SPECIAL TOPIC • OPEN ACCESS

Overview on the management of radioactive waste from fusion facilities: ITER, demonstration machines and power plants

To cite this article: Sehila M. Gonzalez de Vicente *et al* 2022 *Nucl. Fusion* **62** 085001

OPEN ACCESS
IOP Publishing | International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion **62** (2022) 085001 (20pp) https://doi.org/10.1088/1741-4326/ac62f7

Overview on the management of radioactive waste from fusion facilities: ITER, demonstration machines and power plants

Sehila M. Gonzalez de Vicente[1,*], Nicholas A. Smith[2], Laila El-Guebaly[3], Sergio Ciattaglia[4], Luigi Di Pace[5], Mark Gilbert[6], Robert Mandoki[7], Sandrine Rosanvallon[8], Youji Someya[9], Kenji Tobita[10] and David Torcy[11]

[1] International Atomic Energy Agency, Department of Nuclear Sciences and Applications, Vienna International Centre, PO Box 100, 1400 Vienna, Austria
[2] International Atomic Energy Agency, Department of Nuclear Energy, Vienna International Centre, PO Box 100, 1400 Vienna, Austria
[3] University of Wisconsin—Madison, Fusion Technology Institute, Engineering Research Building, 1500 Engineering Drive Madison, WI 53706, United States of America
[4] EUROfusion, Boltzmannstrasse 2, 85748 Garching, Germany
[5] ENEA, CR Frascati, Via Enrico Fermi 45, 00044 Frascati, Roma, Italy
[6] United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom of Great Britain and Northern Ireland
[7] ANDRA, 1/7, rue Jean Monnet, Parc de la Croix-Blanche, 92298 Châtenay-Malabry Cedex, France
[8] ITER Organization, Building 72/4021, Route de Vinon-sur-Verdon—CS 90 046—13067 St Paul Lez Durance Cedex, France
[9] National Institutes for Quantum and Radiological Science and Technology, 2-166 Oaza-Obuchi-Aza-Omotedate, Rokkasho-mura, Kamikita-gun, Aomori 039-3212, Japan
[10] Tohoku University, 6-6-01-2 Aoba, Sendai City, Miyagi 980-8579, Japan
[11] ITER Organization, Building 72/3102, Route de Vinon-sur-Verdon—CS 90 046—13067 St Paul Lez Durance Cedex, France

E-mail: S.M.Gonzalez-De-Vicente@iaea.org, N.Smith@iaea.org, laila.elguebaly@wisc.edu, Sergio.Ciattaglia@euro-fusion.org, dipace.luigi@gmail.com, Mark.Gilbert@ukaea.uk, Robert.Mandoki@andra.fr, sandrine.rosanvallon@iter.org, someya.yoji@qst.go.jp, kenji.tobita.d5@tohoku.ac.jp and David.Torcy@iter.org

Received 9 December 2021, revised 9 March 2022
Accepted for publication 31 March 2022
Published 30 May 2022

Abstract

In the absence of official standards and guidelines for nuclear fusion plants, fusion designers adopted, as far as possible, well-established standards for fission-based nuclear power plants (NPPs). This often implies interpretation and/or extrapolation, due to differences in structures, systems and components, materials, safety mitigation systems, risks, etc. This approach could result in the consideration of overconservative measures that might lead to an increase in cost and complexity with limited or negligible improvements. One important topic is the generation of radioactive waste in fusion power plants. Fusion waste is significantly different to fission NPP waste, i.e. the quantity of fusion waste is much larger. However, it mostly comprises

* Author to whom any correspondence should be addressed.

low-level waste (LLW) and intermediate level waste (ILW). Notably, the waste does not contain many long-lived isotopes, mainly tritium and other activation isotopes but no-transuranic elements. An important benefit of fusion employing reduced-activation materials is the lower decay heat removal and rapid radioactivity decay overall. The dominant fusion wastes are primarily composed of structural materials, such as different types of steel, including reduced activation ferritic martensitic steels, such as EUROFER97 and F82H, AISI 316L, bainitic, and JK2LB. The relevant long-lived radioisotopes come from alloying elements, such as niobium, molybdenum, nickel, carbon, nitrogen, copper and aluminum and also from uncontrolled impurities (of the same elements, but also, e.g. of potassium and cobalt). After irradiation, these isotopes might preclude disposal in LLW repositories. Fusion power should be able to avoid creating high-level waste, while the volume of fusion ILW and LLW will be significant, both in terms of pure volume and volume per unit of electricity produced. Thus, efforts to recycle and clear are essential to support fusion deployment, reclaim resources (through less ore mining) and minimize the radwaste burden for future generations.

Keywords: radwaste management, fusion radioactive inventory, tritium, activation and transport codes, disposal, recycling, clearance

(Some figures may appear in colour only in the online journal)

1. Introduction

Nuclear fusion facilities, such as ITER (an experimental facility under construction in France), DEMO (the next-step facility after ITER), Pilot plant, and future fusion power plants need to be licensed. This is due to the intensity of the 14 MeV neutron flux produced, the remarkable inventory of tritium and the large inventory of radioactive materials activated in the fusion power core and externals [1]. The licensing process implies, in a similar fashion to fission nuclear power plants (NPPs):

- a systematic safety analysis of the plant in each phase;
- the definition of structures, systems and components necessary to bring and maintain the plant in a safe status under any design and beyond the design basis event;
- the definition of operating limits and conditions that define the safe operation domain;
- the assessment of the radioactive wastes produced during operation and dismantling: their classification and integral management approaches for disposal, recycling and clearance.

To address the last item systematically, an International Atomic Energy Agency (IAEA) consultant meeting was held in November 2019. Topics for discussion were the current state of radioactive waste management (RWM) from fusion devices, key challenges supported by technical evidence and practical means to solve the fusion radwaste problem in the absence of recognized standards and guidelines for nuclear fusion plants.

Several important findings were addressed during the meeting, in particular:

- fusion power plant radioactive wastes are significantly different to wastes of fission NPPs, i.e. much larger quantities, large amount of tritium, different radioisotopes, no-transuranic elements, lower decay heat to be removed and lower radioactivity content overall;
- the dominant fusion wastes are mainly composed of structural materials (steels, e.g. AISI 316L and ferritic martensitic steels, such as EUROFER97 and F82H) and functional materials (such as tritium breeders, magnet constituents, etc);
- the relevant long-lived radioisotopes generated after irradiation include isotopes of niobium, molybdenum, nickel, carbon, copper, aluminum and material impurities (such as Co, K, Ag) that might preclude disposal in low-level waste (LLW) repositories;
- several options have been analyzed to recover valuable elements (i.e. tritium, T) and separate long-lived radionuclides (i.e. C-14, Nb-94 and/or Mo-99), in order to define an optimal set of process conditions depending on the final destination of the material (disposal, recycling or clearance);
- specific materials from the tritium fuel cycle also need to be considered as well as those from general operation and maintenance of the nuclear fusion facilities.

This paper outlines the technical challenges facing the fusion RWM approaches (disposal, recycling and clearance), the projected fusion radioactive inventory compared to fission, the influence of the preferred RWM approach on the material selection for DEMO and subsequent power plants, and information on regulatory frameworks in Europe, Japan and the U.S. A list of IAEA publications on the topic can be found in appendix A.1.

2. Description of tokamak fusion designs for waste consideration

The tokamak is currently regarded as the frontrunner magnetic fusion concept [2]. In a typical D–T fueled tokamak device (see figure 1), the first wall (FW), divertor and heating/current drive launchers are the most challenging plasma-facing components and subject to the harsh fusion environment, including 14 MeV neutrons that activate many materials. A thin (2–5 mm) beryllium or tungsten layer is being considered to protect the FW. The highly energetic neutrons penetrate beyond the FW to the blanket, where they displace atoms, transmute the original materials, and generate He and H gases within these materials. The FW/blanket and divertor are expected to be replaced every 5–10 years, depending on the neutron wall loading and operational schedule.

The blanket also attenuates the neutrons and gamma rays, resulting in their capture and conversion of their kinetic energy to heat used to produce electricity. The tritium breeding and heat removal are demanding tasks that require careful selection of the breeding materials (liquid metal, ceramic or molten salt) and coolants (water, liquid metal or gas) and of the arrangement of these materials within the blanket. Due to their low breeding capability, all ceramic breeders require the addition of a beryllium or lead neutron multiplier to improve the neutron flux for tritium breeding. In the power core behind the FW/blanket, there is still significant neutron flux and gamma radiation capable of damaging the components. Therefore, it is essential to have a radiation shield to protect the superconducting magnets and external components.

3. Radioactive waste management: top-level design requirements for fusion power plants

The design of currently operating experimental tokamaks (such as JET) has been primarily focused on plasma formation, control and performance. The radioactive waste is generally considered to be limited and not an issue for these one-of-a-kind devices. Thus, no significant requirements have been imposed from the RWM perspective on the overall design. TFTR was decommisioned in 1999–2002 after tritium campaigns showed the complexity and associated cost of this operation.

Fission nuclear plants generally have an overall harmonic design where all systems and phases of operation have been well optimized, including decommissioning and radwaste management. Considering the lessons learned from NPP waste management and ITER licensing, the growing public acceptance of sensibility about pollution and risks for the environment, related ethical issues of future generations inheriting waste and the scarce resources of some materials, the DEMO and fusion power plant RWM requirements for the design need to include:

- minimization of operational and dismantling radwaste production with the careful choice of materials, optimized layout and shielding aspect;
- segmentation of component design to prolong service lifetime, possible dismantling of elementary parts in order to separate them according to their radioactivity content (and reusability);
- maximization of recycling and clearance;
- minimization of disposal.

Regarding tritium, the waste management criteria need to be oriented to:

- minimization of tritium inventory in structures and components, e.g. qualify adequate permeation barriers, optimize operation parameters and design (e.g. geometrical characteristics);
- facilitation of the detritiation before dismantling, e.g. vacuum vessel (VV) and baking of plasma-facing components at an adequate temperature or through isotopic exchange;
- optimization of detritiation techniques in hot cells for very large components;
- significant improvement of the existing water detritiation system and techniques.

DEMO and fusion power plants may also have toxic materials, such as beryllium and lead, that can be tritiated and contaminate other materials and components. They might also have reactive liquid metals (depending on the choice of breeding blanket), which may require specific passivation or explosion mitigation features. Figure 2 gives a general waste management approach for radioactive waste that needs to be adopted for DEMOs and fusion power plants.

The highest priority needs to be given to avoiding the creation of any waste; this includes removal of superfluous or problematic materials from the activation zone to the greatest extent possible. When possible, material choices, as described elsewhere in this manuscript, to use low-activation materials and operational practices, need to be employed to minimize both the waste activity and volume. Furthermore, any waste that can be decontaminated (e.g. de-tritiated) needs to be and if possible, reused elsewhere in the facility or recycled if technically feasible. Finally, whatever waste remains needs to be disposed of in a safe and secure manner.

4. Fusion radioactive inventory

There is some degree of freedom in the selection of reduced-activation materials for fusion devices to generate only short-lived radionuclides and prevent the creation of significant quantities of intermediate-level waste (ILW) or any high-level waste (HLW) [3]. Materials and alloying elements that produce long-lived radioisotopes (such as Nb, Mo, Ni, Al, Re, Ag, Hf and Cu) should be avoided. Certain impurities (Nb, Mo, Re, Ir, Ag, Co, K) must be controlled to a very low level. Nb impurity in particular impacts the waste level greatly at >100 years and needs to be kept below 1 part per million (ppm) in materials comprising the FW, blanket, divertor, VV and shield.

4.1. Comparison of fusion inventory with other nuclear systems

One of the characteristics of fusion is the advantage of its limited environmental impact, mostly due to the absence of

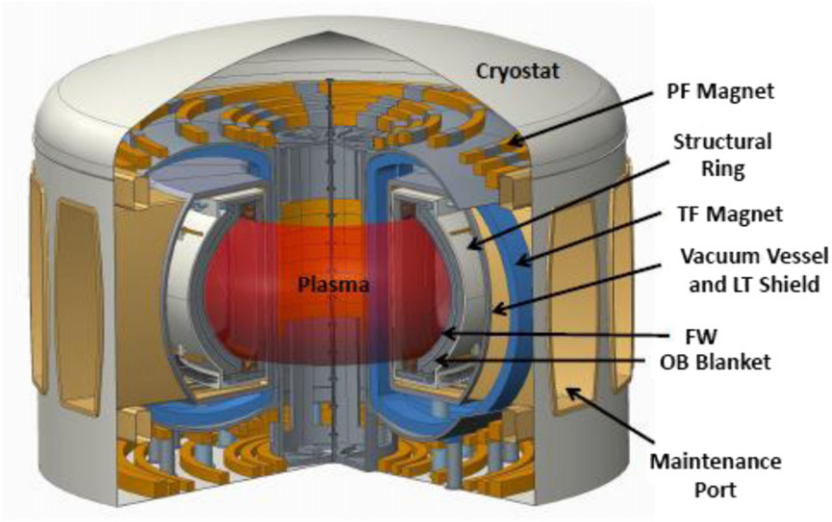

Figure 1. Layout of a typical tokamak power plant. This ARIES-ACT2 conceptual design (developed in the U.S. by the multi-institutions ARIES team) has a major radius of 9.75 m, minor radius of 2.44 m, fusion power of 2637.5 MW and net electric power of 1000 MW. Reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com)[1]. Behind the FW is the breeding blanket that must breed tritium in unprecedented large quantities to sustain the plasma operation [55.6 kg of T per GW of fusion power per full-power year of operation]. This structure would be placed within a biological concrete shield at least 2 m thick (not shown).

Figure 2. Overall conceptual approach that needs to be adopted in DEMO and fusion power plant RWM.

long-lived HLW generation. Nevertheless, the LLW and ILW inventory that fusion generates [1, 2, 4] has to be taken into consideration. The significant amount of LLW and ILW radioactive materials would eventually fill the existing repositories within a short time [5]. To put matters into perspective, figure 3 compares the power core volumes of the ITER device [6], the advanced Advanced Research, Innovation, and Evaluation Study (ARIES) power plants (ARIES-ACT1 & 2) [7], the European power plant conceptual study [8] and the Japan DEMO [9] to ESBWR [10] (economic simplified boiling water reactor)—a Gen-III$^+$ advanced fission reactor. Note that figure 3 reports the actual volumes of fusion power core components (not compacted, no replacements, no plasma chamber).

The large volume of radioactive materials discharged from fusion power plants compared to fission reactors has been analyzed by fusion designers throughout the world [11–14] in recent decades [5].

Essential long-term perspectives suggest reshaping the fusion waste management approach as follows: avoid geologic disposal and maximize the reuse of materials through recycling and clearance, to minimize the environmental impact of fusion, release of space in repositories, recover valuable resources (through less mining of metal alloys and reuse of concrete rubble), and, in the long run, make savings from the high disposal cost [5].

4.2. Fusion versus GEN-IV fission

Recent calculations [15] considered activation waste volumes holistically when comparing waste from fusion to GEN IV fission. Under the current UK regulatory waste classifications system, they found that the European sodium-cooled fast reactor (ESFR) has a lower fraction of ILW or HLW in the structural components (i.e. ignoring fuel) compared to the latest concepts for the European DEMO. Considering DEMO's much larger size (the equivalent containment vessel and interior of DEMO is massive and could be as much as ten times as large as ESBWR—see figure 3). This suggests a significantly greater waste burden from fusion in comparison to fission reactors developed on the same timescales. DEMO may produce as much as 10 000 t of solid waste from in-vessel components alone [16], compared to around only 2000 t from ESFR [15] plus an estimated 300 t of spent fuel produced during ESFR's lifetime [17] resulting in ∼2500 t of waste (HLW, ILW). While ESFR produces four times less waste, it will generate much longer-lived actinide waste.

4.3. Tritium content in fusion waste

Tritium is one of the major isotopes in the radwaste generated in fusion devices. It is essential to assess how much tritium will be absorbed and desorbed during the lifetime of the facility. Tritium content inside the various types of waste is

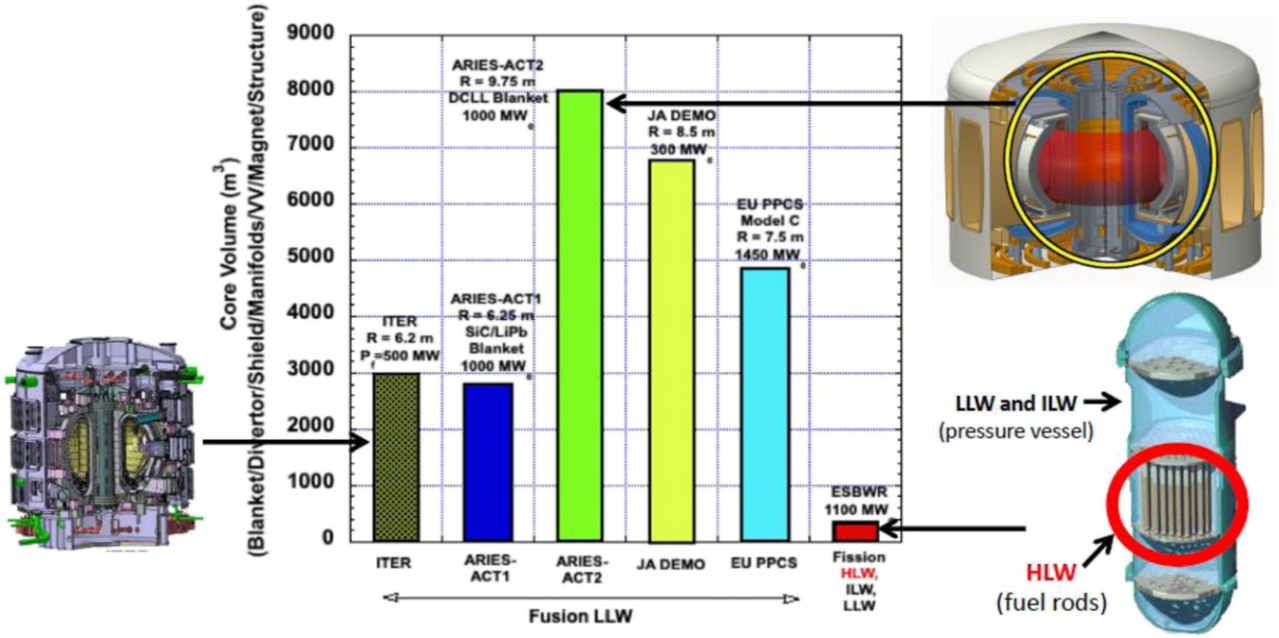

Figure 3. Fusion core volumes of several nuclear fusion plants and ESBWR (U.S. waste estimation). It is noted that these are the core volumes and not the lifetime waste generation including decommissioning waste and balancing of the plant.

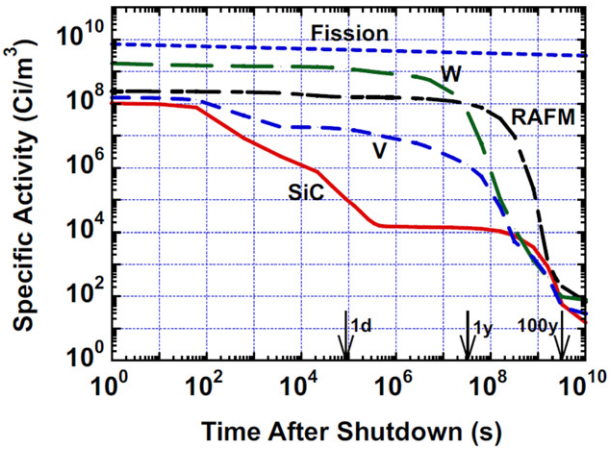

Figure 4. Specific activity of FW made of RAFM for ARIES designs, vanadium, tungsten alloys and SiC/SiC composites (for reference, in steels 1 Ci m^{-3} is equivalent to 4.7 MBq kg^{-1}).

a key parameter for the selection of the waste treatment process and future acceptance in the repositories. It is anticipated that effort will have to be made to recover the tritium from the waste, as current repositories are not designed for large amounts of tritium. This effort is not only to reuse it as a fuel but to reduce potential environmental releases in storage and disposal facilities.

Different detritiation techniques have been investigated at laboratory scales, being thermal desorption in an oven at 800 °C, in a flow of argon gas technique (which may contain hydrogen not exceeding 4% in volume to prevent a hazardous atmosphere) the current reference in terms of efficiency, type of process and impact on safety. In addition, thermal desorption under atmospheric air, thermal desorption with isotopic exchange with gaseous hydrogen, heating with flame, vacuum melting, melting under static hydrogen atmosphere and under argon flow, etc, have been studied. Further research is needed to determine the optimum parameters to remove the hydrogen isotopes while maintaining the efficiency of the process. [18]

The efficiency of detritiation techniques needs to be assessed from a technical-economical point of view based on feedback, modeling, and relevant research and development (R & D) programs, in particular for metallic [19] and plastic waste from housekeeping operations. In many cases, due to the tritium content in waste, decay for periods up to 50 years will remain a mandatory step before foreseeing safe disposal.

The usual scaling methods based on gamma spectrometry cannot be used for tritium measurement in fusion waste. Tritium is generated by direct activation inside materials and also from permeation into the materials from other sources (the latter route is likely to be the dominant source). Therefore, correlation with other activated nuclides is not representative. Various methods are being developed for the measurement of tritium. Three methods have emerged as the most suitable for waste characterization:

- measurement of ^{3}He;
- calorimetry;
- sampling and radiological analysis (destructive method).

The measurement of ^{3}He is adequate only for technological wastes (vinyl, cotton) as it requires long waiting times to stabilize the outgassing and perform the measurement. This technique is more appropriate for old waste and is not valid for metallic waste. Calorimetry is adapted to purely tritiated waste (detection limit of 1.8×10^{14} Bq/drum). Its adaptation to waste with other gamma and beta emitters is possible in theory but has not yet been demonstrated [18]. Sampling

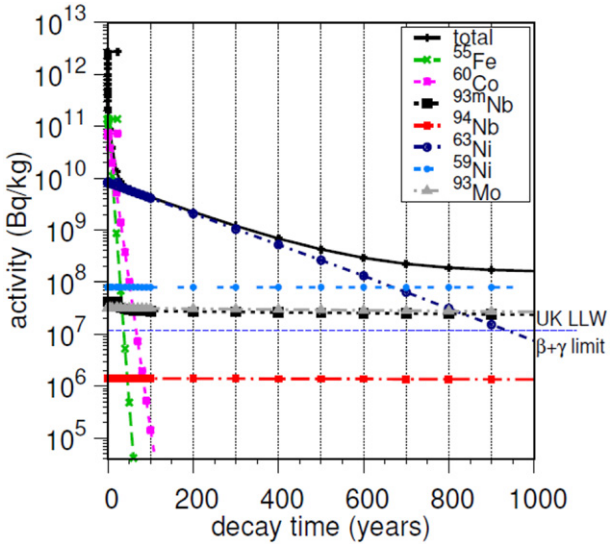

Figure 5. Activity contributions from radionuclides produced in VV SS316 in DEMO. Decay time is the time after operation. EU DEMO has a major radius of 9 m, minor radius of 2.9 m, fusion power of 2000 MW and net electric power of 500 MW [34]. Reproduced courtesy of IAEA. Figure from [4]. © EURATOM 2019.

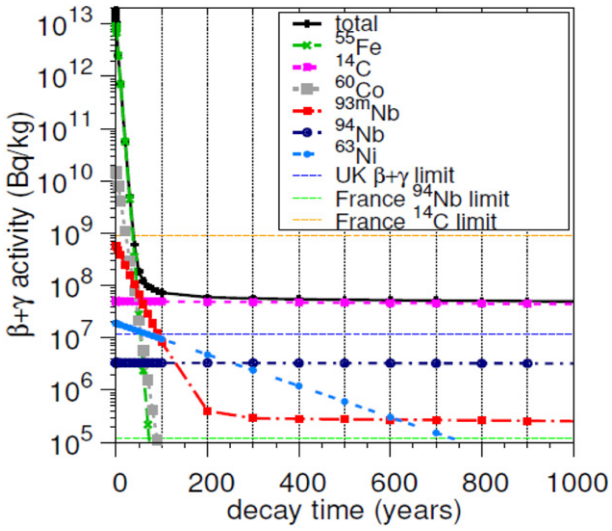

Figure 6. Radionuclide contribution evolution to EUROFER97 activity.

followed by radiological analysis (via destructive methods), despite the drawbacks related to sampling (representativeness, secondary waste, etc), remains the most adapted method for the measurement of tritium activity in fusion waste [18, 20].

4.4. Activation and transport codes, nuclear data for fusion, and uncertainties

The most commonly used transport code for fusion is MCNP, using the FENDL data (see appendix A.2). For activation (and hence waste) calculations, the choice of code and/or library is more varied. In the U.S. and Europe, the ALARA code and FISPACT-II [21] inventory code (and its predecessor FISPACT) are the most widely used, respectively. Recent nuclear data advances are slowly allowing activation calculations within Europe to move away from an over-reliance on the static European activation file (EAF), which has seen no active development since 2010. For EURO-DEMO purposes, TENDL (version 2017) was recently adopted (and approved) as the default library for activation calculations. Appendix A.2 gives further details of the different codes currently available and being developed to support activation, dose and waste calculations.

Under the umbrella of the IAEA, TENDL developers together with UKAEA are enhancing the benchmarking of data libraries for fusion activation calculations by developing a suite of automatic validation exercises using the FISPACT-II code. A benchmark exercise against fusion decay heat measurements performed by JAEA and validation using this data [22] has helped to improve TENDL (and hence JEFF, which takes much of its data from TENDL) and reduce uncertainties. However, uncertainties still exist and further effort to improve nuclear data evaluation, specifically for fusion neutronics, is needed. A useful feature of FISPACT-II, which is recommended for other inventory codes (and transport codes if possible), is the ability to rapidly test the performance of many different nuclear data libraries within the same framework [22]. This allows for a 'sensitivity analysis' as a function of nuclear data to be performed, often leading to insight into any adjustments or re-evaluations required. When performing radwaste calculations the uncertainty in the nuclear data cannot be neglected, although sources of uncertainty in the fusion reactor designs themselves currently dominate the variation in results. For example, the wide variation in EU-DEMO designs involving large changes in reactor size and power output, even in the last few years, would provide very different outputs in terms of radwaste calculations.

In the calculation processes, the neutron energy spectrum of a component is used to determine the induced radioactivity. In the calculation model, neutron streaming must be considered when deriving the neutron energy spectrum because the nuclide that is generated strongly depends on the neutron energy spectrum. Therefore, a 3D reactor model is essential when calculating the neutron spectrum of components such as the blanket segment, divertor cassette, VV and superconducting coil, etc. The geometric arrangement of the blanket modules, divertor cassettes, VV, maintenance ports, poloidal field coil, toroidal field coil, etc, are shown in figure 1 for a typical tokamak. Each design should develop its own calculational model, e.g. ITER, EU DEMO or JA DEMO or U.S. power plants. Assuming toroidal axisymmetry, a sector of the plant can be modeled with reflecting boundaries. The presence of current drive and heating penetration with various injection angles requires that the entire torus be modeled.

Modeling the complex fusion geometry is a challenging task for 3D neutronics, shielding and activation analyses. In recent decades, state-of-the-art neutronics codes have been developed in Germany (McCAD by KIT) [23, 24], in the U.S. (DAGMC by UW) [25] and in China (MCAM by the FDS team) [26–28] to model the fine details of the fusion power core. These tools couple the CAD geometry directly with the 3D MCNP code to diminish the uncertainty attributed

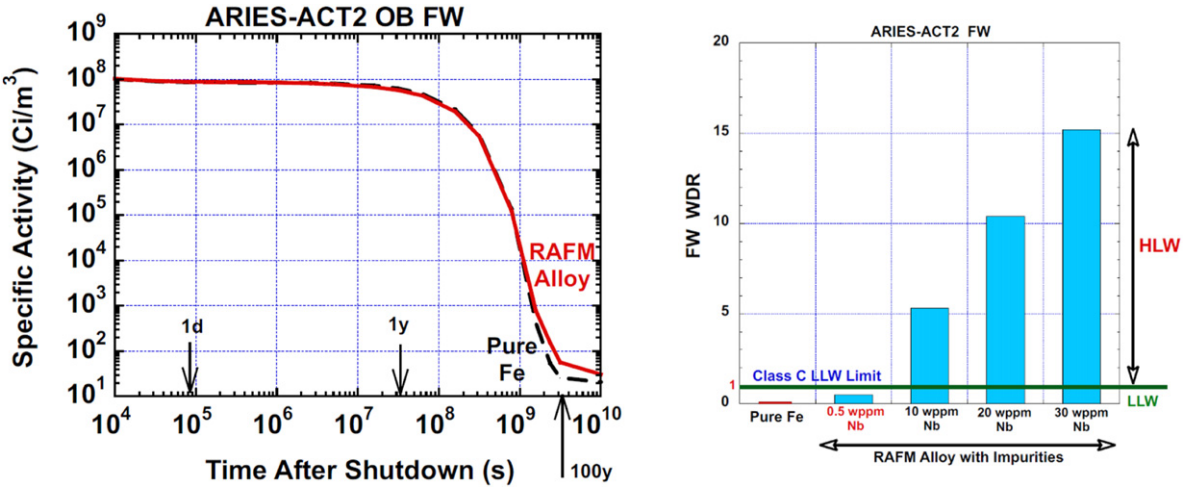

Figure 7. Specific activity of the outboard FW—a highly radioactive component in ARIES-ACT2. Right plot shows the sensitivity of the WDR to the Nb impurity content in the F82H steel.

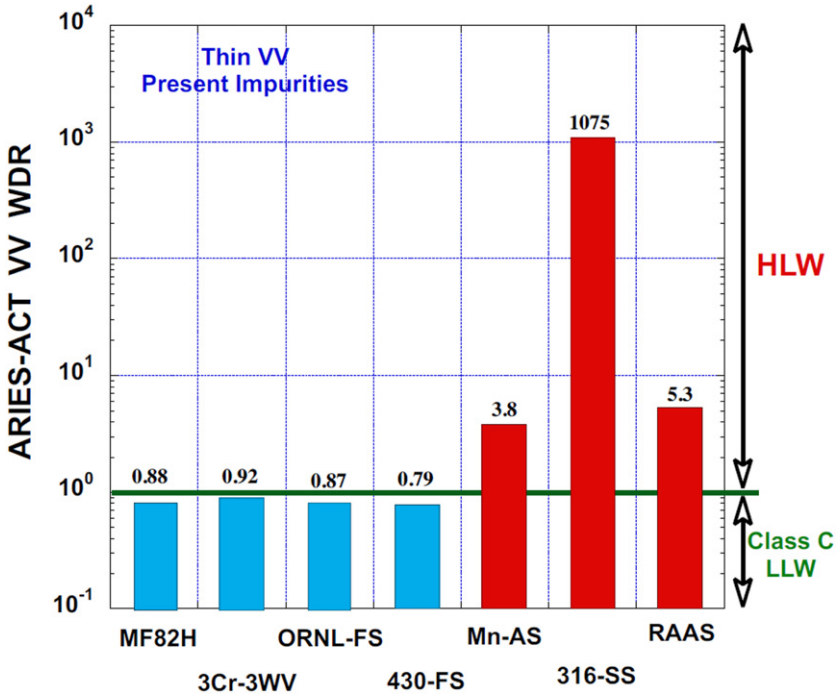

Figure 8. WDR of seven candidate steels for ARIES-ACT VV with 'present' impurities. [30] 2017, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).

to approximations in modeling, making the calculation much more accurate.

4.5. Identification of main contributors to a radioactive inventory

Structural materials derived from the fission industry are inadequate for fusion due to the much higher operating temperature requirement and greater damage from 14 MeV neutrons, which results in notably high helium (and hydrogen) gas production within the structure and quite different He—to displacements per atom ratios compared to fission (typically 10 versus 0.3) [29]. Radiation-resistant low- or reduced-activation steels are being specifically developed, tested and qualified for fusion applications. Since alloying elements and impurities impact the activation level, all fusion materials must be carefully chosen to minimize long-lived radioactive products such as ^{14}C, ^{59}Ni, ^{94}Nb, ^{186m}Re, etc. This requires incorporating waste considerations at the design specification stage and creating a standard for low-activation materials. Manufacturing companies for fusion materials will need to make a serious effort to meet this standard by using highly pure raw materials and strive to exclude or minimize Mo, Nb and Ni, in particular. The main structural material for the fusion power core, except the VV, is the reduced activation ferritic martensitic (RAFM) alloy (such as the F82H Japanese steel and EUROFER97 European steel) that offers an operational

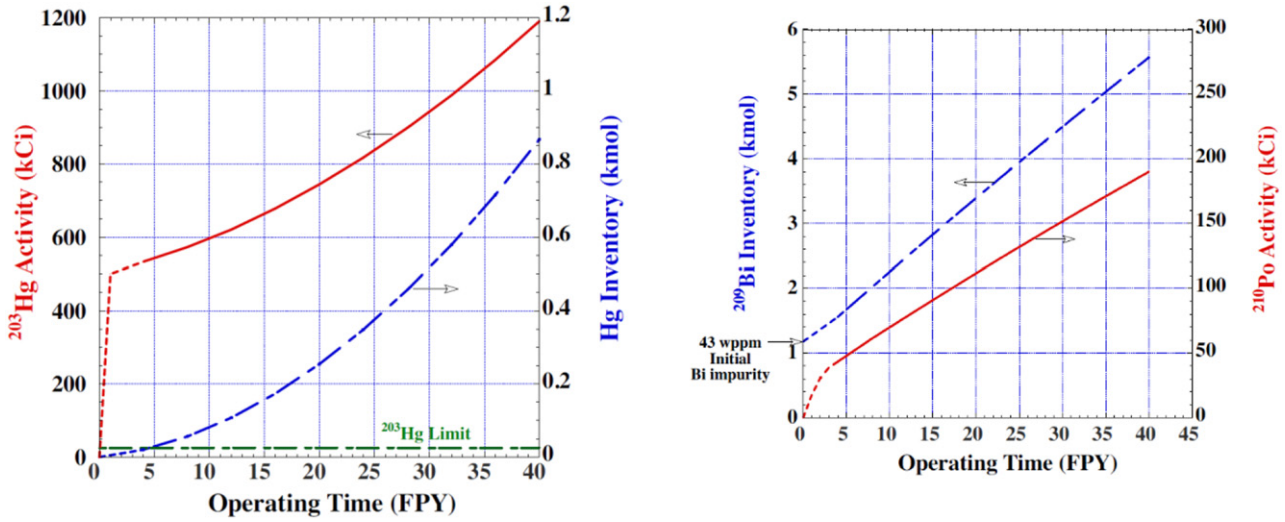

Figure 9. ^{203}Hg inventory (left) and ^{209}Bi and ^{210}Po inventories in PbLi of the ARIES-AT power plant as a function of time [32]. [41] 2018, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).

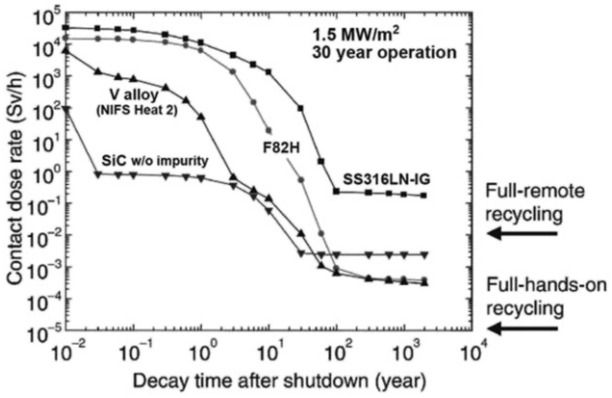

Figure 10. Contact dose rate of fusion materials after irradiation in a fusion reactor (reproduced with permission from [42]. © 2005 The Japan Institute of Metals and Materials).

temperature window between 350 °C–550 °C. New generations of structural steels with enhanced radiation damage tolerance (such as nanoscale oxide dispersion strengthened alloys) are being developed to operate at higher temperatures >550 °C. The relatively newly developed low-activation 3Cr–3WV bainitic steel does not require post-weld heat treatment and has the potential to satisfy the fabrication requirements for large components such as the VV [30]. Other structural materials of interest include tungsten alloys, vanadium alloys and SiC or SiC composites. Rhenium-free tungsten alloy is currently the leading high-Z candidate material for the divertor structure. Upon exposure to fusion neutrons, the candidate materials become radioactive to varying degrees, depending on their activation and decay characteristics. Figure 4 displays the relative specific activity of the four structural materials for the FW of ARIES designs.

4.5.1. Beryllium. Beryllium (Be) is a rare metal that improves tritium production in the breeding blanket by neutron multiplication and moderation. It is a toxic metal and the disposal of Be is challenging. Beryllium may contain trace levels of uranium (up to hundreds of ppm) impurities. The total activity due to the Be addition, after the operational life of the ITER and DEMO plants, was calculated and indicated the presence of transuranics due to these impurities [23, 30–32]. If all 300–400 t of Be in the blanket contained 20–100 ppm of U, the total amount of U in the reactor would amount to approximately 6–40 kgs [32] and, therefore, transuranic elements need to be considered. In the EU DEMO case, the contribution from radioactive alpha-emitting actinide impurities is enough to exceed the UK-LLW (and FR LILW-SL) alpha limit of 4 MBq kg^{-1}. In the JA DEMO case, the U content in the Be needs to be less than approximately 0.85 ppm to meet the final level of 10 MBq kg^{-1}, which is an acceptable level for shallow land disposal in Japan [32]. New purification processes have the ability to reduce U concentration in Be to allowable concentrations for shallow land disposal (∼0.1 ppm) [33].

4.5.2. Steels. In Europe, most of the fusion reactors are constructed from steel. For example, in the current European DEMO concepts, all the internal reactor (in-vessel) components are constructed from the RAFM steel EUROFER97 (appendix A.3), while the VV and ex-vessel components are based primarily around austenitic stainless steels such as SS316 and XM19. Thousands of tonnes of steel will be needed to construct the next fusion devices (after ITER) and so a decommissioning strategy for these materials is of paramount concern.

If austenitic, such as SS316 is used, then the relatively high nickel content (∼12.5 wt% Ni) will dominate the radioactivity on the timescales relevant to decommissioning, recycling and disposal. Of particular concern are the long-lived ^{63}Ni and ^{59}Ni isotopes, although the gamma-emitting ^{94}Nb and ^{93}Mo would also cause difficulties with LLW disposal and/or clearance of irradiated SS316 [4]. Figure 5 shows a FISPACT-II calculation of the time-evolving activity contributions to the activity of SS316 after a typical exposure lifetime in the VV of the European DEMO and illustrates the dominance of these nuclides in the long-term (beyond 50 years) activity of the steel.

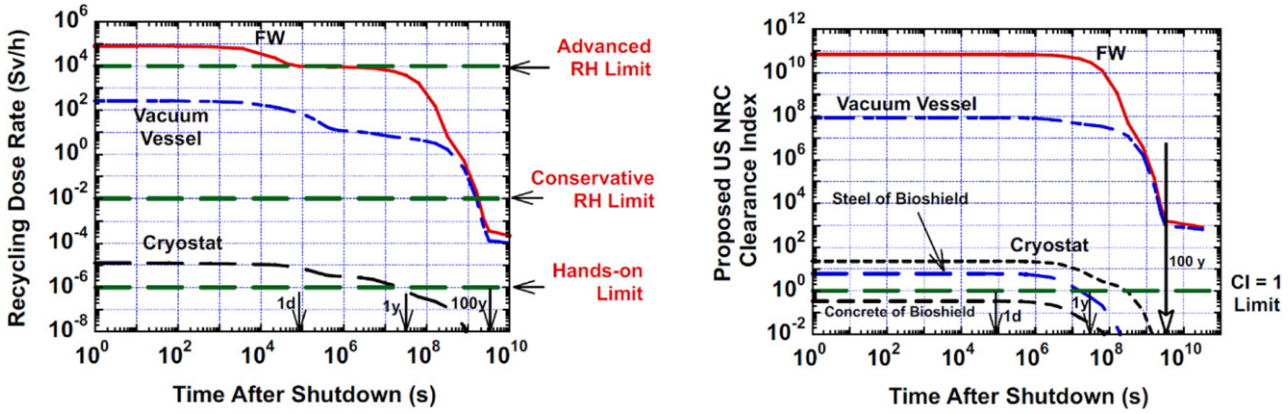

Figure 11. Recycling dose rate and clearance index for selected ARIES-ACT2 components [7]; conservative RH limit estimated as 10^3–10^4 higher than hands-on limit.

For EUROFER97, even with a significantly reduced Nb content compared to typical austenites, ^{94}Nb production is still remarkable [4, 35], and waste steel containing this nuclide at levels higher than around 100 Bq g^{-1} would be difficult to accept in LLW surface repositories. For comparison, the limit at Spain's El Cabril disposal facility for this nuclide is 120 Bq g^{-1} [36]. Another concern for in-vessel steels is ^{14}C [35], particularly when, as with EUROFER97, its production is enhanced by the addition of small quantities of nitrogen to the steel composition to improve its high-temperature performance. This nuclide is only a beta emitter, but extra precautions are necessary for materials containing ^{14}C to limit the chance of release into the environment (typically by water leaching). Figure 6 exemplifies the significance of these two nuclides, showing that ^{14}C could exceed the total activity limit for LLW waste in UK repositories, while the ^{94}Nb activity could exceed the nuclide-specific limit under France's LLW regulations. Note that this calculation, which was performed with FISPACT-II for the latest European DEMO designs, assumed 0.005 wt% Nb and 0.045 wt% N. While the latter concentration may be unavoidable to guarantee the correct operational performance of the steel, the former (niobium) is an impurity with no functional use.

F82H (appendix A.3) is also a RAFM steel designed and developed by Japan, and its nominal chemical composition is Fe–8Cr–2W–0.2V–0.2Ta [37]. For the near-surface disposal of F82H used as an in-vessel component of DEMO, Co, Nb, Ni, Mo and N will be critical elements [38]. The use of high-purity raw materials is essential for reducing Co and Nb content. In addition, material production with a clean process line contributes to reducing Ni and Mo contamination. A recent analysis [39] indicates that S-producing radioactive ^{36}Cl can be a critical element in addition to these elements for near-surface disposal in Japan.

When examined for disposal, F82H steel with >1 ppm Nb could generate HLW according to the U.S. classification of waste, which is unacceptable for the ARIES project. In an effort to reduce the long-term radioactivity, Klueh *et al* [40] provided a list of the lowest 17 'present' impurities that have ever been achieved in large-scale melting and fabrication practices of various steels. They are not specific to any particular steel composition and could be achievable at present with a relatively modest effort and cost. This stresses the need for strict control of the undesirable impurities (particularly Nb and Mo) that tend to generate higher activities of waste materials. Figure 7 shows the highest activity level for the outboard FW of ARIES-ACT2 and the sensitivity of the waste disposal rating (WDR) to the Nb impurity content in F82H steel. Note that F82H steel is unacceptable for large VVs due to the complex heat treatment requirement after welding. Even though austenitic stainless steel (such as the 316-SS) eliminates the need for welds to be tempered at 750 °C, it generates U.S.-HLW because of the high Ni and Mo content. Considering the 'present' list of impurities, the VV barely achieves the desired class-C LLW classification for a few steels, as shown in figure 8 [30]. The newly developed 3Cr–3WV bainitic steel by Oak Ridge National Laboratory (ORNL) mitigates most of the identified VV problems and meets the LLW disposal requirement.

4.5.3. PbLi breeder. The primary radiological concern for the PbLi breeder is from its own radioactive by-products, ^{203}Hg and ^{210}Po. Figure 9 shows the inventories of ^{203}Hg, ^{209}Bi and ^{210}Po in the flowing 600 m^3 PbLi volume of the ARIES-AT power plant [41]. After a few days of operation, the activity is above the radiological limit for ^{203}Hg (25 kCi) and a purification system will be necessary to control its level. The ^{209}Bi inventory is of interest because, as a precursor to ^{210}Po, control of its concentration can serve as a mechanism to limit the ^{210}Po inventory. It is clear from this figure that the ^{210}Po levels are above the radiological limit for ^{210}Po (25 Ci) soon after operation, primarily due to the initial 43 ppm bismuth impurity. Controlling the Bi impurity in PbLi to <5 ppm and installing a ^{209}Bi purification system, rather than a system to remove the radiological hazardous radionuclide ^{210}Po generated during operation, would be more efficient. In order to reduce the buildup of these radiologically hazardous materials in the LiPb breeder, it is necessary to continuously process, filter and purify the PbLi online shortly after operation starts in order to control its quality, avoid contaminating sub-systems, and ensure safe operation. At the end of operation, the PbLi will not be sent for disposal, but rather will be recycled and

refurbished to adjust its Li content before reuse as a breeder in other fusion devices.

4.5.4. Vanadium alloy. Vanadium alloys, such as V–4Cr–4Ti, are candidates for low-activation materials for fusion applications at a high operating temperature window (700 °C), exceeding that of conventional steels (550 °C). An advantage of V alloys is the significantly lower recycling dose rate than RAFM (F82H and EUROFER97) before 100 year cooling, as shown in figures 4 and 10 [42]. As anticipated in other fusion materials, impurity concentrations increase radioactivity of vanadium alloys. Assessments in Dyomina *et al* [43] point out that the Bi impurity at a level of 500 ppm can determine the long-term dose rate at 50–100 years after shutdown. However, they conclude that recycling of V–4Cr–4Ti appears radiologically feasible when remote handling (RH) techniques are developed.

4.6. The need for accurate estimation of fusion radwaste volume

The waste amounts to be generated by the operation, maintenance and decommissioning of fission plants are frequently reassessed. This allows industries and repositories to anticipate the waste services necessary to support the needs of fission energy. However, currently fusion facilities under project are experimental ones. Globally recognized approaches and methodologies are needed to estimate waste production volumes for each physical category of waste during the different phases of tokamak lifecycle (i.e. commissioning, operation, maintenance and decommissioning):

- highly activated metallic waste from tokamak in-vessel component replacement, failure and refurbishment (high activation and dose rate and tritium content);
- less activated and tritiated metallic waste from ex-vessel components (magnets, cooling water pipe and components);
- specific waste from breeding-related materials such as beryllium and Li-based breeders, (activation and dose rate, tritium content, filtered radioisotopes and potential reactivity issues);
- tritiated equipment from the fuel cycle: metallic waste and getter beds only contaminated with tritium;
- plastic waste from housekeeping operations contaminated with activated corrosion products (ACPs), dust and tritium;
- liquid effluents containing ACPs and tritium;
- resins containing ACPs and tritium;
- oils containing ACPs and tritium.

Plastic waste will be produced continuously during operation and maintenance phases of the facilities while metallic waste is mostly collected during the decommissioning phase. Considering that ongoing projects are experimental first-of-a-kind facilities, uncertainties in the preventive and corrective maintenance will remain until their final designs become available.

Establishing accurate waste production estimates also enables one to properly assess the most optimized treatment and management solutions for all lifecycles of fusion facilities. The fission industry can provide substantial feedback on matters of radwaste assessment methods.

Effort has already been made at ITER to improve the accuracy of waste estimate [44]. It is also mandatory to anticipate the necessary R & D to prevent or minimize as much as possible the activation of fusion-specific materials and specific treatment that would be required [45].

It would be necessary to establish a globally recognized approach and methodology to estimate the waste production volume for all radwaste types generated by fusion, not only by the power core.

5. Options for managing fusion radioactive materials

The question of treating and disposing radioactive waste has been raised frequently for both fission and fusion facilities. The recycling and clearance approaches could significantly minimize the volume of radioactive materials assigned to geologic disposal. Based on known issues associated with the disposal, recycling and clearance processes, several key issues and needs were identified [11, 46, 47] for the fusion community to address in the near future. Some of these issues/needs are related to activation areas inside the fusion power core, which can be addressed by fusion designers. Other issues are related to areas outside the fusion power core, requiring industrial experience, fusion-specific R & D programs and regulatory organization involvement. As a next step, the fusion radwaste management scheme needs for its optimization a dedicated R & D programme that covers the existing issues and needs.

5.1. Disposal of fusion radioactive waste

There are two major issues for the treatment, storage and eventual disposal of fusion radwaste—the high initial activity of the materials and the large tritium inventory. The contact dose rate may require the waste to be treated as ILW similar to irradiated fission reactor components (nozzles, grid spacers, etc.) with comparable activities and lifetimes. Tritiated radwaste management plays a key role in the disposal option. Unfortunately, tritium tends to migrate and diffuse through all standard materials (concrete and metals) that are the main constituents of a radioactive disposal facility. As the activity level of tritiated waste might be high ($>10^8$ Bq g^{-1} before treatment for components such as the FW), tritium presents a major challenge, not only for operating the disposal facility, but for managing the environmental releases arising from the disposal of tritiated radwaste.

In defining disposal criteria and requirements for any disposal facility to host fusion-activated waste, appropriate consideration must be given to the activated metal matrices when:

- carrying out the performance assessments required to determine the acceptance levels of radioactive waste for disposal facilities whose site is defined;

- determining general guidelines for the calculation of these limits, considering two important aspects:
  - ∗ their chemical stability and durability, compared to other matrices envisaged for LLW;
  - ∗ the homogeneity and certainty for the evaluation of specific activity content following the melting processes necessary to eliminate tritium and ^{14}C.

Further general issues related to the implementation of disposal are as follows:

- high disposal costs, which continue to increase (for preparation, characterization, packaging, interim storage, transportation, licensing and disposal);
- there are only a few ILW sites in existence and no current HLW sites;
- limited capacity of existing LLW repositories;
- political difficulties siting new repositories limits capacity growth;
- public confidence in the prediction of repository conditions into the future;
- radwaste burden for future generations.

These issues are then complemented by the following needs related specifically to the disposal of fusion waste:

- revised fusion-specific activity limits for the different types of radioactive waste issued by regulatory bodies;
- large-capacity and low-cost interim storage facility with decay heat removal capability;
- repositories designed for tritium-containing materials and/or higher limits of certain lower-risk, long-lived isotopes such as ^{14}C, ^{94}Nb, etc;
- reversible disposal process and retrievable waste (to gain public acceptance and ease licensing).

5.2. Recycling

Recycling has been investigated by fusion researchers since the early 1980s, focusing mainly on selected materials or components [48–50]. In recent times, with the development of advanced radiation-hardened RH tools that can handle up to 10 000 Sv h^{-1}, recycling of highly irradiated materials has become more technically feasible [7, 51–53]. The availability of these new tools has pushed the worldwide fusion community to investigate the recycling option for all fusion components that are subject to very high neutron activation near the plasma and very low levels at the biological shield [51]. Figure 11 indicates that all fusion components could be recycled in less than a year with advanced RH equipment.

The recycling process includes storing in continuously monitored facilities, segregation of various materials, crushing, melting and re-fabrication [11, 54, 55]. The highly radioactive components require special shielding during handling and transportation. Some may even need cooling for several days or weeks to remove the decay heat. Since most fusion radioactive materials contain tritium that could introduce complications to the recycling process, detritiation treatment prior to recycling is necessary for all fusion components.

Regarding the economic aspect of recycling, there was a cost saving in recycling lead shielding bricks at the U.S. Idaho National Laboratory versus disposal in LLW repositories [47]. In addition, a Russian study concluded that recycling is cheaper than disposal [56].

A reasonable recycling experience for very LLW exists in a few countries and advanced RH equipment has been used worldwide in the fission industry, in hot cells and reprocessing plants. While the fission processes may have no direct relevance to fusion, their success gives confidence that advanced RH and processing techniques could be developed to handle high doses (>10 000 Sv h^{-1}) for recycling fusion materials. However, the challenge remains because of the size of fusion components. It is expected that fusion will benefit from the recycling experience being developed at a fast pace to support the worldwide mixed-oxide fuel reprocessing system [51].

Issues related to recycling of fusion components include:

- separation (via RH) of various activated materials from complex (and often large size) components;
- radiochemical or isotopic separation, if needed;
- treatment and remote re-fabrication of radioactively contaminated materials including management of residual He for rewelding;
- radiotoxicity and radioisotope build-up and release through subsequent reuse;
- properties of recycled materials compared to fresh ore and the role of recycled materials: structural or filler;
- handling of tritium-containing materials during recycling;
- management of secondary waste—volume and classification of waste for disposal;
- energy demand for the recycling process;
- cost of recycled materials;,
- recycling plant capacity and support ratio;
- Public, industrial, and political acceptance of recycled nuclear material (particularly for non-nuclear applications).

As above, these issues are complemented by a set of needs related to recycling components

- development and installation of radiation-resistant RH equipment;
- emphasis on ease of disassembly (via RH) of components and constituents (to ease separation of materials after use) in the design process;
- efficient detritiation system to remove T before recycling;
- large and low-cost interim storage facility for tritium decay with decay heat removal capacity;
- industrial-scale recycling infrastructure

5.3. Clearance

According to the IAEA radwaste glossary [57], clearance is defined as the ‘removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body’. In 1996, the IAEA established

the principles underlying the technical estimates of the clearance limits, by issuing an interim report circulated for comment [58]. That report aimed to introduce the exemption and clearance principles and the derivation methods of unconditional clearance levels for solid materials, based on the individual dose criterion of 10 μSv year^{-1}. The proposed IAEA clearance levels in [59] are considered guidelines only, as it is the responsibility of each member state to develop their own national laws. Therefore, in Europe [60], the U.S. [61] and Russia [62], regulatory standards or guidelines were derived and numerous papers dealt with the issue of applying clearance levels in the context of fusion RWM. A comprehensive summary of this issue is provided by the 2006 paper [54]. In general, all in-vessel components are not clearable as their clearance indices (CIs) exceed the limit of unity by a wide margin even after a period of 100 years (see the right-hand side of figure 11). The main contributor to the CI of RAFM-based materials at 100 years is Nb-94 (from Nb impurity). The biological shield and some of the magnet constituents are clearable (with CI $<$ 1), representing $\sim$65% of the total volume of ARIES-ACT2 radioactive materials [7].

What is commonly accepted among all clearance standards is the radiation protection approach based on 10 μSv year^{-1} dose for cleared solids—which is very small. According to the United Nations recommendations, the radiation dose above background level to members of the public from radiation sources other than medical exposure should not exceed 1 mSv year^{-1} [63]. A common approach needs to be developed to derive clearance levels at the national level based on the 10 μSv year^{-1} standard dose for cleared solids, harmonize the scenarios for calculating the doses, and deriving the clearance levels for all radioisotopes of interest to the fusion industry.

Issues related to application of clearance guidelines are as follows:

- impact on clearance index prediction of missing radioisotopes (such as ^{10}Be, ^{26}Al, ^{32}Si, ^{91,92}Nb, ^{98}Tc, ^{113m}Cd, ^{121m}Sn, ^{150}Eu, ^{157,158}Tb, ^{163,166m}Ho, ^{178n}Hf, ^{186m,187}Re, ^{193}Pt, ^{208,210m,212}Bi and ^{209}Po);
- radioisotope build-up and release through subsequent reuse.

Needs related to the application of clearance guidelines are as follows:

- official clearance limits issued by legal authorities;
- accurate measurements and reduction of impurities that deter clearance of in-vessel components;
- reversible assembly components and constituents as a design criterion;
- large-capacity and low-cost interim storage facility;
- clearance infrastructure;
- clearance market.

5.4. Radwaste storage

Based on existing knowledge generated in the ITER licensing process, decay storage is the reference solution for tritiated waste in France, considering French regulation [64]. Currently, these decay storage facilities are not available and could represent an important financial effort to ongoing and future fusion projects. By definition, decay storage is a temporary solution that may require, as a function of the initial tritium activity in the waste, a long (up to 50 years) or very long (about 100 years) decay period. Considerations for the implementation of decay storage include the following:

- it can be promoted as a temporary solution if the disposal options are not currently available or if waste acceptance criteria (WAC) are not attainable;
- it is not a low-cost arrangement;
- it could be a burden for future generations because it is not a final solution.

According to waste hierarchy [65], the immediate treatment (such as detritiation) is preferred. Nevertheless, storage of the waste before disposal could also enable decay of the activated metals and allow downgrading to lower waste categories prior to disposal. When national regulation permits it, clearance levels could be reached for some important waste amounts.

Tritium decay for a period of up to 50 years will likely remain a mandatory step before any movement to disposal when considering potential environmental releases. If significant amounts of other long-lived radionuclides are present in the waste (i.e. above the maximum activity limit of the L/ILW-SL surface disposal), then disposal options need to be created to avoid costly treatment and potentially useless storage.

6. Regulatory framework

Regulatory frameworks are set up by each country, so regulations vary from one state to another. Information about regulatory frameworks for different nations in Europe as well as the U.S. and Japan are available at national regulatory websites and have been summarized at the international approaches to radioactive waste classification, National Waste Programme [66]. Appendix A.4 describes the waste classification approaches of different countries (France, U.S., and Japan are also discussed in more detail below) and is also described in [35]. While not designed with fusion systems in mind, the general principles still apply for the disposal, recycling and clearance of radioactive waste regardless of origin. Guidance materials could be produced in the near future to capture the specific differences between fission and fusion wastes, mainly related to the radioisotope profile. For the disposal option, for example, as the waste from fusion sources is generated, treated and conditioned, the decisions that need to be made will be very similar to the established process for fission. The waste package types will largely be determined by the characteristics required by the disposal site. The disposal site will need to be evaluated, given the specific isotopes in mind, as to how much material can be stored at the site in a safe confinement. This analysis will give rise to the site's WAC and will include (or exclude) the isotopes that can be stored or disposed of there either by name or by characteristic. For example, some European sites simply give total β/γ activity or α activity per mass of waste; in some cases, there may be specific restrictions

on problematic isotopes like tritium. In the U.S., the waste is classified into HLW and LLW based on the WDR.

6.1. France

An interesting case is the French regulations applied to ITER, which is considered a basic nuclear facility 174 (INB174) by *Autorité de sûreté nucléaire*, the French nuclear safety authority. It is supported by its technical advisor the *Institut de radioprotection et sûreté nucléaire*—Institute of Radiation Protection and Nuclear Safety. The French regulations dictate that the nuclear operator defines waste zoning for its facilities. It consists of defining zones producing radioactive waste and those producing non-radioactive waste. These zones are defined based on an analysis of the normal operations foreseen room by room and the potential exposure to activation and/or contamination. All the waste arising from a zone producing radioactive waste will have to be managed as radioactive waste as a function of the ANDRA classification for radioactive waste. There are no clearance levels for radionuclides in solid materials in France.

ITER radioactive waste can be classified into three categories based on its activity and radiotoxicity (note that French abbreviations are used since they correspond to specific acceptance criteria) [18]:

- TFA waste ('Très Faible Activité' meaning very low-level);
- FMA-VC waste ('Faible et Moyenne Activité à Vie Courte' meaning low- and intermediate-level short-lived);
- MA-VL waste ('Moyenne Activité à Vie Longue' meaning intermediate-level long-lived).

No high-level long-lived waste, abbreviated HAVL ('Haute Activité à Vie Longue') is generated by the ITER facility. In addition to the ANDRA categories, because of the use of tritium as fuel in ITER, purely tritiated waste is also considered, e.g. from the tritium plant. This consideration is to enable a specific routing for this type of waste to avoid cross-contamination with waste that is activated and tritiated during interim storage. After radioactive decay, it is anticipated that this waste will be sent to the FMA-VC storage centre [67].

6.2. Japan

In Japan, radioactive waste is classified into two basic categories: LLW and HLW. LLW is further divided into L1 (relatively high-level), L2 (relatively low-level) and L3 (very LLW) wastes in accordance with radionuclide concentration and the type of radiation. A trench type repository, without engineered barriers, at the near surface is considered to be applicable to L3. The disposal of L2 is similar to L3, but repository is required to have engineering barriers (concrete pit type) at slightly greater depth. L1 waste needs to be disposed of in sub-surface, at 50–100 m below ground, with engineered barriers like L2 waste [68]. At present, a LLW storage site is constructed in Rokkasho, operated by Japan Nuclear Fuel Limited, for LLW generated from spent fuel reprocessing. The basic principle for LLW disposal is that the public exposure anticipated by the land disposal does not exceed 10 μSv year^{-1}. Along this principle, the acceptance conditions for the Rokkasho site are defined for several representative nuclides such as ^{14}C, ^{36}Cl, ^{60}Co, ^{63}Ni, ^{94}Sr, ^{99}Tc, ^{129}I, ^{137}Cs and alpha emitters. Note that these conditions are defined for the acceptance to the Rokkasho site only and are different from the general classification levels for LLW.

A clearance system was introduced in 2005 following the IAEA standards [69] for the radioactive materials generated from commercial NPPs and research nuclear reactors. The clearance system is mostly applied for metallic and concrete wastes.

6.3. United States

The U.S. Nuclear Regulatory Commission (NRC) is responsible for radioactive waste generated by commercial power plants and other non-military uses of nuclear materials in the USA. Since the 1940s, the NRC along with its predecessor agency has established requirements for fission power plants and other RWM and storage. The U.S. Department of Energy (DOE) has the responsibility of dealing with radioactive waste from the creation of nuclear weapons and the cleanup of the facilities that manufactured these weapons. The DOE also deals with the waste from materials testing reactors and particle accelerators.

The NRC classifies the waste according to its WDR. The NRC 10CFR61 document [70] provides separate specific activity limits for classes A, B and C wastes for key radioactive nuclides produced in fission reactors, university research laboratories, manufacturing and food irradiation facilities, hospitals, healthcare companies and DOE facilities. The WDR is the ratio of specific activity (in Ci m^{-3}) for an individual radioisotope to its limit (specified by the NRC 10CFR61) summed over all radioisotopes.

In the absence of fusion-specific radwaste regulations, the NRC radwaste requirements for fission power plants are currently applied to fusion as well. There are several types of radioactive waste defined by the U.S. NRC HLW (with WDR $>$ 1) is typically very radioactive and can have high heat generation. It is too dangerous to store anywhere but deep underground ($\sim$600 m below the surface—far away from human life) and requires robust shielding (i.e. such as deep geologic storage) to ensure safety. There is also LLW, which is more relevant to fusion and can be safely disposed of in a near-surface repository. LLW has three classes, called A, B and C [70]. Class A waste is the least hazardous type of LLW. It should be placed 5–8 m deep in the ground. Class C waste is the most radioactive class of LLW. An intrusion barrier, such as a thick concrete slab, is added to class C waste trenches placed $>$8 m deep in the ground. There is another type of LLW, which is not officially defined yet and referred to as greater than class C waste. It does not fit within the LLW category and is not considered as HLW.

The NRC 10CFR61 [70] provides specific activity limits for only eight radionuclides (excluding actinides). This presents a weak basis for selecting reduced-activation materials for fusion and qualifying them as class C LLW for near-surface

disposal. Since the NRC 10CFR61 does not cover all radionuclides encountered in fusion, Fetter *et al* [71] expanded the NRC list considerably and performed analyses in the early 1990s to determine the class C specific activity limits for all radionuclides of interest to fusion using a methodology similar to that of 10CFR61. Although Fetter's calculations carry no regulatory endorsement, they are useful to fusion designers because they include fusion-specific radioisotopes. U.S. fusion designs apply both NRC and Fetter's limits and report the highest WDR for each component.

The U.S. has successfullys carried out the recycling of metals and concrete at small scale within the nuclear industry and at national laboratories. Nevertheless, it is a limited volume, not comparable to the ones expected from fusion, but enough to start to gather experience on the technical feasibility of recycling metals, even if it has been done only on recycling mildly radioactive materials back to the nuclear industry [51].

Beginning in the 1990s, clearance has been performed only on a case-by-case basis during decommissioning projects [47]. In 2003, the NRC issued the NUREG-1640 document [61] for 115 radioisotopes that can be found in four types of clearable materials: steel, copper, aluminum scrap and concrete rubble. More recently, in 2016, the DOE developed a technical standard to support the control, clearance and release of materials, equipment and items from accelerator facilities [5, 72].

In October 2020 and continuing to the present, several Public Forums on Fusion Regulation have been held jointly by the DOE and NRC. This is a major step forward towards the development of a fusion-specific regulatory framework for any type of fusion concept supported by the public or private sector.

7. Conclusion

Fusion is likely to be able to avoid creating large quantities of HLW that require active cooling. However, the expected amounts of fusion-derived ILW and LLW are large. Efforts to recycle and clear are essential to support fusion deployment, reclaiming of resources (through less ore mining), minimizing the radwaste burden for future generations and to continue holding the promise of fusion energy production with a low environmental impact. A waste strategy needs to be developed to mitigate the impact that the large waste volumes could have on the public perception of fusion as a viable and clean alternative source of energy.

Requirements (limits) on radioactive waste production (amount and severity) and their management need to be established at the beginning of the design. These requirements have to permeate the entire project during the design process and include:

- choosing materials and controlling impurities to avoid (as far as possible) the generation of long-lived radioisotopes;
- efficient shielding components to reduce the activation of structures and components as low as reasonably practicable without increasing the overall volume of radioactive materials;
- designing components to make separation according to the level of activation possible (to enable optimized decommissioning);
- choosing materials, processes and components to minimize tritium permeation and retention and to facilitate detritiation; tritium modeling, characterization tools should be developed, and feedback from tritium handling facilities should be utilized;
- reducing radwaste size, cutting of mixed materials, characterization and associated sampling;
- designing advanced RH equipment compatible with fusion radwaste to be integrated in early stages of the plant design;
- continue developing state-of-the-art activation codes and cross-section data that allow designers and material scientists to determine the radwaste management options (disposal, recycling and clearance) available during the design process.

Parallel to the implementation of the above criteria, a strong R & D effort needs to be devoted to recycling and clearance. In addition to addressing their critical issues and needs, the international community would benefit from a common effort and collaboration on the following:

- common approaches to derive clearance levels at a national level by applying the radiation protection approach based on the 10 μSv year^{-1} standard dose for cleared solids in practice. In addition, to harmonize the reference scenarios for calculating the doses and deriving, by proportion, the clearance levels of radionuclides of interest to the fusion industry;
- to reassess the definitions of waste categories and take a more pragmatic view of the different risks associated with fusion waste in comparison to fission and other nuclear waste. In particular, large masses of structural steels (the likely majority of fusion waste other than tritium) have a relatively low risk profile regardless of their absolute activation;
- to set up a globally recognized approach and methodology to estimate waste production volumes and masses for all radwaste types generated by fusion;
- to outline a global industrial solution for fusion-specific waste treatment, benchmarking existing acceptance criteria and sharing them with engineers in charge of fusion radwaste management to allow outsourcing and minimize investment costs for each fusion facility. This could also enable identification of markets and clients for recycled/clearable materials and equipmen;.
- to consider issuing fusion-specific guidelines by regulatory bodies for disposal, recycling and clearance by specifically considering the fusion radionuclide profile since it differs fromstandard fission isotopes. At a minimum, guidance for tritiated wastes would need to be issued or revised as they will have the largest immediate impact and differ the most from fission activation products.

Acknowledgments

This study has been carried out with the support and coordination of the IAEA. The authors gratefully acknowledge the support provided by their organizations to perform this work.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the IAEA or other agencies.

Appendix A

A.1. IAEA guidance materials

Some of the relevant IAEA guides at the overview level are the following:

- classification of radioactive waste (GSG-1) [3]. This safety guide lays out the various types of radioactive waste as defined by their physical characteristics. Fusion wastes can be easily transferred to this framework based on their characteristics;
- policies and strategies for RWM (NW-G-1.1) [73]: this comprehensive document details the various components of a national framework for RWM. This document also gives general descriptions for various types of waste (LLW, ILW, etc.) as well as how to choose an appropriate technology;
- storage of radioactive waste (WS-G-6.1) [74]: the storage of radioactive waste prior to final disposal is an important and key component of an RWM plan and is especially important for the short-lived tritium waste;
- disposal of radioactive waste (SSR-5) [75]: requirement of multiple types of disposal facilities;
- categorizing operational radioactive waste (TECDOC-1538) [76]: a reference that can be used in conjunction with GSG-1 to identify and plan for various waste types based on operational experience and physical characteristics.

There are a number of documents on radioactive waste, specifically on the treatment of specific types of waste (regardless of where the waste was generated in most cases) that could be applied wholly or in part to fusion-derived waste. The following documents typically outline the challenges and approaches to deal with a particular waste stream:

- management of waste containing tritium and carbon-14 (TRS-421) [77];
- predisposal management of organic radioactive waste (TRS-427) [78];
- application of membrane technologies for liquid radioactive waste processing (TRS-431) [79];
- application of thermal technologies for processing of radioactive waste (TECDOC-1527) [80];
- development of specifications for radioactive waste packages (TECDOC-1515) [81];
- management of problematic waste and material generated during the decommissioning of nuclear facilities (TRS-441) [82];
- new developments and improvements in the processing of 'problematic' radioactive waste (TECDOC-1579) [83];
- retrieval and conditioning of solid radioactive waste from old facilities (TRS-456) [84];
- strategy and methodology for radioactive waste characterization (TECDOC-1537) [85];
- mobile processing systems for RWM (IAEA Nuclear Energy Series NW-T-1.8) [86];
- treatment of radioactive gaseous waste (TECDOC-1744) [87].

A.2. Codes and nuclear data libraries typically used for activation and radwaste calculations

See table 1.

A.3. Specification of chemical composition and allowable impurity concentration of RAFM steels

See tables 2 and 3.

A.4. Radioactive waste classification in different countries

See table 4.

Table 1. Computer codes for radwaste assessment.

	Code (developer) [current version]	Functions, notes
Neutron and gamma-ray transport codes	MCNP (LANL, USA) [6.0]	3D Monte-Carlo neutron and photon transport analysis—industry standard, well-validated (https://mcnp.lanl.gov/)
	OpenMC (MIT, community)	3D Monte-Carlo code with open-source development community (https://docs.openmc.org/en/stable/)
	SuperMC (INEST, China)	3D Monte-Carlo neutron transport code (http://fds.org.cn/en/software/SuperMC.asp)
	DAGMC (UW, USA)	Direct use of CAD geometry with MCNP (https://svalinn.github.io/DAGMC/)
	PARTISN (LANL, USA)	1/2/3D discrete ordinate neutron and photon transport code (https://rsicc.ornl.gov/codes/ccc/ccc7/ccc-760.html)
	DENOVO (ORNL, USA)	3D deterministic code (https://ornl.gov/content/denovo-new-three-dimensional-parallel-discrete-ordinates-code-scale)
	ATTILA (USA)	3D deterministic code (https://swmath.org/software/18120)
Inventory evolution codes	FISPACT-II (UKAEA) [4.0]	Well-validated against experiment, OECD/NEA/RSICC distributed (https://fispact.ukaea.uk/)
	ORIGEN (ORNL, USA)	https://ornl.gov/division/rnsd/projects/origen
	ALARA (UW, USA)	State-of-the-art activation code; well-validated; RSICC distributed (https://rsicc.ornl.gov/codes/ccc/ccc7/ccc-723.html)
	ACAB (SPAIN)	http://oecd-nea.org/tools/abstract/detail/nea-1839
	DCHAIN-SP (JAEA)	http://oecd-nea.org/tools/abstract/detail/nea-1603/ aimed at high-energy accelerator-related facilities and was designed to resolve issues regarding spallation neutron utilization facilities
Nuclear data libraries	IAEA FENDL [versions 2.1 and 3.1]	Developed specifically for neutron transport applications in fusion models (not widely used for activation calculations) (https://nds.iaea.org/fendl/; Koning A.J. *et al* 2019 TENDL: complete nuclear data library for innovative nuclear science and technology *Nucl. Data Sheets* 155 1–55)
	JEFF (NEA) [3.3]	Jointly created by the fusion and fission community, includes decay data, and developed in collaboration with other libraries (https://oecd-nea.org/dbdata/jeff/jeff33/index.html)
	TENDL (IAEA/NRG/PSI) [2019]	Automatic processing approach aimed at complete (nuclide + reaction) coverage (https://tendl.web.psi.ch/tendl_2019/tendl2019.html)
	EAF (Europe) [2010]	Specific fusion file, no longer developed and limited format specification, but carefully crafted data
	JENDL (JAEA) [4.0]	Aimed at wide applications (https://ndc.jaea.go.jp/jendl/j40/j40.html)
	ENDF/B (USA) [VIII]	General purpose library (https://nndc.bnl.gov/endf/b8.0/)

Table 2. Specification of chemical composition and allowable impurity concentration of F82H (wt%) [38, 88].

Element	wt%	Element	wt%	Element	wt%
C	0.08–0.12	S	<0.01	Si	<0.2
Cr	7.5–8.5	B	<0.006	P	<0.02
W	1.6–2.2	O	<0.005	Nb	<0.001
Mn	0.05–0.5	Al	<0.04	Co	<0.01
V	0.15–0.25	Cu	<0.05	Ti	<0.01
Ta	0.02–0.10	Ni	<0.1	Fe	Balance
N	<0.025	Mo	<0.05		

Table 3. Specification of chemical composition and allowable impurity concentration of EUROFER97 (wt%) [89].

Element	wt%	Element	wt%	Element	wt%
C	0.09–0.12	As + Sn + Sb + Zr	0.00–0.05	Mo	<0.005
Cr	8.50–9.50	S	<0.005	Nb	<0.005
W	1.0–1.2	B	<0.002	Co	<0.01
Mn	0.20–0.60	Si	<0.050	P	<0.005
V	0.15–0.25	Al	<0.01	Ti	<0.02
Ta	0.10–0.14	Cu	<0.01	Fe	Balance
N	0.015–0.045	Ni	<0.01		

Table 4. Radioactive waste classification in different countries.

Country	Waste classification	Notes
UK	Mainly based on total activity of waste, categorized as either LLW, ILW, or HLW. LLW can be subdivided into VLLW 1 and 2 according to volume.	LLW is waste not exceeding 4 GBq/t alpha activity or 12 GBq/t of beta/gamma activity. UK also allows transition waste that will be exempt after a period of temporary storage. LLW repository at Drigg.
Belgium	Geological disposal for higher-activity waste and disposal to surface facility at Dessel according to a set of radionuclide limits for beta and alpha emitters.	
Finland	Waste classified according to activity. LLW in near-surface landfill or rock caverns; ILW in deeper rock caverns. Spent fuel waste in a geological repository (there is no HLW class in Finland).	LLW $\leqslant$ 1 MBq kg^{-1} ILW $\leqslant$ 10GBq g^{-1}
France	Various categories: HLW, ILW-LL, LLW-LL, LLW/ILW-SL, VLLW, VSLW Based on both activity (of individual nuclides or otherwise) and half-life.	HLW—geological disposal Limits for the critical nuclides in steel.
Germany	There is no fixed system for the classification of radioactive waste, but the general terms LLW, ILW and HLW are used, which are indicated as LAW, MAW and HAW.	For waste below the clearances is the EU directive 96/29/Euratom with 10 μSv concept anchored in the radiation protection ordinance.
Spain	No official waste classification system, but recognizes classes: group C, LILW (inc. VLLW) for waste with short (<30 year) half-life activity; group B, waste from uranium facilities; group D, HLW with long-lived alpha emitters. Group A is waste below clearance level (not subject to control).	Group D—Geological disposal Group C—El Cabril Group B—Surface disposal *in situ*

(*continued on next page*)

Table 4. Continued

Country	Waste classification	Notes
Sweden	No legal classification system, but nuclear industry uses scheme based on waste acceptance WAC. VLLW-SL ($T_{1/2} < 31$ years, dose $<$ 0.5 mSv h^{-1}). LLW-SL (surface dose $\leqslant$ 2mSv h^{-1}) ILW-SL ($T_{1/2} < 31$ years, dose $\leqslant$ 500 mSv h^{-1}). LILW-LL (does not meet the 31 year criteria). HLW (decay heat above 2 kW m^{-3}).	HLW (spent fuel) at Forsmark LILW-LL intermediate depth disposal ILW-SL & LLW-SL—near-surface disposal VLLW-SL—shallow land burial
Switzerland	HLW spent fuel, alpha-toxic waste—alpha emitters exceeding 20 GBq/te, L/ILW (all other radioactive waste).	Deep geological repositories for all classes except waste with half-lives less than 60 days or waste that decays below clearance level in 30 years.
Russia	Both LLW and VLLW classification limits exist with specific tritium limits and total activities (minus tritium).	Waste not meeting the LLW/VLLW criteria (based on a sum of fractions approach) must be disposed of geologically.
USA	NRC classifies the waste according to its WDR. The NRC 10CFR61 document [70] provides separate specific activity limits for class A, B and C waste, for key radioactive nuclides produced manly in fission reactors. Fetter expanded the NRC list and determine the class C limits for all radionuclides of interest to fusion. Recycling of metals and concrete has been done in the U.S. only in the context of the nuclear industry and at national laboratories [51]. Clearance has been performed only on a case-by-case basis during decommissioning projects. Clearable materials contain traces of radioactivity with very small doses $<$ 10 μSv $year^{-1}$.	WDR $>$ 1 means HLW WDR $<$ 1 means LLW: class C WDR $<$ 0.1 means LLW that may qualify for class A Activated materials having recycling dose $<$ 10 000 Sv h^{-1} could be recycled with advanced RH equipment. Activated materials with clearance index (CI) $<$ 1 could be cleared from regulatory control.

ORCID iDs

Sehila M. Gonzalez de Vicente https://orcid.org/0000-0003-3062-3164
Luigi Di Pace https://orcid.org/0000-0002-1515-8885
Mark Gilbert https://orcid.org/0000-0001-8935-1744

References

[1] El-Guebaly L. 2018 Nuclear assessment to support ARIES power plants and next step facilities: emerging challenges and lessons learned *Fusion Sci. Technol.* **74** 340–69
[2] El-Guebaly L. 2010 History and evolution of fusion power plant studies: past, present, and future prospects *Int. J. Energy Environ. Econ.* **18** 115–67
[3] International Atomic Energy Agency 2009 Classification of radioactive waste *IAEA Safety Standards Series No. GSG-1* (Vienna: IAEA)
[4] Gilbert M.R., Eade T., Rey T., Vale R., Bachmann C., Fischer U. and Taylor N.P. 2019 Waste implications from minor impurities in European demo materials *Nucl. Fusion* **59** 076015
[5] El-Guebaly L. *et al* 2017 Integral management strategy for fusion radwaste: avoiding geologic disposal through recycling and clearance Fusion Energy Sciences Advisory Committee (FESAC) (https://burningplasma.org/activities/uploads_tec/El-Guebaly_FESAC_TEC2017_White_Paper.pdf)
[6] ITER Organisation The ITER project available at (http://iter.org/)
[7] El-Guebaly L. 2017 Design and evaluation of nuclear system for ARIES-ACT2 power plant with DCLL blanket *Fusion Sci. Technol.* **72** 17–40
[8] Maisonnier D. 2005 A conceptual study of commercial fusion power plants *Final Report of the European Fusion Power Plant Conceptual Study (PPCS), EFDA-RP-RE-5.0* (European Fusion Development Agreement)
[9] Tobita K. *et al* 2019 Japan's efforts to develop the concept of JA DEMO during the past decade *Fusion Sci. Technol.* **75** 372–83
[10] ESBWR (Economic Simplified Boiling Water Reactor): GE Hitachi Nuclear Energy Nuclear power plants (https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/esbwr.html) (retrieved 14 September 2021)
[11] El-Guebaly L., Massaut V., Tobita K. and Cadwallader L. 2008 Goals, challenges, and successes of managing fusion activated materials *Fusion Eng. Des.* **83** 928–35

[12] Zucchetti M., Pace L.D., El-Guebaly L., Kolbasov B.N., Massaut V., Pampin R. and Wilson P. 2009 The back end of the fusion materials cycle *Fusion Sci. Technol.* **55** 109–39

[13] Di Pace L. 2012 Radioactive waste management of fusion power plants *Radioactive Waste* ed R.A. Rahman ch 14 available at (http://intechopen.com/books/radioactive-waste/radioactive-waste-management-of-fusion-power-plants)

[14] Zucchetti M. *et al* 2019 Progress in international radioactive fusion waste studies *Fusion Sci. Technol.* **75** 391–8

[15] Reid J. *et al* 2021 Comparison of waste due to irradiated steels in the ESFR and DEMO *The European Physical Journal Conferences* **247** 18002 10.1051/epjconf/202124718002

[16] Gilbert M.R., Eade T., Bachmann C., Fischer U. and Taylor N.P. 2017 Activation, decay heat, and waste classification studies of the European DEMO concept *Nucl. Fusion* **57** 046015

[17] Fishwick S. and Anderson J. R. 1992 European Fast Reactor Waste Arisings *Nuclear Assessments Committee, AEA Safety and Reliability, NAC(91)P18 Revision 1*

[18] Rosanvallon S., Torcy D., Chon J. K. and Dammann A. 2016 Waste management plans for ITER *Fusion Eng. Des.* **109–111** 1442–6

[19] Thi Nguyen L.A. *et al* 2017 Desorption dynamics of deuterium in CuCrZr alloy *J. Nucl. Mater.* **496** 117–23

[20] Fichet P. *et al Horizon 2020 programme, TRANSAT* Review of the different techniques to analyse tritium (https://transat-h2020.eu/wp-content/uploads/2020/04/TRANSAT_D2_1.pdf)

[21] Sublet J.-C., Eastwood J.W., Morgan J.G., Gilbert M.R., Fleming M. and Arter W. 2017 FISPACT-II: an advanced simulation system for activation, transmutation and material modelling *Nucl. Data Sheets* **139** 77–137

[22] Gilbert M.R. and Sublet J.-C. 2019 Experimental DECAY-HEAT simulation-benchmark for 14 MeV neutrons & complex inventory analysis with FISPACT-II *Nucl. Fusion* **59** 086045

[23] Grosse D. and Tsige-Tamirat H. 2009 Current status of the CAD interface program McCad for MC particle transport calculations *Conf. Proc.: Proc. of the 2009 Int. Conf. on Mathematics Computational Methods and Reactor Physics* (LaGrange Park: American Nuclear Society) p JRC54365 (https://publications.jrc.ec.europa.eu/repository/handle/JRC54365)

[24] Große D., Fischer U., Kondo K., Leichtle D., Pereslavtsev P. and Serikov A. 2013 Status of the McCad geometry conversion tool and related visualisation capabilities for 3D fusion neutronics calculations *Fusion Eng. Des.* **88** 2210–4

[25] Wilson P.P.H., Tautges T.J., Kraftcheck J.A., Smith B.M. and Henderson D.L. 2010 Acceleration techniques for the direct use of CAD-based geometry in fusion neutronics analysis *Fusion Eng. Des.* **85** 1759–65

[26] Wu Y. (FDS Team) 2009 CAD-based interface programs for fusion neutron transport simulation *Fusion Eng. Des.* **84** 1987–92

[27] Li Y. *et al* 2007 Benchmarking of MCAM 4.0 with the ITER 3D model *Fusion Eng. Des.* **82** 2861–6

[28] Wu Y., Li Y., Lu L. and Ding A. 2006 Research and development of the automatic modeling system for Monte Carlo particle transport simulation *Chin. J. Nucl. Sci. Eng.* **26** 20–7

[29] Sawan M.E. 2012 Damage parameters of structural materials in fusion environment compared to fission reactor irradiation *Fusion Eng. Des.* **87** 551–5

[30] El-Guebaly L. 2013 Design challenges and activation concerns for ARIES vacuum vessel *Fusion Sci. Technol.* **64** 449–54

[31] Barabash V., Eaton R., Hirai T., Kupriyanov I., Nikolaev G., Wang Z., Liu X., Roedig M. and Linke J. 2011 Summary of beryllium qualification activity for ITER first-wall applications *Phys. Scr.* **T145** 014007

[32] Someya Y., Tobita K., Hiwatari R. and Sakamoto Y. 2018 Fusion DEMO reactor design based on nuclear analysis *Fusion Eng. Des.* **136** 1306–12

[33] Kim J.-H., Nakano S. and Nakamichi M. 2020 A novel method to stably secure beryllium resources for fusion blankets *J. Nucl. Mater.* **542** 152522

[34] Federici G. *et al* 2018 DEMO design activity in Europe: progress and updates *Fusion Eng. Des.* **136** 729–41

[35] Bailey G.W., Vilkhivskaya O.V. and Gilbert M.R. 2021 Waste expectations of fusion steels under current waste repository criteria *Nucl. Fusion* **61** 036010

[36] Morales A. 1997 Characterization and acceptance criteria of conditioned radioactive wastes at El Cabril disposal facility *Nucl. Eng. Des.* **176** 177–80

[37] Tamura M., Hayakawa H., Tanimura M., Hishinuma A. and Kondo T. 1986 Development of potential low activation ferritic and austenitic steels *J. Nucl. Mater.* **141–143** 1067–73

[38] Tanigawa H., Someya Y., Sakasegawa H., Hirose T. and Ochiai K. 2014 Radiological assessment of the limits and potential of reduced activation ferritic/martensitic steels *Fusion Eng. Des.* **89** 1573–8

[39] Someya Y., Tobita K., Hiwatari R. and Sakamoto Y. 2018 Fusion DEMO reactor design based on nuclear analysis *Fusion Eng. Des.* **136** 1306–12

[40] Klueh R.L., Cheng E.T., Grossbeck M.L. and Bloom E.E. 2000 Impurity effects on reduced-activation ferritic steels developed for fusion applications *J. Nucl. Mater.* **280** 353–9

[41] Henderson D. 2001 Activation, decay heat, and waste disposal analysis for ARIES-AT power plant *Fusion Technol.* **39** 444

[42] Muroga T. 2005 Vanadium alloys for fusion blanket applications *Mater. Trans.* **46** 405–11

[43] Dyomina E.V., Fenici P., Kolotov V.P. and Zucchetti M. 1998 Low-activation characteristics of V-alloys and SiC composites *J. Nucl. Mater.* **258–263** 1784–90

[44] Torcy D. *et al* 2018 Provisions for ITER decommissioning *International conference on dismantling challenges: industrial reality, prospects and feedback experience Int. Conf. on Dismantling Challenges: Industrial Reality, Prospects and Feedback Experience* (Avignon (France)) pp 22–4 (https://www.sfen.org/evenement/dem-2021/)

[45] van der Laan J.G. *et al* 2016 Radwaste management aspects of the test blanket systems in ITER *Fusion Eng. Des.* **109–111** 222–6

[46] El-Guebaly L. 2007 Evaluation of disposal, recycling, and clearance scenarios for managing ARIES radwaste after plant decommissioning *Nucl. Fusion* **4** 485–8

[47] El-Guebaly L. 2014 Perspectives of managing fusion radioactive materials: technical challenges, environmental impact, and US policy *Radioactive Waste: Sources, Management and Health Risks* ed S. Fenton (Hauppauge: NOVA Science Publishers, Inc.)

[48] 1980 STARFIRE—a commercial tokamak fusion power plant study *Argonne National Laboratory Report ANT/FPP-80-1* Argonne National Lab, IL (USA)(https://inis.iaea.org/search/search.aspx?orig_q=RN:12603252)

[49] Ponti C. 1988 Recycling and shallow land burial as goals for fusion reactor materials development *Fusion Technol.* **13** 157–64

[50] Rocco P. and Zucchetti M. 1998 Advanced management concepts for fusion waste *J. Nucl. Mater.* **258–263** 1773–7

[51] El-Guebaly L.A., Setyawan W., Henager Jr C.H., Kurtz R.J. and Odette G.R. 2021 Neutron activation and radiation damage assessment for W–Ni–Fe tungsten heavy alloys with variable Ni content heavy alloys with variable Ni content *Nucl. Mater. Energy* **29** 101092

[52] El-Guebaly L. *et al* 2005 Current challenges facing recycling and clearance of fusion radioactive materials *University of Wisconsin Fusion Technology Institute Report, UWFDM-1 285* (https://fti.neep.wisc.edu/fti.neep.wisc.edu/pdf/fdm1285.pdf)

[53] Zucchetti M., El-Guebaly L.A., Forrest R.A., Marshall T.D., Taylor N.P. and Tobita K. 2007 The feasibility of recycling and clearance of active materials from fusion power plants *J. Nucl. Mater.* **367–370** 1355–60

[54] Massaut V., Bestwick R., Bróden K., Di Pace L., Ooms L. and Pampin R. 2007 State of the art of fusion material recycling and remaining issues *Fusion Eng. Des.* **82** 2844–9

[55] Kolbasov B. 2014 Some technological problems of fusion materials management *Fusion Eng. Des.* **89** 2013

[56] Bartenev S.A., Kvasnitskij I.B., Kolbasov B.N., Romanov P.V. and Romanovskij V.N. 2004 Radiochemical reprocessing of V–Cr–Ti alloy and its feasibility study *J. Nucl. Mater.* **329–333** 406–10

[57] IAEA 2003 *Radioactive Waste Management Glossary* (https://pub.iaea.org/MTCD/Publications/PDF/Pub1155_web.pdf)

[58] IAEA TECDOC 855 1996 Clearance levels for radionuclides in solid materials: application of the exemption principles *Interim Report for Comment* (TECDOC-855 International Atomic Energy Agency)

[59] Application of the Concepts of Exclusion, Exemption and Clearance 2004 *IAEA Safety Standards Series, No. RS-1.7* (International Atomic Energy Agency) available online (http://pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf)

[60] Deckert A. *et al* Radiation protection 114—definition of clearance levels for the release of radioactively contaminated buildings and building rubble 1999 *Final Report Contract C1/ETU/970040* European Commission (https://ec.europa.eu/energy/sites/ener/files/documents/114.pdf)

[61] El-Guebaly L., Wilson P., Paige D., Team A. and Team Z.-P. 2006 Evolution of clearance standards and implications for radwaste management of fusion power plants *Fusion Sci. Technol.* **49** 62–73

[62] State Atomic Energy Corporation ≪Rosatom≫ and the Federal Environmental, Industrial and Nuclear Supervision Service 2014 The fourth National Report of the Russian Federation on Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (https://rosatom.ru/upload/iblock/8c0/8c0b6fba95869e6673962ee96f467da2.pdf)

[63] United Nations Scientific Committee on the Effects of Atomic Radiation 2000 Sources and Effects of Ionizing Radiation UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. ISBN 92-1-142238-8 (https://unscear.org/docs/publications/2000/UNSCEAR_2000_Report_Vol.I.pdf)

[64] ASN *Summary of the French National Plan for the management of radioactive materials and waste* (https://www.french-nuclear-safety.fr/asn-informs/publications/others-asn-reports/french-national-plan-for-the-management-of-radioactive-materials-and-waste-for-2016-2018#:~:text=The%20National%20Plan%20for%20Radioactive,of%20radioactive%20materials%20and%20waste) 2016–2018

[65] Publications Office of the European Union *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives* (https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=CELEX:32008L0098)

[66] International approaches to radioactive waste classification 2016 *National Waste Program Technical Report NWP-REP-134* LLW Repository Ltd, Cumbria, UK

[67] Zheng S., Pampin R., Lilley S., Na B.C., Loughlin M. J., Taylor N.P. and Barabash V. 2012 Analyses and preliminary results of an updated ITER radioactive waste assessment *Fusion Sci. Technol.* **61** 167–71

[68] 2014 JA LLW classes available at IAEA Global Nuclear Safety and Security Network: IAEA Safety Report (https://gnssn.iaea.org/RTWS/general/shared%20Documents/Waste%20Management/Intermediate%20Level%20Waste/November%202014%20Technical%20Meeting/National%20examples/Japan.pdf)

[69] Application of the concepts of exclusion, exemption and clearance 2004 *IAEA Safety Standards Series, No. RS-1.7* (International Atomic Energy Agency) available on the internet at (http://pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf)

[70] United States National Regulatory Commission *US Code of Federal Regulations, Title 10, Energy, Part 61, Licensing Requirements for Land Disposal of Radioactive Waste. Subpart D: Waste Classification* 2017 (https://nrc.gov/reading-rm/doc-collections/cfr/part061/part061-0055.html)

[71] Fetter S., Cheng E.T. and Mann F.M. 1990 Long-term radioactive waste from fusion reactors: part II *Fusion Eng. Des.* **13** 239–46

[72] U.S. Department of Energy 2016 Clearance and release of personal property from accelerator facilities *DOE-STD-6004-2016* (https://www.standards.doe.gov/standards-documents/6000/6004-astd-2016/@@images/file)

[73] International Atomic Energy Agency 2009 Policies and strategies for radioactive waste management *Nuclear Energy Series No. NW-G-1.1* (Vienna: IAEA)

[74] International Atomic Energy Agency 2006 Storage of radioactive waste *IAEA Safety Standards Series No. WS-G-6.1* (Vienna: IAEA)

[75] International Atomic Energy Agency 2011 Disposal of radioactive waste *IAEA Safety Standards Series No. SSR-5* (Vienna: IAEA)

[76] International Atomic Energy Agency 2007 Categorizing operational radioactive wastes *IAEA-TECDOC-1538* (Vienna: IAEA)

[77] Turner R. 2006 Scrap metals industry perspective on radioactive materials *Health Phys.* **91** 489–93

[78] International Atomic Energy Agency 2004 Predisposal management of organic radioactive waste *Technical Reports Series No. 427* (Vienna: IAEA)

[79] International Atomic Energy Agency 2005 Application of membrane technologies for liquid radioactive waste processing *Technical Reports Series No. 431* (Vienna: IAEA)

[80] International Atomic Energy Agency 2007 Application of thermal technologies for processing of radioactive waste *IAEA-TECDOC-1527* (Vienna: IAEA)

[81] International Atomic Energy Agency 2006 Development of specifications for radioactive waste packages *IAEA-TECDOC-1515* (Vienna: IAEA)

[82] International Atomic Energy Agency 2006 Management of problematic waste and material generated during the decommissioning of nuclear facilities *Technical Reports Series No. 441* (Vienna: IAEA)

[83] International Atomic Energy Agency 2008 New developments and improvements in processing of 'problematic' radioactive waste *IAEA-TECDOC-1579* (Vienna: IAEA)

[84] International Atomic Energy Agency 2007 Retrieval and conditioning of solid radioactive waste from old facilities *Technical Reports Series No. 456* (Vienna: IAEA)

[85] International Atomic Energy Agency 2007 Strategy and methodology for radioactive waste characterization *IAEA-TECDOC-1537* (Vienna: IAEA)

[86] International Atomic Energy Agency 2014 Mobile processing systems for radioactive waste management *Nuclear Energy Series No. NW-T-1.8* (Vienna: IAEA)

[87] International Atomic Energy Agency 2014 Treatment of radioactive gaseous waste *IAEA-TECDOC-1744* (Vienna: IAEA)

[88] Nozawa T. *et al* 2021 *Nucl. Fusion* **61** 116054

[89] Gaganidze E. *et al* 2018 Development of EUROFER97 database and material property handbook *Fusion Engineering and Design* vol 135 pp 9–14