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"Radiation Safety-by-Design" Licensing Approach

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OBJECTIVES & OVERVIEW

(Part 1) Describe phenomenological differences that call for a distinct and evolving licensing regime for emerging compact and modern commercial fusion machines

DEFENCE IN DEPTH LEVELS	Levels 1 & 2 for **FPPs** and **NPPs**		Level 3 for **FPPs**	Level 3 for **NPPs**	Level 4 for **NPPs**	Level 5 for **NPPs**	
STRATEGY	Prevention		Mitigation	Mitigation			
PLANT STATE	Normal Operation	Anticipated Operational Occurrences	Design-Basis Incident or Event	Design-Basis Accident	Beyond Design-Basis Accident (no or limited core damage)	Beyond Design-Basis Accident (severe accident)	Post Accident
OBJECTIVE	Prevention of deviation from normal operation	Control of challenging and abnormal operations	Modified or transitional 'control and containment' of radiological inventories	Control of accident progression within design limits	Control of core damage to avoid severe accident	Mitigation to contain radiological material	Mitigation of radiological consequences
MEANS OF CONTROL	Process systems		Process systems	Process systems			Off-site protective actions and monitoring
		Detection & control syst. with operator actions	Detection & control syst. with operator actions	Detection and control systems with operator actions			
				Engineered safety systems			
PROCEDURES	Operation manuals		On-Site incident operating procedures	On-site & off-site emergency operating procedures AND emergency response plans and procedures			
						Severe accident management guidelines	

Fusion specific levels of Defense-in-Depth compatible with IAEA nuclear safety and security glossary and INSAG-10

(Part 2) Demonstrate that existing regulatory frameworks are effective for licensing fusion machines through their fundamental radiation safety standards

10 CFR Part 30 (Byproduct Materials): Sets the conditions for possession and use of certain types of radioactive materials
- Inventories of radionuclides at SSC level
- Maintenance plan & radsafety aspects
- Focus on SSCs involved with control and containment of radiation & radioactive materials
- HT/HTO atmospheric dispersion and exposure pathways leading to dose projections for critical groups

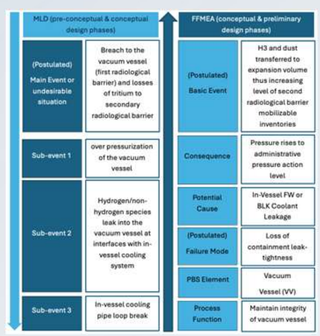
10 CFR Part 20 (Radiation safety): Standards for protecting people from ionizing radiation
- Off-site dose constraints set at 1/10 of public dose limits for H3 releases
- Fuel/Tritium cycle systems and HVAC design performance critical for internal dose management
- Plasma source term (neutrons), shut-down dose rate (activation) and shielding optimization

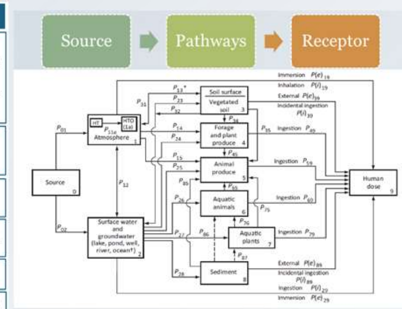
10 CFR Part 37 (Physical Protection): Requirements for physical security of certain categories& quantities of radioactive materials
- Metal impurities (e.g., cobalt in steel) to be avoided
- List is fission-driven and need to be updated for fusion
- Applies mainly for refurbishment during cyclical maintenance & decommissioning activities
- Early engagement and data sharing with Agreement States and US NRC

10 CFR Part 61 (Radwaste management): Licensing requirements for land disposal of radwaste
- Early evidences on novel waste stream/radionuclides key for regulatory improvement
- Technology maturation for recycling approaches is promising and essential
- The recycling of LLW is a global challenge affecting the ANRs and NPP industries, requiring synergistic efforts.

US NRC fusion licensing framework and highlights from 10 CFR applicable Parts (20, 30, 37 & 61) for informing early engagement with Agreement States

(Part 3) Elaborate on "Safety-by-Design" considerations informing design requirements through the integration of radiation safety constraints.





Evidence-based data supporting license application for control and containment of radiation & radioactive materials: e.g., Derived Release Limits of tritium and FMEA on radsafety relevant SSCs

Content

Fundamental Considerations for a **Distinct** and **Agile (Evolving)** Licensing/Regulatory Regime for Commercial Fusion Machines :

i. Differentiating fission and fusion power plants: Implications for fusion licensing regime
ii. The principles of 'Defence-in-Depth' (DiD) as an anchor point to explain the phenomenological differences
iii. Fusion specific code & standards

Part 1: Differentiating FPPs and NPPs (i)

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Key Statement

NPPs Safety analysis rules (DSA, PSA) and integration into safety assessment developed & refined over decades of operating experiences based on radiological risk profiles specific to the phenomenology (reactor behavior) and radiological inventories involved.

Facts

- Conventional nuclear plants maintain substantial inventories of uranium fuel (tens of metric tons), if, significantly damaged, has the potential to lead to severe on-site and off-site consequences.
- Fusion systems contain at most a few grams of mobilized fuel in the active reaction zone .
- Circulating fusion fuel can be quickly redirected into multiple, independent containment or safeguard volumes in the event of abnormal or challenging operating conditions
- The mobilizable portion of the tritium fuel cycle inventory may be as low as 300 to 700 grams (D. Clark et al., 2025), which, under certain site conditions (according to the CSA N288 standard model), corresponds to a dose close to the dose limit for the public (1 mSv) if released off-site.

Main Implication for Fusion Licensing Regimes

A pragmatic and practical, technology-neutral, approach must be used for the analysis and assessment of radiation safety, an approach that is unbiased and does not start from premises that are foreign to its own phenomenology, such as those established for existing nuclear power plants .

Part 1: Fusion-Specific Defence in Depth Levels (ii)

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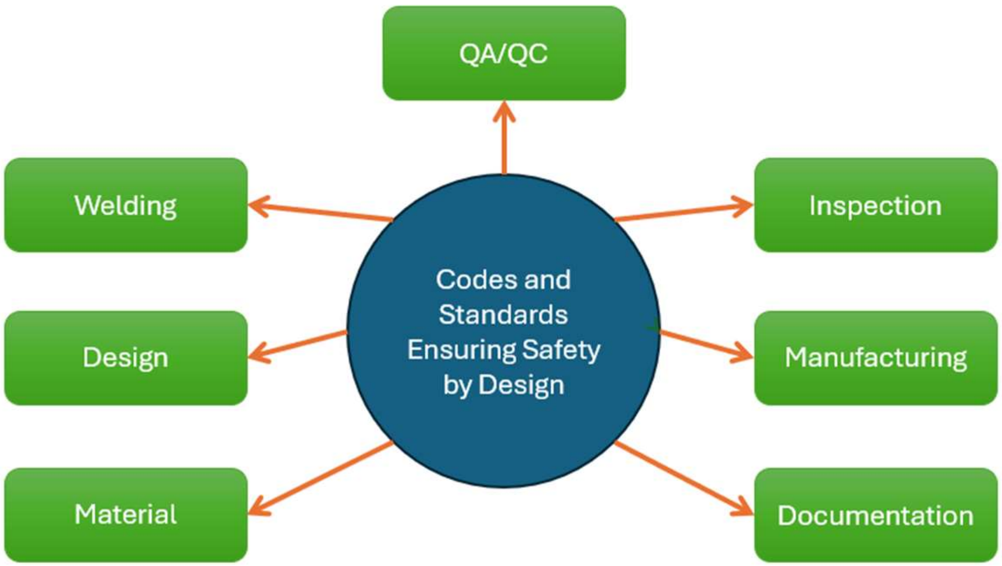
Part 1: Fusion specific codes and standards(iii)



Implications for fusion-specific codes & standards

- Dedicated quality system tailored to fusion.
- Framework evolving with operating experience and rooted in robust and widely understood baseline to facilitate engagement with the supply chain

Facts

- Safety profile of fusion machines differs significantly from fission reactors
- fission codes such as ASME Section III Divisions 1, 2, 3, and 5, along with NQA-1, (ASME, 2025a) unsuitable for fusion applications.
- Intended to address the fission unique failure modes, operational conditions, and safety considerations.
- Emphasizes high-integrity pressure boundaries and components to provide assurance reactor can maintain the configuration of the fuel and its control and moderating reactor temperature
- Attempting to repurpose parts of fission-oriented codes and standards for fusion results in a misapplication of resources and incomplete coverage of fusion-specific needs

Content

Existing regulatory frameworks are effective for licensing fusion machines through their fundamental radiation safety standards :

i. The US NRC model delivered by Agreement States

Part 2: Licensing Framework in USA (i)

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Highlights from Parts of volume 10 of Code of Regulation (Energy) applicable to fusion machines:

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Content

Elaborate on “Safety-by-Design” considerations informing design requirements through the integration of radiation safety constraints:

i. Calculating Derived Release Limits for tritium
ii. Identification of radiation safety constraints for informing SSC design requirements

Part 3: Derived Release Limit for Tritium (i)

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Approach to Regulating Routine Releases

- It is possible for any nuclear facility to have routine releases which are regulated under their operating license
- It is desirable to have a numerical value for allowed releases consistent with the public dose limit as a basis to compare against release and environmental monitoring
- One approach is to use Derived Release Limits (DRLs)

Adapted from CSA N288.1-14 (2014)

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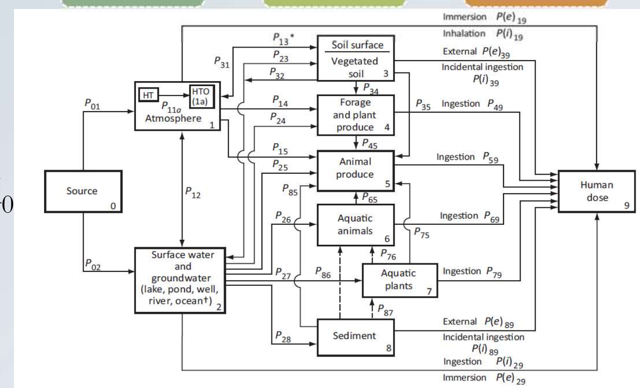

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Environmental Transfer Model

The Advantage

- DRLs are a systematic and defensible way to verify compliance with public dose limits
- Based on source, receptor and pathways
- Use site-specific parameters when possible
- Calculate DRLs before a facility operates
- Perform environmental baseline study
- Environmental monitoring program is used to verify releases are below DRLs
- Can be readily updated if site-specific or input parameters change
- **The model has been validated with decades of CanDU operations**

The Concept

- **You calculate the dose per unit release using activity in compartments (X) and transfer parameters (P) between compartments**
- **The DRL is the ratio of the dose limit (i.e., public dose limit) to the dose per unit release for all pathways considered**

$$DRL = \frac{Dose\ limit}{\left[\frac{X_9}{X_0}\right]} \quad \frac{Bq}{s} \qquad \frac{\frac{Sv}{yr}}{\frac{Sv}{yr}/\frac{Bq}{s}}$$

Part 3:Integration of RadSafety Constraints (ii)

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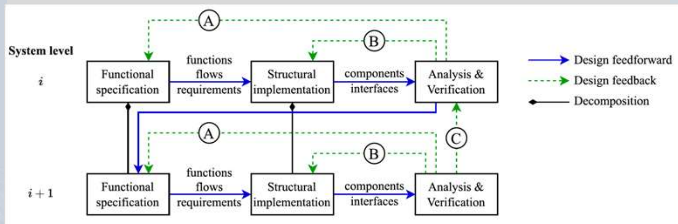
Design feedback flow, from analysis to functional specification of PBSs.
(source: *T.F. Beernaert and al., 2024, www.elsevier.com/locate/fusengdes)*



- ✓ Provides a technology-neutral approach to identifying and integrating radiation safety constraints in early design phases
- ✓ Flow of material and information at key system interfaces
- ✓ Enable early safety analysis without waiting for detailed design elements
- ✓ Represents an ideal model for synergy between physics, engineering, and radiation safety groups for developing an integrated list of PBSs requirements.

Master Logical Diagram input for VV at Pre-conceptual Design (generic example adapted from SEAFP report, 1995)

MLD (pre-conceptual & conceptual design phases)	
(Postulated) Main Event or undesirable situation	Breach to the vacuum vessel (first radiological barrier) and losses of tritium to secondary radiological barrier
Sub-event 1	over pressurization of the vacuum vessel
Sub-event 2	Hydrogen/non-hydrogen species leak into the vacuum vessel at interfaces with in-vessel cooling system
Sub-event 3	In-vessel cooling pipe loop break

Functional Failure Mode Effect Analysis input for VV at Conceptual Design (generic example adapted from SEAFP report 1995)

FFMEA (conceptual & preliminary design phases)	
(Postulated) Basic Event	H3 and dust transferred to expansion volume thus increasing level of second radiological barrier mobilizable inventories
Consequence	Pressure rises to administrative pressure action level
Potential Cause	In-Vessel FW or BLK Coolant Leakage
(Postulated) Failure Mode	Loss of containment leak-tightness
PBS Element	Vacuum Vessel (VV)
Process Function	Maintain integrity of vacuum vessel

Integrated system engineering requirements addressing regulatory (radsafety) and asset protection constraints

- ➢ Provides basis for reliable control & containment of radiation/radioactive material in conjunction with data from neutronics (activation calculation), dose projections, and shielding & HVAC design
- ➢ SSCs all designed with system engineering requirements addressing all constraints
- ➢ Discussed iteratively with TN regulator system by system
- ➢ Integration of Export-Import Control Regs compliance measures in parallel
- ➢ Provide essential information for validating licensing compliance criteria

Next Steps and Regional Impact

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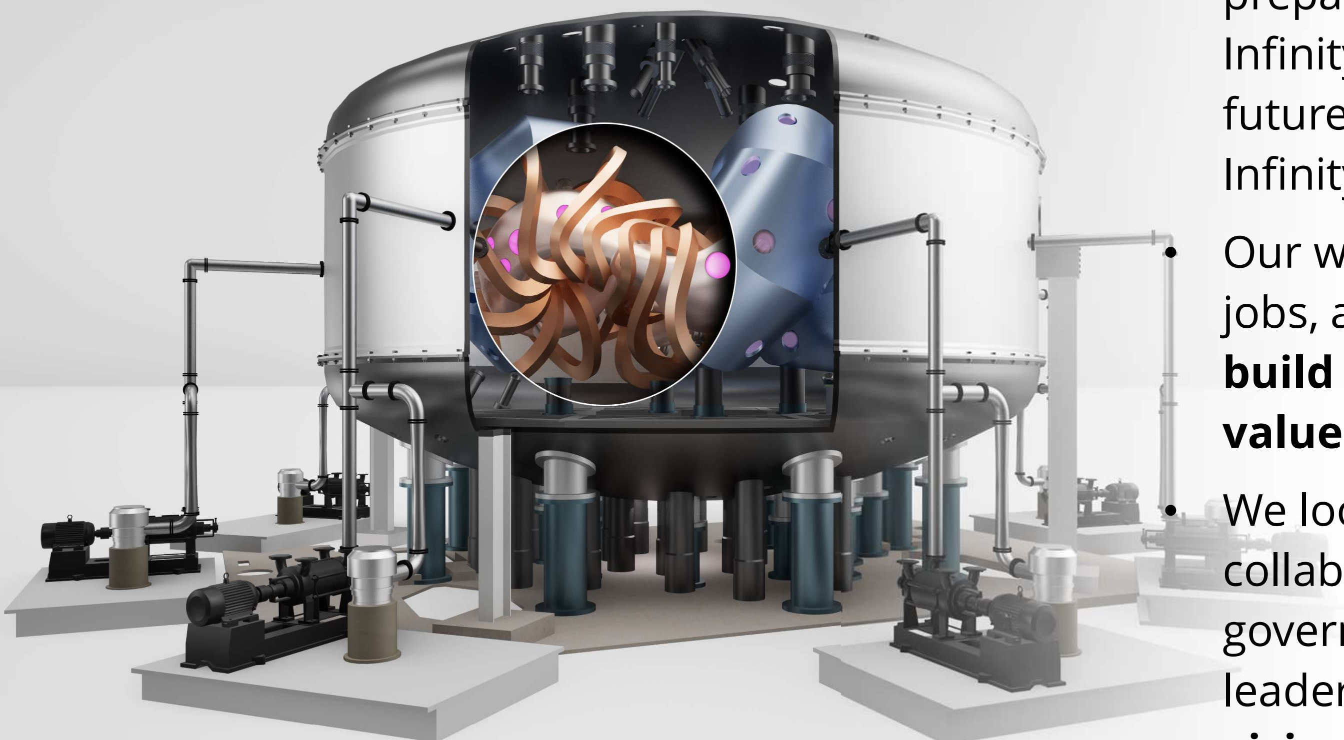

- In partnership with TVA, we are preparing for construction of Infinity One and planning for our future fusion power plant, Infinity Two.
- Our work will create high-quality jobs, attract investment, and **build long-term economic value in the region**.
- We look forward to continued collaboration with industry, government, and community leaders to **realize this shared vision**.