The Role of Neutronics in Radiological Protection Design of Fusion Reactors

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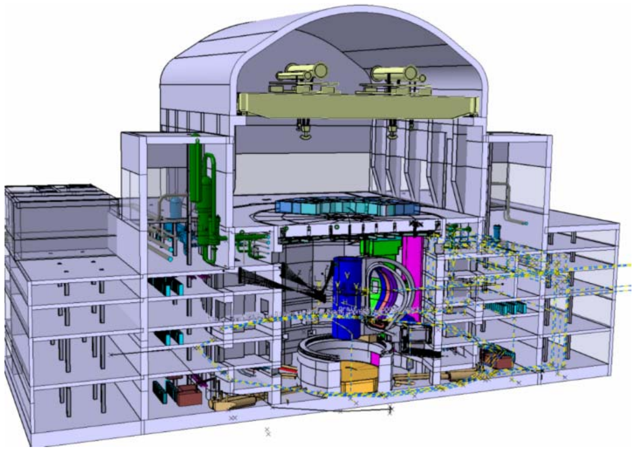

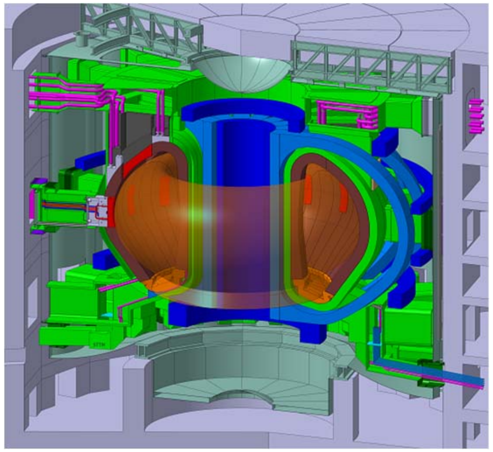

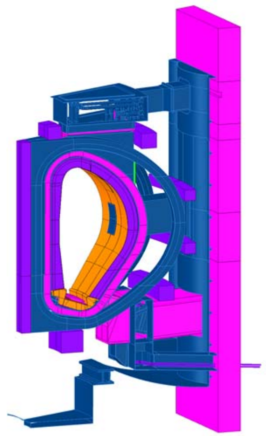

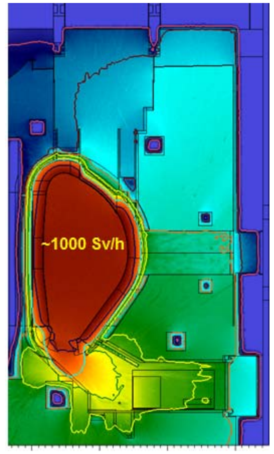

Content

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- Neutronics strategical approach for DEMO
- Radiological Protection Programme
- Generic requirements
- ALARA in design
- Radiation shielding design challenges
- Conclusions

Motivation

- ITER will be the first fusion facitily under nuclear regulation.
  - Experience with regulatory requirements for the licensing.
  - Nuclear safety culture in fusion technology.
- **Nuclear safety implementation** focused on confinement, whereas radiological protection missed commensurate attention
  - Early ORE assessment led to confidence that radiological protection is not an issue.
  - Design and other input data changes require a continuous and persistent effort.
- **Neutronics design and safety support** has driven early conceptual design.
  - Design progress requires adequate neutronics backing.
  - Role in nuclear and safety engineering to be defined.
  - Radiation issues are potential key (safety) design drivers.

Introduction

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- Neutronics plays a fundamental role for the design, operation and safety of these facilities including the evaluation and verification of their nuclear performances.
- Experience in nuclear fusion technology R&D:
  - Improving nuclear safety culture
  - Identification of transversal, plant-level functions
  - Importance of **Nuclear Design Integration**

Identification, analysis and resolution of all radiation induced issues with attention to the design phase.

Neutronics Strategical Approach for DEMO

Neutronics Strategical Approach for DEMO

Progressing Nuclear Design Integration by integration of neutronics workflows in system-engineering design processes.

Design iterations with full accountance of nuclear design and radiological protection objectives.

- Based on
  - Qualified computational methodology
  - Configuration & requirement management
- Aiming at
  - Established procedures

⇨ Validated nuclear performance parameters

⇨ Requirement verification and design validation

Methodological Approach for DEMO

Neutronics workflows stipulated by Neutronics Guidelines.
Recommendation on use of tools, data and requested nuclear responses.

Tools

- Radiation transport: MCNP, TRIPOLI
  - SERPENT, GEANT4, OpenMC …
- Activation: FISPACT-II, ACAB
- Shutdown coupled codes: MCR2S, R2S-UNED, R2Smesh, AdD1S
  - cR2S (to be released)

Data

- Neutron transport: JEFF, FENDL
- Activation: TENDL
- Response files: for damage and gas production

System-Engineering Integration

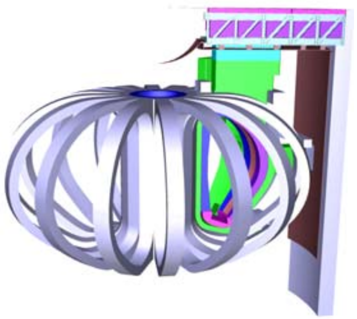
Current focus on prime components

⇨ Requirement Management

- Common understanding of requirements (specifications)
- Complete and good requirements
- Product and process requirements
- Transversal functions and requirements

⇨ Configuration Management

- Configuration definition and change control
- Up-to-date, referenced and applicable data
- Consistency of engineering/configuration and neutronics models
- Data management



S
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„Established Procedures“

„Set of processes, instructions and guidelines which is qualified for the requested purpose usually on the basis of state-of-the art technology, proven methods and tools and good practices.”

- Due to lack of fusion neutronics Codes&Standards there is need to define references and quasi-standards.
- Including generic requirements on roles&responsibilities and suitable qualification/experience of involved actors.
- Including specific technical requirements on the activities and artefacts of the processes.
- Accounts for impact on performance, safety, cost and schedule by graded approach (level of rigorousness).

Radiological Protection Programme

Objectives

- Comprehensive administrative and technical measures to design, operate and maintain the facility from a radiological protection perspective.
- Basis to identify, minimize and limit radiation hazards and exposure to ionizing radiation.
- Covers the full project life-cycle from design to decommissioning.

➢ Develop and implement at (early) design phase.

➢ Provide sound basis to implement principles of radiological protection into organisational and technical processes.

Principles of Radiological Protection

<u>*Source-related and in all exposure situations*</u>

- **Justification**
  - Any decision which alters the radiation exposure situation should do more good than harm.
- **Optimization**
  - The likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.

<u>*Individual-related and in planned exposure situations*</u>

- **Limitation**
  - The total dose to any individual from regulated sources in planned exposure situations (other than medical exposure of patients) should not exceed the appropriate limits.

Radiological Protection at Design Stage

- Normal operation inherently covers maintenance and inspection (M&I) operations to operate and maintain the facility in safe conditions.

➢ **Design for Maintenance**

- Key elements
  - Implementation of radiological protection (part of nuclear safety & security) in a system engineering context.
  - Reliability, Availability, Maintainability and Inspectability (RAMI) assessment.
  - Human and Organisational Factors (HOF) integration.
  - Risk and hazard identification.
  - Radiation and contamination mapping.

⇨ ALARA design process.

Generic Requirements

Consistency of “design” and “safety” baseline

Project Requirements

Project-level technical requirements and common basis for derived system requirements.

Safety objectives and safety requirements consistent with “Safety Requirements”

Safety Requirements

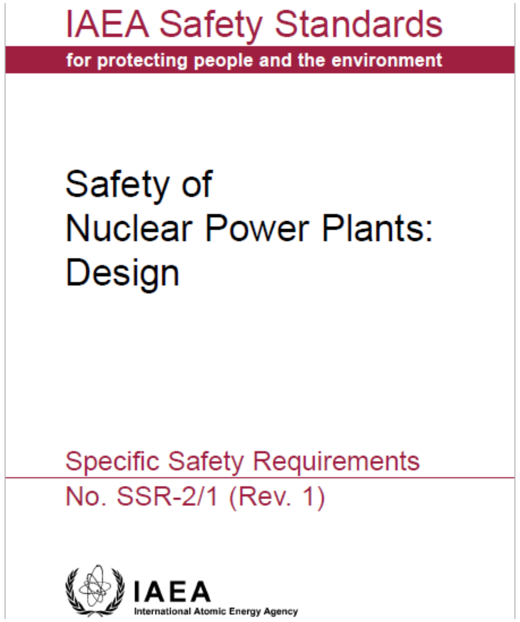
Demonstration of DEMO facility design compliance with the nuclear regulatory framework (or generic site).

Consistency with design assumptions and solutions.

Radiation Shielding and Radiological Protection Requirements

Generic Safety Requirements

- Requirement 81: Design for radiation protection
  - Identification and control of radiation source
  - Selection of materials to minimize activation ALARP
  - Access control and further prevention/mitigation of exposure
  - Radiological zoning
- Requirement 5: Radiation protection in design
  - Establishment of acceptable limits consistent with regulatory requirements
- Requirement 9: Proven engineering practices
  - Design of safety important components according to national/international codes and standards.


IAEA Safety Standards
for protecting people and the environment

Safety of
Nuclear Power Plants:
Design

Specific Safety Requirements
No. SSR-2/1 (Rev. 1)

IAEA
International Atomic Energy Agency

Radiation Shielding and Radiological Protection Requirements

Transversal Project Functions and Requirements

- Non-local shielding problems.
- Requirements are complex functions of many SSC; not necessarily credited by a safety function.
- Plant Breakdown and Functional Breakdown Structure.
  - Identification and definition of transversal functions
  - Performances, functions, constraints, requirements, interfaces.
  - Safety classification
- Transversal (global) analysis
  - To establish requirements
  - To verify requirements
  - To provide nuclear loads


IAEA TECDOC SERIES

IAEA-TECDOC-1851

Integrated Approach to Safety Classification of Mechanical Components for Fusion Applications

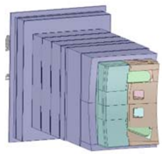
Suggestions for nuclear analysis generic requirements

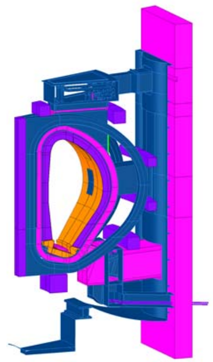
Qualified nuclear analysis process

- Established procedure encompassing planning, preparation, performance (incl. checking), and acceptance
- Verification&Validation with defined requirements on elements of
  1. Input data
  2. Methods, tools, calculations
  3. Results and acceptance criteria.
- Qualification proceeds through appropriate V&V
  - Verification: correct implementation into workflow, estimates of numerical errors
  - Validation: appropriate for intended use, adopting validation metric consistent with acceptance criteria

V&V of input data

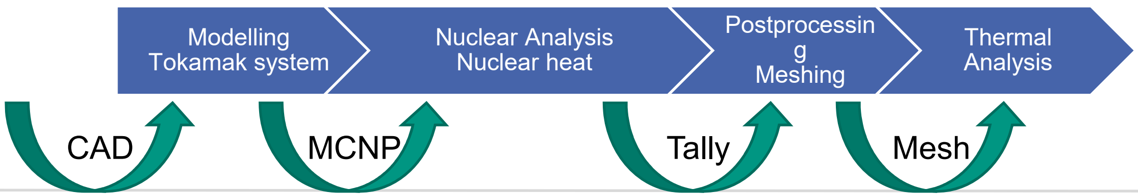
- Problem-specific data
  - Material definitions, geometry models, assembly, operational conditions, environmental conditions, etc.
- Reference project data
  - Same as above, but for general applications
- Generic project-independent data
  - Nuclear cross sections, response functions, etc.
- Deficient/missing data
  - Use of assumptions





Up-to-date, referenced, traceable, applicable

Databases, repositories
Change and version control
Applicability assessment
Continuous improvement
Sensitivity studies



V&V of tools

- V&V with use of experimental and computational benchmarks, often recourse to code-to-code benchmarks.
- Validation is often generic:
  - Not for a particular application.
  - Not referring to a validation metric: consistent with acceptance criteria
- Verification is often incomplete:
  - Calculation verification demands quantitative estimates of the numerical error.
  - Part of the uncertainty assessment of a dedicated analysis.

Verification of radiological protection req.

- For use in Safety Demonstration adopting principles of safety analysis is advisable:
  - Evaluation of safety margins by conservative or best estimate (plus uncertainty) approaches.
  - All possible systematic and random effects to be taken into account.
  - Final result of shielding analysis is upper bound of requested response with, as appropriate, realistic and conservative assumptions.
- Methodology is required
  - To demonstrate sufficient margins in the design.
  - To ensure compliance with assessed requirement.
  - To accommodate design risks.
    - Design factors in conceptual design phases.
    - Overestimation factors (safety factors) for classes of applications.

ALARA in Design

ALARA Design Implementation

- ALARA policy (as subset of a Nuclear Safety Policy)
  - To raise awareness on optimization of radiological protection
  - To commit the project to managerial and individual responsibilities.
  - To introduce the conceptual approach and steps of implementation.
- Practical ALARA implementation by
  - Continuous, predictive and iterative process;
  - Decision-aiding techniques to find the optimized protection solution;
  - Suitable objective means to demonstrate and justify the correct implementation.

ALARA Design Implementation

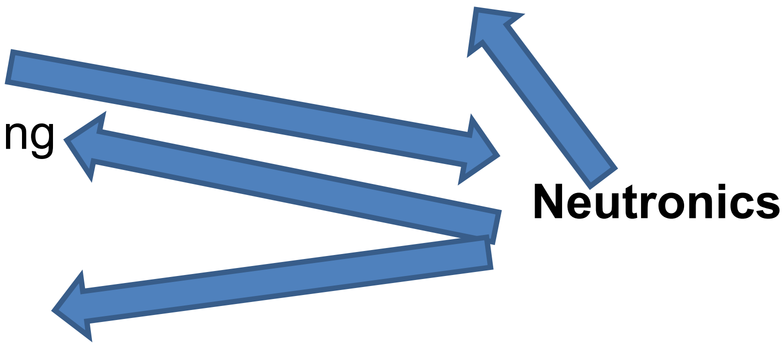
- ALARA process involves
  - Evaluation of the exposure situation and selection of appropriate dose constraints;
  - Identification of protection options (or dose reduction factors);
  - Analysis of options and selection of best option under prevailing circumstances;
  - Implementation of selected option;
  - Feedback from design and operations.

A formalized ALARA design process is not yet developed for DEMO.

⇨ **Neutronics analysis has a fundamental role in the process**

ALARA Design Implementation

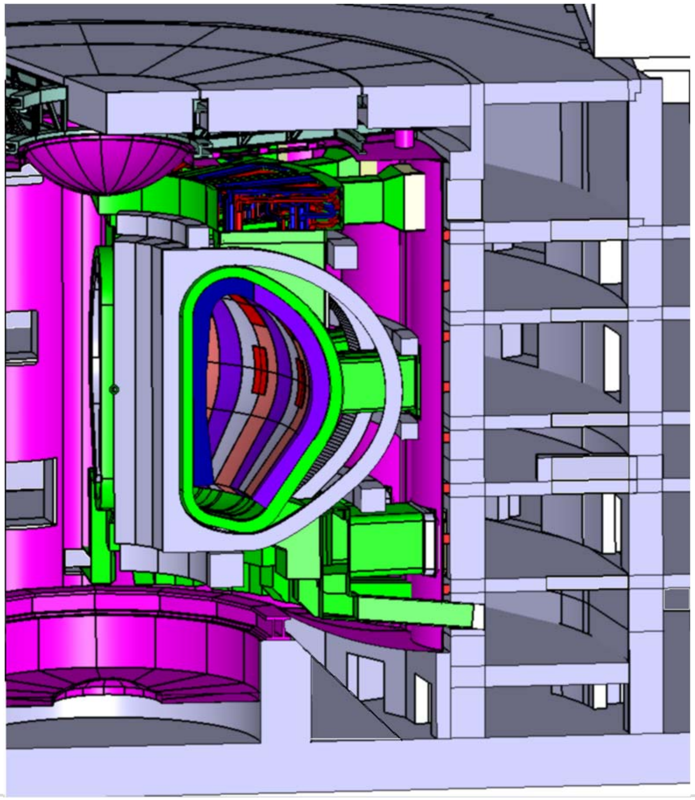
- Pre-requisites
  - RAMI, M&I requirements
  - Maintenance criteria
  - Criteria for layout of SSC in tokamak complex building
  - Zoning definitions (radiation, contamination, ventilation, radwaste, Be, etc.)
- Ingredients
  - Configuration and design models
  - Facility radiation/contamination mapping
  - Safety room book
  - Maintenance plans
  - Possible dose reduction factors



Radiation shielding design challenges

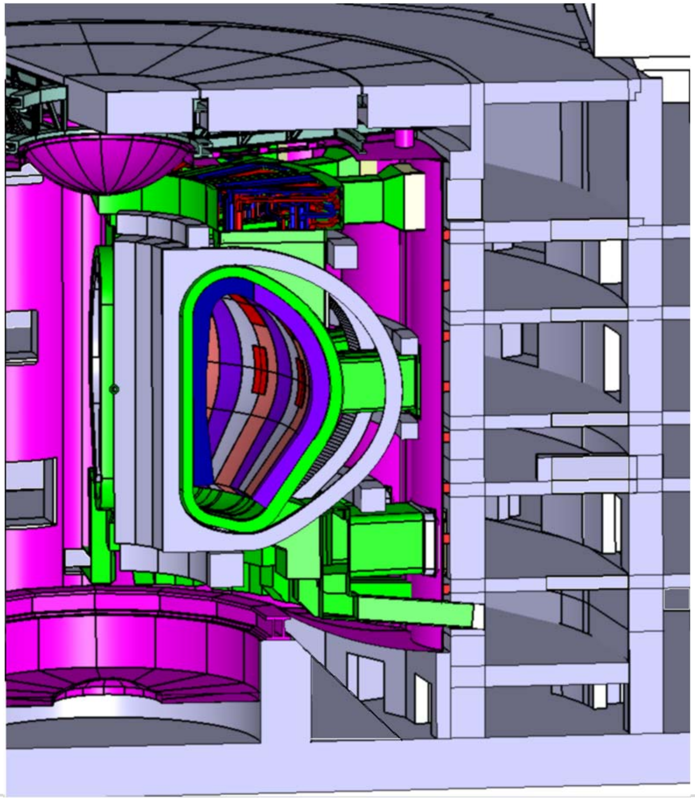
Design constraints

- Shielding objectives
  - Direct/indirect protection
  - Sensitive equipment
  - Planned hands-on maintenance in radiation fields (hostile environment)
- Contradictory and non-compatible technical requirements
  - Functional performances
  - Reliability, Availability, Maintainability, Inspectability (RAMI)
  - Manufacturing and assembly



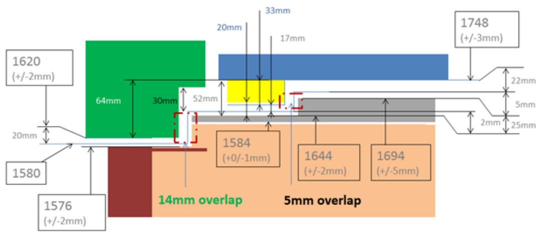
Design constraints

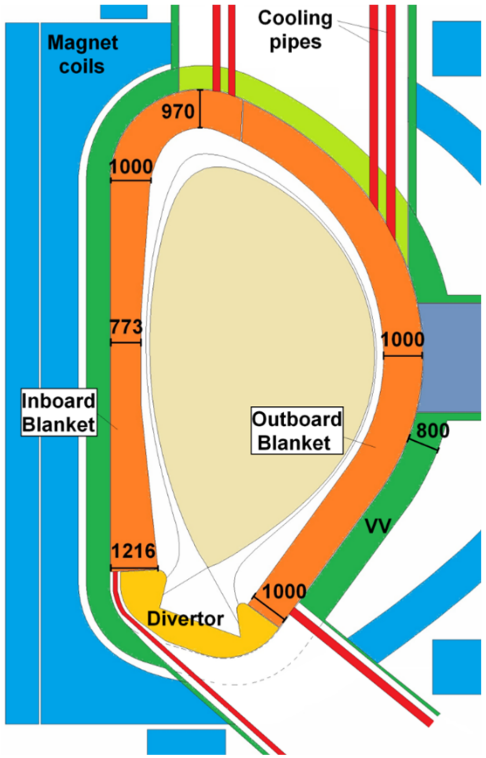
- Design maturity, design interfaces, design integration
  - Late interface definitions
  - Out-of-phase design progress
  - Change management
- Costs, schedule, management, …



Primary shields and port openings

- Assembly gaps between Blanket Modules.
- Number of ports and port openings
- Manufacturing, assembly and maintenance tolerances
- Ports and port plugs contribute to the overall shielding objectives of the primary shield assembly.
- Shielding imperfections due to gaps, penetrations, backfilling, etc.





General aspects for integrated shielding design

- Identification of all relevant radiation source terms: particle, energy, source strength, location, distribution …
- Shielding from the source(s)
  - improve weak shield capabilities of the primary shields
  - Apply primary shields to (potentially) all radiation source terms
- Streaming and leakage mitigation, moderation, absorption, material tailoring and optimization.
  - Shielding of port systems to reduce radiation levels inside the maintenance area.
  - And concurrently: reduce the radiation cross talk and backscattering by enhanced absorption.
  - Use of reduced activation materials.
- Permanent and temporal (gamma) shields.
- ALARA principle applied iteratively during all design phases

DEMO tokamak global shielding improvements

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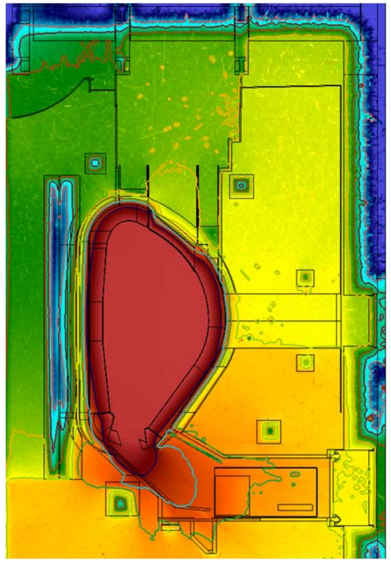

Strategical approach

- Status of protection requirements and priorities
- Assessment of radiation mapping from plasma neutron source
- Identification of key configuration and design options
- Study of advanced „baseline“ configuration: VV and intercoil shields
- Study of various options at port level

Conclusions

- Radiological Protection is a major design driver for fusion facilities due to its global and transversal function and challenging design constraints.
  - Its successful integration supports public acceptance of nuclear fusion technology.
- Neutronics plays a prominent role in Nuclear (Design) Integration to implement a Radiological Protection Programme with practical ALARA design processes.
- Nuclear analysis requirements lead to the need for qualified computational methodology and suitably adopted configuration&requirement processes.
- Dedicated efforts are required on definition of qualified (established) procedures with comprehensive V&V on data and tools.
- This neutronics framework can be utilized in the safety demonstration to verify achievement of radiological protection requirements.

Thank you for your attention!

Acknowledgement
Suggestions and ideas by XXX
Pictures/Data: Courtesy of C. Gliss, C. Bachmann, T. Eade