Aspects of fusion safety considering fission regulations

Past & current safety studies I (focus Europe)

plant specific
- all aspects - operation, maintenance, waste,..
- nuclear installation

principal nature
- fusion power
- struct. material
- coolant
- breeder
- n- multiplier
- PCS
- ........

comparative nature
- plant safety
- concepts

PPCS

SEAFP-1


iter

integral design support
- power plant
- code-validation
- standards (design, licensing, waste,..)
- safety demonstration

WPSAE

ITER

SEAFP-2

SEAFP-99

SEAL

SEAFP-1

principal nature
- fusion power
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- safety demonstration

WPSAE

ITER

SEAFP-2

SEAFP-99

SEAL

SEAFP-1
Past & current safety studies II

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

**Helium-Cooled Pebble Bed (HCPB)**

- In-Vessel
- 8MPa, 500°C
- H₂, H₂O, H₂O, HT, HTO, H₂
- TES
- PCS
- Blanket
- 0.4MPa
- H₂O, HT, HTO, H₂
- Trinitium plant

**Helium-Cooled Lead Lithium (HCLL)**

- In-Vessel
- 8MPa, 500°C
- H₂, H₂O, H₂O, HT, HTO, H₂
- TES
- PCS
- Blanket
- 0.4MPa
- H₂O, HT, HTO, H₂
- Trinitium plant

**Water-Cooled Lithium Lead (WCLL)**

- In-Vessel
- 325°C
- H₂, H₂O, H₂O, HT, HTO, H₂
- TES
- PCS
- Blanket
- 0.4MPa
- H₂O, HT, HTO, H₂
- Trinitium plant

**Dual-Coolant Lithium Lead (DCLL)**

- In-Vessel
- 8MPa, 500°C
- H₂, H₂O, H₂O, HT, HTO, H₂
- TES
- PCS
- Blanket
- 0.4MPa
- H₂O, HT, HTO, H₂
- Trinitium plant

Common features
- EUROFER – structure
- 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 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)

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Fusion Safety in View of Fission regulations | Stieglitz, Wolf, Taylor et al.  
3rd IAEA DEMO Prog. Workshop, Hefei, China, May 2015

_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

- 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

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

Fusion Safety in View of Fission regulations | Stiegitz, Wolf, Taylor et al.

FPP

- 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

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

PWR

- CR, n-poison
- DHR systems
- Multi-stage systems for severe accidents

Fusion Safety in View of Fission regulations | Stieglitz, Wolf, Taylor et al.

3rd IAEA DEMO Prog. Workshop, Hefei, China, May 2015
### 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*

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

---

*INSAG 2010, WENRA2012

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Fusion Safety in View of Fission regulations | Stieglitz, Wolf, Taylor et al.

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3rd IAEA DEMO Prog.
Nuclear power plant safety approach III

Definition of plant state levels in DiD

1 = normal operation
2 = operational occurrence
3 = design basis accident
4 = "severe accident"

acceptable regime

10^2
10
1
10^{-1}
10^{-2}
dose to the public [mSV]

event probability [1/a]
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

<table>
<thead>
<tr>
<th>Dose limits Germany</th>
<th>public: 1mSv/a</th>
<th>worker: 20mSv/a</th>
<th>Evac. dose: 100mSv/a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20µSv/w</td>
<td>2mSv/w</td>
<td>0,3mSv/h</td>
</tr>
<tr>
<td></td>
<td>3µSv/d</td>
<td>0,3mSv/d</td>
<td>0,3mSv/d</td>
</tr>
<tr>
<td>mean nat. dose</td>
<td>1mSv/a</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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

![Graph showing dose to the public vs. event probability]

- BDBA
- DBA
- Anticipated incident
- Bounding accident limit
- Additional safety system
- Enhanced confinement

Gulden, 2012
There are many kinds of safety!!!!

Pathway for consistent treatment ➔ Systematic Safety Analysis (SSA)

![Diagram showing nuclear power plant safety approach]

- Normal operation (mainly governed by radio protection)
- Accidental analysis (radio protection, societal contract)

**INPUT**
- Anticipated plant operation + material
- Source term assessment

**PST** = process source term

**EST** = environmental source term

**Plant Safety Analysis**
- Functional Failure Modes and Effects Analysis (FFMEA/FEMA)

**Dose to public/event**
- (frequency dose)
- Masses waste cat. mSv/y

**Dose conversion factor**
- mSv/y
- man · Sv/y

**Normalization and Classification**
- Nuclide vector operational waste decommissioning waste
- Identification classification
- Management (storage, recycling, treatment/disposal)

**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 adaptations has to be implemented in licensing procedures.

Most percutected 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

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

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

- 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 $\leftrightarrow$ 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=advanced 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
  - 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.
  - 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 $\leftrightarrow$ fission

- 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

International Nuclear and Radiological Event Scale (INES)

- Event severity \( \approx \) ten times greater for each increase in level of the scale

- 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)

*1[www-ns.iaea.org/tech-areas/emergency/ines.asp](http://www-ns.iaea.org/tech-areas/emergency/ines.asp)

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

http://commons.wikimedia.org/wiki/File:INES_en.svg
DEM0 in view of severe accidents II

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

- comparison of DEM0 5kg T with 1.2GW PWR
- Specific potential dose for a MEI, assuming highest release categories, most unfavourable weather conditions and no-counter measures \(^*1\)

<table>
<thead>
<tr>
<th>rad. nuclide inventory [TBq]</th>
<th>FUSION</th>
<th>FISSION (1200MW-generic PWR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium</td>
<td>1.85E6</td>
<td>3.8E6 2.6E5 1.3E5 1.1E3 2.8E6 8.9E6</td>
</tr>
<tr>
<td>specific potential dose rate</td>
<td>1 HTO</td>
<td>6900 1850 1150 500 3 0.2</td>
</tr>
</tbody>
</table>

\(\Rightarrow\) Substantially lower dose rate in FPP

- comparison of a DEM0 (5kg T) with Chernobyl

<table>
<thead>
<tr>
<th>rad. nuclide inventory [TBq]</th>
<th>FUSION</th>
<th>FISSION (Chernobyl- C-Moderated Reactor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium/HTO</td>
<td>1.85E6</td>
<td>1.3E6 2.9E5 2.0E5 850 3.3E6 1.7E6</td>
</tr>
<tr>
<td>spec. potential dose rate</td>
<td>1</td>
<td>2360 2070 1770 390 3 0.05</td>
</tr>
<tr>
<td>acc. release fraction [%]</td>
<td>20</td>
<td>13 4 5 100 100</td>
</tr>
<tr>
<td>spec. potential dose rate by released isotope</td>
<td>1</td>
<td>470 270 70 12 3 0.05</td>
</tr>
</tbody>
</table>

\(\Rightarrow\) Exclusion of INES 6 allows Tritium-release of 9kg !!!

\(^*1\) Gulden, 1993, \(^*2\) Gulden, 1994

<table>
<thead>
<tr>
<th>Isotope</th>
<th>FUSION</th>
<th>FISSION (1200MW-generic PWR)</th>
<th>FISSION (Chernobyl- C-Moderated Reactor)</th>
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</table>
DEM0 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

- Plasma (stored energy)
- Heating systems (none)
- Tritium inventory (stored energy)
- Magnetic energy (stored energy)
- Secondary heat removal system (partially, LOHS ?)
- Station black out (partially)

EUROfusion WPSAE-WP2
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
Unkowns 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
Unkownst 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**

Biological dose rate on cask surface

*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.

- Numerous issues remain open and requires adequate attention.
- Waste management has not been considered.
6. Open issues as identified

Tritium mitigation techniques

- Permeation Barrier

AIM discuss and prepare list of non considered issues in view of DEMO safety
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  Christoph Pistner

- Culham Center for Fusion Energy (CCFE)
  Neill Taylor

- Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit
  (BUMUB) – project sponsor
  Marcus Fabian
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)

Starting H-AVT-Chemistry
Is the ALARA Principle compatible with a Dose Limit Principle?
Dose Concept

Radiologically weighted absorbed dose

- Body dose (equivalent dose)
  - Committed equivalent dose
  - Organ / tissue dose
  - Effective dose
    - weighted sum of organ / tissue doses
    - Committed effective dose
- Dose equivalent
  - Personal dose equivalent
    - Strongly penetrating radiation $H_p(10)$
    - Weakly penetrating radiation $H_p(0,07)$
  - Local dose equivalent
    - Ambient dose equivalent $H^*(10)$
    - Directional dose equivalent $H'(0,07)$

Concept of protection: Dose limits

Concept of monitoring: Dosimetry
Nuclear power plant safety approach VI

- **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 radionuclide inventories
  - Analysis of the incidents / accidents scenarios
  - **Identification of bounding (or enveloping) accidents**
    - Assessment of worst case scenario in view of radiological hazard
  - Early and chronic doses to MEI (=Most Exposed Individual)

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

- Superior safety objectives & goals
- Fundamental safety functions
- Probabilistic success criteria
- Deterministic success criteria

Defence in depth principle
Level 1: prevention
Level 2: control
Level 3: accident management
Level 4: control of severe conditions
Level 5: mitigation of radiological consequences

Risk informed safety requirements applicable to design

* Master logic diagram Gen IV safety approach

Applied in hierarchical from plant to subsystem level (in ITER)
Transferability to DEMO possible
“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)**

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**Top level**

- **basic design**
  - DDD (design description document)

- **System analysis**
  - Accident analysis

- **Postulation of PIE**
  - BoP (Performance)

- **Functional safety basis**
  - confinement,
  - fusion power shutdown
  - Decay Heat Removal (DHR)
  - monitoring, and
  - control of physical and chemical energies

- **Safety Demonstration**

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**Safety objectives**

- Confinement (prevention off-site emergency responses)
- Rad. protection (mitigation of dose limits outside facility)
Consequences for fusion safety concept in transition of ITER ⇒ DEMO

- Definitions safety functions transferrable
- Classification of structure, systems and components (SSC) in safety importance classes (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, H₂-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