Radiological Protection Design Considerations for DEMO

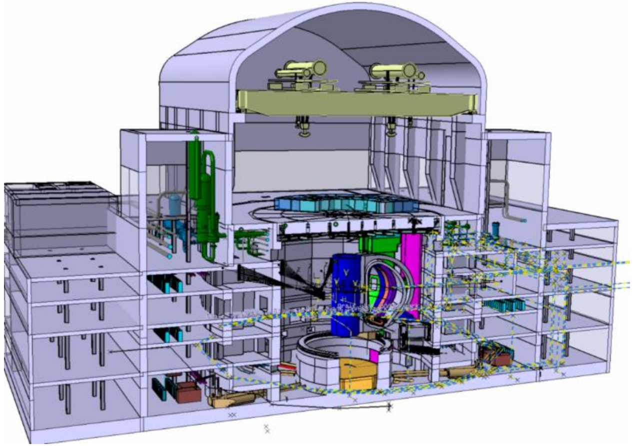
D. Leichtle[a], D. Chauvin[b], T. Pinna[c]

[a] *Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*

[b]*EUROfusion – Programme Management Unit, Garching, Germany*

[c]*ENEA, FSN Deparatment, Frascati, Italy*

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.



Content

- Motivation
- Principles of Radiological Protection
- Approach to Radiological Protection in the Design Phase
- Radiological Protection Design Guideline
- Conclusions

Motivation

Karlsruhe Institute of Technology

- ITER will be the first operating fusion facility under nuclear regulation.
  - Lessons learnt from safety implementation and licensing.
- **Radiological protection objectives** are key challenges considering plant performance, safety and regulatory constraints.
  - High neutron/gamma radiation fields from various distributed sources, high inventories of Tritium and radioactive substances.
  - Underestimation of radiological protection issues based on preliminary and incomplete design data.
  - Design for shielding provisions complicated by evolving plant/system design.
- **Radiological protection objectives** and radiation induced issues are potential (safety) design drivers
  - Requires evolving nuclear design process with ALARA integration at early design phase.

Principles of Radiological Protection

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.

Towards a Comprehensive RP Programme

- Comprehensive administrative and technical measures to design, operate, maintain and dismantle 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.

Hazards of Exposure to Ionizing Radiation

- External radiation exposure from various sources
  - Fusion plasma
  - Activated structures
  - Activated liquids (water, PbLi)
  - Activated dust
  - Activated corrosion products
  - Radiological waste
  - Radiation sources from monitoring, diagnostics, H&CD
  - Radon

- Internal radiation exposure from air-borne sources
  - Tritium
  - Activated dust
  - Activated corrosion products

Approach to Radiological Protection in the Design Phase

Relevant DEMO Objectives

Karlsruhe Institute of Technology

- Stakeholder requirements define **DEMO plant performance objectives**, such as
  - Demonstration of electricity production: typically 300 MWe.
  - Extrapolability of availability (DEMO 30%) to commercial FPP: e.g. 60-90%.
  - Estimation of future full life-cylce economic potential of FPP.
- Similarly, **favourable safety and environmental protection** is to be demonstrated, such as
  - Safety functions are maintained in all situations.
  - Exposure to hazards are controlled, kept below limits and as low as reasonably achievable.

Radiological protection is implemented through the safety function „Limitiation of exposure to ionizing radiation“

Radiological Protection at Design Stage

- Normal operation inherently covers preventive maintenance and inspection (M&I) activities to operate and maintain the facility in safe conditions.
  - ➢ **Design for Maintenance (as plant driver)**
- Few key elements specifically relevant for Radiological Protection
  - Risk and hazard identification
    - Inventory of radiation sources incl. activation sources
    - Radiation and contamination mapping.
  - Maintenance strategy
    - Maintenance inventories
    - Maintenance types (preventive, incl. inspections, corrective and logistics)

➡ **Radiological protection design guideline and ALARA design process**

Design Implementation of RP Objectives

Karlsruhe Institute of Technology

Radiological protection is a challenge …

- Impact on plant performance, integration, maintenance, safety, licensing …
- Complexity of exposure scenarios (sources, configurations, work places …)
- Requirements affect DEMO plant across PBS
- Plant and functional breakdown structure for identification of transversal functions with dedicated requirements, contraints and interfaces.

Maintenance	Plant availability	DEMO Transversal Functions
Materials	Material choices (outside civil works)	
Nuclear Integration	Radiation protection issues	
Vacuum	Vacuum needs (outside fuel cycle)	
Tritium	Tritium related issues (outside fuel cycle and breeding blanket)	

➡ **Radiological protection design is a highly transversal activity**

RP: Maintenance Strategy

- Starting point: Maintenance inventory
  - Maintenance items: based on DEMO PBS and SSC list
  - Maintenance environment: room book data, plant layout (GBS)
- Definition of Maintenance Strategy
  - Preventive Maintenance: any planned and predefined activity aiming to maintain the function of a SSC at the high level of required performance, quality and safety.
  - Corrective Maintenance: any unplanned (and undefined) activity due to failure, aiming to restore the function of the failed SSC at the high level of required performance, quality and safety.

RP: Nuclear Integration

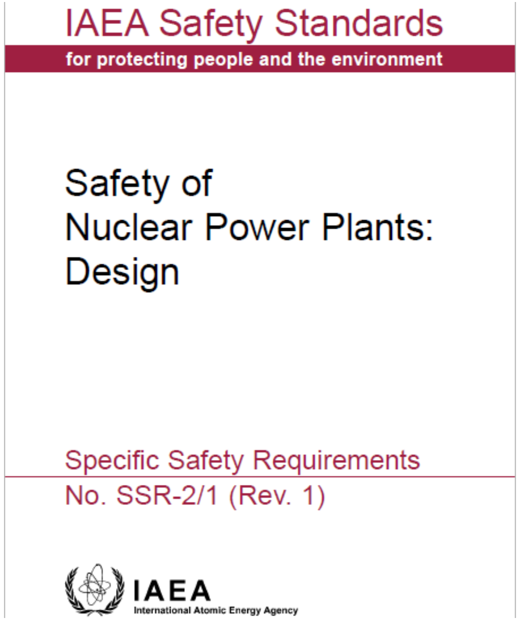
- Starting point: Protection requirements, inventories, shielding architecture
  - Investment and occupational exposure protection
  - Inventories of radiation source terms (including activation sources), SSC with shielding performances
  - Definition of generic shielding architecture (tokamak, nuclear building)
- Nuclear design support
  - Nuclear analyses (including V&V) in support of plant architecture and system design
  - Integration of radiological protection design activities in design processes

➡ **Radiological protection design guideline and ALARA design process**

Radiological Protection&Shielding 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

DEMO Radiological Protection Req.

Karlsruhe Institute of Technology

- Dose limits

Maximum annual individual effective dose	As low as reasonably possible and under all circumstances < 10 mSv per year
Average annual individual effective dose to exposed workers	≤ 2.5 mSv per year
Individual effective dose due to incident situation	< 10 mSv

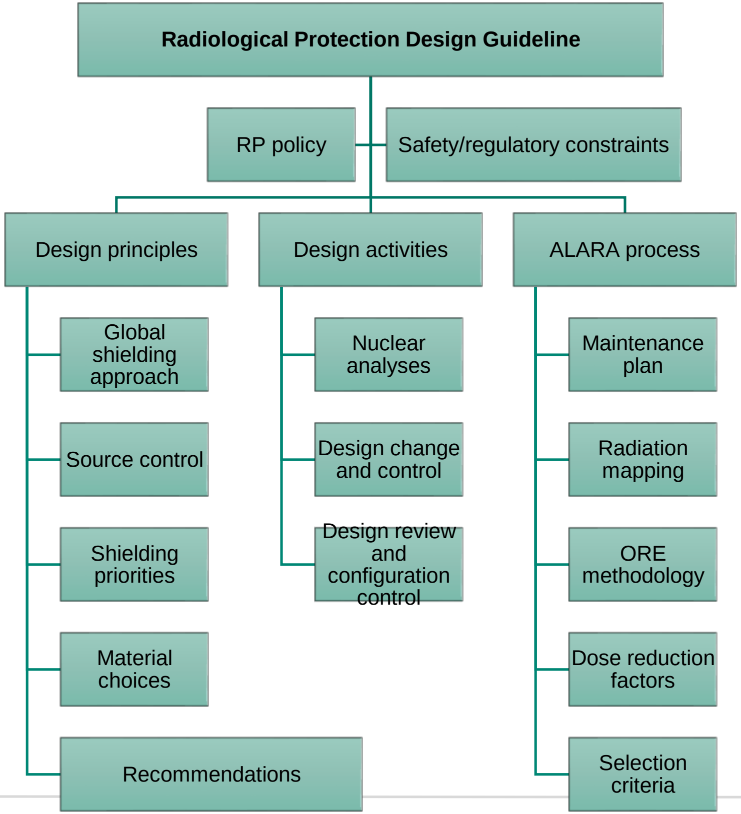
- Radiological zoning

Zone type		Zone identification	Maximum total effective dose (external plus internal)	Maximum external dose to hands, forearms, ankles and feet
Unregulated		White	80 µSv/month	
Supervised		Blue	7.5 µSv/hr	200 µSv/hr
Controlled	Limited	Green	25 µSv/hr	650 µSv/hr
	Specially regulated	Yellow	2 mSv/hr	50 mSv/hr
	Forbidden without specific authorization	Orange	100 mSv/hr	2.5 Sv/hr
		Red	above 100 mSv/hr	above 2.5 Sv//hr

Radiological Protection Design Guideline

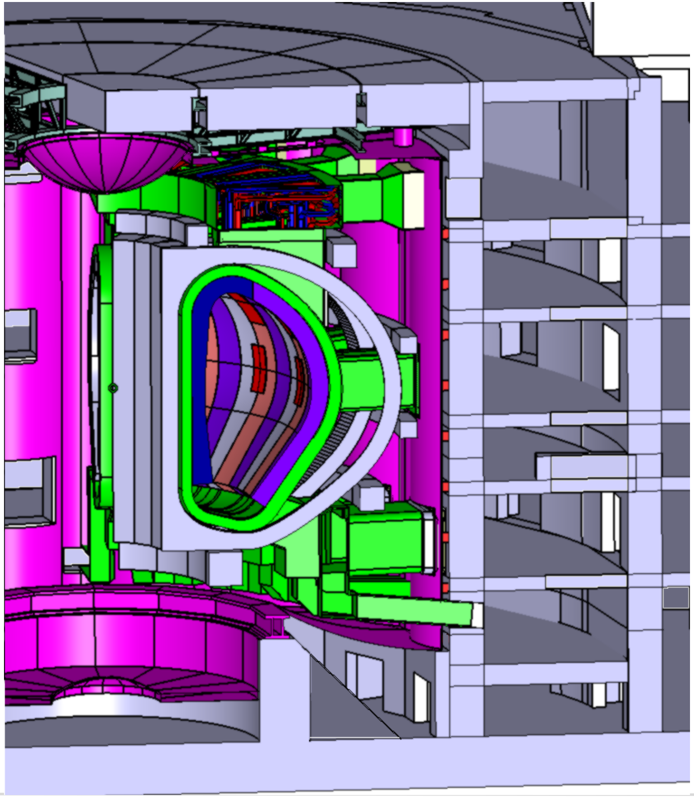
Preliminary Items of a DEMO RPD Guideline

- Purpose of the guideline
  - Introducing a Radiological Protection policy to raise awareness, stipulate commitment to responsibilities and to support the general safety culture.
  - Defining relevant high level design principles/recommendations and activities.
  - Prepare for a formalized ALARA design process.



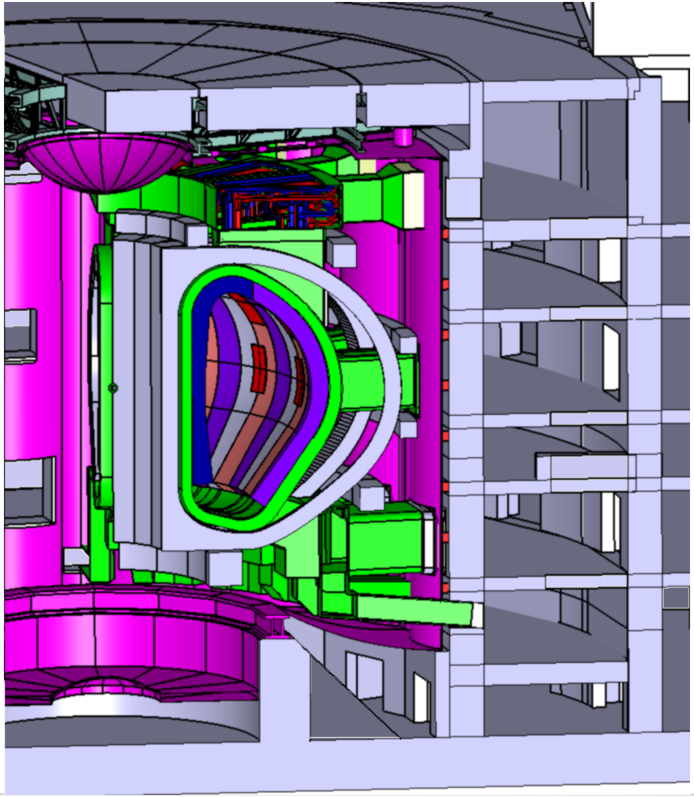
General Aspects for Integrated Shielding Design

- Identification of all relevant radiation source terms: particle, energy, source strength, location, distribution …
- Protection priorities and hierarchy
- Shielding from the source(s)
  - Improve weak shield capabilities of the primary shields
  - Apply primary shields to (potentially) all radiation source terms



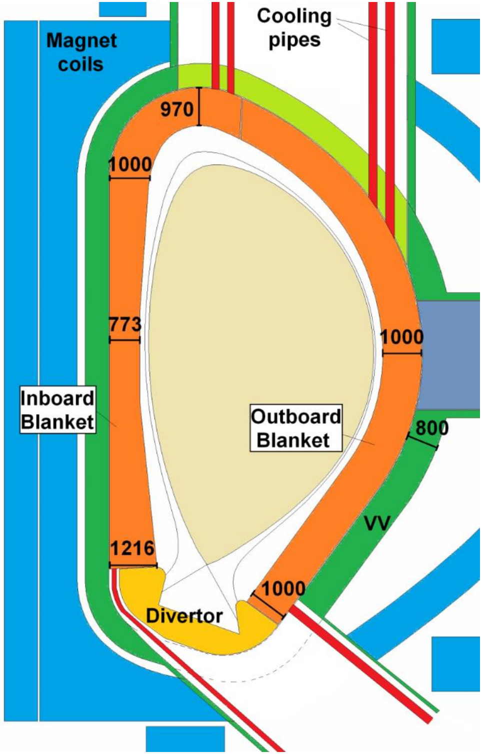
General Aspects for Integrated Shielding Design

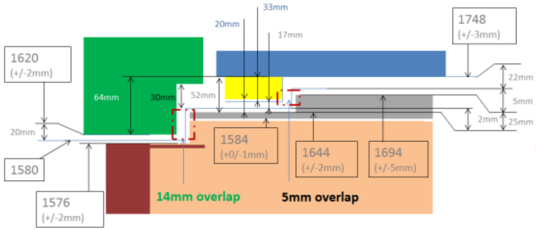
- Streaming and leakage mitigation, moderation, absorption, material tailoring and optimization.
  - Shielding of port systems to reduce radiation levels inside the maintenance area.
  - And concurrently: reduce the radiation cross talk and backscattering by enhanced absorption.
  - Use of reduced activation materials.
- Permanent and temporary shields (during interventions)



Shield Design Issues at DEMO Tokamak Shield

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





Some Generic Design Recommendations

➢ **Design for Maintainability with Radiological Protection background**

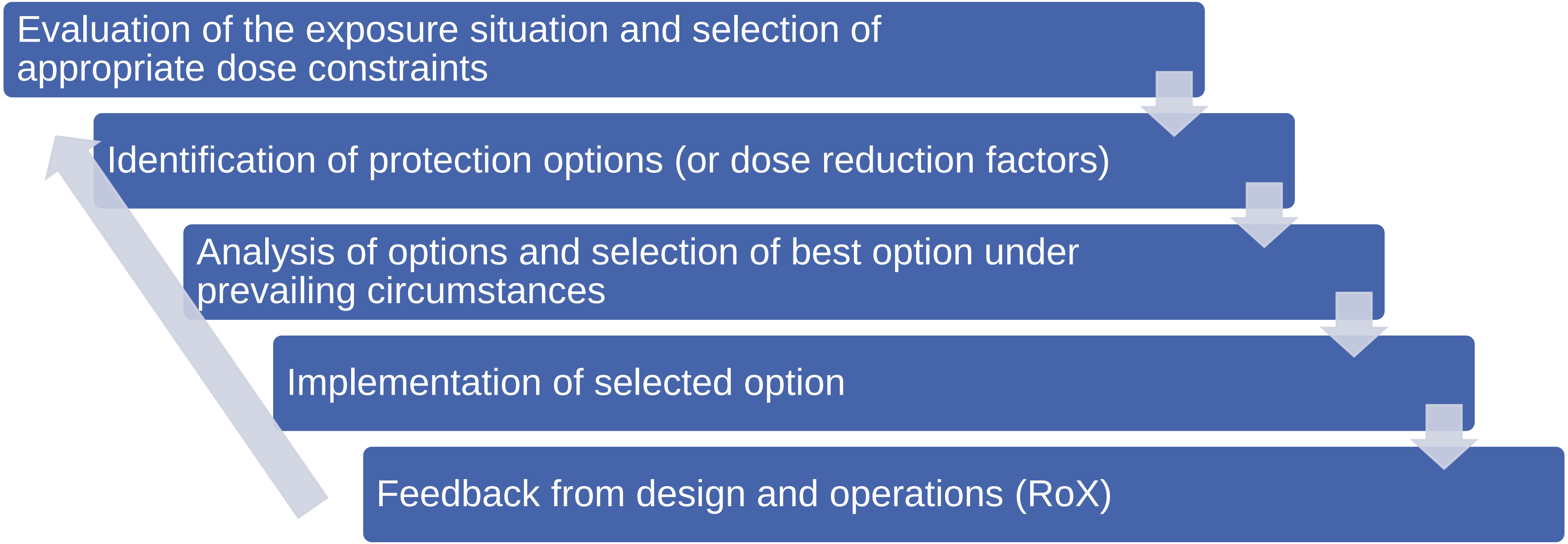
- … start in conceptual design.
- … provide respective design margins.
- … focus on „shielding functions“ and „control of radiation sources“ concurrently.
- … consider „safety design“ broader, include Radiological Protection.
- … simplify, optimize and standardize design solutions to improve reliability (decrease maintenance needs).
- … include stakeholders (systems, transverse functions, …) in the design process.

ALARA Design Implementation

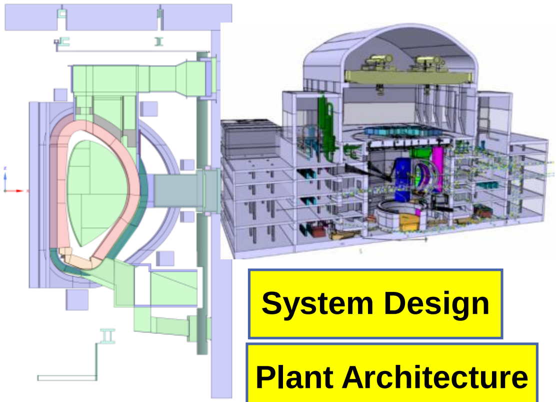
- Practical ALARA implementation by
  - Continuous, predictive and iterative process;
  - Decision-aiding techniques to find the optimized protection solution;
  - Suitable objective means to demonstrate and justify the correct implementation.
- Pre-requisites and inputs
  - RAMI assessment and Maintenance&Inspection needs (as available)
  - Maintenance plans/activities with hands-on work efforts
  - Facility zoning and radiation mapping (room book data)
  - Possible dose reduction factors

ALARA Design Implementation

- ALARA process involves

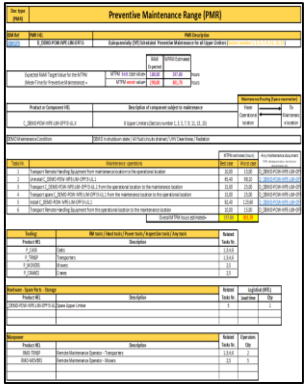


DEMO RP status

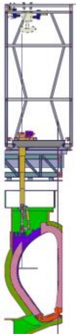


System Design

Plant Architecture



Maintenance



Remote Handling

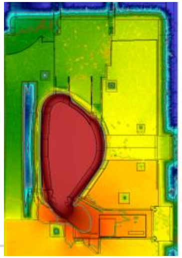
Radiological Protection

System	Task information	Yearly collective doses (p-mSv)
Valves	Lubrication and PM on actuator	12.24
Purification System for corrosion products	Replacement or Test for filters	11.52
Heat Exchanger	Flange leak check	8.64
Buffer Tank	Lubrication and PM on actuator	7.20
Centrifugal Mechanical Pump	Shaft seal replacement	5.76
Electrical Heater	Several activities on Resistor check/repair	2.16
Piping	Visual inspection	1.44

Preliminary ORE assessments

Room book

Neutronics
Radiation transport and activation



Requirements
System Engineering

Component/ location	Requirement	Limit (target)
Port interspace	Shutdown dose rate 12 days after shutdown	~500 µSv/h (target)
Port cells (occasional access)		100 µSv/h (target)
Maintenance hall above tokamak		Tbd.
In-cryostat area, [7]		100 µSv/h (target)
Tokamak building areas beyond port cells requiring frequent access, [7]	Shutdown dose rate 1 day after shutdown	10 µSv/h (target)
Critical electronic equipment	Neutron fluence during operation	0.01 n/(cm²s)
Non-critical electronic equipment		100 n/(cm²s)

Component/ location	Requirement	Limit (target)
Starter blanket FW	Displacement damage to Eurofer	20 dpa
2nd blanket FW		50 dpa
Divertor cassette body (@ 180°C), [8]		6 dpa
Divertor PFCs, [9]	Displacement damage to CuCrZr	10 dpa, possibly up to 20 dpa
VV	Displacement damage	2.75 dpa
	Nuclear heating, [10]	0.5-1 W/cm³ (target)
	Activation, [2]	Minimize (target)
Cutting/re-welding location in IVC cooling pipes	Helium production	1 appm
Superconductors, [11], [12]	Total neutron fluence to epoxy insulator	$10^{22}/m^2$
	Fast neutron fluence to the Nb3Sn	$10^{22}/m^2$
	Neutron fluence to Cu stabilizer between TFC warm ups	$1\text{-}2 \cdot 10^{21}/m^2$
	Nuclear heating in winding pack	50 W/m³

Safety

Inventories, radiation sources
Radwaste

Mobilisable Inventory	Bounding Estimate "2022" picture	Comments
Tritium	6.8 kg (WCLL) 6.6 kg (HCPB)	~70% of this value in-vessel inventory with 25% safety margin added. ~28% in fuel cycle. Some tritium operational and reserve inventories are not included, e.g. the tritium required to restart facility or in storage beds.
Dust	1034 kg	Use of "average" ITER administrative limit scaling, to be refined.
N16	1.75E+17 Bq (WCLL BB PHTS) 4.04E+16 Bq (Divertor PHTS, both WCLL/HCPB PHTS) 9.99E+16 Bq (Divertor Cassette PHTS, both WCLL/HCPB PHTS)	Sum of max estimates from Table 4.2, 4.3 and 4.4, respectively

Conclusions

Conclusions

- Radiological Protection (RP) 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.
- Implementation of technical and administrative measures at early design phase is instrumental for a qualified life-cycle RP Programme.
- EU DEMO project addresses RP design via dedicated Transversal Functions. Nuclear design issues are adressed in a system engineering approach.
- Main elements are identified and progressively developed. Preliminary RP design guideline and ALARA process are in preparation.

Thank you for your attention!

“This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.”

Acknowledgement
Suggestions/Ideas: C. Bachmann, U. Fischer, G. Federici, J. Elbez Uzan, P. Cortes
Pictures/Data: Courtesy of C. Gliss, C. Bachmann and EUROfusion project