ARIES Safety-Related Components and Nuclear Grade Requirements

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Safety-Related Components

- **By definition**, these components should implement safety function, such as:
  - Confine radioactivity
  - Limit public/workers exposure to radiation.

- **Concerns**:
  - Safety-related components are only well defined for DOE experimental facilities and ITER
  - No regulatory guidelines to follow for ARIES commercial power plants
  - Options:
    - Follow existing **NRC** rules for fission plants:

      ⇒ Meet ASME* standards for nuclear grade components

      (Section III (for Boiler and Pressure Vessel) is very costly and restrictive)
    - Develop **new fusion-specific safety standards for fusion power plants**, following 1990s and 2006 DOE Fusion Standards for DOE facilities

      (may take long time to gain ASME approval and to adopt by NRC)
    - Consider **ITER** safety precedents for licensing in France

      (may not be applicable to US fusion power plants).

- **Near-term solution:**

  Three DOE Fusion Standards could provide guidance. They are enforceable for US experiments (NIF, NSTX, DIII-D, FIRE, etc.), but not for commercial power plants.

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* ASME: American Society of Mechanical Engineers.

Safety-Related Components (Cont.)

- **Numerous components in ARIES-DCLL design. Which component is safety-related?**

FW (with W armor?)
Blanket
Shield
Manifolds

Cooled with 80 MPa helium @ 300-450^{o}C

Double-null W divertor

There is no piping design code for 80 MPa helium at 450^{o}C.

Fission gas reactor experts are trying to work on that, but it takes long time).

Flowing LiPb @ 500-700^{o}C. There is no liquid metal piping design code for 500-700^{o}C operations

Water cooled VV (double-walled structure)

TF, PF, and CS Magnets

Plasma heating and current drive systems
PHTS: cooling pipes, pumps, valves, HX, etc
Ports

Cryostat, cryo system

Over-pressure and LiPb tanks

Hot Cells and bioshields
Tritium extraction, fueling, storage systems
Radioactive waste storage

Others?

NRC Standards

NRC Standards for Fission Plants

- **ASME Codes:**
  - **Section III** (Nuclear Design Code for Boiler and Pressure Vessel):
    - Design by analysis
    - Tells how to design, fabricate, and inspect components with required calculations and material strengths
    - Provide directions about best fabrication means
    - Strong on inspection during fabrication and operation using Section XI for In-service Inspection (e.g., every 10-year nondestructive evaluation of pipe welds).
  - **Section VIII** (Design Code for Pressure Vessels):
    - Has provision for subatmospheric vessels
    - Design by rule, not by analysis*
    - Inspections required during assembly, but does not specify inspections after operation.
  - For coolant **piping**, ASME:
    - Dozen different piping codes
    - DOE-STD-6003 and ITER prefer B31.3 that deals mainly with water, but addresses other fluids (e.g., Category M for hazardous fluids that are chemically toxic or pose hazards to personnel or public)
    - Other ASME piping codes deal with refrigerants, fuel gases, coal-plant boiler water, etc.

- ASME Section III N-stamp vessel for nuclear use could cost 10 X (or more) than ASME Section VIII R-stamp vessel for chemical industry use.

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* Prescriptive rules written for different applications may not apply to fusion. For example, highest stresses in some fusion components could be electromagnetic, not fluid pressure stresses. Designing component to formal rules requires much design analysis and documentation, much lead time, and much regulator review time, costing high $.

NRC Standards for Fission Plants (Cont.)

- **Nuclear grade components**:
  - Not tied to specific dose criteria
  - Not tied to whether system is active or passive
  - Concerns:
    - High cost of N-stamp components (4 times or more) due to:
      - Extensive quality assurance standards (big cost item)
      - Stringent testing requirements
      - Complete traceability of items from raw material to finished product (paper work can cost more than item!):
        - » **Material** constituents must meet ASME specs and impurity level, with documentation
        - » **Designers** should follow Section III rigorous design rules, use FEA, and analyze it exhaustively, with documentation
        - » Plans drawn for **fabricators,** with documentation
        - » Fabricator has "hold points" to allow inspection, with documentation
        - » Welding must be performed by **Certified Nuclear Welders**, inspected, radiographed, and documented
        - » After assembly, the vessel is pressure tested to ~125% pressure, test is witnessed by **Certified Inspector**, and documented
        - » If all documentations, inspection, and pressure test results are satisfactory, component receives N-stamp status and is documented.
        - » Documentation is kept on file for the life of the vessel
    - Stringent in-service inspection. Inspection results are documented and kept on file.
  - Insurance company demands all documentations to prove components are well built.
- **N-stamp suppliers** (such as BWX Technologies Inc., Fluor Corporation, etc.) must receive nuclear accreditation certificates from ASME to supply components for nuclear facilities (such as pressure vessel, piping, valves and safety-related equipment).
- DOE self-insures their fusion **experiments** (TFTR, DIII-D, NSTX, etc.), using spirit of **ASME Code Sections III or VIII** . No N-stamp for DOE experimental facilities.

Applying NRC Standards to ARIES

- Which ASME Section should be applied to safety-related components of ARIES? Section III, VIII, or new code to be developed for fusion?

  A: New fusion-specific code to be developed, according to DOE Fusion Standards.

- Is N-stamp required for all ARIES safety-related components ?

  A: Unknown.
  Present Federal Laws state ASME Section III for nuclear reactors.
  ASME Section III may not be appropriate for fusion VV.
  Similar regulations should be written for fusion.

- Could nuclear facilities (such as ARIES) use **off-the-shelf** commercial items for safety-related components?

  A: No, unless OTS items meet NRC requirements for safety components.
  Plant owner/operator can pay for testing OTS components by independent testing agency to prove it and make their case to regulators.
  Or, plant can simply purchase N-stamp components (quicker and probably cheaper).

- Will GEN-III&IV components be N-stamp?

  A: Some will be, but designs are optimized for fewer number of components to bring down:
  - Construction time
  - Construction cost
  - Operating costs (less inspections and tests on fewer components), offering advantage to pay loan quicker.

How do we View our Future Involvement with NRC?

- Will NRC require fusion to fully adopt all rules and regulations inherent with present fission design basis?
- Do we expect NRC to adopt **new** fusion-specific Code that is more consistent with our fusion design requirements?
- Will ASME develop guidance document for fusion power plants and make it part of ASME Code?
- Do advanced fission designs (GEN-III and IV) have applicable codes that are more lenient with regard to QA programs (ASME Section III, etc.)?

  A: No, they made designs simpler with fewer safety-related components, so QA does not cost as much.

DOE Fusion Standards

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DOE Fusion Standards

- **Three DOE reports** provide "requirements" and "guidance" for Safety of Magnetic Fusion Facilities:
  - DOE-STD-6002-96 (22 pages on requirements)
  - DOE-STD-6003-96 (213 pages on guidance for implementing the requirements in large facilities, such as ITER)
  - DOE-HDBK-6004-99 (169 pages on additional guidance for fusion design).

- Standard oriented toward **regulation in DOE environment** as opposed to regulation by other regulatory agencies, such as NRC. However, authors strived to make DOE requirements congruent with NRC rules.

- Reports identified **need to develop fusion-specific codes** and requirements for "items performing safety functions." Justification based on low hazard of fusion facilities (as demonstrated by meeting the no-evacuation criteria) should allow designing to fusion-specific standards, rather than N-stamp.

DOE Fusion Standards (Cont.)

- **Safety-related structures, systems, and components** (SSC) implement two categories of safety functions related to:
  - Public safety during normal operations **and** off-normal conditions
  - Worker safety.

- **Public safety** (related to confinement*) requires:
  - Providing rapid plasma shutdown
  - Ensuring decay heat removal
  - Controlling coolant internal energy
  - Controlling chemical energy sources
  - Controlling magnetic energy
  - Limiting air and water discharges from facility.

- **Worker safety** (related to worker hazards and routine releases) requires:
  - Limiting occupational exposure to radiation
  - Limiting exposure to electromagnetic fields
  - Controlling other industrial hazards and hazardous materials.

- **Safety analysis should demonstrate:**
  - Fusion design is tolerant to failures
  - Design basis event does not damage confinement barriers
  - Design provides high level of protection for public and workers

* Confinement is a barrier that surrounds radioactive hazardous materials designed to prevent or mitigate the uncontrolled release of these materials to the environment.

DOE Fusion Standards (Cont.)

- Structural design considerations:
  - **Vacuum vessel** can be designed to:
    - ASME **Section III** (for designing of thick-walled vessels (e.g., 6-8 inches thick) for high safety factors in holding internal pressure for LWR pressure vessels), **or**
    - ASME **Section VIII** (that has design guides for vessels at subatmospheric pressure).

- Complex nature of many fusion components may require specific analysis under alternate design rules of Section III or VIII (DOE-HDBK-6004-1999).

- Actual stamping of components designed, fabricated, inspected, and tested to ASME Section III or VIII is not addressed in DOE report and considered to be a decision between owner, fabricator, and controlling authority (NRC).

DOE Fusion Standards (Cont.)

- **Safety-related SSCs*** include:

  Primary environmental monitors and portions of process systems, whose failure could adversely affect the environment, or safety and health of the public as identified in the safety analysis.

- **Safety-significant system*** defined as:

  Structures, systems, and components ***not*** *designated as safety-class SSCs but whose preventive or mitigative function is a major contributor to defense in depth (i.e., prevention of uncontrolled material releases) and/or worker safety as determined from hazard analysis.*

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* More definition of these systems are in DOE-STD-3009 "Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses" (March 2006).

Preliminary DOE Classification for Selected ARIES Components

(B. Merrill - INL)

- **ARIES** Safety-related SSC:
  - Vacuum vessel (1st confinement barrier for radioactivity and ultimate heat sink for removing decay heat)
  - Pipes penetrating VV, unless isolation valves separate VV from AEU
    - LiPb system (pipes penetrate VV and contains highly radioactive LiPb)
  - Cleanup/isolation/monitoring systems:
    - Isolation valves for He
    - Rupture disks (to guarantee pressure remains below limit)
    - Monitors for loss of coolants
    - Monitors for Po-210 detection
    - Monitors in detritiation system building (e.g., T monitors that send signal to building HVAC system to isolate building if T air concentration becomes too high and T cleanup system shifts into high efficiency mode to remove T)
  - Confinement building (secondary radioactive confinement barrier).

- **NOT** Safety-related systems:
  - All in-vessel components: FW, blanket, divertor, shield, manifolds (not required for confinement of radioactivity; not needed to ensure public or plant safety)
  - Helium system (providing that isolation valves are placed on helium lines at VV and He contains small amounts of T).

ITER Regulations

ITER Regulations

- Industrial codes and standards selected for ITER:
  - ASME
  - RCC-MR - French design code for pressure vessel (Design and Construction Rules for Mechanical Components of PWR Nuclear Islands. It covers box structures applicable to double-shelled vessel with internal ribs. In 2007, new version of RCC-MR was issued with specific additions introduced to cover ITER VV)
  - French regulatory document ESPN* (Equipments Sous Pression Nucleaire) for vacuum vessel and ports, pressure suppression tank, equipment in primary heat transfer system, most of cooling water systems, much tritium plant equipment, test blanket modules, etc.).

- ESPN discusses radionuclide levels in Bq.

- Some ITER components will be designed and manufactured to ASME (mainly Section VIII), while still falling under ESPN regulations.

- ITER is low hazard facility and does not need an evacuation plan. However, ITER must have evacuation plan – a legal requirement for any French nuclear facility.
  (ITER is responsible for internal emergency plan (evacuating the site), and the town mayor is responsible for external emergency plan (evacuating the public)).

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* ESPN regulations are French implementation of European Directive. Every European country must have similar regulations.

ITER Safety Important Components

(2007 ITER Document: ITER_D_282VAQ v. 1.4)

- ITER **Safety Important Components (SIC)** are associated with:
    1. Confinement of radioactivity
    2. Limitation of exposure
    3. Protection of systems for confinement and limiting exposure
    4. Support of systems for confinement and limiting exposure.

- **SIC functions for releases**:
    – Stop releases of radioactivity to environment
    – Mitigate releases through release reduction function
    – Maintain safety function during design basis events (i.e, perform its SIC function of confinement or mitigation after design basis events, but do not necessarily perform its process function (such as making electricity)).

- **SIC functions for limitations of exposure**:
    – Shielding to limit exposure of workers and public.

Could ARIES Leverage from ITER?

- If yes, ARIES equipment is subject to ESPN regulations if:
  - Its internal pressure can exceed 0.5 bar (gauge) during normal or abnormal (Cat.I – III) situations, **and** it contains > 370 MBq activity (or 370 GBq for T and certain other nuclides) that could be released in case of its failure
  - Activity in **fluid** (not in structure nor in deposits of activation corrosion products) is 370 MBq, 0.01 Ci (or 370 GBq for T, 10 Ci).

- ESPN requires <u>high level of QA, robustness</u>, etc. (as expected for ARIES designs to achieve high availability).

- ESPN requires engaging Agreed Notified Body to do <u>third-party conformance checking</u> of design, assembly, and installation.

- Note that:
  - Components may fall under ESPN, but have no safety function (e.g., blanket)
  - Some SIC are not subject to ESPN
    - ⇒ Being ESPN does not imply SIC classification. There is no link.

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* 370 MBq = 0.01 Curies.

Could ARIES Leverage from ITER? (Cont.)

- **ARIES power plant components that are SIC**:
  - Vacuum vessel
  - Components connected to VV, extending VV confinement boundary (such as ports for maintenance, diagnostics, fuelling, vacuum pumps, plasma heating, etc.)
  - External parts of primary coolants (LiPb and He)
  - Hot cells for refurbishment of in-vessel modules
  - Tritium plant, tritium fueling & cleanup systems, and vacuum exhaust handling system
  - Gaseous, liquid, and solid radwaste handling systems that preclude releases to environment
  - HVAC in LLW building only
  - Short section of secondary cooling water system (up to isolation valve)
  - All safety systems that mitigate releases (air detritiation, confinement systems, stack, filters, radiation monitors, etc) as they have release reduction function.
- **ARIES power plant components that are <u>not</u> SIC**:
  - FW/blanket
  - Shield and manifolds
  - Divertor
  - In-vessel primary coolant circuits
  - Most of HVAC
  - Most of secondary cooling water system
  - Cryostat*
  - Bioshield#.

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* Cryostat is not required to perform any safety function in ITER design basis events.

\# ITER does not classify bioshield as SIC even though it provides safety function. It is called "safety related" and will lead to requirements such as that correct concrete composition is used.

Safety Classification of In-vessel Components

- What could we do differently for power plant like ARIES than for experimental facility like ITER?
- Should we credit in-vessel components with any safety function in safety analysis? (i.e., performing confinement function, keeping in-vessel inventory of **T** and activation products (particularly in dust form) from getting to cooling circuit and thus outside VV).
- **ITER decision**:
  - Not to give any safety credit to in-vessel components (shield and divertor) because they are experimental and could be damaged in severe plasma disruption
  - Safety analyses effectively assume in-vessel components always fail in such events
  - Ex-vessel parts of cooling loops have to perform confinement function and are SIC

    (not only cooling pipes, but many other penetrations such as RF waveguides, T purge lines, diagnostics ducts, etc.).
- **ARIES power plant**:
  - **Option-I**: Find means to completely avoid disruptions
  - **Option-II**: Design highly reliable in-vessel components, making them SIC *instead* of ex-vessel parts of cooling loops and their isolation valves, etc.
  - **Option-III**: Combination if I & II.
  - **Best option?** Hard to say now. It depends on relative cost of each option and innovative **technology to build components that never fail**, particularly divertors.

Remarks and Recommendations

- ARIES fusion power plants will be licensed by NRC as Utilization Facilities (because of radioactive fuel and neutron activation).
- Fusion community, NRC, and ASME should develop fusion-specific standards for safety-related components.
- Nuclear power (fuelled by U or T) will always be expensive, but designing fewer safety-related components helps reduce overall cost.
- Fusion plant has limited hazard compared to fission plant.
- Fusion safety classification requirements may not be more stringent than those applied to reach required **reliability** for **high availability** and/or investment protection

  ⇒ **Safety is not only factor driving cost of fusion materials.**
- High quality parts (with documented proof) will be the standard for fusion plants.
- **All** fusion components (specially safety-related) should go through expensive design work, stringent fabrication requirements, and extensive documentations.
- Cost of fusion components should reflect these rigorous processes.
- Since **cost is unknown**, ARIES Systems Code should evaluate COE for range of material unit costs (1 - 4 times off-the-shelf values provided by L. Waganer).