Target Reliability as an Acceptance Criterion for Component Failure within a Systems Approach to Nuclear Structural Integrity Assessment

2nd International Seminar on Probabilistic Methodologies for Nuclear Applications

Mike Martin – Engineering Associate Fellow, Structural Integrity
Keith Wright – Engineering Associate Fellow, Structural Integrity and Chief Stress Engineer

25 October 2017, Ottawa

Trusted to deliver excellence

Rolls-Royce

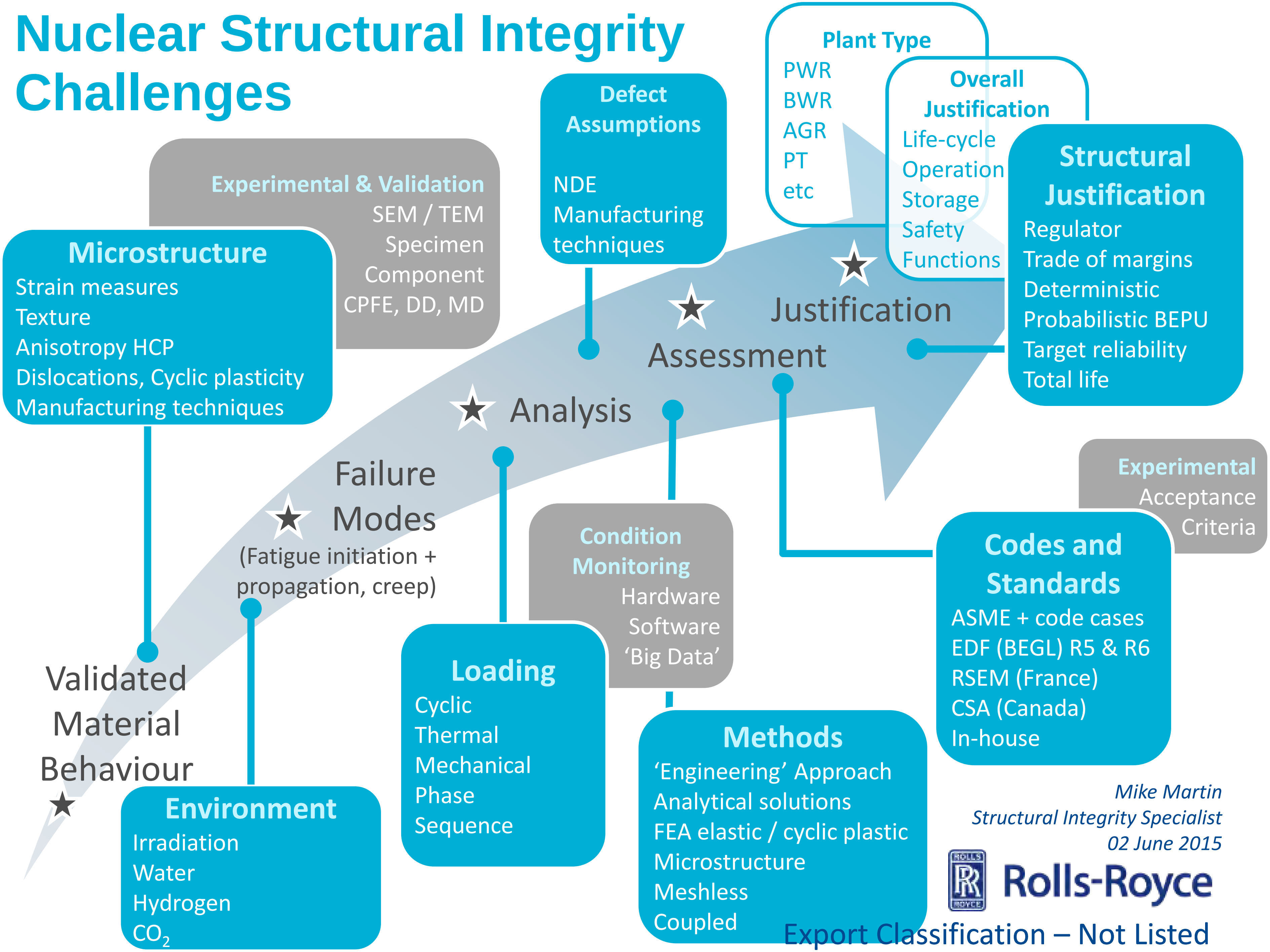
Export Classification – Not Listed

Content

- Background and Drivers
- Probabilistic Approaches
- Predictive Capability
- Systems Approach
- Summary

Background and Drivers

Nuclear Structural Integrity Challenges



Mike Martin
Structural Integrity Specialist

02 June 2015

Rolls-Royce

Export Classification – Not Listed

ASME Design Fatigue Curve: Stainless Steel

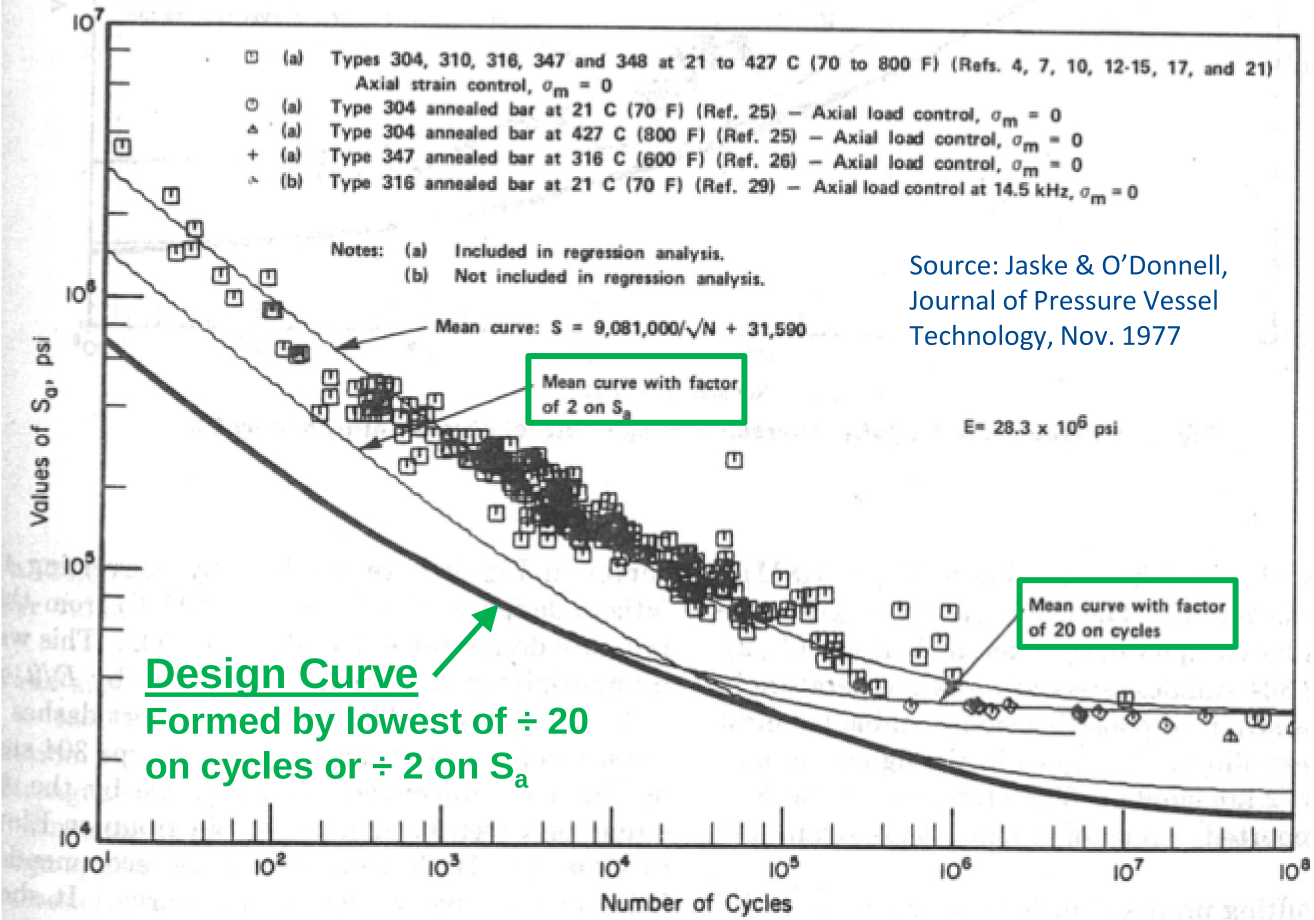


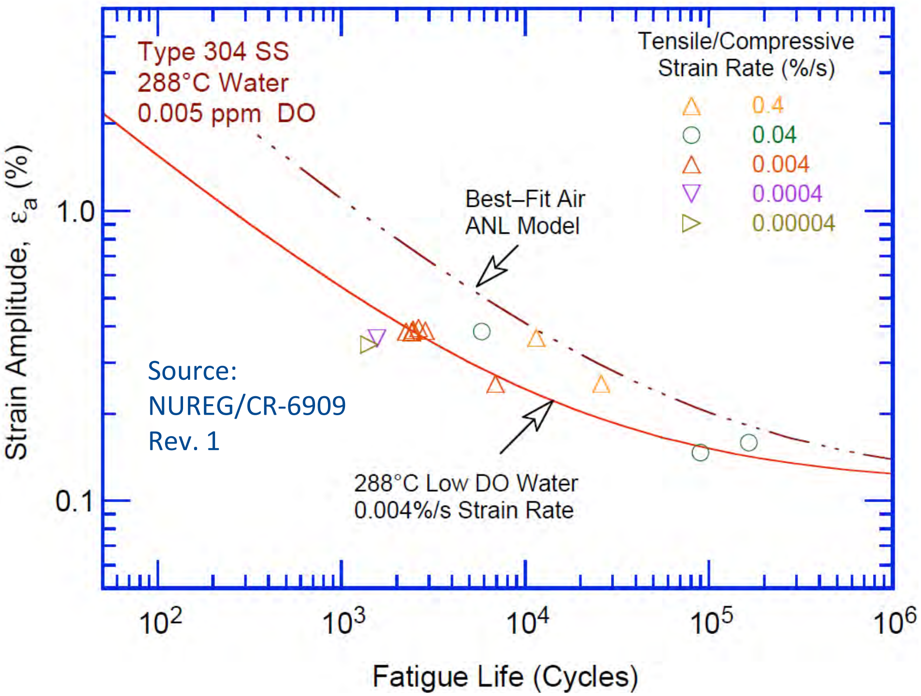
Fig. 3 Fatigue curve for types 304, 310, 316, 347, and 348 austenitic steels

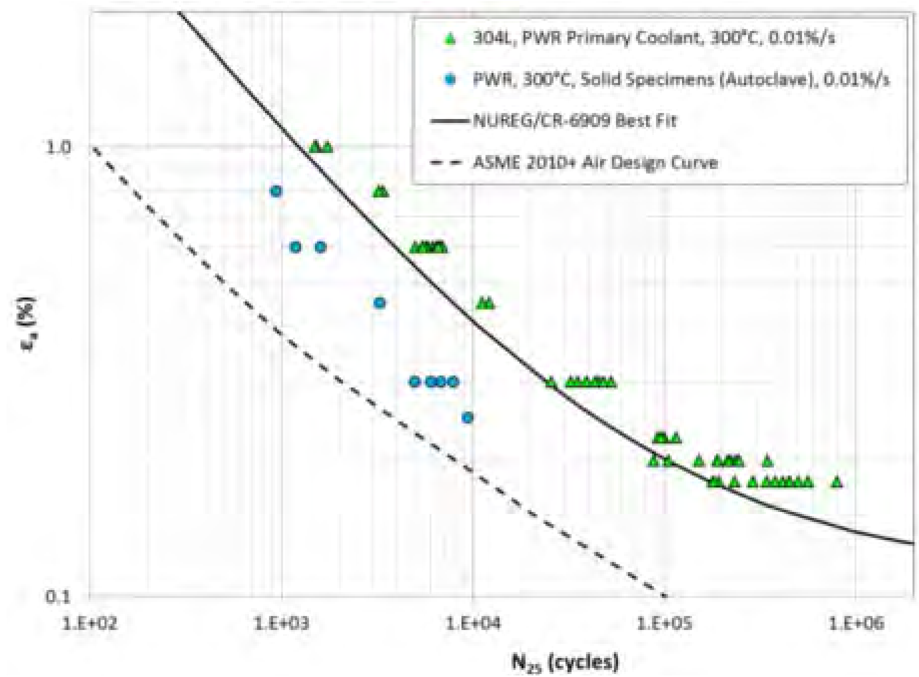
- **Most test conditions:**
  - **Uniaxial strain-controlled loading**
  - **R = -1 (w.r.t. strain)**
  - **Plain specimens**
  - **Polished g.l. surface**
  - **Iso-thermal**
  - **Air environment**
- **"Factor of 20" made up of sub-factors for:**
  - **Data scatter**
  - **Size effects**
  - **Surface finish, "atmosphere", etc.**
- **Design curve includes maximum mean stress correction (modified Goodman)**

- **Best fit to test data: "Langer equation", $\varepsilon_a = A1.(N)^{-n1} + A2$**
- **Design curve was constant from ~1962 until 2010**
  - Updated in 2010: updated best-fit to expanded database; factors of <u>12</u> & 2
  - Changes based on US NRC report NUREG/CR-6909

Rolls-Royce

Effect of PWR Environment





- **Environmental Correction Factor (F_{en}) defined in NUREG/CR-6909:**

  $F_{en} = N_{air,\,RT} / N_{PWR}$ i.e. $N_{PWR} = N_{air,\,RT} / F_{en}$

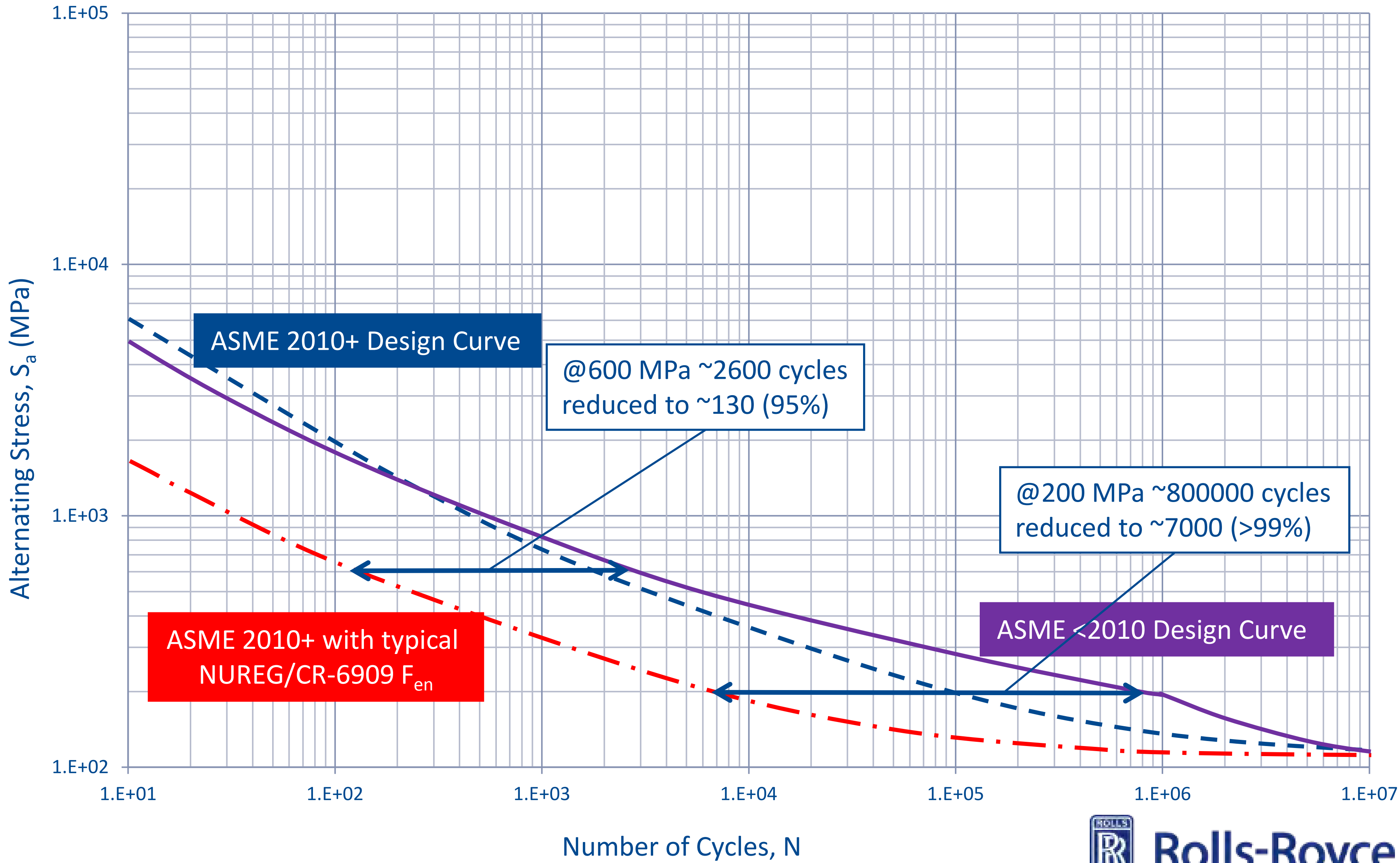
  $F_{en} = f(T, \dot{\varepsilon}, \text{Dissolved Oxygen content})$

- For austenitic stainless steels in PWR primary coolant (low DO),

  F_{en} function based on 200+ PWR test results

  $1.0 \le F_{en} \le 14.1$

Environmentally Assisted Fatigue - The Problem

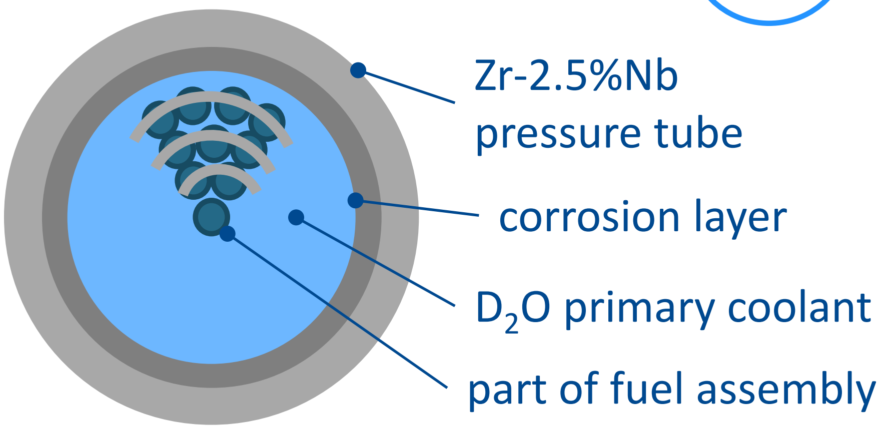


Rolls-Royce

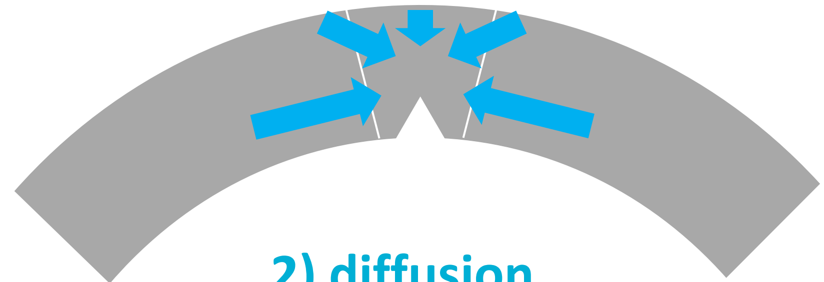
Export Classification – Not Listed

DHC Mechanism

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$

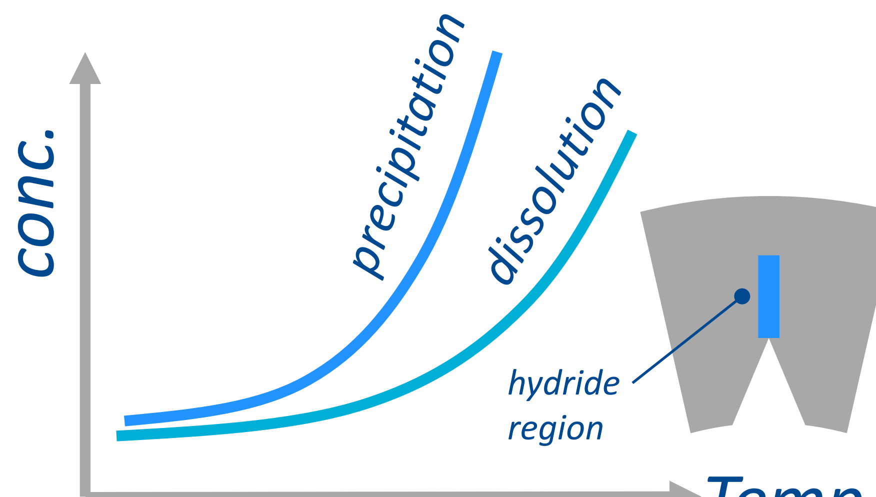


1) corrosion

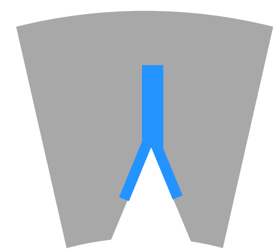


2) diffusion

Driven by gradients in stress, temperature and concentration



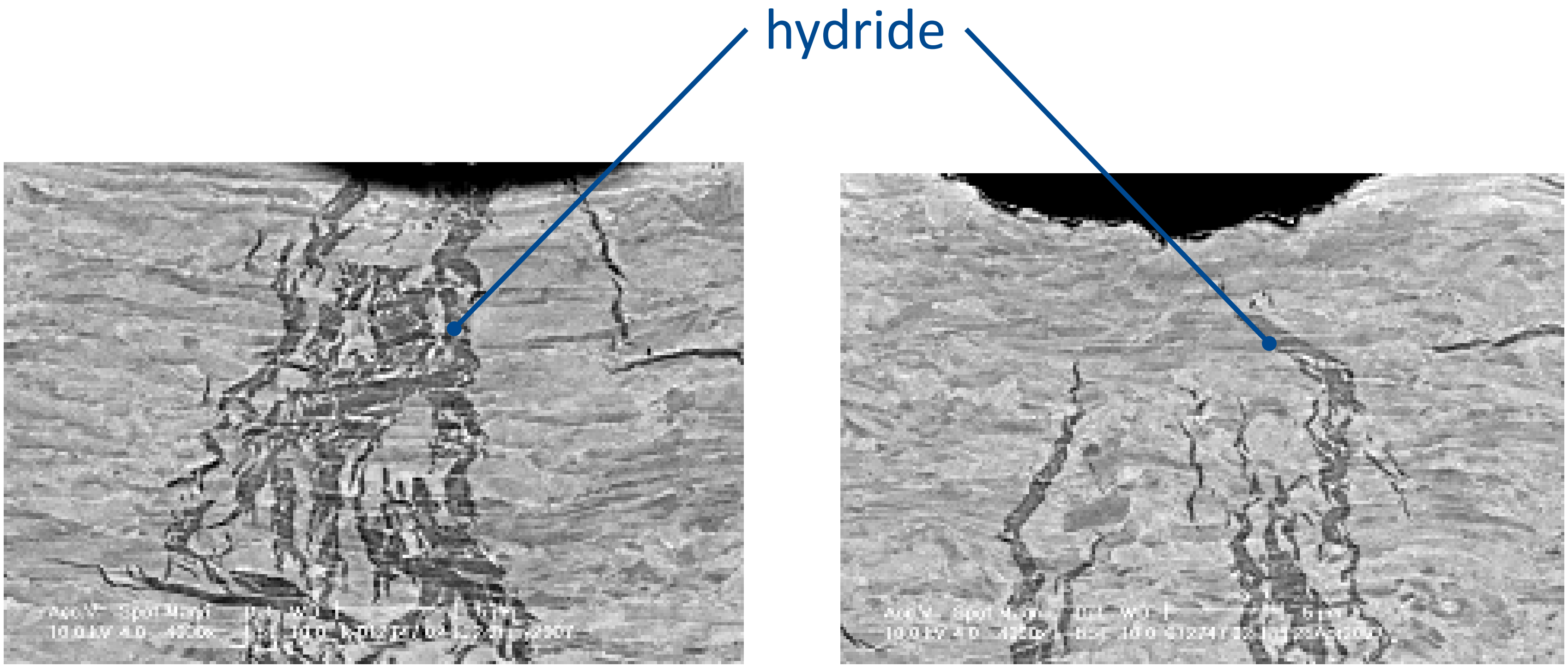
3) precipitation



If load > threshold K_{IH}, hydride cracks, stress concentration advances

4) cracking – self sustaining

Some Hydride Distributions



Delayed Hydride Cracking in Zirconium Alloys – A Review of Mechanisms, Assessment Criteria and Current Developments
E Darby, M Martin and D Scarth
TAGSI / FESI Symposium 2013 Structural Integrity of Nuclear Power Plant

What is meant by ‘Deterministic’?

A deterministic analysis will always produce the same output from a given set of initial conditions or inputs

No randomness

You get the answer in a pre-determined way for a particular set of inputs

But ‘Fully Deterministic’ has become the norm!

- Engineers set **ALL** inputs to conservative if not bounding values
- The meaning of determinism is blurred, if not lost

International Atomic Energy Agency (IAEA) Commentary

Best Estimate Plus Uncertainty

Whilst a best estimate approach to a deterministic analysis is permitted, provided that the uncertainties in the results are allowed for……

It still requires that….. *the remaining margins are adequate*

Other Statements from UK Office for Nuclear Regulation (ONR)

….an adequate margin….

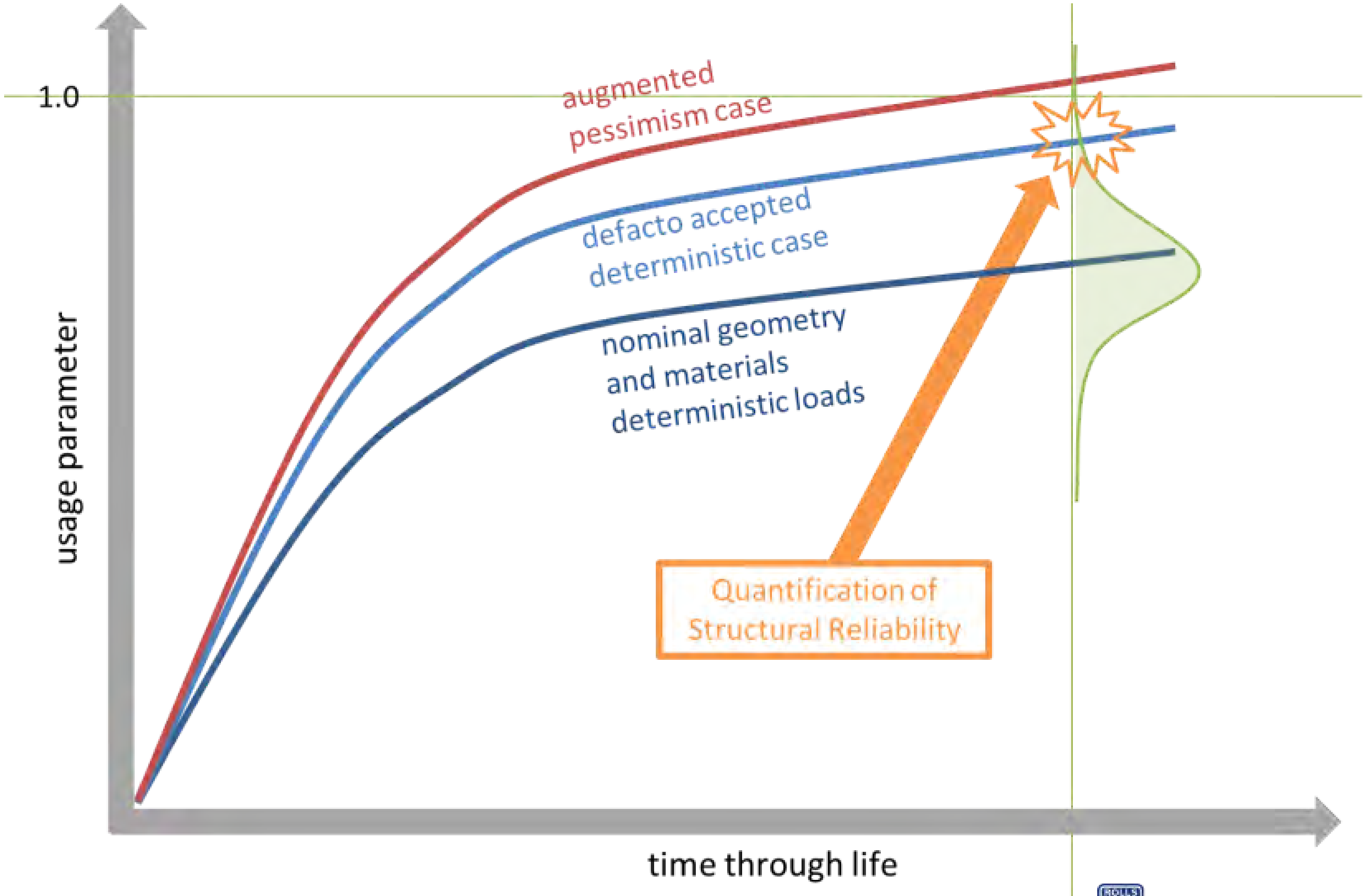
….suitably conservative….

….demonstrably conservative….

….very unlikely….

quantification required!

Setting the Scene….



Probabilistic Approaches

Hierarchy of Assessment Tools

Design Maturity
Manufacturing Data
In-Service Data
Mechanistic Understanding

Structural Justification Tools

Monte Carlo Simulation

Fast Design Tools

First Order / Second Order Reliability Methods (FORM/SORM)
Partial Safety Factors (PSFs)
Monte Carlo Simulation
Linear Perturbation Approaches
Variance Transmission Equation

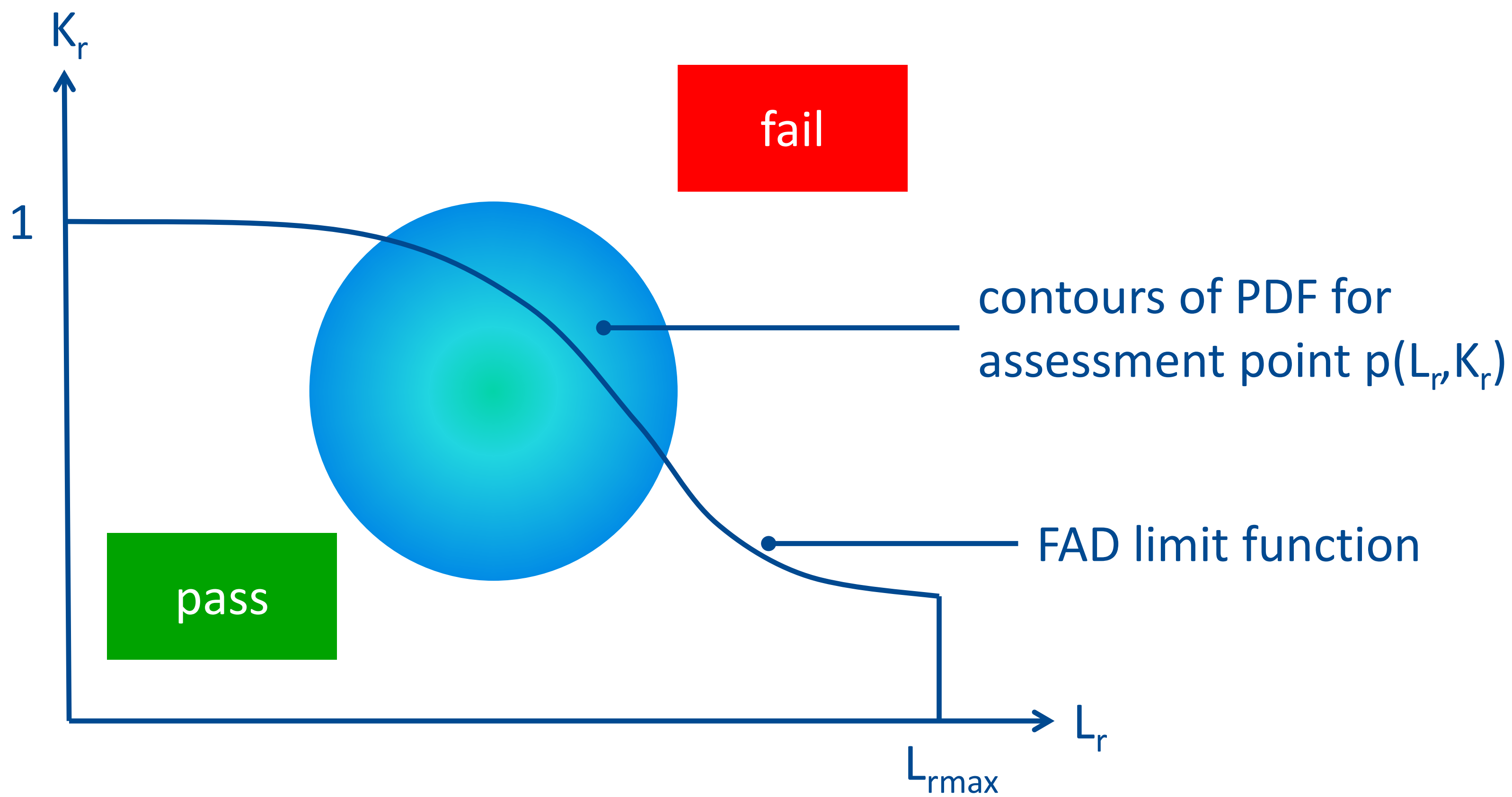
Partial Safety Factors (PSFs)

- Standard approach in structural design codes, eg BS7910, R6, ASME-FFS1/API-579, RSEM etc
- Applies tabulated factor to input data, resulting in margin to failure with quantified target reliability
- Calibrated using Monte Carlo simulation and FAD
- Rolls-Royce currently evaluating this approach with TWI (Cambridge UK)

Variable	COV	2.3×10^{-1} β=0.739	10^{-3} β=3.09	7×10^{-5} β=3.8	10^{-5} β=4.27	10^{-7} β=5.2
Stress	….	….	….	….	….	….
Flaw size	0.1	1.0	1.4	1.5	1.7	2.1
	0.2	1.05	1.45	1.55	1.8	2.2
	0.3	1.08	1.5	1.65	1.9	2.3
	0.5	1.15	1.7	1.85	2.1	2.5
Toughness	….	….	….	….	….	….
Yield strength	….	….	….	….	….	….

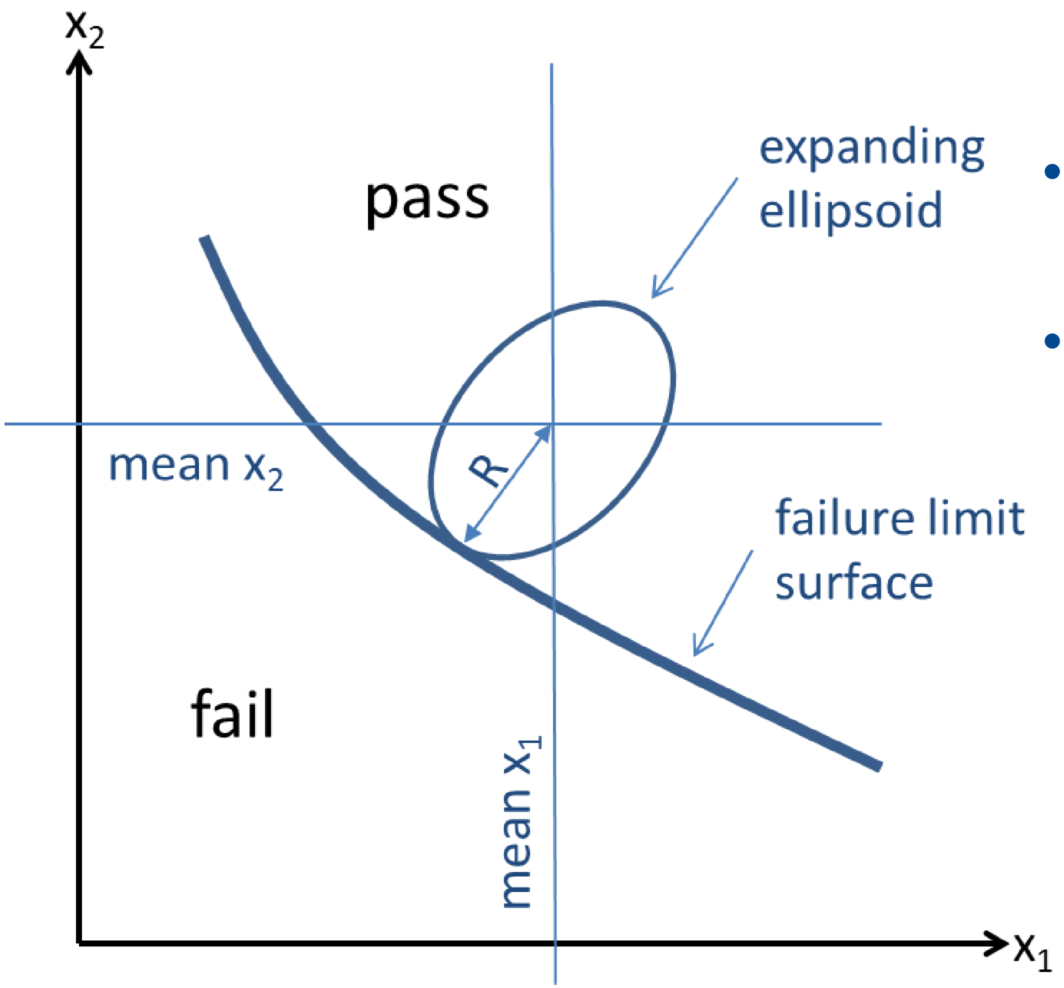
Extract from BS7910 Table K.4

Failure Assessment Diagram (FAD) Probabilistic Visualisation



A review of methods and applications of reliability analysis for structural integrity assessment of UK nuclear plant
R Bullough et al, Int J Pressure Vessels and Piping 76(1999) 909-919

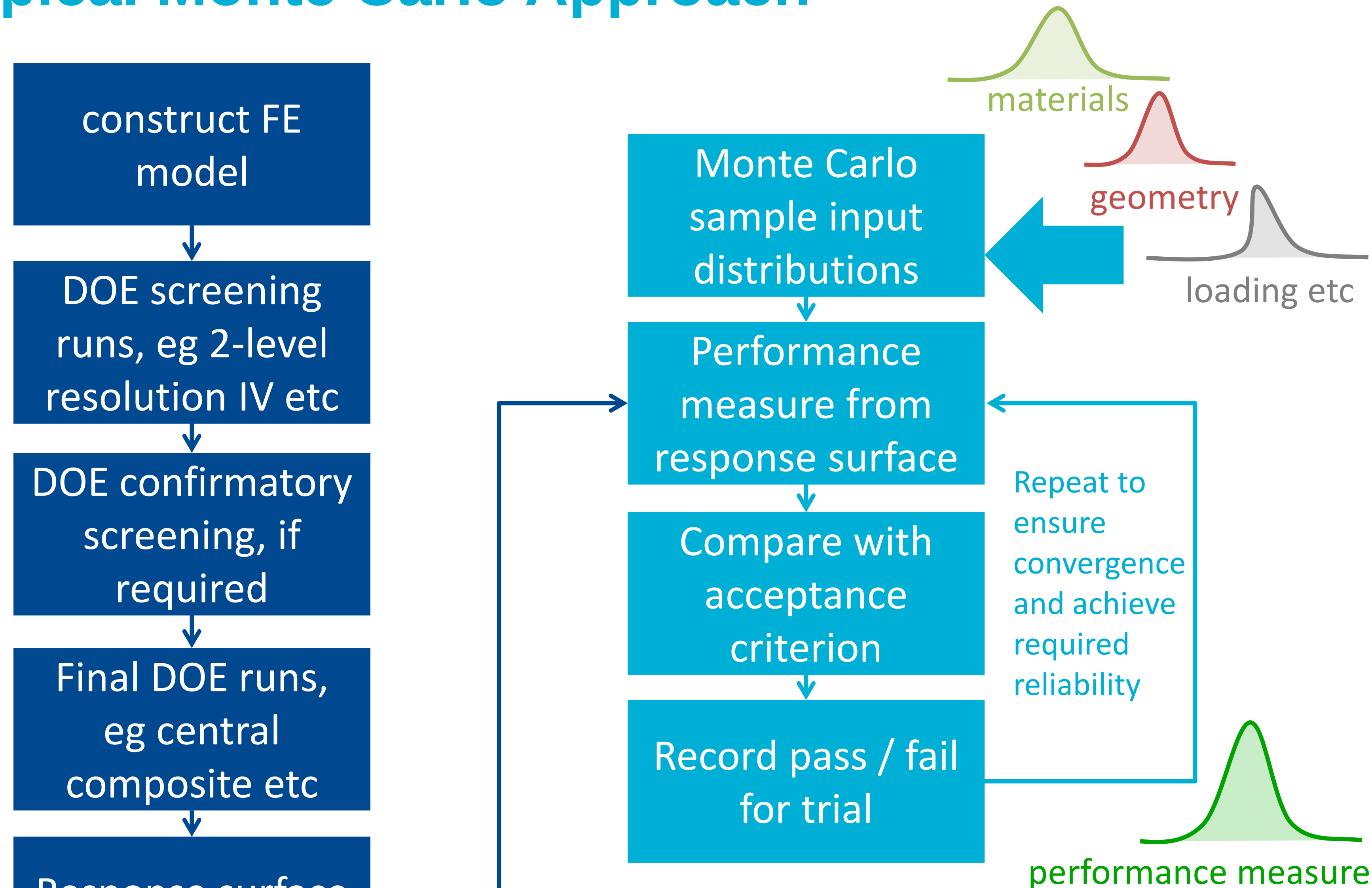
First / Second Order Reliability Methods (FORM / SORM)



- Well established in oil and gas, aerospace, geotechnical….
- Assumption of normality
- Available in software and rapid spreadsheet applications possible in original variable space

FORM, SORM, and spatial modeling in geotechnical engineering
B K Low, Structural Safety 49(2014) 56-64

Typical Monte Carlo Approach



Predictive Capability

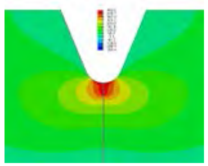
Development of DHC predictive capability

A Comparison of Finite Element Cohesive-Zone Modelling with the Process-Zone Approach for the Prediction of Delayed Hydride Cracking
M Martin, PVP2013-97077, Proceedings of ASME PVP, Paris, France 2013

Stage 1
process-zone
CSA N285.8

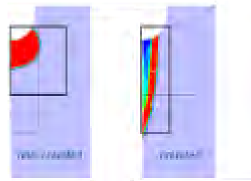
Stage 2
process-zone /
FE cohesive-zone

arbitrary geometry



Stage 3
simple coupled
cohesive-zone

transformation
strain feedback

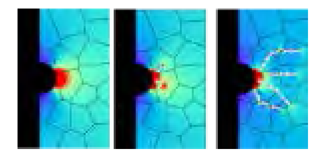


Stage 4
continuum
coupled
cohesive-zone

hydride failure
behaviour

Stage 5
coupled explicit
Microstructural

microstructural
influence



2016 | 2017 | 2021

basic model data, eg KIH

hydride cohesive behaviour

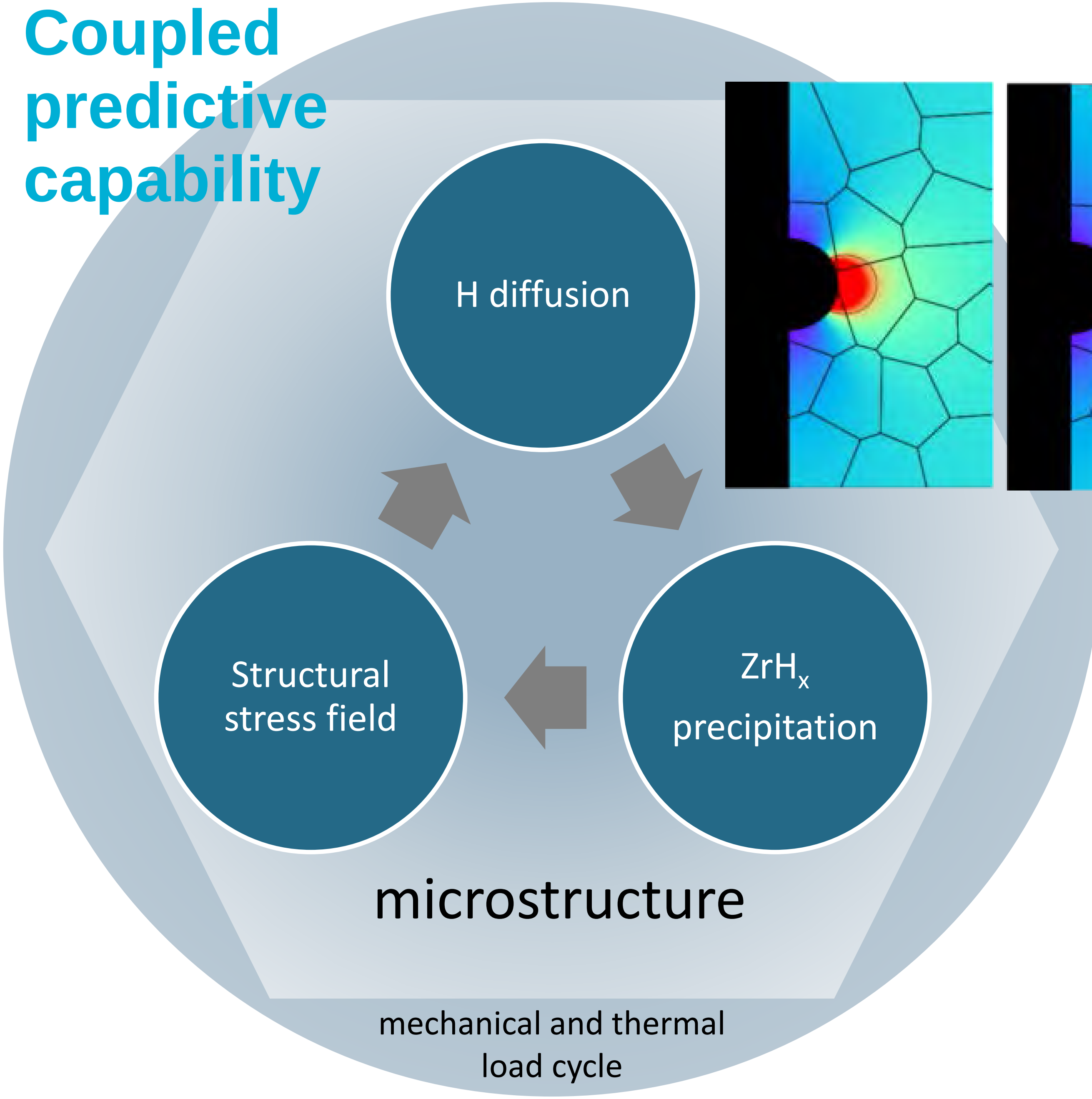
TSS and precipitation

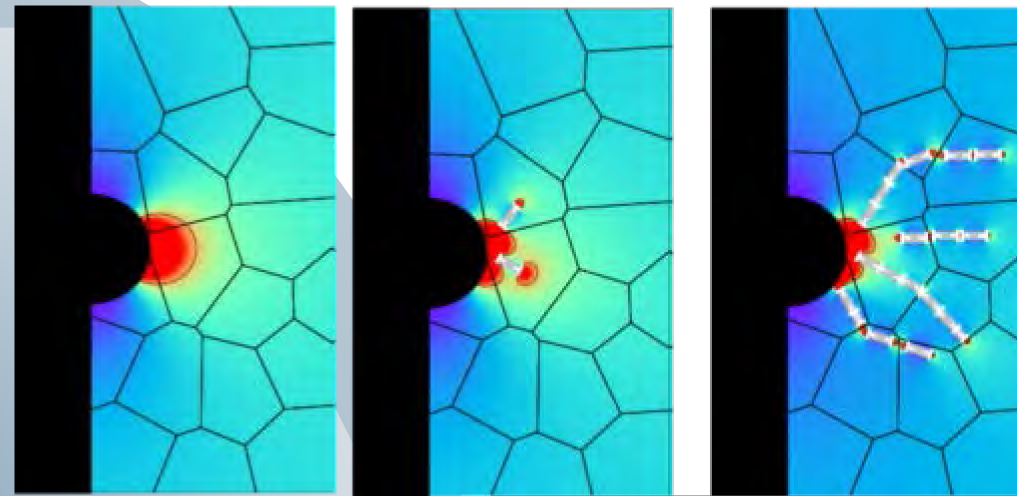
microstructure

Data requirements

Rolls-Royce

Coupled predictive capability

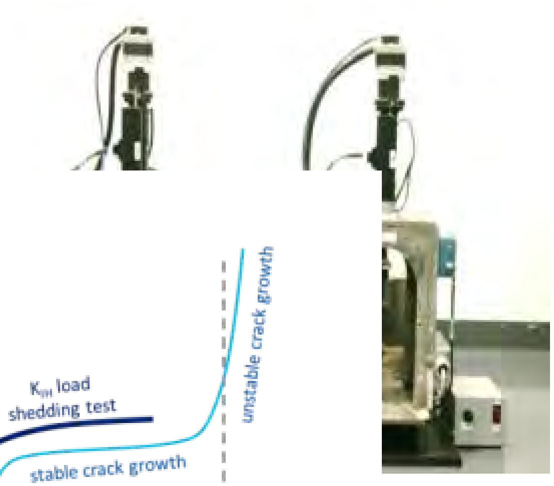


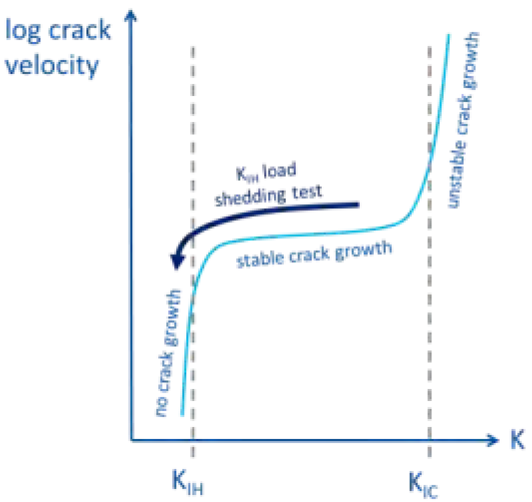


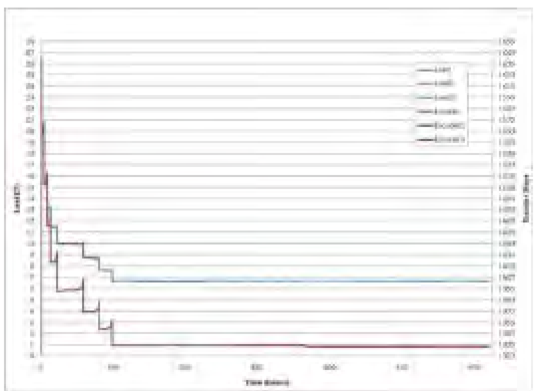
M Patel, Imperial College, 2015
Multiscale modelling of DHC

Validation Testing at Canadian Nuclear Laboratories (CNL)

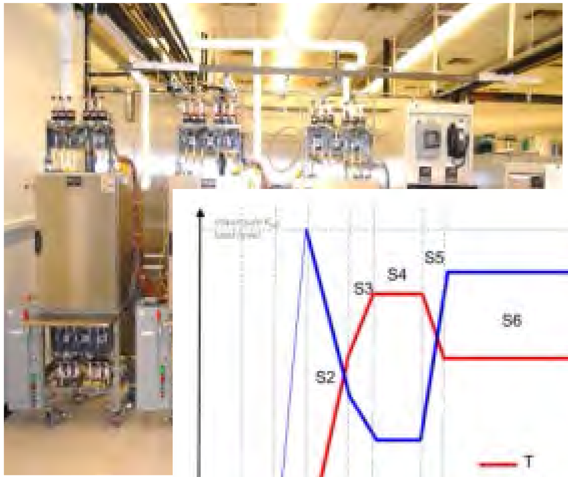
KIH Rigs

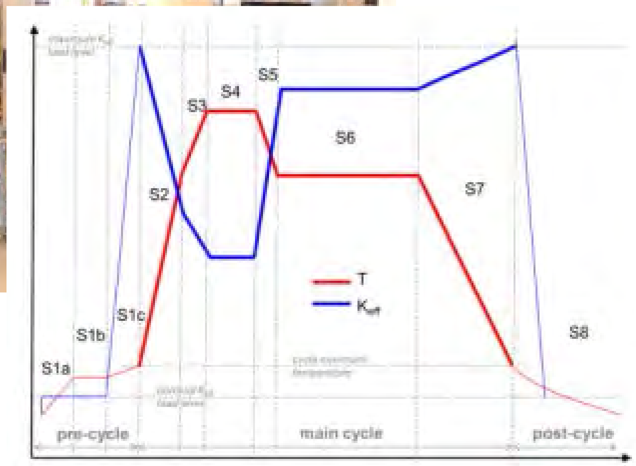




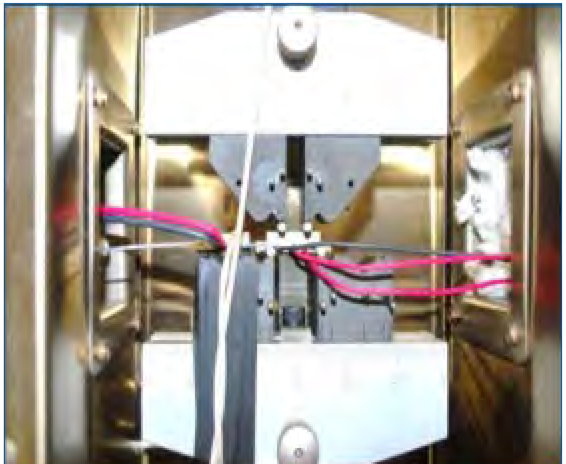


Cycling DHC Rigs





Fatigue Initiation Rigs



Rolls-Royce

Wider Industrial and Academic Network

Rolls-Royce
Nuclear UTC

Imperial College London

HEXMAT

Mitesh Patel 2014
Multiscale modelling of DHC
David Wilson 2015
Mechanistic fatigue initiation model
Said el Chamaa 2016
DHC Characterisation

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Rolls-Royce

KINECTRICS

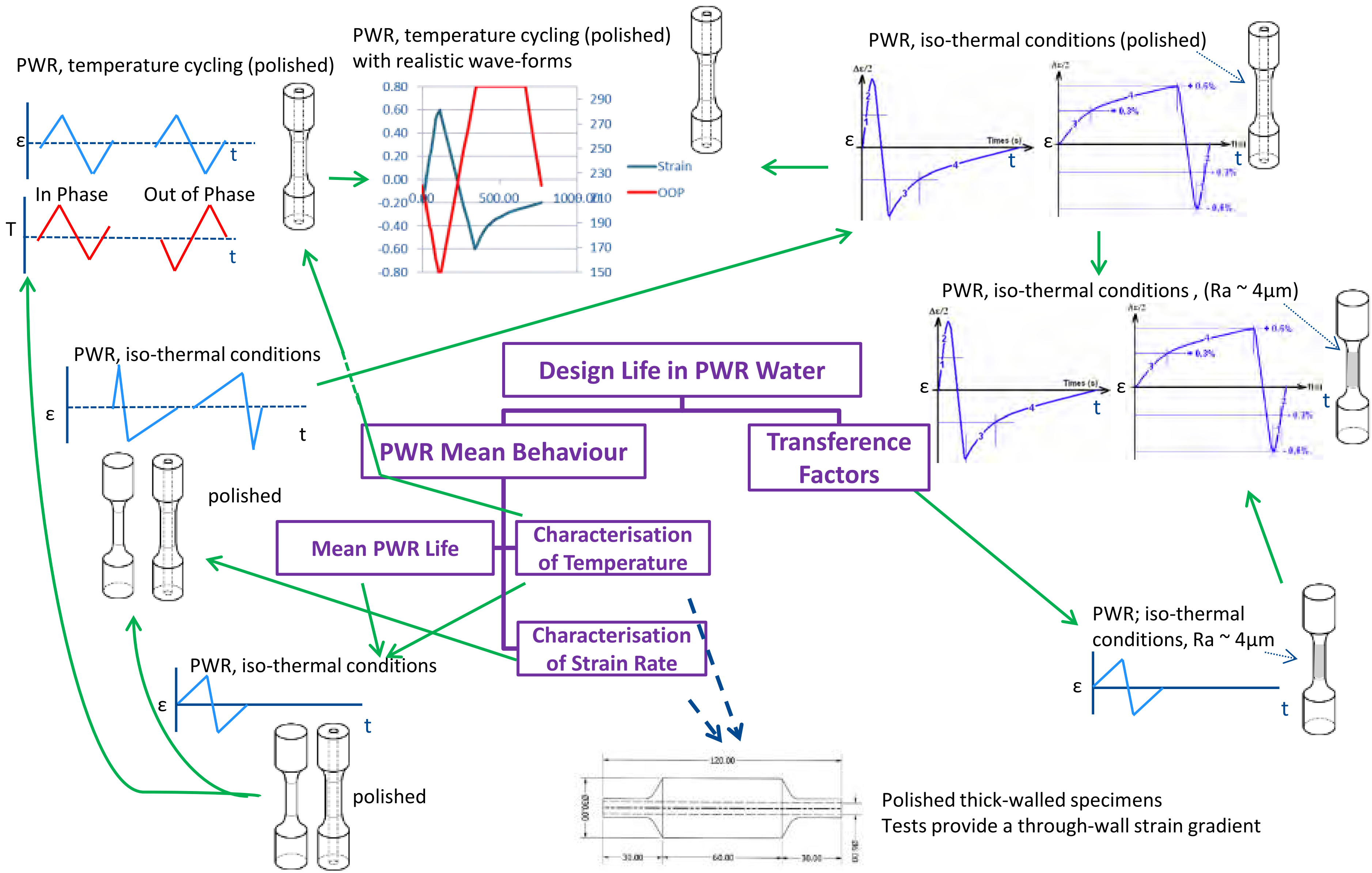
Queen's University

Planned 2017
CSA Industrial coupled model
Experimental validation

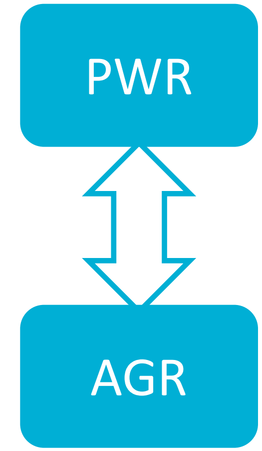
MANCHESTER 1824
The University of Manchester

Planned 2017
Further characterisation work to support models

Testing of Plant-Realistic Loading



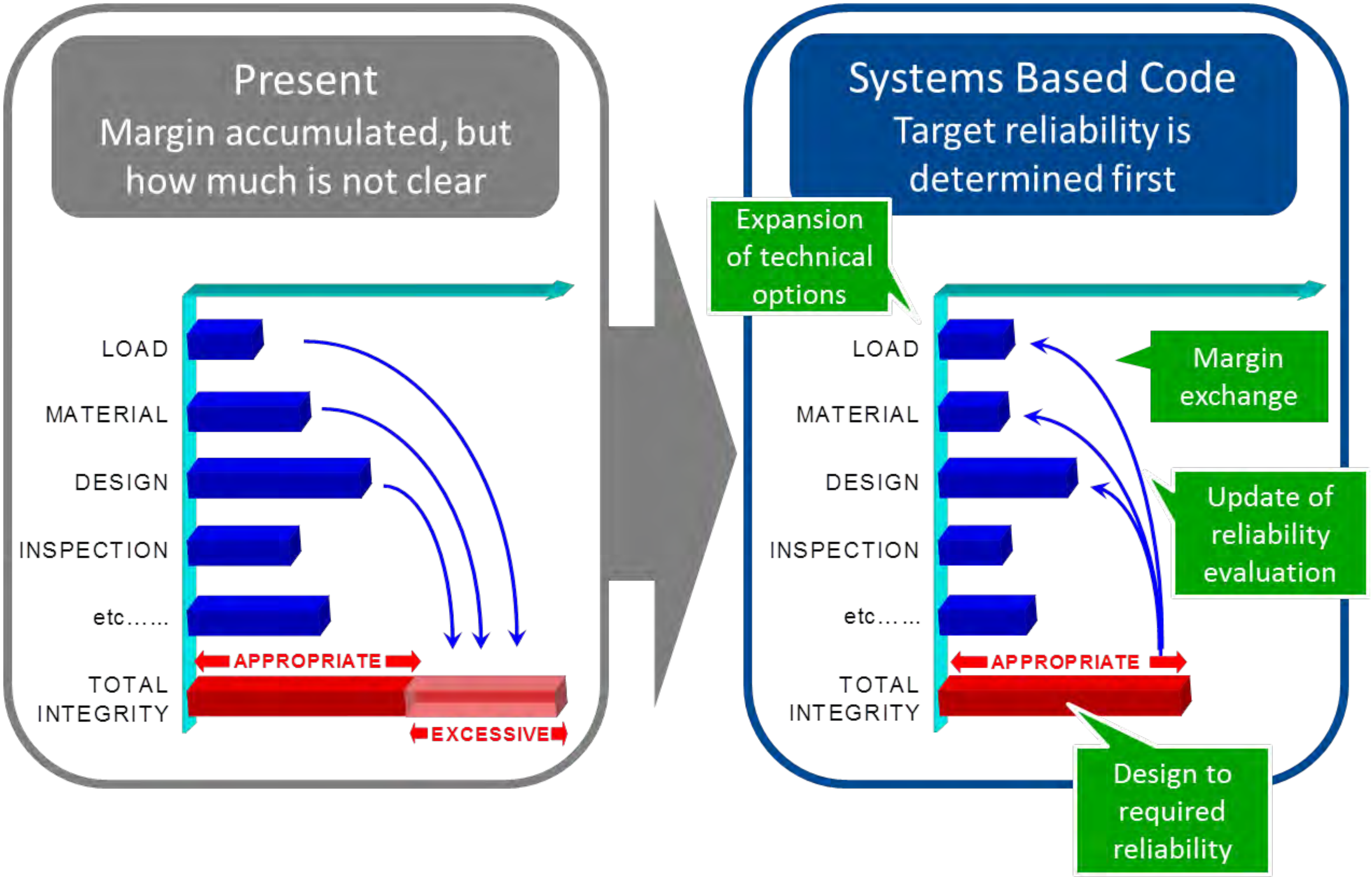
A Way Forward – Total Life Prediction



- Synergy with EDF R5 high temperature approach, particularly at strain gradient
- Life to leakage apportioned:
  - Nucleation / Initiation $$N_{initiation} = A(\Delta\varepsilon)^{b}$$
  - Short growth $$\frac{da}{dN} = B(\Delta\varepsilon)^{c}$$
  - LEFM fatigue crack growth $$\frac{da}{dN} = C(\Delta K)^{d}$$
- Consequence based reliability target and probabilistic consideration of the inputs required .

Systems Approach

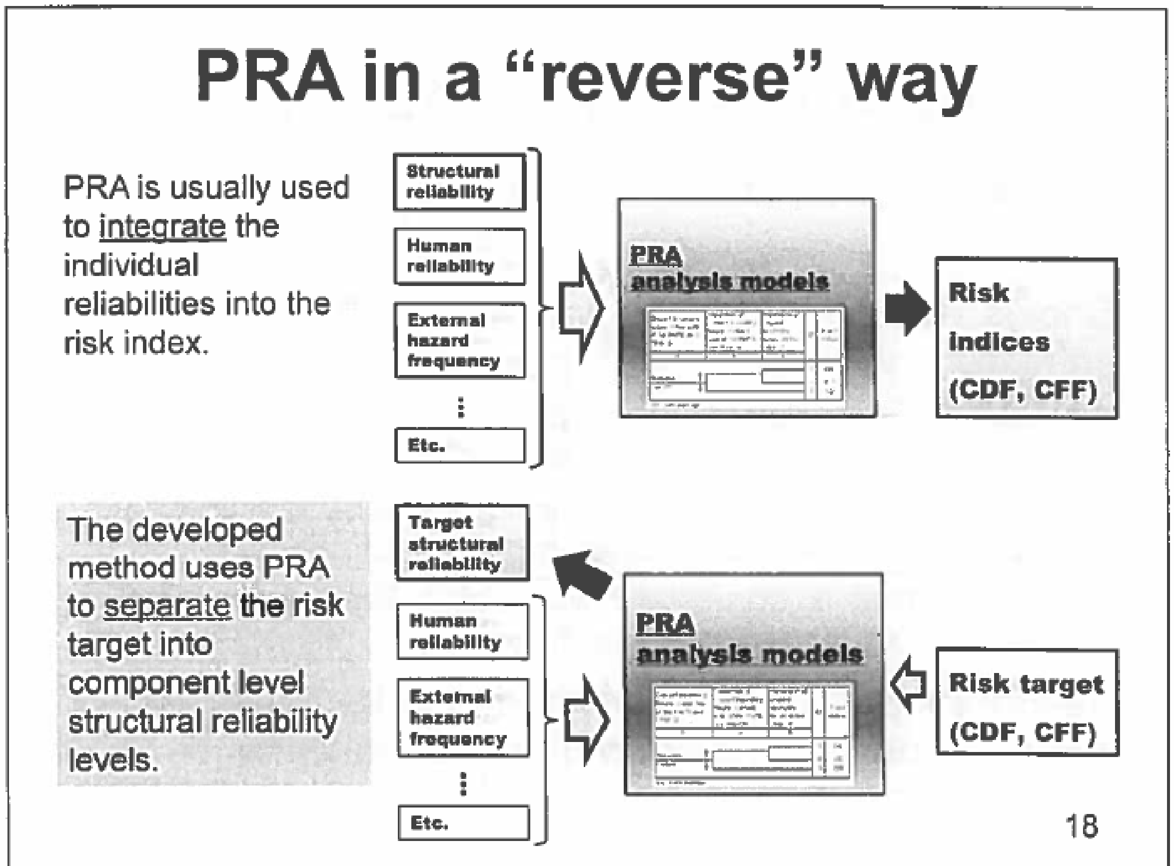
Systems-Based View



Adapted from Systems Based Code – Principal Concept
Y Asada et al, Proceedings of 10th International Conference on Nuclear Engineering, 2002

Proposed Derivation of Target Reliabilities

- Therefore need to be better informed and work back from the core damage frequency targets / plant level safety criteria
- Use of PSA fault tree & Proportion of risk allocated to each system



JSME proposal and ASME Section XI RIM Task Group

Still a need to allow for uncertainties

Development of System Based Code (1) Reliability Target Derivation of Structures and Components
K Kurisaka et al, Journal of Power Energy Systems, JSME, JP, 5, 19-32

Rolls-Royce

Target Reliabilities as Acceptance Criteria

- Assuming our predictive capability is sufficiently developed and validated by testing, what then?

- An acceptable **Fully Deterministic** approach is unlikely for limiting components due to number of inputs involved
- A probabilistic consideration of inputs is required to establish a margin to the best estimate predicted total life. That margin needs to exceed the target reliability derived from an understanding of the contribution to core damage
- Calibrate partial safety factors to achieve the reliability required

Summary

Summary 1

- Higher fidelity modelling provides improved mechanistic understanding of key failure modes of industrial importance

- Coupled analysis paves the way for more integrated analysis approach and improved understanding of contribution to overall reliability

- Academic and wider industry network essential to delivery, as is IT infrastructure

- Regulator engagement throughout is key

Summary 2

- The traditional ASME one-size fits all approach to fatigue is **too conservative**. Deterministic approaches hide behind unquantified margins – not tolerable when compounded as with environmental effects
- We are more informed about environmental effects, certainly on laboratory specimens, but to claim benefit we need **Total Life Prediction**
- Mechanistically informed predictive capability for nucleation and short crack behaviour is required to demonstrate **target reliabilities**
- We need to translate plant level safety criteria to system and component target reliabilities: **Understanding target reliabilities is still some way off !**

Thank You for Listening!