Safety of Fusion Power Plants in View of Fission Regulations

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1. European fusion safety studies
2. Fusion safety approach
3. Comparison of the safety concept between fusion and fission
4. Major results of the review of the fusion safety concept study
5. Application of the transferable fission safety concept to DEMO
6. Open issues for DEMO safety

1. Europ. fusion - safety studies I

- **Safety&Environmental Assessments of Fusion Power (SEAFP-1) 1990-94**
  - Commercial power station blankets (model S1 and S2).
  - Consideration of effluents from normal operation, occupational doses, accidents (worst-case assumption), and waste management.
- **Safety & Environmental Assessment of Fusion Power – Long Term Program (SEAL) 1995-98**
  - DEMO models (WC, BC, BOT, BIT)
  - Aim at broadening the scope and elaborating selected aspects in more detail
- **SEAFP-2 1997-98**
  - Plant models 1, 2 (MINERVA-W), 3 (MINERVA-H)
  - To meet safety goals by low-activation martensitic steels or more advanced materials
- **SEAFP-99**
  - Plant models 4, 5, 6
  - Waste management studies
- **Power Plant Conceptual Study (PPCS) 2001-2004**
  - Model A (WCLL), B (HCPB), C (DCLL), D (SCLL), AB (HCLL)
  - Demonstration of the credibility, the safety and environmental advantages and the potential economic viability of future fusion power plants (FPPs).

Concept differences

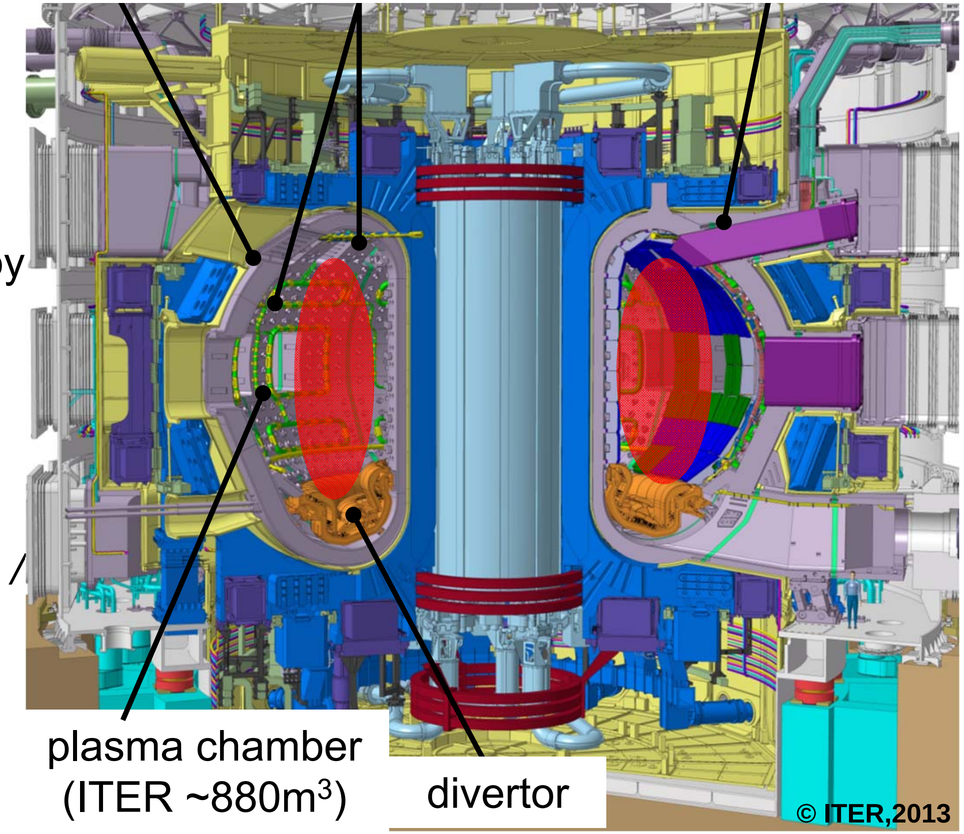
- Fusion power
- Structural material
- Coolant
- Breeder
- Neutron multiplier
- PCS,…………

1. Europ. fusion safety studies II

- **ITER 1998-**
  - A large-scale scientific **experiment** aiming to demonstrate technological & scientific feasibility of fusion energy ($Q \geq 10$)
  - HCPB and HCLL TBMs and other 4 TBMs outside Europe
  - ITER safety & licensing (fundamental structure)

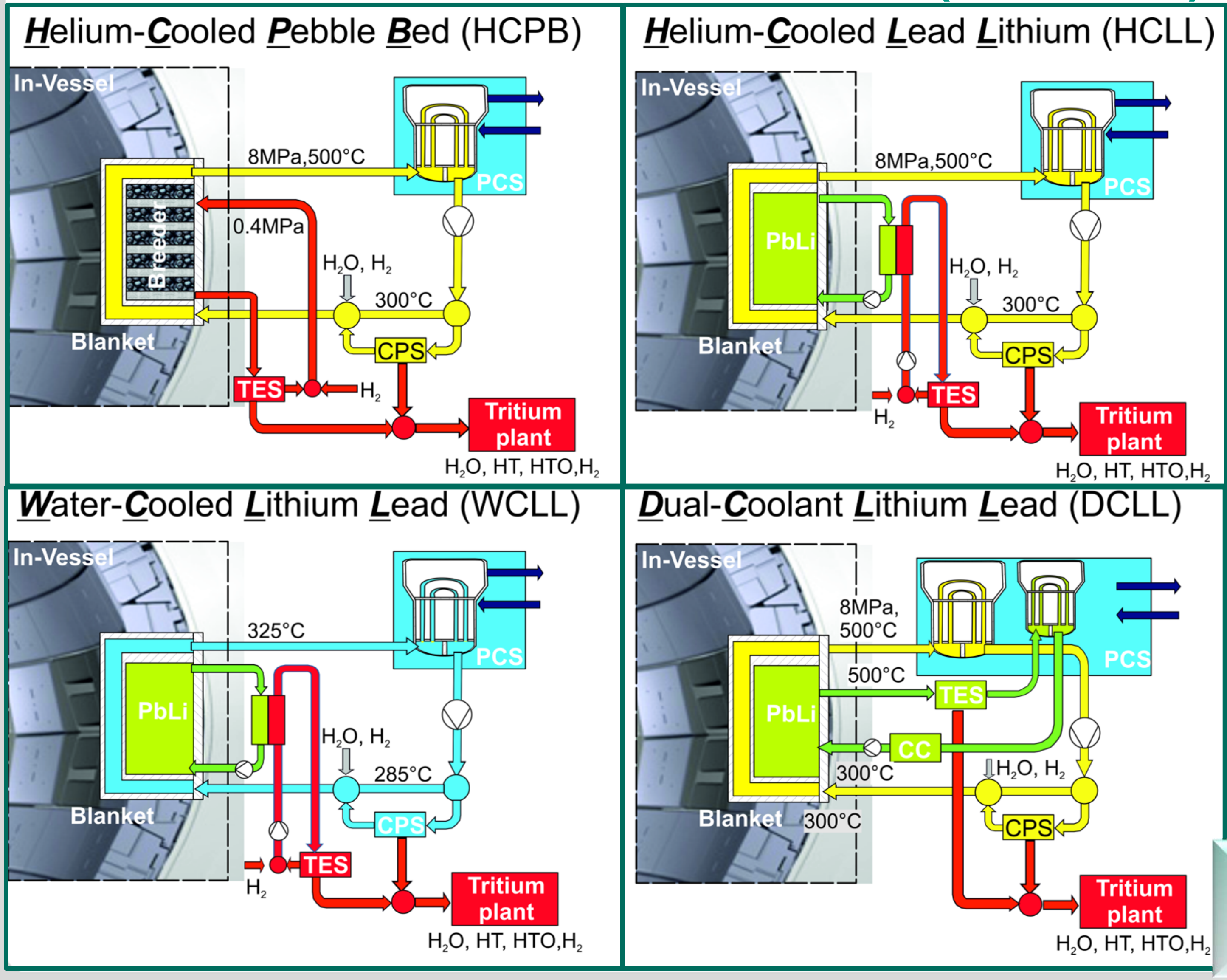
- **DEMO** EFDA roadmap
  - ➡ **Fusion Electricity**
  - Component Design & Engineering Design by EUROfusion
  - Selection from 4 blanket concepts (HCPB, HCLL, WCLL, DCLL)
  - ***WPSAE WBS 2014-2018***
    - *Design and licensing requirements*
    - *Integrated safety analyses / source terms / models & codes*
    - *Radioactive waste management*
  - ➡ Safety demonstration

➡ **Future FPP**



1. Europ. fusion safety studies III - Comparison baseline

▪ Performance of thermonuclear core - Blanket (~83% Power)



Common features

- ❑EUROFER –struct.
- ❑PFC –Material –W

Differences

- ❑Coolant(s)
- ❑Neutron multiplier
- ❑Temperatures
- ❑Neutron wall load
- ❑.....

Consequences

- ❑Diff. enthalpy
- ❑Diff. chem. potential
- ❑Varying components

PCS=Power conversion system
TES=Tritium extraction system
CC =Chemical control
CPS=Coolant purification system

2. Fusion safety approach I

- **Safety requirements***
  - **Protection** of public and environment **against radiological hazards**
  - **Protection** of site workers against radiation exposure according to ***ALARA***-principle (As Low As Reasonably Achievable)
  - Employment of **measures to prevent accidents** and **mitigate** their **consequences**
  - **Elimination** of need for public **evacuation** in any accident
  - **Minimization** of activated waste
- **Safety functions***
  - Primary safety functions
    - *Confinement of radioactive materials*
    - *Control of operational releases*
    - *Limitation of accidental releases*
  - Secondary safety functions
    - *Ensure emergency plasma shutdown*
    - *Provisions for (passive) decay heat removal*
    - *Control of thermal energy (coolant(-s) enthalpy)*
    - *Control chemical energies*
    - *Control of magnetic energy discharge*
    - *Limitation of airborne& liquid operating releases to environment*

*PPCS GDRD 2004

2. Fusion safety approach II

- **Defence in Depth Safety Concept (DiD) ***

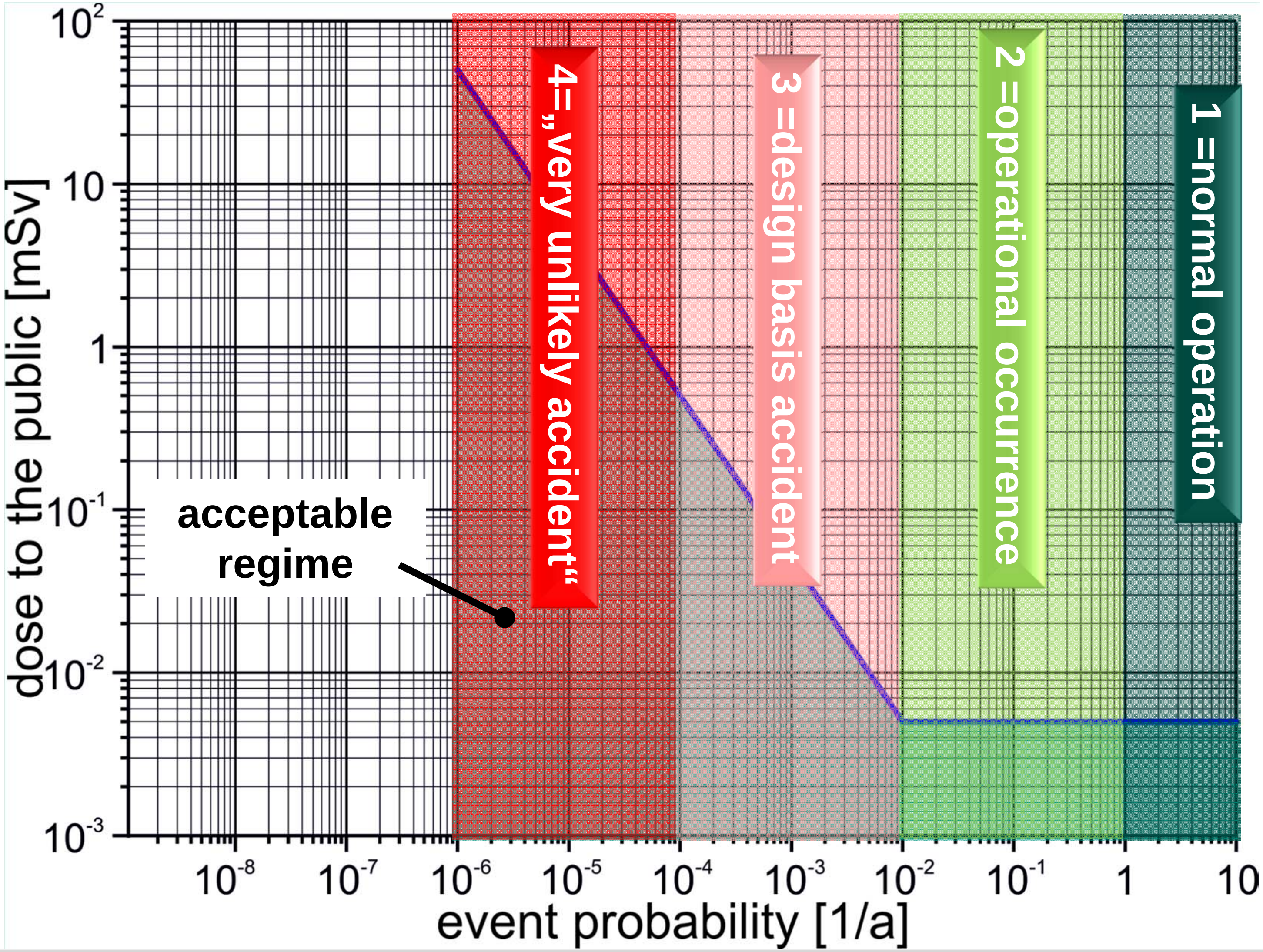
Definition of plant state levels in DiD ➡ solid data base in ITER / PPCS

Lev.	Operational state	Objective	Means	Consequences dose limit
1	Normal operation	Prevention of abnormal operation and failures	Conservative design high quality in construction, operation	No measure
2	Anticipated operational occurrence $f > 10^{-2}$/yr	Control of abnormal operation and detection of failures	Control, limiting and protection systems and surveillance features	Plant shall return to full power in short term (after fault rectification)
3	Design basis accident (DBA) $10^{-2} > f > 10^{-4}$/yr	Control of accidents within design basis (unlikely events)	Engineered safety features and accident procedures	Plant shall return to full power after inspection, rectification & requalification 5mSv/event
4	"very unlikely accident" $10^{-4} > f > 10^{-6}$/yr	Control of severe plant conditions incl. prevention of progression and mitigation of consequences	Complementary measures and accident management	**Plant restart not required** 50mSv/event
5	Post severe accidents $f < 10^{-6}$/yr	Mitigation of radiological consequences (release of radioactive materials)	Off-site emergency response	**Plant restart not required**

*INSAG 2010, WENRA2012

2. Fusion safety approach III

- **Definition of plant state levels in DiD**



*INSAG 2010, WENRA2012

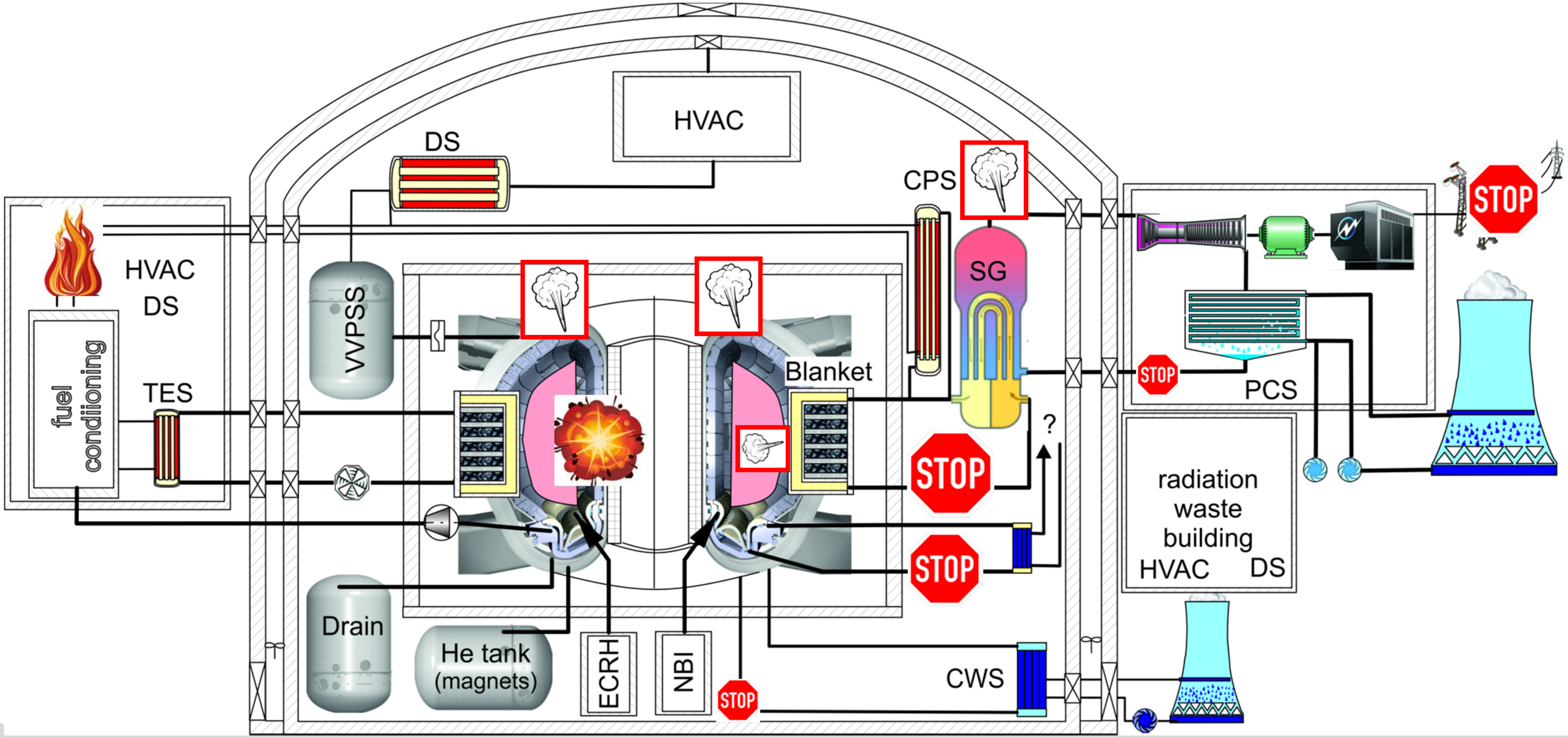
2. Fusion safety approach IV

- **Radiation protection and acceptance criteria**
  - Identification of potential sources of radiation & source inventories
  - Limits of radiation doses to the public and to site personnel in states of operation, maintenance and decommissioning
  - Prevention / mitigation of radiation exposures from accidents
- **Identification of Postulated Initiating Events (PIEs)**
  - HAZOP (Hazard and Operability)
  - MLD (Master Logic Diagram)*
  - FFMEA (Functional Failure Modes and Effects Analysis) / FMEA
- **Event sequences of incidents and accidents, consequences**
  - Determination of the maximum releasable inventories
  - Analysis of the incidents / accidents scenarios
  - Bounding accidents
  - ➡ Assessment wrt to radiological hazard
  - Early and chronic doses to MEI (=***M***ost ***E***xposed ***I***ndividual)

* Several errors/malfunctions have to occur to allow for a release

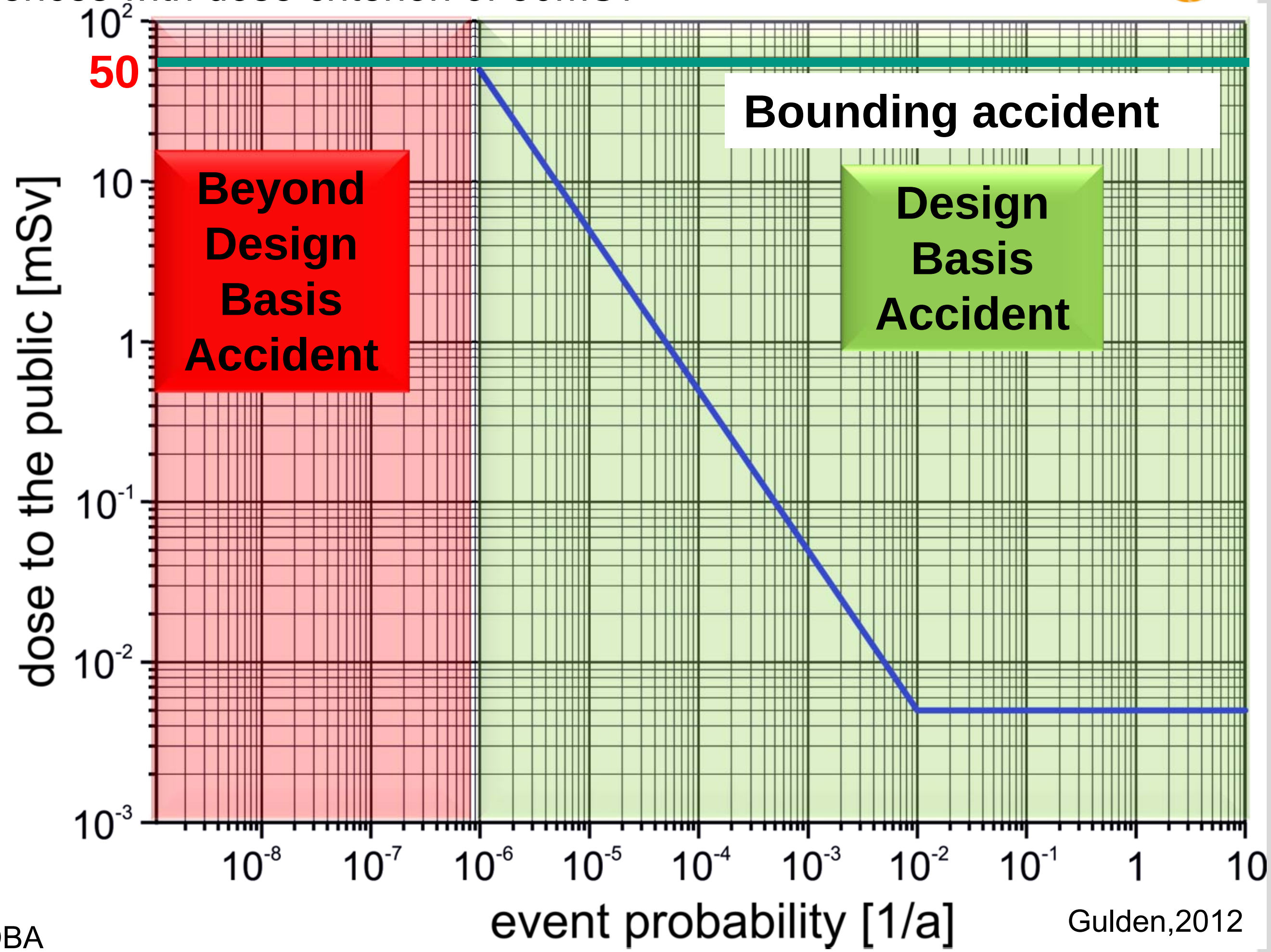
Fusion safety approach V

- **Postulated initiating events (internal events)**
  - Similar as in nuclear power plants such as
    - Loss of flow accident (LOFA),
      Loss of offsite-power (SBO), Leaks (VV, Primary System, …), Fire & explosion
  - Fusion specific events: loss of cryogenic system, arcing , magnet system faults
    ➡ affecting barriers



2. Fusion safety approach VI

- **Safety risk approach**
  - Discrimination
    Design Basis Accidents (DBA) ⟺ Beyond Design Basis Accidents (BDBA)*
  - Bounding accident sequences with dose criterion of 50mSv



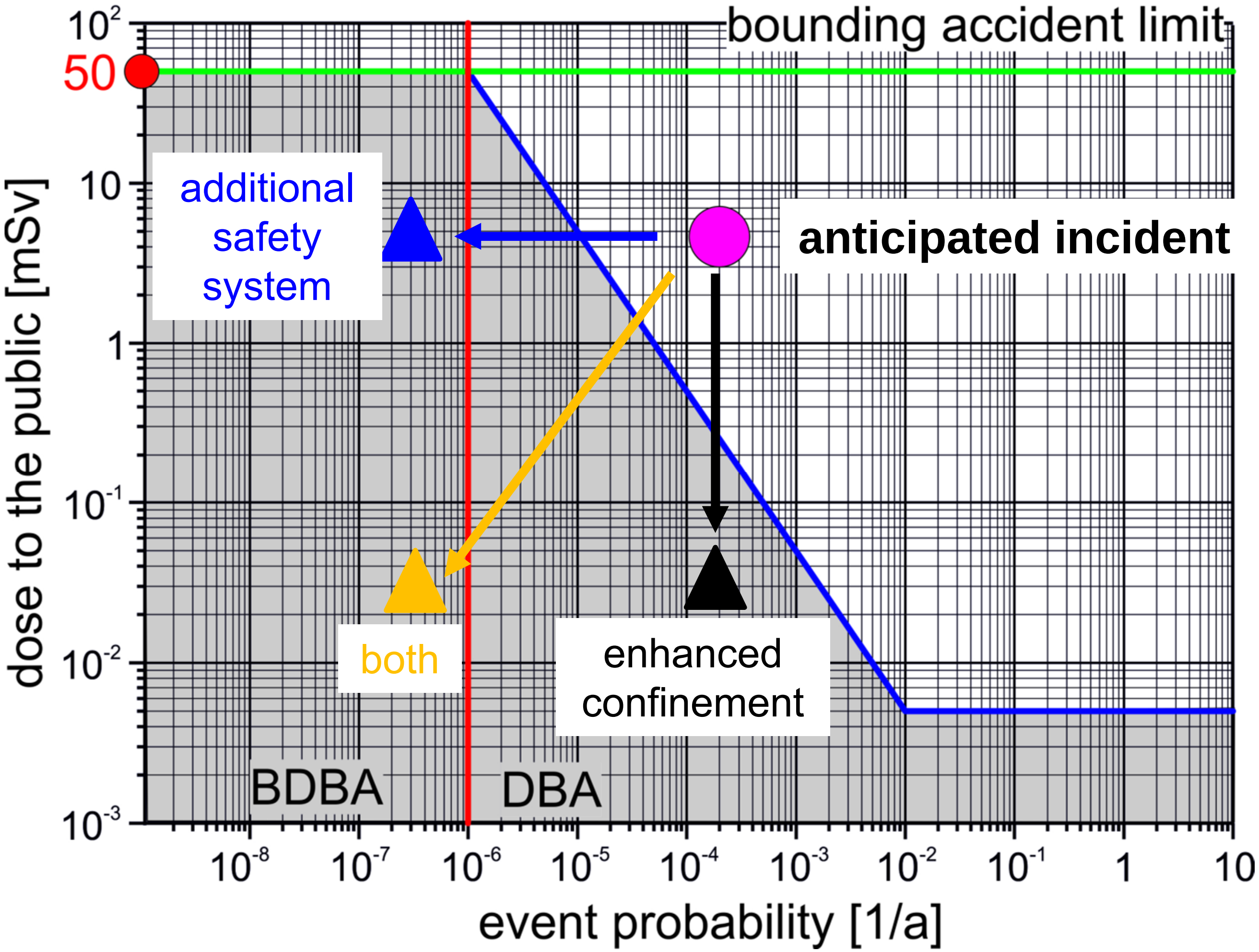
Dose limits Germany

public	worker	Evac. dose
1mSv/a	20mSv/a	100mSv/a
20µSv/w		2mSv/w
3µSv/d	0,3mSv/h	0,3mSv/d
mean nat. dose 1mSv/a		

* Design Basis Extension in ITER ~ BDBA

2. Fusion safety approach VI

- **Safety risk approach**
  - Mitigation into the acceptable risk zone by countermeasures
  - Diminution of dose rate by enhanced confinement



Gulden,2012

3. Comparison of the safety concept between fusion and fission I

- **German nuclear safety regulation, i.e. safety requirements for nuclear power plants (NPP) of 2012*.**
- **Direct application of the current nuclear regulations to a FPP will not be possible without fusion specific adaptions due to the differences in underlying physics and technologies.**
- **Enveloping event**
  - Identification of energy sources causing/accelerating an event
  - Quantification of sources of radioactive inventory (source term(s))
  - Assessment of
    - release fractions (by energy inventories and mechanistic arguments-deterministic),
    - Release time (deterministic) and
    - ambient conditions (weather –probabilistic)

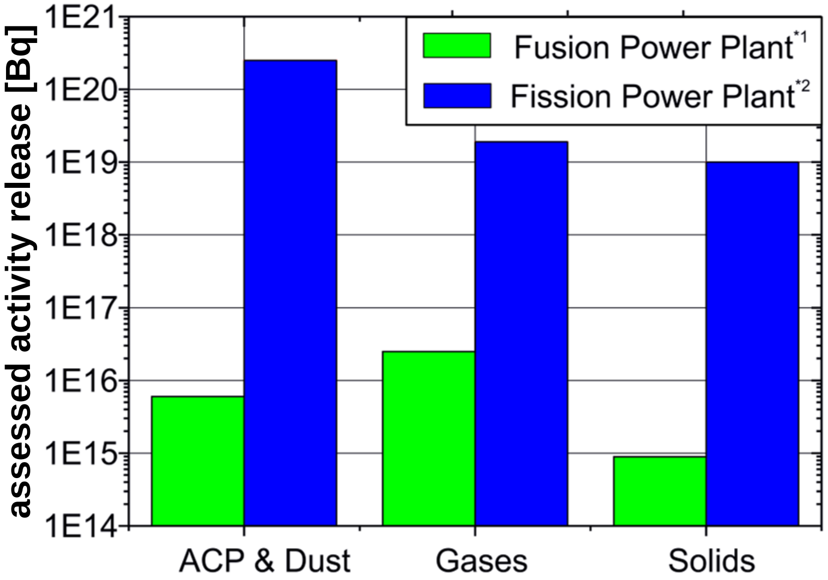
Result

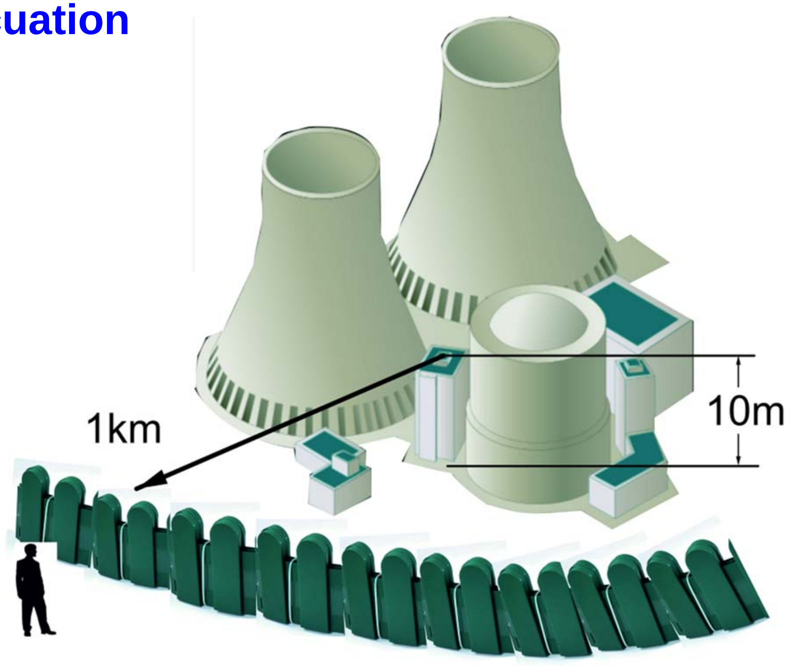
- Analysis of dose rates in three domains (vital area – in plant), protected area (1km at fence border) and to public (>1km) for most exposed individual (MEI)

* Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit: „Sicherheitsanforderungen an Kernkraftwerke“. 22.11.2012.

3. Comparison of the safety concept between fusion and fission II

- **Worst dose rates estimates (for the same power)**
  - Different source terms
    - *Fusion: tritium, dust, activation products, Activated Corrosion products (ACPs), neutron sputtering products. Tritium inventory in the Vacuum Vessel (VV) ~1kg.*
    - *Fission nuclides of PWR: Iodine, Cs-137, noble gases, aerosols, ...*
  - NPP: effective dose of DBA ≤ 50mSv. BDBA e.g. 100mSv ➡ **evacuation**
  - Fusion: bounding accident ≤ 50mSv ➡ **no evacuation**





Doses of FPP reactor concepts several orders of magnitude lower than hypothetical worst-case scenarios of NPPs.

*1 Karditsas,PPCS,2004
*2 Broeders, KANEXT,2011

3. Comparison of the safety concept between fusion and fission III

- **Reactivity control, fuel and inventory**
  - NPP: largest part of the inventory stored inside the fuel rods
    - ➡ requirements for the fuel,
    - ➡ handling and for the control of reactivity and
    - ➡ prevention of re-criticality.
  - Fusion: Excursions of the reaction rate can be excluded due to inherent features of the design

➡
- x *not applied to FPP: control of reactivity*
- ✓ *applied to FPP: shutdown of the facility under any circumstances*

- **Barriers**
  - NPP: multiple barriers on several consecutive levels of defense for confinement of the radioactive materials
  - Fusion: inventories of source terms are not concentrated locally. Active retention functions like detritiation systems are used.

➡
- ✓ *applied to FPP: physical barriers and retention systems*

3. Comparison between the fusion safety concept and the nuclear fission safety concept II

- **Defense in depth and independence of levels of defense**
  - NPPs: several safety functions are ensured by multiple installations related to different levels of defense
  - Fusion: safety concept is also based on the concept of levels of defense.
    - ✓ *assign the safety functions of a FPP to certain level(s) of defense, if plant design will be available*
    - ✓ *applied to FPP: defense in depth, but the independence of the different measures and installations for all safety functions is currently not possible*
- **External events and very rare man-made external hazards**
  - A complete fission reactor safety analysis shall incorporate an analysis of the impact of external events on the plant.
  - In ITER for the first time, and they will be covered in the safety concept of on-going DEMO, as well as for future FPPs.
- **First of its kind**
  - NPP: use of proven technologies and qualified materials as well as validated calculation methods for the safety demonstration based on operational experience
  - FPP: only minor operational experience is available for a power plant.
    - x *not applied to FPP: requirements with respect to the evaluation of the operation experience*

3. Comparison between the fusion safety concept and the nuclear fission safety concept III

- **Cooling**
  - NPPs: decay heat from fuel elements has to be removed to avoid eventual fuel element damage and the break of barriers
  - Fusion: decay heat of in-vessel components at EOC (blanket, divertor, etc.)
  - ➡ ✓ *applied to FPP: requirements regarding cooling*
- **Leak before break**
  - NPP: certain parts of the piping the component integrity is guaranteed by applying the "leak-before-break concept" (LBB) in the plant design.
  - Fusion: LBB concept cannot be assessed currently.
  - ➡ ✓ *applied to FPP: LBB concept*

4. Major results of the review of the fusion safety concept study

Karlsruher Institut für Technologie
Öko-Institut e.V. Institut für angewandte Ökologie Institute for Applied Ecology

- **Fusion safety concepts** relies on **state-of-the-art safety** concepts for nuclear installations containing radioactive environment and is based on DiD concept.
- **Physical & engineering differences** to NPP (e.g. radiologic inventories, stored internal energies, power densities and potential release paths) necessitate **other safety systems** in a FPP ➡ require additional complementary **research**.
- **Implementation** of the major safety functions (inventory confinement, cooling and reactivity control) **similar** ➡ **Translation** into **different technological solutions** (e.g. multiple barriers) mandatory.
- **Fundamental safety principles** wrt. to initiating events and corresponding radiological consequences are **respected**, **but detailed design** (which holds also for probabilistic safety analysis) for quantification **required**.
- **Passive safety features** with additional active and passive safety measures **allow** in principle **limitation** of consequences **within plant**, but **future regulations** will r**equire** also a **robustness to external events**.
- **Confinement** and **reactivity control** (decay heat) by functionality specification addressed and **respected**. ➡ **Demonstration** by validated codes **lacking** (magnets, release fractions, failure modes, …..)
- **Systematic assignment** of measures and installations to safety levels **elaborated**, **but** several **measures** are **addressing different safety levels**.

Feasibility of transferring fission regulations ➡ DEMO safety concept

5. Application of the transferable fission safety concept to DEMO

Superior safety objectives

- Take all reasonably practical measures (design provisions,…) to **prevent accidents** in nuclear installations and to **mitigate their consequences** they should occur.
- Ensure with a **high level of confidence** that, for all possible accidents taken into account in the design of the installation (incl. those of very low probability, any **radiological consequences would be minor** and below prescribed limits (ALARA-principle)
- Ensure that the likelihood of **accidents with serious consequences is very low** (if possible avoidance of any off-site emergency responses irrespective of anticipated event)
- Preservation of investment

Secondary fusion specific safety objectives

- **Minimization of rad-waste**, immobilization of radiologic inventory at any external / internal hazard employing ALARA principle.
- **On-site fuel management and material conditioning** (evt. reprocessing)

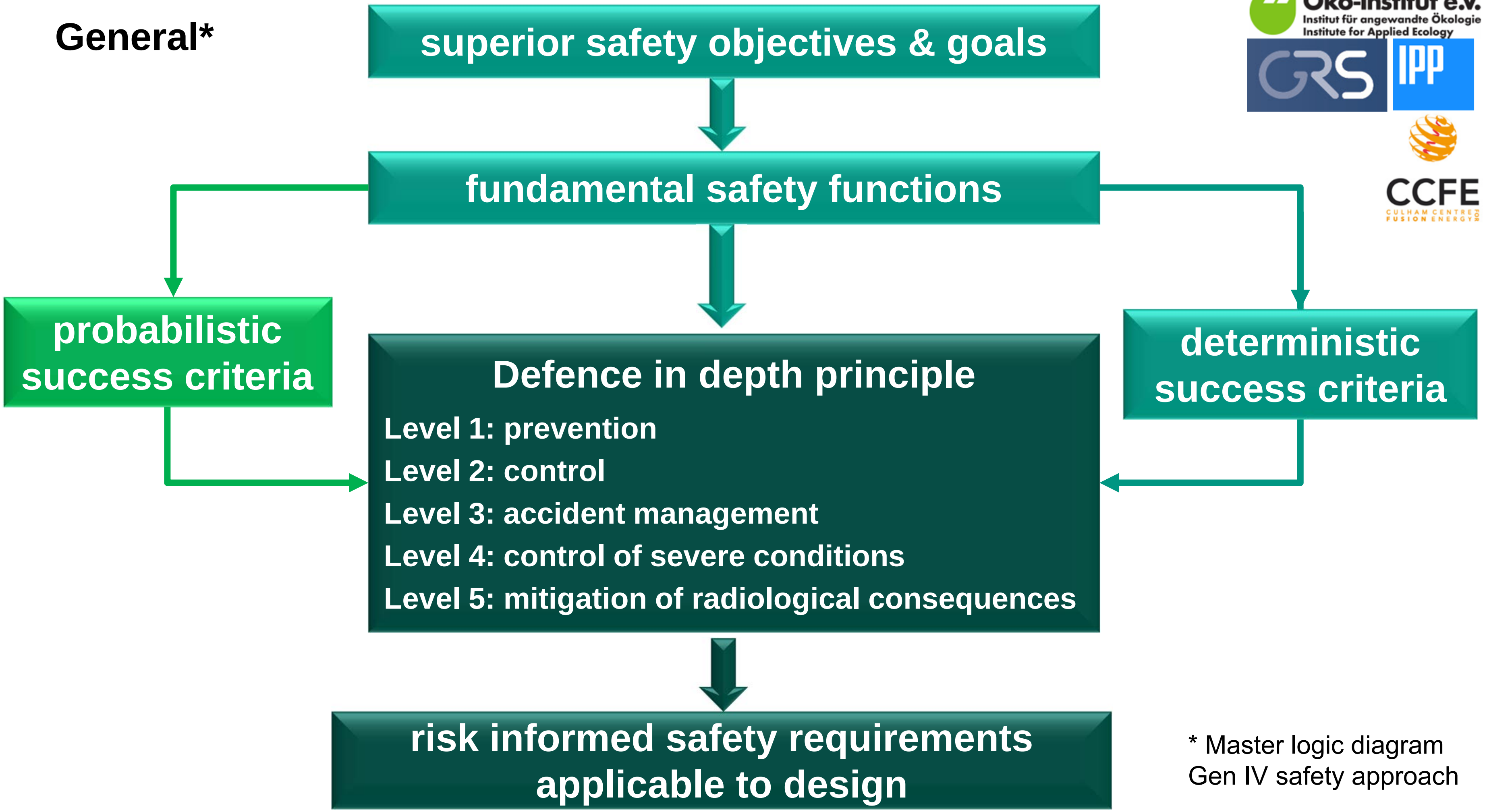
Defence in depth principle (DiD)

Significant differences DEMO to ITER (DEMO≠ITER+ε)

- higher **fluences** (dpa, damage / material) ➡ fluence (fast reactors), energy density (acc.)
- higher **tritium inventories** (enlarged tritium plant, detritiation systems,…)
- large **spatially distributed nuclear inventories** with different damage rates, mobilities (ACP´s, transmutation products, waste storage / management facilities)
- different **energy sources in magnitude**, temporal behavior (decay heat, magnetic system, PHTS-energy production, tritium plant, dust, gas purification, …)

Safety demonstration approach

General*



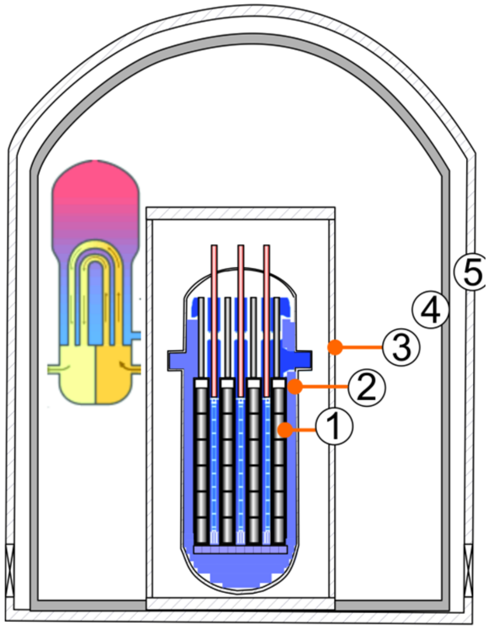
* Master logic diagram
Gen IV safety approach

- applied in hierarchical from plant to subsystem level (in ITER)
- transferability to DEMO possible

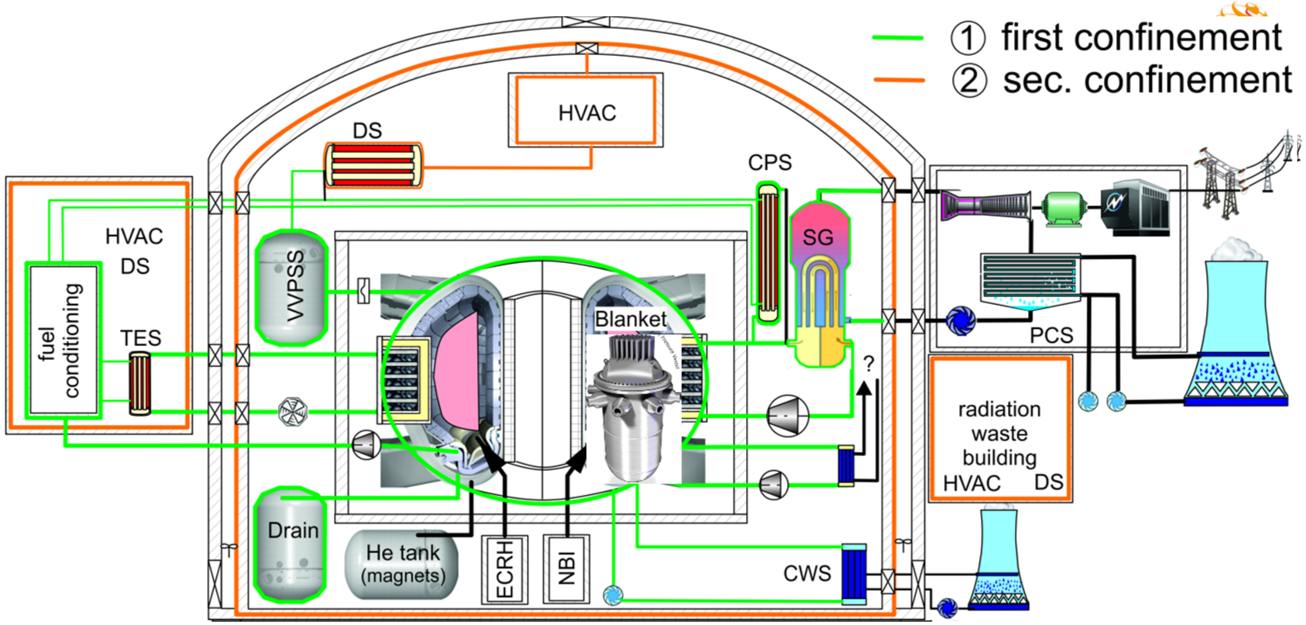
Safety functions

Primary safety functions
- Confinement
- Control of releases
- Limitation of releases

NPP- PWR



FPP

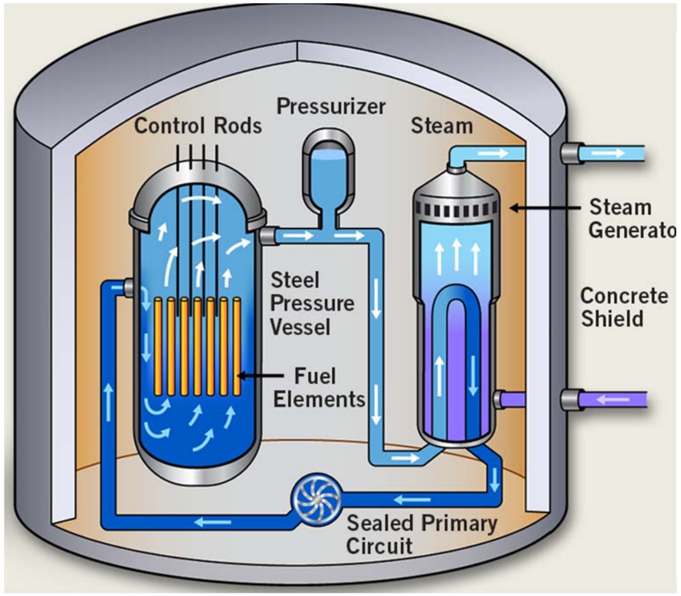


❑ 4/5 static subsequent enveloped barriers	❑ Two static barriers extended over large scale
❑ Static barriers for release control (mainly related to barriers + PAR+ PRS)	❑ Mixture of static and dynamic barriers (DTS, TES, HVACS)
❑ „practical elimination“ of level 5 by design + core catcher + mitigation chains	❑ Large sets of active + passive systems (but lower inventory and energy content ☺)
➡ Compact system, small control volume, high power density, rare release paths	➡ Large volume, low power density, several release paths, dedicated rad. contaminants

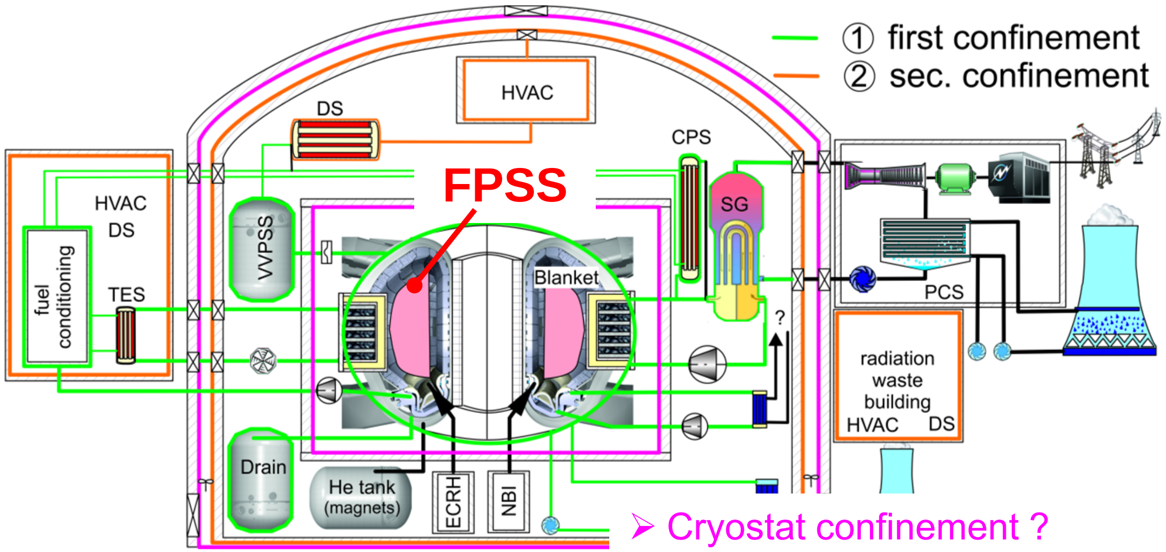
Secondary safety functions

- Terminate nuclear reactions
- Ensure decay heat
- Controlled chemical, magnetic, and thermal discharge
- Limitations of release to ambient

PWR



FPP



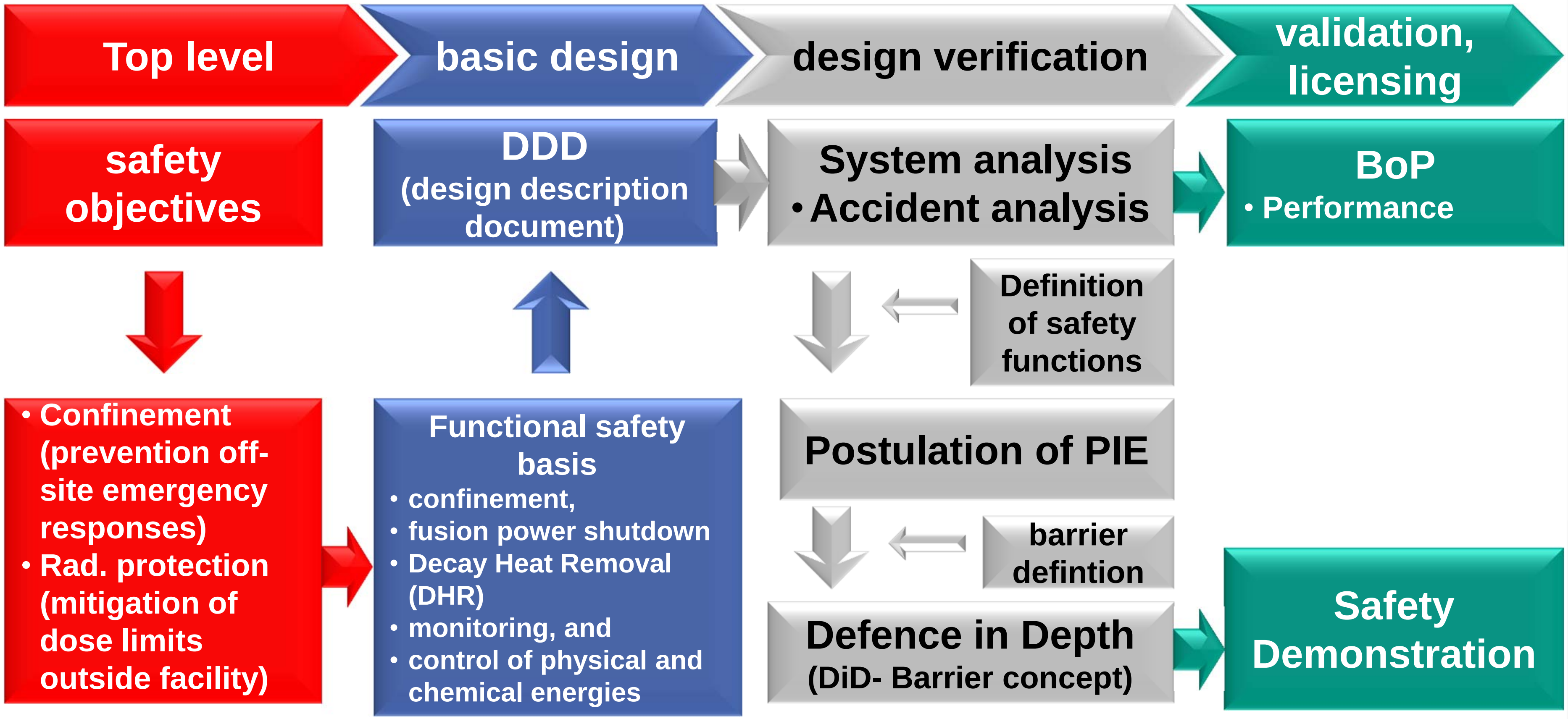
- ➢ Cryostat confinement ?
- ➢ Double-walled containment ?

- Design measures (CR, n-poison)
- DHR systems
- not required (limited on-site storage of SA)
- Multi-stage systems for severe accidents

- FPSS (intrinsic feature-but early detection)
- Passive design provisions
- Physically different sub-systems required
- Mobile species to identify

"Safety – Licensing" – Plant Level

- **ALARA principle for**
  - normal and off-normal events (low event frequency)
  - design robustness and material choice (activation, self-limiting design)
  - maintenance, reprocessing and disposal
- **Safety demonstration (sequential nature)**

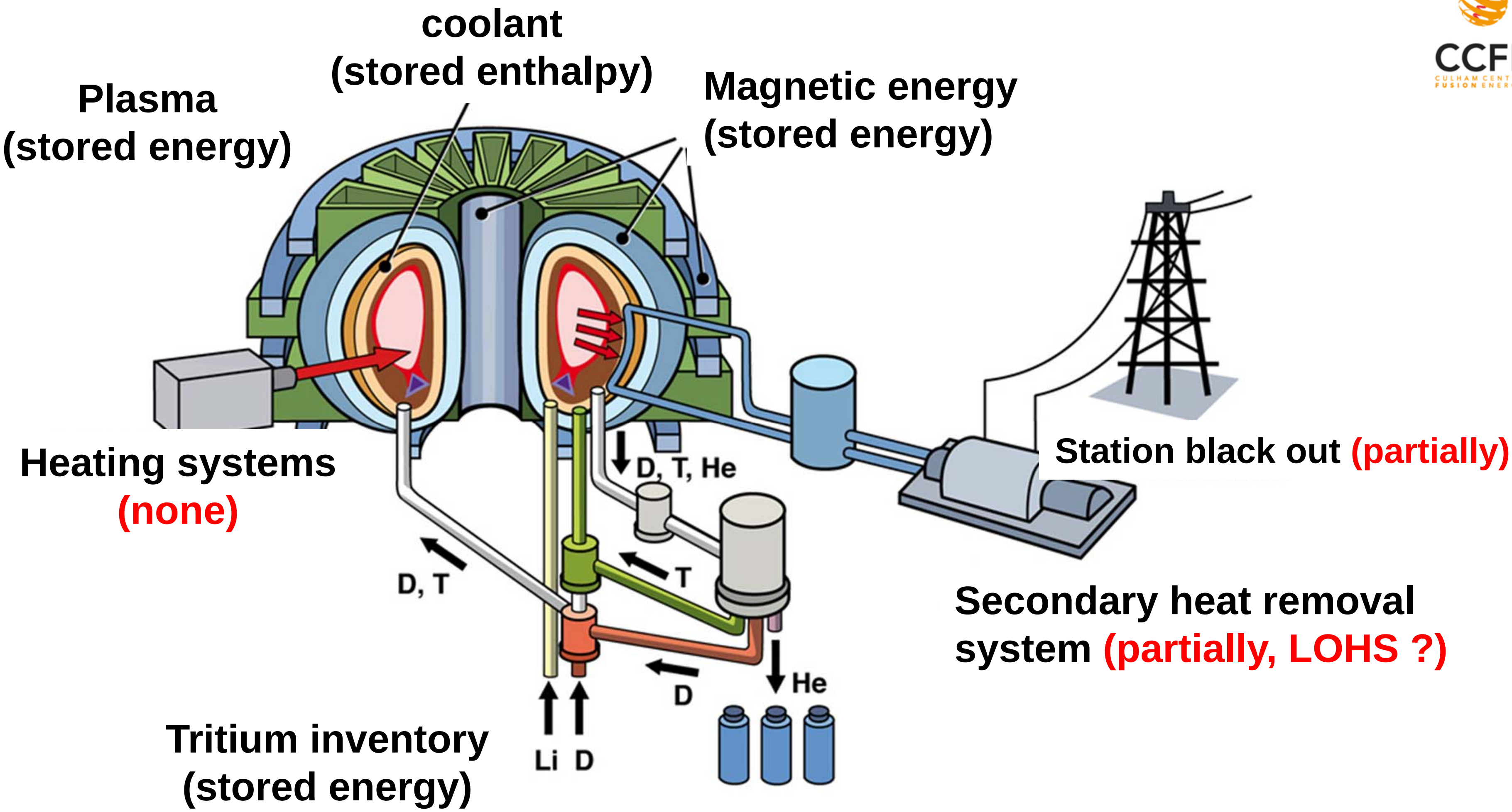


DEMO safety definition of safety functions

- **Consequences for fusion safety concept in transition of ITER ➡ DEMO**
  - Definitions safety functions transferrable
  - Classification of structure, systems and components (SSC) in ***s***afety ***i***mportance ***c***lasses (SIC) adequate (according to inventory or potential to initiate in- / accident)
- **Lessons to learn from ITER**
  - Functionality of safety systems (FPSS, VVPSS, detritiation systems – HVAC, WDS, VDS, CCWS, H_2-dust mitigation, PAR, electric, magnetic discharge units, …)
  - Operational communication and control management
  - Failure rates of safety important novel components, control systems
  - ➡ Enhanced deterministic, probabilistic safety assessment (reduction of margins)
- **Novel to DEMO** (* from N. Taylor, 2012, safety issues for fusion nuclear facilities and lessons learned from ITER)
  - Quasi steady state operation @ high availability
  - Tritium self-sufficiency and considerable larger circulating inventory,
  - Novel material(s) mandatory (design codes, fatigue, safety margins)
  - Energy production
  - On-site storage of activated components (15 blanket+30 divertor generations)
    ➡ on-site reprocessing ?
- **Impact on DEMO safety**
  - ➡ Modified and expanded confinement strategy
  - ➡ Development of complementing additional active and passive safety systems
  - ➡ Development of on-line (+quasi real time) monitoring control systems

6. Unknowns to be identified / assessed

- as identified



6. Open issues

- **Energy inventories wrt.**
  - release time
  - detection of failures
- **Nuclide inventories**
  - release paths / fractions
  - Tritium saturation in structures
  - Diffusion / monitoring in structures
  - Max. allowed release fractions (Be / SiC = ?)
- **Operationalisation of safety by design**
  - PHTSs (Blanket, Divertor, NBI)
  - Material criteria
  - Monitoring control (time scale, redundancy, diversity)
  - Release path @ anticipated failure
- **Dust inventory and removal**

Plasma instabilities
- time scales
- early detection systems / diversity
- prevention measures - shut-down proc.

Magnets
- Evolution of magnet faults (structure, arcing, quench detection, …)
- Station black out requirements

“Nuclear Fuel”
- inventory (free, stored in structures) e.g. temperature dependence
- interaction with structures / residuals
- on-line accountancy
- potential for in-pile failure

Coolant enthalpy
- interaction with in-vessel components
- coolant activation (ACP) & control (e.g. erosion products)
- activity & integrity monitoring
- potential for in-pile failure

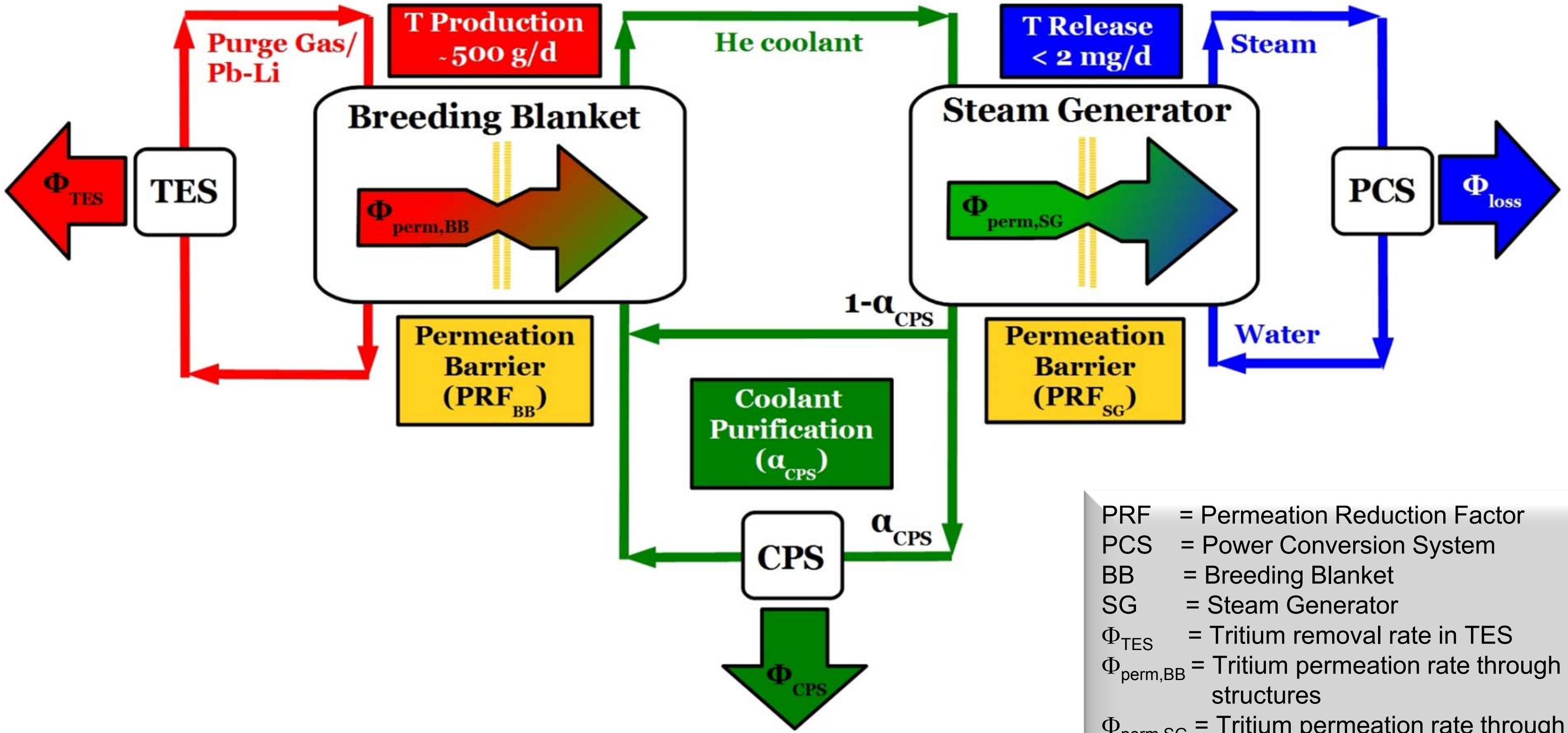
6. Open issues as identified

- **Operational probation of**
  - safety relevant control systems, components or detectors in nuclear environment (accuracy, failure resistance, …)
  - Intrinsic / defined barriers (failure mode, aggravating effects in case of failure, …)
- **Material behavior at high irradiation doses ➡ IFMIF**
  - Material data base (design rules, failure resistance, operational measure/threads)
  - Design margins for design / safety margins to be set
  - Potential interactions with coolants (corrosion/erosion, SCC, IASCC, fretting, fatigue, creep, embrittlement, DBTT, preparation for disposal / separation, …)
  - Tritium retention
- **Nuclear fuel cycle**
  - Tritium inventory
  - TES (Tritium Extraction System) – efficiency, failure scenarios, time scales – doubling time
  - CPS (Coolant Purification Systems) – efficiency, malfunction monitoring, …
  - Tritium mitigation techniques
  - all around the tritium plant …

6. Open issues as identified

Tritium mitigation techniques

- Permeation Barrier

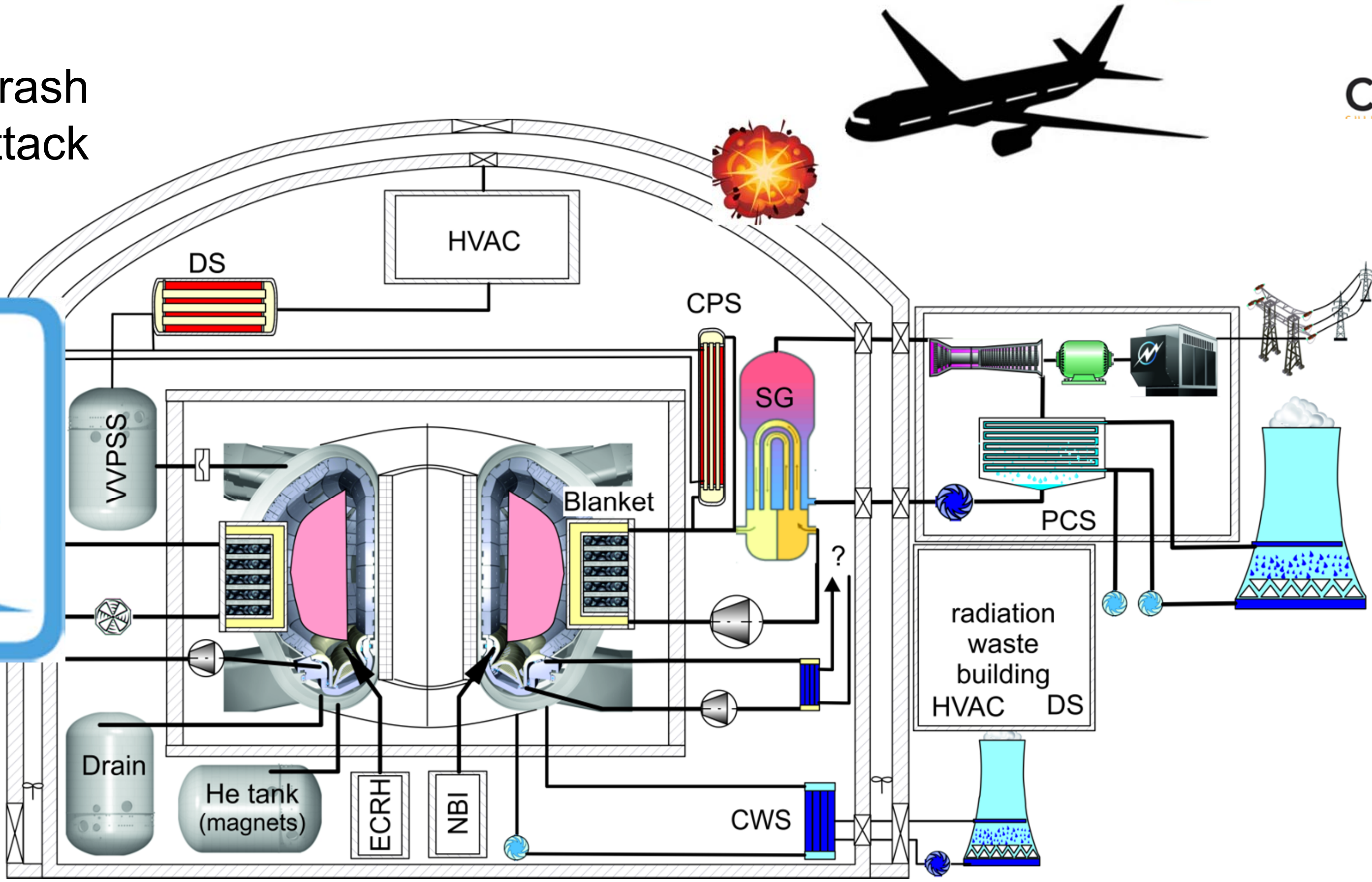


PRF = Permeation Reduction Factor
PCS = Power Conversion System
BB = Breeding Blanket
SG = Steam Generator
Φ_{TES} = Tritium removal rate in TES
$\Phi_{perm,BB}$ = Tritium permeation rate through BB cooling structures
$\Phi_{perm,SG}$ = Tritium permeation rate through SG tubes
Φ_{loss} = total Tritium loss
α_{CPS} = fraction of total mass flow rate

➡ **AIM discuss and prepare list of non considered issues in view of DEMO safety**

6. Open issues as identified

- **Safety against external hazards- (“Fukushima challenge”)**
  - Earthquake
  - Flooding
  - Air plane crash
  - Terrorist attack



➡ More stringent rules for robustness demonstration against external hazards for NPP (➡FPP) are expected

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  Neill Taylor
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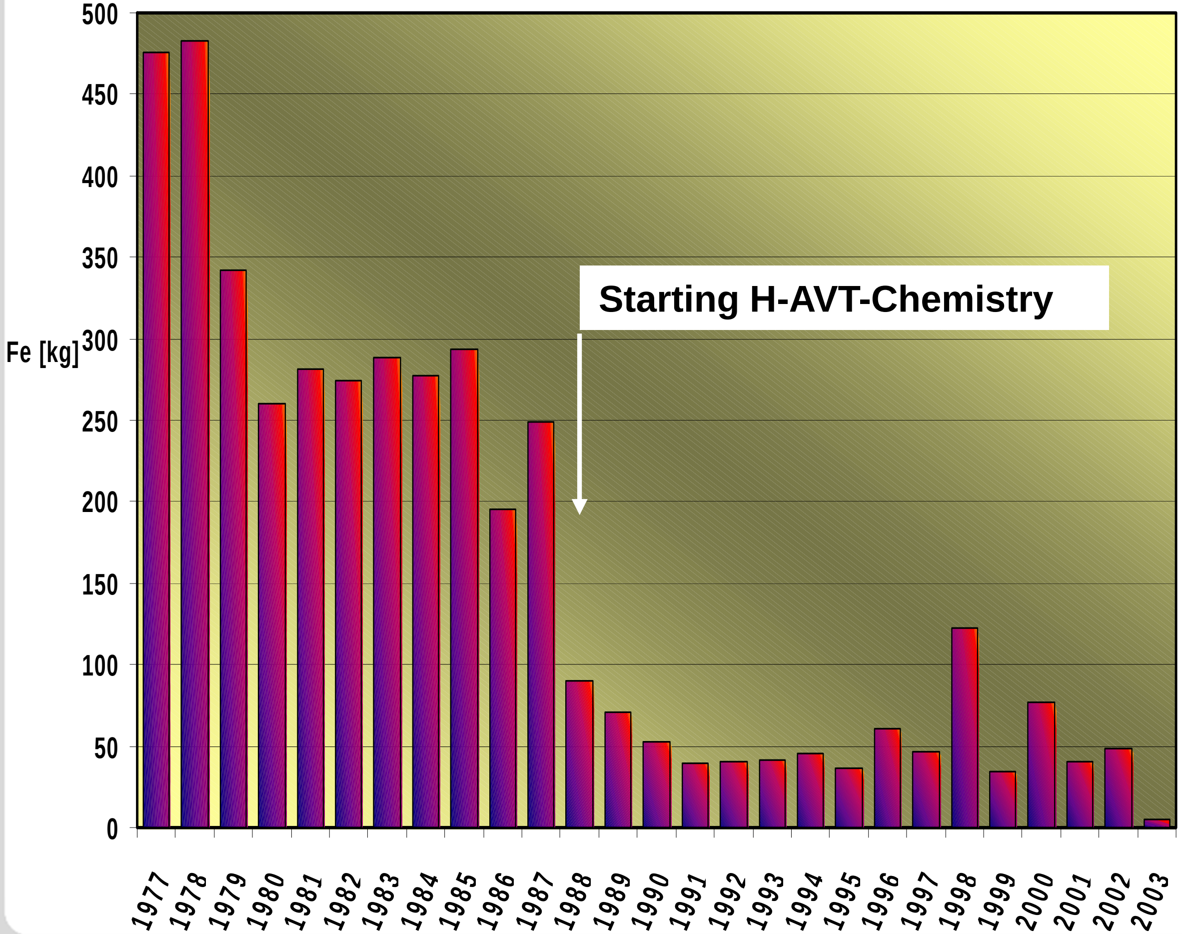
  Marcus Fabian

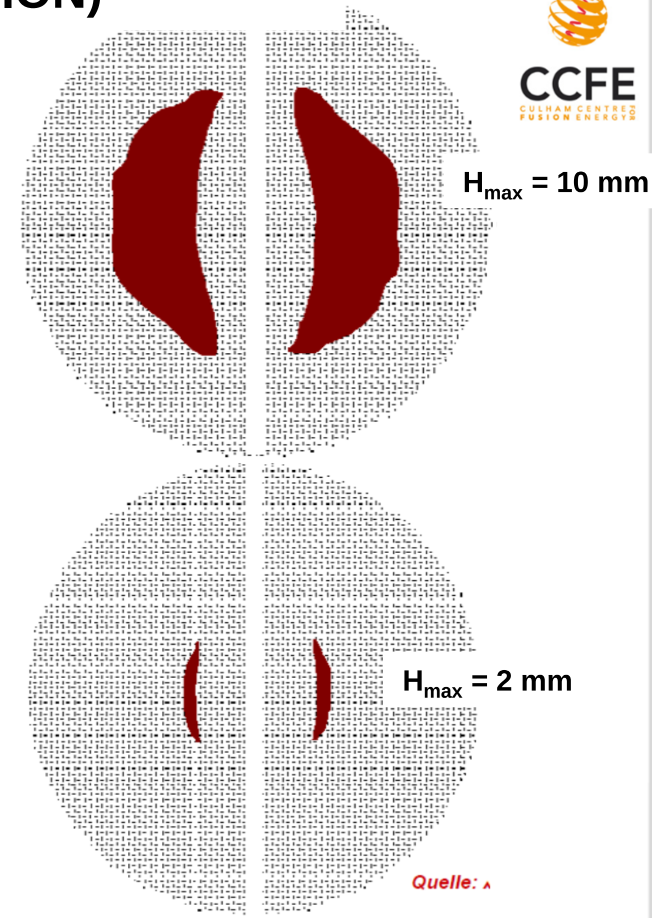
Thank you !

Material corrosion in PWR's

- Iron Ingress into Steam Generators Unit
- Dedicated coolant chemistry (Hydrazine-doping, Ammonia, pH ~10)

➡ **not applicable to fast spectrum systems (e.g. FUSION)**





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