Transferability of the nuclear fission regulation to potential fusion power plants*

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INSTITUTE for NEUTRONPHYSICS and REACTOR TECHNOLOGY (INR)

- General Aspects of Nuclear Regulation Approaches (prescriptive vs. goal oriented)
- General Safety Requirements for Nuclear Installations
- Challenges to be mastered by adaption of fission regulations to fusion
- Regulatory differences between fission and fusion reactors
- Potentially applicable IAEA or European Council directives
- Recommendations for Implementation of Legal and Regulatory Framework for Fusion
    - Structure of legal boundaries
    - Regulatory framework (Safety requirements, Safety Concepts, Fusion specific Aspects)
    - Codes &Standards
    - Interfacing Safety, Security, Safeguards

*Most being part of contractual work for **EU-Directorate-General for Energy** (**European Commission**) accessible at https://op.europa.eu/en/publication-detail/-/publication/e1579af9-8d44-11ec-8c40-01aa75ed71a1/language-en

General Aspects of Nuclear Regulation Approaches

- **Worldwide two classes of nuclear regulation approaches adopted**

Prescriptive approach

(e.g. GER, KOR, China,PR, USA)

- Regulation contains **explicit requirements** the licensee needs to fulfil
- Requirements **contain technology used** in installation
- **Facility-specific safety systems to be installed** are **functionally regulated** down to the detail level

Ads. and disads.

- **Simple** execution by licensee & authorities
- **Traceability & transparency** by all actors
- Deficits for **New Technologies**
  - Regulations need to be set in advance of the facility design
  - development of regulations over time
  - detailed evolutionary knowledge development by licensee and authority mandatory

Goal-oriented approach

(e.g. FRA, UK,… as for JET and ITER)

- **Definition** of major **safety objectives to be met** by installation
- **Responsibility of the licensee** to **demonstrate** that **design & technology** matches objectives at **all operational stages** (construction, operation, decomissioning)

Ads. and disads.

- **Technology neutral**
- **Risk of licensee** receiving no acceptance by authority (evidence of meeting safety objectives not considered adequate)
- **Evolutionary development** of regulation with **pre-scriptive elements** (occupational & operational doses, radiological consequences) and **demonstration proof of procedures -HYBRID**

➡ **likely only an adapted goal-oriented may meet current fusion reactor maturity**

General Safety Requirements for Nuclear Installations*1,2

- **Fundamental Safety Principles (according to GSR, SSR)**
  - **Protection** of public and environment **against radiological hazards**
  - **Elimination** of need for public **evacuation** in any accident
  - **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**
  - **Minimization** of activated waste and **safe confinement** of rad.-waste

➡ **Safety objectives to be met for fusion the same fission reactor are the same**

➡ **requires depiction in a regulatory fusion framework**

- **Approach to demonstrate fulfillment of Safety Principles**
  - Realization of defence-in-depth (DiD) concept to meet safety functions, preservation of barriers & retention functions in any operational condition (internal & external hazards)
  - Application of safety demonstration methodology according to FAIR*3 principle
  - Adoption common nuclear approaches (e.g. "leak before break"*4; ……)
  - Encompassing character of safety demonstration to meet all primary requirements

➡ **Generally same methodological approach but different operationalization (due to different physical principles and components)**

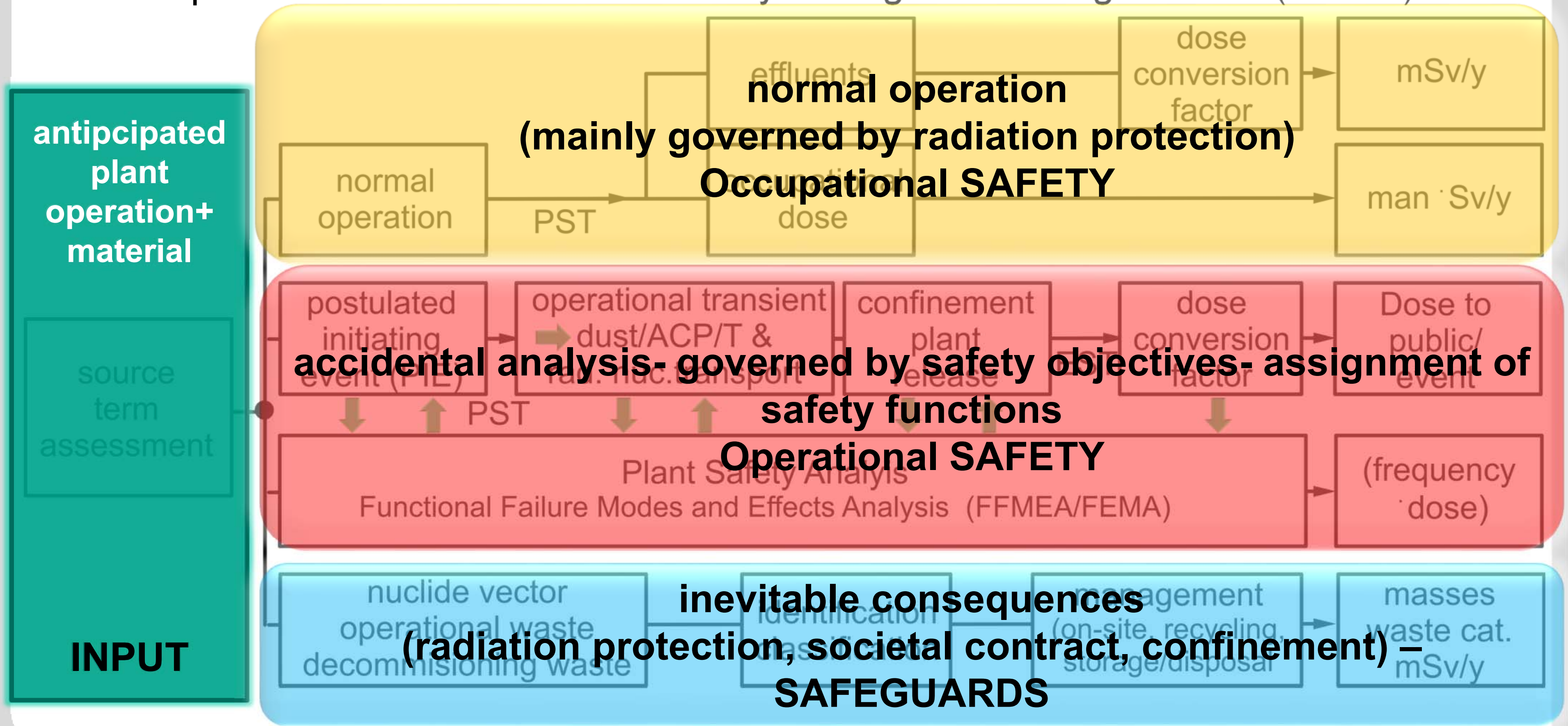
*1 IAEA safety standards series,
*2 Council Directives/Directives of Europ. Parliament

*3FAIR = findable,accessible,interoperable, reproducible
*4 technology and experience dependent

Safety Requirements for Nuclear Reactors

Pre-requisite: **plant description for systematic safety analysis (SSA)**
Regulatory frame: **Preset of Limit, Methodology of Proof**

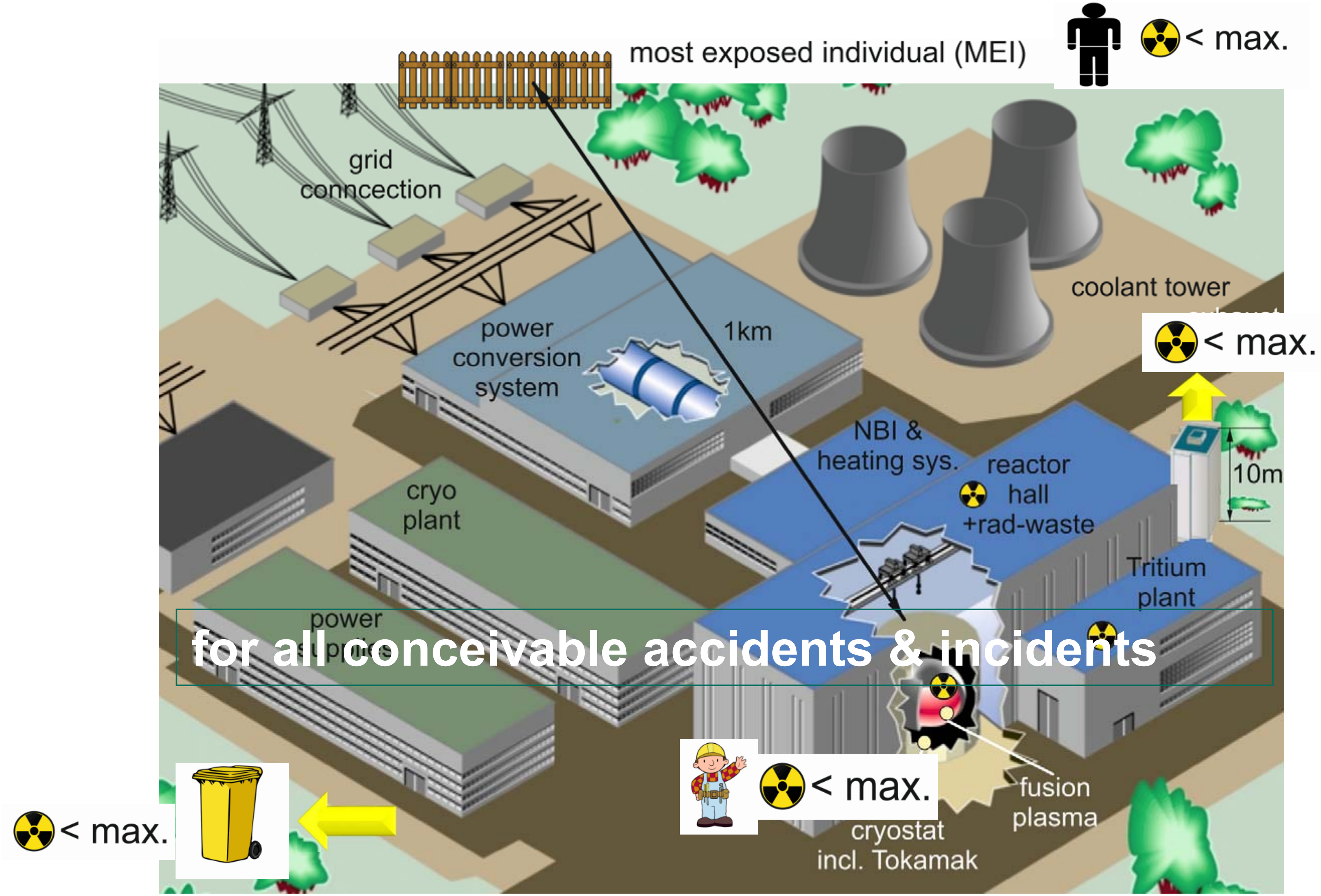
- normal operation — dose to worker on site < limit
- accidental analysis : — worst dose to public (MEI) < limit
- consequences: — mobility in long term storage < limit (what ?)



PST=process source term
EST=environmental source term

Safety Requirements for Nuclear Reactors

- Master Logic diagram (MLD) - Analysis for the generic FPP-plant



Challenges to be mastered by adaption of fission regulations to fusion

Collection of fusion specific open aspects*[1] to be mapped in regulatory frame on reactor scale. Treatment of:

- Radioactive releases to ambient
- Limitation of on-site tritium inventory
- Radiation exposure risks on-site (at operation & maintenance)
- Establishment of a safety concept identifying fundamental safety functions containing also supplementary supporting safety functions for fusion facilities.
- Accidents to be considered for safety analyses scoping internal & external hazards
  - Transients associated with radiological events
  - Non-radiological hazards potentially impacting barriers (confinement)
  - Consideration of the approach in case of Design Extension Conditions (DEC) according to IAEA Safety Standards (emergency manual, documentation of emergency exercises, guidelines for severe accident management *[2])
- Treatment of decay heat removal at operation & during interim storage

Open aspects*[1] for fusion specific development of licensing authority to regularly complement regulatory frame

- Applicability of Codes & Standards for fusion facilities
- Inclusion of internat. & national operational experience feedback of fusion facilities
- Enhancement of fusion specific readiness, capabilities of TSO and regulatory body

*[1] see Perrault, 2016, EA safety standards series, Gandolin 2020, Elbez-Uzan, 2020

*[2] Amendment based on IAEA initiative of 2011, operationally implemented in Germany 2012

Regulatory differences between fission and fusion reactors

Primary safety functions

- Power control
- Radiological on-site inventory (confinement, limitation & control of releases)
- Radiologial consequences at DEC

Fundamentally different physics of Fusion vs. Fission

(fuel, power density & control, inventory, nuclide vector, decay heat, …….)

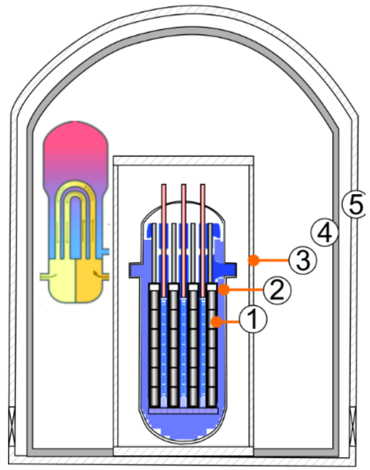
➡ different reactor architecture of fusion and fission plant to meet primary safety functions

Functional similarities are

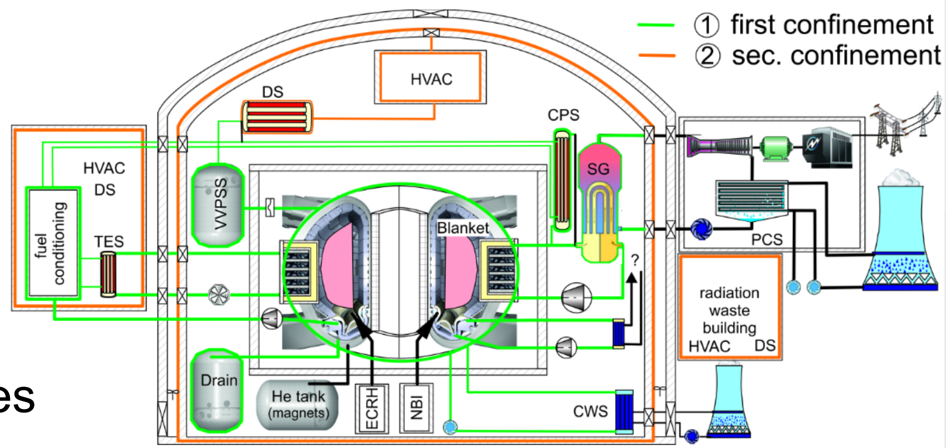
- Static confinement barriers for releases
- Implementation of retention functions
- Shielding
- Provisions for decay heat removal

➡ **But,** fulfillment by entirley different systems, components, physical principles

Fission reactor



Fusion reactor



Regulatory differences between fission and fusion reactors

Regulatory aspects to be covered in operationalization of in any nuclear reactor safety concept

- Operational experience
- Leak-before-break concept
- Provision of measures, procedures, and installations to meet radiological criteria based on inherent physical principles and/or passive as well as active safety systems.
- Enveloping safety concept based on postulated single initiating, multiple failure events, severe plant states with assignment to different levels of defense

Continuous dynamic adaption (development) over time **for** Fusion Reactor **regulation** is required for several reasons:

- First of a kind (FOAK)
- Material licensing, data basis still limited ➡ application of Leak-before-break ?
- Maturity of safety concept on different DiD not fully developed or proven

➡ Multitude of systems, structures and components (SSCs) in a fusion reactor is associated with safety on several DiD-levels

➡ assignment of SSC's in importance classes challenging (and design dependent)

Regulatory differences between fission and fusion reactors

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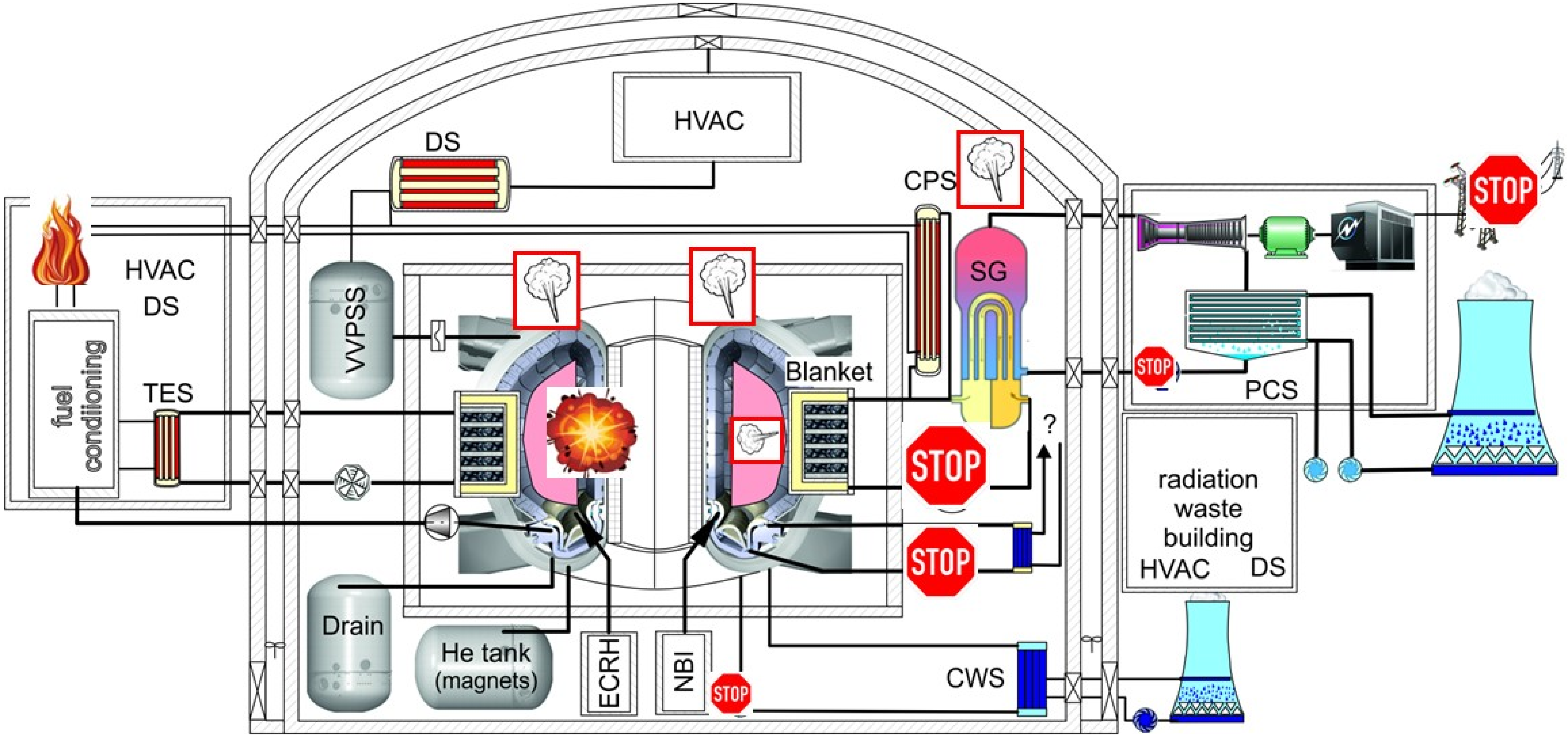
SSC's associated with safety and safety functions (PIE, safety function, …….)

- In-Vessel components (Blanket, Divertor, Limiter, thermal & radiation shields)
- Reactor core confinement (Vacuum vessel & boundaries)
- Primary Heat Transfer System (enthalpy, chemical source, ACP, CPS)
- Magnet systems (stored energy, cryo-system and infrastructure)
- Inner and Outer Fuel cycle (TES, DIR, Fuelling, Vacuum pumps, Tritium plant)
- Power control & diagnostics (HCD, FPSS, Sensors, reactor control system)
- Balance of Plant & Plant Electrical Supply (power management, emergency supply, ….)
- Remote Maintenance (in plant and AMF including rad.-waste)
- Buildings (Tokamak, Tritium plant, radiologic material hosting galleries =static barriers)

ACP =activated corrosion products
CPS= Coolant purification system
TES= tritium extraction system
DIR=direct internal recycling
HCD=Heating Current Drive
FPSS=fusion power shut-down system
AMF=Active waste Management Facility

Regulatory differences between fission and fusion reactors

- **Safety Analyses - Postulated Initiating Events (internal events)**
  - Events are similar as in nuclear power plants such as
    - Loss of flow accident (LOFA),
      Loss of offsite-power (SBO), Leaks (VV, Primary System, …), Fire & explosion
  - **Functional systems coping with timely progression of event not comparable to fission reactors**



Potentially applicable IAEA standards [*1]

Fully applicable are the following IAEA standards

- Standard Series No. SF-1 “Fundamental Safety Principles”
- GSR Part 2 “Leadership and Management for Safety”
- GSR Part 3 “Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards”
- GSR Part 4 “Safety Assessment for Facilities and Activities”
- GSR Part 6 “Decommissioning of Facilities”
- GSR Part 7 “Preparedness and Response for a Nuclear or Radiological Emergency”
- SSR-1 “Site Evaluation for Nuclear Installations”
- SSR-2/1 “Safety of Nuclear Power Plants: Design”
- SSR-2/2 “Safety of Nuclear Power Plants: Commissioning and Operation”
- SSR-3 “Safety of Research Reactors”

Modifications or adaptions refer to

- SSR-4 “Safety of Nuclear Fuel Cycle Facilities”

➡ Here, interface between safety, nuclear security and the state system of accounting for, and control of nuclear material needs to be considered (Tritium)

➡ Terminology of expression referring to nuclear fuel, nuclear fuel cycle, processing of spent fuel require fusion adaptation or amendment if applied to fusion

[*1] or corresponding Europ. Council directives, for details see EC report

Potentially applicable IAEA standards *1

Specific Safety Guides (SSG) require adaptation to Fusion facilities

- **Site Evaluation***2
  - SSG-9 Seismic Hazards in Site Evaluation for Nuclear Installations
  - SSG-18 Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installation
  - SSG-21 , SSG-35, NS-G-3.1, NS-G-3.2, NS-G-3.6

- **Design** (although SSR-2/1, SSR-2/2 and SSR-3 are technology neutral they refer to specifc safety guides containing fission specifities which are not applicable or to be modified parts) *2
  Not applicable are
  - SSG-5, -6, -7, 42 and -43 referring to nuclear fuel
  - SSG-52 Reactor core design
  - SSG-63 Fuel handling and criticality in storage

  modification (adaptions) refer to
  - SSG-30 Safety classification of SSC
  - SSG-34 Design of electrical power systems in NPP
  - SSG-37 Instrumentation and Control Systems
  - SSG-56 Design of Reactor coolant systems
  - SSG-62 Design of Auxiliary Systems , …….
  - NS-G-1.13, NS-G-4.6 Radiation protection for design of NPP and waste management

*1 or corresponding Europ. Council directives, for details see EC report
*2 not complete

Potentially applicable IAEA standards *1

Specific Safety Guides (SSG) require adaptation to Fusion facilities

- **Construction and commissioning** *2
  - SSG-28 Commissioning of NPP
  - SSG-38 Construction of nuclear installations
  - NS-G-4.1 Commissioning and equipment qualification

- **Operation** *2
  Not applicable are
  - SSG-27 criticality safety
  - NS-G-2.5, NS G4-3 core managment and fuel handling

  Modification (adaptions) refer e.g. to
  - SSG-10 ageing management
  - SSG-13 chemistry for water cooled NPP
  - SSG-50 operating experience feedback for nuclear installations
  - …..
  - …….
  - NS-G-2.3 modifications to NPP
  - NS-G-2.6 maintenance, surveillance and in-service inspection in NPP
  - NS-G-2.14 conduct of operations at NPP
  - ……….

*1 or corresponding Europ. Council directives, for details see EC report
*2 not complete

Potentially applicable IAEA standards [*1]

Specific Safety Guides (SSG) require adaptation to Fusion facilities

- **Decommissioning and waste management**
- **Radiation protection**
- **Leadership and management**
- **Safety assessment ➡ relevant safety demonstration in principle applicable provided modifications are integrated**
  - SSG-2 Deterministic safety analysis (e.g. “core melt down” cannot be expected in FPP)
  - SSG-3 PSA level 1 necessitates consideration of FPP design aspects
  - SSG-4 PSA level 2 requires integration of FPP design specifities
  - SSG-20 Safety Assessment and preparation of safety analysis report (misses fusion specific systems)
  - SSG-61 Content of Safety Analysis report demands structural changes for FPP (ordering, logical sequence)

  full applicable are
  - GSG-3 safety case & assessment of predisposal management of rad.-waste
  - WS-G-5.2 safety assessment for decommissioning of facilities using radioactive material

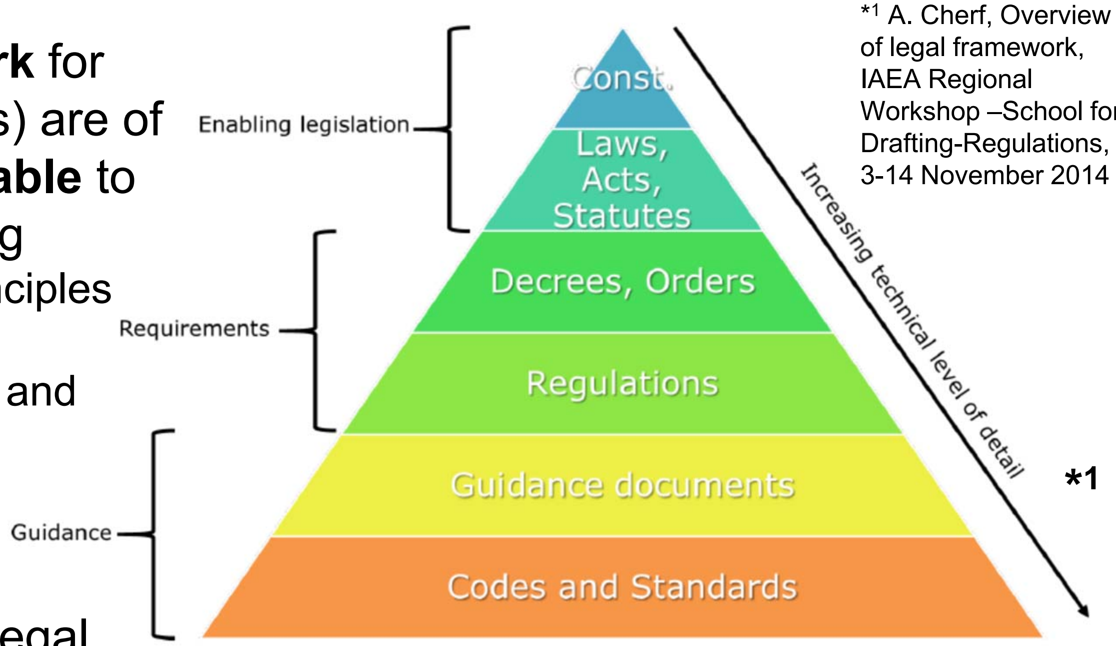
[*1] or corresponding Europ. Council directives, for details see EC report

Recommendations for Implementation of Legal and Regulatory Framework for Fusion

- **Legal and regulatory framework** for nuclear installations (first 3 levels) are of **general nature** and thus **applicable** to **fusion reactors** as well. Applying
  - IAEA-SF1 Fundamental safety principles

  and
  - IAEA-GSR-1 Governmental, Legal and Regulatory framework for Safety

  scopes all elements of a legal and regulatory framework.

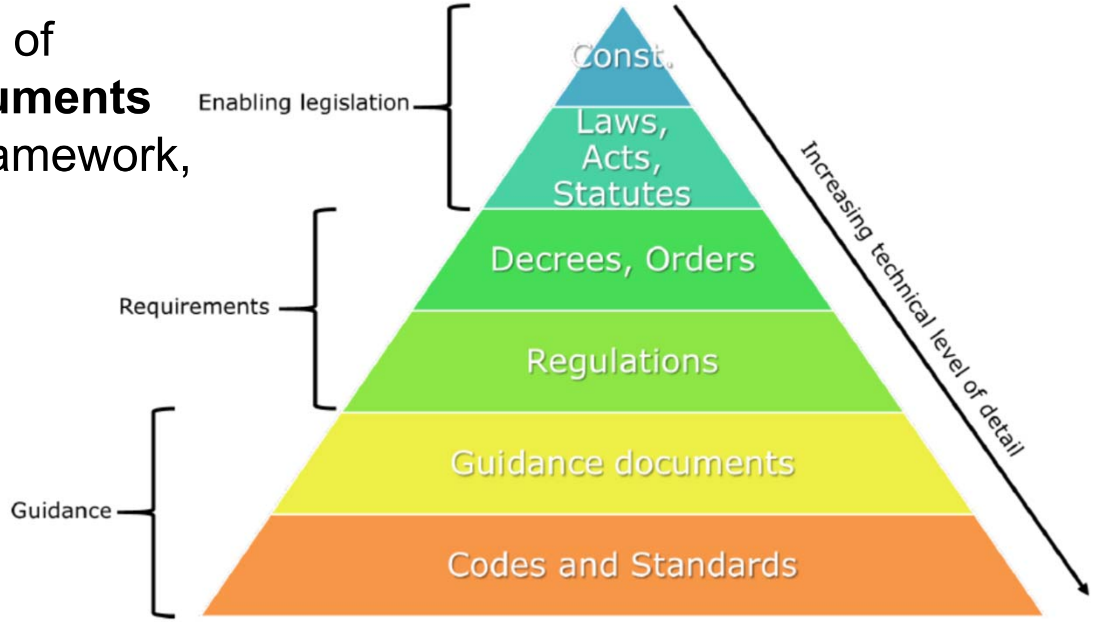


*1 A. Cherf, Overview of legal framework, IAEA Regional Workshop –School for Drafting-Regulations, 3-14 November 2014

- Thus, **implementation** provides legal basis for Fusion power plant as well wrt.
  - Defining competent regulatory authority;
  - Establishing licensing procedure for fusion power plants;
  - Requiring initial assessment of safety & regular reassessment of safety;
  - System for operational experience feedback;
  - Assigning obligation and responsibilities to license holder;
  - Defining high-level safety objective & implementation as high level requirements in legal context ;
  - Establishing adequate on-site emergency organization to cope with incidents & accidents.

Recommendations for Implementation of Legal and Regulatory Framework for Fusion

- **Regulatory framework** consists of **requirements & guidance documents** concretizing the abstract legal framework, essentially formulating **specific requirements** for safe
  - Siting,
  - Design,
  - Construction,
  - Operation and
  - Decommissioning



- These **regulations** contain more specific and technical **detailed requirements** (issued by government, regulatory bodies) and thus require wrt. to a fusion plant

➡ **Adaptation** of regulations taking into account fusion specific aspects

➡ **Reserve options to a goal oriented** achievement of safety objectives

➡ **Allowing for a graded approach** *[1,2] considering the hazard potential of a specific fusion facility

*[1] IAEA, Integrated Regulatory Review Service (IRRS) Report to the Unites States of America, IAEA-NS-IRRS-2010/02, 2011.

*[2] IAEA, “Governmental, Legal and Regulatory Framework for Safety”, IAEA Safety Standard Series No. GSR Part 1 Rev.1, IAEA, Vienna, 2016

Recommendations for Implementation of Legal and Regulatory Framework for Fusion

Safety assessment (SA)

- fully applicable to a FPP in term of methodological approach are IAEA Safety Standards
  - SSG-2 deterministic SA
  - SSG-3 and SSG-4 probabilistic SA

  in conjunction with a Defence in Depth (DiD) concept.
  - DiD level assignment according to occurrence frequency

Fusion power plant (FPP) specific DiD concept and PIE needs to be developed

- DiD requires fusion plant specific postulated initiating events (PIE) covering all DiD-Levels
- PIE need to be grouped and assigned to a DiD level targetting to
  - control the event
  - avoid escalation and aggravation
  - mitigate the consequences

Safety objectives applicable from any nuclear installation derived from IAEA standards

- Acceptance targets and acceptance criteria shall follow radiological criteria (dose limits)*
  (BUT: dose criteria are different in magnitude and quality even in EU-Member states)
  Approaches:
  - Quantitative and/or
  - Qualitative
- **But, fundamental fusion specific safety functions must be derived based on a functional approach to meet the radiological and nuclear safety objective.** (requires modification SSR-2/1)

*EU Directive 2013/59/EURATOM, IAEA Guidelines

Example of Plant state and dose limits EU DEMO reactor

- **Assumed of plant state levels for a FPP according to EU-DEMO ***

Lev.	Operational state	Objective	Means	Consequences dose limit**
1	Normal operation	Prevention of abnormal operation and failures including controls	conservative design high quality in construction, operation	Off-site 0.1mSv/a early Off-site 1mSv/a chron. On-site 5 mSv/a
2	Anticipated operational occurrence $f > 10^{-2}$/a	Control of abnormal operation and detection of failures (e.g. Plasma instabilities)	control, limiting and protection systems and surveillance features	Off-site 0.1mSv/a early Off-site 1mSv/a chron. On-site 5 mSv/a (ALARA)
3	Design basis accident- infrequent fault (DBA) $10^{-2} > f > 10^{-4}$/a	Control of accidents within design basis (unlikely events) by safety systems	Engineered safety features and accident procedures, potential radiological release but no off-site countermeasures	Plant shall return to power after inspection, rectification& requalification On-site 20 mSv/a
3*	DBA -imiting faults $10^{-4} > f > 10^{-6}$/a	Control of severe conditions (prevention progression,mitigation of consequences)	Complementary measures and accident management no off-site intervention	**Plant restart not required** Off-site 10mSv/event (early dose)
4	hypothetical events-DEC $f < 10^{-6}$/a	Mitigation of radiologi-cal consequences (release of radioactive materials)	Postulated multiple failure events; measures of emergency preparedness and response	Off-site 50mSv/event (early dose) , limited countermeasures

*Taylor, et. al., Safety and Environment studies for a European DEMO design concept, Fusion Engineering and Design, Volume 146, Part A, September 2019, Pages 111-114, https://doi.org/10.1016/j.fusengdes.2018.11.049.
** dose limits e.g. from Article 9 of Council Directive 2013/59/Euratom

Recommendations for Implementation of Legal and Regulatory Framework for Fusion

fundamental fusion specific safety functions could address

- Radiation sources and their associated transport (tritium, raddiation, ACP
- Mechanisms affecting shielding and confinement function
- Decay heat removal from PFC (needs to be discussed)*

Concept of multi-level confinement of radioactive inventory

linked to DiD concept and separates

- Barrier function for
- Retention function

Both are fulfilling the confinement function.

Approach as in ITER:

Confinement concept has to provide at least two enveloping concentric barriers to ensure the safe confinement

- during operation (thermonuclear core, tritium containing pipes & plant)
- maintenance (blanket, divertor exchange requires vacuum vessel opening)

Does this require a depiction in specific SSG ?

PFC = Plasma facing components (depdending on position and lifetime, shut-down power can reach 1% of nom. power @ EOC, but could be reduced a safety function only)
ACP= Activation Corrosion Products

Recommendations for Implementation of Legal and Regulatory Framework for Fusion

Fusion specific safety aspects -various energy sources challenging safety of different SSC's, as

- Decay heat
- Plasma energy
- Magnetic energy
- Enthalpy of structure and coolants
- Chemical energy (arising von exothermal reactions in accidental case)
- Electromagnetic sources (ICRH, ECRH, NBI)
- (specific fusion systems e.g. using U-Zr as breeder may face criticality arguments)

According to the development level of fusion power plants

- Safety aspects for functional safety requirements of SSC's are formulated
- Safety functions and assignment of importance classes within the (individual) DiD safety concept are described

but

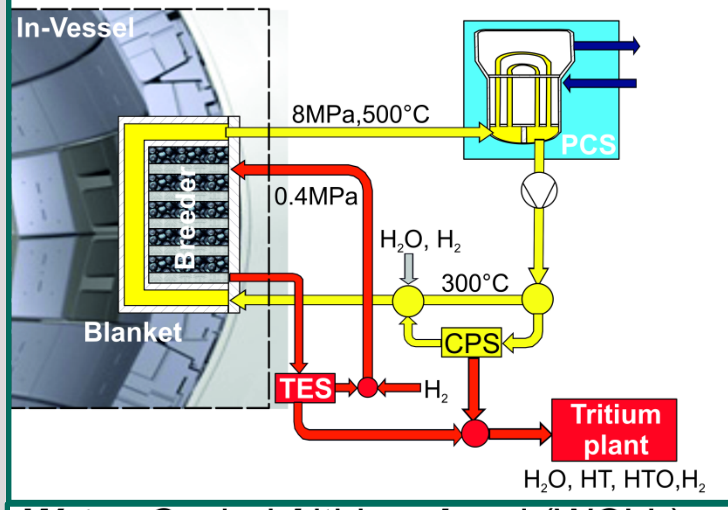
- Guidance documents on SSC design, as well as
- Codes & standards for safety demonstration

are in infancies

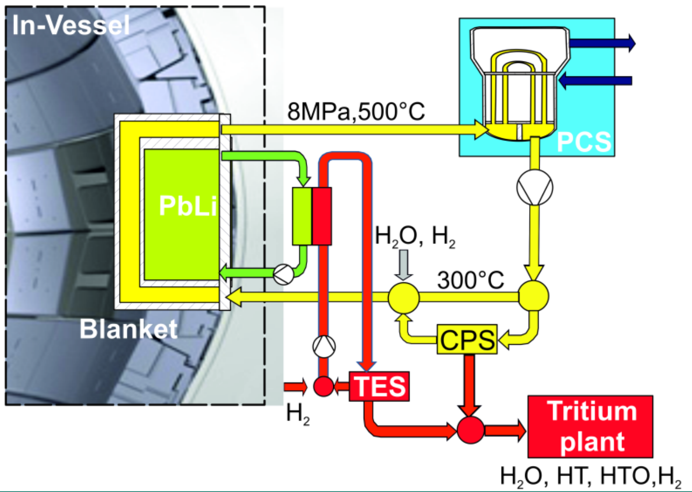
Importance of PFC components - Blanket

- thermonuclear core - Blanket (~83% Power)

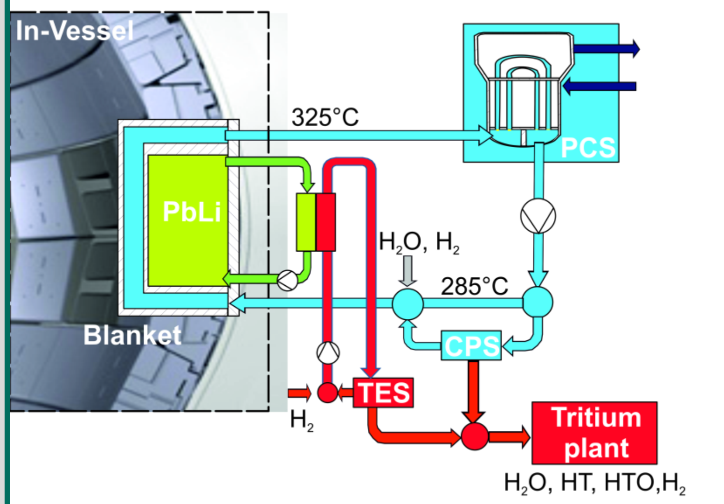
Helium-***C***ooled ***P***ebble ***B***ed (HCPB)



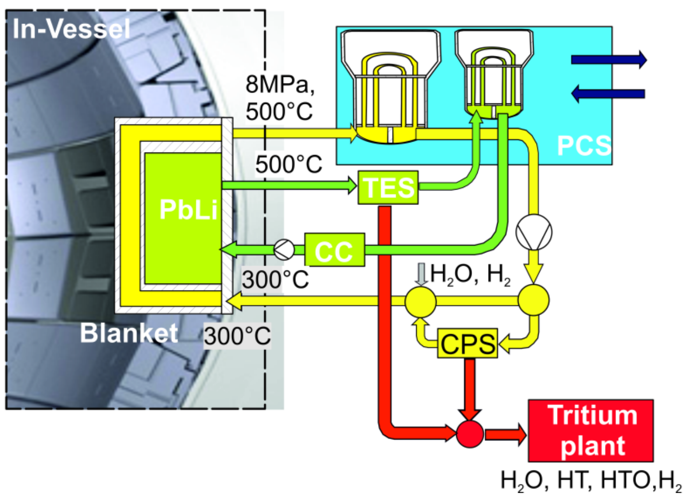
Helium-***C***ooled ***L***ead ***L***ithium (HCLL)



Water-***C***ooled ***L***ithium ***L***ead (WCLL)



Dual-***C***oolant ***L***ithium ***L***ead (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

Action plan for the development of a targeted and proportionate regulatory framework*1 within EU

1. Establish a common legal framework to regulate fusion facilities either by
   - develop a Council Directive like the nuclear safety directive 2009/71/Euratom dedicated to safety of fusion facilities or
   - adapt nuclear safety directive 2009/71/Euratom to scope also fusion facilities
2. Discuss and agree on a defence in depth concept for fusion facilities
   - Applicable plant states
   - Technical acceptance targets
   - Radiological acceptance targets
3. Develop graded approach to be applied to fusion facilities to regulate such facilities commensurate with its radiological hazard potential
4. Develop "Safety requirements for magnetic confinement fusion facilities" with work performed at IAEA to formulate high level safety requirements addressing:
   - Leadership and management of safety
   - Siting
   - Design (general and specific design requirements)
   - Construction and commissioning
   - Operation/Decommissioning
   - Safety demonstration (initial and periodic safety assessments)
   - (emergency preparedness and response)

as derived from Study on the Applicability of the Regulatory Framework for Nuclear Facilities to Fusion Facilities- Towards a specific regulatory framework for fusion facilities . ENER-20-NUCL-SI2.834242 , 2021, Directorate-General for Energy