Project EASICS UK AMR Probabilistic Structural Integrity Guidance

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Presentation RG04, October 7, 2024

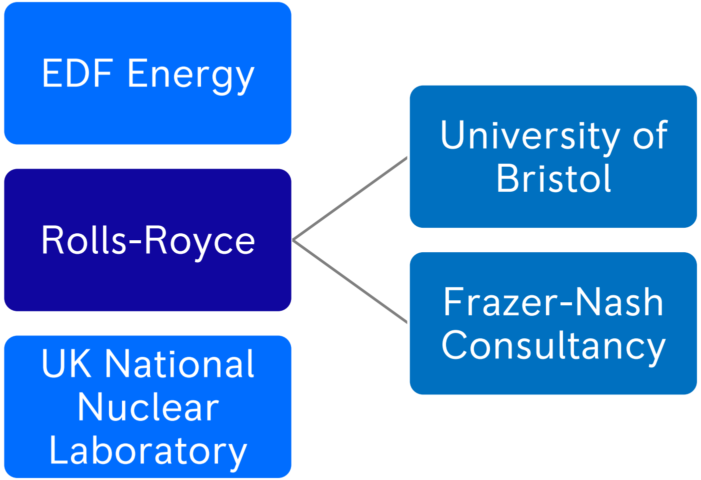
Agenda

01

Background and Introduction to EASICS

EASICS pronounced as ‘E-six’

Establishing AMR Structural Integrity Codes and Standards for UK GDA



- BEIS* Advanced Manufacturing and Materials Phase 2 Project 2019 – 2022
- BEIS Codes & Standards Phase 1 project highlighted shortfall in guidance for AMRs
- EDF Energy led collaboration with Rolls-Royce and UK National Nuclear Laboratory
- Four Work Packages (WPs), with **WP1 focused on the development of probabilistic structural integrity guidance**
- WP1 led by Rolls-Royce and supported by Frazer-Nash Consultancy, UK National Nuclear Laboratory and University of Bristol

**BEIS Former UK Gov. department for Business, Energy and Industrial Strategy*
GDA Generic Design Assessment

SI Codes and Standards Context

- Nuclear SI ‘lifing’ practice is predominantly deterministic using ‘stress-based’ codes such as ASME III, based on **arbitrary factors** applied to inputs
- Leads to **inconsistent** measure of margin to failure (and what does failure actually mean?)
- Tends to result in the **accumulation of pessimism** at the local component / feature level and difficult to evaluate wider system interactions
- Probabilistic and Structural Reliability approaches are considered to provide a **more balanced** approach to evaluating risk and focus of effort
- Probabilistic and deterministic are **complementary** approaches, not polar opposites
- Improvement in **awareness** needed

- Contrasts with Limit State codes such as ISO2394
- Also notable exceptions such as AGR graphite

The Three Ages of Probabilistic SI….

Traditional	Current	Future
• Applied to in-manufacture / operational designs • When deterministic approach demonstrates shortfall	• Applied to conceptual / in-manufacture / operational designs • To improve understanding of margin, sensitivity and enable design space trades	• Embedded in data-centric life-cycle model • To enable as-built and as-operated substantiation (digital twin)

Sound Engineering Practice

ONR non-prescriptive goal-setting environment

EASICS WP1 Objectives

- Provide **procedural guidance** for probabilistic SI, for UK AMR application in support of GDA that could be incorporated in recognised procedure / codes and standards (eg R5, ASME)
- **Principles-based with pan-design applicability** to all components, material degradation mechanisms and structural failure modes, eg fracture, creep rupture, creep-fatigue initiation, crack growth and distortion / deflection based performance are within scope
- **Not restricted to components with a particular level of safety classification** and can be applied to all, including those with the highest reliability requirements
- Use a **data-centric lifecycle approach** throughout the lifecycle starting with early-stage maturity scoping studies and design trade studies leading towards the assessments required for UK GDA
  - Enable the data generated throughout the lifecycle to inform the SI assessment, eg in-service-inspection (ISI) and structural health monitoring (SHM)
- **Emphasis on simplicity** with a hierarchy of approaches

02

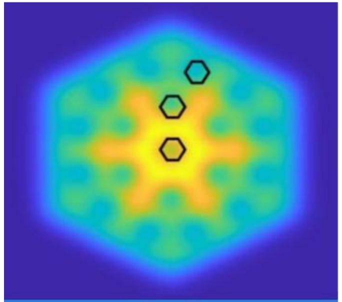
Case Studies and Procedural Guidance

EASICS

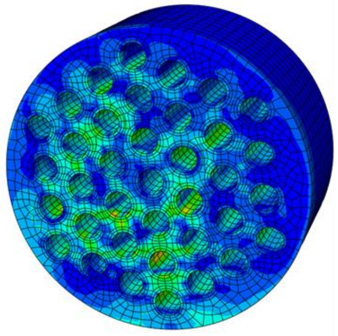
Establishing AMR Structural Integrity Codes and Standards for UK GDA

BEIS Advanced Manufacturing and Materials Phase 2

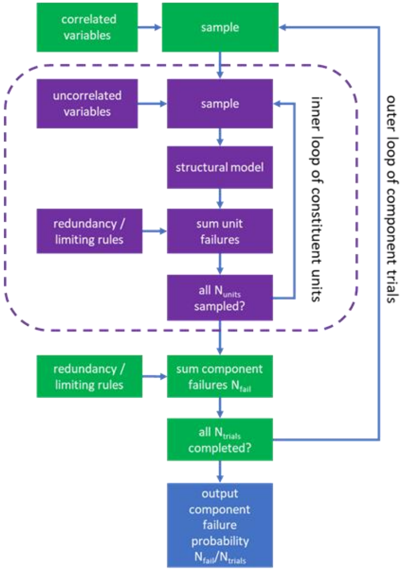
Work Package 1
Structural Reliability Approaches



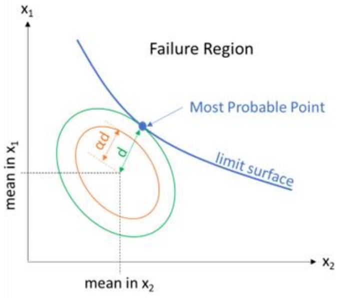
Prototypical Case Studies



Procedural Guidance



	Method	Robustness	Accuracy	Precision	Cost	Difficulty
Level-1 methods	Partial factors	Med	Low	Low	Low	Low
	Pseudo-stochastic	Med*	Med	Med**	Low	Low
Level-2 methods	FORM	Low	Med	Med	Low	Low
	SORM	Med	Med	Med	Low	Low
	FOSM	Low	Med	Med	Low	Low
Level-3 methods	Semi-analytical	High	High	High	Low***	High
	Monte-Carlo	High	High**	Med**	High**	Low
	Surrogate Monte-Carlo	High	High**	Med**	Med	Med



Methods Toolbox

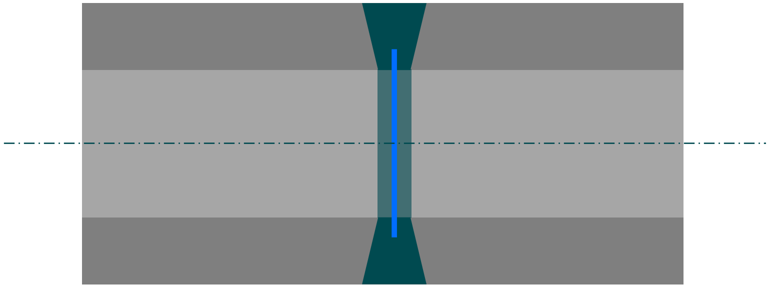
Recommendations

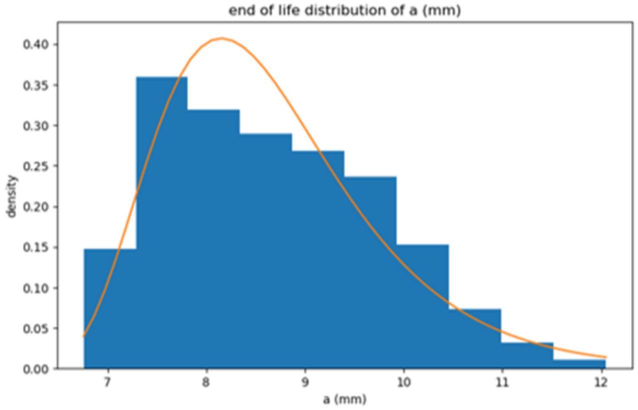
1. Decision on AMR codes & standards direction required, R5 is a strong contender
2. Immediate ONR engagement
3. Immediate application of Level 2 and Level 3 approaches to AMR design studies
4. Define component target reliability from AMR system-level analyses
5. Apply to AMR life-cycle trades and understand data worth
6. Further investigation and validation of Level 1 calibrated design chart approaches
7. Ensure practical approach for management of correlations
8. Develop validated degradation models for novel materials
9. Develop data-centric approach and associated techniques to provide operational insight
10. Engagement and dissemination beyond nuclear field to recognise cross-sector synergies, particularly data methods and life-cycle management

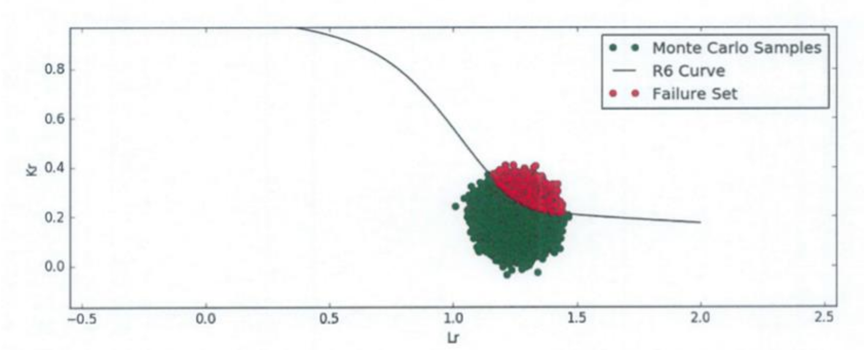
Application of Probabilistic SI to Operational Data

M Martin, R Marshall, P Reed, Data-Centric Structural Integrity Assessment and Risk-Informed Asset Management using Operational data and Probabilistic Updating, PVP2022-84526, Las Vegas, July 2022

- Pressure retaining pipe with fully extended weld defect
- R6 assessment procedure using Option 1 FAD accounting for fatigue crack growth
- Monte Carlo simulation using random sampling from input distributions of material properties and geometry – cracks grown to end-of-life using sampled values

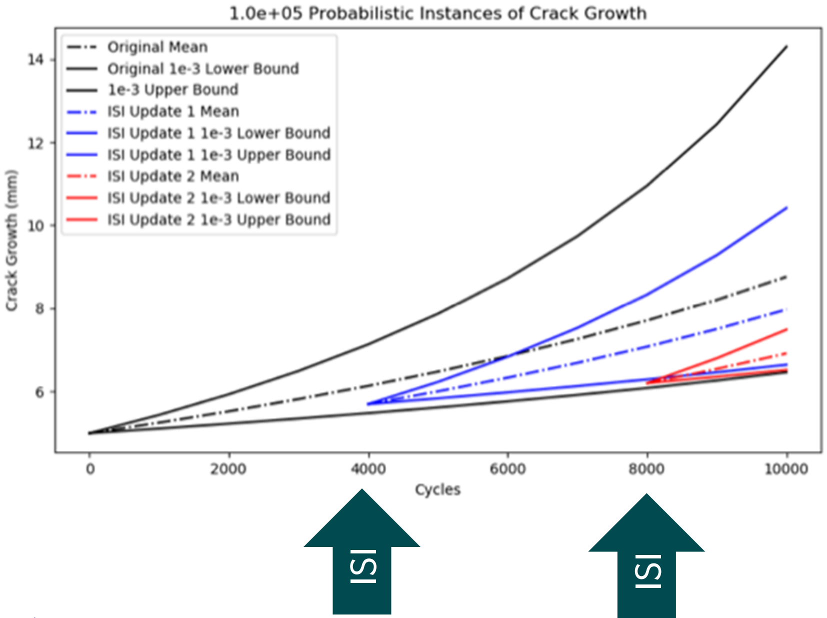




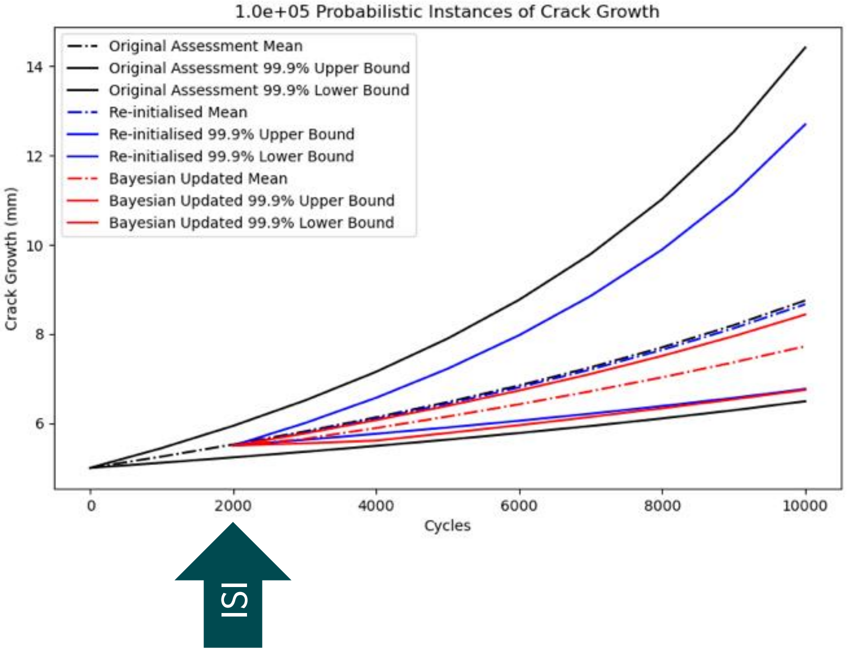


Application of Probabilistic SI to Operational Data – Reliability Updating using In-Service Inspection (ISI)

1) Simple ‘re-setting the clock’ at ISI interval



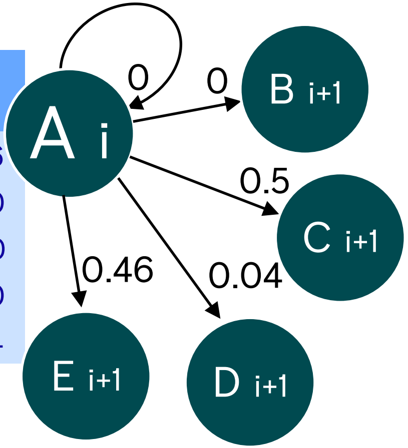
2) Application of Bayesian inference together with ISI

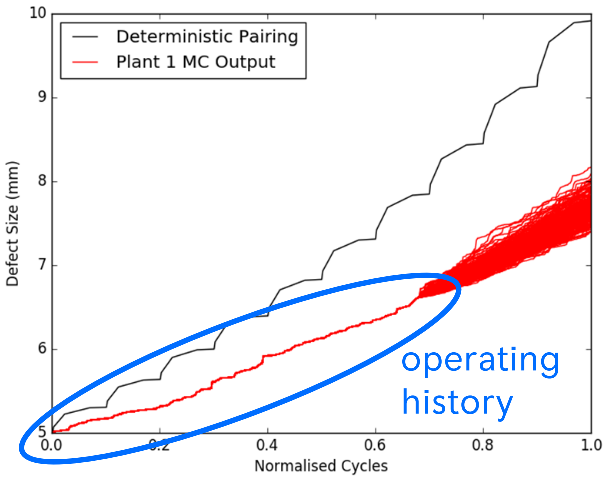


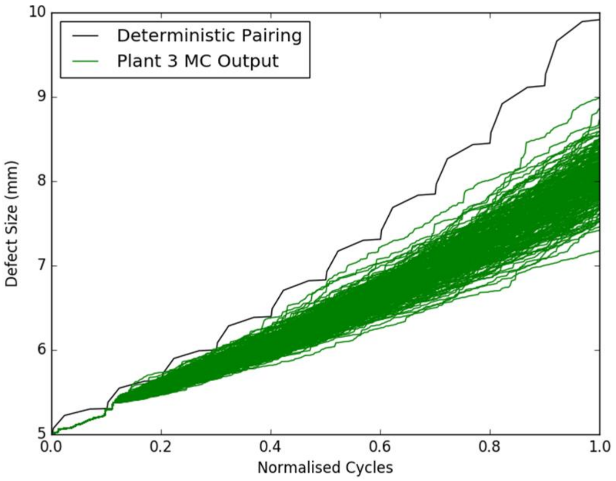
Application of Probabilistic SI to Operational Data – Reliability Updating using Fleet Data

- In fatigue crack growth assessment, typical to pair transients and order sequence of events to maximise damage, potentially highly conservative with unrealistic combinations
- Information on actual transient sequence can be informed by operating data and historical data if available, can be used to generate probability matrix of transient sequence
- Markov-Chain Monte Carlo used to sample transient sequence together with input data
- Opportunity to combine fleet data to inform transient probability matrix and basis for optimising inspection strategy

Transient (i)	Probability of Transient (i+1)				
	A	B	C	D	E
A	0.00	0.00	0.50	0.04	0.46
B	0.00	0.00	0.20	0.00	0.80
C	0.16	0.33	0.51	0.00	0.00
D	0.20	0.00	0.00	0.00	0.80
E	0.05	0.40	0.00	0.01	0.54



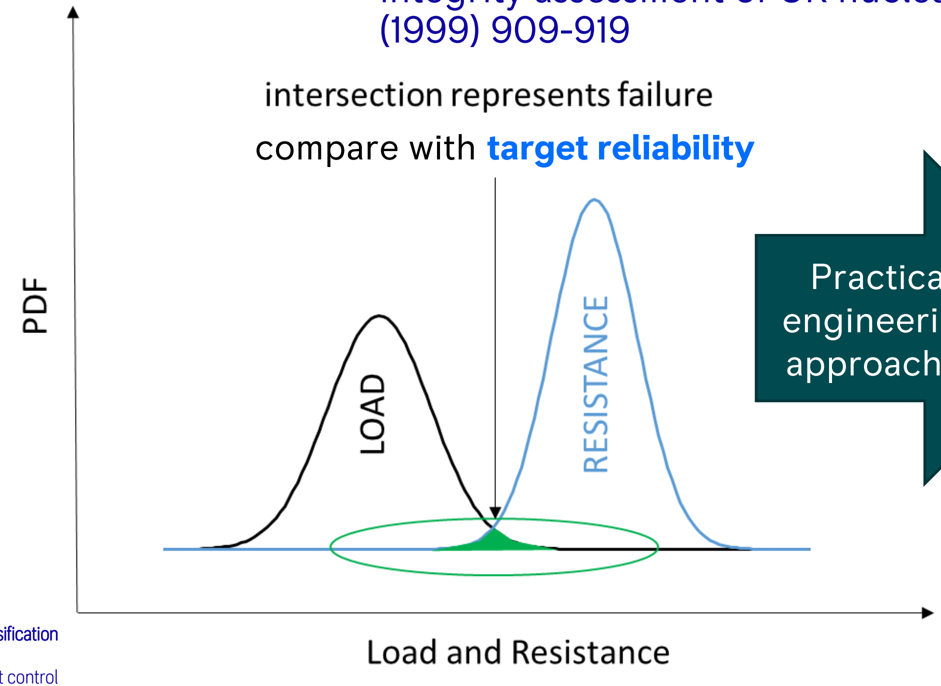


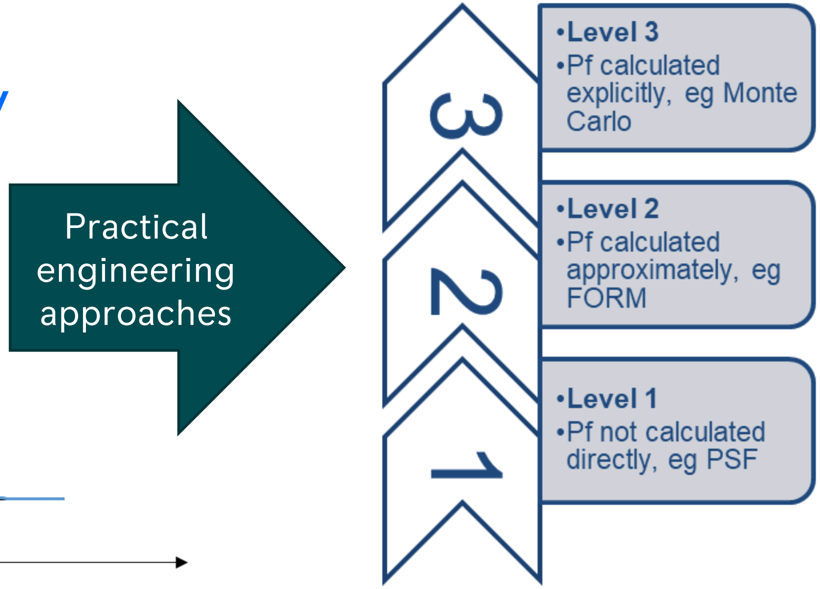


Procedural Guidance

TAGSI The UK Technical Advisory Group on the Structural Integrity of High Integrity Plant
FORM First Order Reliability Method
PSF Partial Safety Factor

- Follows well-established approach from 1999 **TAGSI** subgroup
- R Bullough, VR Green, B Tomkins, R Wilson, JB Wintle, A review of methods and applications of reliability analysis for structural integrity assessment of UK nuclear plant, Int. J. Pres. Ves. Piping 76 (1999) 909-919





Level 3

Select the sampling scheme

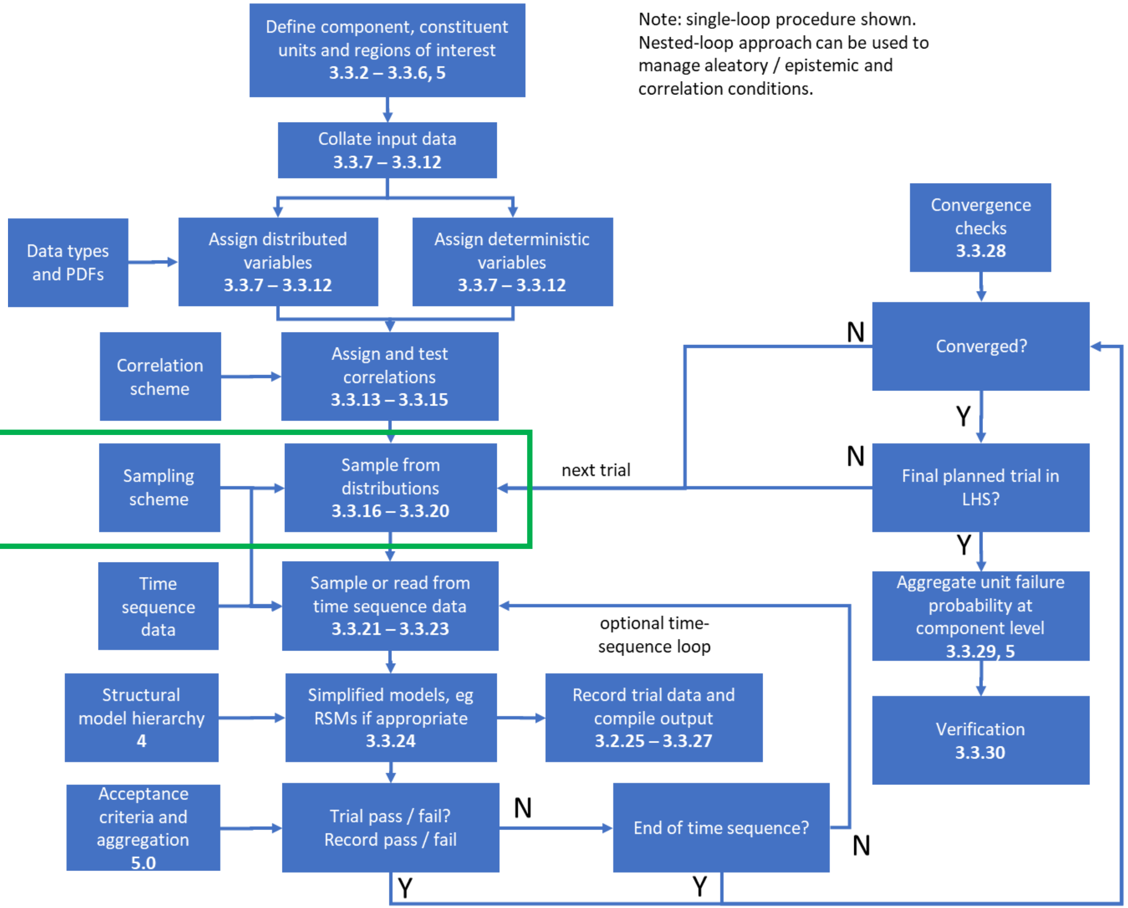
3.3.16 There are several options for implementing the Level 3 sampling scheme, including the use of a brute-force technique such as Monte Carlo Sampling (MCS), a more efficient procedure such as Latin Hypercube Sampling (LHS), or Markov Chain Monte Carlo (MCMC) for more complex scenarios.

3.3.17 LHS requires the generation of the hypercube ahead of the structural analysis stage, and therefore the deterministic input set for each trial is known at the start of the analysis. LHS ensures the full range of each parameter is sampled sufficiently, on its own and in combination with the other parameters. The hypercube splits each parameter distribution into 'bins' of equal probability and each of these bins is then sampled exactly once. The bin ranges are of different sizes to achieve the equal probability requirement. The approach constrains the number of bins to be the same for each distributed variable and the number of bins is equal to the number of trials required to complete a simulation.

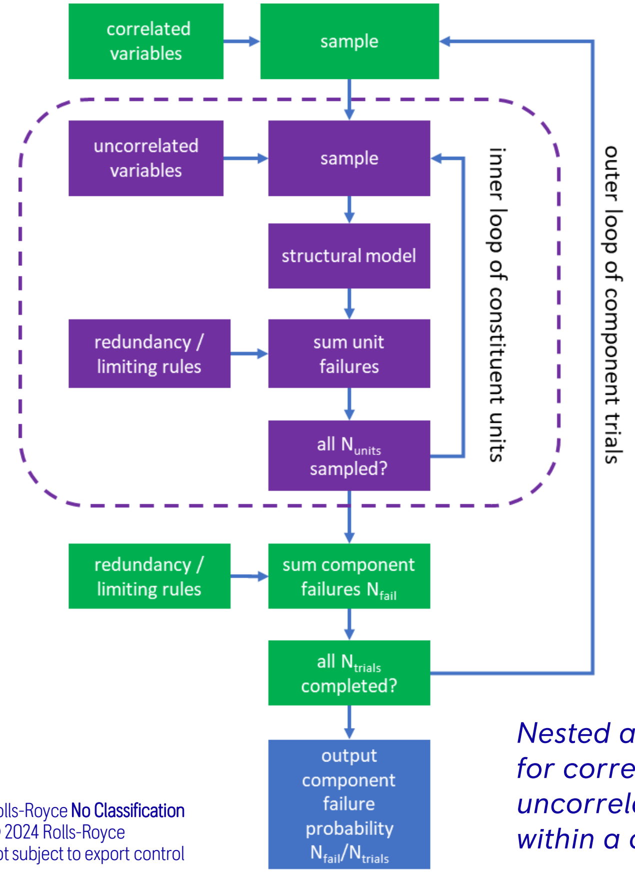
3.3.18 The number of bins selected relates directly to the maximum number of standard deviations from the mean which is sampled. LHS is unable to sample a large number of standard deviations with a small number of trials because the number of trials equals the number of bins, and this would conflict with the requirement for bins of equal probability.

3.3.19 Standard algorithms exist for generation of the Latin hypercube, for example as described in Reference 21, and used in the case studies (Reference 5 – 8). LHS modules are also available in commercial software and open-source programming languages such as Python. LHS can result in a paucity of samples from the extremities of the distributions, in the proximity of the hypercube vertices. Techniques such as orthogonal sampling can be used to improve sampling of the extremities by splitting the hypercube to a secondary set of subspaces which must also have exactly one sample. There are also various importance based sampling schemes available that seek to increase the number of samples in the regions of interest from the distributions – a further description of such techniques is beyond the scope of this guidance.

3.3.20 The use of MCS and LHS relies on the ability to evaluate the cumulative density function of the joint distribution of the probabilistic variables. In some cases, the cumulative density function may be intractable to evaluate, but the probability density function may be tractable. In such cases, MCMC techniques provide a means to produce a sample using a 'random walk' through the solution space. These techniques are frequently required when conducting Bayesian updating using operating data. Further details of sampling methods are provided in Reference 4.



Repeating Units



- Guidance provided on aggregation of failure probability at component level resulting from:
  - Repeating units, and regions within units
  - Correlation between units
  - Limiting / redundancy
  - synergistic effects in degradation mechanisms

Nested approach for correlated and uncorrelated units within a component

03

Future Direction

The TAGSI Four-Legged Approach to SI Safety Case

T·A·G·S·I

The UK Technical Advisory Group on the Structural Integrity of High Integrity Plant

The demonstration of incredibility of failure in structural integrity safety cases, R. Bullough, F.M. Burdekin, O.J.V. Chapman, V.R. Green, D.P.G. Lidbury, J.N. Swingler, R. Wilson, Int. J. Pres. Ves. Piping 78 (2001) 539-552

1. Good Design and Manufacturing Experience

- Well defined loading and temperatures
- Good design based on historical experience
- Good choice of materials
- Good manufacture
- Pre-service inspection
- Good operation and maintenance
- Control of modifications
- Well-defined operator action

2. Testing

- Pressure test
- Proof test analysis including degradation

3. Failure Analysis

- Ma... determination
- Pre-service inspection
- In-service defect growth
- Materials ageing and degradation determination
- Fracture analysis (warm pre-stressing, recharacterisation following snap-through, stable tearing, dynamic crack arrest)

4. Forewarning of Failure

- Leakage monitoring
- Recharacterisation following snap-through
- Material monitoring
- Plant monitoring of operating parameters and precursor events
- Operational feedback from other plant
- Appropriate action in the event of abnormailities

<u>Reflections from practical application:</u>

- Bullough paper discusses worth and time-dependency of legs
- but balance of legs difficult to quantify
- and current approach not amenable to updating with new data

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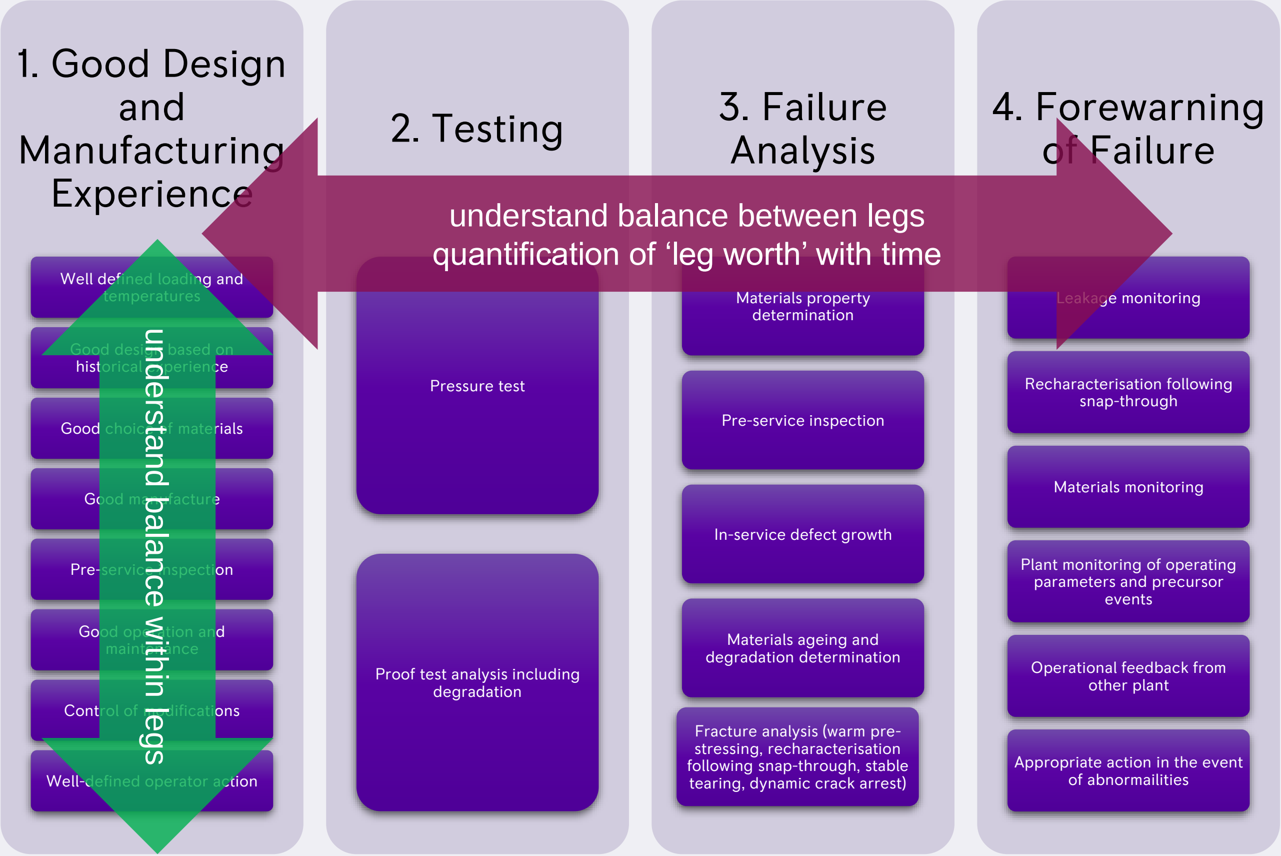


EDF Energy

Imperial College London

The University of Manchester

University of Bristol

UKRI Science and Technology Facilities Council

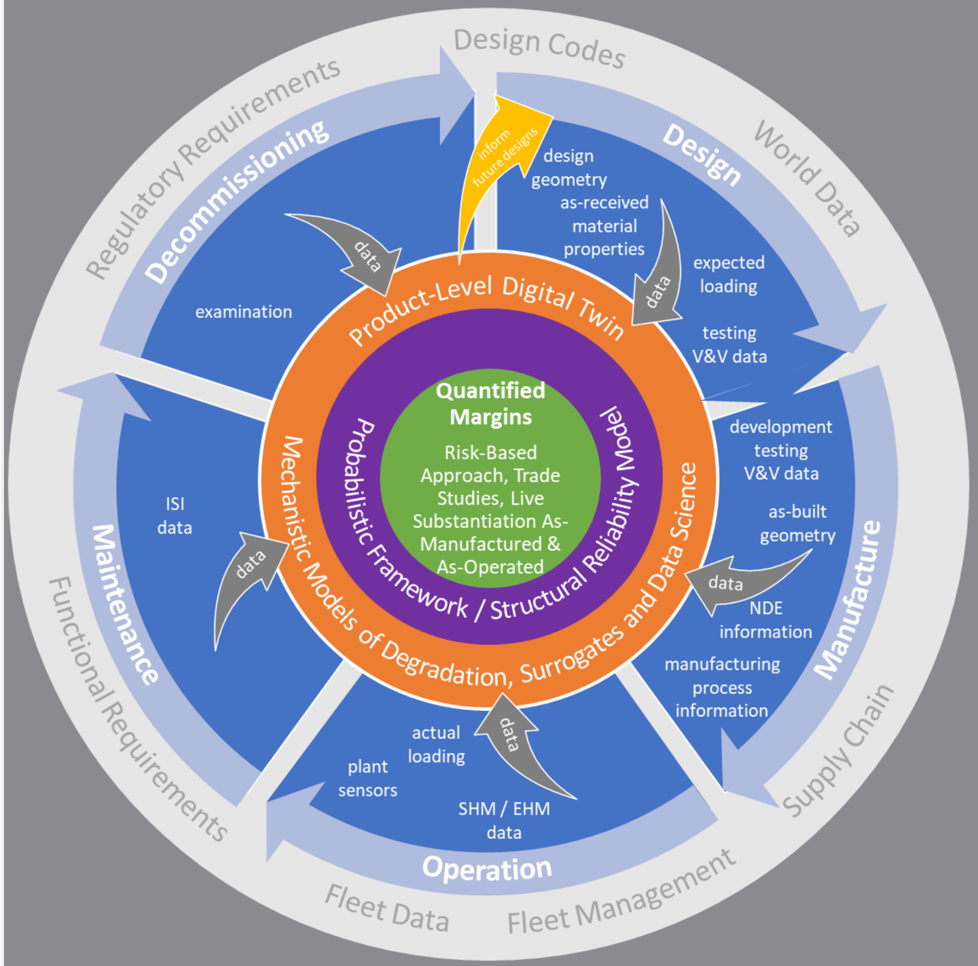
Developing cutting-edge digital technology for nuclear plant design and assessment

SINDRI – Synergistic utilisation of Informatics and Data centric Integrity engineering

The project will harness world-leading expertise to develop key components for digital twins – virtual models of physical entities – that can be used to assess the condition of components of nuclear power plants, and their need for maintenance or remedial work.

Find out more

Data-Centric Engineering



- Holistic use of lifecycle data from raw material and manufacture through to operation, maintenance and decommissioning
- Product and fleet digital twins of degradation mechanisms
- Uncertainty quantification and probabilistics
- Integrated physics-based multiscale models
- Surrogate and reduced order approaches

V&V Validation and Verification
NDE Non Destructive Examination
SHM Structural Health Monitoring
EHM Equipment Health Monitoring
ISI In-Service Inspection

Thank you for your attention!

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