufacture (MoM) –, not necessarily an '**Optimum'** MoM.
- Having a thorough understanding of variability in the manufacturing process – **Process** Failure Modes & Effects Analysis (PFMEA).
- Ensuring risks are appropriately mitigated.



02 USE OF THE ASME CODE

- Rolls-Royce uses the ASME Section III – Rules for **Construction** of Nuclear Facility Components.

- **Construction:** Material, Design, Fabrication, Examination, Testing, Overpressure Protection.

- All components to ASME Section III – **Division 1.**

  Notes.

  a. Not Division 5 – High Temperature Reactors.

  b. Division 4 – Fusion-Energy Related Components.

Section III has five divisions:

Division 1: *Metallic vessels, heat exchangers, storage tanks, piping systems, pumps, valves, core support structures, supports, and similar items.*

Division 2: *Concrete containment vessels.*

Division 3: *Metallic containment systems for storage or transportation of spent fuel and high level radioactive materials and waste.*

Division 4: *Fusion energy related components such as vacuum vessel…….*

Division 5: *As division 1, plus graphite and composite core components and assemblies for High Temperature Reactors.*

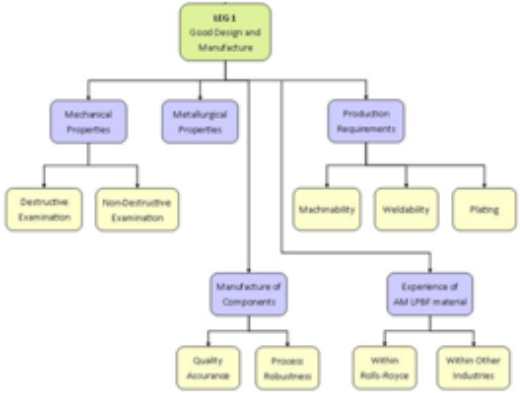
Leg 1 – Good Design & Manufacture

- Design in accordance with the ASME code, e.g. subsections NB, NCD – design rules, NCA (e.g. specification/design report requirements, specifying loading conditions).

- General manufacture/quality assurance in accordance with the ASME code, e.g. NQA, NCA (e.g. material sourcing, control of suppliers, records, inspection, audits).

- Justifying new materials – properties – use of Section II Part D – Mandatory Appendix 5 – Guidelines on the Approval of New Materials Under the ASME Boiler and Pressure Vessel Code.

- Examination requirements.



- Material property data obtained by Rolls-Royce to support Rolls-Royce's justification was subsequently incorporated into ASME Section III code cases and guidance documents.

November 3, 2011

Attachment 2

Powder Metallurgy/Hot Isostatic Processing (PM/HIP)

Table of Contents

CASE
N-834

Approval Date: October 22, 2013

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case N-834
ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components
Section III, Division 1

Inquiry: May ASTM A988/A988M-11 UNS S31603 be used for Section III, Division 1, Subsection NB, Class 1 Components construction?

Reply: It is the opinion of the Committee that, ASTM A988/A988M-11 UNS S31603 may be used for Section III, Division 1, Subsection NB, Class 1 Components in construction provided the following additional requirements are met:

(a) For purposes of welding procedure and performance qualification, this material shall be considered P-No. 8.

(b) The design stress intensity values and the maximum allowable stress values, fatigue design curves, tensile strength and yield strength values, thermal expansion and other properties shall be the same as for SA-240 UNS S31603.

(c) The maximum allowable powder particle size shall be 0.020 in. (0.5 mm) or less.

(d) Following atomization, powders shall be stored under a positive nitrogen or argon atmosphere.

(e) An 8 in. (200 mm) or longer protrusion (extension) shall be added to one end of each item that equals or exceeds the thickest section of that item. The protrusion shall be removed upon completion of isostatic pressing and heat treatment of the item and shall be used for microstructural characterization, density measurements, chemical testing, mechanical testing, and intergranular corrosion testing as required below:

(1) Density measurements and microstructural examination shall be performed at the midsection of coupons removed from the protrusion in accordance with ASTM A988/A988M-11 paras. 8.1.1 and 8.1.2.

(2) In addition to a chemical composition analysis of the final blend powder, an analysis of a sample from each component shall be required.

(3) Intergranular corrosion tests shall be performed using test coupons removed from the protrusion in accordance with ASTM A262 Practice E.

(4) Mechanical property tests, including tension tests and hardness tests, shall be performed using test coupons removed from the protrusion in accordance with ASTM A988/A988M-11, Section 9, Mechanical Properties.

(f) The material shall be examined using the ultrasonic examination method in accordance with NB-2540 over 100% of its entire volume using both straight and angle beam methods. Items that are produced in the form of tubular products shall be examined in accordance with NB-2550.

(g) The material shall not be used for components where the neutron irradiation fluence levels will exceed 1×10^{17} n/cm^2 (E > 1 Mev) within the design life of the component.

(h) Following final hot isostatic-pressing, all surfaces exposed to the process fluid shall be removed by machining or grinding to a depth of 0.008 in. (0.2 mm) or greater. Final accessible surfaces shall be examined by the liquid penetrant method in accordance with NB-2576.

(i) All other requirements of NB-2000 for austenitic materials shall apply.

(j) This Case number shall be marked on the material and listed on the Certified Material Test Report and on the Component Data Report.

Leg 2 – Functional & Performance Testing

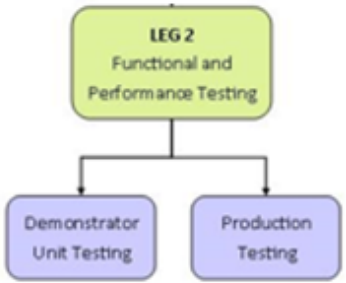
- Cyclic load testing, particularly thermal fatigue, in accordance Appendix II – Experimental Stress Analysis.

- Failure defined as the propagation of a through-wall crack such that a leak would occur.

- Requirement to conduct more cycles by a factor than what will be seen in-service :

  Factors account for effects of size, surface finish, cyclic rate, temperature, statistical variation (number of replicate tests).

  Never less than x1.25, can be approach x5 (i.e. with a one off test).



Leg 3 – Failure Analysis

- Analysis in accordance with the code, e.g. NB3200 – Design by Analysis.

- Protects against:

  Ductile burst.

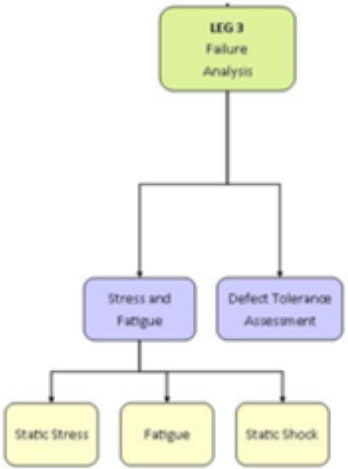
  Gross plastic deformation (large portion of a component).

  Excessive plastic deformation (in a local area, e.g. a discontinuity/transition).

  Fatigue.

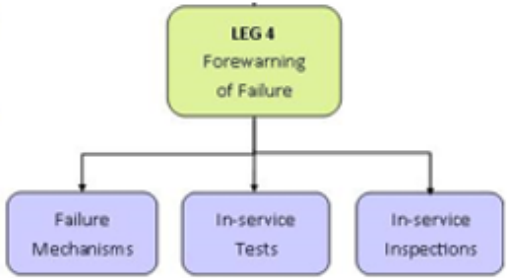
  Non-Ductile Fracture.

  Environmental Effects (just corrosion allowance).



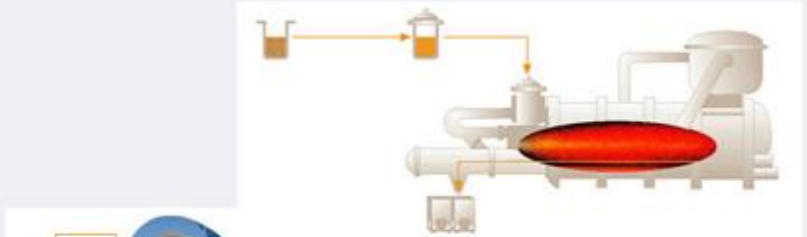
Leg 4 – Forewarning of Failure

- ASME Section XI – In-Service Inspection



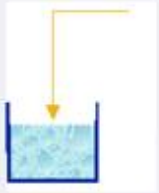
03 HOT ISOSTATIC PRESSING (HIP)

1.Inert gas atomisation to produce powder.



2.Sheet metal capsules filled with powder.

3.Capsules subjected to high isostatic pressure and high temperature to obtain full density.



4.Can pickled or machined off.

- **Project Benefits:**
  - Lead-Time Reduction
    - No tooling development required, thin-can encapsulation - welding of mild steel
  - Cost Reduction
    - Scrap/re-work elimination
    - Material quantity - closer to final shape
    - Machining reduction - closer to final shape

- **Product Benefits:**
  - Material Quality Improvements
    - Cleaner material, no aligned inclusions
    - Homogeneous
    - Isotropic
    - Improved properties can be achieved due to smaller grain size
    - Smaller defect sizes (sieving size)

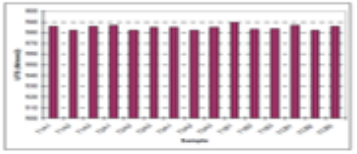
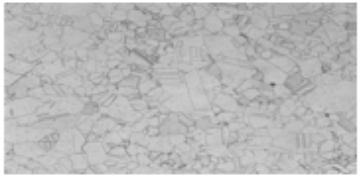
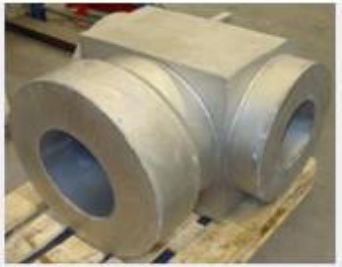
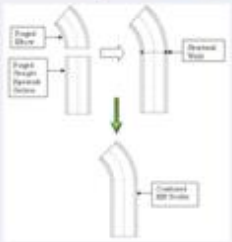


Fig. 4 Tensile Test Results (UTS).



  - Non-Destructive Examination Improvement – Sensitivity increase due to:
    - Homogeneous material structure
    - Finer grain size





Previous work

- Proof of concept
- HIPed test pieces
- Powder filling process

PROJECT FAST (2019-2021)

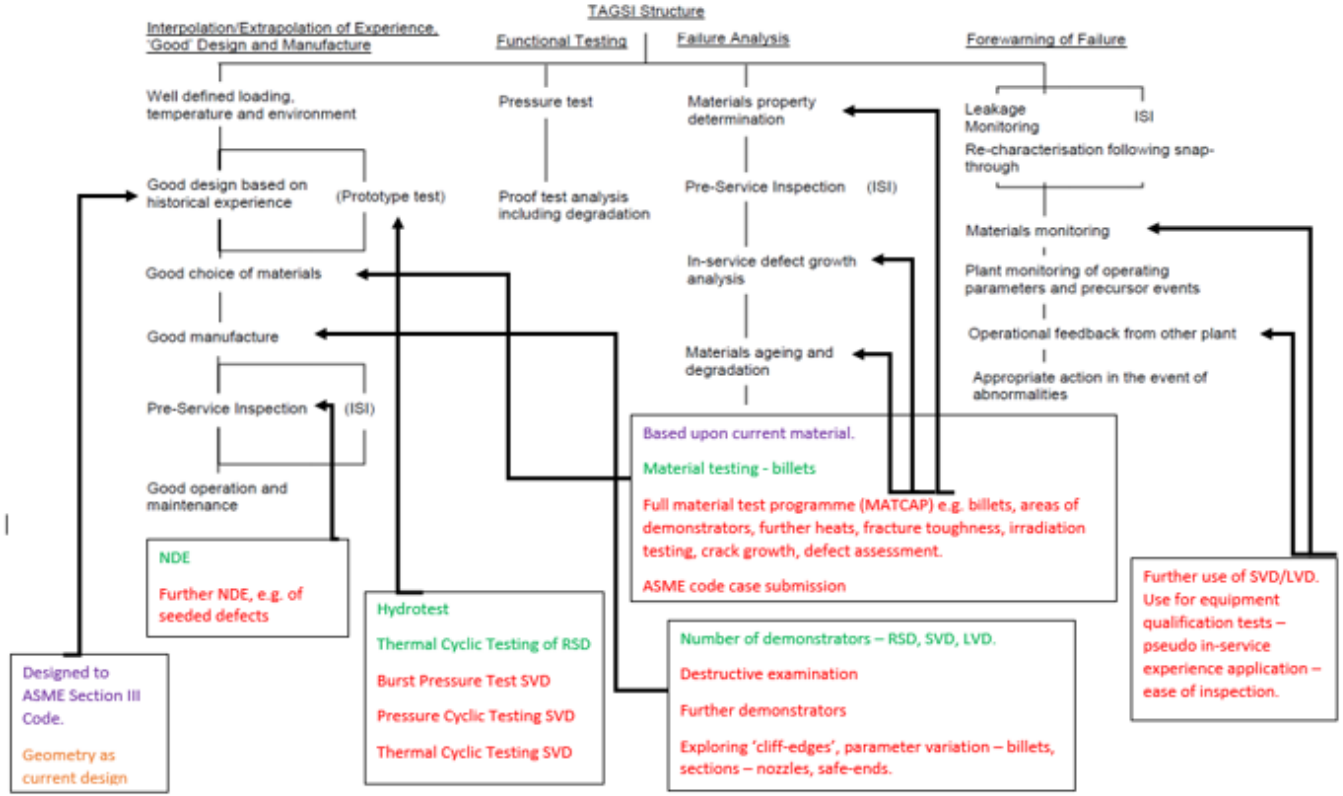
- TSEBW for HIPed SA508
- Manufacture of a Small Vessel Demonstrator (SVD) and hydrostatic testing
- Manufacture of two Large Vessel Demonstrator (LVD) sections
- Manufacture of a Ring Section Demonstrator (RSD) and thermal cyclic testing

Department for Business, Energy & Industrial Strategy

2021+

- Pressure & thermal cyclic testing
- Completed LVD for UK component qualification testing
- Full material property testing programme
- ASME code case submission

2018 2019 2020 2021



- Approach:

  Demonstrator units produced for each application.

  Dimensionally inspected to show geometry can be achieved.

  NDE examination and destructive examination. Units cut up for material microstructural assessment and property testing.

  Near Nett Shape? Some benefits, but design for inspectability was key consideration.

- Approach:

  Independent industry survey.

  Incremental approach:

  - Non-Pressure Boundary
  - Pressure Boundary – Leak Limited
  - Pressure Boundary – Isolable
  - Pressure Boundary - Unisolable

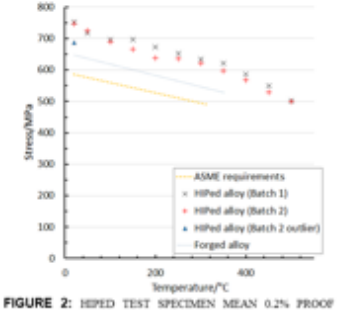


FIGURE 2: HIPED TEST SPECIMEN MEAN 0.2% PROOF STRESS VALUES VERSUS FORGED MATERIAL

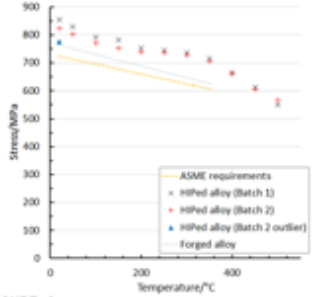


FIGURE 3: HIPED TEST SPECIMEN MEAN ULTIMATE TENSILE STRENOTH VERSUS FORGED MATERIAL

Material equivalence striven for.

		Material Specification	HIP 304LE Cylinder	HIP 304LE Body	Wrought Casts
0.2% Proof Stress		207 MPa	274 MPa	300 MPa	267 MPa
Ultimate Tensile Strength		517 MPa	625 MPa	628 MPa	589 MPa
Elongation %	Longitudinal	40	73	68	65
	Transverse	30			

- Understanding the MoM:

  Defect/risk assessments.

  Mitigating quality control measures.

'The Devil is in the Detail, but so is Salvation'

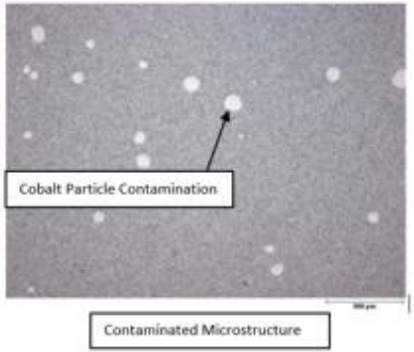
Rolls-Royce

ICONE24-61106
HIPED HARD FACINGS FOR NUCLEAR APPLICATIONS – MATERIALS, KEY POTENTIAL DEFECTS AND MITIGATING QUALITY CONTROL MEASURES

Presented by
Eur Ing J Sulley - *Chief of Engineering Capability*
Co-Author
Dr D Stewart – Technical Specialist

Reference:
ICONE24-61106, 2016 [2]

- **Potential Defects and Mitigating Quality Controls:**
  - **Metallic Inclusions**
  - **Non-Metallic Inclusions – Refractory Materials**
  - **Non-Metallic Inclusions – Melt Oxides**
  - **Porosity**
  - **Grain Growth**
  - **Oxide Formation**
  - **Contamination from Chemical Species**



Contaminated Microstructure

Metallic Inclusions Cause and Mitigation

39

Exclude elemental cleansing 'washes', e.g. 'cobalt' wash.	**If an elemental wash is conducted, any remnant powder may be drawn through in the subsequent material atomisation run.**
Schedule the material production run to follow the exact same material or material family of another order.	Any remnant material from a previous production run will not be adversely different to the material run.
Sacrificial run conducted of the actual material prior to the production run proper.	Any remnant material from previous production runs/washes is most likely to be drawn through in the first quantity of material.
The whole, or specific operations (e.g. sieving), of the production process to be dedicated to a specific material family type.	Any remnant material from a previous production run will not be adversely different to the material run.
Robust clean down of all the equipment.	To remove any remnant material from previous production runs.
The design of the atomiser and sieve to be such that it eliminates/reduces areas where powder can accumulate.	To reduce the risk of remnant material from previous production runs becoming dragged through with the production material.
Examination of a HIPed specimen looking for metallic inclusions.	This is the key mitigating control measure to ensure unacceptable powder is not applied to product.

- Specifications/Standards for key MoM steps.

Rolls-Royce

POWDER MANUFACTURE BY GAS ATOMISATION 2.0

Rolls-Royce

CONSOLIDATION BY HOT ISOSTATIC PRESSING 4.0

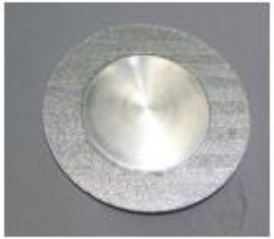
Rolls-Royce	**MATERIAL SPECIFICATION**	**RRMS**
		Version 3.0
		Date 05 AUG 2021
Acceptance Test Requirements for Metallic Powder and Powder Based Product		

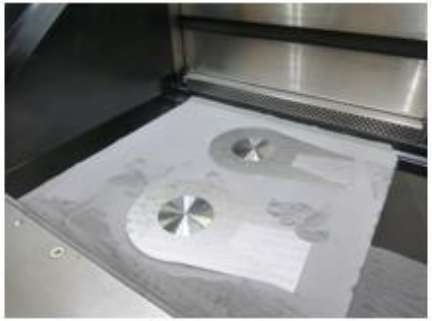
- Walk the process to identify risks.

- Help Suppliers develop robust procedures, e.g. equipment clean down.

04 ADDITIVE MANUFACTURE - LASER POWDER BED FUSION - GLOBE VALVE

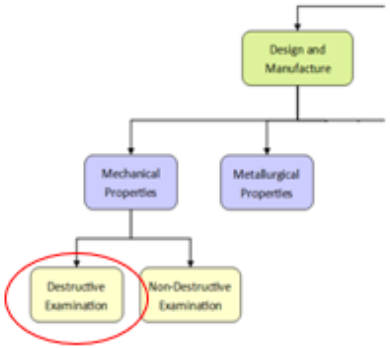
- Safety Critical component.





Leg 1 Good Design & Manufacture

Mechanical Testing

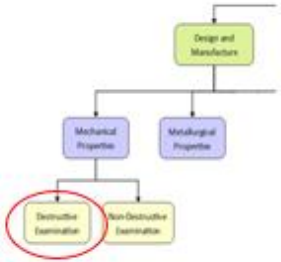


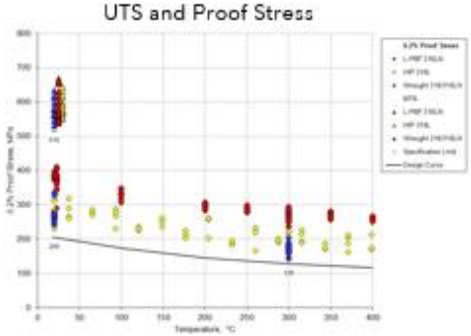
Summary of Mechanical Testing

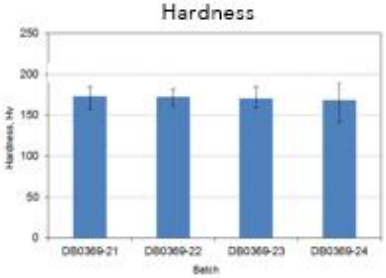
Test Description	Test Method	316LN	Tristelle 5183
Tensile Tests (Ambient & Elevated Temps')	ASTM E8, ASTM E21	✓	✓
Charpy Impact Tests (Ambient & Elevated Temps')	ASTM E23	✓	✓
Hardness Tests	ASTM E92	✓	✓
Elastic Modulus Test (Ambient & Elevated Temps')	ASTM E1876	✓	✓
Thermal Expansion Test (Ambient & Elevated Temps')	ASTM E228	✓	✓
Thermal Diffusivity Tests (Ambient & Elevated Temps')	ASTM E2585	✓	✓
Specific Heat Capacity (Ambient & Elevated Temps')	ASTM E1269	✓	✓
Fatigue Endurance – In-air (Ambient & Elevated Temps')	ASTM E606	✓	✓
Fatigue Endurance – In-de-oxygenated Water (Elevated Temps')	ASTM E606 (spirit of)	✓	N/A
Fatigue Crack Growth Tests – In de-oxygenated Water	ASTM E647	✓	N/A
Fracture Toughness Tests (Elevated Temps')	ASTM E1820	✓	N/A

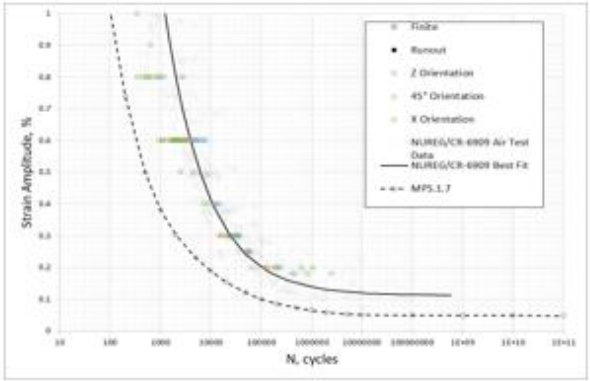
Leg 1 Good Design & Manufacture

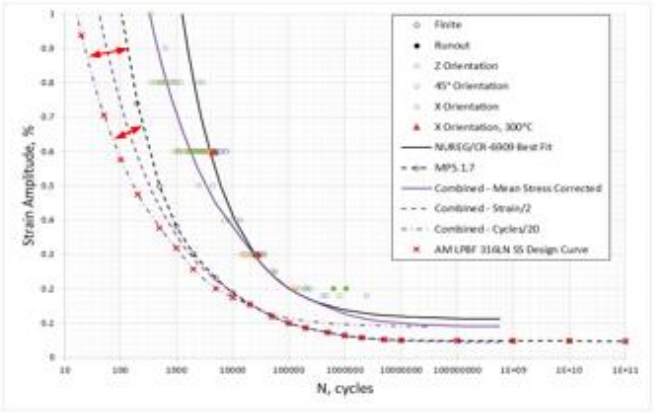
Mechanical Testing





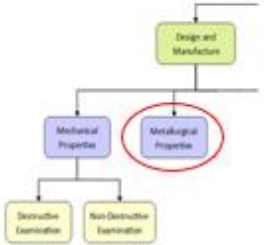






Leg 1 Good Design & Manufacture

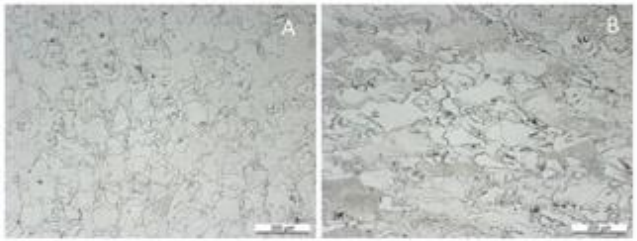
Metallurgical & Corrosion Testing



Summary of Metallurgical & Corrosion Testing

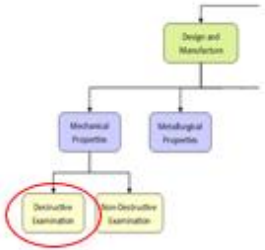
Test Description	Test Method	316LN	Tristelle 5183
Chemical Analysis (Powder & LPBF Sample)	ASTM E354	✓	✓
Microstructure & Grain Size	ASTM E112	✓	✓
Material Inclusion Content	ASTM E45	✓	✓
Macrostructure	ASTM E340	✓	✓
Resistance to Intergranular Attack (Sensitisation)	ASTM A262 Method A & E	✓	N/A
Resistance to Pitting Attack	ASTM G48	✓	N/A
Resistance to Transgranular Attack	ASTM G36	✓	N/A
Resistance to Crevice Corrosion	ASTM G78	✓	N/A

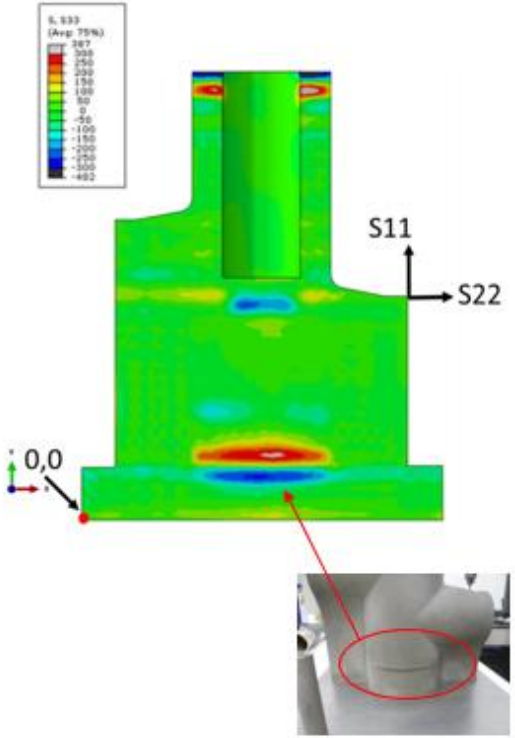
Typical Grain Structures



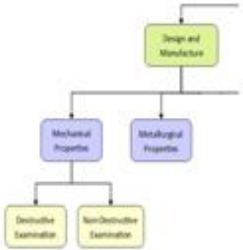
Tristelle 5183 to 316 St St Bond Line

Residual Stress Mapping

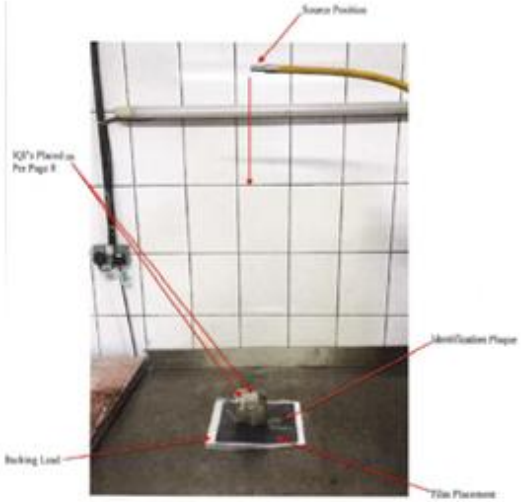




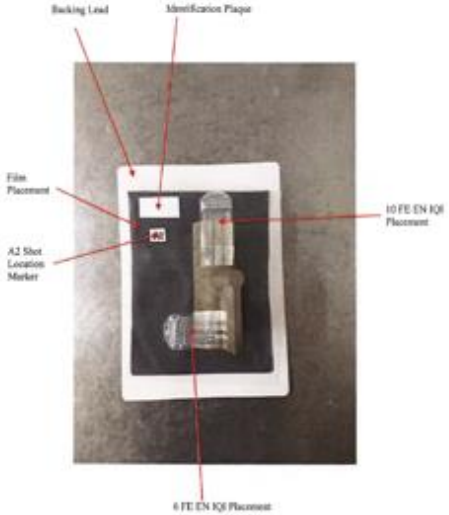
Non-Destructive Testing



50mm MGV Bonnet



15mm MGV Body



- Previous Method – Wrought/HIP bar examined using Ultrasonic Testing.
- AM Method – Radiographic Testing based on near-net-shape and start-of-Life defect characterisation.
- Defect characterisation by expert elicitation used to guide inspection technique and inspection acceptance criteria.
- Future expectation for in-process melt pool monitoring to remove requirement for traditional volumetric examination.

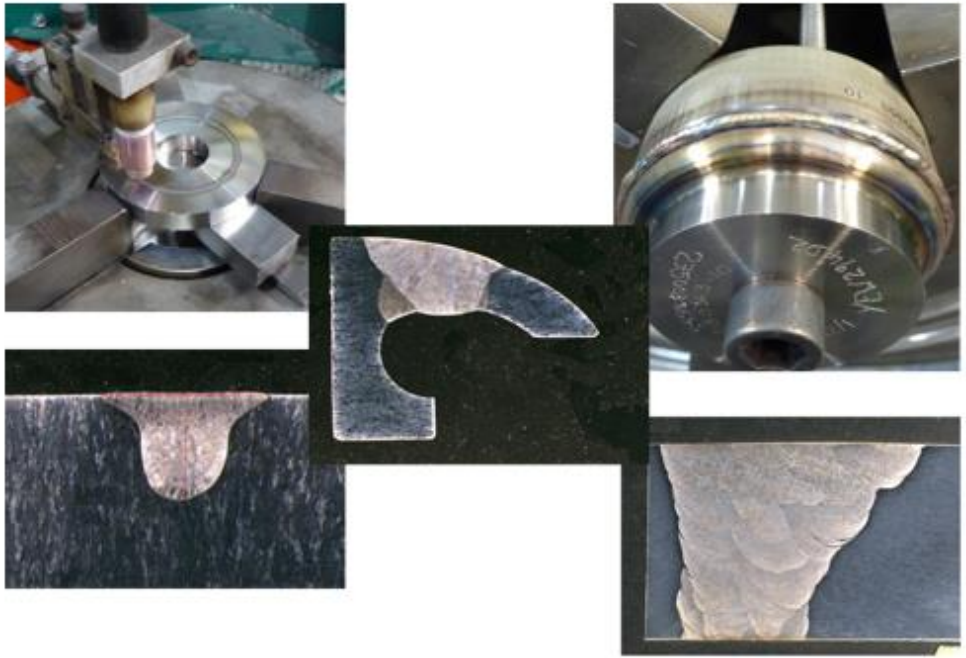
Weldability, Machinability

Weldability Trials.

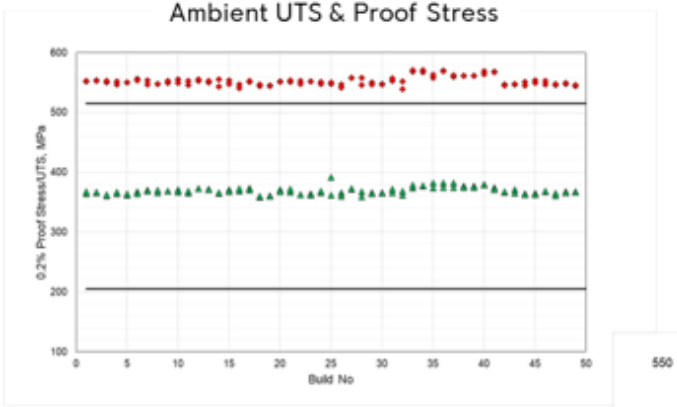
Canopy Weld Trials.

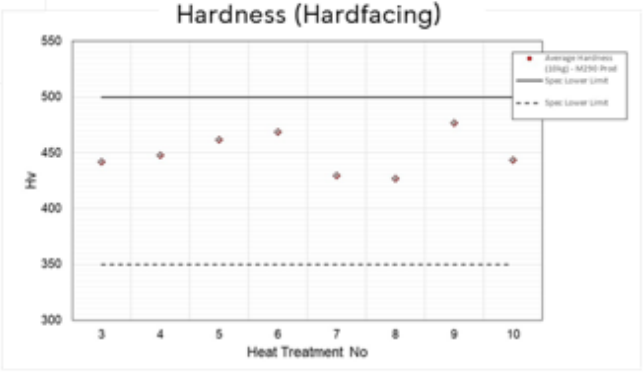
Pipework Stub Trials.

Machining Trials.



Production Test Data and Experience

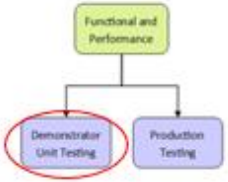




Leg 2 – Functional & Performance Testing

Test Type	Description	Component	Size	Comparison Wrought Valve	Production Test
Hydrostatic	Standard Hydro	Body only	15mm✓ 25mm✓ 50mm✓	No	Yes
	Valve Half Open	Full Assembly	15mm✓ 50mm✓	No	Yes
	Valve Closed	Full Assembly	15mm✓ 50mm✓	No	Yes
Ultimate Hydrostatic	Ultimate Pressure Test	Body only	50mm only✓	Yes	No
Performance	Cold	Full Assembly	15mm✓ 50mm✓	No	Yes
	Hot	Full Assembly	15mm✓ 50mm✓	No	No
	Repeat Cold	Full Assembly	15mm✓ 50mm✓	No	No
Endurance	Hot	Full Assembly	15mm only✓	No	No
Shock	Cold	Full Assembly	50mm only✓	Yes	No
Thermal Fatigue	Thermal Shock	Full Assembly	50mm only✓	Yes	No

Ultimate Pressure Tests



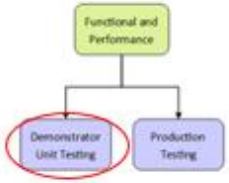
Explore full capability of AM pressure boundary on MGV body.

> 2000 bar applied without failure.

Wrought and AM MGV Bodies Pre-burst Test

Wrought and AM MGV Bodies Post-burst Test

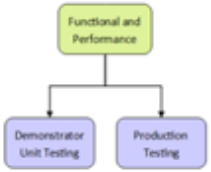
Seismic Loading Tests



Three test orientations on both AM and Wrought valves.

Pre and post test functional checks successful on each valve.

Thermal Fatigue Test (ASME Appendix II)



ASME III, Appendix II assessment used to specify thermal cycle test.

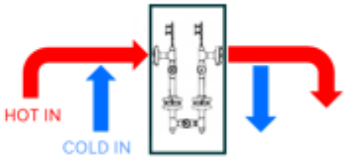
5 x service life – no cracks present (analysis predicted CUF of 0.4).

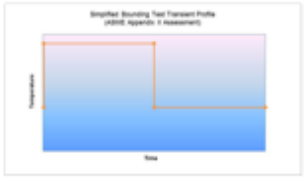
Valves functionally tested after extended life simulation.

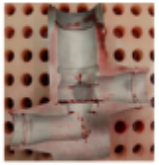
12 x service life (CUF of 1) – no cracks.

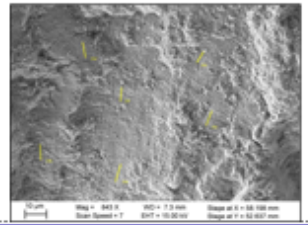
30 x life – evidence of cracking – picked up by NDE.

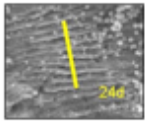
75 x life – max crack depth 6.5mm – wall thickness 13-20mm.



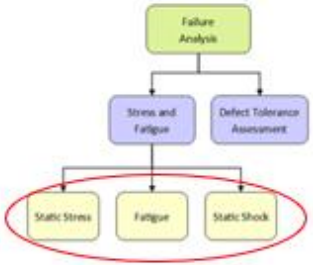


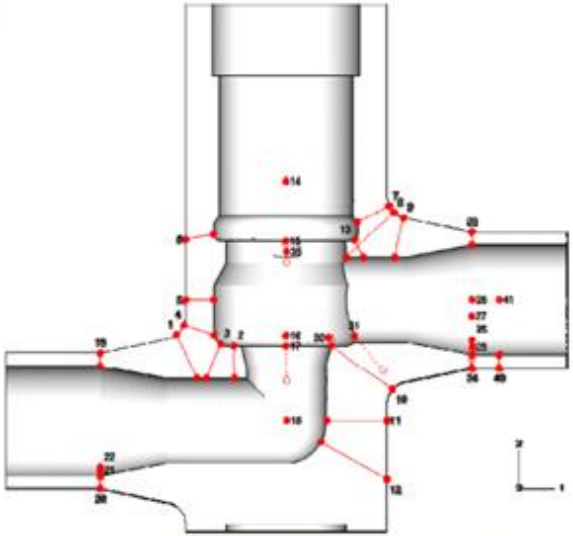




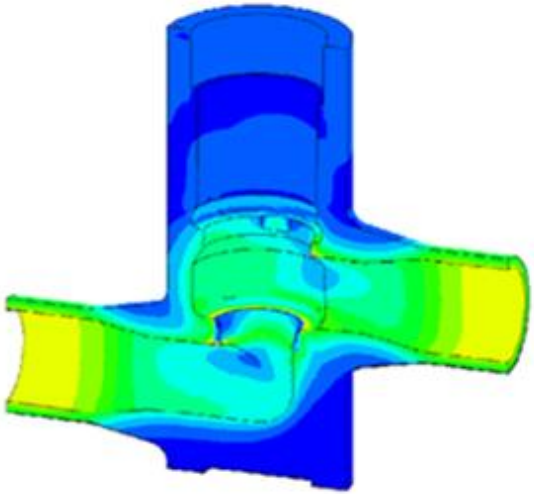


Leg 3 Failure Analysis





Location of Stress Classification Lines for ASME Assessment



Leg 4 Forewarning-of-Failure

- Failure Mode Effects Analysis (FMEA) Review
  - Large margins identified through functional & performance testing.
- In-Service Tests
  - System Hydrostatic and Valve Functional Tests.
- In-Service Inspections
  - External inspections for evidence of corrosion/EAC.

THANK YOU FOR LISTENING!

THANK YOU TO THE IAEA FOR THE OPPORTUNITY TO PRESENT THIS WORK