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Licensing Qualification Issues for the Fusion Component Technology Facility (CTF) and DEMO

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Outline

- Qualification and Licensing
  - Definitions
  - What, why and how?
- Hazard Comparisons: Fusion, Fission, other technologies
- Fusion Safety Function: Radiological Confinement
- ITER Safety Strategy
- Impact on Safety Strategy on the Component Technology Facility (CTF) and DEMO In-vessel Components
- Approach to Regulatory Approval
- Nuclear Design Codes
- Summary

Equipment Qualification

- Components and systems are qualified in all engineering endeavors
- In nuclear systems, the activities that comprise the qualification have two parts:
  - Design/operational validation: Establishment of the operating window and associated operating margins, for the system, ensuring it will function as designed (e.g. heat extraction, tritium behavior, reliability, temperatures, stresses, etc) - *more of an investment protection flavor*
  - Licensing aspects: Providing information needed to support safety analysis or licensing basis for the facility
    - Source terms, failure mechanisms if important, failure rates
    - System behavior under off-normal conditions
- In this talk I will focus more on the licensing aspects

What needs to be licensed?

- All facilities will need to obtain regulatory approval in the US
  - The license from the safety aspect is in large part focused around providing an adequate safety case (e.g. acceptable risk to the public and to workers)
  - CTF would be regulated by DOE
  - DEMO is less clear, perhaps DOE or perhaps Nuclear Regulatory Commission (NRC)
  - Much of the licensing activities are related to safety issues/concerns
    - Safety analysis (source term, accident identification and consequences)
    - Validation of safety methods
  - Some of the licensing activities are related to design verification
    - Commissioning tests of the facility to verify behavior of key components and interaction among components
    - Surveillance program to verify shielding

Qualification/Licensing: Fission vs. Fusion

- There are important differences in the objectives for qualification and licensing for fission compared to fusion
- These are related to
  - The difference in risks of the two systems
  - The difference in safety strategy of the two systems
- What needs to be qualified, how you qualify it (depth and rigor), and why you qualify it are very different

The technical differences between fission and fusion must be understood

- Radioactive inventories in low activation fusion designs have a lower radiological hazard than fission inventories by 1 to 2 orders of magnitude
- Releasability of fusion activation products is lower than releasability of fission products
- Fusion has significant inventories of tritium bu fission does not
- Radioactive inventories in fusion are more distributed than in fission reactors
- Energy sources are more distributed in fusion than in fission (e.g., magnets, decay heat, chemical energy and plasma energy)
- Different decay heat removal requirements - energy density lower and more means to passively remove decay heat in fusion than fission
- Plasma control/shutdown is not like PWR criticality control/reactor shutdown system, neither in required timing nor consequences of failure to shutdown
- Radiological hazard of wastes from a low-activation fusion plant are much less than a fission plant and similar to that of a coal plant of equal thermal power after 100 years

Conclusions: how and why things were done for fission may not be the correct way to do it for fusion!

Comparison of Hazard Characteristics of Different Technologies

HAZARD CHARACTERISTICS	CHEMICAL PROCESS	NUCLEAR FISSION	SPACE	*FUSION*
Single, Concentrated Hazard Locations	Sometimes	Always	Always	*Tokamak*
Distributed Source of Hazard	Almost Always	Reactor Only	Rarely	*Always, Tokamak and Fueling Systems*
Chemical Toxicity	Often	Rarely, Radiation Effect Dominates	Always, but Secondary to Fire and Explosion	*Sometimes C, Be, W, V Dusts*
Fires	Often	Only as a Result of Core Melt Effects	Major Hazards	*Sometimes, if LMs are used*
Explosions	Often	Only As They Result from Core Melt Effects	Major Hazards	*Potentially; H_2, Cryogen, or O_3 Explosions, and Magnet Arc Events*
Radioactivity	Rarely	Always	Payload Dependent	*Always*
Changing Configuration or Operating Mode	Not Important Except in Transportation	Not Important Except in Transportation and Spent Fuel Pool	Important	*Important; Bakeout and Maintenance could lead to Releases*
Human Error	Important	Important	Important	*Important*

Original Table is taken from B. J. Garrick, "The Approach to Risk Analysis in Three Industries: Nuclear Power, Space Systems, and Chemical Process," Risk Management, Expanding Horizons in Nuclear Power and Other Industries, Hemisphere Publishing, 1991, pages 173-181. We added fusion (in italics) for comparison.

Safety Functions for Fusion Facilities

Public Safety Function:
Confine Radioactive & Hazardous Materials

Potential Safety Concerns:
- Ensure Afterheat Removal
- Provide Rapid Plasma Shutdown
- Control Coolant Internal Energy
- Control Chemical Energy Sources
- Control Magnetic Energy
- Limit Routine Airborne and Liquid Radiological Releases

Worker Safety Function:
Control of Operating Hazards

- Limit Radiation Exposures to Workers
- Limit EM Field Exposures
- Control Other Industrial Hazards

From DOE Fusion Safety Standard (DOE STD 6002 96)

[STD 6002 was affirmed in DOE Facility Safety Order 420.1A (May 2002)]

Requirements for Qualification of Radiological Confinement Boundaries

(from DOE Fusion Safety Standard DOE-STD-6002)

- Radioactive and hazardous material confinement barriers of sufficient number, strength, leak tightness, and reliability shall be incorporated in the design of fusion facilities to prevent releases of radioactive and/or hazardous materials from exceeding evaluation guidelines during normal operation or during off-normal conditions.
- In the design of confinement barriers, the principles of redundancy, diversity, and independence shall be considered. Specifically, in the case of multiple barriers, failure of one barrier shall not result in the failure of another barrier if evaluation guidelines could be exceeded. Redundancy and diversity shall be considered in the total confinement strategy if new or untested components of a barrier are used.
- The design basis for confinement barriers shall take into account identified postulated initiating events and extreme loadings and environmental conditions due to anticipated operational occurrences and off-normal conditions as identified in the safety analysis. In addition, consideration should be given to the provision of features for the mitigation of consequences of conditions outside of the design basis to meet the fusion requirement of no off-site evacuation for fusion facilities.
- Consistent with the safety analysis, the design of confinement barriers shall specify an acceptable global leak rate under off-normal conditions taking into account the vulnerable inventories of radioactive and hazardous materials and the potential energy sources available to liberate such inventories. Any confinement barrier, including equipment, penetrations, seals, etc. relevant to the establishment of an acceptable leak rate, shall be designed and constructed in such a way as to enable initial and periodic leak testing.

Basic ITER Safety Strategy

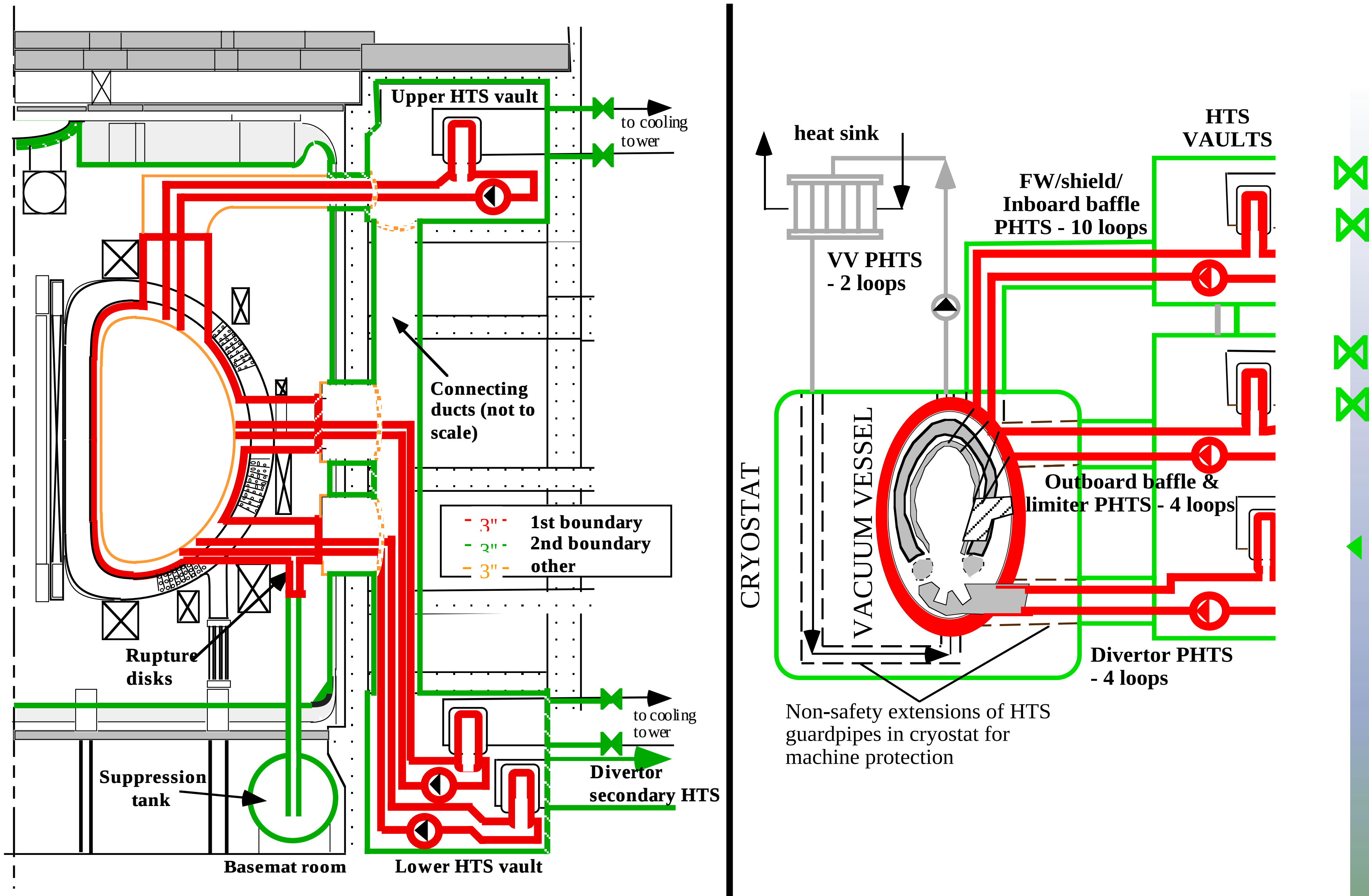
- Implements project objectives ...”to operate safely and to demonstrate safety and environmental potential of fusion power”
- Recognizes ITER is an *experimental fusion nuclear* facility
- Must tolerate uncertainties associated with entering a new plasma physics regime and use of materials with 14 MeV neutron damage
- Must allow maximum design and operational flexibility

ITER Safety Approach

- Minimize safety burden on plasma physics, plasma control, diagnostics, divertor, first wall shield/blanket, and magnets
- Shift safety burden to vacuum vessel, cryostat, heat transport systems, and tritium plant
- Makes safety case more demonstrable because safety is implemented using proven technology

US was heavily involved in the development of this strategy and approach

ITER EDA FDR Confinement Strategy



Radiological Confinement is the Key Fusion Safety Function

- Need to prevent release of radiological inventories to the public
- The use of the double walled vacuum vessel and cryostat has many attractive features
  - Away from radiation and plasma damage
  - Robust structures needed to accommodate fusion stresses anyway
  - Mitigates hazards as close to the source as possible
- ITER safety results suggest that risk is dominated by bypass scenarios in which the confinement boundaries in penetrations are threatened and degrade
  - Assume there are 100 penetrations, and each of the two boundaries in each penetration has a reliability of 10^{-3}/demand (which is optimistic). The probability of failure of two confinement boundaries, independently, in a given penetration is 10^{-6} and the probability of failure of the boundary in any of the 100 penetrations is ~ 10^{-4}, which must be considered in the safety analysis.
- Regulators will be interested in the penetration issue and in ensuring that all threats to the barriers have been recognized and treated in the design
- REGULATORY PRECEDENT SET BY ITER WILL BE CRITICALLY IMPORTANT FOR FUTURE MACHINES

Safety Strategy for CTF and DEMO

- CTF
  - Hazards are similar to ITER
  - Uncertainties still exist but perhaps more on the technology side than on physics
  - Need robust safety envelope to provide maximum operational flexibility
  - Still an experimental machine
- DEMO
  - Will build on ITER experience
  - Hazards still similar to ITER
  - Uncertainties reduced but still probably some exist
  - Still need a robust safety envelope to positively demonstrate the technology
  - Still has an experimental flavor

The ITER safety strategy still makes sense here for both machines.

MFE vs. IFE

- General safety approach and licensing for MFE should be adopted for IFE.
- Need two strong/robust boundaries around radiological inventory in chamber. Still unclear how to implement in an IFE design of either a CTF or DEMO.
- Confinement buildings have been used in previous IFE studies as the second strong barrier
  - The large size of the building could make leak testing even a moderate leak-rate building a costly operational burden
  - Use of the building to get the needed confinement goes against conventional safety practice of confining the hazard as close to its source as possible
  - Part of radiological confinement is to minimize the spread of radioactive contamination in the facility. Having a large area of contamination can be costly in terms of $, maintenance time, and personnel exposure
- Previous IFE design studies did not consider all pathways for release. Penetrations are a key concern as release pathways
  - Where is the boundary in the penetrations -- could imply a very large nuclear boundary
  - Are there natural barriers in the vacuum system lines (e.g. valves) that could be used?
  - Perhaps use of fast-acting, redundant valves in the penetration lines? Will they work as expected in the environment? Can such valves be put in the line given the other functional requirements of the penetration (e.g., vacuum pumping, beam propagation, shielding)
  - The use of open valves that close quickly upon detection of an off normal event does not provide active containment all of the time, only in an off-normal event.
- Not considered an insurmountable problem. Interaction with designers is needed when conceptual designs of such facilities commence

Impact of ITER Safety Strategy on In-Vessel Components

- The key safety related components are the confinement barriers: the VV and cryostat rather than the in-vessel components
- Assume that decay heat can be removed passively, but include an active system plumbed to the vacuum vessel as backup
- In-vessel components will have less safety significance (direct result of the safety strategy to reduce burden on in-vessel components)
  - Threat from a failure of the in-vessel components would be considered in the safety analysis
  - If failure of in-vessel components will not result in a public safety impact (which I think would be true and could be ensured by good design), then its safety significance is lower than confinement boundaries in the facility
  - Shielding issue is not as critical and can be verified via a surveillance program during operation (and is probably more an issue of adequate shielding around the penetrations than the bulk vessel)
  - If bulk shielding is somewhat less than anticipated, what is the impact? I see no direct public or worker safety issue. There could be a performance issue that would reduce the lifetime of the magnets but that has no safety impact per se.

Fusion Experimental Machines and Their Impact on Regulatory Approval

- A key aspect for obtaining regulatory approval is the depth and rigor of the safety analysis
- Experimental fusion machines like CTF and DEMO will be hampered compared to fission because regulators expect:
  - Well developed computer codes used for analysis
  - Codes validated with data different from that used to develop the codes/models
  - Uncertainties in calculations quantified
- Current fusion database is probably inadequate.
- The lack of rigor in safety analysis will lead to a conservative staged approval process by the regulator
- ITER regulatory approval and operation will help by setting a *fusion* precedent and qualifying many systems in the plant (e.g.,pellet injection, pumping, heating, diagnostics)

Verification and Validation Requirements
(from the DOE Fusion Safety Standard DOE-STD-6002)

- Verification and Validation
  - The applicability of the design and safety analysis methods shall be verified and the methods validated. Furthermore, an equipment qualification procedure shall be established for items performing public safety functions to confirm that the equipment is capable of meeting the safety functions for the facility while subject to the environmental conditions (e.g., vibration, temperature, pressure, jet impingement, radiation, humidity, chemical attack, magnetic fields) existing at the time of need. Experimental data used in the design process or in the safety analysis shall undergo formal validation.

Requirements Related to Experimental Use
(from the DOE Fusion Safety Standard DOE-STD-6002)

- Fusion facilities, especially those considered *test* facilities, may by their nature include experimental component modules or equipment. Potential faults in experimental equipment shall be addressed as part of the facility safety analysis. The flexible nature and changing states of the systems also require special precautions to be taken in the design and operation to minimize the effects of human error.
- Experimental equipment shall be designed so that in each operational state it cannot cause unacceptable consequences to the facility, other experiments, workers, or the public. Specific considerations include but are not limited to:
  - Factors in experiments that could cause a breach of any confinement barrier;
  - Factors in experiments that could adversely affect items performing safety functions ;
  - Factors in experiments that could create additional radiological, hazardous, chemical, or other risks;
  - Factors relating to interactions with other experiments or operational activities.

Approach to Regulatory Approval

- Expected to be similar for CTF and DEMO
- Phased approach during facility commissioning
- Verification of design and assumptions in safety analysis during initial startup if data were not available prior to facility operation
- The approach basically starts with restrictive/conservative operating and safety envelopes that are gradually relaxed as more confidence is gained by regulators and facility operators about the performance of CTF and/or DEMO
- Precedence for this approach in light water reactors and other DOE nuclear facilities.
- Reasonable to expect that this approach will be used for ITER or any next step

What design codes are needed?

- Design codes are used as a method to provide structure to design (via rules) and document a minimum level of structural safety margin in the component
- More stringent rules developed for nuclear reactor components (ASME Section III) than for non-nuclear components (ASME Section VIII)
- The difference in the rules was recognized to be related to the inherent hazard/risk of the different facilities
- There are significant cost and schedule issues associated with the development of a code case for materials, and with the production (QA) and inspection of the materials in-service

Code case for ferritic steel for fast reactors: a bad analogy

- It took over ten years to get a code case for fast reactor ferritic steel cladding
- This example is not applicable to fusion because the role of the cladding in a fast reactor is not the same as in-vessel structures
  - Tightly coupled neutronic core with small changes in core geometry can lead to reactivity insertions
  - Failure of the cladding could lead to core reconfiguration and the associated reactivity effects
  - Our safety assessments from ITER, ARIES, and APEX indicate that failure of in-vessel components should not have anywhere near as severe consequences as fission cladding failure

If fusion facilities can be shown to have no significant off-site public safety consequence (by meeting the no-evacuation criteria), do we need to use nuclear grade codes for the confinement boundaries and/or the in-vessel components?

- The decision is largely one between the regulator and the owner/operator of the facility. Investment protection issues may be a stronger driver than safety here.
- Given the safety strategy presented earlier,
  - The use of *nuclear grade* codes for the VV and cryostat (ASME Section III) may not be warranted because of the lower hazard compared to fission. Chemical vessel codes (ASME Section VIII) may be more appropriate.
  - The need to qualify in-vessel components from a safety perspective may be lessened, even at the DEMO stage, because of the lower impact of their failure on safety of the plant
- Again, ITER regulatory precedence will be important here

Summary

- Licensing is needed for any future facility (e.g.,ITER,CTF,DEMO)
- Qualification has both design verification and safety aspects
- Fusion is not the same as fission and thus the approach to qualification should be different. Requirements have been defined in the DOE Fusion Safety Standard.
- The international safety strategy developed for ITER suggests that the confinement boundaries (vacuum vessel, cryostat and associated penetrations) are most important for the safety case.
- Failure of in-vessel components can be accident initiators but should be accommodated by the design and are not analogous to failure of fission reactor cladding. Thus, their overall importance has decreased from a decade ago due to the evolution in safety design philosophy indicated in the US DOE Fusion Safety Standard and implemented in ITER.
- Given the lower risk of a fusion facility, it is not clear that nuclear grade design codes must be used in design of components. Non-nuclear grade codes may be acceptable.
- Given the experimental nature of both CTF and DEMO, a staged approach to regulatory approval is anticipated.
- ITER will provide an important fusion precedent for the safety strategy outlined here, the approach to regulatory approval and qualification of many fusion components.