ARC reactor: A preliminary tritium environmental impact study

ARC reactor: a preliminary tritium environmental impact study

Samuele Meschini*, Raffaella Testoni, Stefano Segantin, Massimo Zucchetti

Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, Turin, Italy

**Corresponding author: samuele.meschini@polito.it*

The fusion pilot power plant ARC is a conceptual design of a D-T Tokamak under investigation at the Massachusetts Institute of Technology. Special attention is paid on the radiological hazard, which until now has been translated in the reduction of materials activation. Indeed, one of ARC main goals is to be fast deployable in any US site: thus, the radiological risk associated to its presence must be minimized, both for the population and the environment. Tritium is one of the main sources of radiological hazard in ARC and it is almost ubiquitous: it is found in the vacuum chamber, in the blanket, in structural materials and in tritium processing and storing components. In this work, a safety analysis is proposed to quantify the radioactivity release following an accidental scenario. Tritium inventories in the main components are estimated starting from the preliminary design of the FLiBe circuit. The source term is quantified assuming the occurrence of a severe accident damaging key components. Afterward, the environmental impact and the doses to the most exposed individuals are evaluated through suitable population doses codes, and ARC compliance with safety limits is assessed.

Keywords: ARC reactor, Tokamak, Safety, Tritium, Radiological release

1. Introduction

ARC (Affordable Robust Compact) reactor has undergone extensive studies in the field of plasma physics [1], heat management [2], materials activation [3] and power production [4]. Results are very encouraging, paving the way for the new reactor design that exploits high temperature superconductors. Furthermore, ARC features a molten salt (FLiBe) breeding blanket, which presents many advantages compared to solid breeders, such as no radiation damage from the high energy neutrons. However, fusion reactors like ARC not only have to demonstrate the technical feasibility, but also the compliance with safety limits when considering radiations and radionuclide releases to the environment. For fusion reactors relying on D-T fuel mixture, tritium presence is one of the main concerns from the safety viewpoint. Indeed, tritium is almost ubiquitous: it is found in the vacuum chamber, in the FLiBe liquid breeder, in structural materials and in tritium processing and storing components. System failures may lead to the release of a fraction of this tritium, with an evident danger for both the environment and the population. Thus, estimating tritium inventories is the starting point for an environmental impact and safety analysis. A preliminary tritium inventory assessment was already carried out for ARC [5]. This work presents a more detailed analysis that focuses on the FLiBe tank and the tritium extractor. Since the tritium extractor technology for ARC has not been chosen yet, three possible alternatives are investigated. Upon the quantification of tritium inventory in the FLiBe tank and tritium extractor, the consequences of accidental scenarios involving the failure of these components have been studied. The early dose and the one-year dose to the population are chosen as figures of merit to assess the severity of such failures.

2. Methodology

ARC is still in a conceptual design phase. As such, many technological choices and most of the required data for a precise assessment are not available yet. Nevertheless, inventories can be estimated and accidents analysed starting from the reactor operating parameters ([1], [2]). The analysis has been performed according to the following steps:

- Estimation of tritium inventory in the FLiBe tank;
- Estimation of tritium inventory in the tritium extractor;
- Comparison of the identified tritium extractor technologies;
- Selection of a possible site for ARC and identification of the Most Exposed Individuals (MEI);
- Quantification of the early dose and the one-year dose to the MEI following an accidental release.

The main hypotheses made in this work are:

- The reactor is operating at nominal, steady-state conditions;
- Tritium permeation and diffusion from FLiBe to the surrounding structures are neglected. The tritium trapped in structural materials may be released in case of severe accidents, but the accidents considered in this analysis do not lead to such consequences;
- Buoyancy and MHD effects are neglected to estimate the tritium inventory in the FLiBe tank. To properly account for thermal and MHD effects a detailed CFD analysis is required. However, a CFD analysis is beyond the scope of this work.

A brief description of the two main components involved, the FLiBe tank and the tritium extractor, is presented in sub-sections 3.1 and 3.2, respectively. The model used to compute the dose to the population is described in the remainder of this section.

2.1 Tritium release, siting and dose to the population

Safety calculations should proceed in parallel with system design. This allows to highlight criticalities and safety issues in time to avoid huge modification on design in advanced phases. In light of this, a possible release scenario is investigated for both the FLiBe tank and the tritium extractors. Following a failure of these

systems, all the FLiBe is assumed to escape the primary containment. This study neglects the presence of a secondary containment in order to verify its actual necessity. Hence, the whole amount of tritium present in the FLiBe is released to the atmosphere in its most dangerous form, namely HTO. To perform dose calculations, ARC has been located at the Pilgrim Nuclear Power Station site, in Massachusetts. This is a reasonable choice, being the site already nuclearized. Meteorological data for the selected site are available at [6]. The predominant atmospheric stability class at the site is class D (47% of occurrences). Hence, stability class D is chosen for the simulation. Stability class D features an average wind speed of 1.5 m/s at the release height of 10m. The plume dispersion has been simulated by taking advantage of HotSpot [7], developed at the Lawrence Livermore National Laboratory. HotSpot provides a user-friendly interface with a dedicated module to compute the early dose to the population following a tritium release. The tritium release, which is assumed to be instantaneous, occurs at a height of 10m.The Most Exposed Individuals have been identified with the closest residents, living at 800m from the site. For them, the early dose was computed with HotSpot, while the one-year dose, which accounts for the effect of a longer exposure following the plume passage, has been estimated through GENII-v2 [8]. GENII was developed at Pacific Northwest National Laboratory (PNNL) to incorporate models recommended by the International Commission on Radiological Protection (ICRP) and the radiological risk estimating procedures of Federal Guidance Report 13 [9]. Compared to HotSpot, GENII-v2 allows for a deeper analysis, including dose calculation by accounting for different exposure pathways. Considering the exposure pathways becomes crucial when the exposure time is increased from hours (early dose) to a year (one-year dose). The exposure pathways considered are food ingestion, external air inhalation and indoor air inhalation. GENII-v2 default input values for food ingestion rates, population diet, external and internal air exposure time have been used. Those values can be considered representative of the average member of U.S. population. Coefficients from ICRP-30/48 were selected for the health impact assessment.

3. Main components description

3.1 FLiBe tank

ARC blanket design foresees cooling channels with a diameter of 2cm and a huge FLiBe tank [1], which acts both as breeder and shielding. To ease the notation, when referring to the tank or the FLiBe inside the tank, also the channels and the FLiBe inside the channels are considered. The tank volume is 350m^3, according to the ARC-2018 MCNP model described in [2]. Almost all the tritium is produced inside the FLiBe channels and tank, due to the reaction Li(n,T)He. The tritium inventory inside the tank and the structural materials is then affected by tritium transport phenomena: as a first approximation, tritium transport is governed by the FLiBe flow, diffusion and permeation. At the same time, FLiBe flow is complicated by the presence of MHD and buoyancy effects. In line with the preliminary nature of the work, both MHD and buoyancy effects have been neglected. Hence, tritium transport is assumed to depend on FLiBe flow only. Under these assumptions, the FLiBe flowing time can be estimated as the ratio between the total mass of FLiBe inside the tank, M_{FLiBe}, and the mass flow rate, $\dot{m}_{FLiBe}$. In ARC, $M_{FLiBe} = 7.0 \cdot 10^5$ kg and $\dot{m}_{FLiBe} = 2.2 \cdot 10^3$ kg/s. Therefore, the FLiBe flowing time is 318s. Once the flowing time is known, the tritium mass in the tank is computed by multiplying the tritium production rate by the FLiBe flowing time, which leads to a mass of 0.32g of tritium. These values are the reference for the accidental release analysis. Input data for the tank analysis are reported in Table 1.

Table 1 - Input data for the tritium inventory estimation in FLiBe tank.

	Value	Unit of measure
Fusion power [2]	525	MW
Tank volume	350	m^3
FLiBe inlet temperature [2]	800	K
FLiBe outlet temperature [2]	900	K
FLiBe average density [10]	2400	kg/m^3
FLiBe average specific heat [11]	2005	J/kg/K
Tritium burn rate [5]	$9.3 \cdot 10^{-7}$	kg/s
TBR [2]	1.08	-

3.2 Tritium extractors

Once the tritium is generated in the breeding blanket, it must be extracted from the FLiBe flow. A dedicated component in the FLiBe loop carries out this function, namely the tritium extractor. Different mechanisms can be exploited to extract tritium from the main flow. Since for ARC no technology has been defined yet, three possible solutions have been investigated: permeation window, gas-bubble column and vacuum disengager. Other technologies commonly used in the chemical industry, such as metal getter bed, solvent extraction or cold trapping, are not applicable to tritium extraction [12]. Indeed, a huge and expensive apparatus would be required for the extraction parameters of interest if these technologies were used. Two parameters have been chosen as figures of merit to compare the extractors: the volume occupied by the system and the timescale involved in the extraction process. Extraction efficiency was considered as well, but a direct comparison is not possible due to the absence of literature data for the permeation window.

A double-cylindrical-tube-type permeation window is considered in this work. The permeation tube technology takes advantage of tritium diffusion: in a double-cylindrical tube, FLiBe flows in the inner tube upstream, while a purge gas, usually He, flows downstream in the annulus. The outer wall is impermeable, while the inner is permeable, to allow for tritium permeation from FLiBe to He flow. Relevant quantities for the evaluation of the exchange area can be found in [12]. It is important to note that the model described in [12] provides the exchange area to achieve a given tritium extraction flux. No values for the efficiency of this system are reported.

Gas-bubble column exploits the enhanced mass transfer between the fluid flow and the gas bubbles. The fluid flows downstream in a column, while a gas (He) is injected from the bottom of the column. The injected gas starts forming bubbles, which greatly improves mass transfer between the gas and the fluid. Tritium is caught by the bubbles and finally extracted. A very detailed description of this system can be found in [13]. Extraction efficiency is reported to be 99.9998% with a 64s contact between FLiBe and He [14].

In vacuum disengager, FLiBe falls through a column, in droplets. Tritium inside FLiBe droplets can thus diffuse to the droplet surface and escape as free gas. The tritium in gaseous form is then pumped out of the column. Analytical solution for tritium extraction can be found in [15]. The theoretical extraction efficiency for one stage is around 99.7%, for a two-stage system is 99.999% [16] (system designed for the extraction of about 380 g/day). Information about system dimension can be found in [16]. Additional information on the working principle and data can be found in [17]. The reference parameters for the tritium extractors analysis are reported in Table 2.

The design parameters of the extractor affect the tritium release in case of accidents. Furthermore, routine tritium leakages are also dependent on the extraction efficiency. In fact, the tritium that is not removed from

FLiBe can easily permeate the tubes of the heat exchangers, located downstream of the extractor. The heat exchanger can be equipped with a permeation barrier that stops tritium permeation, with efficiencies up to 99.5% [18]. The remaining 0.05% is lost to the environment if additional safety measures (e.g., filters) are not implemented. For the present analysis no additional safety measures are assumed.

Table 2 - Tritium extractors design parameters.

	Value	Unit of measure
Permeation window [12]		
Inner tube diameter	2	cm
Inner tube thickness	0.1	cm
Inner tubes per outer tube	64	-
Gas-bubble column [14]		
Height	5	m
Diameter	2	m
Extraction efficiency	99.9998%	-
Contact time	64	s
Vacuum disengager [16]		
Height	5	m
Diameter	2	m
Efficiency 1 stage	99.7%	-
Efficiency 2 stages	99.999%	-

4. Results

4.1 Tritium extractors comparison

Results for the different tritium extractor technologies are shown in Table 3 and Table 4. Concerning the permeation window, it is likely that a huge exchange area would be required. The exchange area depends both on the pipe materials and the tritium molar fraction in FLiBe. Regarding the materials, a ferritic steel and niobium are proposed in [12]. However, the exchange area is almost independent on the material for small tritium molar fraction (<10^{-7}) in FLiBe. The tritium molar fraction in the FLiBe flow entering the extractor is $1.05 \cdot 10^{-8}$, which leads to an exchange area of $5 \cdot 10^{5}$ m^2. This value is derived from the relation between tritium molar fraction and required area from [12], for a tritium diffusivity in FLiBe of 10^{-9} m^2/s. The required exchange area can be achieved with 1000 outer tubes 12m long for a single pass system. Different combinations of number of outer tubes and tube length can be used. The tube length of 12m can be considered as a reasonable upper bound: longer tubes may lead to unacceptable pressure drops, huge footprint and cleaning issue. Shorter tubes lead to higher real volumes of the system. In fact, even considering the space occupied by the tubes only (neglecting free space between the tubes), the volume of the system is 250m^3, much larger than the reference volume of the gas-bubble column and the vacuum disengager (15.7m^3). The tritium extraction process timescale is computed as the ratio between tube length and FLiBe average speed inside the tube. The tritium loss to the environment is not evaluated because the tritium extraction efficiency is missing from the reference design [12].

Table 3 - Permeation tubes analysis results.

	Value	Unit of measure
Required area	$5 \cdot 10^5$	m^2
Number of outer tubes	1000	-
Required length per tube	12	m
Timescale	72	s

Concerning gas-bubble columns, the reference system is designed to process a tritium flow of 900 g/day. In ARC, a tritium flow of 88.6 g/day is expected, which suggests a possible optimization of system dimensions and contact time between gas bubbles and FLiBe. Both the volume and the timescale involved are much lower than those of permeation tubes. Finally, vacuum disengagers show the best performances among tritium extractors. The theoretical extraction efficiency is lower than that of the gas-bubble column, leading to higher losses to the environment. However, the reference values may be outdated.

Table 4 - Timescale and tritium loss for the three tritium extractor technologies analysed. Tritium loss for the permeation window is not available due to missing data for the extraction efficiency.

	Permeation window	Gas-bubble column	Vacuum disengager
Timescale (s)	72	64	1
Tritium loss to the environment (Ci/day)	N.A.	8.4	42.0

Both gas-bubble columns and vacuum disengagers lead to a very small tritium loss to the environment during nominal operations. Losses have been calculated assuming a 99.5% retention efficiency of the heat exchanger permeation barrier downstream of the extractors. Reported values of 8.4 mCi/d and 42.0 mCi/d are well below guidelines limit (9.65 Ci/d) [19].

4.2 Dose to the population

Once the routine releases have been estimated, tritium releases following an accidental scenario have been computed. The dose to the MEI following a complete release of FLiBe from the FLiBe tank or from the tritium extractor is reported in Table 5 and Table 6. Despite the huge amounts of FLiBe lost, the low tritium concentration in FLiBe makes the radiological releases acceptable.

Table 5 – Results for FLiBe tank complete release.

FLiBe released (kg)	$7.0 \cdot 10^5$
Tritium released (g)	0.32
Tritium released (Ci)	3090
Early dose (mSv)	$1.34 \cdot 10^{-1}$

Table 6 - Results for tritium extractor complete release.

	FLiBe released (kg)	Tritium released (g)	Tritium released (Ci)	Early dose (mSv)
Permeation tubes	$1.59 \cdot 10^5$	0.072	702	$2.28 \cdot 10^{-2}$
Gas-bubble column	$1.41 \cdot 10^5$	0.064	622	$2.75 \cdot 10^{-2}$
Vacuum disengager	2200	0.001	9.8	$4.21 \cdot 10^{-4}$

The early dose is extremely low for all the releases, even in the absence of additional safety barriers between the system and the population. Thanks to the extremely low timescale involved in the extraction process of the vacuum disengager (one second), the amount of tritium released is almost negligible.

In addition to the early dose, this study computes the one-year dose due to the exposure to the radionuclides in the area close to the accident (0-2 km). Calculation were performed taking advantage of the GENII-v2 code [8]. Results show a much higher dose value than the early dose previously computed. For the worst-case scenario (tank failure), a dose of 7 mSv is evaluated for the inhabitants in the 2km-radius area. The major contribution comes from food ingestion, with fruits at the top. The relative weight of each exposure pathway is shown in Figure 1. The one-year dose is well below the reference value defined by the NRC regulation (250 mSv) under accident conditions (Title 10, § 50.67) [20], and lays below the suggested range by the ICRP (20-100 mSv) for extreme situations [21].

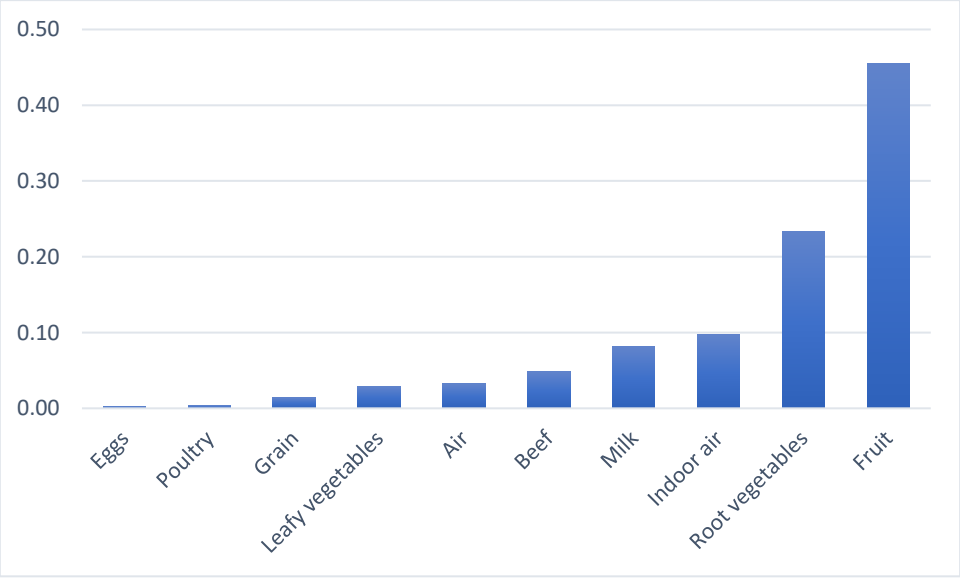

Figure 1 - Relative weight of the different exposure pathways to the one-year dose.

5. Discussion

Even though ARC tritium inventory is of the order of kilos, the analysis estimated that only a very small fraction is present in the liquid blanket. Due to the large spectrum of accidents that may involve FLiBe and lead to tritium releases, a tritium mass of 0.32g only is suitable from the safety viewpoint. More detailed analysis on FLiBe flow inside the tank, accounting for both buoyancy and MHD, may confirm this result. A similar reasoning applies for the tritium extractors, which contain a small amount of tritium as well. This value

ranges from 0.001g for the vacuum disengager to 0.072g for the permeation window. The volume occupied by the permeation tubes is quite large, because of the low tritium concentration in FLiBe. This may be a limiting factor for permeation tubes, making the other two alternatives more appealing. Gas-bubble columns are a good trade-off between technological maturity and performances, whilst vacuum disengagers, even if highly performing, still need an experimental validation.

The one-year dose value is quite large (7 mSv). However, there are many reasons to expect a much lower dose if an accident takes place. First, as explained previously, the secondary containment was completely neglected. In light of this result, a secondary containment seems desirable. Second, a full release of FLiBe and tritium was assumed. Therefore, the result can be considered highly conservative. Finally, most of the exposure is related to local food ingestion ($\cong 85\%$). Reducing local food consumption can be an effective way to mitigate radiological releases of this magnitude.

6. Conclusions

This work provides a preliminary assessment of ARC tritium inventory in the FLiBe tank and tritium extractors, and its environmental impact following accidental releases. With the current design parameters, a tritium inventory of the order of kilos is expected in the whole system. Nevertheless, less than a gram is found in the tank and in the tritium extractor. The early dose to the most exposed individuals following the failure of the tank or the tritium extractor is at least two order of magnitudes lower than the background radiation dose. Conversely, the one-year dose is significative, suggesting the implementation of proper safety measures, such as multiple safety barriers to prevent FLiBe and tritium releases.

Future works should target three goals: first, a detailed description of the FLiBe thermal fluid dynamics inside the tank, to refine the tritium inventory in FLiBe. Second, a quantification of tritium buildup inside the structural materials, which may constitute a non-negligible fraction of the tritium inventory. Third, the development of a model for the estimation of the radioactive dust in the vacuum vessel, or, alternatively, an experimental setup which emulates an ARC-like environment, to assess the radiological hazard and compare it to the tritium hazard.

Acknowledgements

The present work has been carried out under the PhD scholarship funded by ENI.

The authors would also like to thank R. Patrick White for his precious advices and fruitful conversations.

References

[1] B. N. Sorbom *et al.*, “ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets,” *Fusion Eng. Des.*, vol. 100, pp. 378–405, 2015, doi: 10.1016/j.fusengdes.2015.07.008.

[2] A. Q. Kuang *et al.*, “Conceptual design study for heat exhaust management in the ARC fusion pilot plant,” *Fusion Eng. Des.*, vol. 137, no. August, pp. 221–242, 2018, doi: 10.1016/j.fusengdes.2018.09.007.

[3] S. Segantin, R. Testoni, and M. Zucchetti, “ARC reactor–Neutron irradiation analysis,” *Fusion Eng. Des.*, vol. 159, p. 111792, 2020.

[4] S. Segantin, A. Bersano, N. Falcone, and R. Testoni, “Exploration of power conversion thermodynamic cycles for ARC fusion reactor,” *Fusion Eng. Des.*, vol. 155, p. 111645, 2020.

[5] M. Zucchetti, Z. Hartwig, S. Meschini, S. Segantin, R. Testoni, and D. Whyte, “ARC reactor: Radioactivity safety assessment and preliminary environmental impact study,” *Fusion Eng. Des.*, vol. 162, pp. 112–132, Jan. 2021, doi: 10.1016/j.fusengdes.2020.112132.

[6] Entenergy Nuclear Operations, “Pilgrim Nuclear Power Station Annual Radioactive Effluent Release Report,” 2018.

[7] S. G. Homann and F. Aluzzi, “HotSpot health physics codes version 3.0 user’s guide,” *Lawrence Livermore Natl. Lab. CA, USA*, 2013.

[8] B. A. Napier, D. L. Strenge, J. V Ramsdell, P. W. Eslinger, and C. J. Fosmire, “GENII version 2 software design document,” Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2004.

[9] Environmental Protection Agency, “Cancer Risk Coefficients for Environmental Exposure to Radionuclides,” 1999. [Online]. Available: https://www.epa.gov/sites/production/files/2015-05/documents/402-r-99-001.pdf.

[10] G. J. Janz, G. L. Gardner, U. Krebs, and R. P. T. Tomkins, “Molten Salts: Volume 4, Part 1, Fluorides and Mixtures Electrical Conductance, Density, Viscosity, and Surface Tension Data,” *J. Phys. Chem. Ref. Data*, vol. 3, no. 1, pp. 1–115, Jan. 1974, doi: 10.1063/1.3253134.

[11] S. Cantor, “Physical Properties of Molten-Salt Reactor Fuel, Coolant, and Flush Salts.,” Oak Ridge, TN: Oak Ridge National Laboratory. Report No.: ORNL-TM-2316, 1968.

[12] F. Satoshi, N. Masabumi, and S. Akio, “Calculation of Recovery Rates of Tritium from Flibe Blanket,” *Fusion Technol.*, vol. 39, no. 2P2, pp. 1073–1077, 2001, doi: 10.13182/fst01-a11963386.

[13] H. L. Shulman and M. C. Molstad, “Gas-Bubble Columns for Gas-Liquid Contacting,” *Ind. Eng. Chem.*, vol. 42, no. 6, pp. 1058–1070, 1950, doi: 10.1021/ie50486a017.

[14] A. Fukada, S. Edao and Y. Sagara, “Experimental Study of Counter-current Extraction Tower for Tritium Recovery in Flibe Blanket of Fusion Reactor,” 2008, [Online]. Available: https://nifs-repository.repo.nii.ac.jp/?action=repository_action_common_download&item_id=4030&item_no=1&attribute_id=25&file_no=1.

[15] G. R. Longhurst, R. A. Anderl, and R. S. Willms, “Tritium loss in molten Flibe systems,” *Fusion Technol.*, vol. 38, no. 3, pp. 376–383, 2000, doi: 10.13182/FST00-A36153.

[16] R. W. Moir *et al.*, “HYLIFE-II: A molten-salt inertial fusion energy power plant design - final report,” *Fusion Technology*, vol. 25, no. 1. pp. 5–25, 1994, doi: 10.13182/FST94-A30234.

[17] I. J. Dolan, G. R. Longhurst, and E. Garcia-Otero, “Vacuum disengager for tritium removal from HYLIFE-II reactor flibe,” *Fusion Technol.*, vol. 21, no. 3 pt 2B, pp. 1949–1954, 1992, doi: 10.13182/fst21-1949.

[18] C. Forsberg, G. (Tony) Zheng, R. G. Ballinger, and S. T. Lam, “Fusion Blankets and Fluoride-Salt-Cooled High-Temperature Reactors with Flibe Salt Coolant: Common Challenges, Tritium Control, and Opportunities for Synergistic Development Strategies Between Fission, Fusion, and Solar Salt Technologies,” *Nucl. Technol.*, pp. 1–24, Dec. 2019, doi: 10.1080/00295450.2019.1691400.

[19] W. Kuan and M. A. Abdou, “New approach for assessing the required tritium breeding ratio and startup inventory in future fusion reactors,” *Fusion Technol.*, vol. 35, no. 3, pp. 309–353, 1999, doi: 10.13182/FST99-A84.

[20] Nuclear Regulatory Commission, “U.S. Nuclear Regulatory Commission Regulations: Title 10, Code of Federal Regulations.”

[21] ICRP, “The 2007 Recommendations of the International Commission on Radiological Protection,” *ICRP Publ. 103.*, vol. 37, no. (2-4), 2007.