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Abstract. During operation fusion reactor components will be exposed to long periods of neutron irradiation. As such, a reactor's structural steels will become activated and need to be disposed of as radioactive waste. Previous studies have shown that such wastes can struggle to meet low level waste requirements meaning that costly geological disposal may be required.

In order to explore the waste expectations of steels from European DEMO-like fusion reactors, several radioactive waste management systems have been investigated. This includes their low level waste criteria, currently available disposal sites and planned future developments. This information was used to analyse the results of DEMO-like inventory simulations of potential reactor steels. The simulations were performed with the inventory code FISPACT-II and the TENDL2017 nuclear data library.

The results suggest that when steels are exposed to near plasma neutron fluxes they will struggle to meet the majority of low level waste requirements. For lower neutron fluxes, typical of reactor containment vessels, the waste expectations can be more positive, with several steels able to meet some low level criteria. It can be concluded that steels should not be expected to be consistently internationally classified as low level waste 100 years after reactor shut down. As all activated fusion waste cannot be disposed of in a single location, it is recommended that waste disposal strategies are included in any fusion reactor proposal before construction begins. These strategies need to align with the radioactive waste regulations the proposed reactor will be subject to.

Keywords: waste classification, steel radioactivity, low-level waste repositories, inventory simulations, fusion waste

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1. Introduction

As the world's energy needs continue to grow new sources of abundant energy, that do not contribute to carbon dioxide emissions, are required. Nuclear energy does not directly produce carbon dioxide and can provide significant energy output. Unfortunately, traditional nuclear fission plants produce high level radioactive waste (HLW). Nuclear fusion promises to be an ideal energy solution with the public perception being that fusion power plants will provide nuclear energy and producing little to no radioactive waste (RW).

In reality all fusion power plants are expected to produce large amounts of radioactive material, due to their expected scale. This is a result of the high flux of neutrons, produced at approximately 14 MeV in the fusion of deuterium and tritium, impinging on the reactor structure as they are not constrained in the burning plasma.

These neutrons will cause nuclear activation and damage within reactor components. This is a concern during the operation of a potential fusion power plant, as damage will require maintenance and nuclear activation will hamper this. At reactor end of life (EOL) the activated material will have to be disposed of as RW. For fusion power to be commercially and publicly viable reactors must try to minimise this waste and adhere to strict waste constraints. The waste from the first generation of commercial fusion reactors should ideally all be classified as low level waste (LLW) from 100 years after EOL.

Previous work [1, 2, 3] on the waste expectations from the European DEMO fusion reactor concept suggest that this will be challenging to achieve. Several of the plasma-facing and near plasma components are predicted to fail to meet LLW requirements 1000 years after reactor EOL. Other studies of expected activated fusion wastes with the AREIS reactor concepts [4, 5] have suggested that EOL LLW classification could be achieved for fusion reactor components, but the volume of LLW produced would be very large. In these cases the near plasma materials are not expected to be cleared from regulatory control for over 100 years. These works and others [6, 7, 8] have also suggested that the waste burden of fusion could be reduced via recycling reactor materials, specifically for use in nuclear industry. However, the technological requirements for such wide scale recycling and reuse of activated components still requires development.

Typically RW is classified based on the activity of the sample and the sources of this activity. These classification schemes then determine how the waste will be disposed of. It should be noted that the structural steel waste from fusion which does not meet LLW criteria is classed as intermediate level waste (ILW), as it is not expected to require active cooling, a common defining feature of HLW. The past studies cited used the waste classification schemes from the UK, France and the US, these differ in their requirements despite using a similar classification structures. This is common; while most waste systems will include commonly named classifications (low level, intermediate level, high level etc.) there is no guarantee that a given sample will achieve the equivalent waste classification in different repositories. This is because waste criteria, such as sample

activity limits, can and do differ between repositories, making absolute classification of a given sample difficult. For the waste expectations for fusion to be fully understood a review of current waste repositories is required so that simulation results (such as those used in [1, 2, 3]) can be fully contextualised.

The major contributor to expected fusion waste are structural steels, as these will make up a significant proportion of an operating fusion reactor. The DEMO torus is expected to have a mass on the order of thousands of tonnes for example. The previous work only considered some of the steels planned for use in the DEMO reactor: the European reduced activation steel Eurofer and the stainless steel SS316. Future fusion facilities may make use of these and/or a number of other steels, therefore the waste expectations of various steels needs to be assessed. This will allow the waste expectations from the first generation of fusion power plants to be better understood. This paper reviews a selection of international of LLW repositories and criteria, highlighting and discussing their differences. The results of detailed inventory simulations with FISPACT-II [9] and the TENDL2017 nuclear data library [10] have then being analysed with these criteria to assess the waste disposal prospects for various potential fusion steels. This includes an extension beyond the normal steels considered for fusion applications.

2. Low and intermediate level waste repositories and criteria

2.1. Current LLW and ILW repositories

It is common practice to dispose of very low level waste (VLLW), LLW or ILW with a limited concentration of long-lived (half-life, $t_{1/2} > 30$ years) in near surface repositories (NSRs), often referred to as near surface disposal (NSD). Sub-surface (underground) facilities are used for higher activity waste [11, 12] with deep geological repositories (DGRs), or geological disposal facilities (GDFs), being considered for radioactive waste (RW) with higher contents of long-lived radionuclides. Several countries are planning to construct such DGRs as well as centralised processing and temporary storage facilities [11] to manage their current RW.

Several factors determine how RW should be disposed of; the national regulations implemented by the relevant waste management organisations (WMOs), the operational limits of particular interim storage facilities and the acceptance criteria at the chosen disposal sites [11, 13, 14]. Details of the major radioactive waste management projects that are currently implemented and those planned within the Euroatom community, for example, are discussed in [15].

As the fusion waste is desired to be LLW 100 years after shut down, this work will focus on surface and NSD options. The waste management systems studied are those of the UK, US, Russia, France, Spain and Japan. Details of repositories and regulations operating in these countries are given in table 1. Section 2.4 details the classification criteria these waste management systems employ. The RW management policy in these

Table 1. Current status of long-term management and near surface disposal of RW for waste management systems under study.

Country	Current RW repositories and storage facilities	Transportation and import regulations
United Kingdom [17, 11, 12]	• LLWR Drigg (LLW) • Sellafield and Sizewell B (LLW/ILW/HLW) • Dounreay (ILW/LLW) • Springfields (VLLW/LLW) • Harwell storage facility (VLLW) [18, 19]	Allows transport or RW via road, rail and sea. Conditionally allows import of RW for disposal (may change as the UK has left the European Union). Allows the import of spent nuclear fuel (SNF) for reprocessing, returning the reprocessed materials and by-products.
United States [20, 11, 12]	• Barnwell, SC (VLLW/LLW) • Hanford, WA (VLLW/LLW) • Andrews, TX (VLLW/LLW) • Clive, UT (VLLW) • WIPP, New Mexico (ILW/LLW) • Hanford,WA (LLW) • INL, ID (LLW) • West Valley, NY (LLW) • Savannah River Site, SC (LLW)	Allows transport via road, rail and sea. Allows the import of SNF from research and non-power reactors for disposal. Works with the IAEA (International Atomic Energy Authority) and others to remove and protect vulnerable nuclear material from civilian sites worldwide [21].
France [22, 11, 23]	• CIRES (VLLW) • CSA l'Aube (LLW) • Morvilliers (VLLW)	Allows road and rail transportation. Allows the import of SNF for reprocessing, which is returned. No RW either originating from abroad or resulting from the processing of SNF or RW can be imported.
Russian Federation [24, 11, 12]	• UECC, Novouralsk (LLW+ILW) • MCC, SCC, RIAR sites (liquid LLW/ILW) • PA Mayak, near-surface water reservoirs (liquid LLW) • PIMCU (solid LLW).	RW can be transported via road, rail and sea. Allows import of the returned SNF from research and power reactors (built by the USSR) for reprocessing and disposal.
Spain [25, 11, 12]	• El Cabril, Corboda (Low Intermediate Level waste (LILW)/ VLLW) • CIEMAT (LILW)	Currently, no transportation for any HLW or SNF. Importing RW is prohibited.
Japan [26, 11, 12]	• Rokkasho-Mura Disposal Center (LLW) • Tokai Reprocessing Plant and DSD (VLLW) • JNFL repository (LLW/VLLW)	Allows road, rail, maritime transportation of SNF for reprocessing in Europe. Re-entry of exported SNF and RW is allowed. RW import of hazardous and other wastes for final disposal is restricted.

countries (with the exception of France and Spain) conditionally allows import of the RW for disposal. A broader summary of the LLW repositories in other countries is available in [16].

2.2. Future Outlook on LLW Waste Repositories

Several countries are currently undertaking, or have plans for, the expansion of existing as well as constructing new NSD facilities [11, 12, 16]. For the particular waste management systems under study, at time of writing:

- The UK are constructing 2 extra vaults at the LLWR Drigg site [27] and planning a GDF.
- The US are constructing a federal LLW disposal facility on site a the Portsmouth Gaseous Diffusion Plant [28].
- France is constructing a disposal vault for outsized waste packages (VLLW). This was initiated in 2016 at CIRES [22]. Additional storage vaults are under construction at CSA l'Aube [23]. There are also plans for the construction of the INTERMED tritiated waste storage facility for ITER, with commissioning planned for 2026 or 2027.
- The Russian Federation are designing two new NSR (LLW/ILW) to be constructed at existing sites; SSC, PA Mayak, UECC, and Sosnovy Bor [24].
- Spain is planning to construct two additional cells at El Cabril [29] to reach an authorised capacity of 130,000 m^3 for VLLW.
- Japan plans to increase capacity at the Rokkasho waste facilities [26].

In addition than those directly studied in this work, other countries are also expanding their ILW/LLW disposal facilities. Belgium has proposed the construction of a disposal facility at Dessel [30] (similar to the Centre de l'Aube in France and El Cabril in Spain). The conversion of the Konrad mine into a repository for LLW/ILW with negligible heat generation is ongoing in Germany [31], commissioning is scheduled for 2021. A landfill repository for low intermediate level waste (LILW) is expected to be commissioned in Lithuania and their are plans to establish a NSR for LILW by 2020 [32]. Updates on the status of the RW treatment and disposal programmes are available at the IAEA Country Nuclear Power Profiles [33].

2.3. Future disposal requirements for fusion wastes

The waste disposal requirements for future fusion facilities will need to consider a number of factors. Firstly, the acceptance limits for RW in some of the the available LLW repositories require that the 'origin' of the waste should be indicated. Thus a 'fusion' origin would have to be added to the regulatory documentation. This may affect how fusion waste is disposed of, as solid steel waste will require different disposal options when compared to liquid waste with the same activity for example. At time of writing, the import of RW for disposal is mostly prohibited/restricted, so fusion waste will likely have to be disposed of in the same country where the waste was produced, i.e. where the fusion power plant is. Therefore countries planning on allowing the construction of fusion facilities will have to account for fusion waste when defining future RW policy.

The reprocessing of the RW from fusion in large quantities is expected to also be an issue, so a centralised fusion waste facility may be beneficial. What is deemed the 'best' method/requirements for fusion waste disposal will have to be decided by fusion plant operating countries long before the first generation of reactors are decommissioned.

2.4. LLW classification criteria from RW systems studied

When determining if a given sample meets a repositories LLW requirements a number conditions must be meet. Typically these are global, sample-wide, specific activity limits (Bq per unit mass or volume) or specific activity from given nuclide sources. Many waste repositories make use of a 'Sum of Fractions' concept when determining if a mixed sample (i.e. one containing many nuclear species) can meet a given repositories waste requirements. This sum is defined in equation 1,

$$S_F = \sum_i \frac{N_i}{L_i} \leq 1. \tag{1}$$

Here N_i is the specific activity for a given nuclide i and L_i is the limit on that specific activity prescribed by a given waste classification system for nuclide i. It is desired that $S_F \leq 1$, how that can interpreted as and which nuclide's activities should be summed will depend on the waste system in question.

The assessment criteria believed to be used in the waste management systems under study are summarised below. These criteria are derived from available documentation, but may not be fully representative of the complete set of requirements a sample may have to meet to be placed in a given repository.

(i) **UK**: The UK's low level waste strategy [34] uses simple global limits [35] for total α and $\beta + \gamma$ specific activities for bulk classification. For a sample to be classified as LLW it must have activity from α sources less than 4 MBqkg^{-1} and the sum of activities from $\beta + \gamma$ sources less than 12 MBqkg^{-1}. The UK criteria also include a VLLW category, this defines radioactive material which can be disposed of in specific commercial and industrial landfill sites. As the radioactive waste from fusion is expected to require technical disposal the UK's VLLW class will not be considered in this work.

(ii) **US**: In the USA LLW is divided in to three waste classes: A, B, and C with A representing the least active samples, C the most active [36]. All waste which meets one of these classes criteria is considered for near surface disposal. Class A waste is expected to be contaminated equipment and clothing, Class B waste is typical of reactor components and sealed radioactive sources. With Class C covering same as Class B, but with higher allowed activities. The USA uses specific activity limits on two groups of nuclides to define the waste classes:

  (a) Group 1, long lived sources ($t_{1/2}$ >100 years). This groups imposes limits on 7 nuclides and the sum of transuranic ($t_{1/2}$ >5 years, $Z \geq 92$) activities.

  (b) Group 2, intermediately lived sources. Limits imposed on 5 nuclides and the sum of activities from nuclides with $t_{1/2}$ ≤5 years.

A sample must meet a given classes activity limits and produce a 'Sum of Fractions' using those limits ≤ 1 to achieve a given class. The group 2 nuclides only need be considered if Class A is achieved by the group 1 criteria.

(iii) **France**: France's LLW criteria are based on a set individual radionuclide limits. In total the specific activities from 41 nuclides are assessed when classifying a sample, with a further 75 nuclides having a declaration threshold activity without specific waste limits [37, 38]. These limits are defined according to the expected activity from a given nuclide and its half-life. France does not have limits on a samples total α, β or γ activity.

(iv) **Russian Federation**: The Russian radioactive waste management system includes both LLW and VLLW waste classification criteria. These use specific activity limits for activity from tritium, $\beta + \gamma$ emitters minus tritium, α emitters and transuranic α emitters [39]. In order for a mixed sample to undergo NSD it must also meet a 'Sum of Fractions' (see equation 1) criteria using limits from 9 nuclides, if it fails to do so the sample must be disposed of geologically.

(v) **Spain**: Spain splits LLW into 3 categories which, from highest to lowest allowed activities are: LILW level 2, LILW level 1 and VLLW. The LILW classifications use specific activities from individual nuclides; 10 common to both levels (with differing limits for each level) and an additional 21 nuclides included in level 1. The LILW criteria also include limits on global α and $\beta + \gamma$ specific activity. VLLW classification requires a sum of fractions (see equation 1) of 133 nuclides, which include those studied for LILW classification. The result of the sum of fractions is referred to as an acceptance index. If this index is below 1 and the sample meets LILW level 1 criteria it can be classified as VLLW.

(vi) **Japan**: The Japanese radioactive waste management system uses specific activity limits on 33 nuclides to determine if a sample needs to be disposed of as radioactive waste. If a sample breaches these clearance limits it is then subjected to Japan's waste classification criteria. Japan separates LLW into three categories: L3 very low activity LLW, L2 relatively low activity LLW and L1 relatively high activity LLW. Only L3 and L2 waste is considered for NSD with L3 using trench disposal and L2 concrete lined pits. L1 waste undergoes sub-surface, but not geological disposal. A sample is assigned a categorisation by studying the specific activity from 8 nuclides and a its total α emissions [40]. Unlike the other waste criteria with global activity limits, Japan's waste system does not include any limits on global β or γ activity.

2.4.1. Limits of interest to fusion

Previous studies [1, 2, 3] of waste expectations of fusion have identified that activity from ^{3}H, ^{63}Ni, ^{94}Nb and ^{14}C can pose significant challenge to achieving LLW classification. The presence of ^{99}Tc can also be a problem in some steels due to its long half life. Where present, the maximum allowed specific activity limits for these nuclides and

Table 2. Table showing the maximum allowed activities of nuclides critical to fusion radioactive steel waste. It should be noted that the differing units make direct comparisons difficult. The Russian system does not includes a specific $\beta + \gamma$ limit, instead subtracting the ^{3}H activity. Dashes indicate that the waste system does not have a limit for that given nuclide/activity source.

	Activity Limits (Bqkg^{-1}) [† Bqm^{-3}]						
Country	α	$\beta + \gamma$	^{3}H	^{14}C	^{63}Ni	^{94}Nb	^{99}Tc
UK	4×10^{6}	1.2×10^{7}	-	-	-	-	-
US	-	-	$^{\dagger}1.48\times10^{12}$	$^{\dagger}2.96\times10^{12}$	$^{\dagger}2.59\times10^{14}$	$^{\dagger}7.4\times10^{9}$	$^{\dagger}1.11\times10^{11}$
France	-	-	2×10^{8}	9.2×10^{7}	3.2×10^{9}	1.2×10^{5}	4.4×10^{7}
Russia	1×10^{3}	$1\times10^{7}(-^{3}\mathrm{H})$	$^{\dagger}1\times10^{11}$	$^{\dagger}3\times10^{12}$	$^{\dagger}2.59\times10^{14}$	$^{\dagger}7.4\times10^{9}$	$^{\dagger}1.1\times10^{11}$
Spain	3.7×10^{6}	3.7×10^{7}	1×10^{9}	2×10^{8}	1.2×10^{10}	1.2×10^{5}	1×10^{6}
Japan	1×10^{7}	-	-	1×10^{13}	1×10^{10}	-	1×10^{11}

global sources from the UK, France, Spain, USA, Russia and Japan's waste management systems are shown in table 2. What is first noticeable is that all of the US limits and some of the Russian limits are defined by unit volume, this makes directly comparing the limits difficult. Such a comparison can easily be made when considering a defined sample as it will have a given mass and volume. Where the US and Russian limits share common units they are or almost are identical; this is likely due to the limits having common origins from IAEA waste safety standards [41]. The values themselves appear originate from the US Nuclear Regulatory Commission [42]. Another feature of note in table 2 are the higher magnitude of the Japanese limits. This would suggest that sample will more readily achieve a LLW classification in Japan when compared with other waste management systems studied.

3. Prospective steels for fusion

3.1. Steels under study

The neutron fluxes that will be experienced by fusion plasma-facing or near-facing components are expected to induce high levels of nuclear activation. To counter excessive activation in fission or fusion environments steels have been developed which are intended to be resistant to nuclear activation. These Reduced Activation Ferritic/Martensitic (RAFM) steels were first developed in the 1980's [43, 44], but the growing needs of the global nuclear industry has lead to increased development in recent years [45, 46, 47, 48]. Unfortunately, these RAFM steels do not often possess the mechanical properties required for structural reactor components or are not qualified to the necessary safety regulation standards, and so it is likely that more conventional stainless steels will still be used in major components of future fusion reactors, including the vacuum vessel. RAFM steels are currently only foreseen to be used in the near plasma or in-vessel regions of fusion reactors, where the irradiation fluxes are particularly

severe, with traditional stainless steels used in other (outer) areas.

This work will study a selection of RAFM and non-RAFM steels. These are detailed in table 3 which contains a description of the steel origins, their intended uses and whether they have been designed as a RAFM steel or not. The elemental compositions of the steels used in this study are shown in table 4. It should be noted that these steels are in different stages of development or technological readiness. The non-RAFM steels are currently mass produced so their compositions are well known and relativity fixed, whereas this is not true of the RAFM steels. The latter are often experimental materials and as such their elemental compositions are subject to change. For example, F82H was developed in the 1980's and can still show variations in composition [49, 50, 51].

3.2. DEMO-like irradiation of possible fusion steels

In order to assess the possible waste classifications of the steels in table 3, inventory simulations under irradiation conditions representative of two regions of the proposed DEMO reactor have been performed. The two regions studied are the Blanket, a near plasma facing region where tritium breeding occurs, and the Vacuum Vessel (VV), which is the primary containment of the fusion plasma. The two flux spectra used in the simulations shown are in figure 1. These fluxes have been extracted from neutron transport simulations performed using MCNPv6.2 [70, 71] for a DEMO concept model produced by the European research program used in previous work [1]. It should be noted that the EU-DEMO reactor concept is continuously evolving. As such the fluxes and results presented in this work should be considered approximations of those expected from a finalised DEMO-like reactor design.

The two components studied will have different life times in the DEMO reactor and therefore will require different irradiation schedules. The VV is not planned to be replaced at any point during DEMO's approximately expected 22 year lifetime, where as the first blankets on DEMO are to be replaced after 5.2 years [72, 1]. The results presented in this study are for second set of blanket modules, which will experience 14.8 years of use and thus represent the worst case scenario from an activation perspective, and will be the blanket components at EOL. It is assumed that a year of downtime will be needed to replace the Blankets, while two further periods of 8 months downtime will be needed during the second phase of operation for further maintenance (divertor replacement). These pauses in operation are included in the irradiation schedules used in this work. The inventory simulations have been performed using the FISPACT-II [9] inventory code, the TENDL2017 nuclear cross section data library [10] and the UK decay2012 decay data library. One kilogram of each steel was exposed to each of the irradiation scenarios described, and then decay-cooling was simulated for time steps from 1 second to 1000 years after irradiation (DEMO EOL).

The resultant activation curves for the Blanket and VV irradiations for each steel studied are shown in figures 2 and 3, respectively. These are plotted from 10 years to 1000 years after EOL. Comparing the two sets of activation curves, the higher flux

Table 3. Table detailing the steels under study. These have been separated in to RAFM steels and those which are not RAFM steels.

Steel	RAFM	Description
Eurofer	Yes	Sometimes referred to as Eurofer97 [52], it has been in development by the European Union materials community for over two decades. It is intended for use in DEMO and other fusion reactors, but is not mass produced at time of writing [53, 54, 55].
Hiperfer	Yes	High Performance Ferrite [56] was originally developed for conventional thermal power plants. It has been shown to have qualities favourable for a plasma-facing material in a fusion reactor [57]. The final mass produced composition has not been confirmed.
Rusfer	Yes	Also referred to as EK-181 [58], it has been developed in the Russian Federation for use under high neutron flux conditions. It has been produced on the order of thousands of kilograms [59].
CLAM	Yes	The China Low Activation Martensitic (CLAM) steel [60] is under development at the Institute of Nuclear Energy Safety Technology (INEST). It is designed for industrial applications as well as use in ITER. While scale model of components have been produced, CLAM's composition will likely be subject to changes when it is mass produced [48, 61].
F82H	Yes	A steel originally developed by the Japan Atomic Energy Research Institute (JAERI) as one of the second generation of RAFM steels [46, 49]. A modified composition was been developed by an International Energy Agency (IAE) collaboration [50, 62]; this composition has been produced several times [50, 51, 48].
XM19	No	A Nitrogen strengthened austenitic steel. Also known as Nitronic 50 stainless steel and UNS S20910. It is primarily used in the chemical, marine, nuclear and food processing industries. Composition taken from [63, 64]
Inconel 718	No	A austenitic nickel-chromium-based steel. It is often used to construct cryogenic storage tanks. Composition taken from [63, 64]
SS316	No	Stainless Steel Grade 316 is a standard molybdenum-bearing grade austenitic stainless steel. Molybdenum is included to improve anti-corrosion properties. It has been commonly used in nuclear reprocessing plants and some fast nuclear reactors in India [65]. Composition taken from [63, 64]
Steel 660	No	Steel Grade 660 is a precipitation hardening austenitic stainless steel. It was developed to be a high strength steel at high temperatures ($\sim$ 700 °C). It is used to construct jet engines and gas turbines. Composition taken from [63, 64]
ASTM G91	No	ASTM Grade 91 is ferritic-martensitic steel micro-alloyed with Vanadium and Niobium. It used in fossil fuel power plants due to its high resistance to thermal fatigue and has seen use in nuclear facilities. It is produced in two varieties referred to as type 1 and type 2. Type 2 differs from type 1 by requiring stricter composition for the enhancement of creep resistance. Both will be considered in this work, composition taken from [66, 67, 68, 69].

Table 4. The elemental composition, by weight percentage, of the steels studied.

Element	XM19	Inconel 718	SS316	Steel 660	G91-T1	G91-T2
Fe	56.26068	17.73411	63.684	52.2163	87.34	87.544
Al	-	0.5	-	0.350002	0.02	0.02
As	-	-	-	-	-	0.01
B	-	0.006	0.001	0.01	-	0.001
C	0.059305	0.08	0.03	0.079074	0.12	0.12
Co	0.05	0.1	0.05	0.200002	-	-
Cr	22.0001	19.00018	18	14.75017	9.5	9.5
Cu	-	0.300001	0.3	-	-	0.1
Mn	4.999998	0.35	2	2.000011	0.6	0.5
Mo	2.25	3.000009	2.7	1.250011	1.05	1.05
N	0.300011	-	0.08	-	0.07	0.07
Nb	0.299999	5.100016	0.01	0.100001	0.1	0.1
Ni	12.49993	52.49996	12.5	25.50009	0.4	0.2
P	0.04	0.015	0.025	0.04	0.02	0.02
S	0.03	0.015	0.01	0.03	0.01	0.005
Sb	-	-	-	-	-	0.03
Sn	-	-	-	-	-	0.01
Si	0.999987	0.349996	0.5	0.999994	0.5	0.4
Ta	0.01	0.05	0.01	0.05	-	-
Ti	-	0.899723	0.1	2.124361	0.01	0.01
V	0.19999	-	-	0.299988	0.25	0.25
W	-	-	-	-	-	0.05
Zr	-	-	-	-	0.01	0.01

Element	Eurofer	Hiperfer	CLAM	Rusfer	F82H
Fe	88.248	75.1	88.739	86.0183	89.3312
Al	0.01	-	-	0.003	0.01
Ag	-	-	-	-	0.002
As	0.05	-	-	-	0.002
B	0.002	-	-	0.006	0.0003
C	0.11	0.02	0.1	0.15	0.1
Co	0.01	0.0067	-	-	0.005
Cr	9.0	16.5	8.76	11.17	8.0
Cu	0.01	-	-	0.01	0.01
Mn	0.4	0.186	0.42	0.74	0.1
Mo	0.005	-	-	0.01	0.001
N	0.03	0.004	0.04	0.04	0.005
Nb	0.005	1.0	-	0.01	0.00005
Ni	0.01	0.0081	-	0.03	0.03
O	0.01	0.005	0.006	-	0.005
P	0.005	-	0.1	0.001	0.005
S	0.005	0.01	0.005	0.006	0.002
Sb	0.05	-	-	-	0.0005
Sn	0.05	-	-	0.0057	0.001
Si	0.05	0.3	0.05	0.33	0.1
Ta	0.12	-	0.16	0.08	0.04
Ti	0.02	-	-	-	0.05
V	0.2	-	0.22	0.25	0.2
W	1.1	4.2	1.4	1.13	2.0
Zr	0.05	-	-	-	-

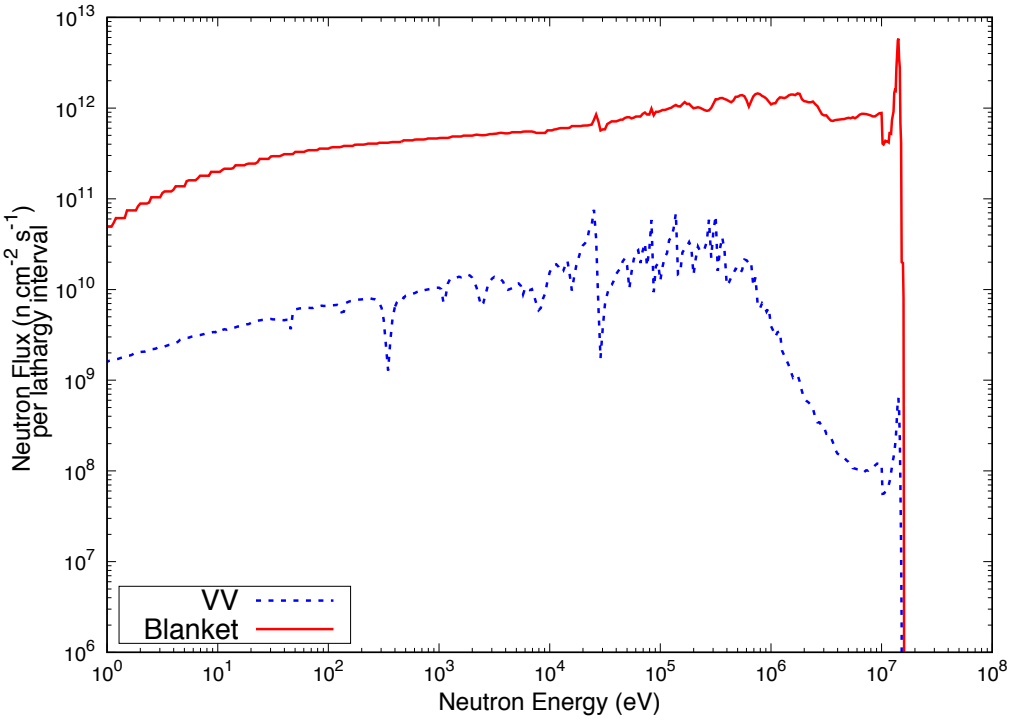

Figure 1. Figure showing the neutron flux spectra used in the inventory simulations. The solid blue red line is the Blanket region flux spectra, the dashed red line that of the Vacuum Vessel. Both flux spectra were obtained from a conceptual design for a DEMO fusion reactor using the Monte Carlo transport code MCNP.

energy spectrum of the Blanket results in higher activities when compared to the VV results, despite the shorter irradiation time. Under both irradiation scenarios most of the RAFM steels produce the lowest activities. Hiperfer's higher activities from 50 years after EOL are due to emissions from Nb isotopes ^{93m}Nb and ^{94}Nb. This is a consequence of Hiperfer's high, for a RAFM steel, Nb content (see table 4). Here ^{93m}Nb is primarily produced via inelastic neutron scattering, $^{93}\mathrm{Nb}(n,n')^{93m}\mathrm{Nb}$, and ^{94}Nb via neutron capture, (n,γ), reactions on ^{93}Nb. On long time scales (centuries and beyond) it is activity from ^{14}C ($t_{1/2} = 5730$ years) which dominates RAFM steel activity in both regions, which is produced from the $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ reaction.

The non-RAFM steel activities are typically dominated by ^{63}Ni from 50 years after EOL. Under these irradiation conditions ^{63}Ni is created by the $^{62}\mathrm{Ni}(n,\gamma)^{63}\mathrm{Ni}$ and $^{64}\mathrm{Ni}(n,2n)^{63}\mathrm{Ni}$ reactions. The reduction in Ni content is a major difference between the RAFM and non-RAFM steels (see table 4). As they have the lowest Ni content of the traditional steels, the G91 compositions show the lowest activities of such steels from 50 years post EOL. When under Blanket-like irradiation, figure 2, the G91 steels ^{63}Ni contribution is overtaken by the activity from ^{91}Nb. Figure 1 shows that as well as higher fluxes the blanket region experiences more higher energy, $> 10^6$eV, neutrons which will produce different reaction pathways. ^{91}Nb is produced primarily by nucleon

knock-out reactions $(n, 2n)$ or (n, np) on ^{92}Mo (the former followed by decay of ^{91}Mo). These occur more readily at higher incident neutron energies, so greater levels of ^{91}Nb production occur in the Blanket.

4. Activated steel waste assessments

The waste criteria discussed in section 2.4 have been used to assess the waste classification expectations of the DEMO-like steel inventories. The results and classifications presented here assume that no processing of the material has taken place and that the material has not been polluted from other sources e.g ^{3}H diffusion. Work is ongoing studying possible processes to remove carbon [73] and tritium [74, 75] from reactor materials before disposal. As details on how successful these processes can be on large scale operations are currently unavailable the results of these processes have not been included here, but these process will likely be employed as part of a fusion waste strategy.

4.1. Global Activity limits

As table 2 shows, several of the waste classification systems studied use total α and $\beta+\gamma$ activity as part of their criteria. These specific activities have been calculated for each of steels studied and they are presented in figure 4 for times after DEMO EOL. The upper panels of figure 4 show the expected levels of α activity from each of the steels for the blanket (upper right panel) and VV (upper left panel) irradiation scenarios. In both cases the activities plotted are several orders of magnitude below the enforced limits given in table 2. It can therefore be concluded that long term α activity is not expected to be a concern for fusion steel waste. It is interesting that the RAFM steels (see table 3) typically show higher α activities than the non-RAFM steels. This is a result of the RAFM materials increased W content (see 4) meaning greater number of α emitting W and Os isotopes are present at EOL. It should be noted that in nuclear decay data several W (^{183}W, ^{184}W, ^{186}W) isotopes are assigned theoretically predicted α decay modes which have yet to be experimentally observed due the the expected long half lives ($\sim 10^{21}$ years) [76].

The $\beta+\gamma$ specific activities for each steel for times after EOL (lower panels of figure 4) follow what was seen in the steel's activation curves; figures 2 and 3, with all steels producing higher activities under blanket conditions when compared to those of the VV. The steels with Ni content $\geq 0.5\%$ show higher activities on desired decommissioning time-scales, 50-100 years post EOL. For the blanket scenario, no steel is able to meet either the UK or Spain's $\beta+\gamma$ limit after 100 years and only F82H's $\beta+\gamma$ activity achieves the higher Spanish limit, requiring 500 years to do so. These results show that no steel irradiated under DEMO blanket conditions should be expected to be classified as LLW in the UK for over 1000 years and that few may be under Spain's waste classification system.

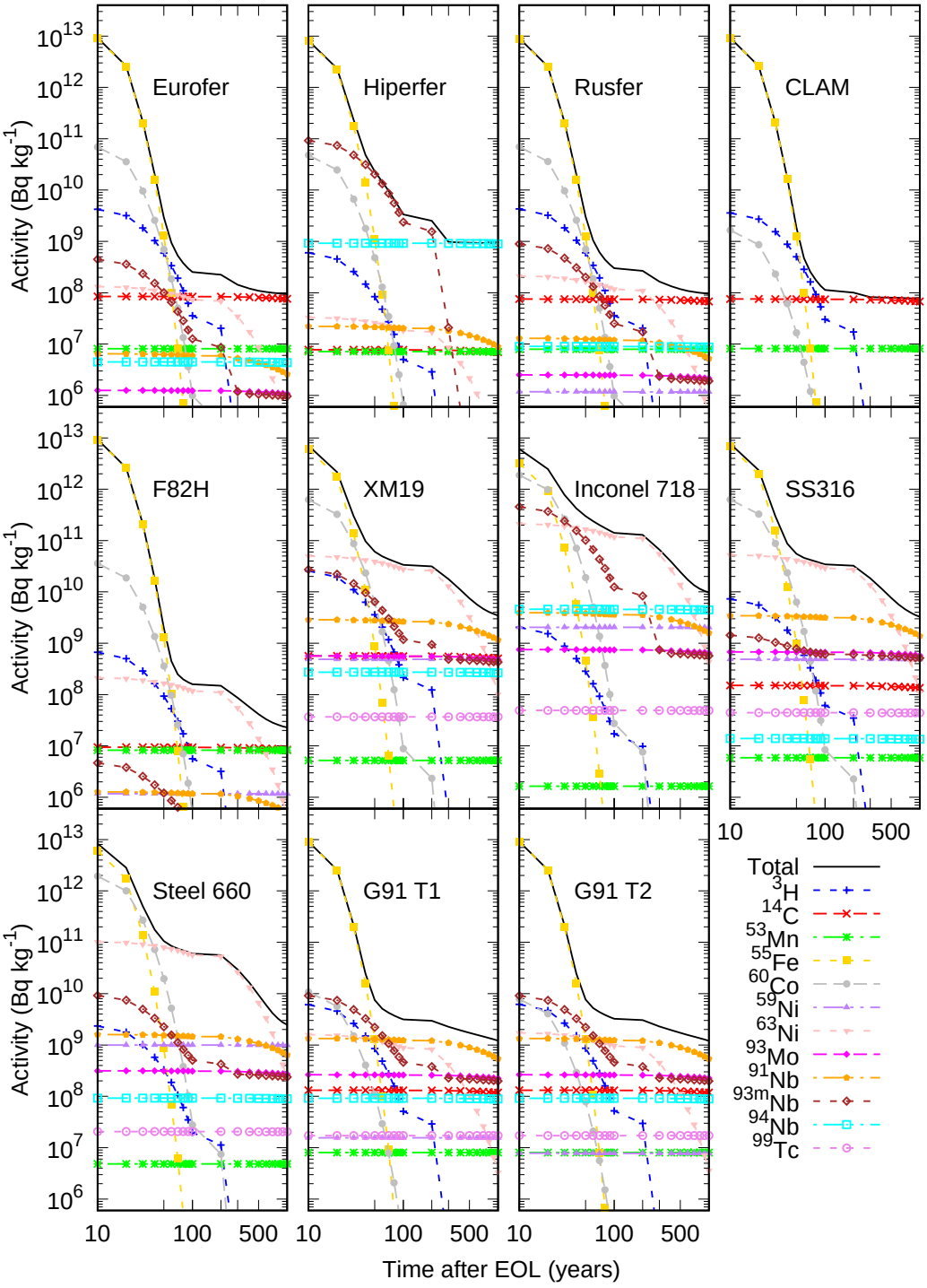

Figure 2. Figure showing the expected activation as a function of time for each of the steels studied for a DEMO Blanket region irradiation. Also plotted are the contributions to the total activity from the most dominant radionuclides. The x-axis ticks represent 10, 50, 100, 200, 300, 500, 1000 years after reactor EOL.

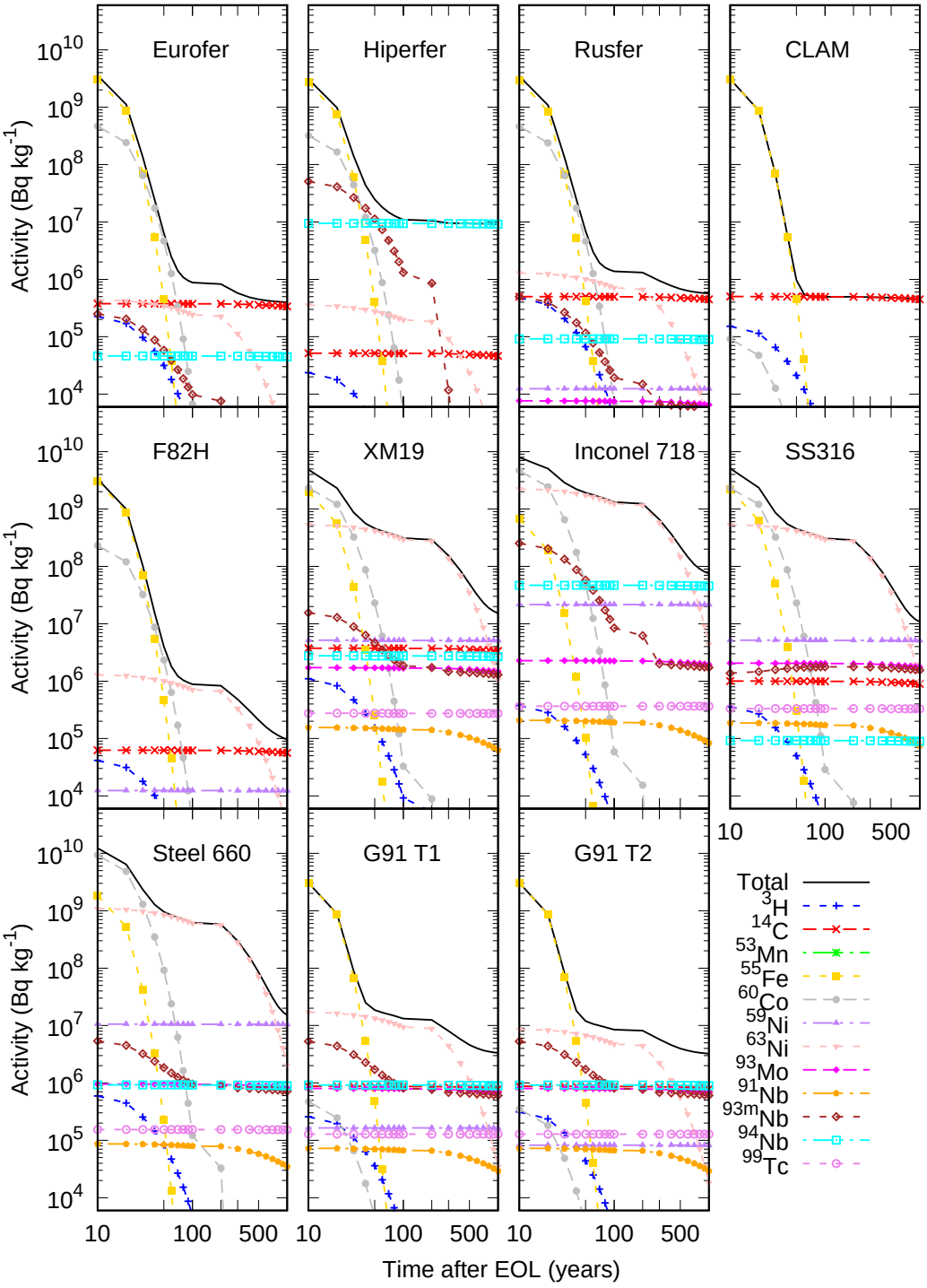

Figure 3. Figure showing the expected activation as a function of time for each of the steels studied for a DEMO Vacuum Vessel region irradiation. Also plotted are the contributions to the total activity from the most dominant radionuclides. The x-axis ticks represent 10, 50, 100, 200, 300, 500, 1000 years after reactor EOL.

The lower VV $\beta+\gamma$ activities give greater levels of adherence to the relevant limits, see the lower left panel of figure 4. After 50 years only 4 steels do not meet Spain's limit and 5 steels can meet the UK limit. The industry standard austenitic stainless steels have the worst activation prospects. Of the non-RAFM steels only the G91 compositions are able to meet either of the LLW limits plotted earlier than 500 years after EOL. Comparing the VV $\beta+\gamma$ curves in figure 4 to the steel activation curves in figure 3 it can be determined that the increased activity seen in SS316, XM19, Inconel 718 and Steel 660 is a result of ^{63}Ni activity. This prevents these steels from meeting the UK LLW requirements and possibly Spain's LLW criteria. All of the RAFM steels are able to meet the LLW criteria in the VV, but Hiperfer may struggle to meet the UK limits, this is a result of the increased Nb activity discussed earlier and seen in figures 2 and 3.

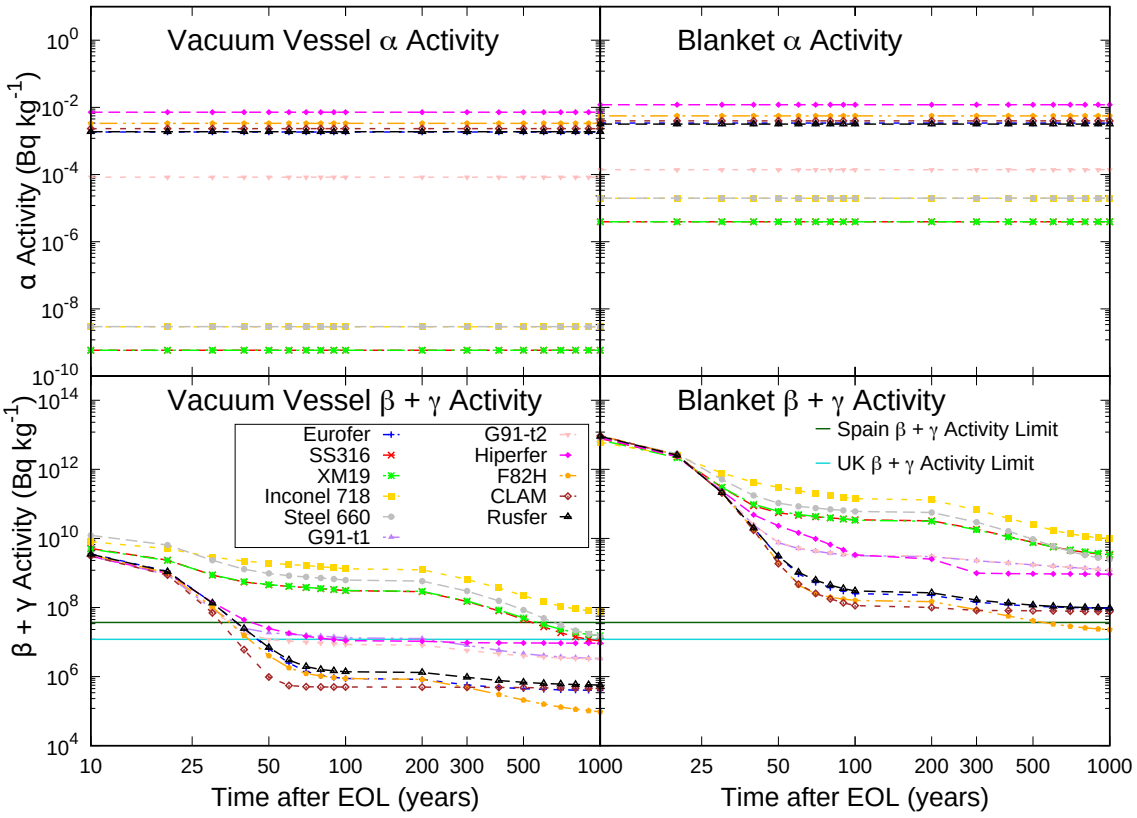

Figure 4. Figure showing the total α (upper panels) and $\beta+\gamma$ (lower panels) specific activities for both the blanket (right panels) and Vacuum Vessel (left panels). The $\beta+\gamma$ limits from the UK and Spain's LLW criteria are also plotted for reference.

4.2. Individual Nuclide Limits

100 years after reactor EOL activities from the relevant nuclides given in table 2 have been extracted from each steel inventory, these are presented in figure 5. The limits

in table 2 which were given in Bqm^{-3} have been converted to Bqkg^{-1} so that direct comparisons can be made between the waste management systems studied. This was done via the reciprocal of the steels density which as assumed to be 7.9 gcm^{-3} for all steels.

The ^{3}H activities (top left panel of figure 5) show that the VV irradiations do not produce enough ^{3}H to pose a problem for meeting any low-level waste criteria. The blanket results demonstrate that all of the steels studied are expected to produce ^{3}H at levels which may be greater than LLW requirements: all steels can meet the Spanish limit, but all steels will fail to meet the Russian Federation's limit. The short half-life of ^{3}H (12.32 years) does mean that longer cooling times after EOL can remove ^{3}H as a waste concern, but if the 100 year target is to be kept ^{3}H activity may be a waste classification issue.

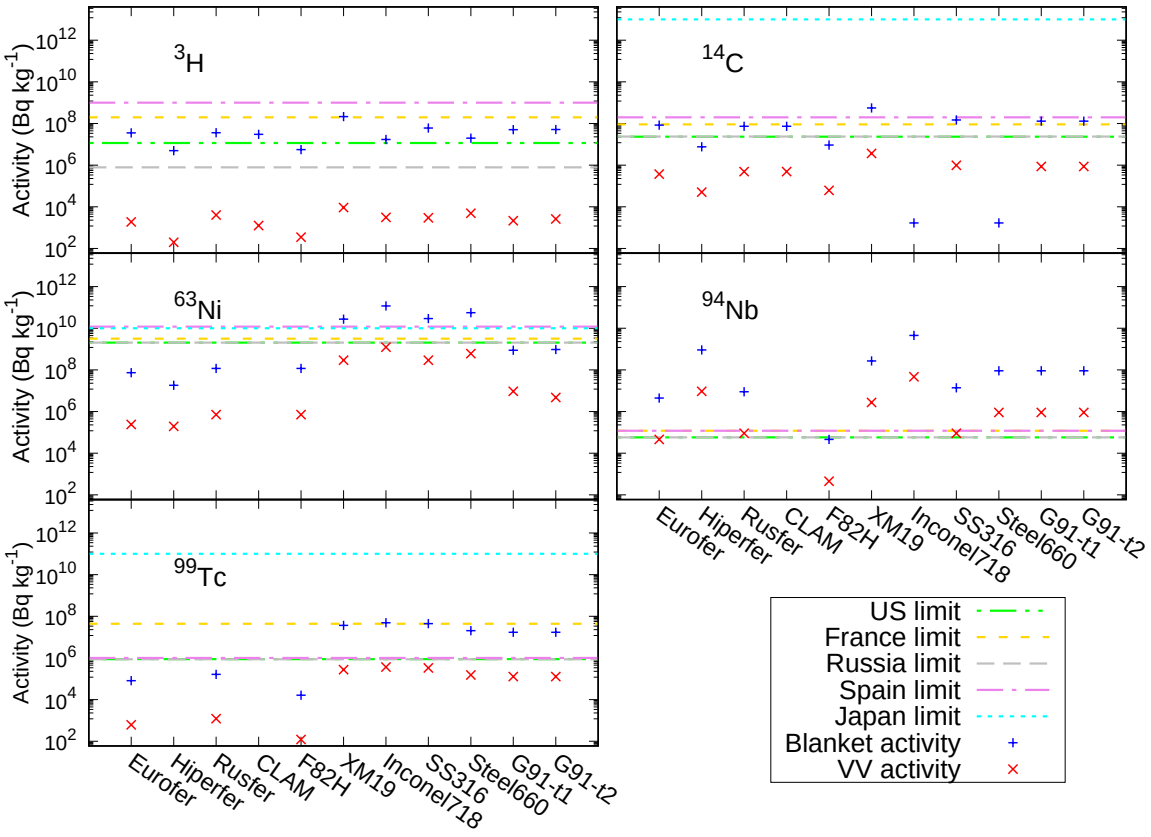

Figure 5. Figure showing the specific activities 100 years after EOL for ^{3}H (top left), ^{14}C (top right), ^{63}Ni (middle left), ^{94}Nb (middle right) and ^{99}Tc (bottom left) in the steels studied for the blanket and VV irradiations. Also plotted are relevant LLW activity limits for each nuclide from the waste management systems studied, values for these can be found in table 2. Where no data points are shown a steel either does not transmute the particular nuclide under irradiation or it is produced in smaller quantities than the scale would allow.

The ^{14}C activities (top right panel of figure 5) show similar classification behaviour

to that seen with ^{3}H, all of the VV activities are able to meet all limits and the blanket activities are able to meet some. Four steels produce ^{14}C activities which are below all limits in both irradiation scenarios: Hiperfer, F82H, Inconel 718 and Steel 660. The non-RAFM Inconel 718 and Steel 660 are expected to produce very low levels of ^{14}C as the do not contain any N in their compositions (see 4). As figures 2 and 3 demonstrate ^{14}C activity can be a significant concern for long term activity, especially for RAFM steels, so the N content of such materials should be minimised as much as possible to avoid excessive ^{14}C production. It is worth noting Japan's ^{14}C limit, which is several order of magnitude greater than the other limits studied. The ^{14}C allowance is this high as the Japanese waste management system includes intermediate depth disposal (∼50m subsurface) as LLW [40]. This could allow steels which fail to meet LLW requirements in all other systems to be called LLW under Japan's criteria.

The reduction of Ni content in the RAFM steels produces lower ^{63}Ni activities, see the middle left panel of figure 5. All RAFM steels which produce ^{63}Ni are able to meet all limits under VV and blanket conditions, with CLAM not producing any ^{63}Ni due to it containing no Ni (see table 4). The non-RAFM steels are able to meet all limits for VV irradiations, with the lower Ni G91 steels able to achieve this for the blanket irradiations as well.

^{99}Tc (bottom left panel of figure 5) activities reveal how the differences between RAFM and non-RAFM steels can affect the expected activation products. ^{99}Tc activity is not a waste concern for any of the RAFM steels studied; Hiperfer and CLAM produce little to no ^{99}Tc and the other RAFM steels produce activities below all studied limits. ^{99}Tc is predominantly created via the β-decay of ^{99}Mo which itself is created by the ^{100}Mo$(n, 2n)^{99}$Mo and ^{98}Mo$(n, \gamma)^{99}$Mo reactions. As Hiperfer and CLAM do not contain any Mo they produce little ^{99}Tc, where as the other RAFM steels contain lower amounts of Mo. The non-RAFM steels all show similar ^{99}Tc activity with only the VV results able to meet all limits. While this may not be a major concern for fusion waste as non-RAFM steels not expected to see use in the blanket, the activities are comparable to the prescribed limits. A change in irradiation conditions or materials compositions could push these activities higher and therefore lead to additional waste concerns.

Of the nuclides highlighted in this work the ^{94}Nb activities (middle right panel of figure 5) show the worst adherence to the specified waste limits. Under the blanket irradiation scenario only CLAM and F82H can meet all of the limits, although the F82H blanket activity is similar to the lowest ^{94}Nb limits, those of the US and Russia. All other steels blanket ^{94}Nb activities are orders of magnitude above the LLW limits, suggesting that these steels may struggle to be classified as LLW under many waste management systems. Three additional steels, alongside CLAM and F82H, are able to meet some or all of the ^{94}Nb activity limits under VV conditions: Eurofer, Rusfer and SS316. CLAM, F82H and Eurofer can meet all limits under VV conditions, but Rusfer and SS316 can only meet France and Spain's limits. These five steels have the lowest Nb content, but most will still struggle to meet LLW requirements if ^{94}Nb activities are directly used as part of the classification criteria.

Table 5. Table showing LLW classifications after 100 years for the steels studied (see table 3). Classifications have been found for both blanket and Vacuum Vessel irradiations

	Blanket						Vacuum Vessel					
Steel	UK	US	France	Russia	Spain	Japan	UK	US	France	Russia	Spain	Japan
Eurofer	ILW	ILW	ILW	ILW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
Hiperfer	ILW	ILW	ILW	ILW	ILW	LLW	LLW	ILW	ILW	ILW	ILW	LLW
Rusfer	ILW	ILW	ILW	ILW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
CLAM	ILW	LLW	LLW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
F82H	ILW	LLW	ILW	ILW	LLW	LLW	LLW	LLW	LLW	LLW	LLW	LLW
XM19	ILW	ILW	ILW	ILW	ILW	LLW	ILW	ILW	ILW	ILW	ILW	LLW
Inconel 718	ILW	ILW	ILW	ILW	ILW	LLW	ILW	ILW	ILW	ILW	ILW	LLW
SS316	ILW	ILW	ILW	ILW	ILW	LLW	ILW	LLW	LLW	ILW	LLW	LLW
Steel 660	ILW	ILW	ILW	ILW	ILW	LLW	ILW	ILW	ILW	ILW	ILW	LLW
G91 T1	ILW	ILW	ILW	ILW	ILW	LLW	ILW	LLW	ILW	LLW	ILW	LLW
G91 T2	ILW	ILW	ILW	ILW	ILW	LLW	LLW	LLW	ILW	LLW	ILW	LLW

These results confirm that ^{94}Nb is the radionuclide whose production in steels under fusion conditions must be addressed with the highest priority; either Nb must be minimised in starting compositions, a viable technology must be found to extract Nb or ^{94}Nb during waste processing, or the international community must reconsider the classification of ^{94}Nb, which is after all a pure beta-emitter that can, in principle, be readily shielded against.

Figure 5 also shows how the nuclide limits can differ between waste management systems. For some nuclides, such as ^{94}Nb for example, the limits are comparable and the resulting classifications should be expected to be similar. The limits for other nuclides, such as ^{3}H, are spread more widely and as such are more likely to give classification differences. It would be expected that all LLW limits are comparable and therefore waste classifications are internationally consistent, but the limits themselves do suggest that this is not the case. What is the best approach to LLW classification is not the subject of this work but, this work does suggest that more international alignment on waste limits would be advantageous.

4.3. Full Waste Classifications

100 years after reactor EOL the specific activities of the radiation sources relevant to each waste classification were extracted and compared to the prescribed limits. Any other calculations, such as a 'Sum of Fractions' (see equation 1), were performed. Making use of all of the necessary parameters and limits, whether the steel inventories could achieve a LLW classification has been assessed with the results given in table 5. Here ILW means a steel failed to meet any LLW requirements of a given waste management system and is classified as ILW, LLW means a LLW class was achieved.

The prospect of any steel being able to consistently meet all of the LLW

requirements in both regions studied is low. When exposed to Blanket irradiation conditions nine of the eleven steels studied can not be called LLW in 5 of the 6 waste systems studied in this work. All of the steels can LLW under Japan's criteria, but these can differ significantly from the other criteria studied. The steels CLAM and F82H are the best performing steels from a waste classification perspective in the blanket scenario. CLAM and F82H can be LLW under the US, Spanish and Japanese waste management systems, with CLAM also able to meet France's LLW criteria. It is the presence of ^{108m}Ag which causes F82H to be ILW in the French system. F82H is the only steel with any Ag in its composition (see table 4) and it is likely an impurity, which if minimised could improve waste performance.

More steels are able to meet LLW requirements under VV irradiation conditions. Only three steels, XM19, Inconel 718 and Steel 660, show identical waste classification performance under both Blanket and VV conditions. This is caused by the high Ni content of Inconel 718 and Steel 660 alongside XM19's Nb proportion. These are considered the worst performing steels and would not be recommended for use in fusion power facilities if potential activation was the primary concern. The RAFM steels show the best classification performance in the VV, with 4 of the 5 studied able to be classed as LLW in all waste management systems. Hiperfer, the only RAFM steel to not achieve LLW under all criteria, is hindered by its high Nb content (table 4) which, as figure 5 demonstrates, causes a greater build up of ^{94}Nb. RAFM steels do not meet the structural requirements of a VV steel, but could have some use as non-structural components.

SS316 and the G91 steels are able to be VV LLW under several waste classification criteria. The total $\beta+\gamma$ activity of SS316 prevents UK and Russian LLW classification, which is caused by ^{63}Ni activity. This is not an issue for the low Ni G91 compositions. It should be noted that SS316's individual ^{63}Ni activity is below nuclide specific limits; it is the total $\beta+\gamma$ activity which breeches the UK and Russia's requirements. The G91 steels produce increased levels of ^{94}Nb when compared to SS316, this prevents Spanish and US LLW classification in the VV. These results show that it should not be expected that VV's from DEMO-like fusion reactors will consistently be LLW on the 100-year timescale. The choice of steel can not guarantee an improvement in expected waste classification as the different activation products produced may be subject to separate waste criteria.

It was stated in section 2.1 that waste samples with low concentrations of long lived nuclides are typically considered for near surface disposal. Figures 2 and 3 show that all steels, under either irradiation scenario, show significant activity from long lived nuclides. This may mean that even if LLW criteria can be met, NSD may not be a realistic expectation for some fusion steels.

5. Conclusions

This work has reviewed several countries radioactive waste management systems and presented expected steel waste classifications from inventory simulations for DEMO-

like irradiation conditions. These suggest that currently available steels can struggle to achieve LLW criteria when subjected to the high neutron fluxes expected in fusion reactors. Waste disposal systems which include global limits on $\beta + \gamma$ specific activity will likely not be able to accept such fusion steel waste as LLW due to the production of longer lived β-emitters such as ^{94}Nb, ^{14}C and ^{63}Ni. The lower fluxes associated with vacuum vessel conditions do allow steels to more readily achieve LLW status, but many of the best performing steels in this region may not possess the structural and mechanical properties required. The steels with the worst adherence to LLW criteria in the lower flux regions typically fail to meet criteria due to excessive ^{63}Ni or ^{94}Nb activity. These results would suggest that vessel and in-vessel steels may struggle to be LLW 100 year after EOL.

The expected waste classifications of steels which have been subject to high neutron fluxes, such as those in the DEMO blanket, can be similar between reduced activation (RAFM) and traditional stainless steels 100 years after EOL. The reduced activation materials typically show lower specific activities, but these are often not low enough to affect the resultant waste classification; an interesting observation which could lead one to question whether the benefit of RAFM – lower activation – is sufficient to warrant the engineering challenges associated with them.

The CLAM and F82H blanket irradiation classifications (table 5) suggest that it is possible for plasma-facing and near-plasma steels to be considered LLW under specific criteria. That neither CLAM or F82H can be LLW in all waste classification systems studied shows that such a classification can not be expected to be internationally consistent for a given sample. The lack of international consistency between waste management systems lowers the value of waste classifications, suggesting that LLW samples in different regulatory systems are not truly comparable. It should be noted that while most steels cannot be called LLW for most repositories none of the steels class as high-level waste (HLW) under any regulatory system.

The results of this work may easily be misconstrued as a suggestion that some waste classification systems are more favourable or more advantageous than others, this is not the intent. It needs to be stressed that the national location of a fusion power facility cannot be chosen based on the regulatory systems it will be subject to. It is desired that fusion energy be internationally appealing and for this to be true the fusion waste burden needs to be appreciated fully, before the construction of reactors. This work does not suggest that activated waste from fusion facilities is deserving of different treatment, but that more internationally consistency on waste limits would be beneficial. Any move to impose more consistent criteria must consider the radioactive waste burdens of all producing industries, fusion included. Ultimately, the decision on how radioactive waste is classified and disposed of remains the jurisdiction of the national governments responsible for the waste.

The results presented here add to the growing body of work highlighting the issues faced by activated wastes from fusion. If fusion is to become a commercially and socially viable power solution the expected wastes need to be fully appreciated so that the

correct disposal procedures are in place. As mentioned previously no inventory reduction techniques were assumed to have been applied and these approaches may lessen the waste burden of fusion. It should be stressed however that no inventory reduction or waste mitigation approaches will fully eradicate radioactive waste from fusion facilities.

Acknowledgements

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