Use of Sensitivity Studies and Initial Safety Assessments to Rank Tritium Radiological Risk by Sub-System for the STEP Fuel Cycle

Adam Cooper, Tritium Capabilities Lead (STEP Fuel Cycle), UK Atomic Energy Authority, Culham Campus, Abingdon, OX14 3DB

Michael Lord, Head of Engineering (STEP Fuel Cycle), UK Industrial Fusion Solutions, Culham Campus, Abingdon, OX14 3DB

Within the Spherical Tokamak for Energy Production (STEP) fusion power plant, the primary objectives of the Fuel Cycle are to remove and process the plasma exhaust and reinject any unspent fuel, within a continuous and contained system that has minimal discharge to the environment. Fusion fuel cycles are complex systems, with many technologies used to detritiate many working fluids, and there are many parameters that influence the expected discharge to the environment. The STEP Fuel Cycle team have used an Atmospheric Dispersion Model and undertaken a number of sensitivity studies to identify the powerplant, sub-system and flow parameters that influence the tritium-to-stack discharge levels. In parallel, the fuel cycle team have also assessed unmitigated tritium inventory releases from the fuel cycle major sub-systems. The steady-state mass balance modelling of the STEP Fuel Cycle was undertaken with a range of outputs feeding into the stack dispersion model using Advanced Dispersion Modelling Software (ADMS-6). The study found that, of the fuel cycle sub-systems, the efficiency and functional performance of the Hydrogen Purification and Recovery System (HPR) and Water Detritiation System (WDS) had the greatest impact on stack emissions. Stack height also had a significant contribution, as did the efficiency and functional performance of the Gas Detritiation System (GDS) and Air Detritiation System (ADS) sub-systems.

The initial tritium radiological safety assessment for unmitigated inventory release, provides a higher fidelity assessment of relative sub-system radiological risk than simply equating the sub-system risk directly to the sub-system tritium inventory. The results of the sensitivity study and initial radiological safety assessment will allow the STEP Fuel Cycle team to focus future work to ensure that design-for safety and design-for-environment are appropriately targeted. For example, system optimisation, modelling efforts and technology development can be focused effectively to minimise the discharge to the environment during conventional plant operations.

Introduction

The Spherical Tokamak for Energy Production (STEP) programme is a UK-led initiative to design and build the UK's first prototype fusion energy plant in West Burton, Nottinghamshire. Although it is generally accepted that the worst-case hazard is lower for fusion than for fission, the hazard profiles are fundamentally different for each plant type. One of the major hazards present in most fusion power plants is the presence of tritium, a radioactive gas, which is required in significant quantities to facilitate deuterium-tritium fusion.

Tritium emits low-energy beta particles that are unable to penetrate the skin. Elemental tritium and its isotopologues therefore pose a relatively mild external radiological hazard, Nonetheless, particular attention must be given to the high mobility of tritium when in gaseous form. Moreover, the radiological hazard is significantly increased when tritium is present in complex-compound and / or aqueous form due to greater biological uptake.

The STEP fuel cycle (Lord, 2024) conducts several functions which are represented at a high level in Figure 1. The sub-systems of the fuel cycle handle tritium in a variety of chemical forms and concentrations, depending on the application. Since only a small fraction of injected fuel undergoes fusion, and due to tritium's scarcity and environmental impact, the fuel cycle must be designed to achieve high recovery and recycling efficiency. Nonetheless, some quantity of tritium will be released from the fuel cycle during standard operations due to practical limitations in processing technologies. These emissions will be reduced in accordance with as low as reasonably practicable (ALARP) and best available technique (BAT) principles, but it is not always clear which measures are most effective in reducing these given the first-of-a-kind nature of fusion plants and the complexity associated with integrating many sub-systems within an architecture of multiple loops. Similarly, sub-systems within the fuel cycle will each have a tritium inventory which could be released in an accident scenario.

Processing systems within the STEP fuel cycle can be categorised into four main functions:

1) Extraction of tritium from breeder blankets and recovery from coolants
    a. Tritium is produced in-situ within the tokamak through lithium neutron capture to generate additional fuel and assure self-sufficiency.
    b. A fraction of the breeder blanket tritium will permeate into the blanket and plant coolants with undesirable tritium transport exacerbated by high partial pressures and temperatures. Hence there is a functional requirement for the fuel cycle to recover tritium from the blanket and coolants undertaken (respectively) by the Tritium Extraction System (TES) and Coolant Detritiation Systems (CDS).

2) Injection and rapid recycling of fuel

   a. Fuel is prepared by the Fuel and Gas Control (FGC) system and injected via the Matter Injection (MI) systems into the tokamak where the fusion reaction takes place.

   b. With a high proportion of the injected fuel exhausting the confined plasma without having fused, there is remains a functional requirement to continuously exhaust the unspent fuel to prevent excessive plasma dilution from the fusion product ^{4}He. The vacuum pumping system (VPS) ensures the tokamak chamber is held to ultra-high vacuum to prevent plasma dilution and also acts to undertake the first level of separation of the bulk unspent fuel from the helium and fuel additives. It is advantageous to direct the bulk unspent fuel back to the injection systems with minimal processing to reduce the plant tritium inventory. This is facilitated by the technology choices for the VPS and backed by the downstream Recycle Clean-up System (RCS) which purifies the recycled fuel via further rapid processing.

3) Isotope adjustment and purification

   a. Fuel which is not recycled within the rapid recycling loop is processed by the hydrogen purification and recovery (HPR) system, which selectively separates hydrogenic from non-hydrogenic species. The hydrogenic feed is then sent to the isotope adjustment system (IAS) where the isotopic ratio is tuned to meet the tokamak fuelling requirements.

   b. A further set of systems are present to remove and manage seeded impurities from the fuel gas. Seeded impurities are added to the fuel to assist with heat management of the plasma and these species need to be removed from the exhaust by a series of sub-systems. These sub-systems are expected to contain little tritium but will contain other neutron-activated species which require management and processing.

4) Detritiation, recovery and concentrating systems

   a. The "tritium recovery" systems primary function are to protect the environment by removing tritium present in low concentrations in a variety of process streams. The recovered tritium is concentrated and processed into a useful form then fed back to the FGC.

   b. The gas detritiation system (GDS) removes tritium from tokamak gases which have not been recovered by previous processes, to ensure that tritium levels are ALARP and suitable for release to the stack. Tritium is converted to water for capture and then transferred to the water detritiation system (WDS) for recovery back into elemental tritium.

   c. The air detritiation system (ADS) recovers tritium, which has permeated or escaped into containment atmospheres and the surrounding plant room air. Again, tritium is captured as water and transferred to WDS. It is common to convert and capture tritium as water because, in many cases, the selectivity and effectiveness of heavy water processing methods are much higher than for gaseous tritium

   d. The WDS processes tritiated water received from several process gases and returns it to gaseous tritium before it is further isotopically concentrated within the trace tritium recovery (TTR) system..

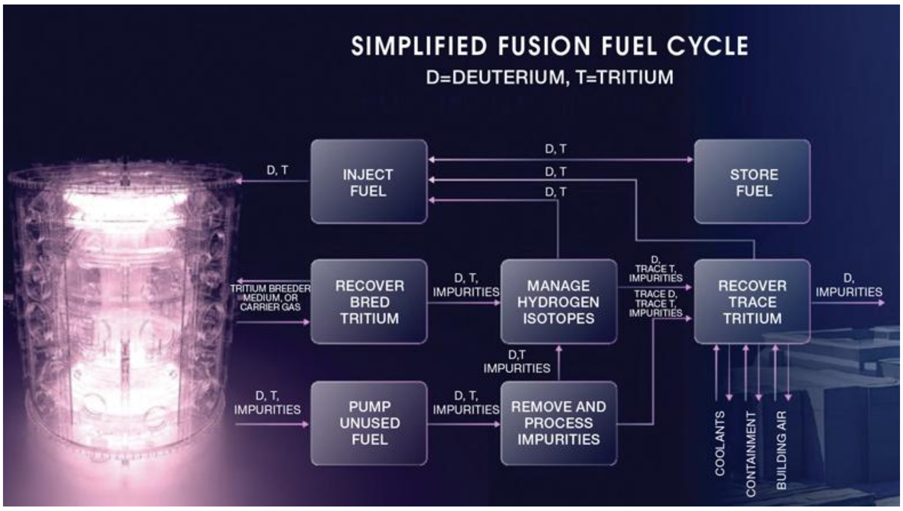

Figure 1 – Diagram of a fusion fuel cycle which shows a simplified but accessible illustration of the main fuel cycle functions

It is valuable at an early stage of design to assess the predicted dose consequences of worst-case tritium release events such that the relative hazard within the fuel cycle can be established. This provides valuable context to system designers and allows the prioritisation of safety measures. Similarly, early activities to assess the relative impacts of fuel cycle parameters on tritium emissions under normal operating conditions is a valuable activity in deciding where best to direct development effort to ensure that BAT is demonstrated and that emissions are reduced.

Methodology

Radiological Safety Assessment

The initial radiological safety assessment consisted of a structured approach with the following steps. Firstly, the expected tritium inventories within both fuel cycle sub-systems and the cumulative tritium inventories for the overall fuel cycle were defined. Worst case unmitigated conditions were then defined for each sub-system that were evaluated under a ground-level tritium release scenario, assuming complete conversion of HT to HTO – a conservative estimate for fire or explosion events. Non-stack adjacent sub-systems were also assessed for a ground level release with complete conversion of HT to HTO, but with a decontamination factor (DF) of 10 applied. A DF was applied on the basis that the facility and structures provide a degree of tritium hold-up which reduces the discharge. Stack-adjacent systems were assessed for a tritium release via the stack with complete conversion of HT to HTO with no DF applied. Assuming complete conversion of HT to HTO is a typical conservative estimate for fire and explosion scenarios.

Air dilution coefficients were then calculated for members of the public in accordance with NRPB-91 (Clark, 1979) using Category F weather for ground level releases and the maximum of categories A, B, E and F weather for stack release scenarios. The effective release height is taken as 1/3 of the stack height to account for mixing into the wake of the building. Dose consequences due to inhalation and skin absorption of tritium for members of the public are calculated according to internal UKAEA standards.

Sensitivity Study

The sensitivity study quantified how sub-system performance parameters influence public dose, thereby outputting guidance for design optimisation and environmental protection prioritization. The outcome of the study means the fuel cycle design team is better placed to focus its efforts during the design definition phase on improving modelling accuracy and optimising sub-system performance of the sub-systems systems and the plant parameters which have the greatest effect on minimizing emissions. This is in accord with the application of as low as reasonably practicable (ALARP) and best available technique (BAT) principles.

A mass balance model was developed based on a simplified flowsheet of the fuel cycle. A range of pessimistic, nominal and optimistic tritium recovery fractions was derived for each sub-system based on expert assessment from the sub-system owners. The degree of low-level tritium loss from sub-systems into the surrounding room air was also accounted for. The model was used to calculate the expected tritium emissions from each scenario which was used as an input into the air dispersion modelling.

Before running a full parameter sweep, an initial coarse screening of dispersion modelling inputs was conducted to elucidate which values and settings would be worth including within the sensitivity study. Then a baseline model of the West Burton site was developed. The model was kept constant throughout all analysis other than the variables under investigation: HT/HTO emissions, stack height, stack diameter, stack efflux velocity, and stack temperature. The model includes receptor points at nearby population centres as well as footpaths on the boundary of site.

Due to the large number of permutations to be assessed, setup and analysis of the dispersion models was automated via the development of a custom MATLAB script. For the parameters of interest, the script 1) calculates all permutations, 2) identifies the set of unique emissions (noting that many permutations of sub-system performance result in similar emissions and can therefore be grouped to reduce computational time) and 3) generates the necessary dispersion model files using a template baseline model.

Dispersion modelling was then conducted via gaussian plume modelling in ADMS 6 (CERC, v6.0.0.1). ADMS 6 outputs the long-term average concentration of HT and HTO in Bq m^{-3} based on real-life meteorological conditions (data from the nearby RAF Scampton site from 2021 was used). Analysis and conversion of the results to a dose was again automated via a custom MATLAB script. Doses were calculated for each of the receptor sites identified, as well as the maximum dose across all modelled areas. Dose calculations were conducted in accordance with the procedures described in ICRP-119 (Eckerman, 2012).

The data was then analysed via a design of experiments (DoE) approach using Minitab (v21.2) through which statistical analysis was conducted to determine the relationship between the input factors (i.e. sub-system performance and stack parameters) and outputs (i.e. dose to the public).

Discussion

Radiological Safety Assessment

As expected, dose consequences to the public were found to be significantly higher for the scenarios in which the conversion of HT to HTO was assumed. This is because the radiological hazard of HTO is known to be much greater than HT due to the enhanced ability of the body to uptake tritium in water form. Conversely, when HT is inhaled the vast majority is again exhaled thus limiting the dose consequences to an individual. Tritium is a low energy beta emitter in which the beta particles have insufficient energy to penetrate the epidermis. These findings highlight the importance of minimising the formation of HTO from HT where practical. With the STEP plant likely to contain tritiated water coolants and with fuel cycle systems deliberately oxidising HT to HTO in order to benefit from the highly effective means of using water to capture tritiated species when other gases are present, it is not expected that the hazard can be eliminated. Nonetheless efforts should be taken to reduce onsite tritiated water volumes and concentrations.

Furthermore, the release of HT caused by, or followed by, a fire or explosion poses a serious hazard not only due to the explosion itself but also the oxidation of the HT present. Many fuel cycle processes are operating at low or ambient temperatures with tritium gas present and therefore any potential release of tritium should be prevented from encountering high temperatures or an oxygenated environment. Fortunately, most tritium systems are expected to employ an extra layer of passive containment, in addition to the process pipework, termed secondary containment. This is typically a stainless steel shell within which there is an inert gas environment. Leaks or pipework breaches within the primary containment are released into the secondary containment which provides a dual role of recovering tritium and preventing the formation of explosive environments. Nonetheless, secondary containment faults or internal process hazards may still lead to containment breaches for which HTO formation is the main driver of radiological hazard.

Similarly, the assessment found that directing releases via the stack to promote greater dispersion significantly reduces ground level concentrations experienced by members of the public close to the plant. Dose results in these scoping calculations indicate the reduction to be approximately one order of magnitude. It is expected that most process faults will not lead to a significant event which would breach the confines of the building and would instead result in the release of radiological gases through the ventilation system eventually resulting in stack release.

The segregation of tritium inventories is also an important consideration. Some fuel cycle sub-systems, such as vacuum pumping, and isotope adjustment, will require many individual units to meet the required process flow-through and therefore present a good opportunity to reduce safety consequences through appropriate segregation. The separation of tritium inventories in different sub-systems is likely to be an important aspect of the safety case. Ideally, when a fault occurs the associated release should be as small as possible. Further consideration is required as to assure the independence of adjacent but segregated systems and to prevent common mode failures. One example considered is the potential overpressure of one system from which, if not appropriately mitigated, might lead to fragment damage to an adjacent system. In this scenario, the segregation of the adjacent tritium inventories is in question if pressure protection is not sufficient. Ensuring the segregation of isolatable tritium inventories is therefore dependent not just on the means for isolating process units, but also the assessment method and mitigation measures necessary to assure the segregation of these inventories is maintained under fault conditions.

Finally, the assessment identified two areas which may pose significant safety challenges – the tritium extraction system (TES) and the tokamak first wall. Both systems are highly integrated into the tokamak complex and exhibit high tritium inventories for which there is likely to be significant uncertainty in the precise inventory during operations. Furthermore, the tritium present is expected to be in chemically and physically complex forms and will be operated at high temperature by design. These areas require particular attention in future work but are challenging to assess due to the high level of uncertainty and low level of maturity in the current design of the respective fuel cycle sub-systems that shall manage the tritium concentrations in the first wall and blanket.

Sensitivity Study Results

The tritium recovery performance under steady state operations of several of the sub-systems assessed were found to have a relatively small or negligible impact on dose to the public. The efficiency of tritium extraction from the blanket purging gas and from the coolant streams were largely unimportant to stack emissions due to the assumptions used in this work. Both the blanket purging and coolant streams are predominantly closed loop systems and therefore tritium which is not extracted simply remains in the purge gas or coolant. Although this has implications on the required flow rates and/or the achievable tritium inventories (and thus safety in off-normal events), the impact on emissions is minimal. Similarly, the required rate of tritium extraction from the coolants and the purge gas is relatively low when compared to other flow rates in the fuel cycle. It is important to note that this work assumed no leakages, whereas some coolant configurations in the fission industry are known to be an appreciable percentage of the total coolant.

The performance of systems which are near to the tokamak were typically also found to exhibit a relatively small impact on dose received by the public. The vacuum pumping and recycle clean up systems process large flow rates of tritium gas but are separated from the stack under normal conditions by at least two downstream detritiation systems. As such, variability in their performance is more easily mitigated by recovery of any excess tritium in these systems.

However, the hydrogen purification and recovery (HPR) system, which is located immediately downstream of the vacuum pump and recycle clean up systems, was found to have a very significant impact. HPR is responsible for removing impurities from a large flow rate of tritium gas and re-directing most of the flow back for re-injection before passing any remaining tritium to the lower concentration, lower flow rate "Tritium Recovery" systems. Although HPR is not stack adjacent, its performance was more impactful on reducing dose to the public than any of the stack-adjacent systems apart from water detritiation (WDS). For the parameter ranges tested, the impact of HPR (Figure 2) was more significant than a change in stack height. Although the exact reasons for its ranking cannot be elucidated from the data, it is assumed that its large impact occurs due to the large flow rates of tritium flowing through this sub-system and the greater degree of uncertainty associated with its performance due to the novelty of the technology. The "pessimistic" recovery fraction implemented for HPR was 90% whereas this value was typically 99% for most other sub-systems.

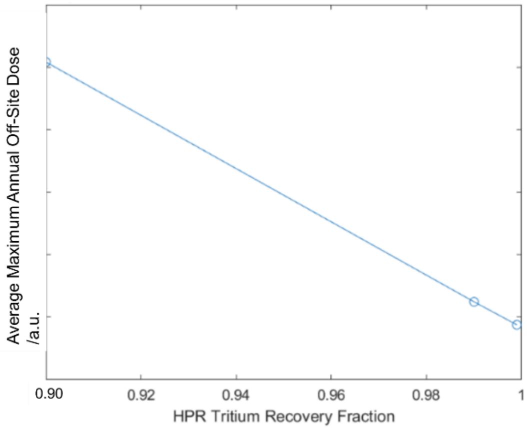

Figure 2 – Interaction plot showing the effect of HPR tritium recovery fraction on the normalised annual off-site dose across all permutations. The y-axis is normalised to the same scale for all figures presented in this paper to allow direct comparison.

Of the stack adjacent systems, WDS has the largest tritium flow rate. It is therefore unsurprising that its performance has a large impact on stack emissions (Figure 3). The role of WDS is to take a range of HTO streams from different sub-systems and convert them into a tritium-enriched gas phase which is returned to the fuel cycle for further processing and re-injection, and a tritium depleted/detritiated gas phase which is of suitably low tritium concentration to release to the stack. The role of WDS is crucial as upstream detritiation systems typically remove tritium from their respective process gases by converting HT to HTO and then capturing this HTO. The HTO must be effectively converted back to tritium gas in WDS to close the fuel cycle loop. The development and performance verification of WDS technology is therefore expected to be a critical factor in assuring the safety and environmental performance of the fuel cycle.

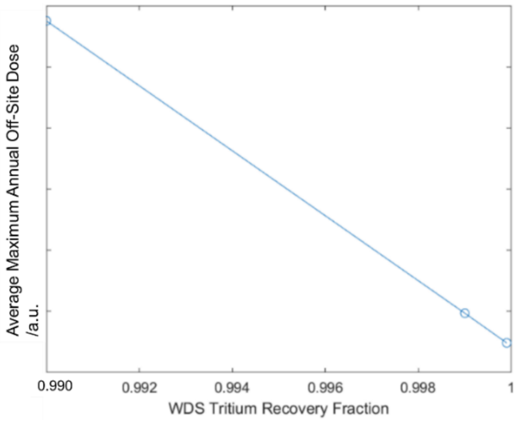

Figure 3 – Interaction plot showing the effect of WDS tritium recovery fraction on the normalised annual off-site dose across all permutations. The y-axis is normalised to the same scale for all figures presented in this paper to allow direct comparison.

Stack height (Figure 4) also had a large effect on the calculated dose received by members of the public. An increase in stack height from 80m to 130m led to a decrease in dose received by almost four times. This is concordant with previous findings where ground release was indicated to lead to approximately one order of magnitude greater in dose when compared to stack release. Stack height is therefore a powerful parameter in reducing potential radiological harm to the public in both normal and off-normal conditions, but consideration must be given to the diminishing returns and increasing cost as height increases. More analysis of stack height and associated costs is required to demonstrate BAT.

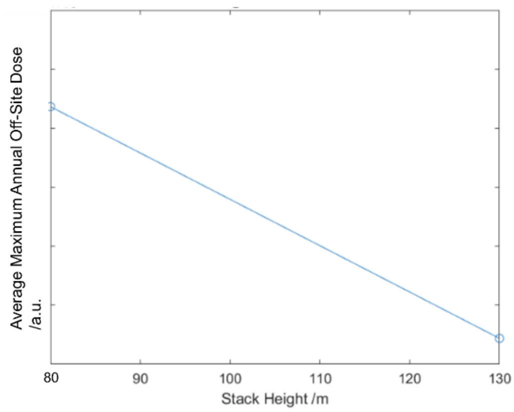

Figure 4 – Interaction plot showing the effect of WDS tritium recovery fraction on the normalised annual off-site dose across all permutations. The y-axis is normalised to the same scale for all figures presented in this paper to allow direct comparison.

Though assessed, the effect of efflux temperature and stack diameter (which consequently affects efflux velocity for a fixed flow rate) was found to be minimal (Figure 5). Consideration should be given to the importance of stack diameter when buildings are included in future dispersion models. Efflux velocity, as a proxy for diameter, can have significant impacts on building wake formation and downwash and thus on dispersion in the surrounding area.

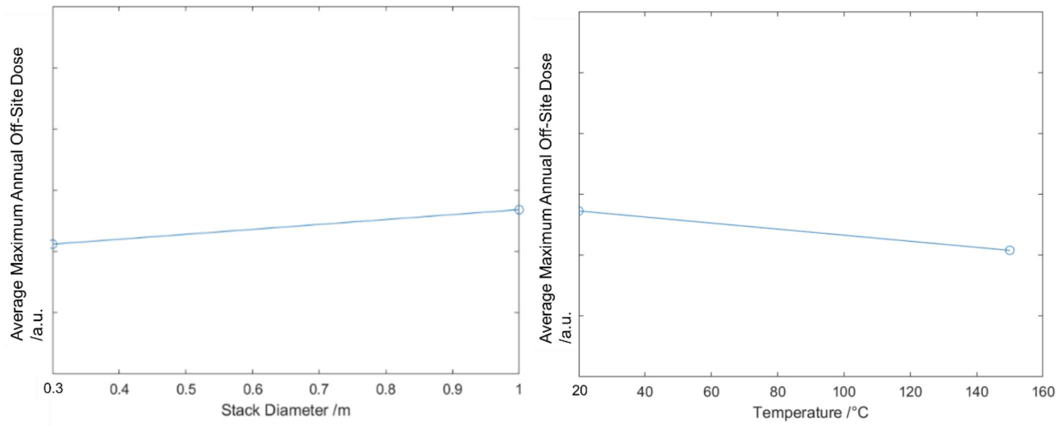

Figure 5 – Interaction plot showing the effect of stack diameter (left) and efflux temperature (right) on the normalised annual off-site dose across all permutations. The y-axis is normalised to the same scale for all figures presented in this paper to allow direct comparison.

Sensitivity Study Limitations

Despite the valuable insight from the sensitivity study results and outcomes it is important to frame the study by noting several key limitations. Firstly, the performance of each sub-system was treated with a single recovery fraction whereas sub-system's performance will often be determined by a series of physical/and or chemical transformations and the fidelity of this work gives little indication as to which of these individual processes plays the most important role. Although this work has identified the sub-systems which have the greatest impact, further analysis is required regarding the development or validation work which is necessary to obtain or improve the expected performance. One aspect of this is lack of differentiation between Q_2 and Q_2O in the model fidelity. Though the previous analysis has shown that tritiated water is the main driver of radiological hazard, the nature of some sub-systems may mean that it is more effective to have a lower overall recovery fraction if the Q_2O content in any unrecovered gas is reduced i.e. to favour high efficiency for capturing tritiated water over high efficiency of converting Q_2 to Q_2O.

Secondly, the methodology used does not consider the likelihood of any particular scenario and weights all options equally. The analysis results may therefore be biased by extremes in the dataset which are feasible but unlikely opposed to feasible and more probable. Future work would benefit significantly from assigning a probability to each scenario such that a distribution could be obtained giving information on not only the most likely results, but also the variance that might be expected due to specific sub-system performance.

Thirdly, due to a lack of sufficient design data at the time of the study, buildings on the site are not modelled and the stack is in isolation. Buildings can have a significant effect of tritium dispersion through effects such as downwash and wake formation and therefore the absence of buildings may have unrealistically improved or reduced the impact of stack parameters when compared to fuel cycle parameters. Future work intends to incorporate these buildings as design information becomes available, at which point the findings from this study will require reassessment. Moreover minimising environmental discharges to population centres will be a key factor in determining the positioning of the plant on the West Burton site as well as the orientation of those buildings.

Finally, the method for determining stack emissions for each scenario was via expert assessment of likely performance from sub-system owners, coupled to a mass balance. One obvious piece of further work is to improve and validate individual sub-system models but also to construct and apply an integrated fuel cycle process model. An integrated process model (which is under development) could link specific sub-system parameters to potential public dose and more readily provide the capability for architecture optioneering to reduce the environmental and safety consequences of the fuel cycle.

Conclusions

The presented sensitivity study serves to identify key overarching safety principles and the most significant levers for reducing emissions within the STEP fuel cycle architecture. This understanding will inform the safety-by-design and design-for-environment approach and enable appropriate prioritising of development and validation activities to ensure the safety and environmental consequences of the STEP fuel cycle are demonstrably BAT and ALARP. The sensitivity study has identified main outcomes which will aid designers with hazard management during the development of the STEP fuel cycle and plant.

1) Minimising the Formation of HTO and Optimising HTO Handling Sub-Systems

Minimising the formation of HTO, where practical, will have a significant impact on the dose received. Systems which handle inventories of HTO must have robust measures in place to prevent the spread of material under fault scenarios, and measures must be in place for all other systems handling tritium gas to prevent exposure to ignition sources and oxygenated environments.

2) Application of a Stack and Inventory Segregation

HPR and WDS were identified as the sub-systems which, for the assessed performance range, had the greatest impact on stack emissions and dose received by the public, and the effect of stack height is broadly equivalent and thus warrants further analysis to establish the appropriate cost-benefit curve of increased stack height. Also identified was the importance of engineering ventilation systems to direct tritium releases up the stack and mitigating against ground-level releases. This effect can be compounded by appropriate segregation of tritium inventories, particularly where this is easily implemented by sub-system architecture, to minimise the releasable tritium inventory. However, the use of appropriate protective measures and rigorous substantiation is critical to assure the segregation of these tritium inventories under fault conditions and avoid the potential for common mode failures of isolated process units.

3) Scope for Future Work

The sensitivity study has several key limitations leading to modelling improvements which could be readily implemented in future implications. These include improving the mass balance fidelity to capture individual process steps within sub-systems, differentiating between the speciation of tritium gas vs tritiated water, the inclusion of buildings in future dispersion models, and linking sub-system performance to validated property data within an integrated fuel cycle model.

Acknowledgements

This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.

The authors would like to recognise and thank the many individuals who contributed to or supported this work: Omar Afify, Alicia Buck, Hazel Connelly, Mark Hinchcliffe, Warren Lee, Tim Lowe, Toby Meatyard, Ajmal Mohammed, David Perry

References

Clarke, R. H., 1979, A Model for Short and Medium Range Dispersion of Radionuclides Released to the Atmosphere, National Radiological Protection Board, NRPB-R91

Eckerman, K., Harrison, J., Menzel, H-G., and Clement, C. H., 2012, Compendium of Dose Coefficients based on ICRP Publication 60, ICRP-119

Lord, M., Bennett, I., Harrington, C., Cooper, A, Lee-Lane, D., Cureton, A., Olde, C., Thompson, M., Jayasundara, D., and Meatyard, T., 2024, Fusing together an outline design for sustained fuelling and tritium self-sufficiency, *Philos. Trans. R. Soc. A*, 382, 20230410