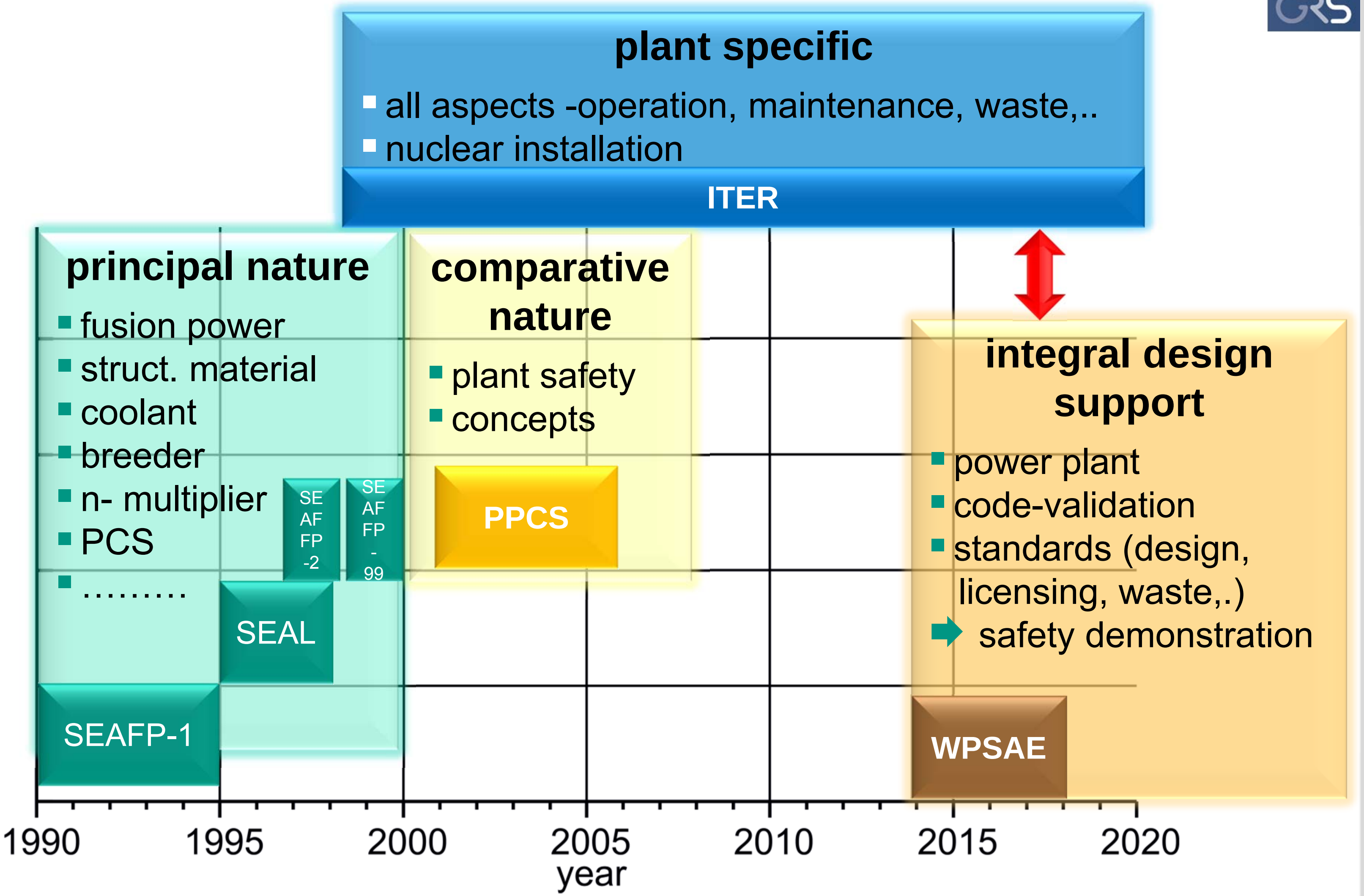
Aspects of fusion safety considering fission regulations

R. Stieglitz, R. C. Wolf, N. Taylor , L.V. Boccaccini, D. Carloni, W. Gulden, J. Herb, X. Z. Jin, C. Pistner, J. Raeder, N. Taylor, A. Weller

INSTITUTE for NEUTRONPHYSICS and REACTOR TECHNOLOGY (INR)

- **Past &current fusion safety studies**
- **Fission & Fusion Power plant concepts**
- **Nuclear power plant safety approach**
- **Comparison of safety concept fusion ←→ fission**
- **DEMO in view of severe accidents**
- **Unknowns to be identified / assessed → EUROfusion**
- **Summary & Recommendations**

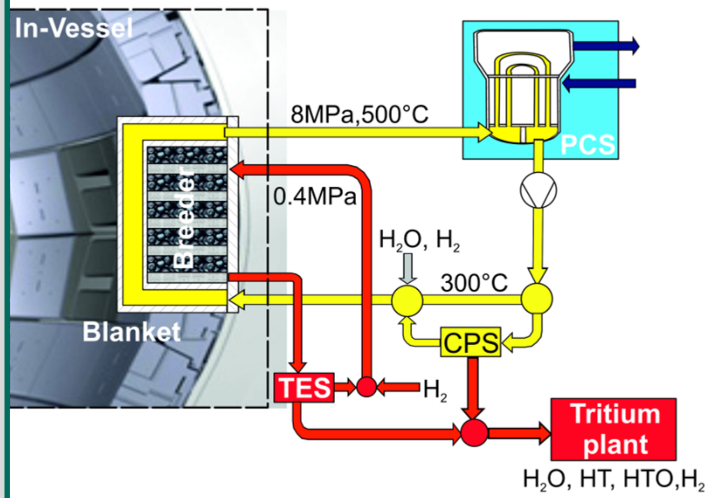
Past & current safety studies I (focus Europe)



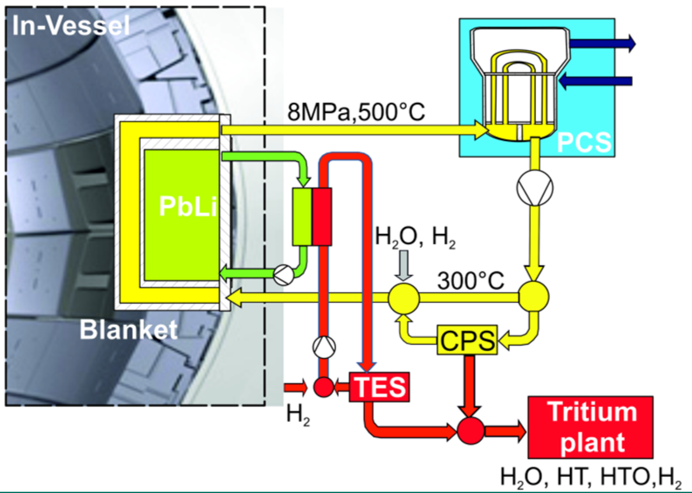
Past & current safety studies II

- focus mainly on thermo-nuclear core - Blanket (~83% Power)

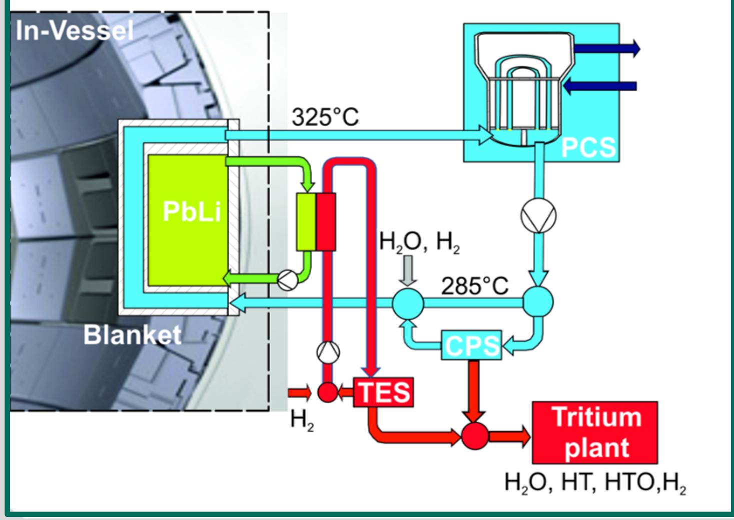
Helium-Cooled Pebble Bed (HCPB)



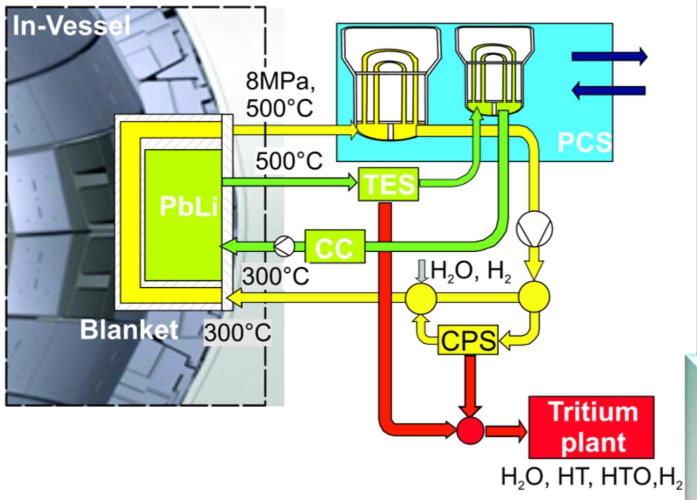
Helium-Cooled Lead Lithium (HCLL)



Water-Cooled Lithium Lead (WCLL)



Dual-Coolant Lithium Lead (DCLL)



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

Past & current safety studies III

Methodology

- transition from conceptual level to integral approach

Consequences in view of DEMO-FPP development

- specification of design & licensing requirements ➡ **general plant safety approach**
  - safety requirements ➡ safety functions ➡ safety concept
  - safety importance classification ➡ design options to match requirements
  - ➡ **general safety principles document**
- integrated safety analysis ➡ **plant safety demonstration**
  - operational mode (duration, availability, ISI&R*, design limits)
  - quantification of source terms (fuel, activ. materials, effluents, plant logistics)
  - identification of energy potentials (magn., chemical, plasma, thermal)
  - internal events and external events and hazards
  - ➡ **development of validated tools, uncertainties, QA measures**
  - ➡ **analysis in view of worst case with respect to plant and environment**
  - ➡ **preliminary safety document**
- Radioactive waste management ➡ **public acceptance**
  - waste (liq., sol., gas) logistics (RH, casks), separation (hot cell), immobilization
  - clearance, dose rates (nuclide spec.)
  - quantity reduction
  - ➡ **safety and disposal concept**

*ISI&R=In-Service Inspection and Repair

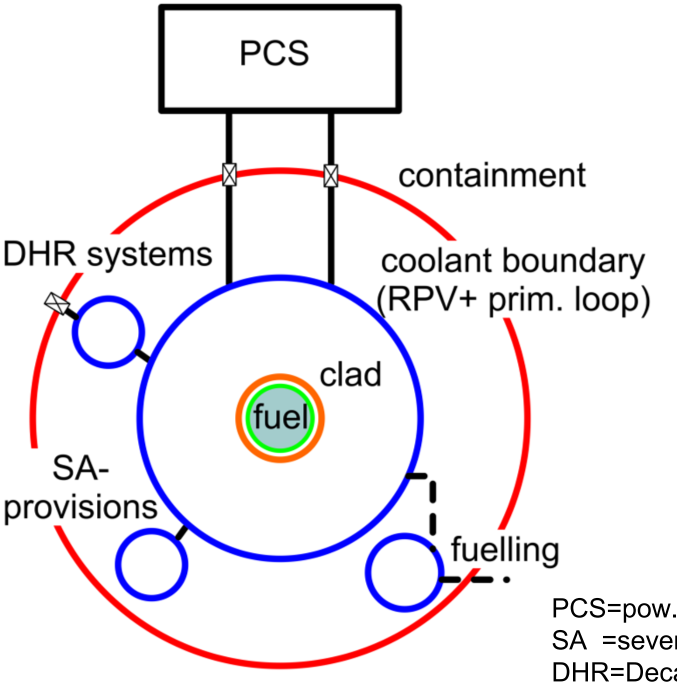
Power plant concepts

Nuclear Power Plant (NPP)

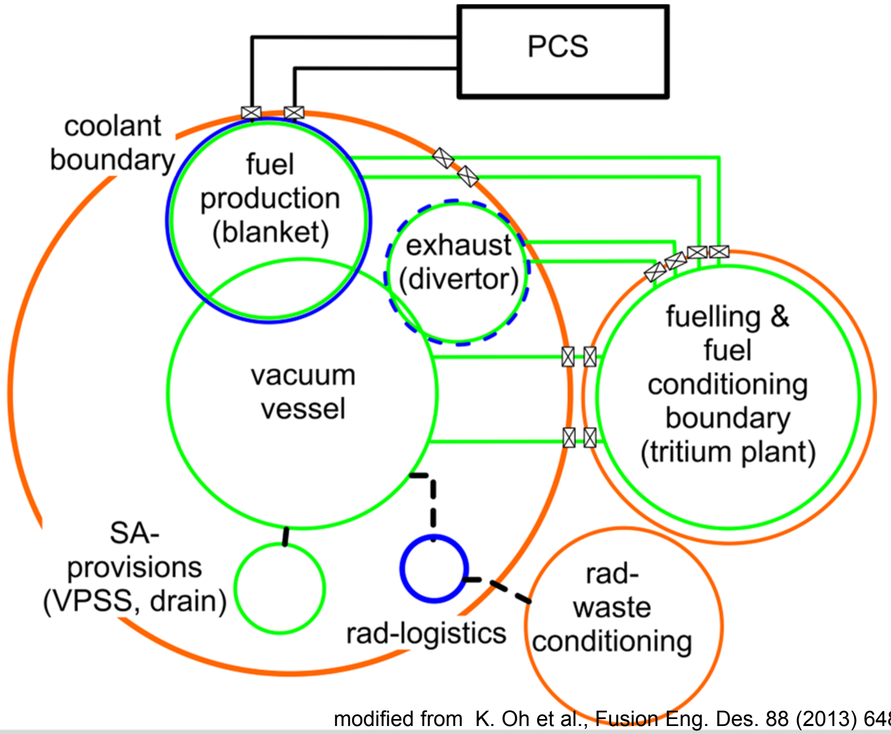
- nested physically static barriers
- high volumetric power density
- off-site fuel conditioning
- criticality prevention measures
- 1% of P_{th} decay power
- very high radioactive inventory

Fusion Power Plant (FPP)

- 2 static but also dynamic barriers
- low volumetric power density
- on-site fuel management
- criticality arguments absent
- 0.6% of P_{th} decay power
- high radioactive inventory (many mobile, different nuclide vectors)



PCS=pow. conv. System
SA =severe accident
DHR=Decay heat removal



modified from K. Oh et al., Fusion Eng. Des. 88 (2013) 648

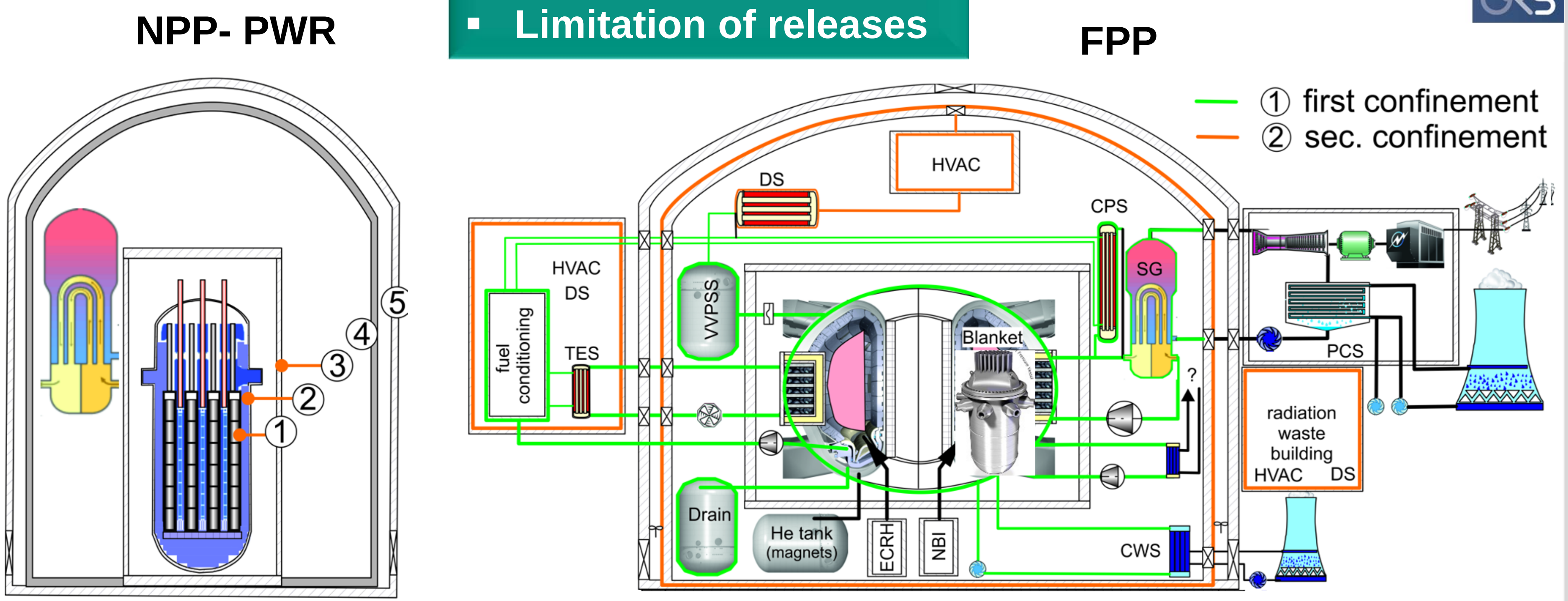
Nuclear power plant safety approach I

- **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 power shutdown*
    - *Provisions for decay heat removal (potentially passive)*
    - *Control of thermal energy (coolant(-s) enthalpy)*
    - *Control chemical energies*
    - *Control of other potentially likely energy discharges or interactions*
    - *Limitation of airborne& liquid operating releases to environment*

*PPCS GDRD 2004

- Safety functions

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



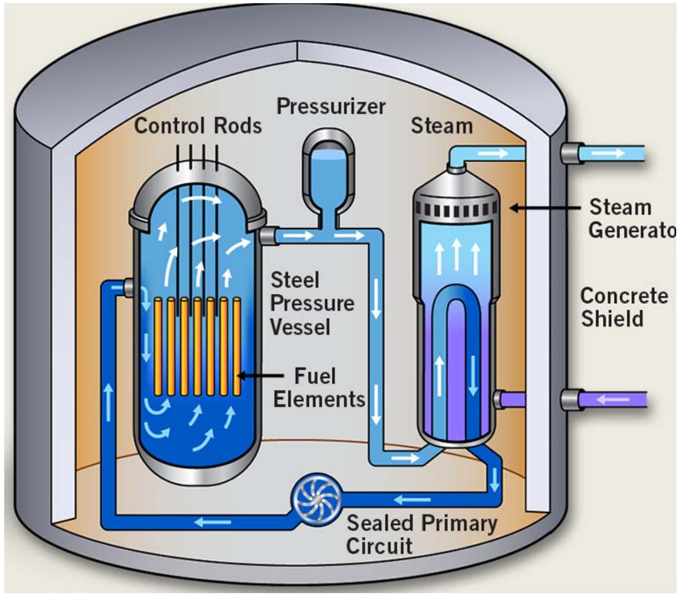
- 4/5 static subsequent enveloped barriers
- Static barriers for release control (mainly related to barriers + PAR+ PRS)
- „practical elimination“ of level 5 by design + core catcher + mitigation chains
- ➡ Compact system, small control volume, high power density, rare release paths

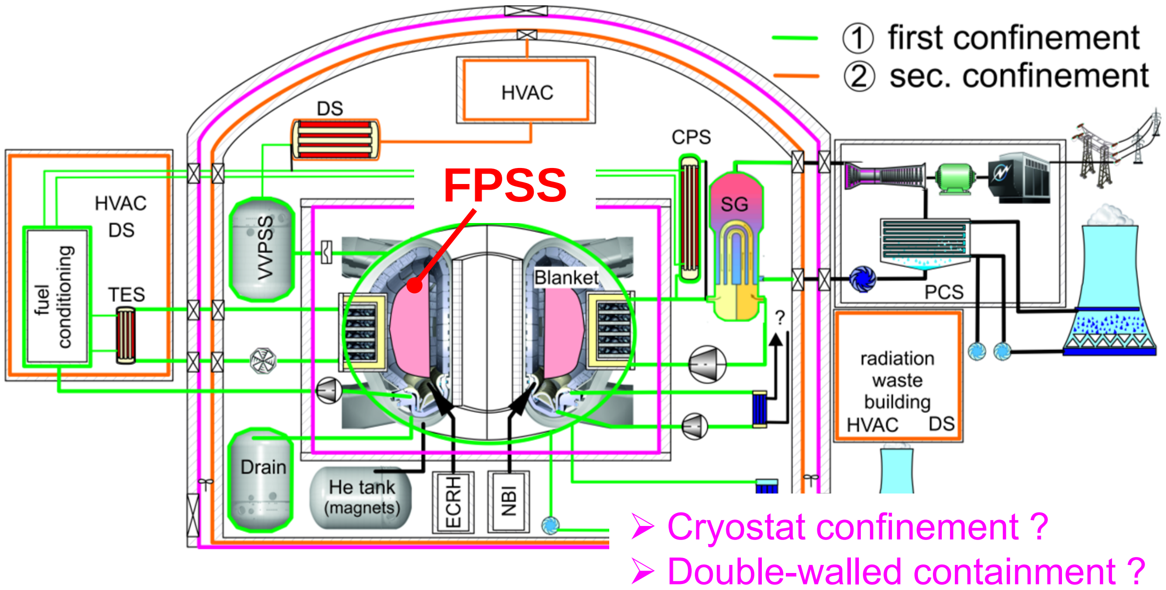
- Two static barriers extended over large scale
- Mixture of static and dynamic barriers (DTS, TES, HVACS)
- Large sets of active + passive systems (but lower inventory and energy content ☺)
- ➡ Large volume, low power density, several release paths, dedicated rad. contaminants

Secondary safety functions

- terminate nuclear reactions
- ensure decay heat removal
- controlled chemical, magnetic, and thermal discharge
- limit release to environment

PWR | **FPP**





- 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

Nuclear power plant safety approach II

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

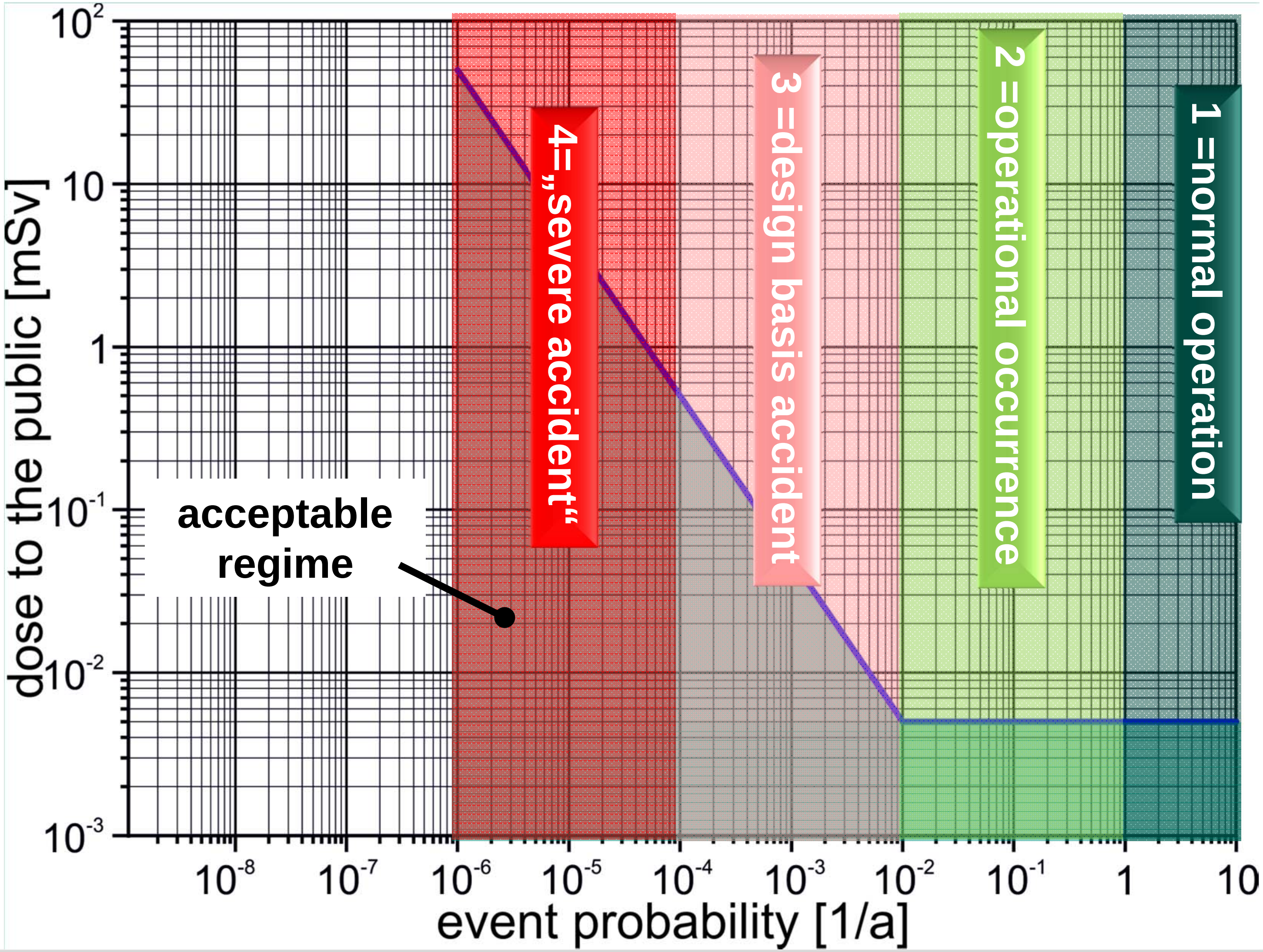
Definition of plant state levels in DiD ➡ solid data base in ITER / PPCS

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

Nuclear power plant safety approach III

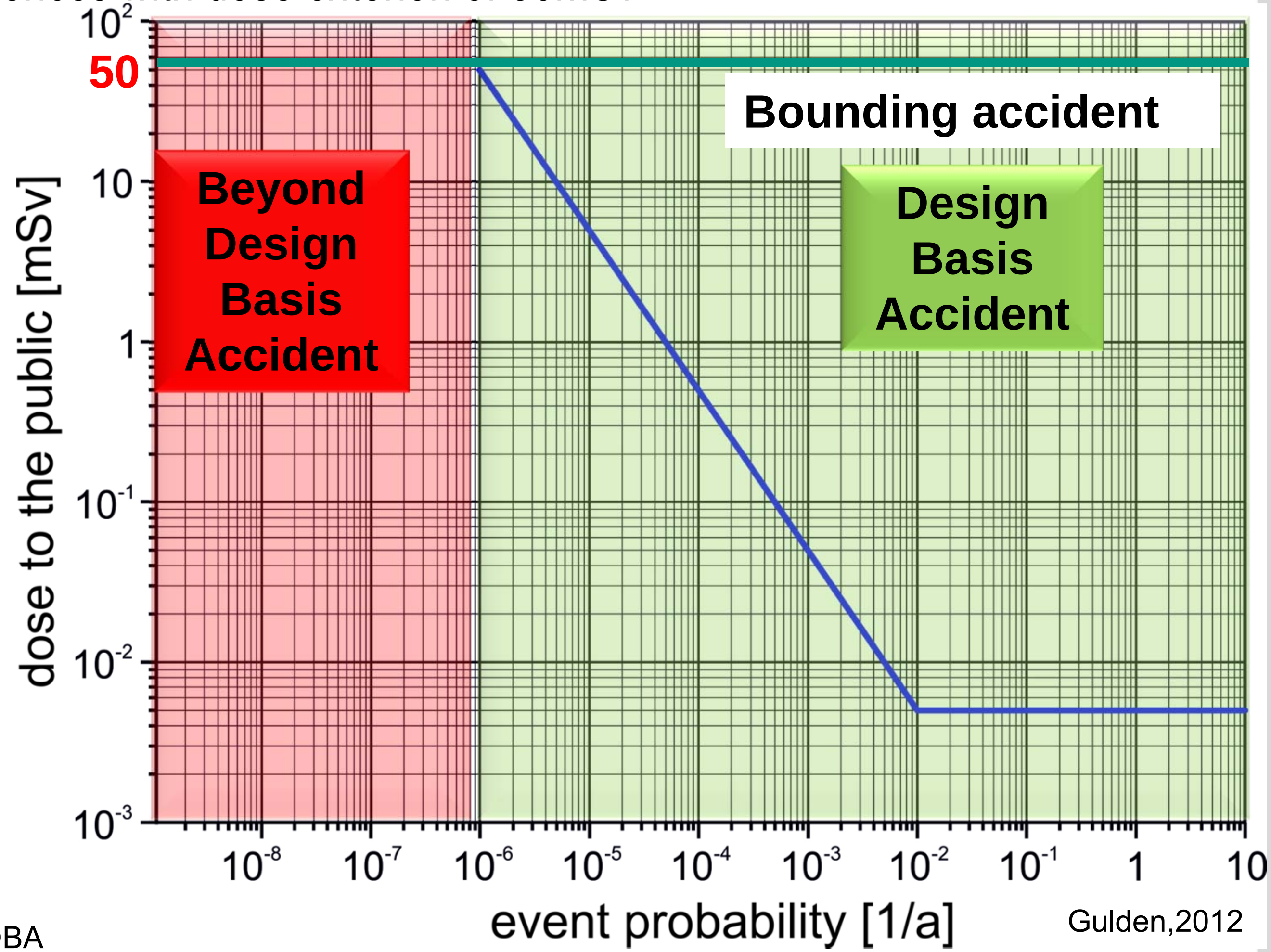
- **Definition of plant state levels in DiD**



*INSAG 2010, WENRA2012

Nuclear power plant safety approach IV

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



Dose limits Germany

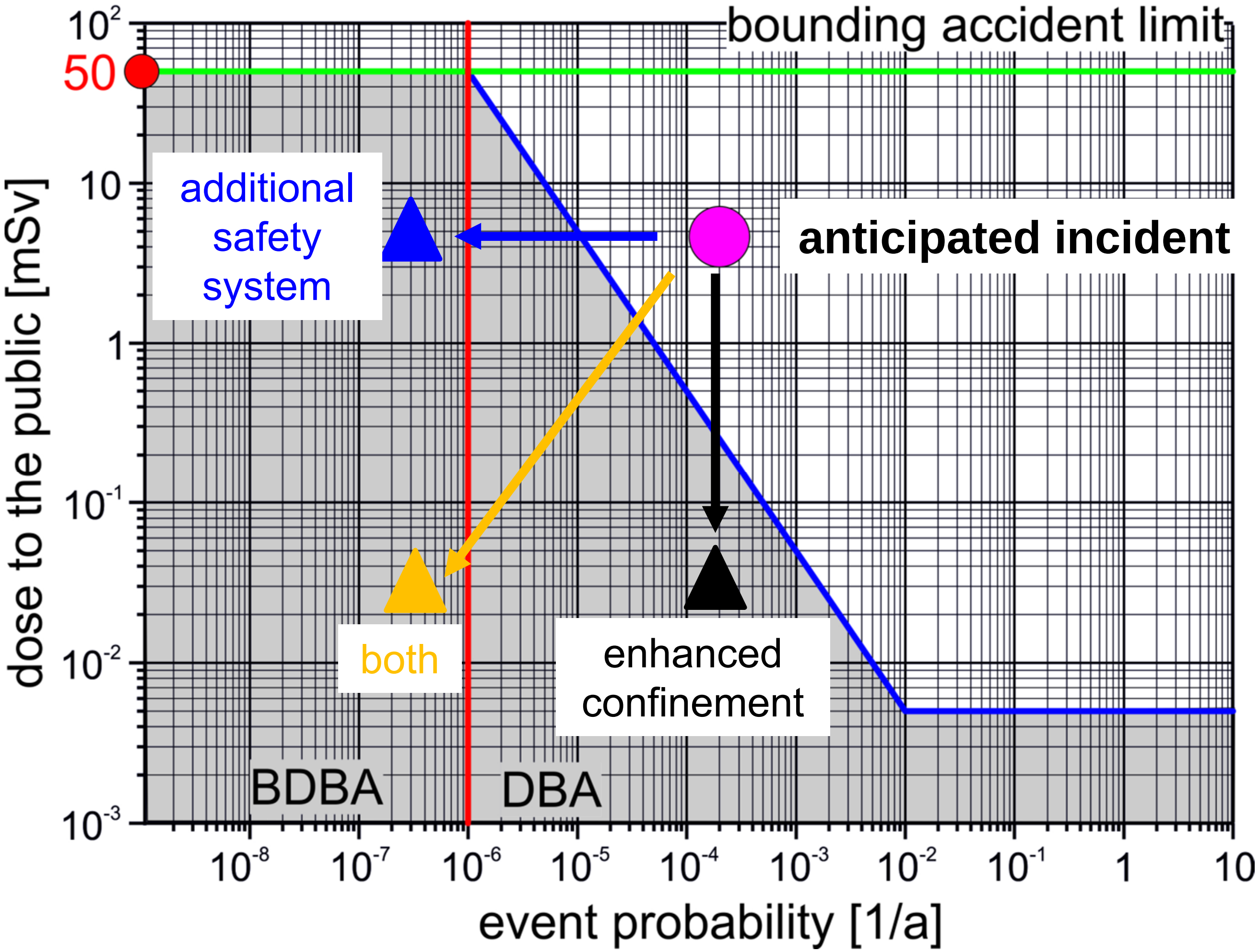
public	worker	Evac. dose
1mSv/a	20mSv/a	100mSv/a
20µSv/w		2mSv/w
3µSv/d	0,3mSv/h	0,3mSv/d

mean nat. dose 1mSv/a

* Design Basis Extension in ITER ~ BDBA

Nuclear power plant safety approach V

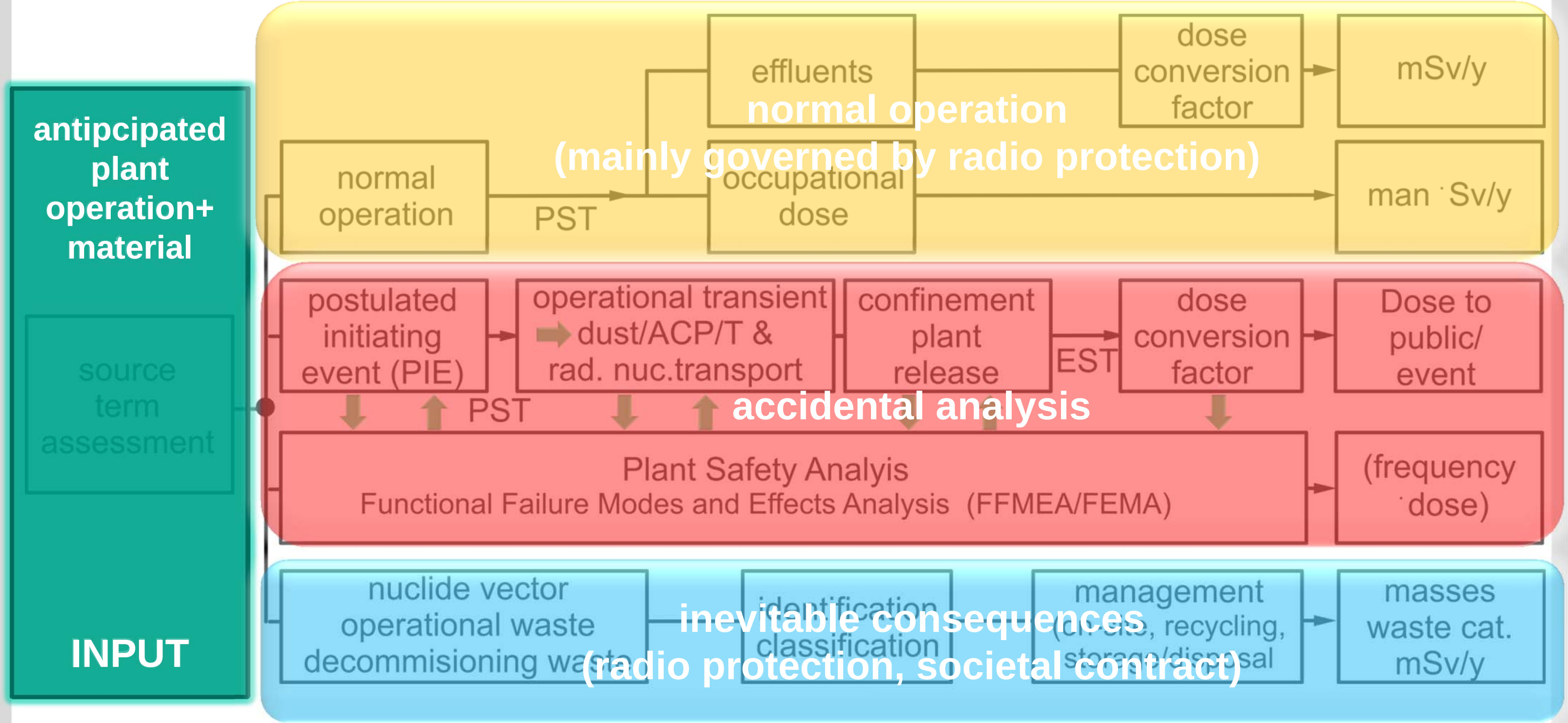
- **Safety risk approach**
  - Mitigation into the acceptable risk zone by countermeasures
  - Diminution of dose rate by enhanced confinement



Gulden,2012

Nuclear power plant safety approach VI

- There are many kinds of safety!!!!
- Pathway for consistent treatment ➡ Systematic Safety Analysis (SSA)



PST=process source term
EST=environmental source term

➡ **all to be matched for a nuclear plant license**

Comparison of safety concept fusion ←→ fission

General:

- **Physics/technology basis of FPP differs from NPP**

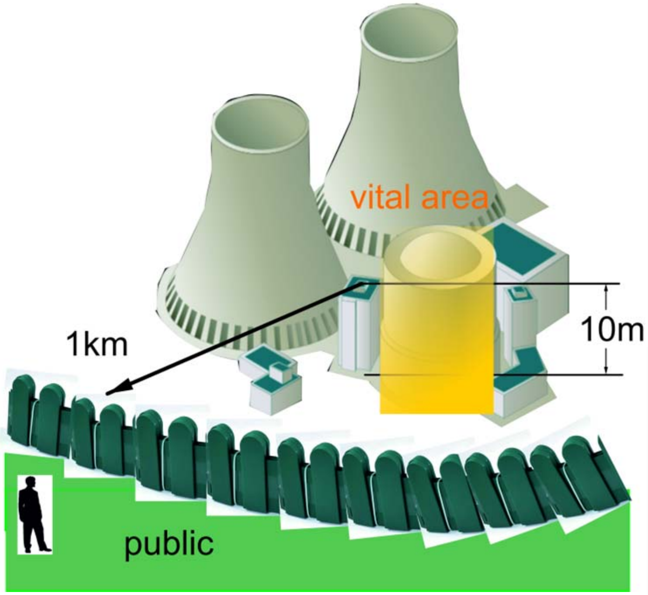
➡ **fusion specific adaptions has to be implemented in licensing procedures.**

Most percepted argument = public safety in terms of radiological hazard

- **Enveloping event by maximum radiologic release**
  - Identification of **in-plant** energy sources causing/accelerating an event
  - Quantification of sources of radioactive inventory (=source term(s))
  - Assessment of
    - release fractions (by energy inventories +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*)



* MEI=Most Exposed Individual .

Comparison of safety concept fusion ←→ fission II

Main energy inventories in a FPP for enveloping event

Energy Source	Energy	Reference
in-vessel fuel (DT)-(self-limiting in case off accident)	~ 325 GJ	SEAFP, SEIF
magnetic field	~ 200 GJ	SEAFP, SEIF
plasma thermal energy	1 to 2 GJ	SEAFP, SEIF, PPCS
primary coolant water enthalpy	~ 400 GJ	SEAFP, SEIF

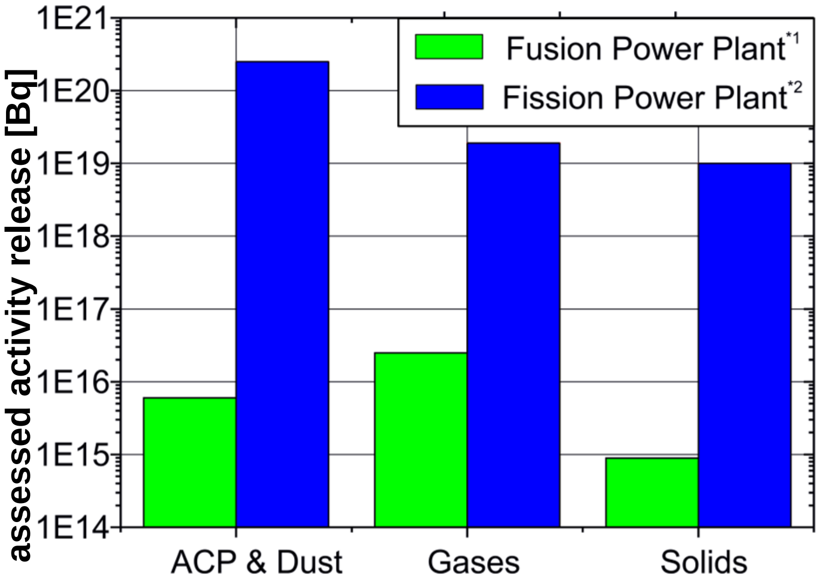
But be careful

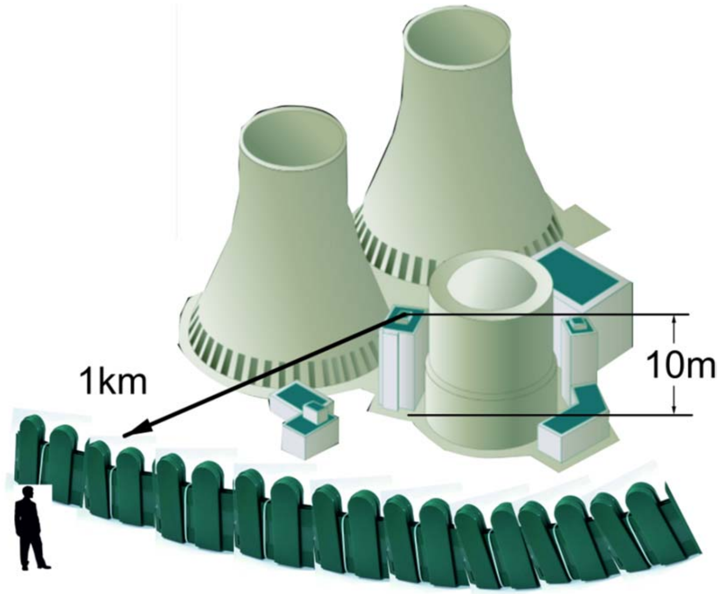
- potential chemical interactions are not considered
- considerations limited to blanket, contributions may require incorporation of divertor, heating systems other PFC with different nuclide vector
- ACP content due to unknown coolant chemistry problematic
- lack of validated tools to predict temporal evolution (conservative assessments by now)

* ACP=activated corrosion products.

Comparison of safety concept fusion ←→ fission III

- **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**





accidental releases FPP by in-plant energies several orders of magnitude lower than in NPPs.

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

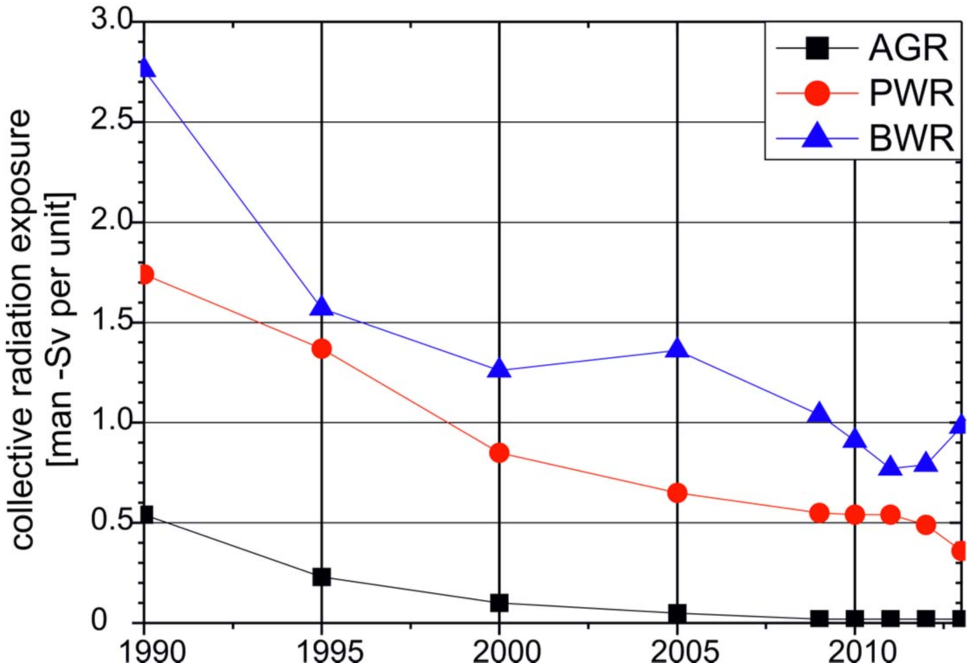
Comparison of safety concept fusion ←→ fission IV

- **Is assumption of maximum releases justified ?**
  - Assume 1kg T- to be released
  - ➡ worst case dose to public 0.4Sv (1km distance from release point)
  - ➡ Safety concept mandatory
- **Is specification of allowable radionuclide inventory a reasonable approach?**
  - From plant safety aspect and operational aspects - **yes !**

Advantages
- specification of nuclides to be used in structure
- coolant chemistry/purification required to assure operation
- man/machine operation
- …….

Example
- Evolution of collective dose in NPP`s by adapted coolant conditioning and material choices

Learnt
- Dedicated procedures/material selection yield dose rate reduction of 10



AGR=adanced gas reactors,
PWR=pressurized water reactor
BWR=boiling water reactor
* WANO, 2013, Performance indicators of NPP

Comparison of safety concept fusion ←→ fission VI

- **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: plasma 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*

Comparison of safety concept fusion ←→ fission VII

- **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*

Comparison of safety concept fusion ←→ fission VIII

- **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*

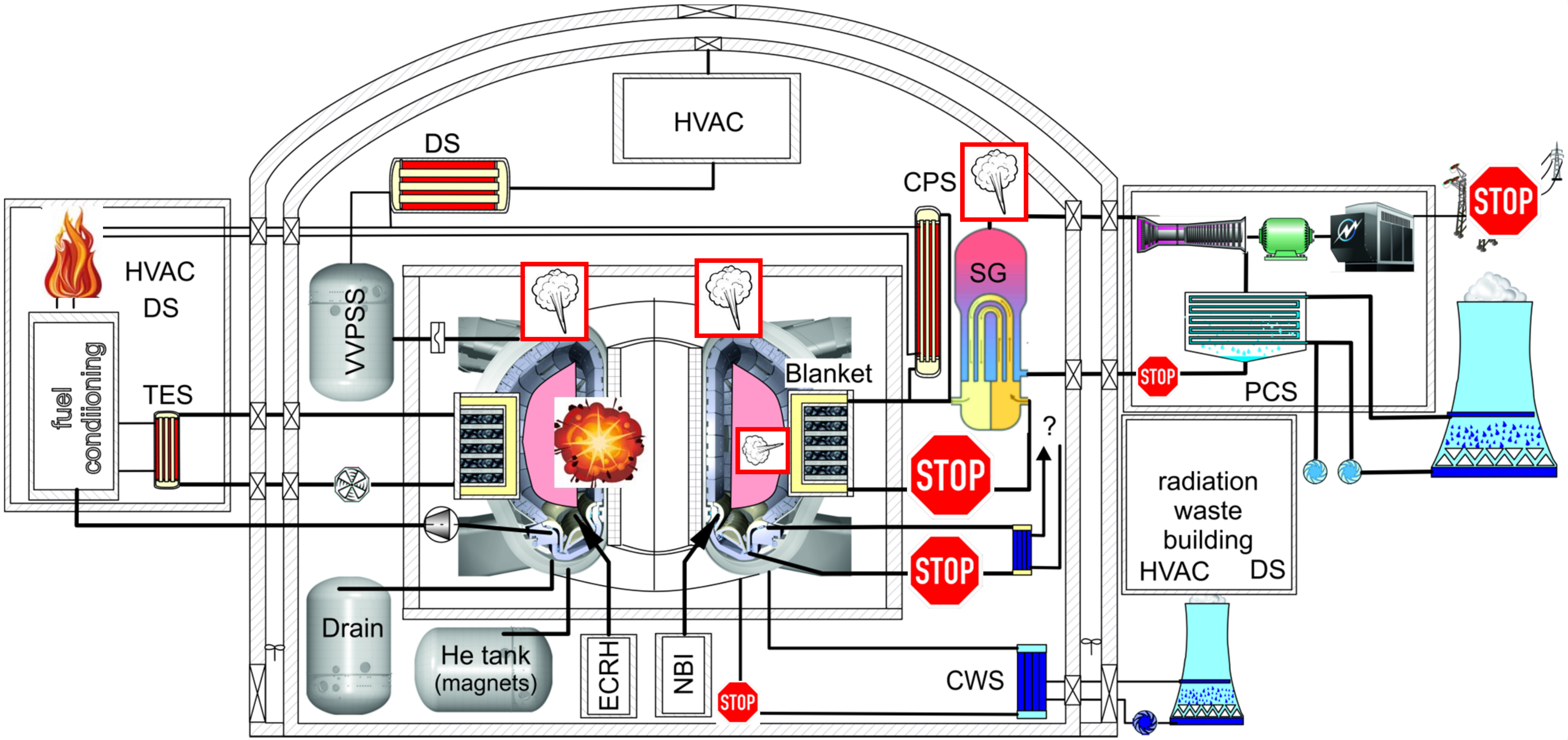
- **Leak before break**
  - NPP: certain parts of the piping the component integrity is guaranteed by applying the "leak-before-break concept" (LBB) in the plant design.
  - Fusion: LBB concept cannot be assessed currently.

  ➡ ✓ *applied to FPP: LBB concept*

Comparison of safety concept fusion ←→ fission IX

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
- Additional fusion specific events: loss of cryo-system, arcing, magnets ➡ affecting barriers



Comparison of safety concept fusion ←→ fission X

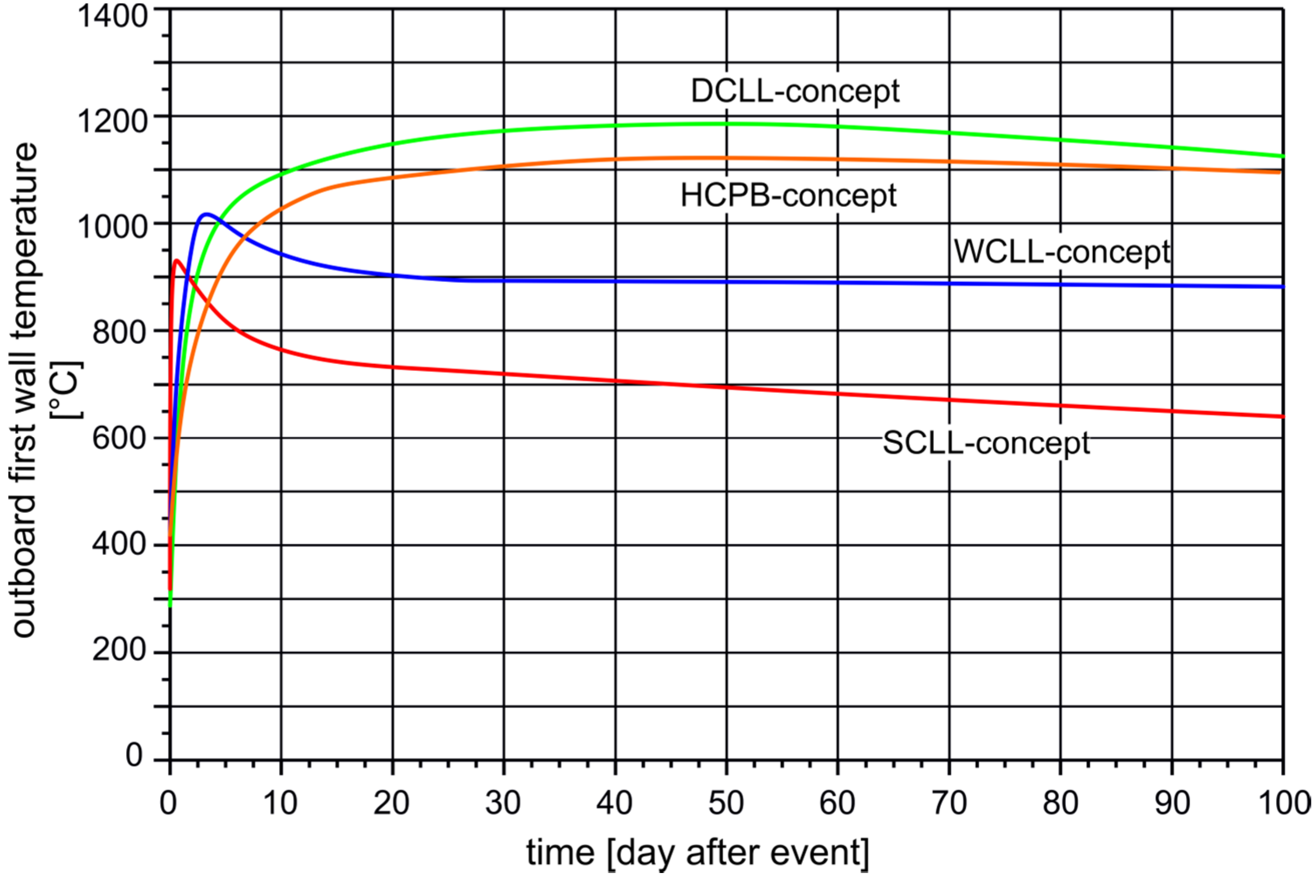
- Most crucial radiological event =Loss of coolant accident (LOCA)

Goal

- Safe heat removal without loss of functional integrity or

Example:

- LOCA in PPCS



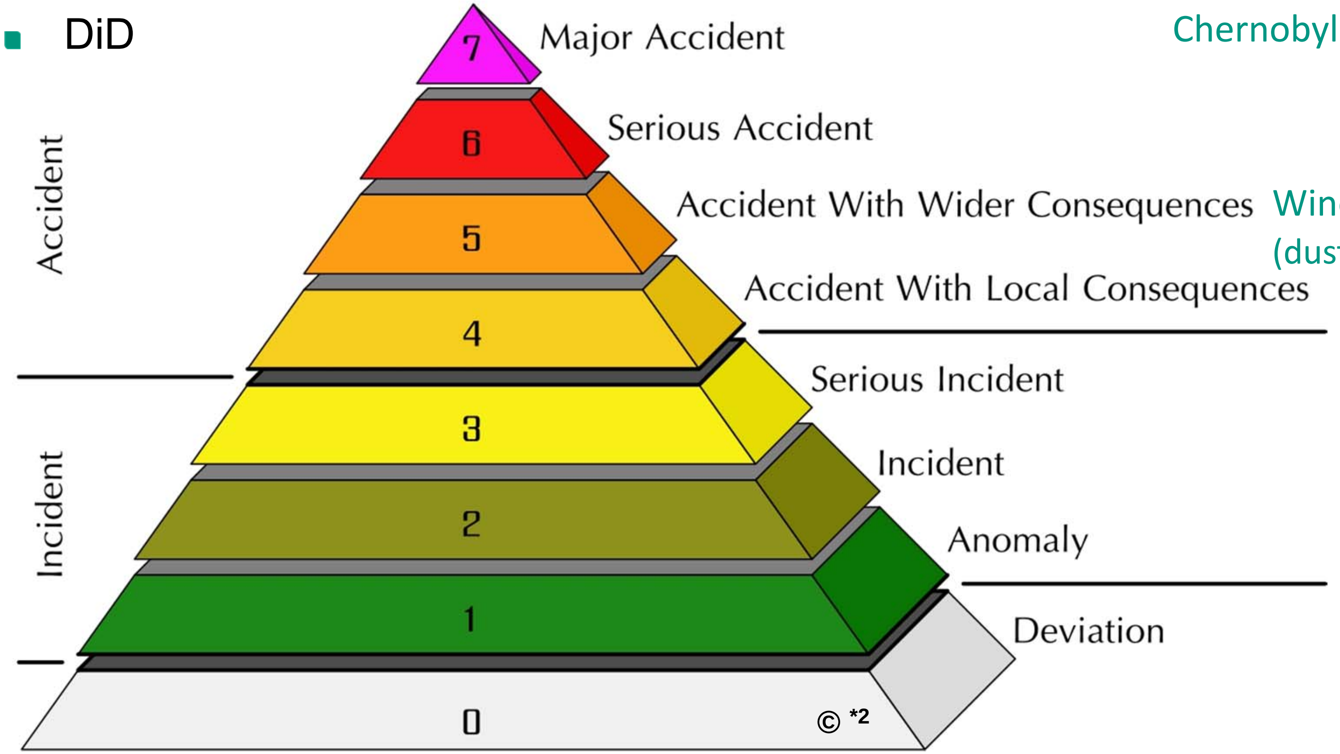
Note:

- Any safety demonstration design and system (including sec. side) dependent !

DEMO in view of severe accidents I

International Nuclear and Radiological Event Scale (INES)

- Event severity ≈ ten times greater for each increase in level of the scale*1
- Areas of impact:
  - People and environment
  - Radiological barriers and control
  - DiD



Chernobyl (1986), Fukushima (2011)

Kyshtym (1957)

Windscale (1957), TMI (1979)
(dust) (gaseous FP release)

*1www-ns.iaea.org/tech-areas/emergency/ines.asp#1

*2"INES en" by Silver Spoon. Licensed under CC BY-SA 3.0 via Wikimedia Commons http://commons.wikimedia.org/wiki/File:INES_en.svg#/media/File:INES_en.svg

DEMO in view of severe accidents II

How much radionuclide inventory is acceptable to exclude for an enveloping event exceeding INES-6?

- comparison of DEMO 5kg T with 1.2GW PWR
  - Specific potential dose for a MEI, assuming highest release categories, most unfavourable weather conditions and no-counter measures [*1]

	FUSION	FISSION (1200MW-generic PWR)					
Isotope	Tritium	^{131}I	^{137}Cs	^{90}Sr	^{239}Pu	^{88}Kr	^{133,135}Xe
rad. nuclide inventory [TBq]	1.85E6	3.8E6	2.6E5	1.3E5	1.1E3	2.8E6	8.9E6
specific potential dose rate	1 HTO 0.1 HT	6900	1850	1150	500	3	0.2

➡ Substantially lower dose rate in FPP

- comparison of a DEMO (5kg T) with Chernobyl

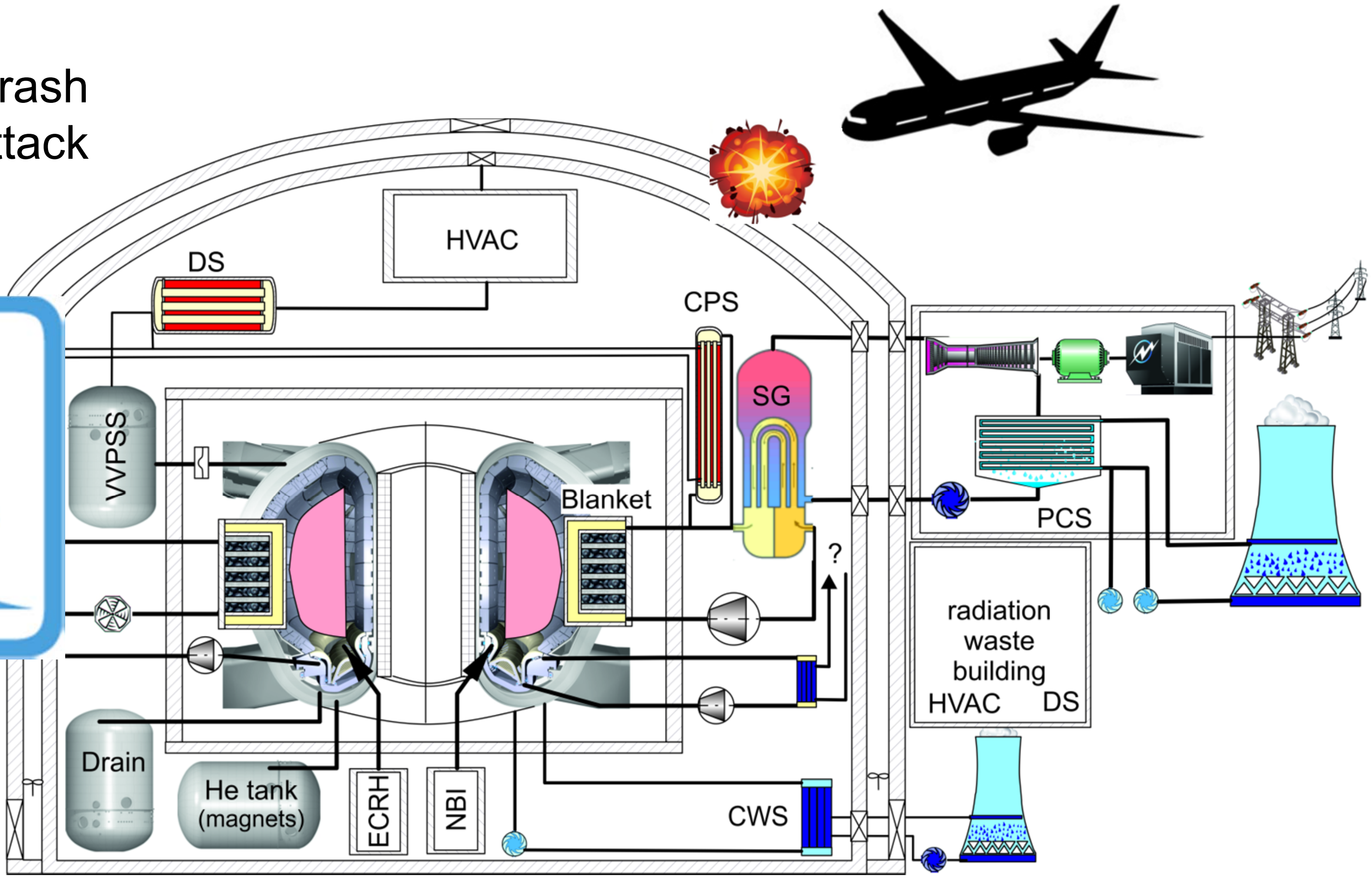
	FUSION	FISSION (Chernobyl- C-Moderated Reactor)					
Isotope	Trit./HTO	^{131}I	^{137}Cs	^{90}Sr	^{239}Pu	^{88}Kr	^{133,135}Xe
radio nuc. inventory [TBq]	1.85E6	1.3E6	2.9E5	2.0E5	850	3.3E6	1.7E6
spec. potential dose rate	1	2360	2070	1770	390	3	0.05
acc. release fraction [%]		20	13	4	5	100	100
spec. potential dose rate by released isotope	1	470	270	70	12	3	0.05

➡ Exclusion of INES 6 allows Tritium-release of 9kg !!!

[*1] Gulden ,1993, [*2] Gulden, 1994

DEMO in view of severe accidents III

- **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

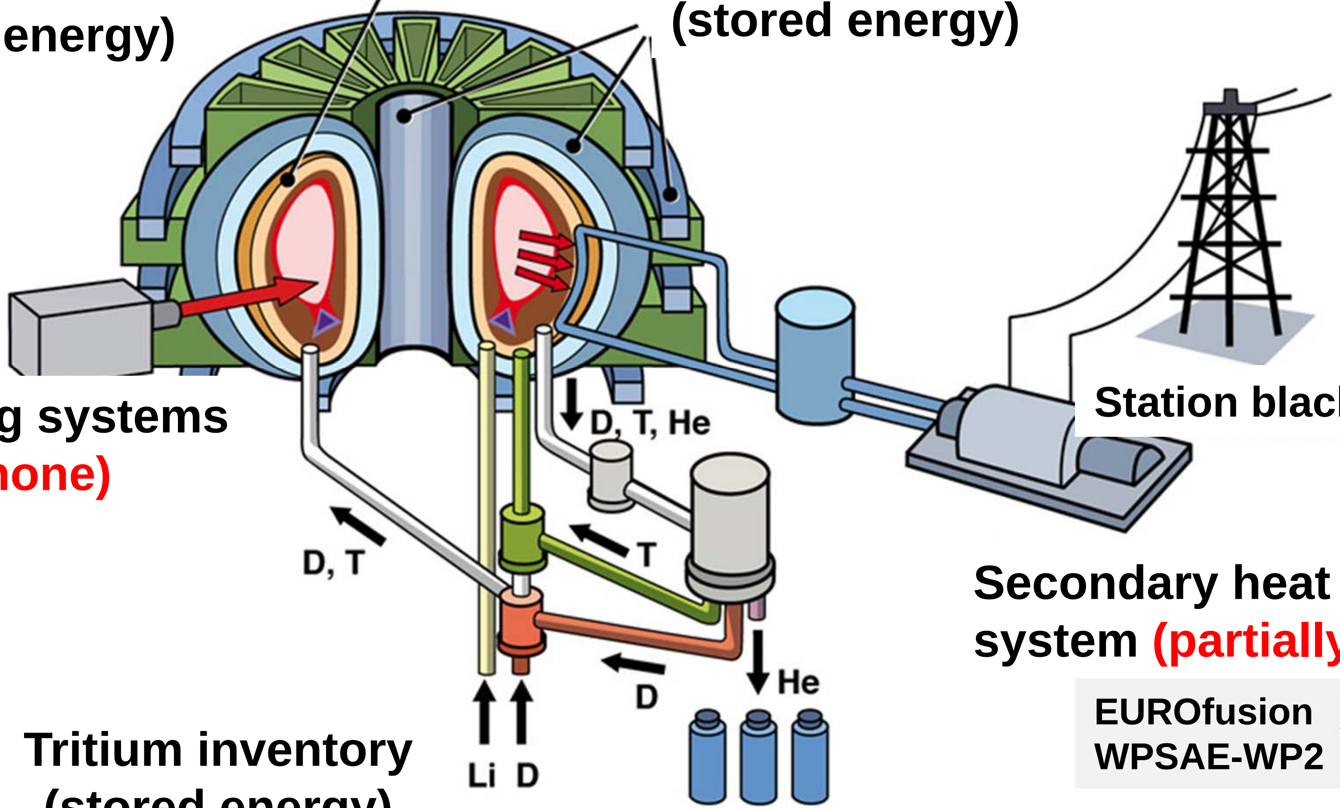
Unknowns to be identified / assessed I

- as identified

coolant
(stored enthalpy)

Plasma
(stored energy)

Magnetic energy
(stored energy)



Heating systems
(none)

Station black out (partially)

Secondary heat removal
system (partially, LOHS ?)

EUROfusion
WPSAE-WP2

Tritium inventory
(stored energy)

Unknowns to be identified / assessed II

- **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

Unknowns to be identified / assessed III

- **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 …
- **Waste management**
  - Extraction, Handling , Reprocessing, Clearance

EUROfusion WPSAE-WP2

EUROfusion WPSAE-WP2

Unknowns to be identified / assessed IV

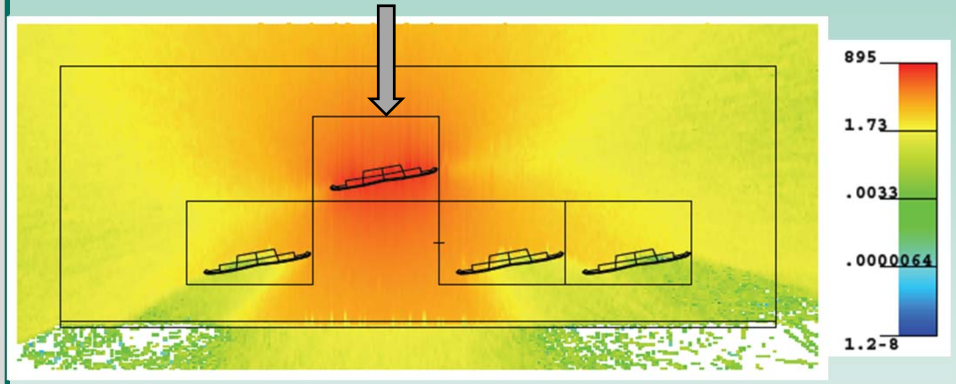
- Waste management starts from the extraction (RH) to the hot cell integrated along the entire path and duration

Example: ITER Transfer cask radiation doses*

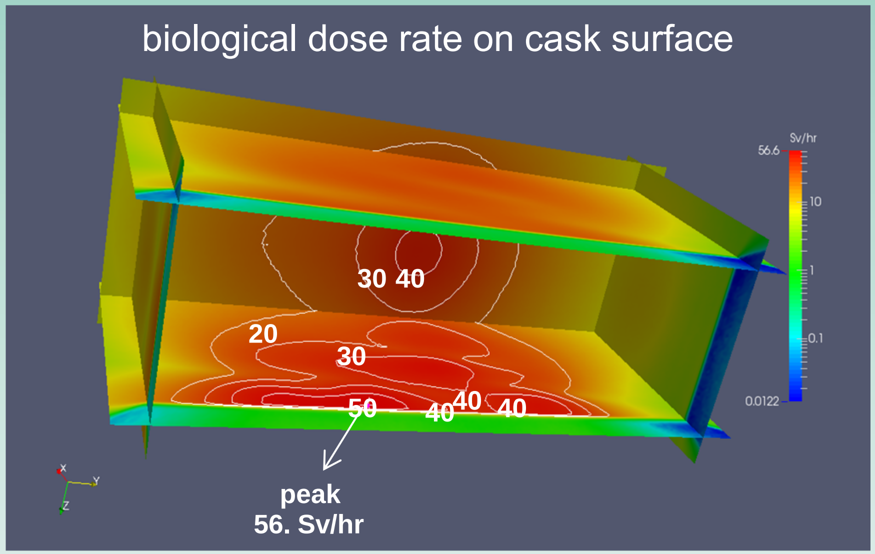
- Transfer Cask Radiation Doses

single FW modules in Transfer Cask

Shut-down dose rate map [Sv/h] for activated FW module in transfer cask



Four FW modules in Transfer Cask



*1FW module (BLK#15) . irradiated in ITER (B-lite), 21 days decay, *R2Smesh, U. Fischer et al. 2013*

Summary & Recommendations

- Fusion safety concepts relies on state-of-the-art safety concepts for nuclear installations containing radioactive environment and is based on DiD concept.
- Similarities and differences between safety concepts of fusion and fission. Main reasons for differences are radioactive inventories in plants and relevant potential release paths
- Plant-internal events do not result in conditions requiring off-site evacuation
- Systematic assignment of measures & installations to the different levels of defence (as required by internat. fission regulations) has to be performed once an adequately detailed design level of a FPP is attained.
- Safety function "cooling" demands detailed design of in-vessel components (blanket&others) and necessitates demonstration of safe decay (passive) heat removal➡ development of validated tools mandatory
- External hazards must be included in the future safety analysis

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- Numerous issues remain open and requires adequate attention
- Waste management has not been considered

EUROfusion WPSAE-WP2

Contributors

- **Max-Planck-Institut für Plasmaphysik (IPP)**
  Jürgen Raeder, Arthur Weller, Robert Wolf
- **KIT**
  Lorenzo Virgilio Boccaccini, Dario Carloni, Fabrizio Franza, Xue Zhou Jin, Werner Gulden
- **Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)**
  Joachim Herb
- **Öko-Institut e.V. (Institute for Applied Ecology)**
  Christoph Pistner
- **Culham Center for Fusion Energy (CCFE)**
  Neill Taylor
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  Marcus Fabian