Taylor & Francis
Taylor & Francis Group

Fusion Science and Technology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ufst20

Tritium Opportunities and Challenges for Fusion Developments Worldwide—CNL and UKAEA View

Stephen Strikwerda, Paul A. Staniec, Monica Jong, Ben Wakeling, Stephen Reynolds, Ian Castillo, Sam Suppiah, Hugh Boniface, Donald Ryland, Todd Whitehorne, Kathrin Abraham, Steve Wheeler, Damian Brennan & Rachel Lawless

To cite this article: Stephen Strikwerda, Paul A. Staniec, Monica Jong, Ben Wakeling, Stephen Reynolds, Ian Castillo, Sam Suppiah, Hugh Boniface, Donald Ryland, Todd Whitehorne, Kathrin Abraham, Steve Wheeler, Damian Brennan & Rachel Lawless (2024) Tritium Opportunities and Challenges for Fusion Developments Worldwide—CNL and UKAEA View, Fusion Science and Technology, 80:3-4, 607-615, DOI: 10.1080/15361055.2023.2210277

To link to this article: https://doi.org/10.1080/15361055.2023.2210277

FUSION SCIENCE AND TECHNOLOGY · VOLUME 80 · 607–615 · APRIL–MAY 2024

DOI: https://doi.org/10.1080/15361055.2023.2210277

Tritium Opportunities and Challenges for Fusion Developments Worldwide—CNL and UKAEA View

Stephen Strikwerda,[a]* Paul A. Staniec,[b] Monica Jong,[b] Ben Wakeling,[b] Stephen Reynolds,[b] Ian Castillo,[a] Sam Suppiah,[a] Hugh Boniface,[a] Donald Ryland,[a] Todd Whitehorne,[a] Kathrin Abraham,[a] Steve Wheeler,[b] Damian Brennan,[b] and Rachel Lawless[b]

[a]*Canadian Nuclear Laboratories, 286 Plant Road, Chalk River, Ontario, K0J 1J0, Canada*
[b]*United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom*

Received November 24, 2022
Accepted for Publication April 28, 2023

Abstract — *The commercial generation of electricity and high-temperature thermal energy via fusion technology remains one of the promising alternatives to help meet the challenging targets to decarbonize the global energy system. Fusion technology can play a significant role as part of the long-term switch away from carbon-based fuels for electricity and heat due to high energy output, usage of abundant fuel that can be made available without environmental degradation, and avoidance of long-lived and toxic transuranics.*

Many countries have their own fusion research and development programs, while large research efforts are being undertaken in multicountry collaborations, such as ITER. Recently, fairly new (semi-) commercial organizations have been successful in initiating independent development programs funded by government grants and private investments.

Different fusion reactor technologies still share many challenges, with one of the major issues being the management of the deuterium-tritium (DT) fuel cycle and associated auxiliary systems. These different fusion technology developers could benefit immensely from existing and available DT expertise, allowing them to focus primarily on the physics and mechanical aspects of their reactor technologies while finding support for common tritium technological challenges through collaboration. As world-leading experts in DT technology, Canadian Nuclear Laboratories (CNL) and the United Kingdom Atomic Energy Agency(UKAEA), are well positioned to support such needs of the fusion industry.

This paper broadly explores the worldwide DT challenges, identifies opportunities where tritium expertise is key to the development of fusion infrastructure, and presents a view of how CNL and UKAEA are addressing these opportunities for the various fusion developers. This paper presents a holistic view that may be informative to future tritium roadmap and decision-making exercises conducted within the community.

Keywords — *Tritium processing, fusion reactors, infrastructure, regulation.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

The delivery of fusion solutions for power generation has attracted increased attention and significant private investment in the last 36 months.[1] The majority of fusion power plant technologies that have been proposed are planning to use deuterium-tritium (DT) reactions to provide the most energy-favorable route to positive energy production. Historically, tritium capabilities have been targeted for delivery just in time for large fusion DT experimental milestones. This has allowed for directing the initial investment toward early milestones, such as achieving confinement and first plasma. However, the subsequent integration of the tritium infrastructure has

---

*E-mail: stephen.strikwerda@cnl.ca

frequently proved more challenging than anticipated and led to program delays. The resulting extended timeframe and associated additional costs have been accommodated by large long-term national research projects, but could be prohibitive to private companies.

High-performance DT plasma is now being targeted in multiple facilities on short timescales, which are more ambitious than those previously envisaged. This represents a significant change in the challenge portfolio associated with tritium technology and requires a substantial review of the landscape. It has increased the severity of risks associated with tritium supply, tritium breeding, DT fuel processing, tritium emissions, waste, regulation uncertainty, and limited specialist availability. Canadian Nuclear Laboratories (CNL) and the United Kingdom Atomic Energy Authority (UKAEA) plan to use their knowledge and existing capabilities to support the accelerated delivery of tritium technologies to meet the expected expanding demand for tritium processing infrastructure at different scales. CNL and UKAEA are both accustomed to taking leading roles working with technologies at different maturity levels and supply chains to aid industry and academia.

II. TRITIUM SUPPORT FACILITY DEVELOPMENTAL STAGES

The European fusion program has different tritium plant requirements to support the increasingly large tokamak devices (JET, ITER, and DEMO) for demonstrating growing magnitudes of fusion performance.[2] Similarly, it is expected that commercial ventures will follow a series of increasingly challenging fusion-related gates/milestones and set the tritium infrastructure requirements and investment at each stage accordingly.

Historically, many national and international publicly funded programs have hosted evolving iterations of fusion devices at separate locations. Consequently, supporting tritium plants were single-purpose constructions specific to one iteration of a fusion reactor technology and not required to significantly upgrade or upscale to support subsequent larger, higher-performance reactors. However, developing bespoke one-off tritium plants for each iteration of a fusion device will be an unattractive prospect for private ventures, each requiring significant financial and time investments in design, regulatory approval, construction, and commissioning. Therefore, the first new challenge is enabling the reuse and repurposing of the tritium facilities to scaleup and modify the plant performance to meet the increasing and changing demands of evolving demonstration devices. These upgrades must be carried out on short timescales compared to the residual radiological activity of the equipment.

While many currently proposed fusion reactors are of different designs, most will ultimately share common high-level requirements for tritium support facilities and associated auxiliary systems, and therefore, their demonstrator evolutionary stages will be similar. CNL and UKAEA's experience with tritium facilities will be a great asset when designing future facilities to ensure there is a viable, timely, and cost-effective path to appropriate upgrades as ventures progress.

While the ultimate scale of the supporting tritium plant will vary in line with the reactor design and approach being considered, with differing tritium flow and inventory requirements, the development stages of the infrastructure will be similar for most cases and can be divided into four to five incremental stages. Thus, in Fig. 1, the *x*-axis represents the relative complexity and size of the plant for any unique demonstrator requirements, while the *y*-axis indicates the growing technology readiness level (TRL) requirements and supply chain maturity. The requirements are summarized in Table I and are as follows:

A. The most basic setup is only available to experiments that may be demonstrated with negligible inventories and gas volumes. Here, tritium can be delivered directly from small, sealed vials and any trace unburnt tritium vented directly to the atmosphere. This requires only minimal containment and monitoring, and little infrastructure.

B. The next stage is reached as soon as inventories surpass the small amount of tritium that can be acceptably vented directly. Exhaust gases must be processed to capture the unburnt tritium, which can later be reprocessed by external third parties. Full containment and monitoring are required. The exhaust detritiation and capture represents a low energy cost.

C. This stage is reached when experiments require a tritium feed that cannot be viably (due to cost or availability) continually sourced externally. The unburnt and captured tritium must now be recycled in house and returned to the feed. Burnt tritium may be replaced with occasional external top-ups. The addition of the reprocessing systems increases the plant's operational energy costs.

D. Once the experiment is burning considerable tritium, it will become less viable to replace via external top-ups of tritium. At this stage, local breeding is required to offset the tritium

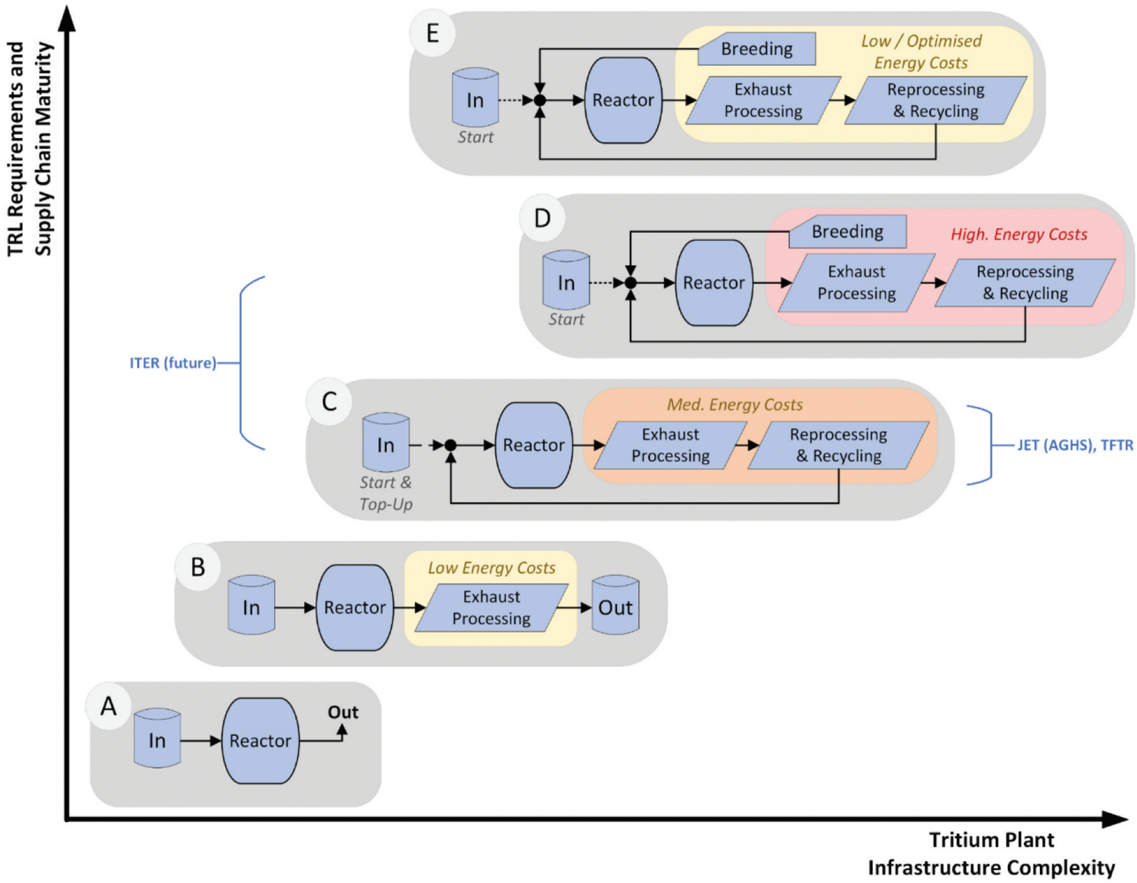

Fig. 1. The development of a tritium plant and fuel cycle supporting a fusion demonstrator facility divided into five incremental stages. JET and TFTR are indicated as stage C. The future ITER plant could be identified as C or D, as breeder demonstrators may be incorporated, but ITER is not planned to be self-sufficient.

TABLE I

Requirements of a Tritium Plant and Fuel Cycle Supporting a Fusion Demonstrator Facility Divided into Five Incremental Stages

Requirement	A	B	C	D	E
Full secondary containment and monitoring		✓	✓	✓	✓
Feed: external per experiment	✓	✓			
Feed: startup + top-up			✓		
Feed: startup only				✓	✓
Exhaust processing to capture unburned tritium		✓	✓	✓	✓
External processing of captured tritium		✓			
Reprocessing of captured tritium (return to feed)			✓	✓	✓
Breeding of tritium				✓	✓
Optimization of process					✓
Can support batch operation	✓	✓	✓		
Can support continuous operation			✓	✓	✓

consumption to produce a self-sufficient fuel cycle. The additional breeding and recovery systems further increase the plant's operational energy costs.

E. The final stage is optimization of the process and potentially reducing the flexibility of the infrastructure to reduce operational overheads to increase the economic viability of the final infrastructure. The optimized processes and technological solutions lower the plant's operational energy costs compared to stage 4.

III. CHALLENGES AND OPPORTUNITIES

Work on various national fusion programs has identified fundamental challenges linked to power-plant-scale tritium plants, with each of the challenges having its own complexities and interdependencies. Here, the authors outline some of the key challenges and opportunities where CNL/UKAEA can support emerging demonstrator initiatives.

III.A. Supply and Logistics of Startup Tritium

Regardless of the tritium-breeding plans, all nuclear fusion reactors relying on tritium fuel will require a supply of external tritium to enable an efficient startup. The tritium supply currently has multiple challenges: export controls, limited supply availability (both in inventory and civilian suppliers), and restrictively small transport containers.

Regardless of the tritium-breeding plans, all nuclear fusion reactors relying on tritium fuel will require a supply of external tritium to enable an efficient startup. For member countries of the Nuclear Suppliers Group, the transfer of dual-use materials, such as tritium, require legal measures to ensure the peaceful end use of tritium and nonproliferation controls.[3] If there is no agreement in place, nuclear fusion organizations need to engage with their governments to develop this at an early stage, as agreements can be slowed down by a multitude of political issues.

At this time, large inventories of civilian tritium are limited to two CANDU tritium removal facilities: Darlington, Canada, and Wolsong, Korea, and the presently available inventory is limited to a few tens of kilograms. The lack of tritium inventory stock and sources represents a challenge to an expanding DT fusion community, as full-scale fusion reactors such as CFETR, DEMO, K-DEMO, and STEP will each need a few kilograms of tritium for an efficient startup.[4–7] Even greater tritium inventories will be committed to supporting large-scale experiments with limited breeding capabilities, such as ITER.[8] It is likely that there will be insufficient tritium inventory supply to support the rapid growth of fusion demonstrations. If tritium inventories start to become depleted, national governments may begin to consider these inventories to be strategic assets.

To reduce this risk, fusion organizations should contact tritium suppliers far in advance to ensure an adequate tritium supply will be available to meet the milestones of their reactor deployment. The current upsurge in DT fusion demonstrators is a significant opportunity for investment and development in tritium supply and the associated logistics. Increased tritium sales and expressions of interest will improve the economics of tritium extraction from existing heavy water reactors and invite potential investment into additional sources, thereby potentially increasing the global tritium inventory and the number of tritium suppliers in the long term, such as the Cernavoda Tritium Removal Facility (TRF).[9] UKAEA has recent experience in the import of tritium from Canada, and thus this experience from both sides of the process is available to be shared.

Tritium transport logistics is also an area requiring rapid development. Most civilian tritium is transported from the Darlington TRF to the CNL in the CNL's 50-g tritium container and then distributed via the smaller General Electric Healthcare Type B(U) 3605D, which can only contain up to ~11.2 g of tritium.[10] These logistics are insufficient to support upcoming fusion demonstrator experiments or to provide startup fuel for future fusion power plants where the transport of kilograms of tritium from suppliers and between fusion sites will be required. To enable seamless global tritium logistics, leading fusion organizations and tritium suppliers should collaborate on the development and licensing of a large standard tritium container. CNL has the expertise to develop and license large tritium transport containers once a path forward is agreed on between suppliers and consumers.

III.B. Breeding and Extraction of Tritium

Full-scale DT fusion reactors will consume more tritium than can be practically supplied externally. Instead, tritium must be produced from breeder blankets (see Ref. [11] and references therein). However, lithium breeder blanket technologies and the associated tritium extraction are at a low level of development. A number of breeder blanket technologies have been conceptually identified that breed tritium in differing carrier mediums and concentrations, which necessitate different extraction methodologies. The concept of lithium first walls and divertors may also impact this selection.[12,13] Each of these arrangements must be reviewed, with promising candidates selected for experimental assessment and then incrementally scaled up from lab scale to demonstration scale.

The generation of high fluxes of neutrons for testing breeder blankets is challenging and costly. Therefore, at demonstration scale, the testing should ideally utilize the neutron flux from operational fusion demonstrators, which has the added benefit of more closely mimicking real conditions. CNL has conducted studies for private fusion firms, giving recommendations on what extraction techniques are best to pursue for the development of their breeder blanket and for the preliminary sizing for tritium extraction and processing. To begin the process of lab-scale demonstrations, CNL has selected one initial option and is currently designing test molten lead lithium eutectic loops.

Fuel containing a natural isotopic ratio of lithium may become ^{6}Li depleted, especially if fast neutrons are shielded or deenergized by material between the breeder blanket and the plasma, requiring a more rapid wholesale replacement or ^{6}Li top-up. Current ^{6}Li stockpiles and production are limited to military activity, with separation historically resulting in high mercury emissions.[14] The available neutron flux and impact on the breeder blanket fuel will need to be assessed for each demonstrator arrangement. CNL is currently planning an assessment of the supply of lithium and a development path for new or revised technology for civilian lithium isotope separation.

III.C. Processing and Recycling of DT Fuel

A tritium processing plant is required to perform multiple functions to support a fusion reactor: capturing and recycling unburnt DT fuel, removing any impurities, isotopic balancing, and storage. The topics of breeding and detritiation are covered in other sections.

To date, the only tritium plants that have fueled a DT reactor are the Active Gas Handling System (AGHS) at JET (recently reprocessing over 1 kg of tritium during DTE2) and the TFTR.[15–17] These operate in a batch mode to support limited short-pulse reactions. Future power plants will either operate high-frequency pulses or semicontinuous plasmas (depending on the reactor technology). A batch infrastructure does not practically or economically scale up to provide sufficient throughput for such operations and instead a continuous mode of plant operation is required.[18]

In a batch mode, process subsystems take in a finite quantity of gas and process it before releasing it fully, and the cycle repeats. In a continuous mode, gas is moving continuously through the subsystem or the gas levels are otherwise regularly topped up and bled out. Predominately, this concerns the infrastructure relating to the exhaust processing, impurity processing, and isotopic rebalancing/separation functions. For example, for isotope separation, gas chromatography can be used as a batch process, whereas cryogenic distillation can be used for continuous processing.[19,20]

The batch mode infrastructure is well established and is still directly applicable to many upcoming early demonstrators (A, B, and C in Fig. 1). Only once the demonstrator has evolved toward the latter stages (C, D, and E in Fig. 1), will operations need to switch to a continuous mode of operation. It is economically attractive for the plant infrastructure to be designed to accommodate this shift or upgrade.

The optimal configuration for a continuous fuel cycle tritium loop is still to be decided and will likely be specific to the fusion device's requirements. A continuous tritium loop was demonstrated (without breeding or coolant processing) in the 1980s at the Tritium Systems Test Assembly (TSTA),[21] which was subsequently decommissioned in 2003.[22] However, this involved passing the full process loop through a cryogenic distillation system, which has implications for high operational costs and mobile tritium inventories. New architectures, including isotopic rebalancing with only partial streams entering isotopic separation, are now being considered.

While existing technologies suitable for batch operation at modest scale mostly have a high TRL, this cannot be said for some of the technologies applicable to high-flow and continuous operation (e.g., inline tritium monitoring, direct internal recycling, quick response for storage and delivery systems). Meanwhile, breeding, extraction, and associated coolant technologies have very low TRLs. The complexity of combining new and existing technologies into new configurations for operating in continuous mode and demonstrating tritium compatibility, while minimizing mobile tritium inventories and operational costs, will be challenging.

These challenges are exacerbated due to the large parameter space associated with the many different fusion approaches currently being explored. There is no clear consensus on inventory and flow scales, coolant mediums or breeder materials, and extraction routes. Furthermore, each fusion approach also offers differing off-normal conditions that must also be accommodated. Last, the tritium inventory must be minimized for safety and regulatory assurances, as well as startup viability, meaning moderate changes in operating configurations and scale can potentially have a significant impact on the infrastructure design and technology selection. A holistic knowledge and understanding of the different tritium technologies, and the potential impact of different demonstrator design choices, is therefore essential when identifying pathways forward.

With a suitably broad knowledge of the technology landscape, CNL and UKAEA are continuing to work to identify key gaps and to advance the TRL for a selection of technologies relevant to the continuous fuel cycle. UKAEA is currently in the process of building The ITER Relevant Tritium Loop (TIRTL) facility, a reduced-scale pilot plant demonstration of a continuous fuel cycle. This operational experience will support the development of future tritium plants and will act as a test bed of new and maturing technologies. Furthermore, UKAEA has extensive experience gained from operating the AGHS for several decades, while undergoing several upgrades, which can be used to support current demonstration activities.

III.D. Recovering Fugitive Tritium and Reducing Emissions

Like hydrogen, tritium in elemental form will leak through small cracks and permeate through warm metals. Tritium leaks and permeation, especially into the coolant loops,[23] could result in unacceptable levels of tritium contamination and emissions. Similar issues have been experienced in heavy water reactors and their TRFs,[24,25] but are exacerbated in the fusion DT fuel cycle by higher temperatures and large flows of high-concentration elemental tritium. Using previous studies on tritium emissions and abatement from CANDU reactors and TRFs will be useful to minimize leakage throughout the fuel cycle lifetime. Tritium compatibility guidelines have been developed by various groups, which have measures to reduce tritium leakage. In order to reduce tritium permeation, materials, coatings, and manufacturing techniques are being developed, and permeation through them are being tested with tritium at CNL and UKAEA. These barrier materials will be especially useful for hot, thin-walled applications, such as heat exchangers.

Regardless of efforts in reducing tritium leaks and permeation, the capture of fugitive tritium must be included in the DT fuel cycle design. This is done by using secondary enclosures, capturing or scrubbing tritium from air or gas, and treating tritiated water. Various air and water detritiation technologies are fully developed and commercialized for the CANDU industry and at UKAEA. These will only require minor changes to fit various DT fuel cycle needs, and both organizations can advise in these fields.

III.E. Disposal and Recycling of Tritiated Waste

Operating a fusion facility will lead to some components becoming neutron activated, tritium contaminated (absorption and permeation), or both. Such radioactive waste from fusion reactors will differ from the fission industry, and thus established disposal routes may need to be verified as appropriate for the fusion industry. New disposal routes may be required to be developed to complement existing routes and ensure the continued availability of these routes post expected lifetimes, which in many cases have been based on forecast arising rates based on existing fission plants without considering a future fusion industry. Waste classifications and disposal route waste acceptance criteria should also be reviewed to assess the specific hazards associated with fusion radioactive waste following a risk-based approach.

The tritium levels in CANDU waste make it especially relevant for fusion, and this is currently being experienced at CNL as the old tritium facility is being dismantled. UKAEA is similarly developing a program for the decommissioning of JET.[26] Separation and decontamination techniques will help reduce the radioactive waste liability, such as the techniques being developed at UKAEA's Material Detritiation Facility.[27]

It is essential to minimize the generation of radioactive waste over the full lifecycle of a tritium plant (i.e., operation and decommissioning) for economic and environmental reasons, and for public acceptance of fusion power. UKAEA has established lifecycle expertise gained through managing the full lifetime of JET.

Reducing tritium permeation will have the greatest impact on both retention in materials and on fugitive emissions, which can be achieved through improved material selection or advanced coatings, and CNL and UKAEA are already working in this area. Optimizing processes in the DT fuel cycle will further reduce the tritiated waste by decreasing the exposed material or increasing lifetimes, such as using lessons learned from UKAEA's AGHS facility and information gained at the new Hydrogen-3 Advanced Technology TIRTL facility.

III.F. Regulation Related to the DT Fuel Cycle

Delayed regulatory approval could present a significant risk to project deadlines, and therefore, early engagement is important. However, one of the key challenges faced by the developing fusion community is the lack of regulatory frameworks explicitly supporting the tritium fuel cycle in fusion power plants. This problem is further compounded due to the risk of a global environment with disparate legal frameworks. Where relevant frameworks exist, they are often focused on nonproliferation aspects and the nuclear fission environment. In the absence of prescriptive guidance and frameworks, entities designing the first DT power plants and demonstrators must engage in detailed discussions with regulators. Many regulatory bodies are rightly cautious and conservative concerning the regulation of active materials, but the absence of existing nuclear fusion power plants leads to limited relevant examples that new safety cases can draw on. Specifically, there is an absence of operational data for large-scale and continuously operating tritium fuel cycles. It is essential that facilities with operational experience in tritium fuel cycles (even if only limited to batch-mode operations or laboratory-level tritium handling) support engagement with global regulators and assist with generating the supporting information required to assure regulators and support safety case developments.

Globally, there is a need for international and governmental bodies to develop more fusion-specific regulator frameworks and guidance, rather than amalgamate fusion power into fission frameworks. Many bodies have already started to explore their regulatory approach, including the United Kingdom,[28] Canada,[29] and the European Union,[30] where review exercises are underway. Therefore, there is a time-limited, but very important, window of opportunity for the fusion industry to engage internationally to avoid the regulation of tritium technology becoming divergent and impeding international collaboration and investment.

A separate, but related, challenge is the absence of equipment that is manufacturer certified for tritium operation, which hinders approval processes due to the considerable time needed to qualify and demonstrate individual components. This currently relies on the support of a narrow pool of experts with familiarity in tritium operation, and is not a long-term sustainable approach. There is therefore a need for the development of internationally accredited equipment tritium standards, which will be especially valuable in supporting smaller commercial startups.

III.G. Development of a Skilled Workforce

With the recent upsurge in commercial fusion startups and demonstrators, a shortage of a skilled and experienced tritium workforce will become increasingly pronounced. Those with experience in DT fuel cycle design and experimental work are in short supply, with those having experience in DT operations especially scarce. There are undoubtedly some transferable skills that are shared with those working in the fission industry, but there will still be a need for some retraining.

It is essential that this limited pool of experience be leveraged and disseminated effectively through training programs, collaborations, and commercial partnerships. The mobility of the workforce will be greatly enhanced by the international cross acceptance of qualifications via the harmonization of regulations. In particular, the wealth of operational experience gained by a small number of individuals must be shared to support the design of next-generation tritium plants and to build on recent lessons learned. These individuals should be used as consultants to maximize the dissemination of their experience. This could also include providing an intermediary interface with manufacturing industries to act as intelligent customers for new bespoke components.

Given the anticipated expansion of the fusion sector in the coming decades, it is important to begin training and growing the next generation of tritium scientists and engineers. The community must provide tritium handling and DT fuel cycle training for students and apprentices and establish career development pipelines for the future workforce. UKAEA and CNL are well placed to share the considerable tritium operational experience they have gained over recent decades.

IV. COLLABORATIVE RESEARCH AND DEVELOPMENT AND THE NEED FOR A TRITIUM ROADMAP

There are many common challenges facing the fusion community. The success of timely on-grid fusion power requires that information and experience is well communicated within the community, within the limits of commercial sensitivity. Well-communicated research approaches and interlinked research themes on these common challenges will increase the success rate on set timelines and will allow for targeted investments in research and development. Cross-cutting initiatives that prevent excessive and unnecessary duplication of efforts will therefore be hugely beneficial. While there have been a few recent roadmap exercises, these have been focused on specific device initiatives and timetables. There is, therefore, a strong need for a global roadmap to support the common challenges in the broader tritium fuel cycle community. The UKAEA is currently in collaboration with the International Atomic Energy Agency and conducting a landscape survey of the tritium community. UKAEA and CNL are collaborating with the Fusion Fuel Cycles and Blankets Workshop (2023) initiated by Commonwealth Fusion Systems to deliver a tritium roadmap.

V. CONCLUSIONS

The rapidly increasing private investment in the fusion sector and the growth of different fusion demonstrator concepts with ambitious delivery milestones can only have a positive impact on the realization of fusion power plants. However, this draws into focus the number of challenges involved in providing timely supporting tritium fuel cycles and infrastructure for continuous self-sufficient operation. This includes securing adequate tritium startup supplies, the development of breeder blankets and infrastructures, the development of tritium processing and waste handling technologies, engagement with regulators and industry, and growing the limited workforce with tritium knowledge. It should be recognized that these challenges are common to all tritium plants regardless of the specific reactor technology being demonstrated.

The substantial tritium handling and operation experience gained by UKAEA and CNL over the past decades will prove invaluable to the DT fusion community. It is essential that the community engage with and leverage this knowledge effectively. UKAEA plans to engage with stakeholders in the development of a fusion fuel cycle roadmap, which will provide an important step in identifying a common path forward.

Disclosure Statement

No potential conflict of interest was reported by the authors.

References

1. "The Global Fusion Industry in 2022, Fusion Companies Survey by the Fusion Industry Association," Fusion Industry Association (2022); https://www.fusionindustryassociation.org/copy-of-about-the-fusion-industry.
2. "European Research Roadmap to the Realisation of Fusion Energy," EUROfusion (2018); https://www.euro-fusion.org/eurofusion/roadmap/.
3. "Guidelines for the Transfers of Nuclear-Related Dual-Use Equipment, Materials, Software, and Related Technology," INFCIRC/254/Rev.12/Part 2; Nuclear Suppliers Group; https://www.nuclearsuppliersgroup.org/images/NSG_Part_2_2022.pdf (current as of Nov. 21, 2022).
4. R. J. PEARSON, A. B. ANTONIAZZI, and W. J. NUTTALL, "Tritium Supply and Use: A Key Issue for the Development of Nuclear Fusion Energy," *Fusion Eng. Des.*, **136**, *Part B*, 1140 (2018); https://doi.org/10.1016/j.fusengdes.2018.04.090.
5. J. C. SCHWENZER et al., "Operational Tritium Inventories in the EU-DEMO Fuel Cycle," *Fusion Sci. Technol.*, **78**, *8*, 664 (2022); https://doi.org/10.1080/15361055.2022.2101834.
6. M. KOVARI et al., "Tritium Resources Available for Fusion Reactors," *Nucl. Fusion*, **58**, *2*, 26010 (2017); https://doi.org/10.1088/1741-4326/aa9d25.
7. M. LORD, UK Atomic Energy Authority, "STEP Start-Up Tritium," Personal Communications (2022).
8. "ITER Research Plan with the Staged Approach (Level III – Provisional Version), Appendix I: Tritium Availability," ITER report ITR-18-003, ITER Organization (Sep. 2018).
9. N. TRANTEA, "Cernavoda Tritium Removal Facility Project Status and Plan," presented at the 13th Int. Conf. on Tritium Science and Technology (Tritium 2022), Bucharest, Romania, October 16–22, 2022.
10. "Certification for Type 8 Radioactive materials Package Design," U.S. Nuclear Regulatory Commission (May 18, 2021); https://www.nrc.gov/docs/ML2113/ML21138A943.pdf (current as of Nov. 21, 2022).
11. F. A. HERNÁNDEZ and P. PERESLAVTSEV, "First Principles Review of Options for Tritium Breeder and Neutron Multiplier Materials for Breeding Blankets in Fusion Reactors," *Fusion Eng. Des.*, **137**, 243 (2018); https://doi.org/10.1016/j.fusengdes.2018.09.014.
12. A. V. VERTKOV et al., "Comparative Analysis of Lithium First Wall Concepts for Tokamak with Reactor Technologies," *Plasma Phys. Rep.*, **47**, 1245 (2021); https://doi.org/10.1134/S1063780X21110258.
13. A. DE CASTRO et al., "Lithium, a Path to Make Fusion Energy Affordable," *Phys. Plasmas*, **28**, 050901 (2021); https://doi.org/10.1063/5.0042437.
14. "Managing Critical Isotopes: Stewardship of Lithium-7 Is Needed to Ensure a Stable Supply, United States Government Accountability Office (GAO), Report to the Ranking Member, Subcommittee on Oversight, Committee on Science, Space, and Technology, House of Representatives," Report GAO-13-716, U.S. Government Accountability Office (2013).
15. M. KEILHACKER, M. L. WATKINS, and JET TEAM, "D-T Experiments in the JET Tokamak," *J. Nucl. Mater.*, **266–269**, 1 (1999); https://doi.org/10.1016/S0022-3115(98)00811-3.
16. R. J. H. PEARCE et al., "New Safety and Technical Challenges and Operational Experience on the JET First Trace Tritium Experiment," *Fusion Sci. Technol.*, **48**, 274 (2005); https://doi.org/10.13182/FST05-A926.
17. R. J. HAWRYLUK, "Results from D-T Experiments on TFTR and Implications for Achieving an Ignited Plasma," *Phil. Trans. R. Soc. A.*, **357**, 443 (1999); https://doi.org/10.1098/rsta.1999.0336.
18. C. DAY et al., "The Pre-concept Design of the DEMO Tritium, Matter Injection and Vacuum Systems," *Fusion Eng. Des.*, **179**, 113139 (2022); https://doi.org/10.1016/j.fusengdes.2022.113139.
19. R. LASSER et al., "The Preparative Gas Chromatographic System for the JET Active Gas Handling System—Tritium Commissioning and Use During and After DTE1," *Fusion*

Eng. Des., **47**, 301 (1999); https://doi.org/10.1016/S0920-3796(99)00088-5.

20. D. PARK et al., "Dynamic Optimization of Cryogenic Distillation Operation for Hydrogen Isotope Separation in Fusion Power Plant," *Int. J. Hydrogen Energy*, **49**, 24135 (2021); https://doi.org/10.1016/j.ijhydene.2021.04.199.
21. J. ANDERSON et al., "Experience of TSTA Milestone Runs with 100 Grams-Level of Tritium," *Fusion Technol.*, **14**, 438 (1988); https://doi.org/10.13182/FST88-A25171.
22. C. TESCH et al., "Tritium System Test Assembly (TSTA) Stabilization," *Fusion Sci. Technol.*, **48**, *1*, 258 (2005); https://doi.org/10.13182/FST05-A923.
23. A. SANTUCCI et al., "The Issue of Tritium in DEMO Coolant and Mitigation Strategies," *Fusion Eng. Des.*, **158**, 111759 (2020); https://doi.org/10.1016/j.fusengdes.2020.111759.
24. A. ANTONIAZZI and C. WU, "Pathways to Tritium Emissions from CANDU Stations," CANDU Owner's Group (COG) COG-07-3060 (June 2009).
25. L. RODRIGO, "Tritium Emission Sources in Darlington Tritium Removal Facility," CANDU Owner's Group (COG) TN-09-3064 (Dec. 2009).
26. "JET Decommissioning and Repurposing," UK Atomic Energy Authority (Nov. 9, 2022); https://www.gov.uk/government/publications/jet-decommissioning-and-repurposing (current as of Nov. 23, 2022).
27. M. KRESINA et al., "Preparation of Commissioning of Materials Detritiation Facility at Culham Science Centre", *Fusion Eng. Des.*, **136**, *Part B*, 1391 (2018); https://doi.org/10.1016/j.fusengdes.2018.05.019.
28. "Toward Fusion Energy: The UK Government's Proposals for a Regulatory Framework for Fusion Energy," Department for Business, Energy & Industrial Strategy, UK Government (Oct. 1, 2021); https://www.gov.uk/government/consultations/towards-fusion-energy-proposals-for-a-regulatory-framework (current as of June 20, 2022).
29. "Review of the Canadian Nuclear Safety Commission's Regulatory Framework for Readiness to Regulate Fusion Technologies," Canadian Nuclear Safety Commission (CNSC), report RSP-762.1 (March 2022).
30. M. PAPADOPOULOU et al., "Exploring Regulatory Options for Fusion Power Plants," Publications Office of the European Union (2021); https://data.europa.eu/doi/10.2777/980320.