Metallurgical Challenges associated with using Grade 91 steels at Elevated Temperature

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Advanced Non-Light Water Reactors – *Materials and Component Integrity Workshop*
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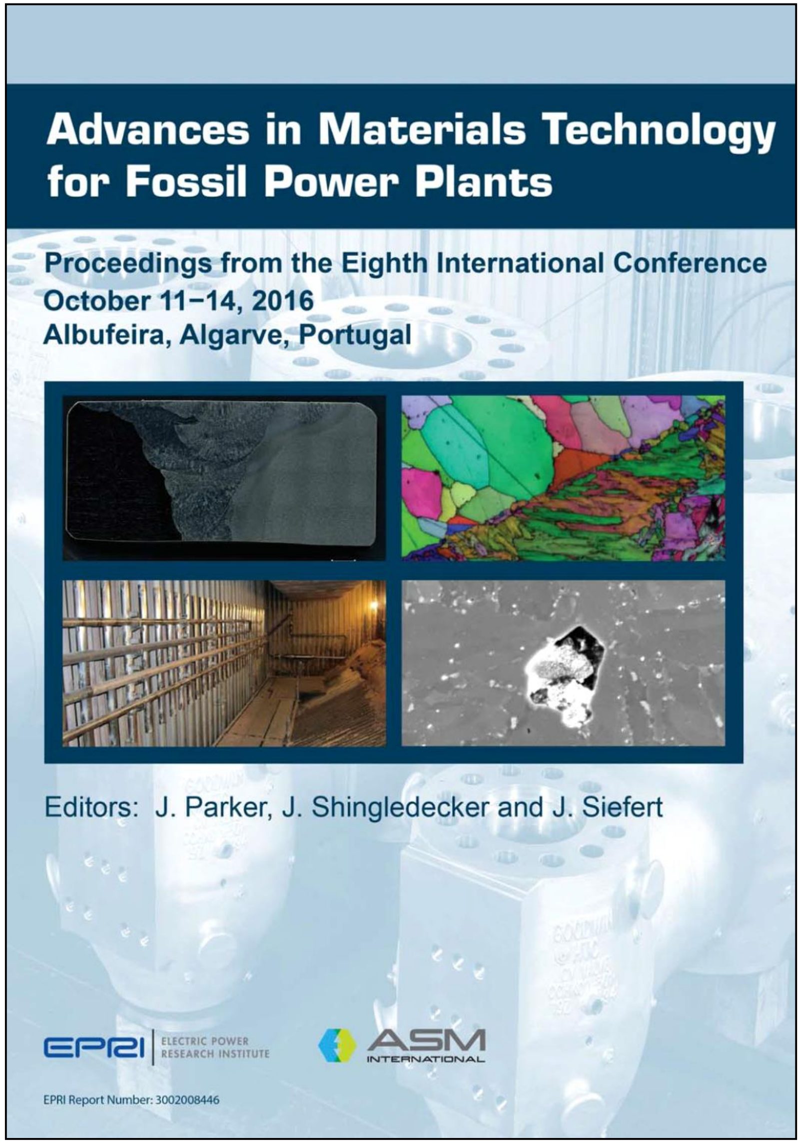
EPRI History of Materials Research

Includes key collaborations with Energy Sector Stakeholders and Global Technology Transfer including involvement with International Conferences. For example

- "0th" Conference: Chicago, IL (1987)
- 1st-London, UK (1995)
- 2nd-San Sebastian, Spain (1998)
- 3rd–Swansea, Wales (2001)
- 4th–Hilton Head, SC (2004)
- 5th–Marco Island, FL (2007)
- 6th–Santa Fe, NM (2010)
- 7th–Waikoloa, HI (2013)
- 8th–Albufeira, Portugal (2016)
- 9th – Nagasaki , Japan (2019)

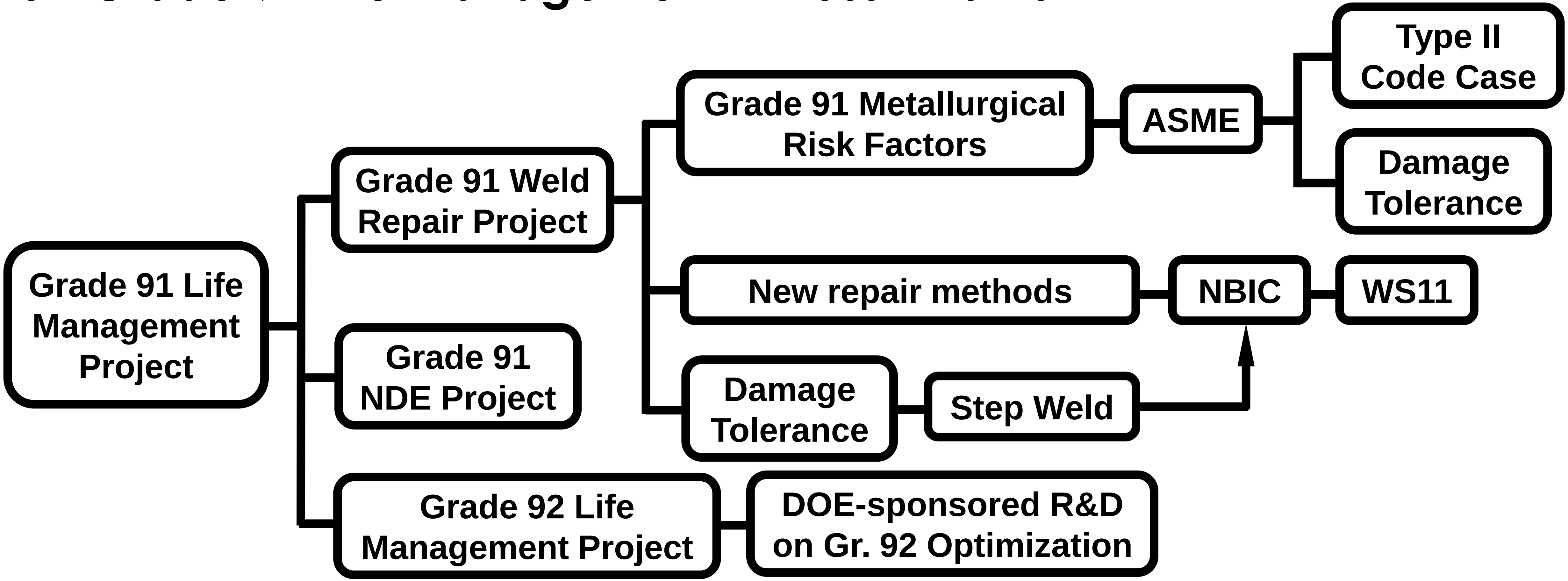


EPRI's extensive experience in high temperature materials performance offers benefit to Advanced Nuclear applications, in general, and long term service issues, in particular

Introduction

- Design codes for alloys used in high energy applications typically specify that the components fabricated will exhibit homogeneous composition, microstructure and properties. Experience has shown that these assumptions may not be valid.
- This presentation highlights known problems associated with heterogeneity in as manufactured components and welds with particular reference to Grade 91 steel.
- There is growing recognition that further work is required to understand the factors affecting variability and then to use this knowledge to underpin solutions.
- Solutions may involve use of non traditional fabrication methods

EPRI Library of Information on 9%Cr Steels initiated by collaboration on Grade 91 Life Management in Fossil Plants

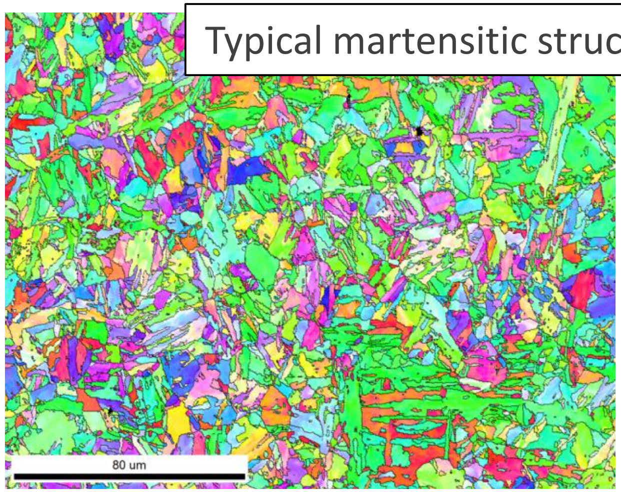


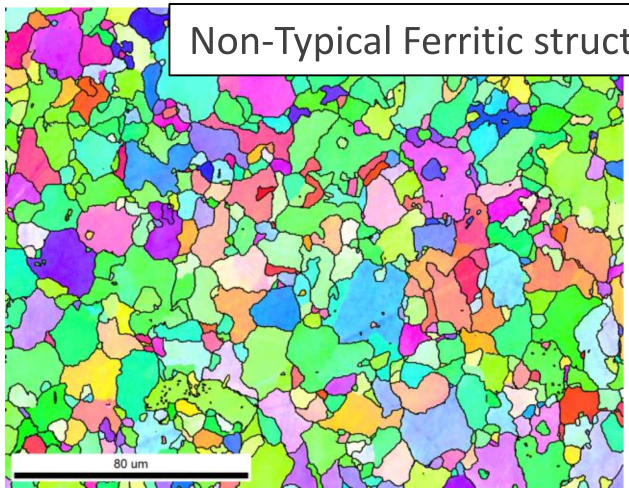
Now over 100 reports on 9%Cr steels - comprehensive understanding linking Fabrication to Microstructure and Performance

Components can exhibit significant microstructural variability. Proper documentation of microstructure is NOT straightforward.

Heterogeneity linked to manufacturing issues, including:

- Steel Composition,
- Steel Making,
- Segregation
- Hot Working method and conditions,
- Degree of Hot Reduction,
- Heat Treatment History, such as:
  - Normalizing Temperature,
  - Normalizing Time,
  - Cooling Rate from Normalizing, and
  - Tempering temperature, time and controls



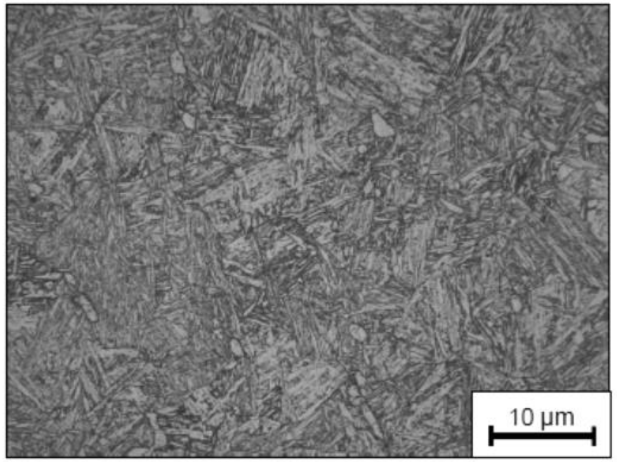


see 'The Effect of Metallurgical Factors & Stress State on the Performance of High Energy Components Manufactured from Creep Strength Enhanced Steels' Parker and Siefert, ECCC Conference 2017

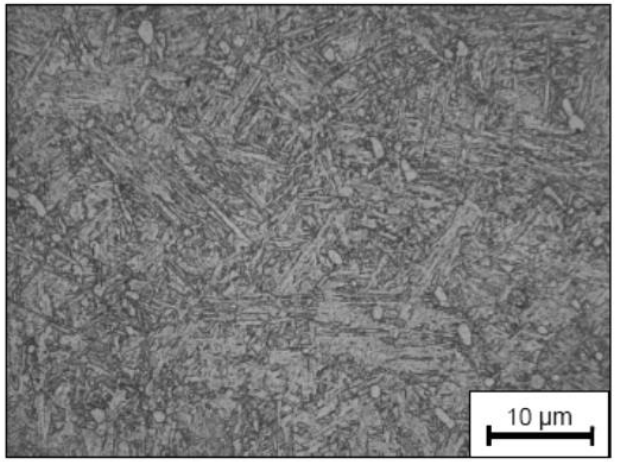
Imaging Methods Critical to Meaningful Characterization

Etching followed by optical metallography reveals a microstructure which appears martensitic

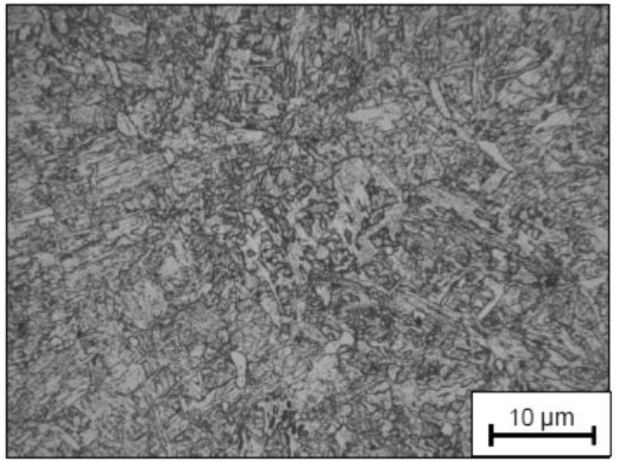
840°C – 197 HV_{10}



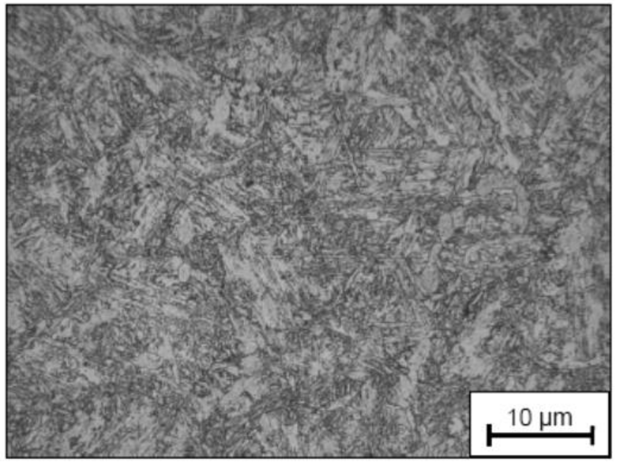
860°C – 167 HV_{10}



900°C – 162 HV_{10}



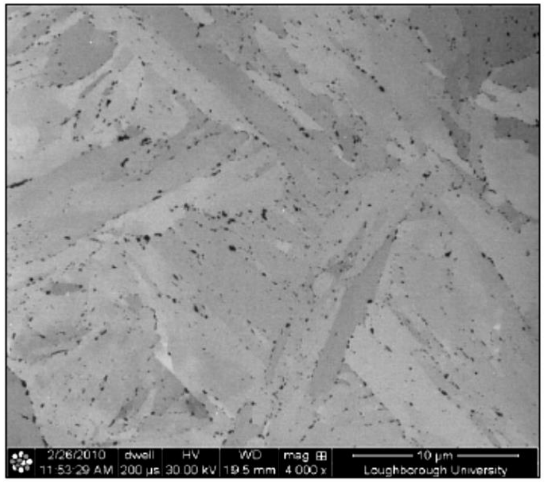
920°C – 161 HV_{10}



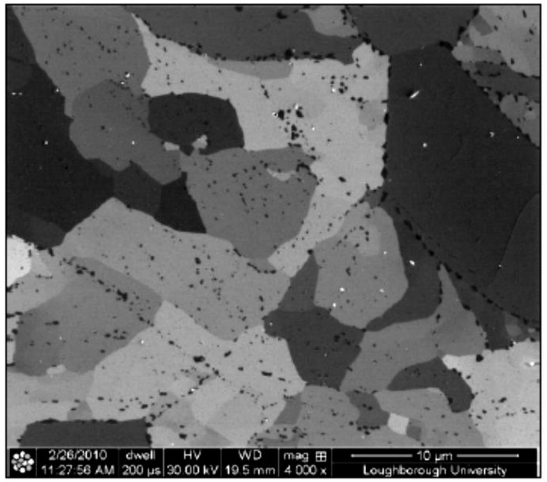
Reference Loughborough University

Ion Beam imaging reveals the true non martensitic structure and the precipitate distribution.

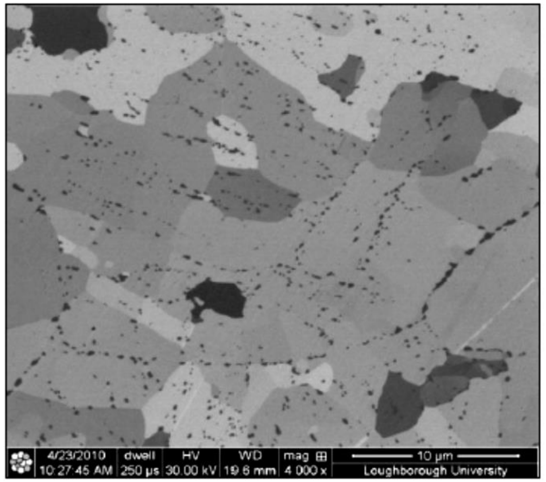
P92 - 800°C



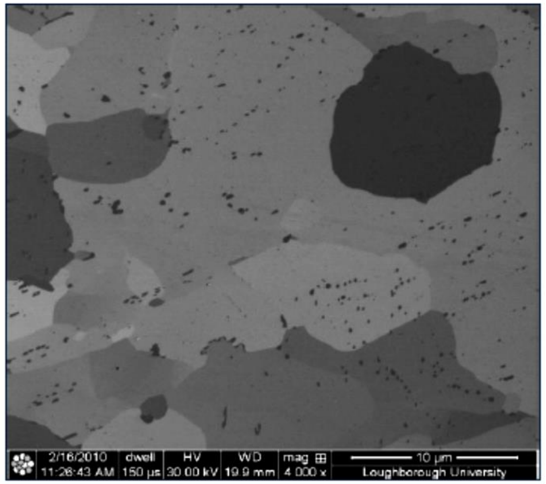
P92 - 880°C



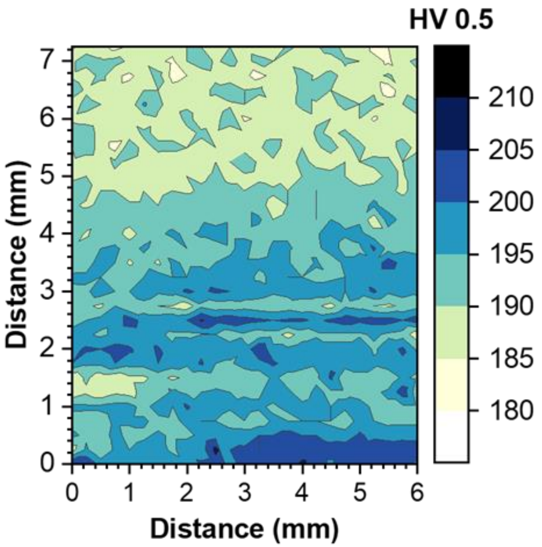
P92 - 900°C

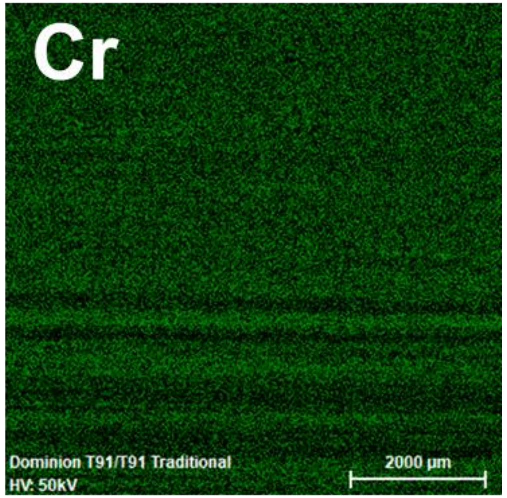


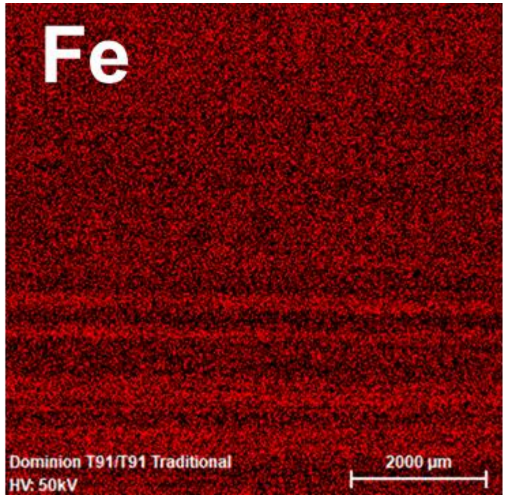
P92 - 960°C

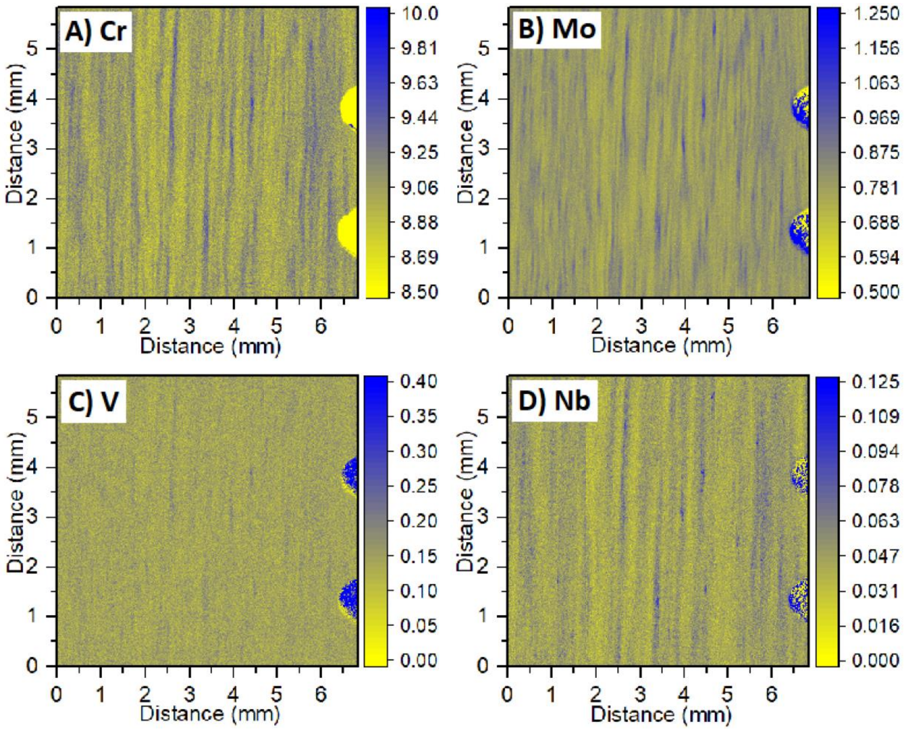


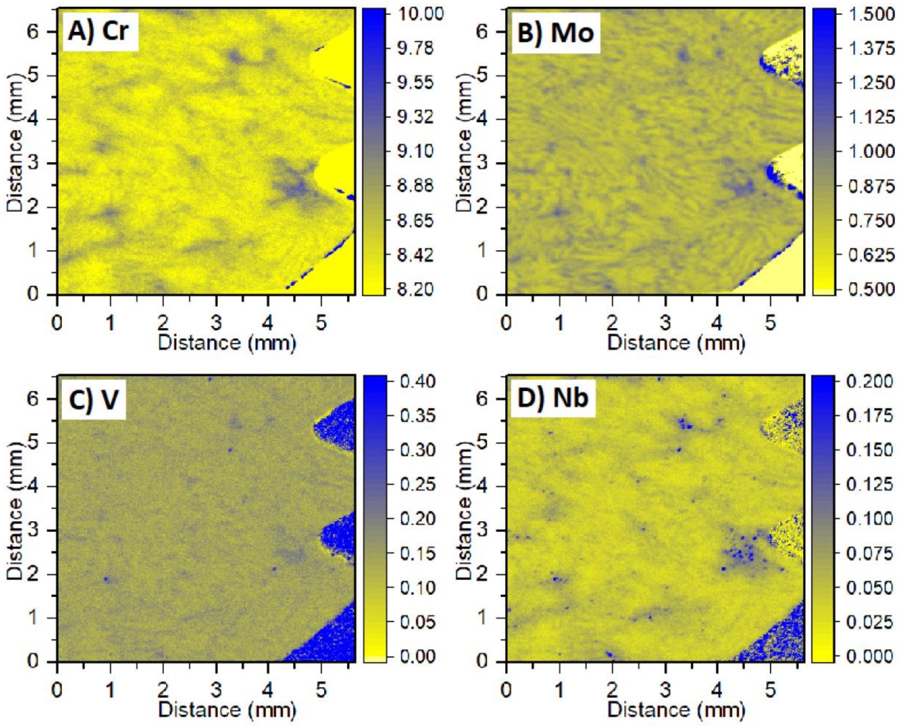
Detailed Characterization reveals heterogeneity of composition in Grade 91 components



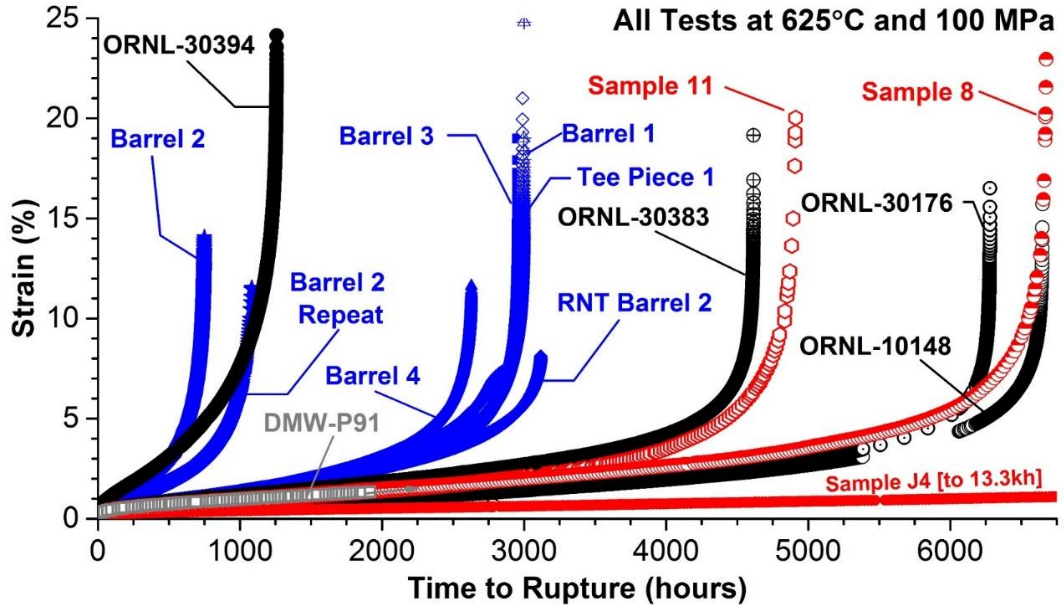


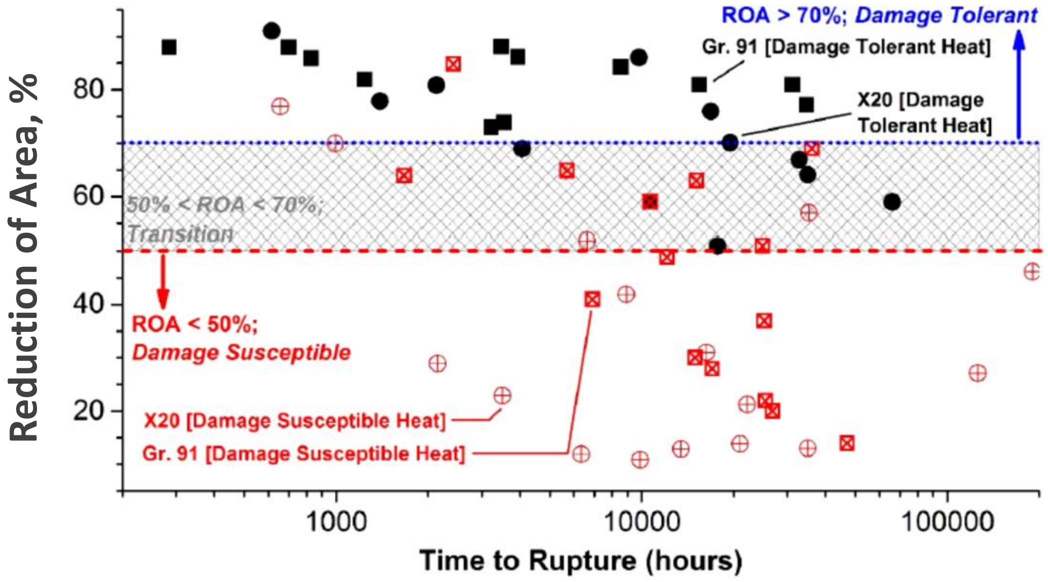


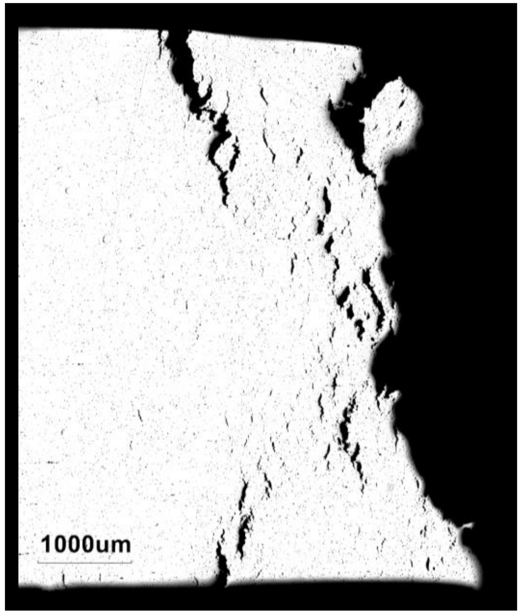


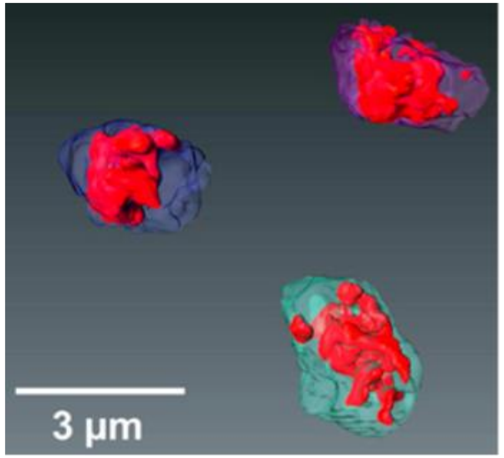


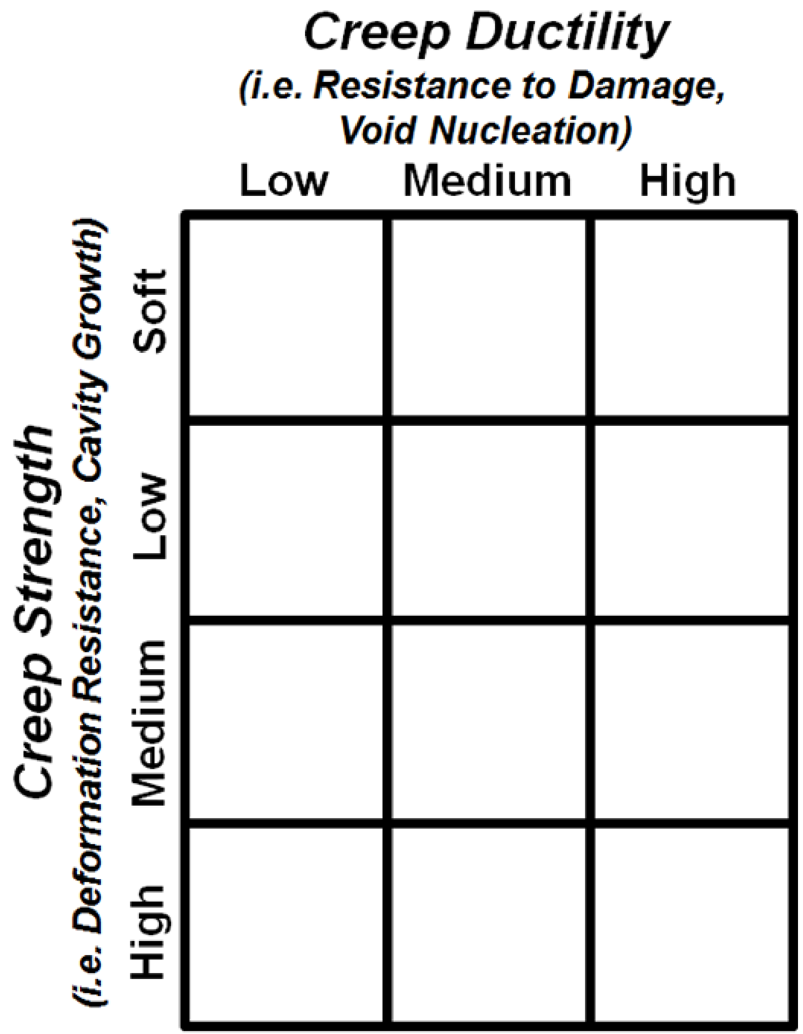
Variable Creep for Smooth Bar Tests in Grade 91 Steel Parent







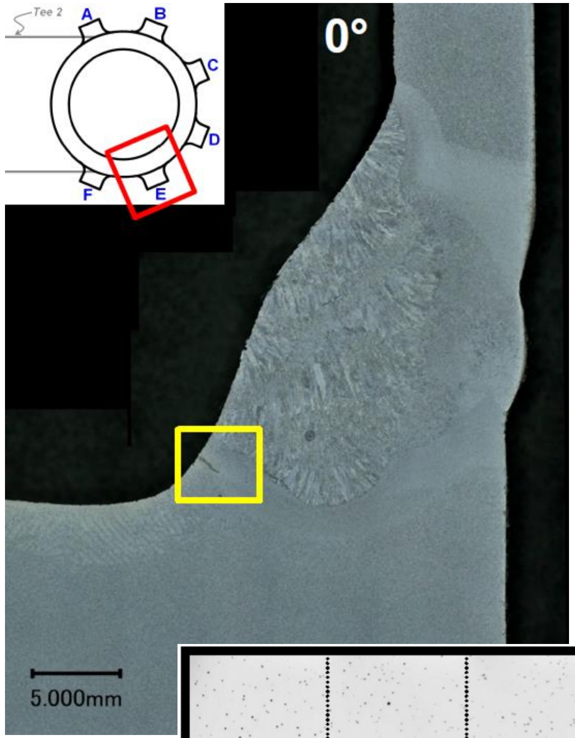




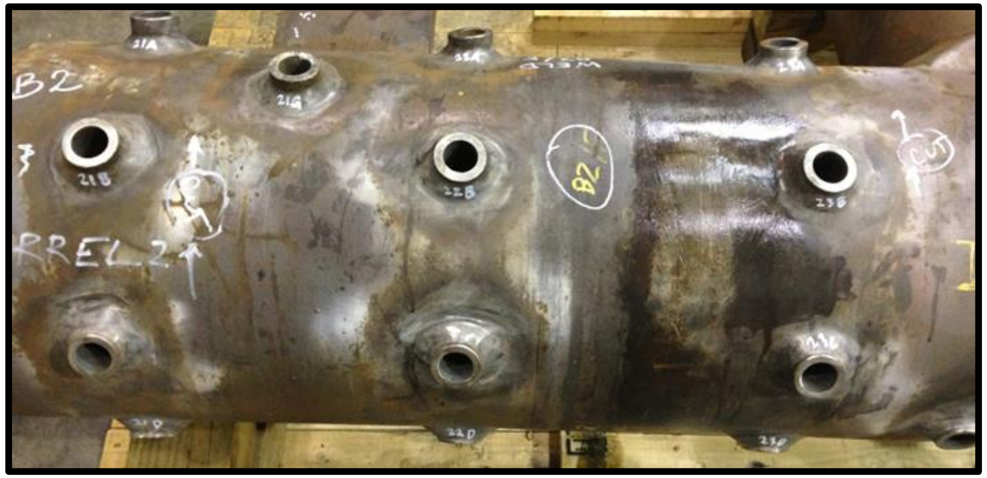
Focused ion beam (FIB) milling allows detailed 3D characterization of individual creep voids which are not previously exposed

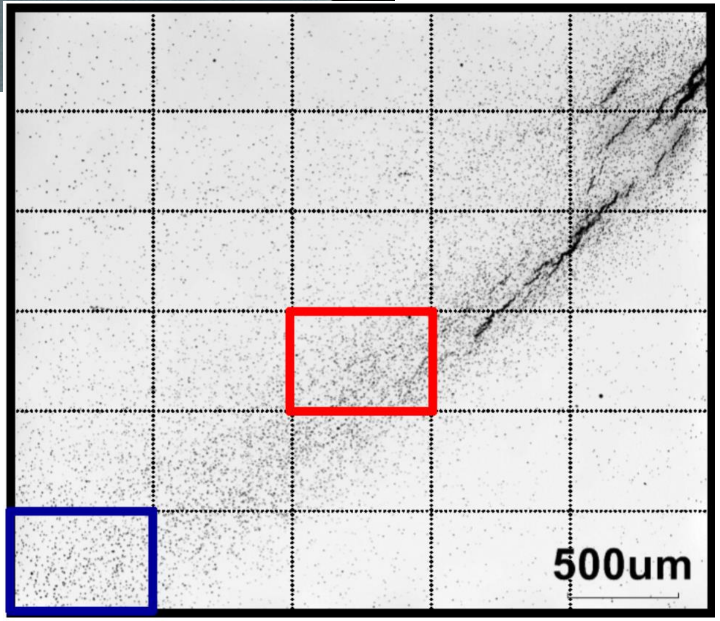
In-service Creep Cracks in Grade 91 Welds

- Expected Performance > 200,000 hours
- Cracking at stub & attachment welds after about 50 000 hours; Replacement at about 79 000 hours
- Operational temperature ~570°C in line with Design
- Component Stresses in line with Design



Stub	Ground	Crack at 0°		Crack at 180°	
		Cracking?	Length (mm)	Cracking?	Length (mm)
22A	No	No		No	
22B	No	Yes	2.0	No	
22C	Yes	Yes	0.5	No	
22D	No	Yes	1.67	Yes	1.43
22E	Yes	Yes	1.6	No	
22F	Yes	No		No	

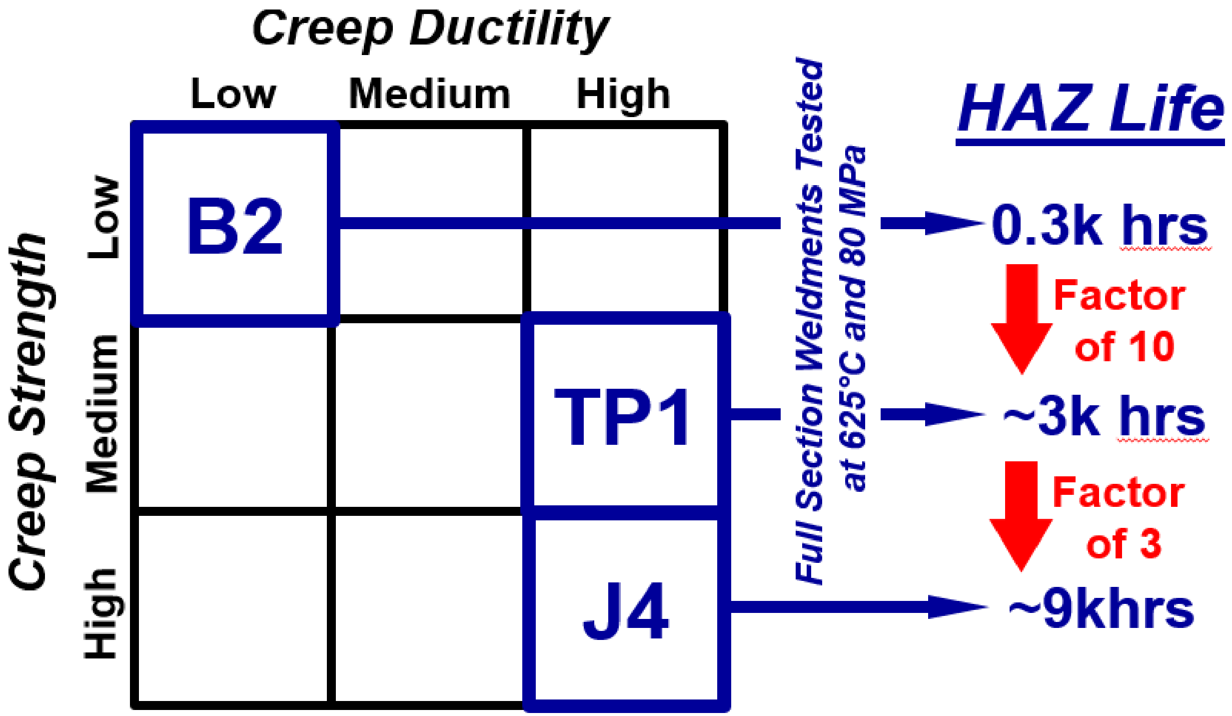


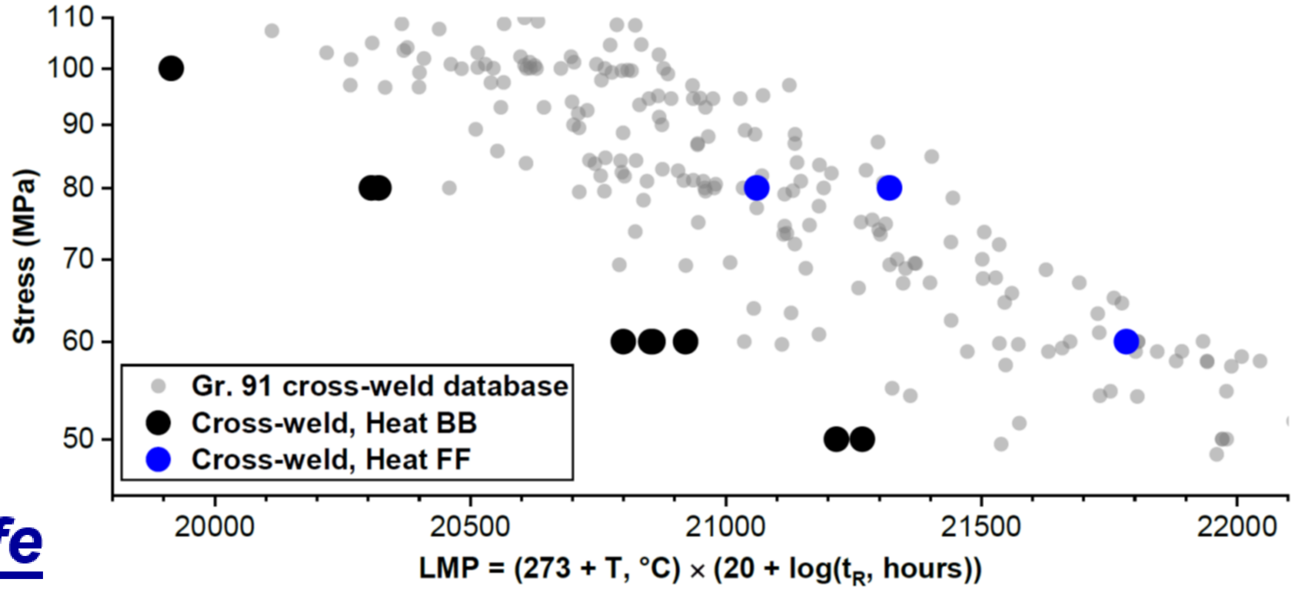


S. J. Brett and J. D. Parker. "Creep Performance of a Grade 91 Header." *International Journal of Pressure Vessels and Piping 111* (12), 2013. pp. 82 to 88.

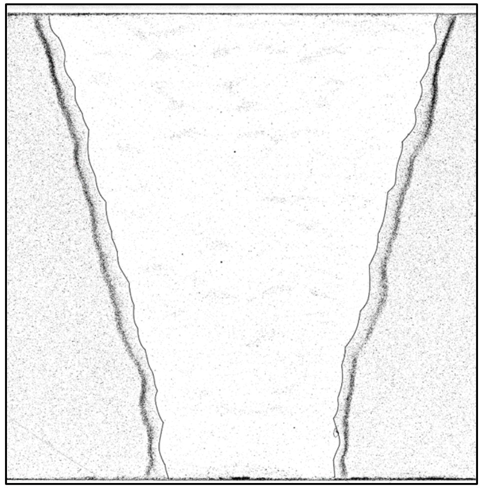
Metallurgy of Grade 91base steel influences creep of weld HAZs,

Creep Life of Welds changes by up to **30** depending on cavity susceptibility of base steel

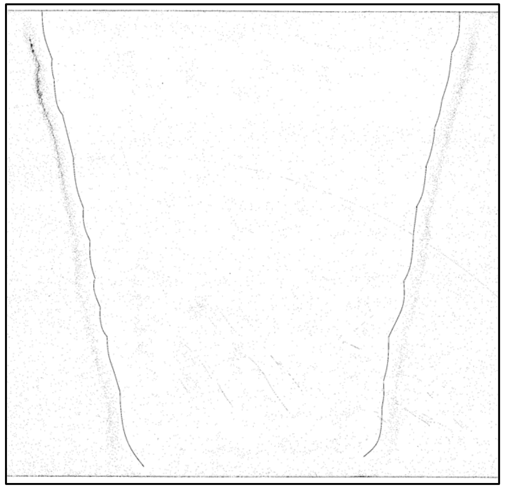




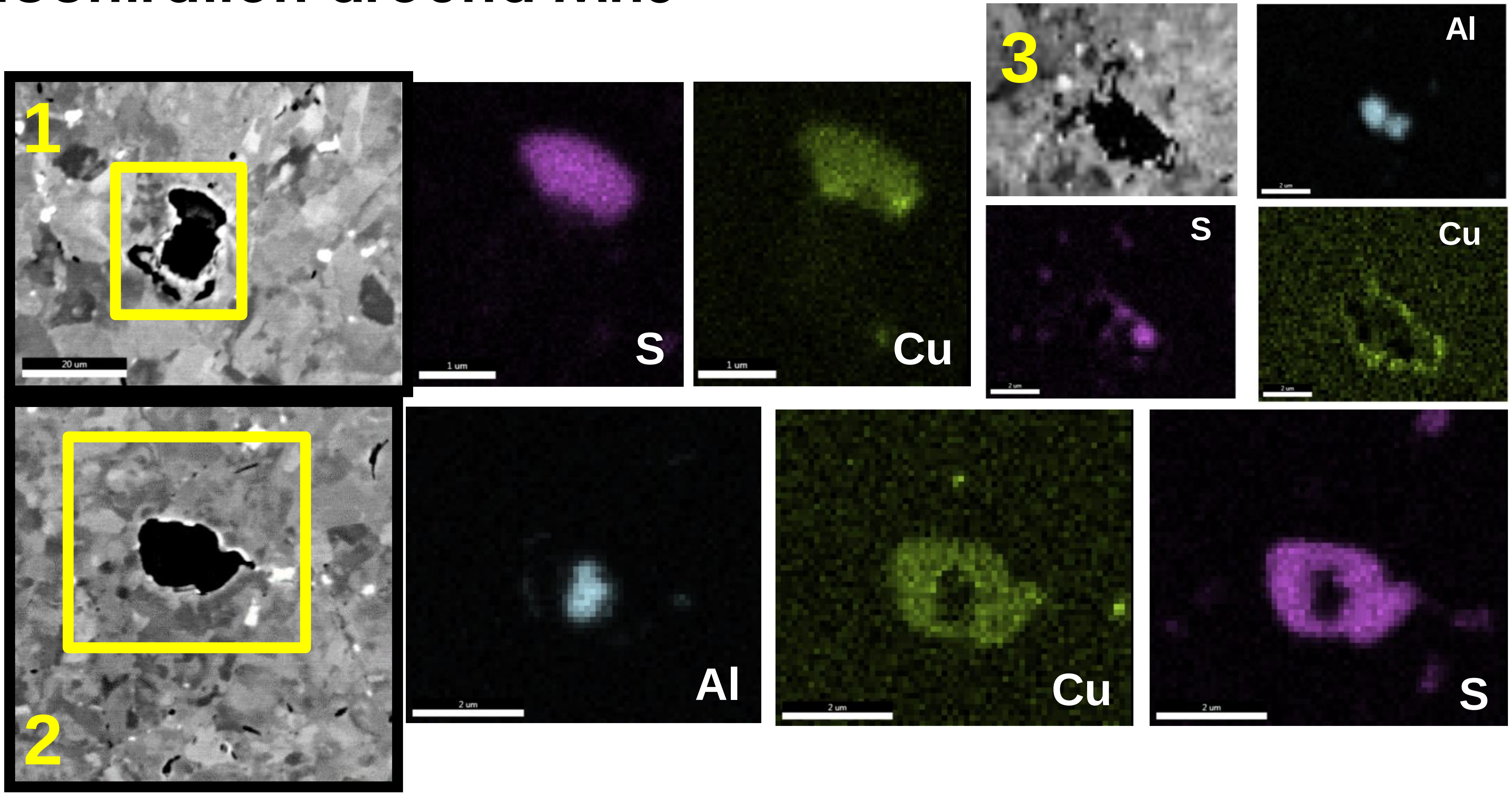
● Life 1,685h



● Life 13,201h



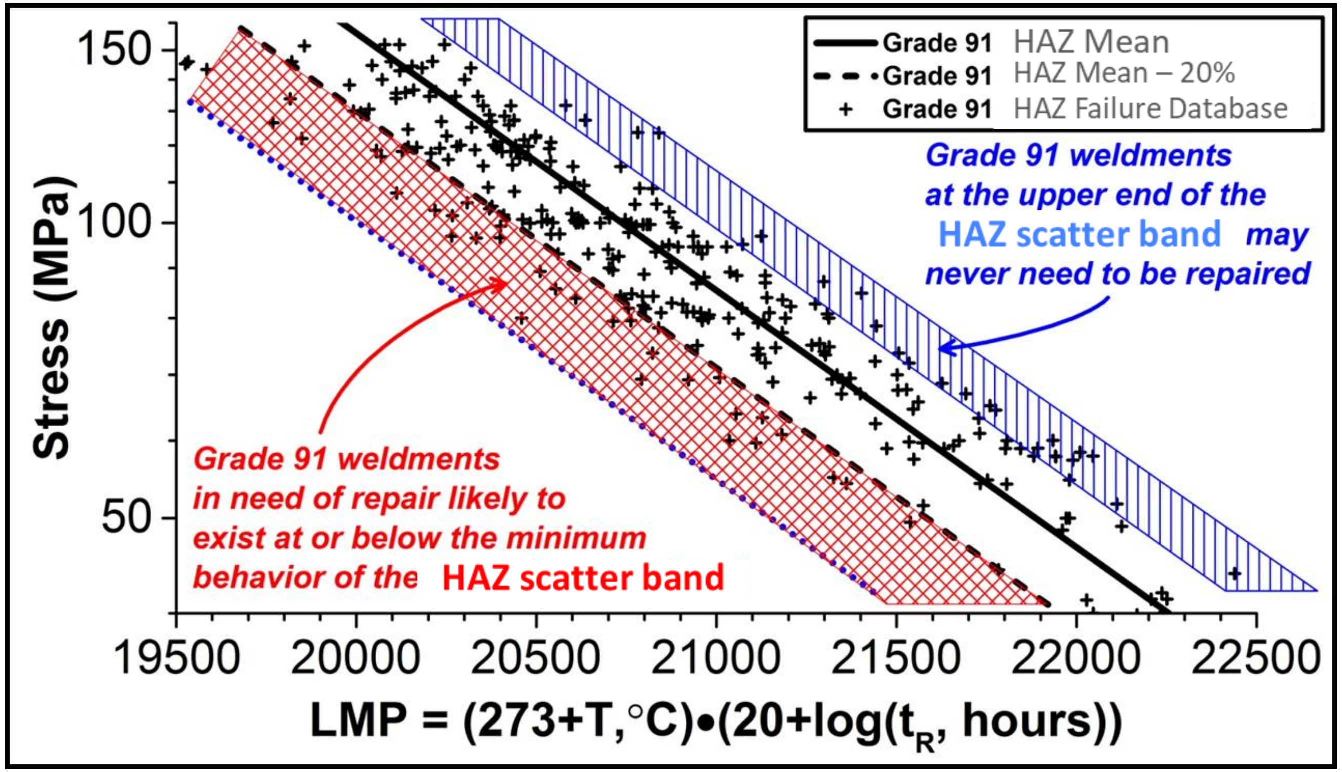
Cavities in Grade 91 steel linked to Inclusions: Cu Concentration around MnS



In Cavity Susceptible Steels Cu was frequently found around inclusions

Summary of Observations Grade 91 steel (Creep Life Finite)

- Low (very) Creep Strength typically linked to ‘bad’ (very) Heat treatment
- Low Creep Ductility linked to ‘hard’ particles which are present after steel making – this are difficult to change by heat treatment
- Complexity of Problems increased by segregation (heterogeneous)
- Low ductility failures associated with Factors which promote cavity nucleation and growth
  – Metallurgical AND Stress State
- Lower bound heat affected zone life linked to a high density of voids,
- Upper bound heat affected zone life noted in cavity resistant steel
- Lower bound poor damage tolerance



VERIFICATION OF ALLOWABLE STRESSES IN ASME SECTION III, SUBSECTION NH FOR GRADE 91 STEEL

PART 1: BASE METAL

Table 1. Chemical specifications for Grade 91 (wt %)

Element	SA-182*	SA-213*	SA-387*	EN 10216-2
C	0.08-0.12	0.08-0.12	0.08-0.12	.08-0.12
Mn	0.30-0.60	0.30-0.60	0.30-0.60	0.30-0.60
P	0.020max	0.020max	0.020max	0.020max
S	0.010max	0.010max	0.010max	0.010max
Si	0.20-0.50	0.20-0.50	0.20-0.50	0.20-0.50
Ni	0.40max	0.40max	0.40max	0.40max
Cr	8.0-9.50	8.0-9.50	8.0-9.50	8.0-9.5
Mo	0.85-1.05	0.85-1.05	0.85-1.05	0.85-1.05
Cb	0.06-0.10	0.06-0.10	0.06-0.10	0.06-0.10
N	0.03-0.070	0.03-0.070	0.03-0.070	0.03-0.07
Al	0.04max	0.04max	0.02max	0.04max
V	0.18-0.25	0.18-0.25	0.18-0.25	0.18-0.25
Ti			0.01max	
Zr			0.01max	

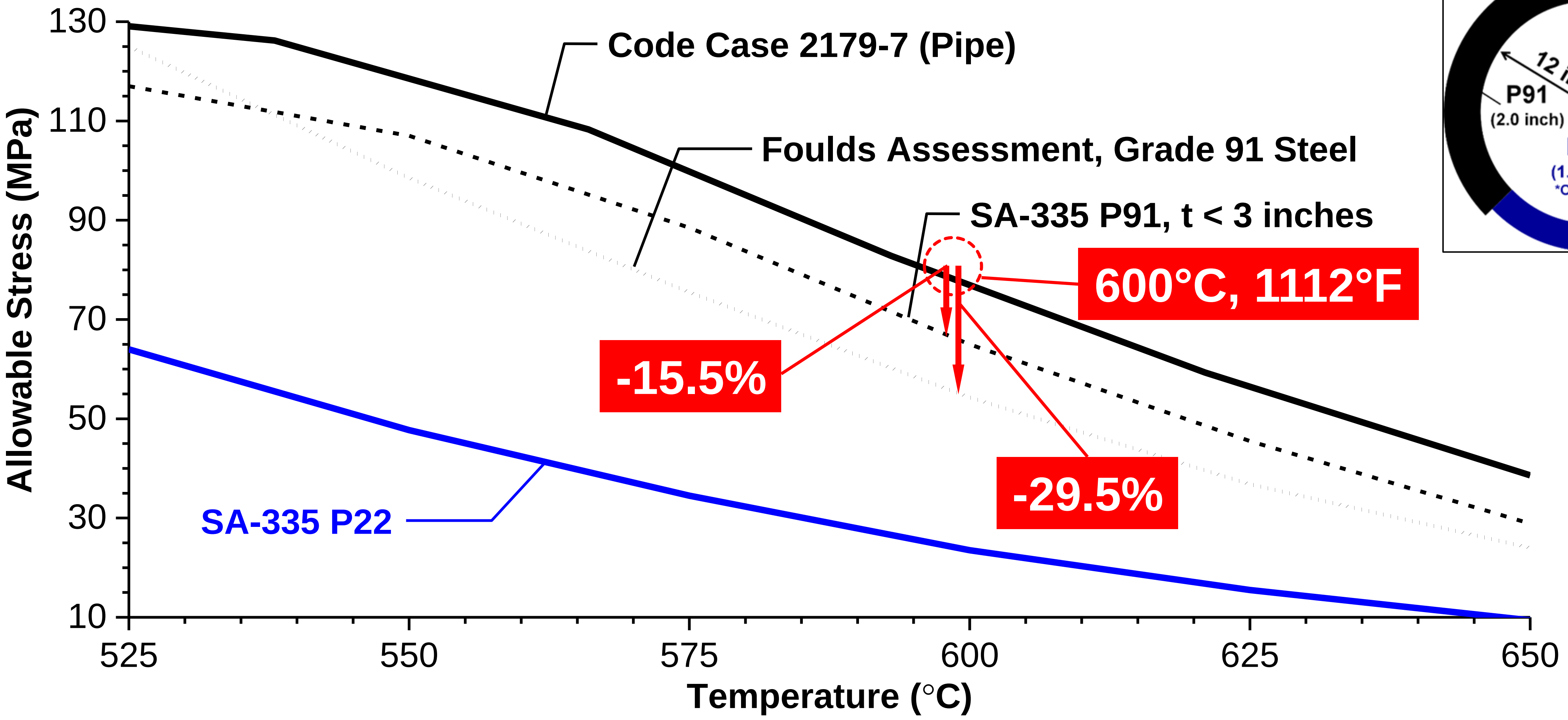
ASME Code Case 2864, 2016

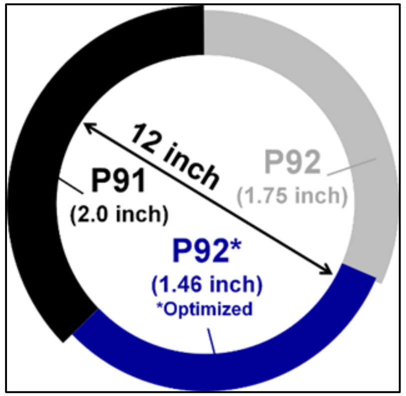
Table 1
Chemical Requirements

Element	Composition Limit, %
Carbon	0.08–0.12
Manganese	0.30–0.50
Phosphorous, max.	0.020
Sulfur, max.	0.005
Silicon	0.20–0.40
Chromium	8.0–9.5
Molybdenum	0.85–1.05
Tungsten, max.	0.05
Nickel, max.	0.20
Vanadium	0.18–0.25
Columbium	0.06–0.10
Nitrogen	0.035–0.070
Copper, max.	0.10
Aluminum, max.	0.020
Boron, max.	0.001
Titanium, max.	0.01
Zirconium, max.	0.01
Arsenic, max.	0.010
Tin, max.	0.010
Antimony, max.	0.003
N/Al ratio, min.	4.0

Comparison of Current and New Allowable Stress Values 91 & 92

In 2009, the specified Allowable Stress values for Grade 92 steel were reduced to be 15.7 ksi, 12.0 ksi, 8.6 ksi and 5.6 ksi for use temperatures of 1050 ºF, 1100 ºF, 1150 ºF and 1200 ºF respectively. **Allowable stresses of Grade 91 reduced in 2018.**





Advanced Reactors (AR)

- EPRI's ***Advanced Reactors (AR)*** technical focus area primarily addresses the next generation of nuclear reactors (often referred to as Generation IV)
  - Includes R&D relevant to light water SMRs and fusion technologies
- Objective is to build the technical foundation needed to ensure advanced reactors are real, deployable generation options **when** and **at scale** needed
- Program is evolving four years after launch
  - Formal incorporation into the EPRI Advanced Nuclear Technology (ANT) program portfolio
  - **New AR Supplemental project now available, providing low-cost access to and engagement in EPRI AR research collaborative**

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Research and Development to Support Deployment of Advanced Nuclear Energy Systems

Issue:
Advanced nuclear energy systems bring a new set of technology-related questions, and investigating and evaluating these questions can be resource-intensive.

Solution:
This supplemental project will provide time- and cost-saving assessments, analysis and guidance addressing various aspects related to advanced reactors:

- Owner and operator requirements
- Economics and market conditions
- Risk and safety considerations
- Advanced materials and manufacturing
- Fuel reliability and performance
- Energy storage and renewables integration

Background, Objectives, and New Learning
EPRI is expanding its global collaboration with governments, utility members, and advanced reactor developers/vendors to inspire new lines of thinking that can inform prioritization of and investment in relevant technology development while ensuring alignment of that development with societal and market needs.

Through collaborative R&D and workshops, this project provides participants access to three advanced reactor technical areas within EPRI's Advanced Nuclear Technology program:

1. Requirements and guidance
2. Technology assessment and strategic analysis
3. Targeted technology development

Proposed activities in 2020–2022 timeframe include:

- Evaluating global markets for non-electric products and missions
- Developing an improved cost model for new nuclear construction
- Identifying and defining novel design attributes for advanced reactors for increased flexibility, resiliency, and competitiveness
- Developing a molten-salt-reactor component reliability database
- Revision of the EPRI siting guide for advanced reactor applications

Benefits
Participants will have direct input into the identification and prioritization of R&D activities under the EPRI ANT Advanced Reactors Technical Focus Area and gain access to experience, expertise, and training opportunities that can enhance the design, evaluation, licensing, construction, and operational capabilities of advanced nuclear energy technologies. Many of these benefits apply to both fission and fusion energy technologies.

- Awareness of the latest developments in advanced material and manufacturing R&D activities relevant for service at high temperatures and under irradiation.
- Safety assessment tools and methods tailored to support progressive maturation of designs from pre-conceptual to final design. These tools and methods provide a structured framework and approach to complement and facilitate development of a safety case and quantitative risk assessments.
- Economic and market analyses based on state-of-the-art energy and economy modeling tools to inform long-range energy generation planning and business case development.

EPRI AR Scope:
Scouting + R&D Portfolio

Scouting and Engagement

- Innovation network
- Awareness and understanding

Requirements and Guidance

- Align design with customer needs
- Leverage existing nuclear industry experience
- Assemble and disseminate best practices

Strategic Analysis and Technology Assessment

- Economic analysis and market insights
- Safety-in-design
- Technology and manufacturing readiness

Technology Development and Transfer

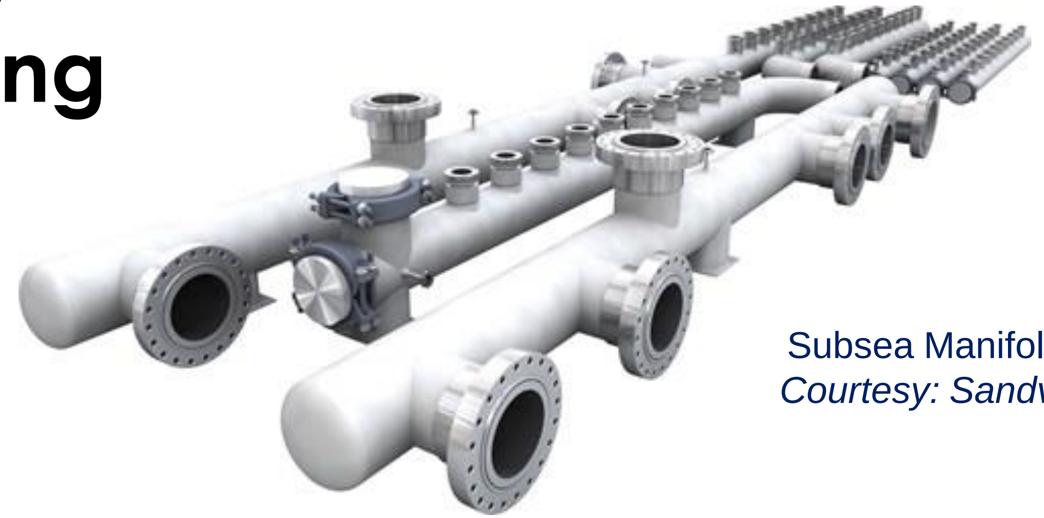
- Address common needs and gaps through collaboration
- Leverage and extend EPRI core competencies
- Technology transfer

Advanced Materials and Manufacturing

Powder Metallurgy-
Hot Isostatic Pressing

Why PM-HIP?

- Near-net shaped components
- Homogenous microstructure
  - Ease of inspection!
- Elimination of welds
- 4-6 months lead times typical
- Ideal for multiple penetration applications (RPV or CNV head) vs expensive forgings



Subsea Manifold.
Courtesy: Sandvik

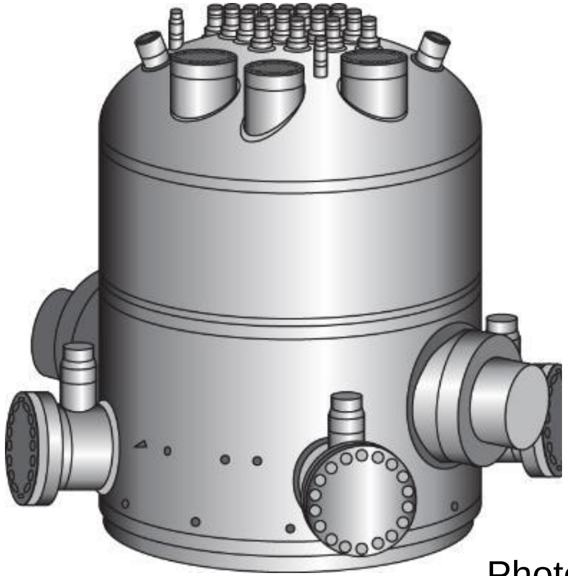
40” diameter HIP Vessel
Courtesy: Isostatic Forge International

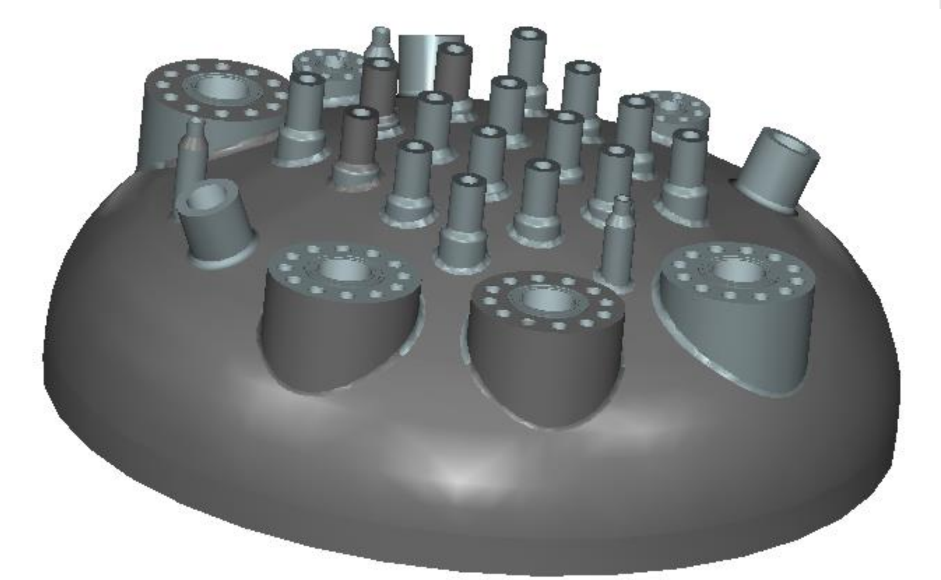
Large Bore Valve
(courtesy Roll-Royce)

NNS Reactor Coolant Pump Impeller (courtesy Framatome and Albert & Duval)

3600lb (1630kg) BWR Nozzle

Small Modular Reactor Upper Head--Example





Photographs courtesy of EPRI and NuScale Power

- Approximately 44% scale
- Single monolithic structure
- A508 Class 1, Grade 3
- 27 penetrations
- 1650kg (3650lbs); 1270mm (50 inches) diameter
- Next, 2/3-scale head
- Need larger HIP Vessel -- ATLAS

DOE Project: DE-NE0008629

Summary of Benefits of Clean Homogeneous Steels

Improved Properties include Reduced variability (Uncertainty) and

- Lower FATT, higher fracture toughness, higher upper shelf energy
- Better creep strength and ductility
- Higher yield strength
- Higher low cycle fatigue strength
- Greater resistance to SCC initiation
- Uniform radial and longitudinal properties

These improved Properties should offer performance benefits such as:

- Increased life under conventional service conditions,
- Increased critical crack size (greater duration of stable crack growth)
- Greater opportunity for weld repair,
- Reduced damage initiation sites provides a lower risk of cracking during Flexible Operation.

A simple take away is "well made, clean steel components reduce variability in properties and provide the margin which aids Damage Tolerance"

Together...Shaping the Future of Electricity

Recent EPRI Position Papers / Theses Loughborough Uni

- *Life Management of 9Cr Steels – Damage Tolerance Assessment of Header End Cap Geometries* , EPRI, Palo Alto, CA: 2018 *3002011049*
- *Life Management of 9%Cr Steels – Damage Tolerance Assessment of Novel Step Weld Geometry for Girth Welds in Thick-section Components,* EPRI, Palo Alto, CA: 2018 *3002011053*
- *Life Management of 9%Cr Steels – Damage Tolerance Assessment of a Common Hot Reheat Lateral Geometry,* EPRI, Palo Alto, CA: 2018 *3002011051*
- Xu Xu https://repository.lboro.ac.uk/articles/Microstructural_evolution_and_creep_damage_accumulation_in_Grade_92_steel_weld_for_steam_pipe_applications/9230171
- Gu
- https://repository.lboro.ac.uk/articles/Microstructural_investigation_of_creep_behaviour_in_Grade_92_power_plant_steels/9230141
- Siefert https://repository.lboro.ac.uk/articles/The_influence_of_the_parent_metal_condition_on_the_cross-weld_creep_performance_in_Grade_91_steel/8309882