Technical Meeting on Experience in Codes and Standards for Fusion Technology

Report of Contributions

https://conferences.iaea.org/e/425

Contribution ID: **2** Type: **Oral**

Suggestions on FPP Primary System Design Standards from a Security Perspective

Safety design is an important part of the design of nuclear power reactor. It is a necessary step of nuclear system design and a key requirement for the reactor operation permit. In the Fusion power plant（FPP）preliminary design, the breeder blankets and heat transfer system need consider the tritium release and heat remove. There is no codes and standards for this design. In this report, the risks, safety function and classification of the blankets and heat transfer system will be discussed, and provide suggestions for developing the codes and standards.

Technical Categories Addressed

Heat transfer systems (how to extract the heat)

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Session Classification: Tritium Breeding Systems

Contribution ID: **3** Type: **Oral**

Challenges in Adapting Existing Nuclear Standards for Fusion Breeding Blanket Design and Manufacturing

Nuclear design codes and standards play a critical role in ensuring the safety, reliability, and efficiency of systems, structures, and components in the nuclear industry. Developed by internationally recognized bodies (such as ASME, AFCEN, etc.) based on decades of operational experience and research, with extensive contributions from field experts, these standards reflect proven practices, evolving technologies, and lessons learned from nuclear operations world over. These codes and standards (e.g., ASME BPVC, AFCEN RCC-MRx, etc.) provide rigorous guidelines for material selection, design methodologies, fabrication, inspection, and quality assurance. In addition, they help establish a common framework for regulatory compliance, reducing operational risk and facilitating international consistency and collaboration and are very essential for safeguarding public safety and upholding credibility of the nuclear sector [1-2].

While the existing codes and standards are well-established frameworks for fission reactor components as these codes were primarily developed based on materials, loading conditions, and operating environments typical of fission systems, they present significant limitations when applied to fusion reactor components and lack provisions for the unique challenges encountered in fusion. That said, codes like RCC-MRx offer significant advantages over the ASME BPVC for the design of fusion-specific components, such as the breeding blanket, thanks to their more comprehensive treatment of high-temperature behaviour, irradiation effects on candidate materials, and support for advanced manufacturing techniques. Nevertheless, important gaps remain, and continued development is essential to fully address the complex requirements of fusion reactors. For instance, while RCC-MRx explicitly recognizes diffusion welding as a special welding process applicable to both homogeneous and heterogeneous alloy joints, the ASME BPVC does not. Furthermore, neither code currently includes provisions for additive manufacturing techniques even for components classified as Safety Important Component-3 (SIC-3) or Safety Related (SR) or non-SIC, despite its growing importance in producing complex geometries typical of fusion reactor designs [3-4].

The present work highlights these important aspects by critically examining the applicability of existing nuclear design codes, particularly assessing the RCC-MRx and ASME BPVC, to fusion reactor components, with a focus on the breeding blanket design and manufacturing. It assesses the strengths and limitations of both the codes in addressing fusion-specific challenges and their progress toward harmonization through integration within national regulatory licensing frameworks. By pinpointing existing gaps and outlining areas for improvement, this work aims to support the ongoing development and adaptation of nuclear codes to better meet the complex requirements of fusion energy systems.

Technical Categories Addressed

Structural materials

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Session Classification: Materials and Manufacturing

Contribution ID: **4** Type: **Oral**

Justification Approach and Codification of Advanced Manufacturing Techniques for Nuclear Fission Components

The approach taken by Rolls-Royce Nuclear to justify the application of advanced manufacturing applied techniques to nuclear plant components, The components are classed to the ASME Section III nuclear design code as Class 1, which are used in the primary circuit and support systems of fission nuclear reactor plants. The manufacturing techniques covered are: Hot Isostatic Pressing (HIP) and Laser Powder Bed Fusion. The components covered are: vessels, piping, piping components, valves, pump bodies, the material being High Alloy Steel. The approach, utilising the TAGSI methodology, covers the material and component testing regimes applied, with reference to ASME codification requirements.

Technical Categories Addressed

Materials data

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Session Classification: Materials and Manufacturing

Contribution ID: **5** Type: **Invited Speaker**

Strategic Approach to Codes and Standards for the Structural Integrity of STEP

Codes, standards and structural integrity are multidisciplinary fields in which UKAEA has a distinguished history of groundbreaking research and innovation, delivering significant economic benefits and enhancing energy security for the UK. After decades of worldwide research and development including recent world records for inertial and magnetic fusion energy, fusion is progressing steadily from experiment and concepts towards prototype and commercial fusion power plants. Over the next decade, the focus in the fusion is expected to be shifting from plasma physics to addressing technology and engineering challenges, from the conceptual design phase to engineering design and construction, concurrently transitioning from purely publicly funded effort to private-public partnerships. This transition necessitates overcoming highly complex engineering challenges across all the technology readiness levels and significantly increasing the scale of engineering delivery systems, on the scale from millions to billion pounds of investment. A critical step to enable this transition is to develop a fusion codes and standards solution for future prototype fusion power plants, ensuring high standards of public, environmental, and investment protection while maximising economic benefits.
This work reviews the needs for codes and standards for STEP and outlines a strategy aimed at providing effective solutions to enhance confidence that the STEP programme objectives can be achieved. The strategy is based on STEP's objectives, baseline design, operational philosophy, and the current global fusion codes and standards landscape. The STEP-driven strategy identifies critical gaps and challenges that must be addressed, proposing clear priorities and plans to tackle them. The scope of codes and standards is considerable in breadth, must covering the entire STEP plant. It also demands significant depth to address fusion-specific research and development gaps, as well as the complexity necessary to define and manage interfaces, ensuring both horizontal and vertical integration across the whole STEP plant. It also requires knowledge in depth to address significant research and development gaps in fusion-specific systems, as well as the complexity needed to define and manage interfaces between codes, striving towards horizontal and vertical integration across the STEP whole plant. This underscores the necessity of a holistic and coordinated approach and strategy.
This strategy will not only support the realisation of STEP with the highest safety standards and ensure structural integrity but also safeguard investments and strengthen the fusion
ecosystem. It marks a significant new chapter in shaping the future of fusion, with STEP serving as the vehicle driving progress and innovation. By integrating other ongoing efforts from UKAEA' s contributions to AFCEN, ASME, EUROfusion and IAEA, the UKAEA working group aims to establish a comprehensive pathway to address engineering challenges, develop fusion codes and standards, and ensure regulatory compliance, thereby ultimately advancing the path toward commercial fusion energy.

Technical Categories Addressed

Other Systems

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Contribution ID: **6** Type: **Oral**

Comparison of potential code & standards for tritium breeding blanket and application of RCC-MRx in CN ITER HCCB TBM-set

Currently there are a lot of code and standards for nuclear facilities and pressure vessels, i.e. ASME BPVC III, ASME BPVC VIII, RCC-MR/MRx, EN 13445, GB/T 150, etc. The design rules are not quite consistent, especially for definition of allowable stresses, hydrostatic pressure, welding joint coefficient, elastic analysis criteria. In this presentation, the rules from different standards are compared, and current application of RCC-MRx on design and fabrication of CN ITER HCCB TBM-set is introduced also.

Technical Categories Addressed

Tritium breeder blankets (ex. molten salts, liquid metals)

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Session Classification: Tritium Breeding Systems

Contribution ID: **7** Type: **Oral**

DEMO DESIGN CRITERIA FOR IN-VESSEL COMPONENTS –STRATEGIC VISION AND OVERARCHING CONSIDERATIONS

In-Vessel components in fusion nuclear systems have to withstand a very harsh combination of loads and environmental conditions which leads to designs that are significantly more complex and distinct from those of fission components. The ability to accurately predict component performance in in-vessel conditions, factoring in suitable design margins against critical failure mechanisms, is an overarching concern from a safety as well as investment protection perspective for the realisation of DEMO fusion power plant.

This requires a critical evaluation of the typical failure mechanisms that are usually considered for design assessment of existing nuclear components. This evaluation shall consider both their relative individual significance from a limit state design perspective as well as their applicability for the selected in-vessel components'materials and the fusion in-vessel operating conditions. Furthermore, the possibility of ductile and brittle failure mechanisms being intertwined over the design life of a fusion component requires clear understanding and evaluation of potential synergistic effects to optimise the component life and prevent premature component failures in service.

One possible approach to achieve this objective is the development of specialized material models that can simulate material responses in the plastic regime even beyond maximum tensile strength (utilizing post-necking residual deformation capacity), along with advanced predictive visualization of component behaviour under various loading conditions. These advanced, non-linear FE methods provide scope for recalibration of the stringent limits imposed against damage modes within the conventional nuclear design codes and standards. They provide opportunities to expand the design space with a clear basis for defining pragmatic allowable damage margins for different failure mechanisms, thereby addressing plant-level requirements for a maintenance-free operational period as mandated by the DEMO project. Simultaneously, they ensure overall alignment with the broader IAEA definitions and anticipated regulatory expectations.

To that end, this presentation will highlight the driving objectives, structure and status of the DEMO Design Criteria for In-Vessel Components (DDC-IC), currently under development in EUROfusion. Their goal is to complement the existing codes and standards and to provide a higher level of granularity in the structural integrity design qualification approaches specific for fusion in-vessel components. The presentation will also highlight the salient aspects associated with the design principles and associated design rules that are under consideration within the DDC-IC. This will include the arguments serving to investigate the core assumptions and theoretical basis associated with selected design rules within existing codes and standards as well as the avenues being explored to address the "gaps".

The short-term objective of this initiative is to establish the DDC-IC as a viable single point of entry for DEMO in-vessel component design rules to ensure consistency and coherence in DEMO concept design assessment activities. It is also anticipated that over the longer-term, the DDC-IC will be systematically developed as a fully integrated and harmonized guideline for structural integrity qualification of standardised fusion in-vessel component designs.

Technical Categories Addressed

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Session Classification: Development of Codes and Standards

Contribution ID: **8** Type: **Oral**

The Need for Codes and Standards in Lead-Lithium Eutectic Manufacturing for Breeder Blanket Applications

Lead–lithium (PbLi) eutectic is a cornerstone material for fusion breeding blankets, serving both as a tritium breeder and neutron multiplier. It has emerged as the leading candidate across most liquid blanket concepts: forming the basis of the DCLL, WCLL, and HCLL designs in the EUROfusion DEMO programme; underpinning the WCLL blanket under evaluation in ITER's Test Blanket Module programme; and featuring in self-cooled variants explored in conceptual reactor studies such as ARIES-AT (US), HiPER (EU), and KOYO-F (Japan).

Its performance, however, is extremely sensitive to compositional accuracy and impurity levels. Recent analyses of commercial PbLi ingots by B. Garcinuño et al., 2022 revealed lithium contents varying from 3–18 at% and metallic impurity concentrations exceeding 400 ppm, with oxides and carbonates frequently present. Such deviations shift the melting point away from the eutectic (235 ℃), alter thermophysical properties, and can significantly bias tritium solubility and diffusivity values—parameters central to ensuring reactor-scale tritium self-sufficiency.

At EX-Fusion, we recently completed the first high-purity batch synthesis (EX-LLE-1), achieving reactor-grade PbLi via controlled atmosphere alloying with ICP-AES verification of trace metal impurities. This experience underlined the absence of harmonized standards for PbLi manufacturing, characterization, and acceptance criteria. While codes exist for structural alloys and pressure vessel steels, no equivalent framework governs breeder material production. Current efforts rely on ad-hoc protocols, often non-reproducible across suppliers and laboratories.

We propose that the development of fusion-specific codes and standards for PbLi should cover:

1. Constitutive specifications: lithium content fixed at 15.7 at% ± tolerance, isotopic enrichment targets, and impurity thresholds (metallic and gaseous).
2. Characterization protocols: mandatory use of complementary techniques (ICP-OES/MS, XRD, SEM-EDX, LECO gas analysis) to assess metallic and non metallic impurity content, and assure compositional & structural fidelity.
3. Fabrication QA/QC procedures: environmental controls to prevent Li and Pb oxidation, standardized sampling methods, and traceability of batches to nuclear materials QA standards.

Establishing such standards would reduce experimental discrepancies, provide reliable input data for tritium transport modeling, and ensure that reactor-grade PbLi is safe for irradiation. Together, these are prerequisites for the consistent qualification of breeder blanket technologies across international programs. Without codified manufacturing standards, scaling PbLi supply from laboratory kilograms to industrial tonnes risks bottlenecks in blanket deployment and undermines the licensing basis for fusion pilot plants.

Technical Categories Addressed

Tritium breeder blankets (ex. molten salts, liquid metals)

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Session Classification: Materials and Manufacturing

Contribution ID: **9** Type: **Oral**

Recent advancements in pressure codes & standards for fusion power plants

The purpose of design codes and standards is to establish national or international standards that consist of a set of rules based on state-of-the-art knowledge, experience, and experimental feedback from facilities. The design and construction of any fusion reactor should make use of appropriate codes and standards to provide quality assurance and control for the structural integrity and safety of these plants, such as pressure vessels which cover vacuum vessels, breeder blankets, and high-pressure cooling components. The codes provide the bridge between different suppliers, participants, researchers, designers, manufacturers, and regulators. The documents can be viewed as a live document that are updated as better operational experience, knowledge, and scientific advancements become available.

The first edition of American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel (BPV) Section III Division 4 "Fusion Energy Devices"construction code and standard was released in June 2023. In 2024, Division 4 released its 5-year strategy to develop a construction code and standard for pressure vessels for fusion power plants. This marks the beginning of the activities, and one task is to write the materials qualification requirements to bring in "fusion-grade"structural materials within the Division for use in the future.

This presentation has three objectives: 1) provide update on the development of the codes and standards for fusion power plants 2) outline a proposal for the materials qualification route for Division 4 which outlines the testing requirements, standards, assessment methodologies, environmental effects such as corrosion and irradiation, and 3) update the fusion community on the work undertaken by Oxford Sigma in . The code must reflect the best practice and community needs/requests, and this talk will aim to ensure the community has a vision of how the design codes and standards that exist today, align and overlap with one another.

Technical Categories Addressed

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Session Classification: Development of Codes and Standards

Contribution ID: **10** Type: **Oral**

An Overview of Work Contributing to Fusion Codes and Standards at the University of Manchester

The University of Manchester has an established and growing presence in the fusion space. We are currently a partner of the Fusion Power Centre for Doctoral Training and the lead institute of the new Fusion Engineering CDT. This demonstrates our excellent capabilities in translating from low TRL level research to a position where codes and standards can be developed. We are also part of the Dalton Nuclear Institute, the largest and most advanced nuclear research capability in UK academia, and the Henry Royce Institute, the UK's advanced materials national centre. In addition we have strong links with industry and the supply chain, from fusion start-ups to more established engineering companies. We recognise the importance codes and standards play in the development of fusion power devices.

Our research includes fundamental materials characterisation, both experimentally and through modelling. We look at materials for varied applications across fusion, including plasma facing, structural and microwaves. We have capabilities in ion irradiation of materials through the Dalton Cumbria Facility. Our experimental characterisation facilities characterise materials from the atomic scale (through our electron microscopy centre, including in situ testing capabilities (hardness, tensile tests, heating)) to large scale engineering testing (loading rigs etc). This means we are able to obtain data for fusion relevant materials across a range of scales. We also are established users of the national lab facilities at Harwell, Diamond Light Source and ISIS Neutron and Muon Source. These capabilities are essential for carrying out reproduceable testing and materials qualification.

We work extensively in the materials manufacturing space. This involves novel welding and additive manufacturing. We have experience in electron beam welding of tungsten and reduced activation ferritic martensitic and austenitic steels, as well as associated heat treatments, characterisation and modelling. We are also working on Digital Twins development and coupling our manufacturing capabilities with novel finite element models.

We have also recently began working in the tritium space and have a group looking at the influence of tritium on material properties. Materials qualification is this space will be vital going forward as we head towards the development of appropriate codes and standards.

Building on our experience in fundamental materials science, applied engineering and strong links with industry we propose the need to develop a university based miniature version of the UK's flagship Spherical Tokamak for Energy Production (STEP programme). This should primarily be built using additive manufacturing techniques. The impact is multi-fold through the following key areas: providing an avenue for training the next generation of scientists and engineers, allowing for the development of engineering standards and protocols for building a tokamak, demonstration of novel additive manufacturing techniques, a test-bed for concepts for the STEP programme and a stimulus for supply chain and economic development in the UK. This will be a vital mechanism for code and standards development as we move from an era of ad-hoc fusion device development to a unified engineering-driven approach.

Technical Categories Addressed

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Session Classification: Materials and Manufacturing

Contribution ID: **11** Type: **Oral**

Perspectives on Consensus-Based Codes and Standards to Support and Enable a Robust Supply Chain for Commercial Fusion Energy

EPRI was established as an independent, nonprofit research organization to deliver technical solutions and address emerging R&D needs to support the delivery of safe, affordable, reliable, and sustainable electricity for the public benefit. EPRI's mission is primarily executed through the application of R&D by member utilities and other providers of electricity and energy resources. As an owner-operator facing organization, EPRI has supported the development, demonstration, and deployment of new technologies for electricity and energy generation, transmission, distribution, and end-use. EPRI previously investigated fusion energy in the 1970s and 80s and published its first utility requirements document for fusion in 1982—a decade before developing its better known Utility Requirements Document for Advanced Light Water Reactors. In light of the growth in private sector interest and investment in fusion technologies and notable technological advances in the past decade, EPRI has returned to fusion with a new strategic R&D program.
Based on EPRI's experience, a key part of commercializing new energy technologies is the establishment of a stable supply chain. The development and application of consensus-based codes and standards for emerging technologies can support and enable the emergence of an engaged, informed, and robust industry supply chain prepared for scaling of production beyond one or a few-of-a-kind. Accordingly, EPRI is engaged with the development of fusion-specific codes and standards, including via direct support for the accelerated development of ASME Boiler and Pressure Vessel Code Section III Division 4, Rules for Construction of Fusion Energy Devices. EPRI is also interested in supporting right-sized quality standards that reflect fusion unique safety and performance characteristics and accelerating qualification of advanced materials and manufacturing methods for commercial fusion applications.
For some fusion-specific materials and components, existing suppliers may not exist—requiring new entrants to assume the risks and overcome the barriers to entry associated with a new enterprise. However, for many fusion plant materials and components, capable suppliers likely exist—but many will still need to be convinced to take on the risk of investing in anticipation of an emerging technology and new customers instead of focusing on existing and/or proven customers and markets. Participants in a commercial supply chain to support a future commercial fusion energy sector need to consider a number of actions and investments well in advance of filling orders from a fusion customer. Having a framework of industry informed, consensus-based codes and standards in place can serve to inform prospective suppliers and vendors in this commercial endeavor. Absence of standard methods, parameters, and best practices places the entire burden for determining specifications and requirements for products and process on the customer, the supplier, or both. While materials and components for experimental, demonstration, and first-of-a-kind fusion plants will invariably involve bespoke and prototype fabrication and manufacturing, a truly commercial fusion sector will need the production quality, scale, and standardization provided by a mature framework of codes and standards in addition to appropriate regulatory frameworks and technology maturation.

Technical Categories Addressed

Structural materials

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Session Classification: Materials and Manufacturing

Contribution ID: **12** Type: **Oral**

UKAEA Experience with the Development of Fusion Codes & Standards

UKAEA is committed to the development of codes and standards for the wide-ranging fusion technologies. In this talk, an overview of the UKAEA engagement with codes and standards development organisation such as ASME, BSI and ISO will be presented considering the UK fusion regulatory framework. Also, UKAEA view on key challenges facing the realisation of fusion codes and standards will be discussed highlighting important aspects the fusion sector shall consider for successful and timely realisation of fusion codes and standards.

Technical Categories Addressed

Other Systems

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Session Classification: Development of Codes and Standards

Contribution ID: **13** Type: **Oral**

Fusion Codes & Standards: Current Challenges and Future Directions

The development of fusion energy requires robust, harmonised Codes and Standards (C&S) to ensure safety, reliability, and regulatory acceptance. Kyoto Fusioneering (KF) has extensive experience applying ASME, JSME, RCC-MRx, and CSA frameworks to real projects, including hydrogen isotope permeation sensors (TRI-PRISM) and the UNITY-2 tritium facility. KF actively contributes to shaping future standards through participation in ASME BPVC Section III Division 4 and ISO initiatives via BSI, providing technical input and data from advanced blanket and fuel cycle systems.

Despite progress, significant gaps remain: qualification pathways for high-temperature and reduced-activation materials (e.g., SiCf/SiC, vanadium alloys, RAFM steels) and the absence of fusion-specific acceptance criteria for tritium permeation barrier coatings. Addressing these challenges requires international collaboration, experimental validation, and pragmatic approaches that avoid overly restrictive requirements at this early stage. KF advocates for ASME to lead global harmonisation efforts, supported by evidence-based processes, to enable safe, efficient, and timely deployment of fusion technologies worldwide.

Technical Categories Addressed

Other Systems

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Session Classification: Development of Codes and Standards

Contribution ID: **14** Type: **Oral**

Collaboration in Fusion Codes & Standards: Practices from SWIP and a Call for Global Partnership

As a pioneer in Chinese fusion research and a key part of China Fusion Energy Company, the Southwestern Institute of Physics (SWIP) is at the forefront of developing vital Codes & Standards (C&S). This presentation shares our experience in establishing key domestic standards (covering vacuum, materials, breeding blankets, and safety) and leading international efforts, including publishing the first dedicated fusion standard and developing new ones within ISO.

We will provide a practical case study on the challenges of international co-development, such as reconciling technical viewpoints and managing complex stakeholder input. Finally, we aim to initiate broader collaboration with global partners to jointly address gaps and accelerate the development of a unified global C&S framework for commercial fusion energy.

Technical Categories Addressed

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Session Classification: Development of Codes and Standards

Contribution ID: **15** Type: **Invited Speaker**

Introduction of Korean DEMO and Korea's Experience with Codes and Standards

K-DEMO is a conceptual design project led by Korea to demonstrate the feasibility of a fusion power plant, targeting net electricity production, tritium self-sufficiency, and structural integrity under operational and accidental conditions. Its development requires not only advanced technology but also a regulatory framework tailored to fusion-specific hazards, such as tritium management and activated materials. Korea has accumulated practical experience through ITER participation, domestic safety assessments, and international collaborations. The experiences related to codes and standards have been consolidated through Korea's participation in ITER, the design of KSTAR, and various rsearch activities in the field of fusion.

Technical Categories Addressed

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Contribution ID: **16** Type: **Oral**

Experience of developing a specific fusion safety related standard

Started from 2022, an ISO standard item was proposed to summarise requirements to the safety systems due to the application of the superconducting technology in magnetic fusion facilities. The initial consideration was to analyse how the radiation safety and new technologies such as the superconducting technology may be cross-affected. To date, it is moving towards the ballot of the final DIS (Draft International Standard) stage following the standard development procedure. The limitation and difficulties have been learned and identified along with the process due to several reasons, e.g. the immaturity of the fusion safety system and framework, the overlap of the radiation safety between fusion and fission applications, the narrowness of the specific technology application in fusion, and the prevention of the content repetition from other existing and under-development standards. The lessons learned via the specific experience will be presented. Moreover, some preliminary thoughts will also be presented on the development need of code and standard in order to support the qualification required by fusion safety.

Technical Categories Addressed

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Session Classification: Development of Codes and Standards

Contribution ID: **17** Type: **Oral**

STANDARDS REQUIREMENT AND DEVELOPMENT IN MANUFACTURING OF WATER-COOLANT TRITIUM BREEDING BLANKET COMPONENT

Tritium breeding blanket is the core component in the future fusion power plants, which is responsible for tritium breeding, neutron shielding and heat extraction. In order to realize these functions, the blanket component usually is designed as a box-structure modular made of steel plates, into which the tritium breeding materials and neutron multiplying materials were filled. To exhaust the nuclear heat in the blanket, a serial of cooling channels was installed in the steel plates. In the operation of the fusion reactor, the high-pressure coolant will be injected into the cooling channels. Therefore, the blanket component usually is considered as a pressure vessel. In addition, the blanket component is working under high energy neutron irradiation. To ensure the cleanliness of the fusion device, the reduced-activation ferritic-martensitic steel (RAFM steel) has been chosen as the structure materials. Therefore, in the design and manufacturing process of the blanket module, we not only need to carry out the development of manufacturing technology, but also simultaneously consider the safety issues during the component's usage, as well as the relevant material technology requirements and manufacturing technology specifications.
In this report, some recent research progress in the manufacturing technology of blanket module will be presented firstly, including the development and batch production of RAFM steel plates and tubes, as well as the research on forming and inspection technologies for internal coolant channels. Then, we will show the standardization efforts in blanket module manufacturing technology. In the R&D of CFETR-WCCB module manufacturing technology, we have collaborated with participating enterprises to establish a group standard for the manufacturing and inspection technologies of water-cooled blanket modules. This standard primarily specifies the structural composition, manufacturing techniques, technical requirements, inspection methods, inspection rules and reporting for WCCB module. Notably, it introduces, for the first time, a classification management system for welding-related processes in the fabrication and assembly of WCCB module. Additionally, we are conducting research on the development of manufacturing technologies for the BEST-TBM blanket module and its operational scenarios in fusion reactor facilities. The most significant challenge currently faced is the standardized management of manufacturing and inspection technologies. For instance, as a pressure vessel, each weld in the blanket module development process requires process qualification and inspection technology development. However, RAFM steel, being a novel material, is not covered by existing pressure vessel standards, necessitating their extension and updating.

Furthermore, we are advancing additive manufacturing technologies for blanket modules, which raises the issue of establishing technical specifications for additively manufactured RAFM steel in fusion reactors. A critical first step involves accumulating mechanical property data and neutron irradiation resistance data for additively manufactured RAFM steel.

Technical Categories Addressed

Structural materials

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Session Classification: Tritium Breeding Systems

Contribution ID: **18** Type: **Oral**

Experience in Codes and Standards for Blankets at SWIP

The blankets in Fusion reactor include both shielding blankets and tritium breeding blankets, both of which have been extensively researched at the Southwestern Institute of Physics (SWIP) under the Nuclear Industry Corporation. Based on the absorption of hot helium leak detection technology for shielding blankets, SWIP has published an international standard, ISO 4233: Reactor technology —Nuclear fusion reactors —Hot helium leak testing method for high temperature pressure-bearing components in nuclear fusion reactors. Currently, SWIP is drafting the standard Beryllium and Beryllide Alloy Pebbles for Neutron Multiplier based on the absorption of neutron multiplier technology for tritium breeding blankets. This standard will help ensure the tritium self-sustainability and applicability of beryllium and beryllide in fusion reactors or devices. It will specify the general technical requirements, test methods, quality certification documents, packaging, transportation, and storage requirements for beryllium and beryllide alloy pebbles used as neutron multipliers in fusion reactors.

Technical Categories Addressed

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Session Classification: Tritium Breeding Systems

Contribution ID: **19** Type: **Oral**

How to Develop Production-Level Software for the Fusion Energy Industry in Decentralised Research Environments

As a nuclear technology, fusion energy may be subjected to the stringent regulatory environments such as nuclear (fission) power plants. Software codes and standards need to be developed in acknowledgement of the uncertain regulatory environment, and to meet the Technology Readiness Level (TRL) required to deploy and operate a fusion power plant. Currently, the most mature fusion technologies are only at the small/medium scale demonstration (TRL < 4/5). As technologies develop from research through to deployment, the dependent software must be productionised to produce robust and licensable systems.

Across the diversity of the nuclear sector, there are countless examples of regulations and guidelines that contextualise the current international regulatory environment into which fusion energy is emerging. Examples include EURATOM Nuclear Safety Directive [Directive 2009/71/EURATOM and 2014/87/Euratom], the United States Nuclear Regulatory Commission's publication "Digital Systems Software Requirements Guidelines"[NUREG/CR-6734], and the IAEA publication "Digital Instrumentation and Control Systems for New and Existing Research Reactors"[STI/PUB/1914 ¦ 978-92-0-118320-0]. All three of these documents address the stringent regulations and criteria for operation and standards for software systems that are used to run nuclear facilities.

This work will focus on how fusion energy research can adopt standard approaches from other industries at the individual, group, and institutional levels to support the deployment of fusion energy in line with nuclear industry standards.

The software practices that the fusion industry needs to commercialise its digital products already exist across other industries, such as nuclear energy, finance, and "big tech". These practices include data and software lifecycles, continuous integration and continuous deployment workflows (CI/CD), automated packaging and documentation tools and more. Codes and standards for software can be developed by incorporating these practices.

To institutionalise coding and data best practices, the decentralised nature of the research environment must be acknowledged. Institutional policies to raise standards must support, not hinder, this style of work. Several key ways to support standards and development are:

- Repository templates (including package configurations and automation tools)
- A "Community of Practice"for data, software, and productionisation
- Including code and data practices in graduate training programmes
- Training on the responsible use of AI tools and copilots

This approach facilitates development and raises standards, without restricting the work practices of researchers.

Beyond this, more restrictive policies can be introduced to enforce change. For example, minimum software standards for presenting at conferences or requiring that software is open-sourced during the academic publication process. Such policy changes should only be made alongside the support needed to comply with the new policies.

Regarding the practical implementation of such policies, a long-term view is required. The development project should have a roadmap, with milestones and key performance indicators to measure progress. Raising the TRL of software in fusion is a long-term activity, requiring time and commitment. Through the adoption of practices and standards from other industries, software for fusion systems can be developed to a level that can be deployed in a power plant.

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Session Classification: Software

Contribution ID: **20** Type: **Oral**

Challenges Related to Tritium Transport in Fusion Reactors: From Component to System Level

Tritium management is central to the safe and economic operation of future fusion power plants, yet it remains one of the most complex aspects of reactor design. At the component level, accurate prediction of hydrogen isotope behaviour in breeder materials, structural alloys, and plasma-facing components is required to ensure compliance with safety standards on tritium retention, permeation, and inventory. Advanced modelling tools such as FESTIM enable detailed simulations of tritium transport, trapping, and release across materials and interfaces, offering insights into component performance under fusion-relevant conditions. At the system level, the integration of tritium transport into plant-wide analyses is essential for licensing and design optimisation. Tools such as PathView support this by enabling dynamic simulations of tritium flow across interconnected subsystems, from breeder blankets and permeator units to fuel cycle components.

To support these efforts, we have initiated the Hydrogen Transport Materials (HTM) database, an open-source repository of validated diffusivity, solubility, and trapping parameters for a broad range of fusion-relevant materials. By providing transparent, curated datasets, the HTM database complements modelling activities and reduces uncertainty in tritium predictions.

This presentation will highlight the challenges in bridging component-scale physics with system-scale modelling, and discuss implications for the development of applicable codes and standards. Particular attention will be given to areas where existing standards (e.g. for structural materials or pressure boundaries) are insufficient to capture tritium-specific phenomena such as isotope exchange, permeation under neutron irradiation, and transient release. Establishing appropriate methodologies for validating models and integrating shared data resources like HTM into design practices will be key for ensuring both regulatory compliance and public confidence in tritium-handling strategies for next-generation fusion reactors.

Technical Categories Addressed

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Session Classification: Tritium Breeding Systems

Contribution ID: **21** Type: **Invited Speaker**

ITER’s Experience in Codes & Standards for the Engineering of Tokamaks

This presentation provides an overview of ITER’s experience in selecting, adapting, or developing mechanical Codes & Standards for the design and construction of Tokamak components such as magnets or Vacuum Vessels and their internal components. Particular attention will be given to aspects unique to fusion, such as Electro-Magnetic loading, cryogenic temperatures, and vacuum environments. The discussion will encompass the historical background, the status and the lessons learned. Finally a plan aimed at enhancing the dissemination of ITER’s experience within the fusion community will be shared, an initiative intended to support other fusion stakeholders in establishing practical design & construction rules that could be used for the engineering of Tokamaks.

Technical Categories Addressed

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Contribution ID: **22** Type: **Oral**

Tritium in Fusion Energy: Ensuring Traceable and Responsible Deployment

Liberty Fusion is a New Mexico–based startup pursuing Plasma-Jet Magneto-Inertial Fusion (PJMIF), a cost-focused path to commercial fusion energy. Our mission is to achieve sub-$50/MWh electricity through scalable plasma gun–driven systems. In parallel with technical milestones (high-fidelity simulations, prototype plasma gun design, and relocation of the Plasma Liner Experiment from Los Alamos), Liberty Fusion is engaging in policy and standards development. Specifically, we are addressing tritium accountability, safety, and proliferation-resistance as early design requirements, ensuring commercial readiness and regulatory acceptance.

Liberty Fusion is developing a framework for tritium accountability that addresses the regulatory and safeguards gaps expected in commercial fusion operations. Current systems rely on batch-based inventory and environmental monitoring, which are insufficient for continuous operations handling 100+ kg of tritium annually. To address this, we are proposing a permissioned blockchain accountability framework. This system ensures immutable, verifiable records of tritium flows across facilities, processing systems, and international transfers. By integrating IoT-enabled real-time monitoring with smart contracts for compliance automation, the approach provides both operational practicality and international safeguards compatibility.

We systematically benchmark against:
• Existing nuclear material safeguards (IAEA INFCIRC/153, NSG export guidelines).
• National regulations for tritium handling, particularly Canada, South Korea, and EU frameworks.
• Fusion-specific initiatives, such as European Fusion Development Agreement reports and U.S. DOE tritium handling protocols.
• Parallel industries, including pharmaceutical cold-chain blockchain trials and uranium accountability frameworks, to derive transferable best practices.

This comparative analysis highlights where fusion-scale tritium operations diverge from current regulatory practices, identifying areas requiring new standards.

1. Inventory Control
   • Gap: Batch-based calorimetry/mass spectrometry have 2–10% uncertainty, inadequate for 100+ kg/yr tritium operations.
   • Proposed C&S Need: Standardized real-time monitoring protocols (e.g., blockchain-linked IoT sensors).
2. Breeder Blanket Oversight
   • Gap: No accepted measurement standards for in-situ tritium breeding.
   • Proposed C&S Need: Protocols for continuous breeding rate measurement and accountability.
3. Retention and Permeation Accounting
   • Gap: Up to 2.2 kg of tritium retained annually in reactor materials, unaccounted.
   • Proposed C&S Need: Codes for estimating, monitoring, and reporting retention.
4. Transfer and Waste Accountability
   • Gap: No chain-of-custody standards for intra-site transfers, waste processing, or decommissioning recovery.
   • Proposed C&S Need: Smart contract–based transfer verification; waste-stream tritium monitoring standards.
5. Cross-Border Transport
   • Gap: Export controls inconsistent; no international verification of end-use compliance.
   • Proposed C&S Need: International blockchain-based ledger for tritium shipment verification, modeled on nuclear export controls.

References:
• NSG Guidelines for Nuclear Transfers (INFCIRC/254/Rev.14/Part 1) –export thresholds for tritium.
• IAEA INFCIRC/153 –general safeguards obligations (note: tritium excluded).
• EPA & CNSC tritium safety regulations –environmental release monitoring.
• Science & Global Security, Vol. 5 (Kalinowski, 1994) –tritium safeguards challenges.

Technical Categories Addressed

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Session Classification: Software

Contribution ID: **23** Type: **Oral**

The relationship between the regulatory frameworks and codes & standards for fusion facilities

Codes and standards (C&S) play an important role in the regulatory frameworks for both, radiation protection and nuclear facilities. Currently, internationally different approaches for fusion regulation either already exists or are currently being developed based either the regulatory framework for radiation protection or nuclear facilities. Thereby, the fusion regulatory framework most likely should be technology neutral, meaning it should be applicable to magnetic or inertial confinement and other approach.
Even though, C&S do not immediately pose binding requirements their content can become requirements in the licensing process through their application by the competent authority and their integration in the licensing documentations.
The IAEA Safety Fundamentals (SF-1) and the General Safety Requirements for Safety Assessment for Facilities and Activities (GSR Part 4 (Rev 1)) include a graded approach. This graded approach needs to be implemented by specifying criteria when/if certain safety functions shall be implemented for a certain facility or activity and how such safety functions should be qualified. The requirement to implement certain safety functions is typically set in higher level regulatory documents whereas the way how to implement a certain level of qualification for a safety function is given by C&S. Examples are the German Safety Requirements for Nuclear Power Plants as higher level document and the KTA standards.
Up to now, no country has such higher-level fusion specific regulatory requirements. But there exists already different international C&S for safety relevant systems of fusion facilities (e. g. ISO 16646 and ISO/FDIS 18518). It will be discussed how such C&S can potentially set requirements for the use of certain safety functions and a certain level of qualifying them even though the decisions were not yet made at a higher level in the regulatory framework. If C&S were e.g. based on the technical implementation for a single application for which a certain regulatory regime is applicable, they might include requirements set by that regulatory regime. Such requirements could be the consideration of certain operational boundary conditions, to withstand certain internal or external events, or qualification requirements like the application of the single failure criterion. Unintentionally, such C&S could lead to an interdigitation between radiation protection regulation and nuclear facilities regulation if they become international standards.

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Session Classification: Applicability to Regulation Frameworks and Safety

Contribution ID: **24** Type: **Oral**

SPARC PROGRESS AND CONTINUED DEVELOPMENT OF THE CODE OF RECORD FOR THE DEVELOPMENT OF ARC

In March 2023, the U.S. Nuclear Regulatory Commission (NRC) unanimously agreed to regulate fusion energy facilities under the byproduct materials framework of 10 CFR 30—commonly applied to particle accelerators and medical irradiation systems—rather than the 10 CFR 50/52 framework for fission reactors. This approach mirrors that of the U.K., where fusion facilities are overseen by the Health and Safety Executive and the Environment Agency, rather than the Office for Nuclear Regulation. Both countries have now codified these regulatory decisions into law [1,2]. This shift reflects a growing global consensus to regulate fusion based on its risk profile, which is more similar to that of particle accelerators than fission reactors. The goal is to apply appropriate regulations from the start, adjusting as needed, rather than imposing fission regulations and stripping away irrelevant requirements. Other countries, including Canada, Japan, Germany, and Italy, are also moving toward a similar regulatory approach for fusion facilities, aligning with the private sector's developments in this field.

Most literature on tritium, waste, and safety in fusion energy is based on large public projects like ITER and DEMO. However, no privately funded companies are pursuing such large-scale facilities due to cost and different missions. This makes relying on this literature inaccurate for current private fusion designs. Advances like high-temperature superconducting magnets now enable tokamaks to be built about 40 times smaller than ITER. Private developers are also designing tritium handling systems to optimize processing and minimize on-site inventories. For instance, SPARC, our experimental tokamak, will use about 10 grams of tritium, compared to ITER's 4,000 grams for a similar mission. Focused on public acceptance, private fusion designs aim to use less tritium, produce less waste, and avoid emergency off-site evacuation plans. Therefore, applying ITER-based regulations to these smaller, safer private facilities is not appropriate. Commonwealth Fusion Systems (CFS) has actively participated in NRC public meetings [3] to emphasize these differences and highlight the safety features of private fusion approaches [4, 5, 6, 7, 8].

The NRC's Staff Requirements Memo on SECY-23-0001 [9] called for a new Volume 22 of NUREG-1556 to provide regulatory guidance specifically for fusion energy systems, ensuring consistent guidance across the National Materials Program. NUREG-1556 Volume 21 has been a solid foundation for creating fusion-specific guidance in Volume 22. In collaboration with the NRC and Agreement State partners, Volume 21 guided the SPARC materials license application, granted in October 2024 [10]. This broad-scope radioactive materials license for SPARC marks a key milestone toward operating the world's first commercially viable net-energy fusion machine. The license permits CFS to possess, use, and store radioactive materials on the SPARC site. Given the shared subsystems between SPARC and ARC (CFS's future fusion power plant in Chesterfield County, Virginia [11]), the guidance from the SPARC licensing process will be broadly applicable to future fusion machines. In preparing the SPARC application, CFS has gathered lessons learned and ideas for improving the new fusion-specific NUREG-1556 volume, including tritium systems design, material accountancy, and security…

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Session Classification: Applicability to Regulation Frameworks and Safety

Contribution ID: **25** Type: **Oral**

Fusion Materials and Codes and Standards for Fusion Energy

One of the largest factors severely limiting the anticipated pace to realize fusion on the grid is the development of a set of basic fusion materials, qualified and validated in expensive irradiation campaigns. Initiated by an international working group, Clean Air Task Force's "Material Database for Fusion"(MatDB4Fusion) aims to collect all kinds of material properties data which are relevant for fusion device design, supported by many public and private entities from different countries. It shall act as a single reference for all design approaches, assess data gaps and improve focus of experimental campaigns, accelerate creation of codes and standards and provide sufficient data for machine learning solutions. This effort is coupled with an integrated involvement in the global efforts to develop codes and standards for fusion energy. Clean Air Task Force will present a summary of the global efforts currently underway in this space and its global involvement in the different efforts –and like our materials efforts, making this information publicly available with the goal of decreasing the timeline to commercial fusion energy.

Technical Categories Addressed

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Session Classification: Materials and Manufacturing

Contribution ID: **26** Type: **Oral**

Strategic Use and Development of Codes and Standards to Enable the Deployment of Fusion Power Plants

This presentation examines strategic approaches to fusion codes and standards development, emphasizing three key principles: leveraging existing commercial industry standards, allowing adequate operational experience and design standardization prior to establishing fusion-specific requirements, and assessing the most efficient and appropriate regulatory applications for codes and standards. The discussion will highlight how codes and standards can primarily ensure supplier quality and specification adherence while exploring applicability to regulatory frameworks for emerging fusion technologies.

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Session Classification: Applicability to Regulation Frameworks and Safety

Contribution ID: **27** Type: **Oral**

Development of C&S for fusion in-vessel components: from ITER to DEMO

In the fission industry, nuclear installations are designed and constructed following established Codes and Standards (C&S), developed over decades based on operational feedback and regulatory requirements. In contrast, fusion facilities lack a harmonized regulatory framework and their safety hazards are different from those of fission plants. Additionally, while mission-critical components - such as In-Vessel Components (IVCs) - may not be classified as safety-related and might be exempt from regulation, they must still adhere to the highest quality standards for investment protection and operational reliability.
To address these challenges, ITER adopted a multi-code approach, combining industrial codes – such as ASME and RCC-MRx - with ITER-specific design criteria and guidelines. Despite the comprehensive documentation generated by ITER, key challenges still remain due to regulatory uncertainties and extended operational domain of IVCs in future fusion power plants.
To bridge these gaps, EUROfusion, in collaboration with Fusion for Energy (F4E), is actively working on the development of C&S for DEMO IVCs. A major focus is the development of the RCC-MRx code for the EU Test Blanket Modules, which will provide critical information for the design of the Breeding Blanket. In parallel, EUROfusion is developing specific DEMO Design Criteria for In-Vessel Components (DDC-IC), introducing new design rules and alternative damage assessment methodologies to enhance performance while reducing excessive conservatism.
The DDC-IC aims to serve as a structured guide for DEMO IVC design, establishing a robust foundation for future fusion reactors. This work provides an overview of EUROfusion's efforts and the current status of DDC-IC development.

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Session Classification: Development of Codes and Standards

Contribution ID: **28** Type: **Oral**

Perspectives on US test facilities towards development of a fusion pilot plant

In order to advance to the construction and operation of a Fusion Pilot Plant (FPP), numerous engineering and technology advancements are required. In order to de-risk the design and operation of an FPP, as well as to qualify materials and components, a number of test stands have been considered for construction. These include a Fusion Prototypic Neutron Source, a Blanket Test Facility, a Fuel Cycle Test Facility, and the Material Plasma Exposure experiment. Efforts towards the development of these facilities in the US, as well as the context of similar international facilities, will be discussed.

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Session Classification: Materials and Manufacturing

Contribution ID: **29** Type: **Oral**

Status of magnet development for fusion machines and applicable design criteria

An overview of the current development and design concepts of the magnet systems needed to confine plasma in devices under construction and future fusion machines will be presented. Design concepts will include both low and high temperature superconductors. Design criteria and possible codes and standards which can be applied during conception, development and construction of these complex magnet systems will also be outlined.

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Session Classification: Materials and Manufacturing

Contribution ID: **30** Type: **Invited Speaker**

Overview of fusion standards in China

This presentation primarily presents the development of China's fusion standards, as well as the current information and status regarding nuclear safety regulations and standards. It briefly outlines the specific practices of standard - related activities carried out by us based on tasks such as the ITER project, including the current Specialized standards, national standards, and international standards.

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Contribution ID: **31** Type: **Invited Speaker**

An Overview on Development of Codes and Standards for Tokamak Fusion Power Plant in Japan

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Machine Protection System (MPS) development lifecycle

A Machine Protection System (MPS) is a fundamental component of any fusion facility, serving as the first line of defence for safeguarding essential equipment and ensuring operational integrity under both normal and off-normal conditions. As fusion devices progress toward higher power, increased complexity, and extended operational regimes, the MPS assumes a central role within the overall plant safety and reliability. It protects critical subsystems from damage caused by faults, abnormal transients, or control malfunctions, thereby preserving asset longevity and minimising downtime.
This presentation showcases a comprehensive overview of the MPS, structured around its complete lifecycle from conceptualisation to operation. It examines the formulation of system specifications, the systematic identification and analysis of hazards, and the implementation of risk reduction strategies. Furthermore, it discusses the detailed design, integration, and operational considerations that underpin the realisation of a reliable protection system in a fusion environment. The presentation also outlines the standards that inform the whole process, ensuring alignment with functional safety requirements.

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