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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.

DDC-IC Driving objectives.

- **Developing novel deterministic design criteria for in-vessel components from first principles supported by refined FE based assessment approaches.**
  - Accurate prediction of component performance in the dominant inelastic regimes.
  - Expanding the design space by circumventing the approximations and inherent conservatisms in simplified inelastic assessment approaches.
  - Addressing load combinations difficult to access by conventional assessment approaches.
  - Addressing failure mechanisms for which inelastic design rules are absent or "insufficient" in existing codes & standards.
- **Supporting development of component designs given the hazards and constraints associated with maintenance and inspections.**
- **Addressing investment protection expectations to achieve a minimum maintenance-free operational period through minimizing the possibility of premature failure of key components in service.**

DDC-IC Salient aspects.

- **Comprehensive validation testing and material qualification programs (including high heat flux testing and irradiation campaigns) and validated material models for DEMO IVCs.**
- **Tailored damage limit(s) for each failure mode through augmentation of the classical damage criteria level definitions to address component limit state and minimum safe life expectations.**
- **Contextualised nomenclature for indication of design margins against different failure mechanisms using the definition for onset of failure to demarcate different damage classes.**
- **Consolidated design specifications for selected DEMO in-vessel components including tailored guidelines on operating conditions, loads, materials and manufacturing procedures.**
- **Dedicated modelling and design guidelines for brazed joints.**

DDC-IC Design rules.

Design rule	Overview
Exhaustion of ductility	Rupture assessment using failure strain limits derived as functions of temperature and triaxiality at failure (post-necking) to address ductile failure by both void distortion or coalescence considering post-necking residual deformation capacity.
Creep-fatigue crack initiation	Crack initiation assessment using effective allowable limit on aggregate damage from non-linear creep-fatigue interaction considering cyclic softening behaviour.
Multi-axial fatigue crack initiation	Crack initiation assessment to address non-proportional (tension-torsion) loading based on Lagoda-Macha-Sakane principle to identify critical plane and associated normal strain energy density amplitude to evaluate initiation endurance limit.
Fatigue crack growth	Fatigue crack growth and crack instability assessment using fracture mechanics principles supported by contemporary FE based J integral evaluation.
Fast fracture	Semi probabilistic assessment method using contemporary fracture toughness-temperature-failure probability master curve derived using FE based cohesive zone modelling techniques and experimental data to aid fracture tolerance evaluation considering probabilistic variations in fracture toughness and fracture toughness gradients in the DBTT regime.

DDC-IC Chapters.

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.

DDC-IC Methodology.

- **"Direct Route" for design by analysis underpinned by limit state design approach.**
  - Comprehensive component safe lifetime assessment through evaluation against gross incremental (ductile) damage, crack initiation/ stable crack growth and fast fracture considering the combined effects of irradiation and temperature on the material and the structural/ functional design constraints.
  - Strategic assignment of design margins using the R6 failure assessment curve to account for potential alternating/ synergistic effects between fast fracture and ductile damage and address component lifetime/ failure tolerability expectations depending on quality class.

DDC-IC Key developmental considerations.

- **Sufficiency of theoretical basis and validity of assumptions underpinning the design rules considering complex and unprecedented design challenges.**
  - Synergistic effects of 14 MeV neutron irradiation, 4 K to 1400 K operating temperature, thermal cycling, monotonic/cyclic mechanical loads, electromagnetic loads/ disruptions and plasma-wall interactions.
  - Novel candidate materials and associated characteristics (e.g. material hardening/ softening, DBTT) considering high lifetime neutron-fluence/ dpa and He production/ permeation anticipated in DEMO.
  - Non-standard geometric features, manufacturing/ assembly methods (e.g. brazed joints).
- **Robustness of the proposed assessment methodologies in the face of multiple unknowns (limited testing in foreseen operational conditions, time dependant material property changes during service and lack of empirical experience on component failure in service).**
- **Validation of design concepts through assessments against a limited set of key representative load cases and failure modes through building in informed conservatism in the assessments.**

DDC-IC Material models.

- **Validated constitutive models to accurately characterize candidate material behaviour in non-linear regime under monotonic/ cyclic loading conditions.**
  - Modified Chaboche model(s) to include the cyclic softening behaviour of EUROFER and CuCrZr through a specially designed formulation to describe the strain-memory effects and stress relaxation during the creep hold time.
  - Voce non-linear isotropic hardening model and elasto-plastic model with kinematic variables (for monotonic plasticity evolution until UTS) for exhaustion of ductility assessment of EUROFER & CuCrZr.
  - Calibration of material models for varying strain rates, strain ranges and temperatures .

Conclusions.

- **The DDC-IC aims to support Mission 6 of the European Research Roadmap to the realization of Fusion Energy for integrated DEMO design and system development through**
  - Providing a standardised and targeted structural integrity assessment guideline for fusion in-vessel component designs to address unprecedented commercial fusion reactor operational requirements.
  - Providing alternative (refined) routes for structural integrity assessment against selected life limiting failure mechanisms to relax conservatisms in existing design codes and increase design space.
  - Ensuring coherence in the design assessments involving multi-code approach by providing guidelines on selection and correct application of design rules from other codes and standards for fusion components.
  - Providing a framework for design qualification that can be adapted (as required) for evolving concept designs through controlled adjustments to design rules and assessment procedures to address safety or licensing requirements.
- **The key challenges for the DDC-IC development in the near term include**
  - Targeted validation of design rules to DEMO relevant operational envelope.
  - Material property characterization and material models calibration for DEMO relevant conditions.

Project partners.

KIT Karlsruhe Institute of Technology · UK Atomic Energy Authority · cea · sck cen · ENEA · JÜLICH Forschungszentrum

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