IAEA Technical Meeting on Experience in Codes and Standards for Fusion Technology

EUROfusion

DEMO DESIGN CRITERIA for In-Vessel Components – Strategic vision and overarching considerations

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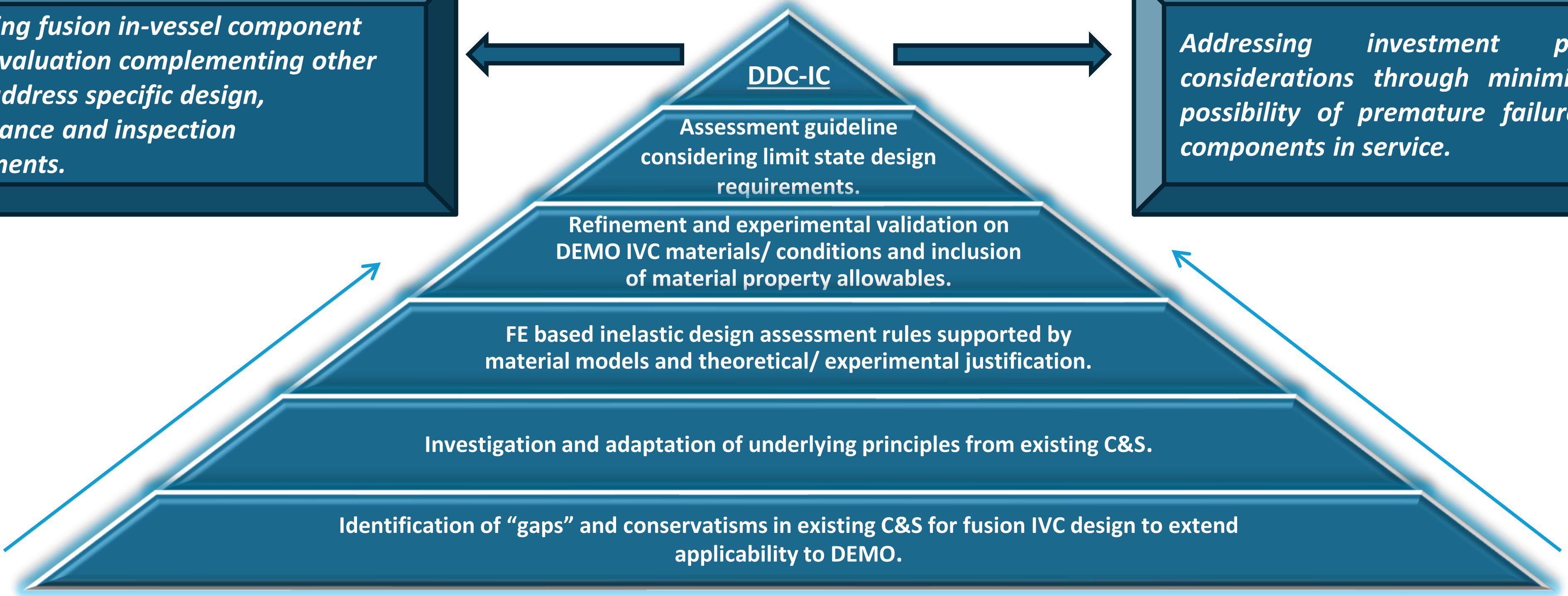
DDC-IC - Strategic vision.

A fully integrated and harmonized guideline for structural integrity design assessment of commercial fusion reactor in-vessel components adopting specially formulated inelastic design by analysis rules supported by advanced non-linear Finite Element (FE) based assessment procedures and probabilistic assessment methods.

Supporting fusion in-vessel component design evaluation complementing other C&S to address specific design, maintenance and inspection requirements.

Addressing investment protection considerations through minimizing the possibility of premature failure of key components in service.



DDC-IC development strategy

DDC-IC overview.

Methodology.

- **"Direct Route" for design by analysis underpinned by limit state design approach.**
- **Comprehensive design life assessment -** *crack-initiation/crack growth, fast fracture and incremental plastic damage.*
- **Design margins using R6 failure assessment curve -** *to address synergism between fast fracture and ductile damage.*

Basic approach.

- **Considering limit state requirements specific to each component –** *based on structural/ functional requirements*.
- **Comprehensive validation testing and material qualification programs** - *high heat flux testing and irradiation campaigns.*
- **Informed design margins** – *considering material properties, R6 failure curve and limit state criteria.*

DDC-IC document structure.

PART A: General Provisions Strategic challenges, key fusion principles, baseline design/technological developments.	**PART B: Design Criteria and Analysis Procedures** Methodology and approach, damage classification, material properties, design rules & analysis procedures.
PART CA: Analysis Examples Component level examples demonstrating application of design rules, salient aspects underpinning FE analysis (e.g. mesh topology, element selection).	**PART CB: Justification of Design Criteria** Theoretical basis/ validation arguments for design rules, damage classification approach and material models.

Overview of pertinent C&S and "gaps".

SDC-IC

- Structural design criteria for ITER in-vessel components.
- Simplified DBA rules for ductile and brittle failure mechanisms (cyclic, steady and monotonic loading), time-dependant fatigue (including creep fatigue interaction for homogenous structures) and buckling.
- Radiation effects considered up to a maximum limit of 15 dpa (but typically up to 5 dpa).

ASME-Sec VIII Div 2

- Guidelines for the design of pressure vessels and multi-chambered vessels operating at internal/ external pressures exceeding 15 psi.
- Procedures for elastic, limit load and elastic-plastic analysis.
- Failure mechanisms covered include plastic collapse, buckling, failure from cyclic loading (ratcheting and fatigue).
- Radiation effects not considered.

RCC-MRx

- Design and construction rules for sodium fast reactors, research/ experimental reactors, and fusion reactors.
- Covers "P" type damages (such as excessive deformation, plastic instability, fracture) resulting from monotonic/ constant loads and "S-type" damages (such as progressive deformation, fatigue) resulting from repeated application of loading.
- Radiation effects are considered (up to 15 dpa?).

Gaps to be addressed.

Candidate material properties and material behaviour characterisation. **Non- standard loads (14 MeV irradiation, 4-1400k temperature, EM loads, cycling).**	**Incomplete coverage of design rules/ material properties for HRP/ brazed joint interfaces and inspection requirements.**
Incomplete coverage of design rules for specific failure mechanisms. Simplified approaches can have conservatisms and cannot address complex load evolutions.	**Validity of theoretical basis and assumptions underpinning the design rules. Validity of design rules for anticipated through-life dpa.**

DDC-IC - Design rules selection.

Basis for selection of failure mechanisms

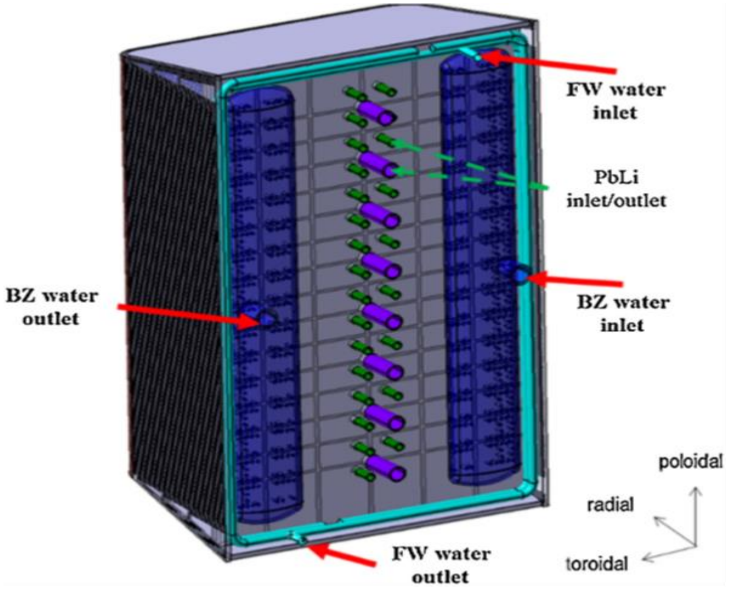
Preliminary studies carried out at the pre-concept design phase which identified the life-limiting failure mechanisms.

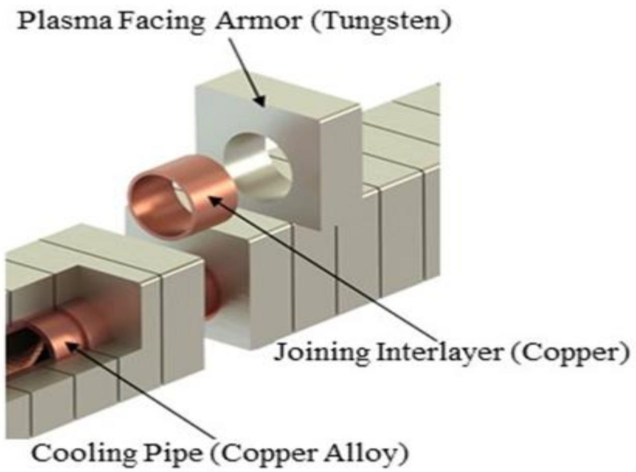
Breeding Blanket

Primary stresses due to coolant pressure further exacerbated by EM loads. Secondary stresses from nonhomogeneous temperature fields. Cyclic thermo-mechanical loading in pulsed operation.

Divertor

Primary stresses due to coolant pressure further exacerbated by EM loads. Secondary stresses from thermal loads (surface heat flux and thermal cycling). Residual stresses (from manufacturing processes).





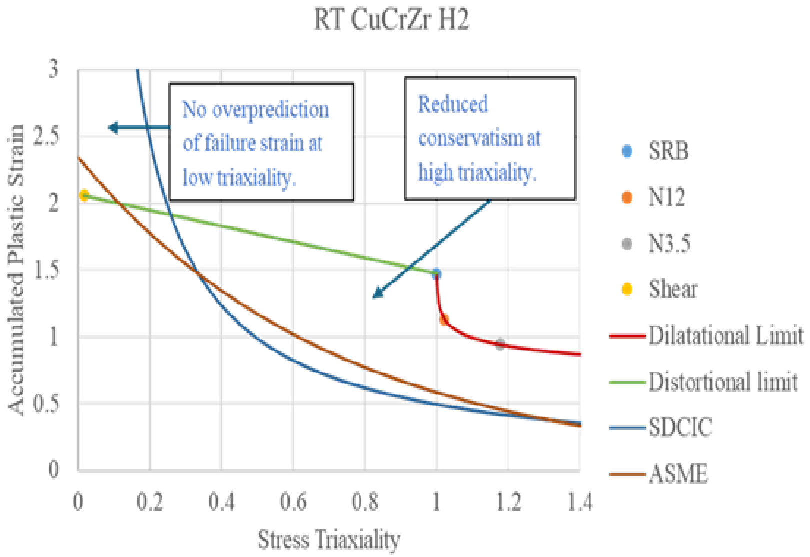
DDC-IC Design rule – Exhaustion of ductility.

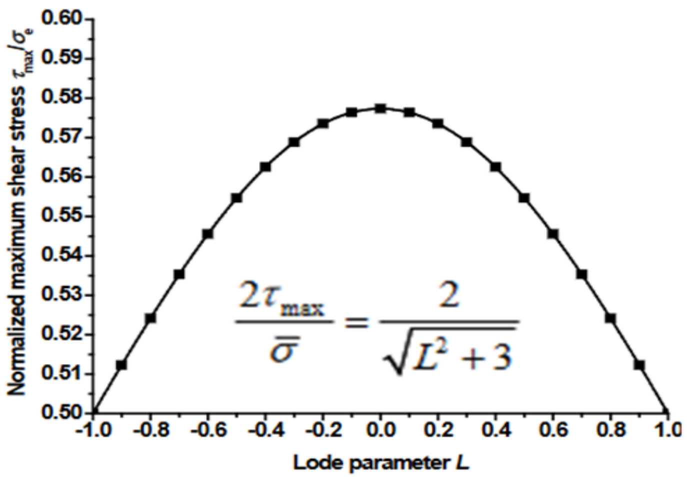
Overview

- Rupture assessment using failure strain limits derived as functions of temperature and triaxiality at failure.
- Addressing ductile failure by void distortion and void coalescence separately considering post-necking residual deformation.
- Accumulated plastic strain limit equations associated with the two damage mechanisms constitute the failure criteria.

Key considerations

- **Two key shortcomings in existing C&S are addressed**
  - Currently, the strain to failure for a given triaxiality may be underestimated.
  - Different damage mechanisms dominate at different triaxiality levels (void growth at high triaxiality and void distortion at low triaxiality).
- **Rule may consider path dependance of plastic failure. May involve inclusion of triaxiality function in the material model.**

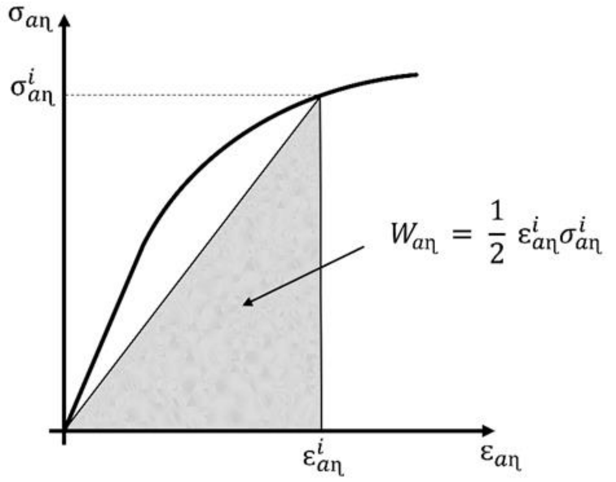




DDC-IC Design rule – Multi-axial fatigue crack initiation.

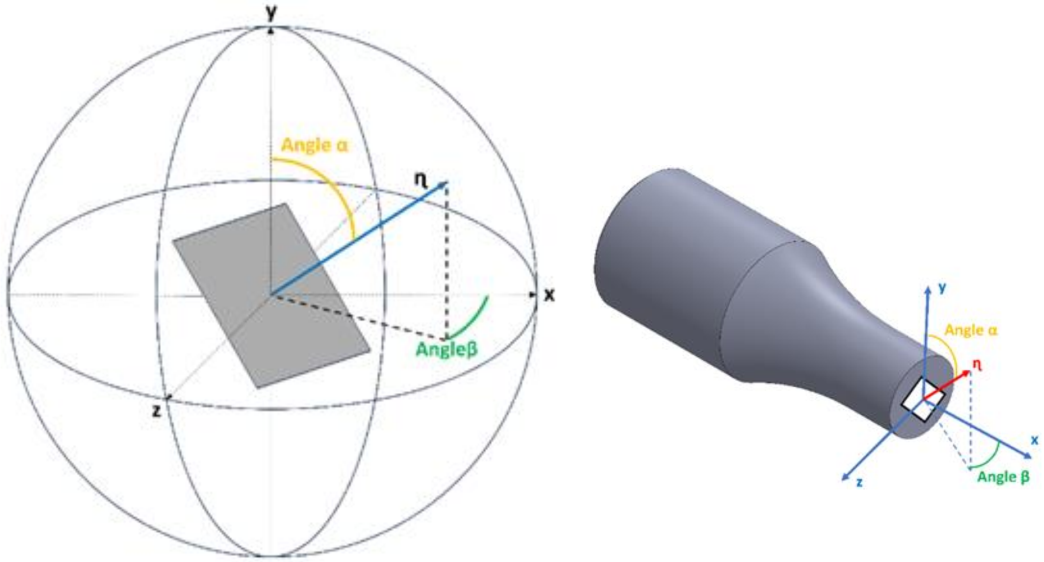
Overview

- **Crack initiation assessment to address non-proportional (e.g. tension-torsion) loading based on Lagoda-Macha-Sakane principle.**
- **Requires identification of a "critical plane" which has maximum strain energy density amplitude normal to it to evaluate initiation endurance limit.**



Key considerations

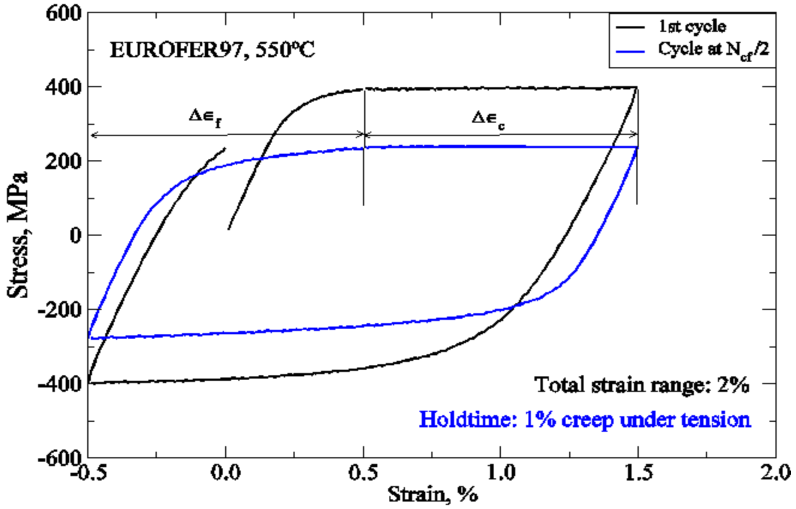
- **Direct evaluation of strain energy density - failure cycle relationship from the strain amplitude - failure cycle curve and the material stress strain curve.**
- **For "non-proportional" loading (such as out of phase tension combined with torsion), the applied strain energy may serve as a suitable parameter for assessment against crack initiation.**
- **FE simulation can help to determine the critical plane through consideration of all possible orientations of planes in a given point of the sample .**



DDC-IC Design rule – Creep-fatigue crack initiation.

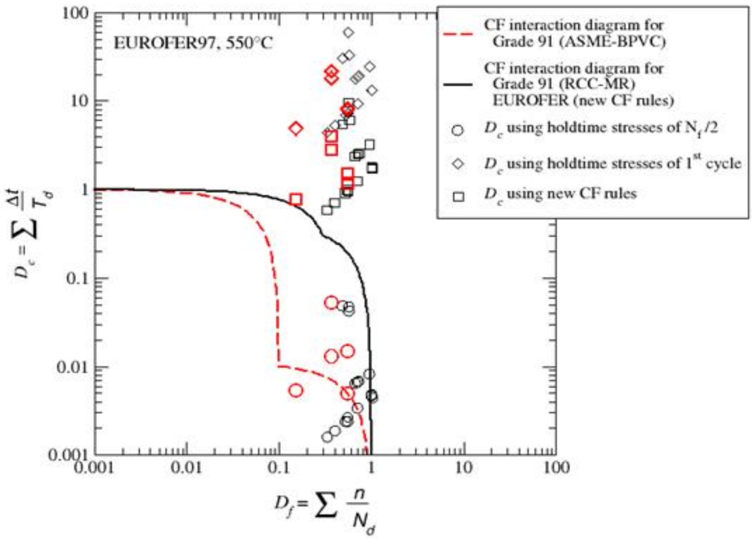
Overview

- **Extension of RCC-MRx and ASME rules for crack initiation assessment using effective allowable limit on aggregate damage from non-linear creep-fatigue interaction.**
- **Design life damage considering cyclic softening effect evaluated through a simplified strategic approximation using the component response derived from one loading cycle.**



Key considerations

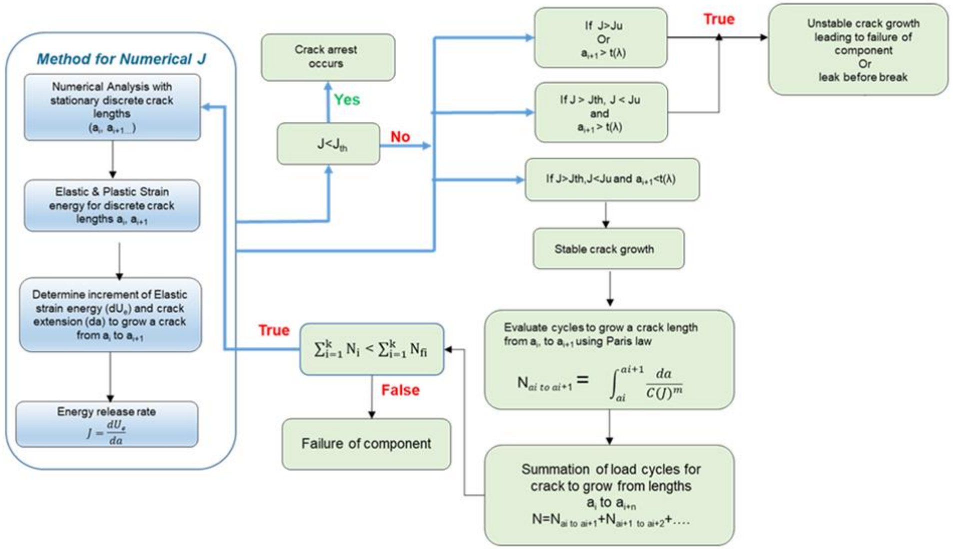
- **Cyclic softening effects can reduce the tensile and creep strengths of certain materials (such as EUROFER97) under cyclic loading.**
- **Allowable total creep-fatigue damage is a variable dependent on the creep and fatigue damage usages, respectively (non-linear creep fatigue interaction).**
- **Combined hardening material model can be used for full simulation of softening behaviour over successive loading cycles until cycle stabilisation (if required).**



DDC-IC Design rule – Fatigue crack growth.

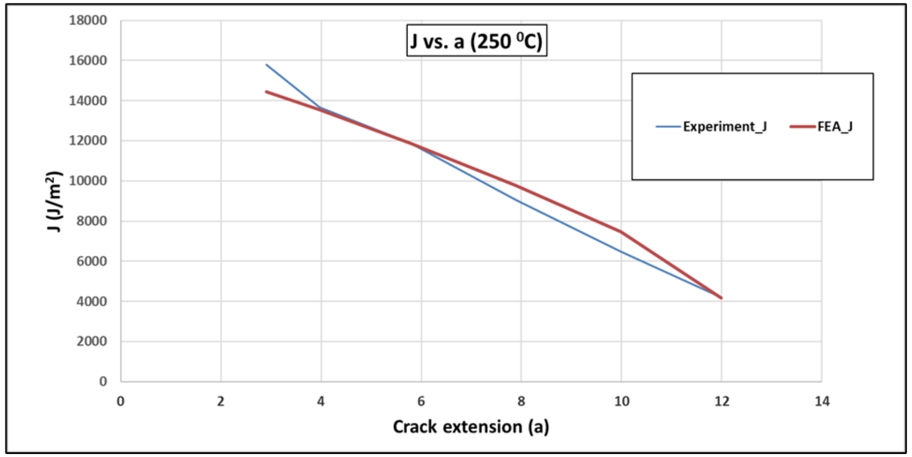
Overview

- Crack growth and arrest/instability assessment using fracture mechanics principles and contemporary J integral evaluation approach.
- Fatigue crack growth rate evaluation using Dowling and Begley equation.
- Estimation of cycles to failure (for crack growth up to critical size).



Key considerations

- J integral evaluation to circumvent path independence issues for cyclic loading strain history.
- Interplay of temperature and irradiation and the ensuing alternation between ductile and brittle behaviour over the design life.
- Variable amplitude cyclic loading (e.g. due to plasma sweeping).
- Local strain ahead of pre-crack (derived from FE) as a complementary route for crack initiation assessment.



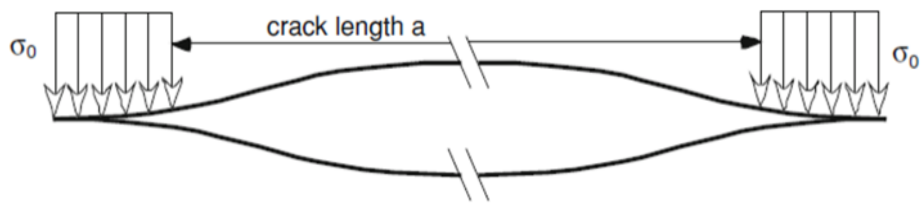
DDC-IC Design rule – Fast fracture.

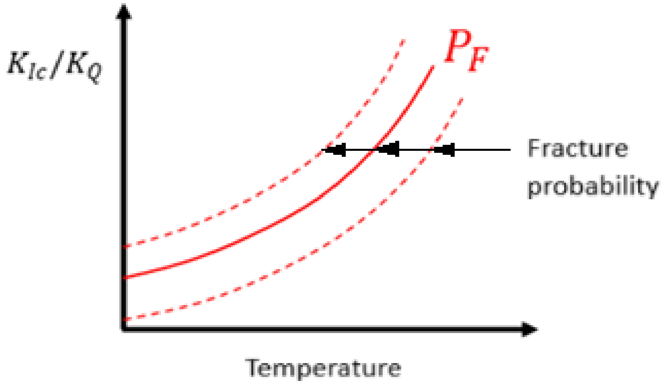
Overview

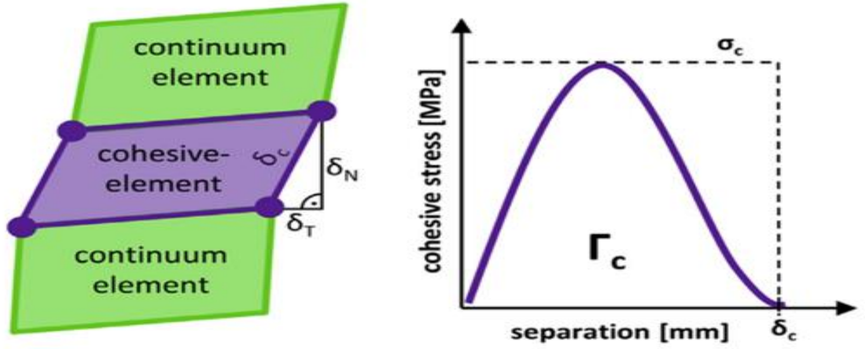
- Semi-probabilistic fracture tolerance evaluation considering probabilistic variations in fracture toughness.
- Fracture toughness-temperature-failure probability curves derived using Cohesive Zone Modelling and experimental data.
- Considering fracture toughness, outer fibre strength and cohesive energy as key parameters.

Key considerations

- Failure probability applicable to each fracture toughness value (and temperature) depending upon the applied cohesive stress (correlated with the Weibull distribution).
- Simulation of crack propagation in components using CZM considering fracture toughness gradients in the DBTT regime.
- Fracture toughness and DBTT considered as field variables whose values are influenced by the irradiation dose, operating temperature and He exposure.







DDC-IC - Material Models.

- Analytical material models to describe the constitutive behaviour of the candidate materials under monotonic and cyclic loading conditions (key for successful implementation of the “direct” design by analysis approach).

- Constitutive material models provided in the DDC-IC include:

Modified Chaboche model(s)	Voce non-linear isotropic hardening model/ elasto-plastic model with multiple kinematic variables	Creep models
Elasto-viso-plastic hardening model to consider cyclic softening behaviour. Captures strain-memory effects and stress relaxation during the creep hold time (EUROFER97/ CuCrZr).	Monotonic plasticity evolution until UTS for exhaustion of ductility assessment (EUROFER97/ CuCrZr).	Modified time hardening equation for primary creep and combined time hardening equation for primary plus secondary creep (EUROFER97).

- For shear dominated loading cases, combined hardening model recommended for assessment against exhaustion of ductility (due to possibility of load reversal).

- Models calibrated for varying strain rates ($3e^{-3}$ to $3e^{-4}$ s^{-1}), strain ranges (0.4 to 1.5%) and temperatures (RT to 550°C).

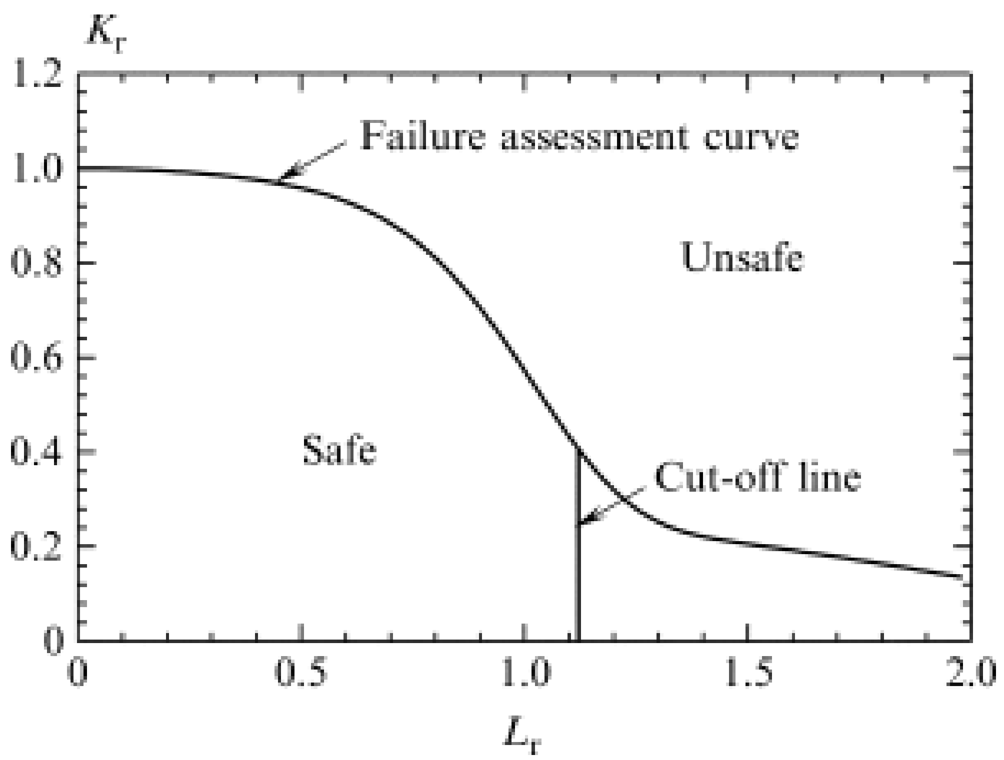
Adaptation of R6 Failure Assessment Diagram.

Overview

- The plastic damage accumulation has an influence on the margin against fast fracture.
- The procedure can be applied when crack growth and plastic strain accumulation (in the remaining ligament) can be expected to occur.
- The margin against fast fracture as a function of accumulated plastic damage can be used to predetermine "design limits".

Key considerations

- Ductile and brittle behaviour may be intertwined over the course of the design life of an IVC including defect initiation and propagation.
- For evaluation using a limited number of load cases with associated uncertainties, some in-built conservatism in the assessments will help.
- This approach may provide a basis to identify conservative limits on the "accumulative" damage to address lack of empirical information on the anticipated loads and component failures in service.



DDC-IC – Damage evaluation and classification scheme.

Basic rationale

- For in-vessel components, an augmented definition of damage is needed due to limit state considerations.
- The limit state may be determined by a combination of factors (e.g. dimensional stability, material ductility limit, intercomponent spacing, critical crack depth).
- Synergistic effects between brittle and ductile failure modes may drastically affect component design life.

Recommended approach

- Adaptation of the component-level damage limit criteria (A-D) in IAEA Tecdoc 1851 to specify target limits on damage considering incremental damage and fast fracture using component limit state considerations.
- Adoption of “damage classes” to indicate the extent to which the design is expected to resist the “onset of failure” with respect to each failure mechanism.

Example assessment presentation

Component	Operating condition	Target Damage Class	
		Failure mechanism -1	Failure mechanism -2
A	Normal operation	D-0	D-1
	Accident	D-1	D-10
	Design Extension Condition	D-10	D-100

- *If multiple incremental failure mechanisms are considered, then assess the severity of each failure mechanism w.r.t the component limit state to determine the target class.*
- *Taking the overall component damage limit (A-D) into consideration.*
- *Assignment of D-100 class would imply that for the specific operating condition, protection against that specific failure mechanism is not a concern.*

DDC-IC - Foreseen developmental challenges.

- **General requirements.**
  - Design rules to evolve synchronously with the design concepts and anticipated operational envelope.
  - Material properties may vary with loading history. e.g. Strain to rupture may be a function of irradiation dose and temperature.
  - Highest quality standards needed (investment protection considerations).

- **Design challenges due to candidate material behaviour.**
  - Tungsten has low fracture toughness, high DBTT and may be further embrittled due to irradiation and Helium.
  - Loss of ductility of Copper (in brazed joints) due to irradiation and He exposure. (accommodating the differing thermal expansion).
  - Irradiation of EUROFER97 may shift the DBTT in the affected regions of a component and lead to differential deformation during shutdown-start up cycle.

- **Irradiation damage assessment.**
  - Expected damage in fusion components is nearly 3-4 times that seen in fission reactor components.
  - Expected production rate of transmutant Helium would be nearly 30-40 times that observed in fission reactors
  - Achieving target fusion displacements per atom (dpa) in reasonable time needs dedicated test facilities.

- **Developmental constraints.**
  - Exhaustive testing for each manufacturing treatment and environmental condition may be impractical (limited material availability).
  - Regulatory expectations not fully established.
  - Multiple unknowns - Lack of a comprehensive database of anticipated loads and component failure rates based on fusion neutron spectra to inform probabilistic assessment .

DDC-IC – Other developmental considerations.

Design Rules Harmonization ⇨

- Comprehensive inelastic assessment procedure through harmonization of guidelines from multiple sources.
- Guidelines on damage limits/ load cases for selected components.
- Coherence in the simplified elastic design assessments and avoiding "cherry picking".

Brazed joints design ⇨

- Limits for weld thickness or acceptable limits on weld stresses (lack of field experience).
- Guidelines on numerical modelling of brazed joints.

Probabilistic assessment ⇨

- Accounting for uncertainties in input data (loads, dimensions, material properties).
- Implementing partial safety factors (or "margins" on loads and/or resistances) calibrated for a target failure probability.

Conclusions – DDC-IC key aim and salient aspects.

- A fully integrated inelastic design by analysis methodology supported by refined FE based assessment approaches and constitutive material models.
- Alternative design rules for structural integrity assessment to relax conservatisms in existing design codes and increase design space.
- Comprehensive assessment methodology using limit state approach and R6 FAD to assess synergistic effects between ductile and brittle failure modes.
- Assessments against a limited set of key representative load cases and failure mechanisms with adequate justification.
- Framework that can be adapted for evolving concept designs through controlled adjustments to address unprecedented and evolving requirements.
- Dedicated modelling/design guidelines and material characterization for brazed joints.
- Evaluating uncertainties in design parameters through probabilistic methods.

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Thank you

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