Integrity of Nuclear Structures

Material Degradation and Mitigation by Nondestructive Evaluation

1.	Introduction to Structural Reliability in Nuclear Engineering

1.1.	Risk based reliability engineering
1.2.	Mitigation Strategies
1.3.	Basics on Nuclear Power
1.4.	Pressurized components of NPP
1.5.	BWR-Fukushima Accident
1.6.	Specifics of nuclear power engineering
1.7.	Degradation of nuclear structures during operation I
1.8.	Degradation of nuclear structures during operation II
1.9.	Degradation of nuclear structures during operation III

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

2.	Focus on Steel
2.1.	Steel qualities
2.2.	Ferrite alloys
2.3.	Austenitic alloys
2.4.	Nickel base alloys
2.5.	Welding

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

3.	Mitigation Strategies – The world is never perfect
3.1.	Structure design Rules
3.2.	Flaw minimization
3.3.	Flaw detection
3.4.	Unexpected events

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

4.	Nondestructive Material Evaluation
4.1.	Contrast and resolution
4.2.	Physical measurement principles
4.2.1.	Wave physics: X-ray methods
4.2.2.	Wave physics: Ultrasonic methods
4.2.3.	Visual inspection and thermography
4.2.4.	Electromagnetic methods
4.2.5.	Micro-magnetic material characterization
4.2.6.	Surface crack imaging methods
4.2.7.	Special technologies (Particle beam methods, microscopy)

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

5.	**Case Studies**
5.1.	Corrosion and abrasion
5.2.	Cracking
5.2.1.	Fatigue cracking
5.2.2.	Trans crystalline cracking
5.2.3.	Thermo shock cracking
5.2.4.	Inter-crystalline cracking
5.3.	Early fatigue material degradation (pores, short cracks)
5.4.	Surface and subsurface degradation
5.4.1	Residual stress state
5.4.2.	Particle damage (n-embrittlement; H-loaded surfaces)
6.	**Health Monitoring**
7.	**Conclusive Discussions**

Risk Based Reliability Engineering

INSTRUCTIONAL OBJECTIVES

- Risk Assessment of Technical Structures
- Life Time and Life Extension
- Failure Modes and Cases

Risk Based Reliability Engineering

Engineering Lessons

NO OVERCONFIDENCE - SEVERE ACCIDENTS MAY HAPPEN

GLOBAL COOPERATION IN SAFETY ENGINEERING

APPROPRIATE EVALUATION AND PROTECTION AGAINST EXTERNAL HAZARDS

**CONTROLLED SYSTEM SAFETY DESIGN RULES (INSAG)
-DEFENCE IN DEPTH & INHERENT/PASSIVE SAFETY-
ACCORDING TO THE LATEST STATE-OF-THE-ART**

Two simultaneous challenges

Economy

★

Safety

Risk based reliability engineering

Published by Elsevier
in association with the European Safety and Reliability Association

Reliability Engineering and System Safety is an international journal devoted to the development and application of methods for the enhancement of the **safety** and **reliability** of **complex technological systems**, like **nuclear power plants**, chemical plants, hazardous waste facilities, space systems, offshore and maritime systems, transportation systems, constructed infrastructure and manufacturing plants. The journal normally publishes only articles that involve the analysis of substantive problems related to the reliability of complex systems or present techniques and/or theoretical results that have a discernable relationship to the solution of such problems. An important aim is to achieve a balance between academic material and practical applications.

Risk based reliability engineering

RELIABILITY ENGINEERING:

emphasizes

dependability

in the lifecycle management of a product

or

ability of a system or component

to function under stated conditions

for a specified period of time

RELIABILITY :

Theoretically defined
as the probability of failure (the frequency of failures)

or in terms of availability:
a probability derived from reliability and maintainability.

Reliability plays a key role in cost-effectiveness of systems.

Risk based reliability engineering

RELIABILITY ENGINEERING ⟷ ***SAFETY ENGINEERING***

focuses on costs of failure caused by system downtime, cost of spares, repairs, personnel and cost of warranty claims.

focuses normally not on cost, but on preserving life and nature; deals with particular dangerous system failure modes

ECONOMY

SAFETY

common methods for analysis require input from each other

Risk based reliability engineering

DEPENDABILITY:
a measure of a system's
availability, reliability, maintainability

Attributes
A way to assess
the dependability of a
system

Threats
An understanding
what can affect
the dependability
of a system

Means
Ways to increase
a system's dependability

ATTRIBUTES

System Qualities

Availability
Readiness for correct service

Maintainability
Ability for undergoing modifications and repairs

Safety
Absence of catastrophic consequences

Integrity
Absence of improper system alteration

Reliability
Continuity of correct services

Security
Absence of externally originated errors

Assessment of Attributes

Quantitative

- Availability
- Reliability

**Basic Safety Design*
Leak before Break

Qualitative

- Integrity
- Safety
- Maintainability
- Security

State of Engineering
Quality Assurance
Design*

THREADS

System Degradation

Three main terms – the fault-error-failure chain

Fault → **Error** → **Failure**

Fault	Error	Failure
Its presence in a system may or may not lead to a failure (Flaw – Defect)	System error causes discrepancies between Intended and actual System behavior	System displays behavior that is contrary to its specification.

Risk based reliability engineering

Material Degradation
of
pressurized components

is a system fault

becoming a system error
when critical for designed loads

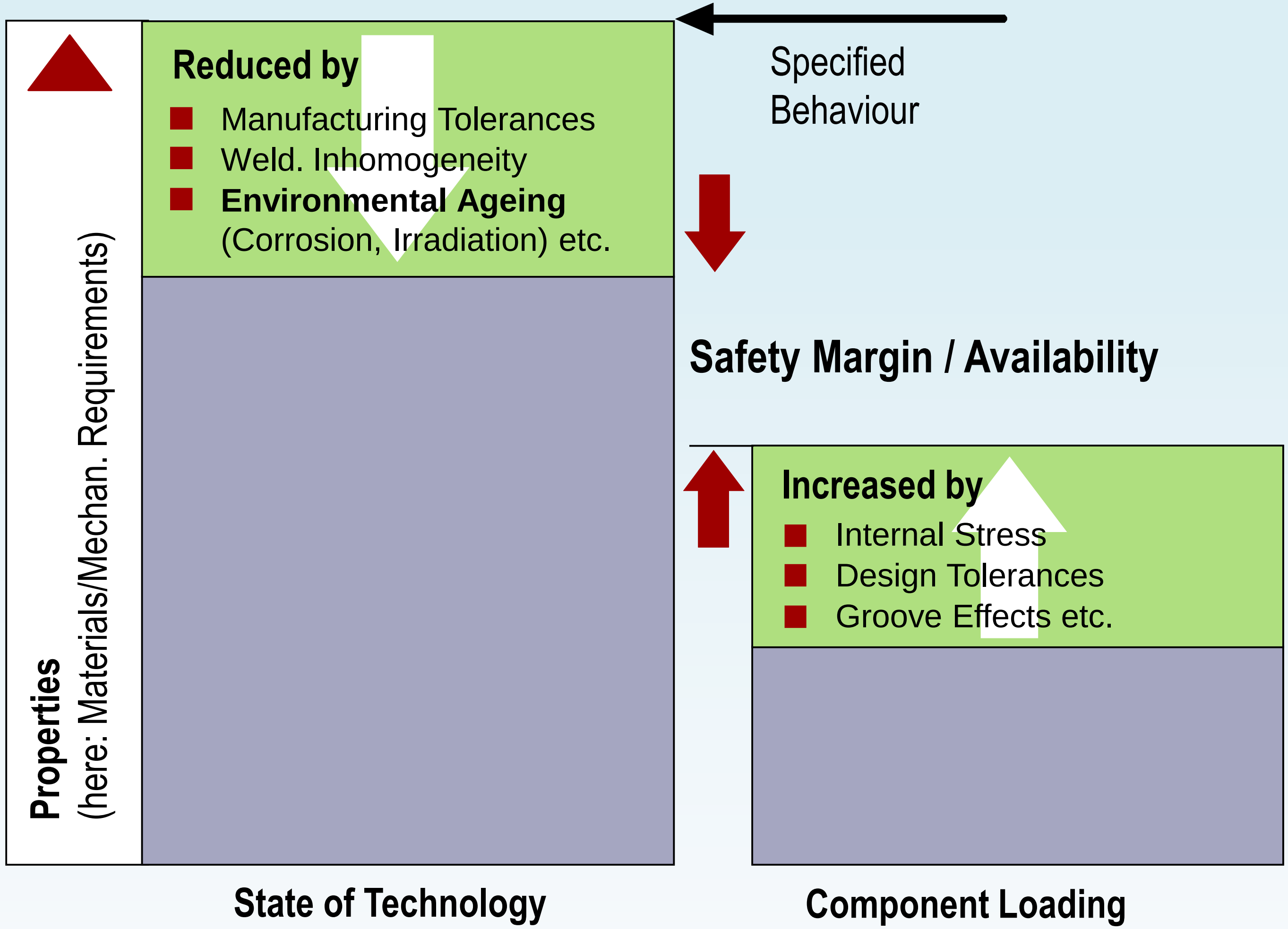
and leads to failure
without countermeasure

Concept of Safety Margin and Availability over the whole Life Time

With permission of AREVA

Properties determined by

- Materials
- Manufacturing
- Chemistry
- Thermal Hydraulics
- Fluid Dynamics
- Function



R & D → Lay-Out → Manufacturing → Operation → Service → Decommissioning

MEANS

System Stability

Means break the fault-error-failure chains
They increase the dependability of a system

Prevention	Forecasting	Tolerance
Design Testing QA	End of service life Design Tests State of Engineering	Mechanisms allow a system to still deliver the required service in the presence of faults

Risk based reliability engineering

MEANS

System Stability

Removal → **Neutron Embrittlement**

Faults/errors must be detected in time via appropriate maintenance cycle → **Steam Generator Tubing**

Stochastic Approaches

We don't know everything exactly

We assess the problem by statistics

By definition, risk is a stochastic quantity

We know everything, we are certain

Risk (failure) assessment of complex systems

asks for stochastic approaches

Risk estimates
in reliability engineering and safety engineering
differ in consequences

WEIBULL DISTRIBUTION

Applied in reliability and safety engineering for the assessment of:

- **Failure/Hazard Rates**
- **Material Strength Variation**

Probability Density Function of a Weibull Random Variable:

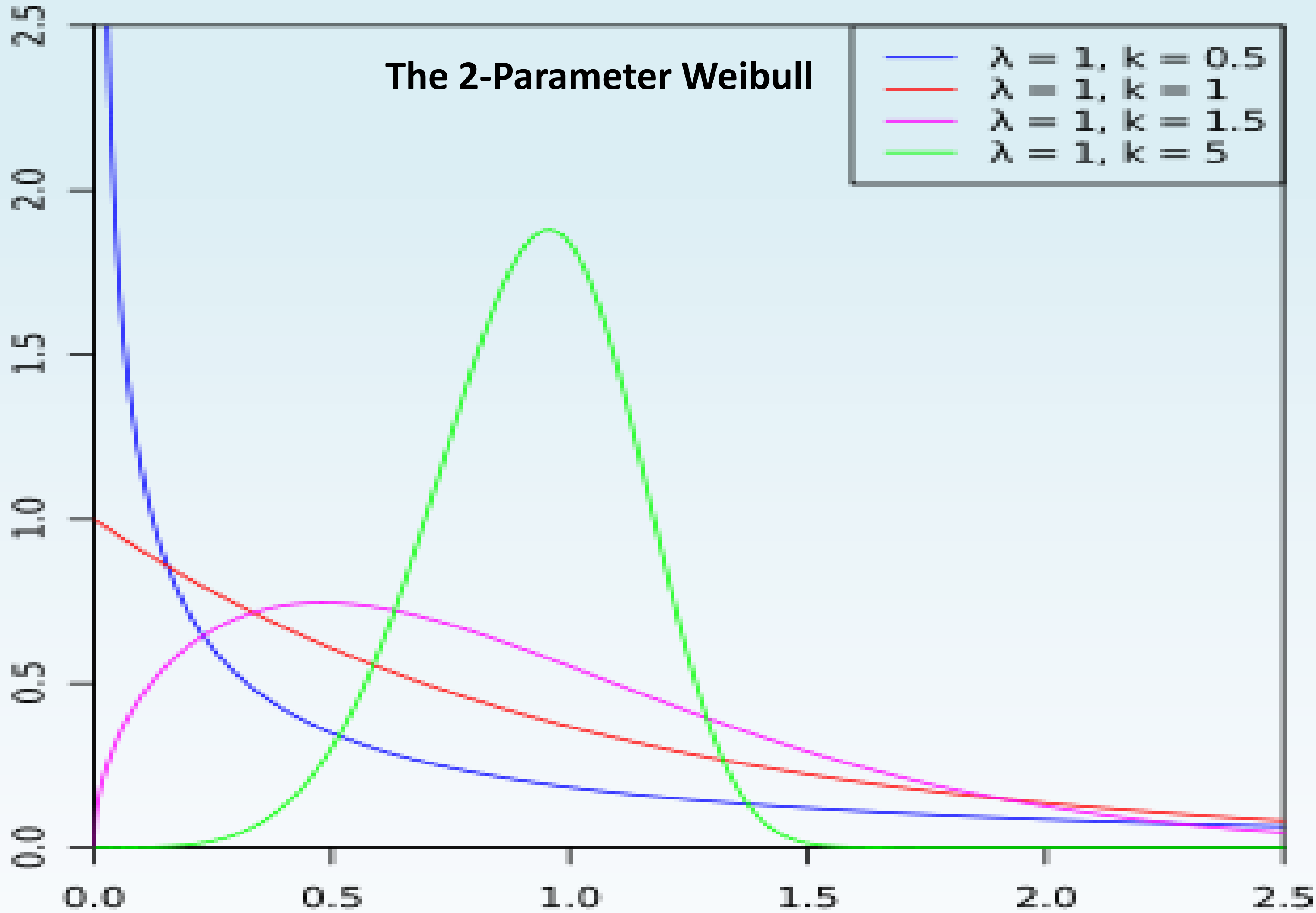
$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0, \\ 0 & x < 0, \end{cases}$$

$k > 0$: shape parameter
$\lambda > 0$: scale parameter

$k = 1$:exponential distribution
$k = 2$: Rayleigh distribution

Risk based reliability engineering

Probability density functions of great versatility



The failure/hazard rate *h* is given by:
(quantity *X* is a "time-to-failure“)

$$h(x;k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}.$$

In the field of material science, the shape parameter k of a distribution of strengths is known as the Weibull modulus.

Failure Rate

If the quantity *X* is a "time-to-failure",
the shape parameter *k* indicates:

k **< 1: the failure rate deceases over time**
“infant mortality and /or
defective items fail early

k **= 1: the failure rate is constant over time**
random external events are causing hazards or failure

k **> 1: the failure rate increase over time**
there are aging processes (material degradation)

MEANING OF DESIGN

NUCLEAR SAFETY ENGINEERING

DEFENSE IN DEPTH
with
PROBABILISTIC RISK ANALYSIS

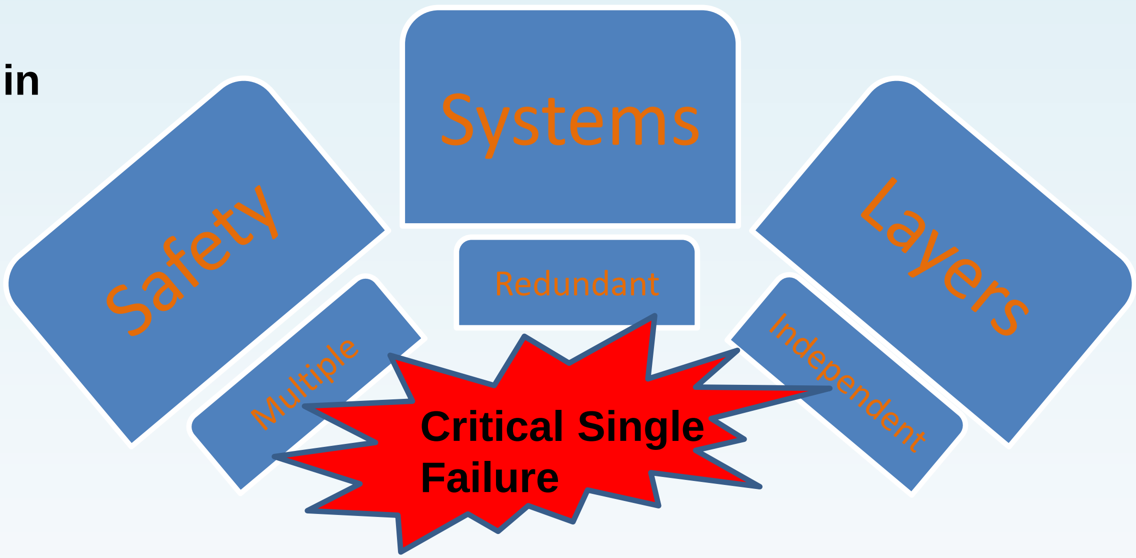
INHERENT SAFETY DESIGN
with
HIGHEST BASIC REQUIREMENTS

Broad Claim on System Safety Engineering Resilient Structures that Mitigate & Recover from Catastrophic Failures

Defense in Depth

NUCLEAR SAFETY SYSTEMS (as defined by the NRC)

- **Shut down and maintain in shut down condition**
- **Prevent the release of radioactive material**



Risk based reliability engineering

PROBABILISTIC RISK EVALUATION for COMPLEX SYSTEMS
(SYSTEM SAFETY ANALYSIS)

MAGNITUDE (SEVERITY) of CONSEQUENCES	X	LIKELIHOOD (PROBABILITY) of OCCURENCE

Risk based reliability engineering

ROBUST BASIC SAFETY DESIGN

INHERENT SAFETY DESIGN of CONTROL SYSTEMS + **PASSIVE SAFETY DESIGN of SAFETY SYSTEMS**

"An 'inherently safer' approach tries to:

- Avoid or eliminate hazards
- Reduce their magnitude and severity and likelihood of occurrence by careful attention to the fundamental design and layout"

Risk based reliability engineering

WEAKNESS:

Probabilistic Risk Assessment does not account for UNEXPECTED FAILURE MODES

Difficult Modeling of “COMMON-CAUSE” FAILURES

SYSTEM SAFETY RESEARCH (MIT):
“Any complex system,
no matter how well it is designed and engineered,
cannot be deemed failure-proof”

COMMON CAUSE FAILURE

Definition:

Common Cause (Mode) failures are dependent multiple failures originating from a common cause.

The treatment of common cause failures is extremely important in assessments of the risk associated with nuclear power plant accidents

(Fukushima accident)

Common causes may originate from:

Inappropriate procedures and poor design

Poor maintenance and quality control error

Material degradation

COMMON CAUSE FAILURE

refers to events which are not statistically independent.
A single fault - particular of random character - may cause failures in multiple parts of a system. due to environmental conditions or aging.

Common cause lines degrade design redundancies

Physics of Failure

An approach to reliability that uses modeling and simulation to design-in reliability. This approach models the root causes of failure such as fatigue, fracture, wear, and corrosion.

The concept involves the use of degradation algorithms that describe how physical, chemical, mechanical, thermal, or electrical mechanisms evolve over time and eventually induce failure.

Cause for Nondestructive Material Testing

Manufacturing | **Maintenance**

Assured Material State as designed

(quantitative) Flaw Inspection | **Material Characterization**

Risk based reliability engineering

NDT increases dependability -
as we will see later.

We have to understand limits and opportunities for its contribution to safety engineering

What is a flaw ?

What is a defect ?

CATASTROPHIC NUCLEAR ACCIDENTS ARE INEVITABLE

Safety Indicator:
Frequency f of Core Melt Accidents

NRC (**Mandated)**: f < 1 in 10,000 years
Modern design: f < 1 in 100,000 years

"First and most elementally, nuclear accidents happen… we can never have confidence that we will succeed absolutely."
(*John Ritch, Director General, WNA)*

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