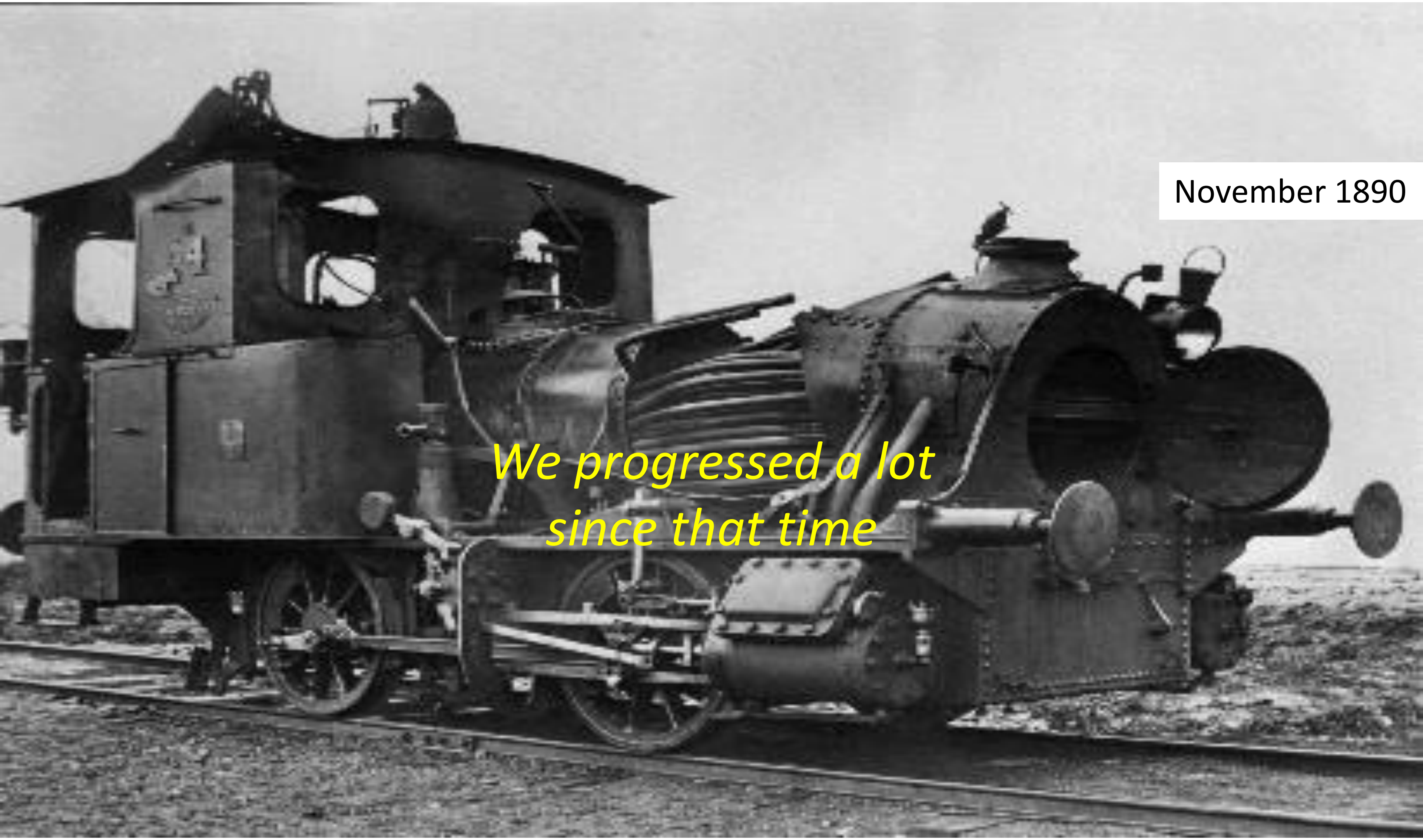
Mitigation Strategies



1. Introduction to Structural Reliability in Nuclear Engineering

Structural Integrity

Structural integrity is the ability of a structure or a component to withstand a designed service load, resisting structural failure due to:

fracture
deformation, or
fatigue.

Structural integrity is a concept often used in engineering, to produce items that will function adequately for their

designed purposes
for a
desired service life.

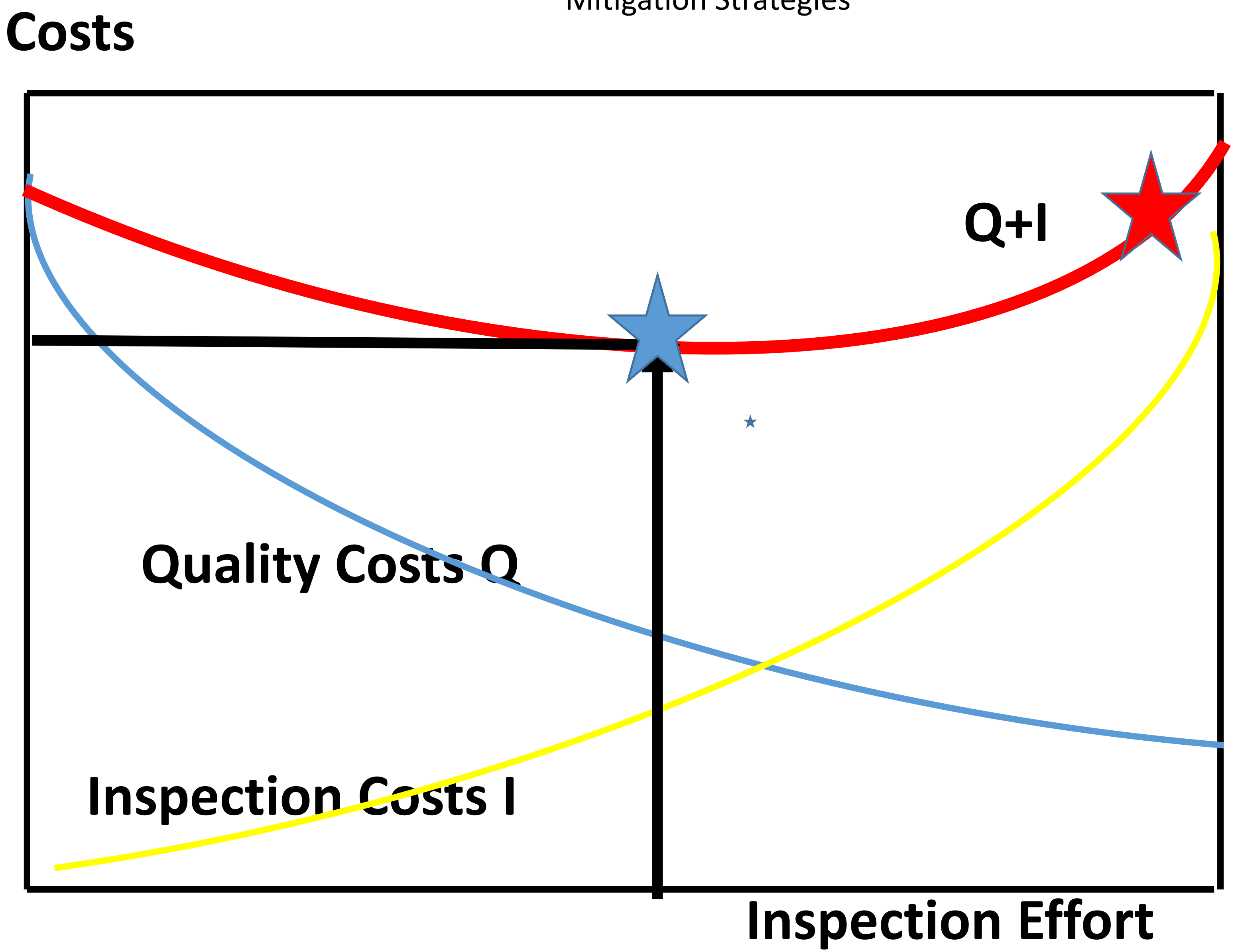
System Engineering Rules for Reliable and Safe Structures

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.

Safety

relates to only
very specific system hazards
that could potentially
lead to severe accidents.
It deals with
dangerous events for
life and environment.


Costs
Q+I
Quality Costs Q
Inspection Costs I
Inspection Effort

Mitigation Strategies

Safety-Oriented Approach

Safety Measures

Priorities

1. Priority

Main Goal

Inherent Safety Measures

Dangers:
avoid
eliminate
contain

Hazards:
constrain
eliminate
protect

2. Priority

Engineering Method

Multilevel Safety Measures

Quality Assurance
Protective Systems
Safety Installations
etc

Safety Related Design Rules

Redundancy
Diversity
Spatial separation
etc

Hazard Reduction & Risk Minimization

SAFETY ENGINEERING

DESIGN

- Strictly controlled
- Common cause failure
- Passive systems
- Inherent safety

MANUFACTURING

- Regulations and codes
- Quality management
- Quality certification
- Independent assessment

OPERATION

- Maintenance
- Degradation control
- Unexpected events

DISPOSAL

- Dismantling
- Renaturization
- Waste management

SAFETY ENGINEERING

DESIGN

Inspection-oriented
- Design
- Dimensioning

MANUFACTURING

In-Production Inspections
- Independent expert
- Manufacturer
- Construction company

OPERATION

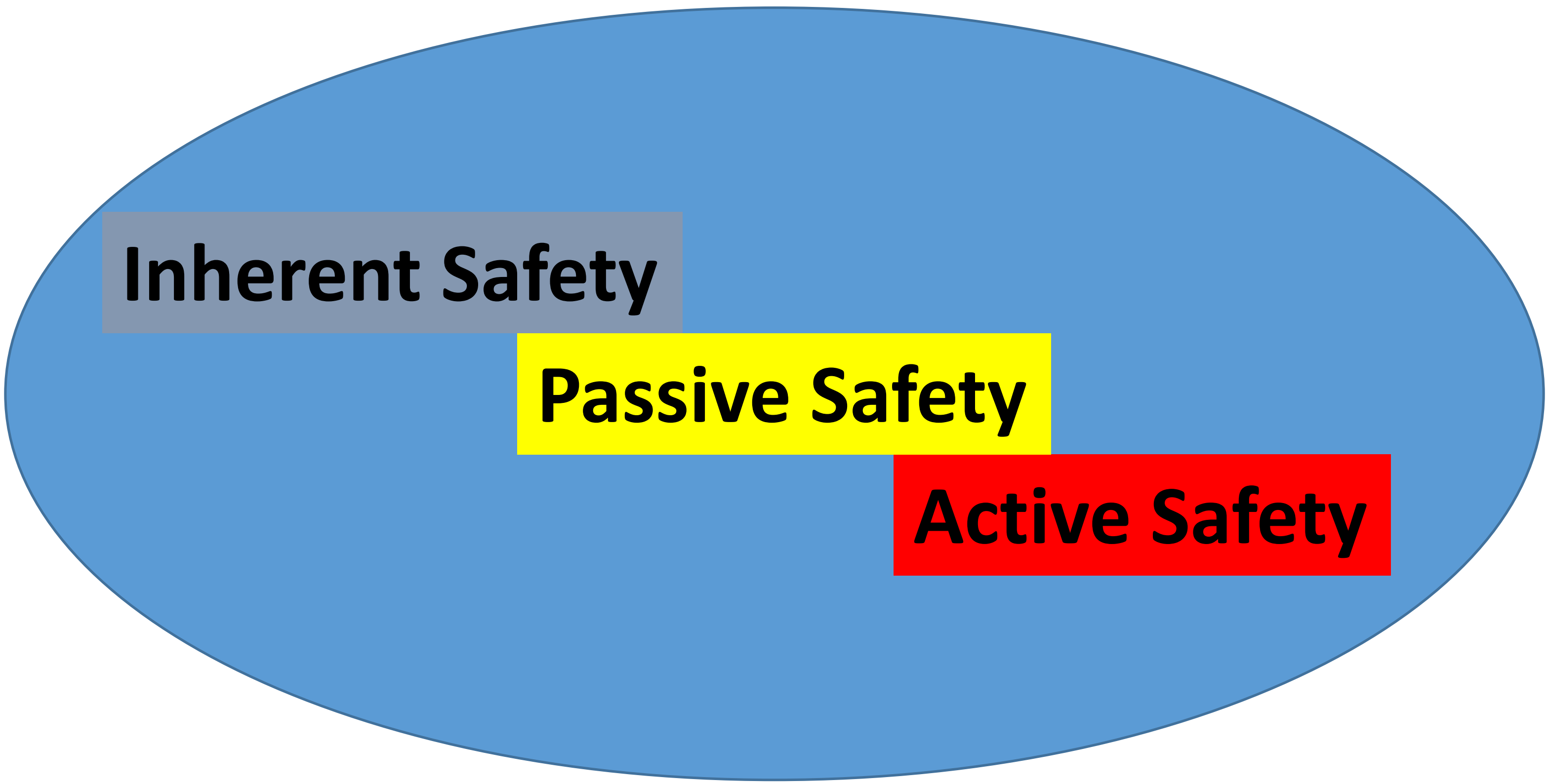
- Reference Inspections
- In-service Inspections
- Health Monitoring

DISPOSAL

Storage Control
- Pollution
- Non-proliferation

NDT Contributions

Safety Feature Design of Nuclear Systems



Degree of Passive Safety

The International Atomic Energy Agency (IAEA) classifies the degree of "passive safety" of components from category A to D depending on what the system does not make use of:

no moving working fluid
no moving mechanical part
no signal inputs of 'intelligence'
no external power input or forces

INHERENT SAFETY

Main methods for achieving inherently safer design:

Minimize: Reducing the amount of hazardous material

Substitute: Replacing one material with another of less hazard

Moderate: Reducing the strength of an effect

Simplify: Designing out problems rather than adding additional equipment or features to deal with them.

Two further principles:

Error Tolerance: Equipment and processes can be designed to be capable of withstanding possible faults or deviations from design, e.g. piping and joints capable of withstanding the maximum possible pressure if outlets are closed.

Limit Effects: Designing and locating equipment so that the worst possible condition gives less danger, e.g. gravity will take a leak to a safe place.

Fault Tolerance Design
(Common for Software)

A fault-tolerant design enables a system to continue its intended operation, possibly at a reduced level, rather than failing completely, when some part of the system fails

Fault-tolerant systems are typically based on the concept of redundancy

Fault tolerance is particularly sought after in high-availability or life-critical systems

A structure is able to retain its integrity in the presence of damage due to causes such as fatigue, corrosion, manufacturing flaws, or impact

Damage Tolerance

Commonly used in aerospace engineering)

A structure is damage tolerant through its ability to sustain defects safely until repair can be effected. Damage tolerant engineering design is based on the assumption that flaws can exist in any structure and propagate with usage.

It applies principles of fracture mechanics (crack growth rates, critical crack dimension) in combination with a maintenance program that that will result in the detection and repair of accidental damage, corrosion and fatigue cracking before such damage reduces the residual strength of the structure below an acceptable limit.

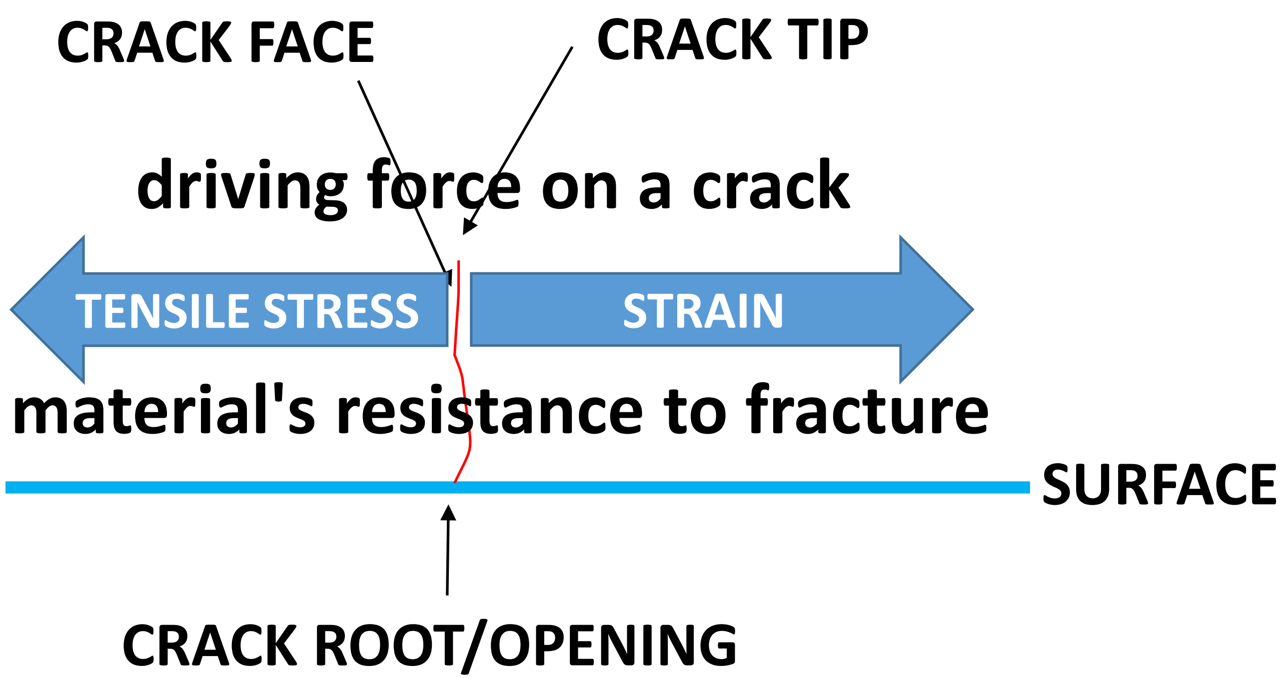
Safe-Life Design

Not all structure must demonstrate detectable crack propagation to ensure safety of operation.

Some structures operate under the safe-life design principle, where an extremely low level of risk is accepted through a combination of testing and analysis that the part will ever form a detectable crack due to fatigue during the service life of the part.
This is achieved through a significant reduction of stresses below the typical fatigue capability of the part.

Cracks in Structures
“Fracture Mechanics”

Fracture mechanics is concerned with the study of the propagation of cracks in materials.



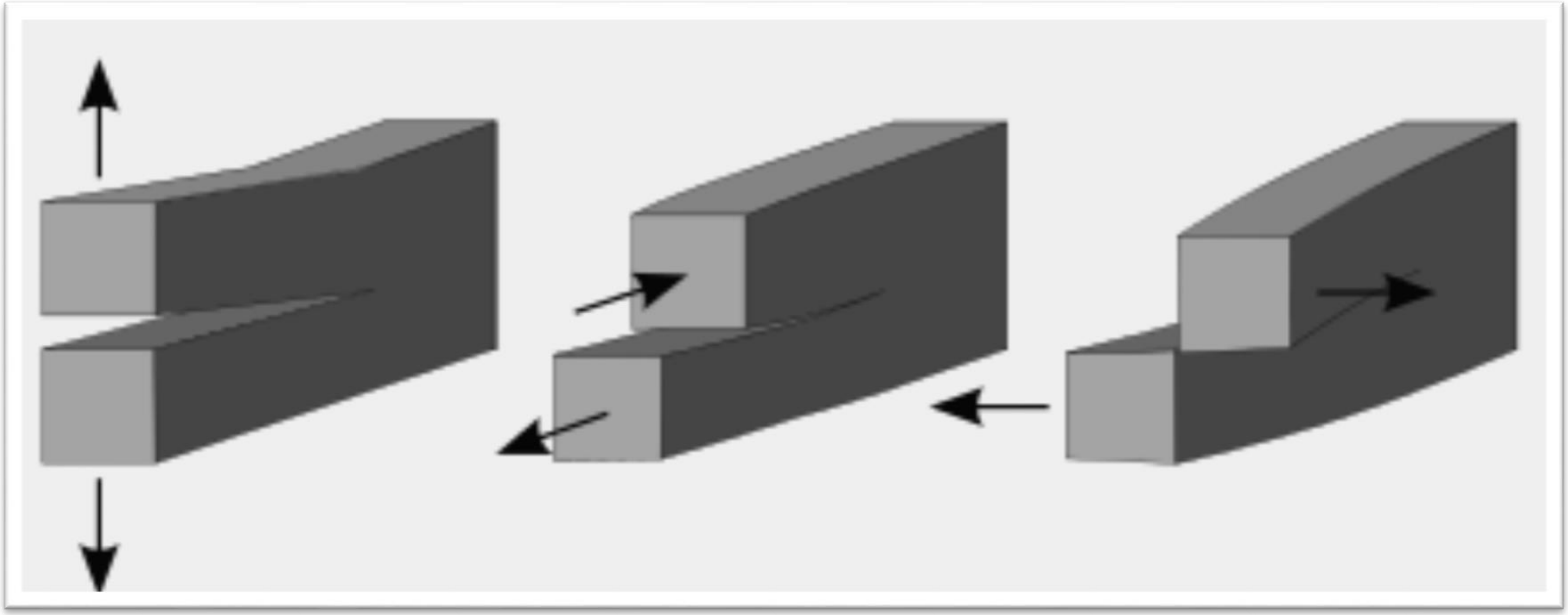
Cracks in Structures
"Fracture Mechanics"

FM uses:

methods of analytical solid mechanics
to calculate the driving force on a crack

experimental solid mechanics
to characterize the material's resistance to fracture.

Cracks in Structures
"The Three Fracture Modes"



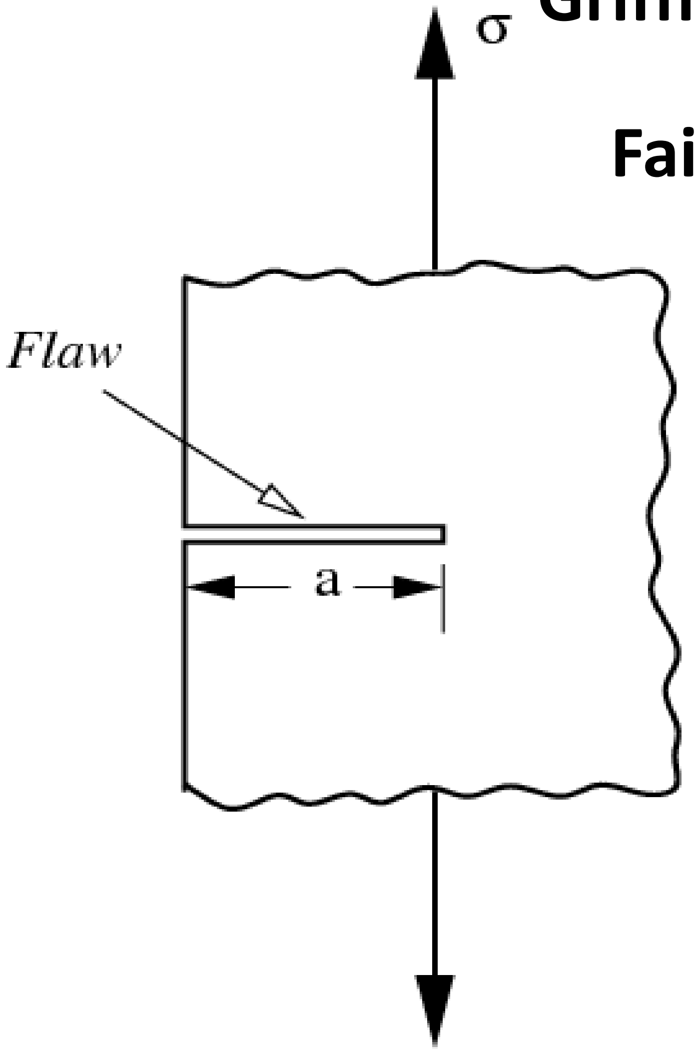
Mode I fracture – Opening mode
(a tensile stress normal to the plane of the crack)

Mode II fracture – Sliding mode/in-plane shear
(a shear stress acting parallel to the plane of the crack and perpendicular to the crack front)

Mode III fracture – Tearing mode/out-of-plane shear
(a shear stress acting parallel to the plane of the crack and parallel to the crack front)

Cracks in Structures

“Griffith's Criterion” (1921)



Failure Criterion for brittle materials:

$$\sigma_f \sqrt{a} \approx C$$

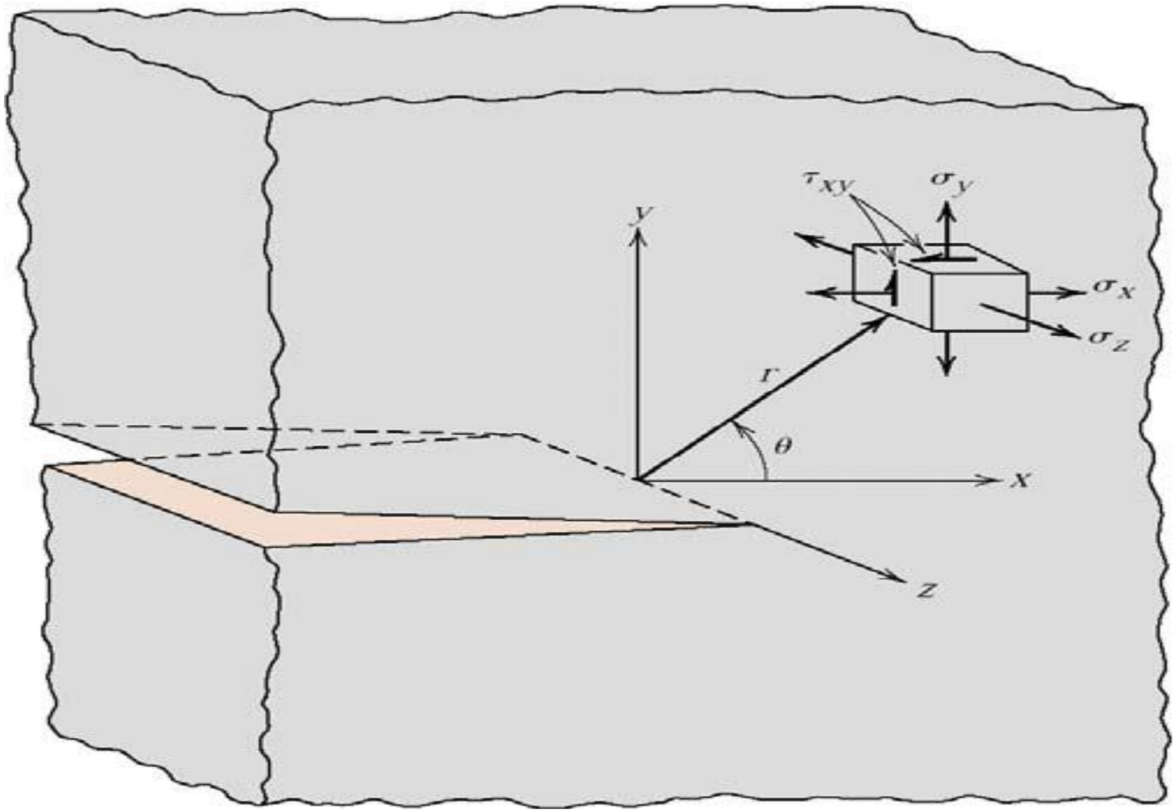
σ_f ***Fracture Stress***

Griffith's experiments were motivated by two contradictory facts:

- **The stress needed to fracture bulk glass: ~100 Mpa**
- **The theoretical stress needed for breaking atomic bonds: ~10,000 MPa**

Cracks in Structures
Thermodynamic Approach

Stress (and hence the strain) at the tip of a sharp flaw in a linear elastic material is infinite (Linear elasticity theory).



Cracks in Structures
Thermodynamic Approach

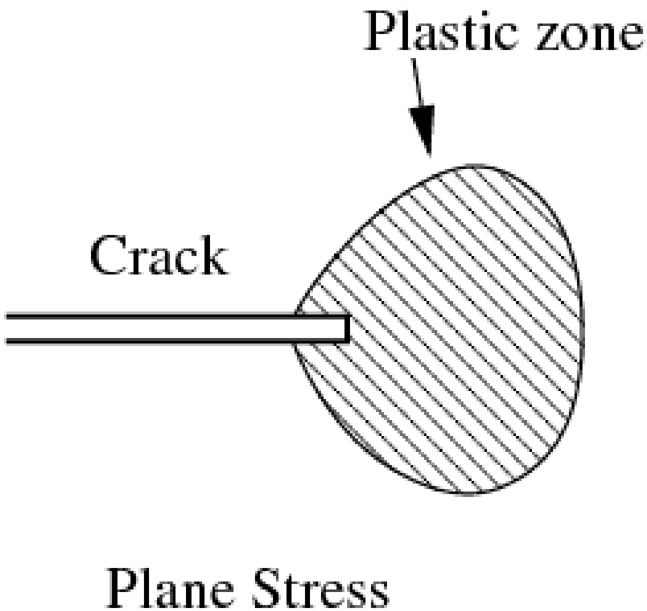
Griffith developed a thermodynamic approach
to explain the relation that he observed.

The growth of a crack requires the creation of two new surfaces
and hence an increase in the surface energy.
Solving the elasticity problem of a finite crack in an elastic plate,
he found an expression for C
in terms of the surface energy of the crack.

$$C = \sqrt{\frac{2E\gamma}{\pi}}$$

E: Young's modulus
γ: surface energy density

Cracks in Structures
"Irwin's Modification" (1957)



For ductile materials such as steel,
the surface energy (*γ*)
predicted by Griffith's theory
is usually unrealistically high.

During World War II,
a group working under G. R. Irwin
at the U.S. Naval Research Laboratory
realized that
plasticity must play a significant role
in the fracture of ductile materials.

Cracks in Structures

In ductile materials a plastic zone develops at the tip of the crack

The plastic loading and unloading cycle near the crack tip leads to the dissipation of energy as heat.

A dissipative term has to be added to the energy balance relation:

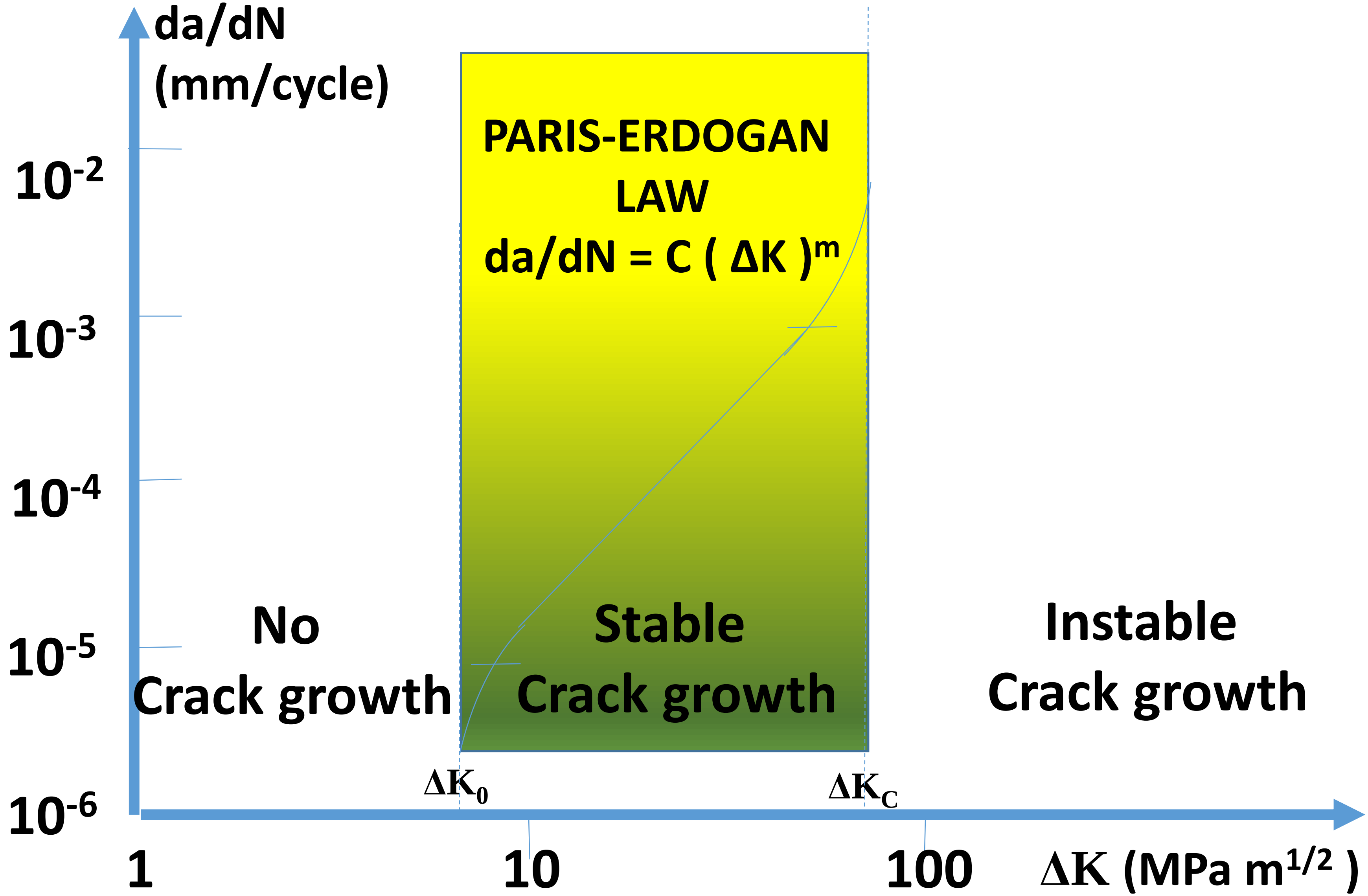
$$G = 2\gamma + G_p$$

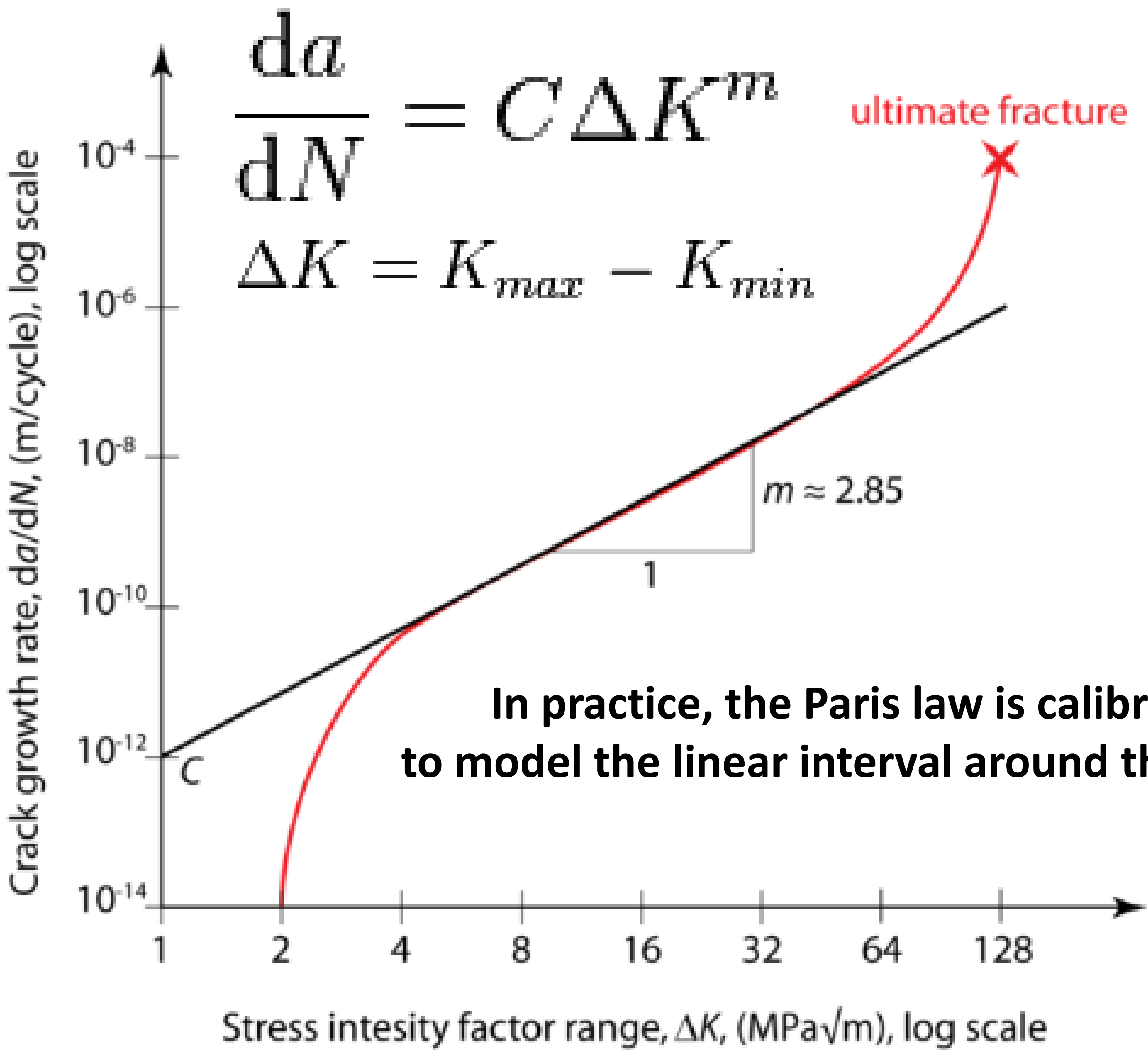
Modified version of Griffith's energy criterion:

$$\sigma_f \sqrt{a} = \sqrt{\frac{E\ G}{\pi}}.$$

$$G \approx 2\gamma = 2\ J/m^2$$

$$G \approx G_p = 1000\ J/m^2$$


da/dN
(mm/cycle)
PARIS-ERDOGAN
LAW
da/dN = C (ΔK)m
10-2
10-3
10-4
10-5
10-6
No
Crack growth
Stable
Crack growth
Instable
Crack growth
ΔK0
ΔKC
1
10
100
ΔK (MPa m1/2)



In practice, the Paris law is calibrated to model the linear interval around the center

FLAW MINIMIZATION

CONCLUSION

BY DESIGN AND QUALITY
WE MINIMIZE FLAWS
WITH THE OBJECTIVE OF DEFECT FREE STRUCTURES AND MATERIALS

?NO CRACKS?

THERE ARE CRACKS
THERE ARE FAILURES

FLAW MINIMIZATION

JUST ONE EXAMPLE FOR DEFENCE IN DEPTH DESIGN

THERE IS A CRITICAL CRACK

LEAK-BEFORE-BREAK DESIGN

The structure will not fail before we see it leaking

LEAK-BEFORE-BREAK DESIGN
JUST ONE EXAMPLE FOR DEFENCE IN DEPTH DESIGN

Leak-before-break is a design procedure intended to ensure that pressure vessels fail by the relatively benign mechanism of leaking rather than by explosive fracture.

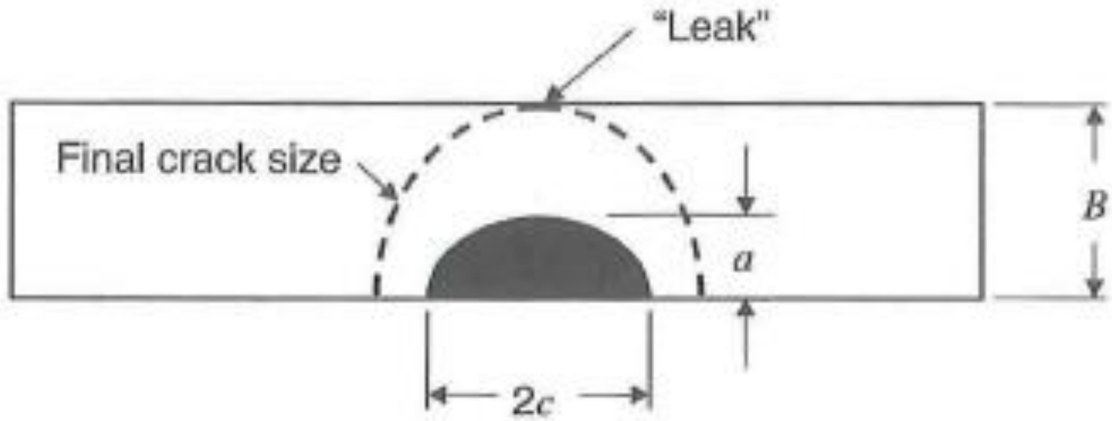
LEAK-BEFORE-BREAK DESIGN CONCEPT

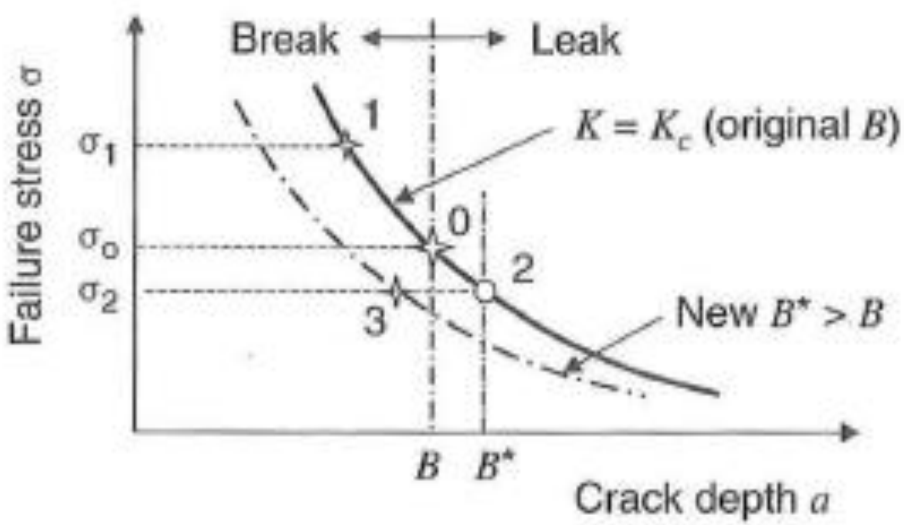
If the pressure is repeatedly removed and reapplied (or if the vessel contains a corrosive material), the surface cracks will grow by fatigue and/or stress corrosion cracking until one of two failure modes occurs.

First, if the cracks extend "slowly" and pierce the wall thickness before the critical stress intensity factor Kc is reached, the vessel will leak and the hoop stresses will vanish as the pressure is relieved.

If, however, K reaches the material fracture toughness Kc before the crack penetrates the wall thickness, the crack will extend suddenly, resulting in a catastrophic explosion (break).

LEAK-BEFORE-BREAK DESIGN





Schematic representation of leak-before-break conditions for a pressure vessel

LEAK-BEFORE-BREAK DESIGN

The designer's task is to ensure that the vessel will never "break" in service.

This challenge is represented by the "failure" stress-crack depth plot shown by the solid line that represents a line of constant stress intensity factor

$$K = \sigma\sqrt{\pi a}\beta = K_C$$

For critical crack depths less than the wall thickness B, fracture (break) occurs when $K > K_C$.
The largest stress σ_0 that can be applied without causing fracture occurs when the crack depth a equals the wall thickness B (point 0).
If the stress is less than σ_0, the crack penetrates the wall, causing the vessel to leak before the crack reaches a size that would fracture the vessel.

LEAK-BEFORE-BREAK DESIGN

If the hoop stress exceeds the "leak" value a_O, as shown by point 1, the designer has several options to return the safer leak condition. The hoop stress may be reduced by decreasing the internal pressure or by increasing the wall thickness B, leading to point 2.

These are potentially conflicting approaches. Although the hoop stress (and K) will decrease for larger B (e.g., B* > B in Figure), it is possible that the fracture toughness could also decrease with the larger wall thickness, and the fracture condition may actually be exacerbated (point 3).

One needs to know the K_C versus B behavior for the material in question in order to make the correct design decision.

Material degradation

Material Characterization

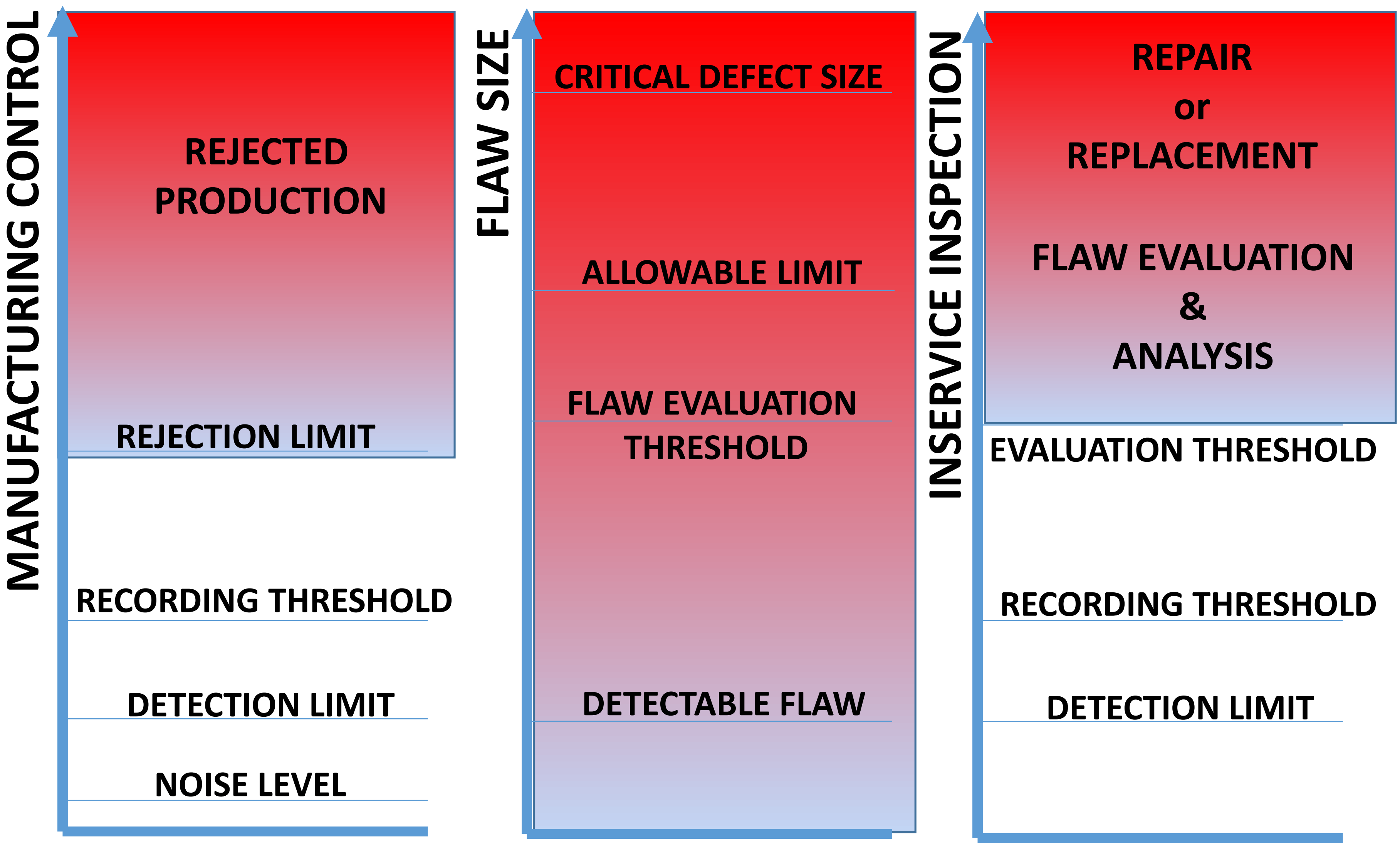
Another design option would be to select a new material with a larger fracture toughness Kc for the same material thickness.

Types of Failures

- **Overload of Structure** (critical stress level)
- **Structure Instability** (due to design or material choice), causing the structure to fail from fatigue or corrosion
- **Manufacturing Errors**: improper selection of materials, incorrect sizing, improper heat treating, failing to adhere to the design, or shoddy workmanship
- **Defective Materials**
- **Unexpected Problems** (Vandalism, sabotage, and natural disasters)

HOW TO DETECT CAUSES or THE ROLE OF NDT

INDICATION-FLAW-DEFECT



CONTRIBUTION OF NDT

Crack growth, as shown by fracture mechanics, is exponential in nature (Paris' law).

A desire for reasonable inspection intervals, combined with the exponential growth of cracks in structure has led to the development of non-destructive testing methods which allow inspectors to look for very tiny cracks.

Examples of this technology include eddy current, ultrasonic, dye penetrant, and X-ray inspections.

HOWEVER:
CAN WE CHARACTERIZE MATERIAL DEGRADATION BY MEASURING MICROSTRUCTURE DEPENDANT ΔK?

CONTRIBUTION OF NDT

STILL LIMITED

FLAW TYPE
MATERIAL STRUCTURE
ACCESS

FLAW INITIATION & GROWTH
MATERIAL DEGRADATION
CAUSE EVALUATION

TARGETED

CODES & REQUIREMENTS
CERTIFICATION & VALIDATION
DETECTION & EVALUATION

QUANTITATIVE NDT
NEW METHODS
HEALTH MONITORING

CONCEPT of DEFENSE-IN-DEPTH

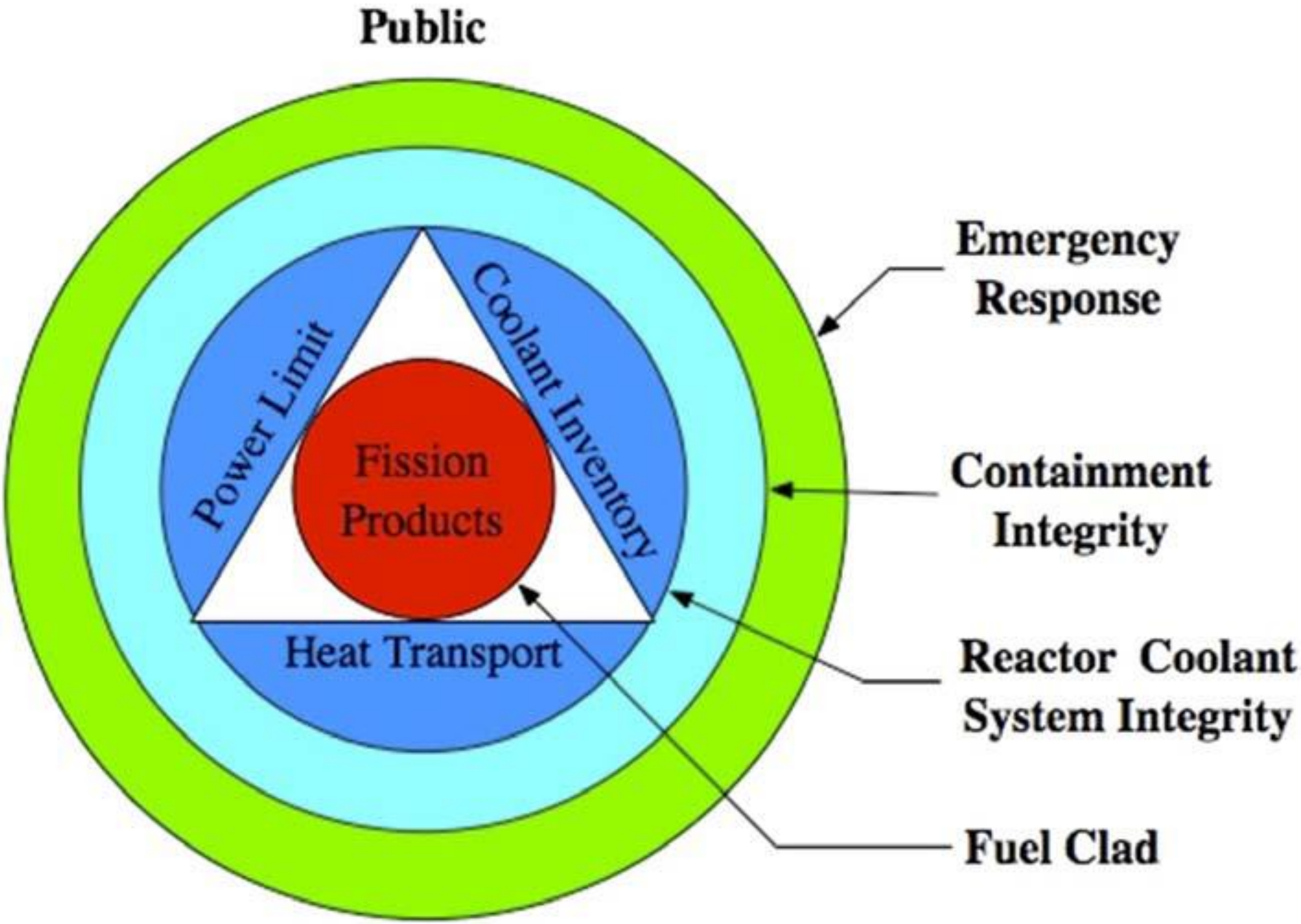
In nuclear engineering and nuclear safety, defense in depth denotes the practice of having multiple, redundant, and independent layers of safety systems for the single, critical point of failure: the reactor core.

Defense-in-depth

An approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials.

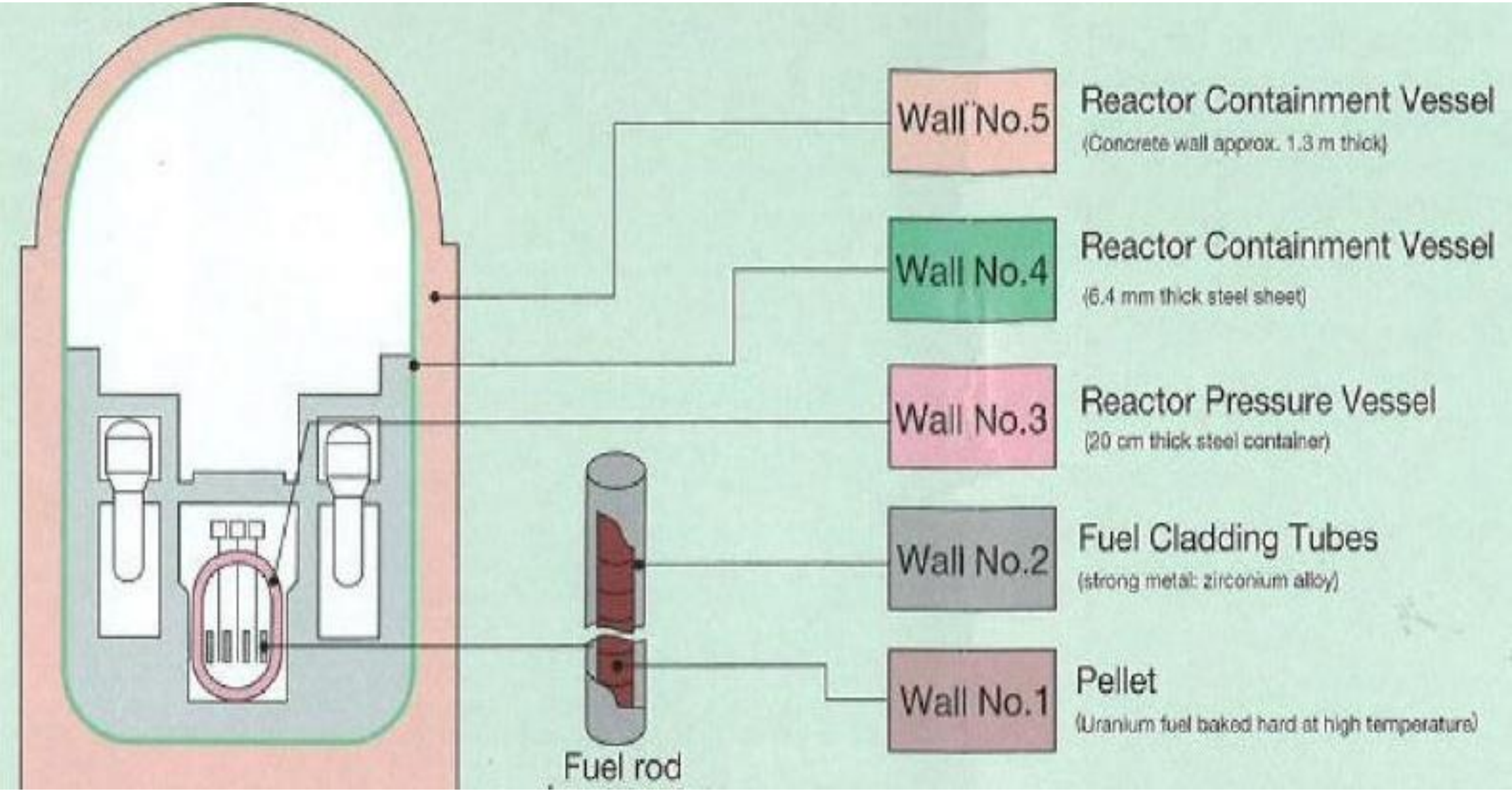
Multiple independent and redundant layers of defense compensate for potential human and mechanical failures. Defense-in-depth includes the use of :
access controls,
physical barriers,
redundant and diverse key safety functions,
and emergency response measures.

NRC Glossary



Defense in depth — barriers to radiation release

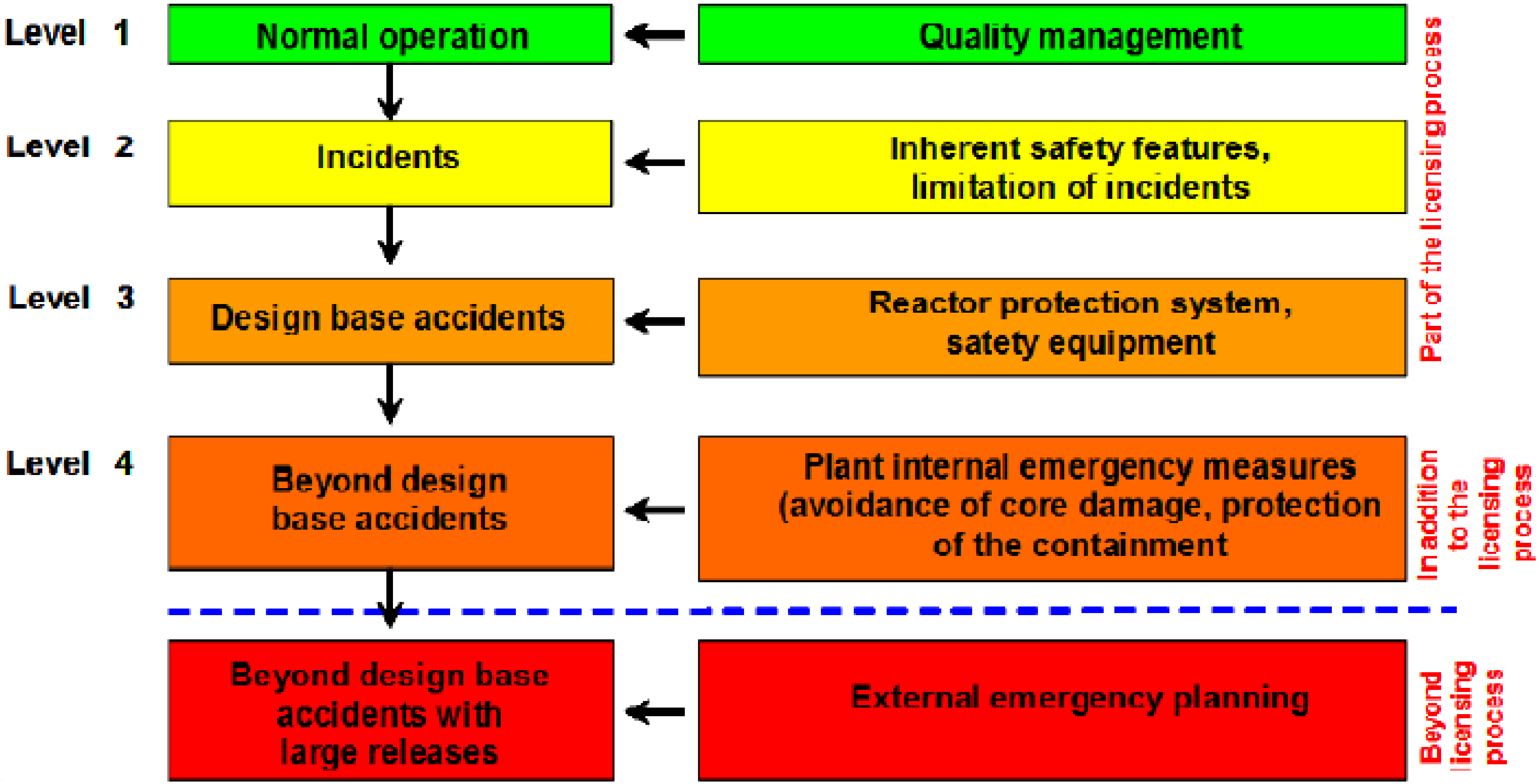
Westinghouse 1000MeV)



Five Walls of Protection
Plus passive cooling systems (water and air)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Possible States of a Nuclear Installation: Corresponding Protection Levels and Related Safety Measures



EXAMPLE OF LINES OF DEFENCE

Level 1: Prevention of abnormal operation and failures by:

High quality in construction and operation

Level 2: Control of abnormal operation and detection of failures by:

Control limiting and protection systems & other surveillance features

Level 3: Control of accidents within the design basis by:

Engineered safety features and accident procedures

Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences by:

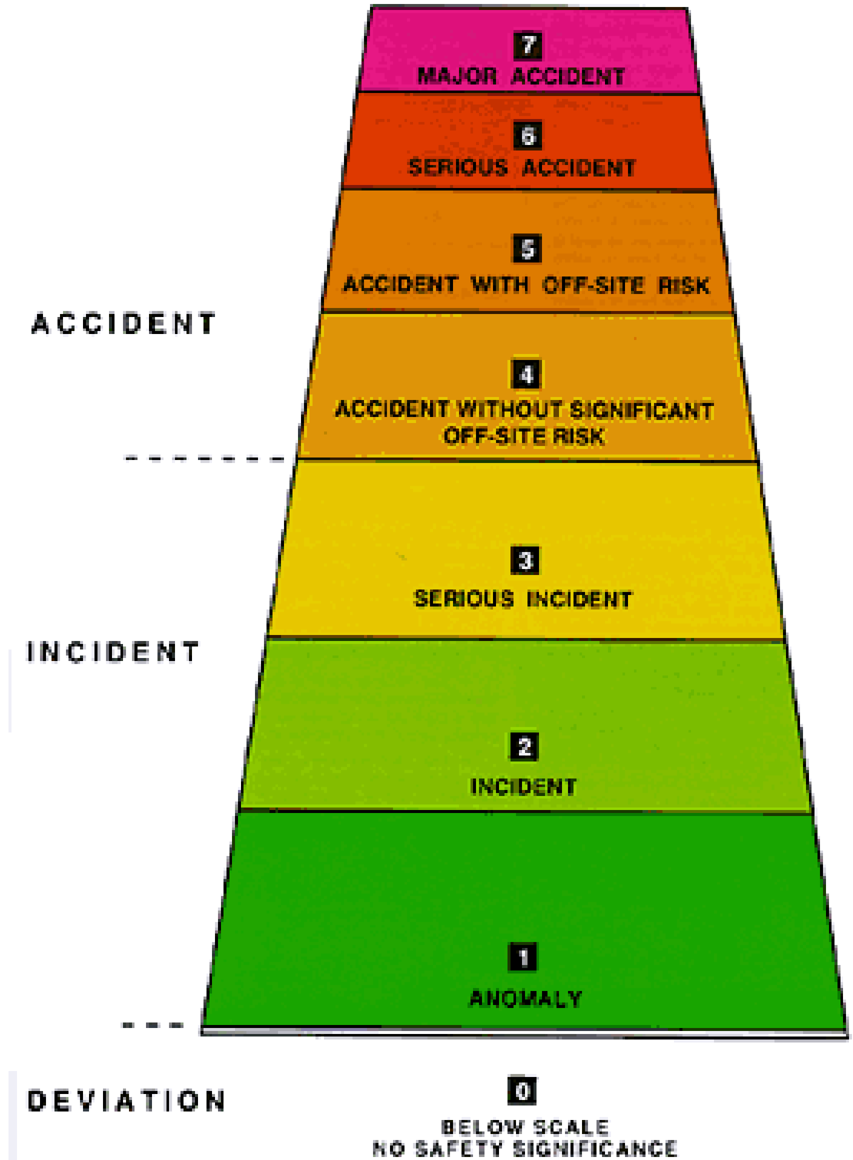
Complementary measures and accident management

Level 5: Mitigation of radiobiological consequences by:

Off-site emergency response

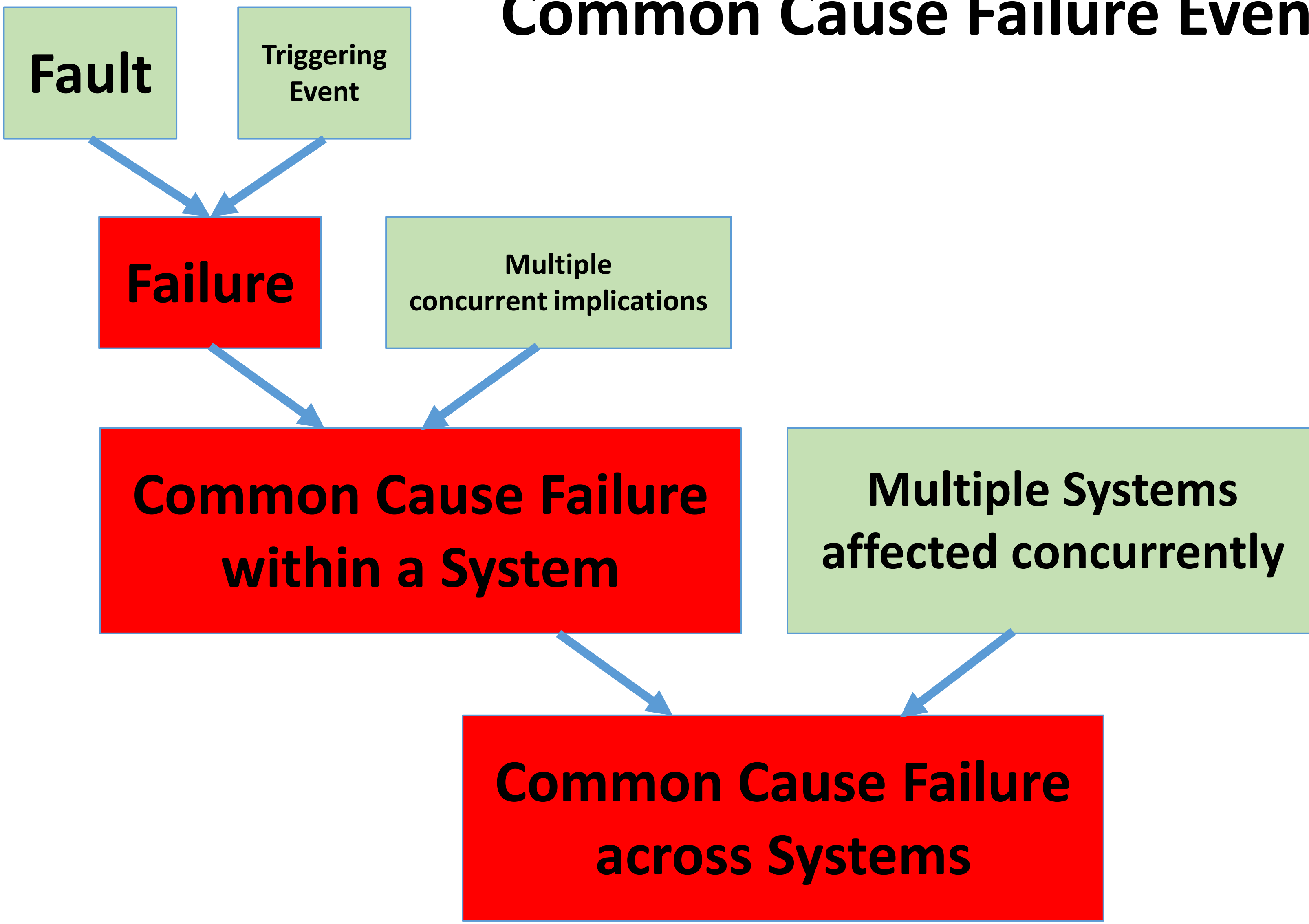
UNEXPECTED EVENTS

Mitigation Strategies



The international Nuclear Event Scale

Common Cause Failure Event



CONCLUSION I

WE CANNOT EXCLUDE HAZARDS

WE CAN ONLY MINIMIZE THE RISK

BY

- **SAFETY CULTURE**
- **PROFESSIONAL RESPONSIBILITY**
- **CONTINUING IMPROVEMENTS**

CONCLUSION II

WE MUST ASSURE THE QUALITY
WE MUST CONTROL THE STRUCTURAL STATE

BY

- **NONDESTRUCTIVE FLAW EVALUATION**
- **NONDESTRUCTIVE MATERIAL CHARACTERIZATION**

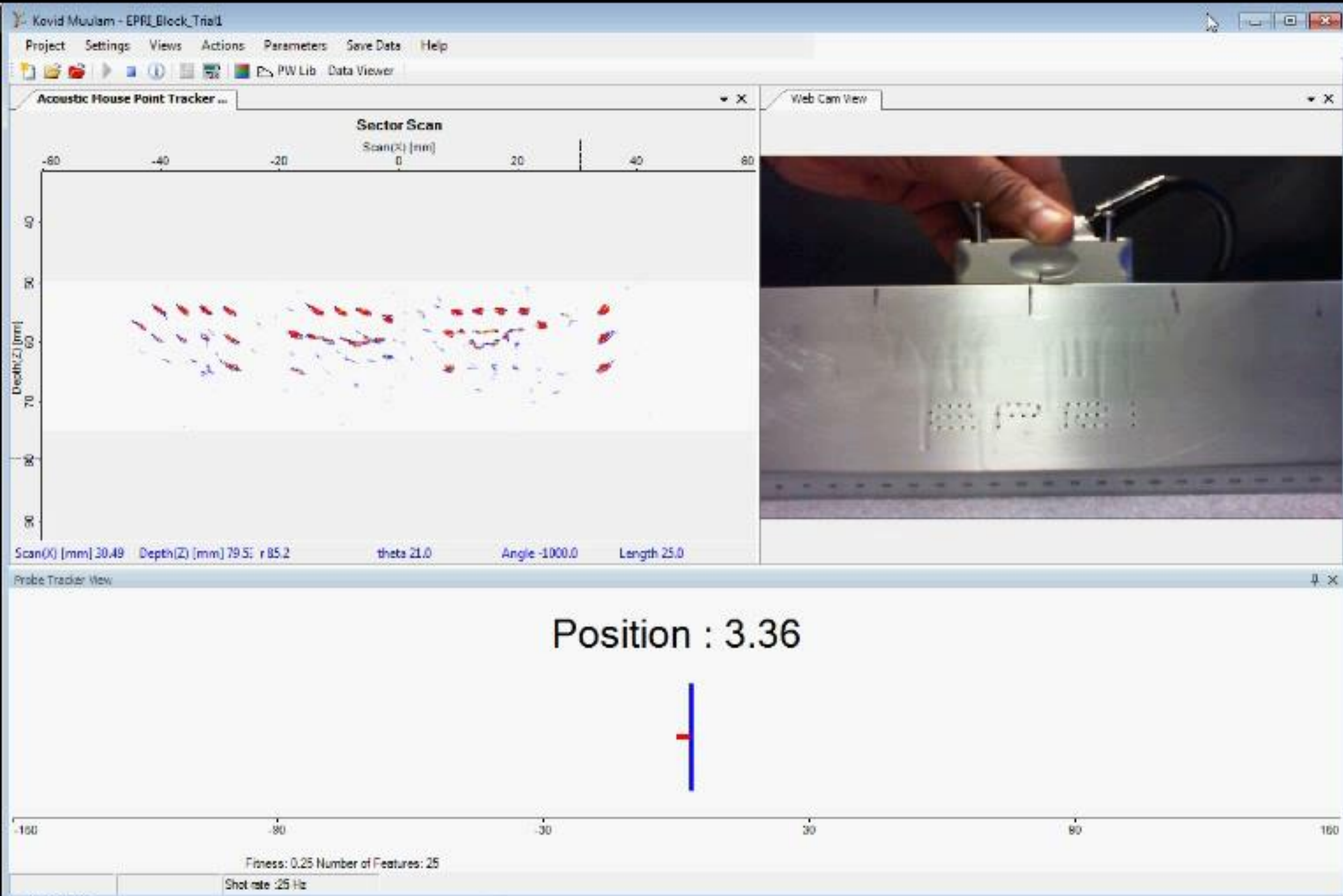
CONCLUSION III

CAN WE EVALUATE FLAWS QUANTITATIVELY?
CAN WE CHARACTERIZE MATERIAL PROPERTIES?

THERE ARE MANY CHALLENGES
FOR YOUNG SCIENTISTS
&
PIONEERS

CONCLUSION III

LET US SEE A NICE MOVIE


Kovid Muulam - EPRI_Block_Trial1
Project Settings Views Actions Parameters Save Data Help
PW Lib Data Viewer
Acoustic Mouse Point Tracker ...
Web Cam View
Sector Scan
Scan(X) [mm]
-60 -40 -20 0 20 40 60
Depth(Z) [mm]
40 50 60 70 80 90
Scan(X) [mm] 30.49 Depth(Z) [mm] 79.5: r 85.2 theta 21.0 Angle -1000.0 Length 25.0
Probe Tracker View
Position : 3.36
-160 -80 -30 30 80 160
Fitness: 0.25 Number of Features: 25
Shot rate :25 Hz


Kovid Muulam - TestTrack_WithLiftOff
Project Settings Views Actions Parameters Save Data Help
PW Lib Data Viewer
Acoustic Mouse Point Tracker ...
Sector Scan
Scan(X) [mm]
Depth(Z) [mm]
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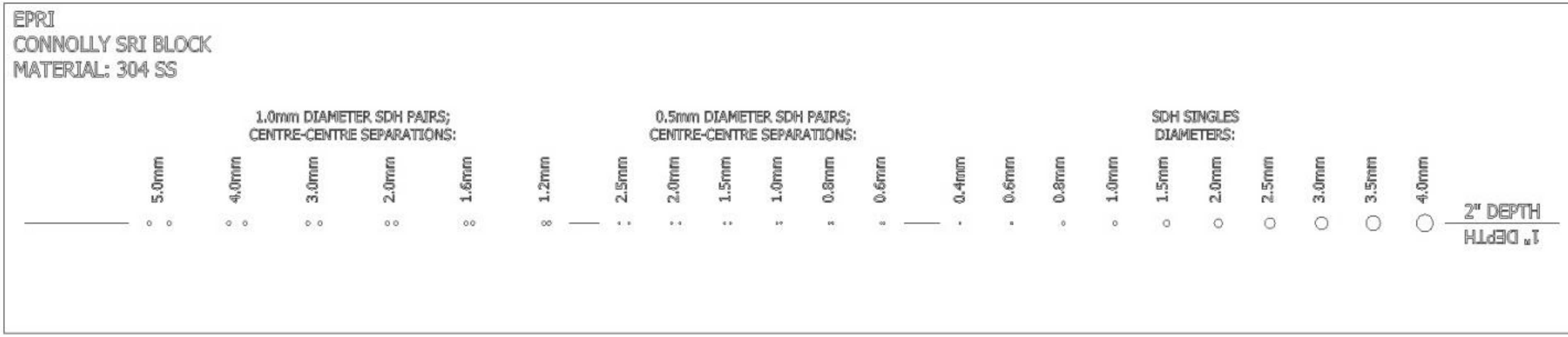
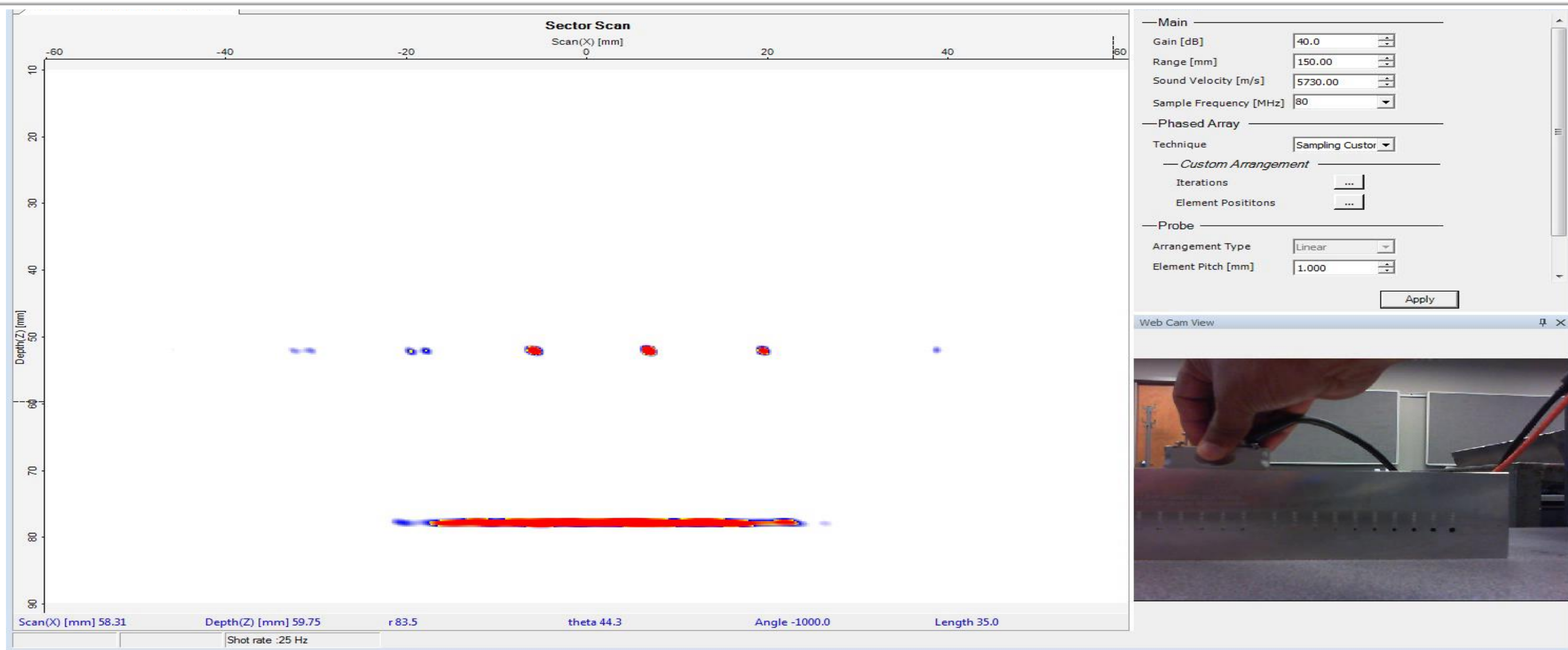
Sample Frequency [MHz] 80
Phased Array
Technique Sampling Custor
Custom Arrangement
Iterations
Element Posititons
Probe
Arrangement Type Linear
Element Pitch [mm] 1.000
Apply
Web Cam View
Scan(X) [mm] 35.71
Depth(Z) [mm] 75.92
r 83.9
theta 25.2
Angle -1000.0
Length 35.0
Shot rate :25 Hz





Resolution Test

Literature

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2. *Protecting against common cause failures in digital I&C systems of nuclear power plants*, Vienna : International Atomic Energy Agency, 2009, IAEA nuclear energy series, ISSN 1995–7807 ; no. NP-T-1.5, STI/PUB/1410 ISBN 978-92-0-106309-0
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Defense-in-depth

Elegant degradation is a term used in engineering to describe what occurs to machines which are subject to constant, repetitive stress.
Externally, such a machine maintains the same appearance to the user, appearing to function properly. Internally, the machine slowly weakens over time. Eventually, unable to withstand the stress, it breaks down.
Compared to graceful degradation, the operational quality does not decrease at all, but the breakdown may be just as sudden.