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Regulatory framework towards fusion energy in Germany: preliminary results and open issues

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Abstract: The paper introduces preliminary results of the German project for regulation of future fusion facilities (ReFus) which was started in January 2025. It presents the existing German regulatory framework and how it was applied for the licensing of the stellarator Wendelstein 7-X. The analysis demonstrates that the German radiation protection law and its subsequent rules and regulations are already generally applicable to fusion. However, certain adaptations and clarifications are recommended to simplify the licensing process, especially with respect to a graded safety approach considering the broad scope of future facilities from demonstrators up to full size power plants.

Keywords: nuclear fusion; radiation protection; radioactive waste; licensing of fusion facilities; regulation of fusion; hazard potential

1 Introduction

Germany has a strong track record in research and operation of plasma and nuclear fusion facilities. With the ASDEX

Upgrade tokamak at Garching, the world leading stellarator Wendelstein 7-X (W7-X) at Greifswald, and relevant participation in further international fusion projects such as ITER and the European demonstration fusion power plant (DEMO), significant contributions have been made in various research activities for magnetic confinement fusion. Furthermore, for a few years now, a very active community of start-ups and industrial partners has been growing in Germany, cf. (Federal Ministry of Education and Research 2023; Haefner et al. 2023). However, beyond research and technological issues, a key question is how to licence different fusion facilities ensuring the necessary level of safety and equally supporting the flexibility and openness in a rapidly evolving field. The research project ReFus is focusing on the future regulation of fusion facilities in Germany and especially on the key questions: What is the “necessary” level of safety and is it already covered by existing regulations or which clarifications might be meaningful? First results of the project were presented at the FEC 2025 (Schmollack et al. 2025).

Fusion research in Germany has been focussed on magnetic confinement fusion (MCF) technologies for a long time, with both experimental tokamak and stellarator facilities having been built. ASDEX Upgrade is a tokamak facility. Research performed there is used to support plans for ITER, DEMO and a possible future fusion power plant. Experiments both at ASDEX Upgrade and W7-X use hydrogen (protium) and deuterium as fuel, but no tritium. As a key component of the deuterium-tritium fusion reaction, tritium is indispensable for the operation of ITER and DEMO. Research institutes from Germany are contributing to ITER and DEMO and especially to tritium related issues including the fuel cycle. As inertial confinement fusion (ICF) research has been historically driven by military interests, mostly in the US and in France (Federal Ministry of Education and Research 2024), it is only in the last few years that research into ICF has become more present in Germany (Haefner et al. 2023).

Start-up companies based in Germany are working on a range of fusion energy technologies: on MCF using stellarators and on ICF. The companies are mostly focusing on the deuterium-tritium fusion reaction. Compared to ITER and DEMO, companies set tighter timelines and aim at constructing

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demonstrators in the 2030s–2040s (see e.g. Ditmire et al. 2023). Besides companies based in Germany, other start-up companies are active in the German discussion on the regulatory framework. Finally, there are also several companies from the evolving supply chain for existing and future fusion facilities that play an important role in the German fusion technology landscape. With a background of world-leading stellarator and laser technology experiences, Germany strives for a leading role in the fusion race (Federal Ministry of Education and Research 2023). Several start-up companies in Germany have announced plans to build fusion facilities in the next few years, calling for an evaluation of the current regulatory framework and necessary extensions and adaptations (Acatech 2026).

2 The German regulatory framework

Radiation protection law and nuclear law aim to protect life, health and real assets, ensure safety and environmental protection, and compliance with international and national standards. In Germany, this regulatory framework is governed primarily by two laws: the Atomic Energy Act (Atomgesetz, AtG) (Federal Republic of Germany 2012) and the Radiation Protection Act (Strahlenschutzgesetz, StrlSchG) (Federal Republic of Germany 2017). A system of further regulations, recommendations and rules is arranged hierarchically beneath them. Figure 1 shows an overview of the principal structure, the extent to which different legal sources are binding and examples. This system forms the current framework for regulating fusion facilities. However, this raises the question of whether it is fit for effective licensing of new fusion facilities up to future fusion power plants.

The Atomic Energy Act primarily regulates the handling of nuclear fuel and the life-cycle of nuclear installations. As the act defines “nuclear fuel” as fissionable material such as

U-233, U-235 and Pu-239, fuel for fusion reactors does not fall under this definition. In addition, nuclear installations – according to the Atomic Energy Act – are limited to facilities that handle nuclear fuel, thus not covering fusion. Consequently, fusion facilities do not fall under the licence requirements of the Atomic Energy Act.

The Radiation Protection Act (Federal Republic of Germany 2017) provides the regulatory framework for protecting individuals and the environment from the effects of ionising radiation. It governs licensing requirements for the construction and operation of facilities generating ionising radiation as well as for handling of “other radioactive substances”, such as tritium. Furthermore, fusion facilities are included under the Radiation Protection Act due to their classification as “installations for the generation of ionising radiation”, as defined in Section 5 of the Act which explicitly addresses “plasma installations”. Thus, fusion facilities are currently regulated under the Radiation Protection Act, which furthermore lists documents, e.g. the safety report, required for licensing approval in its annex 2.

Further requirements relevant for fusion facilities are covered in the Radiation Protection Ordinance (Federal Republic of Germany 2018), which includes dose and concentration limits for radioactive effluents, limits for exemption and exclusion, dose limits for workers and the public under operation conditions as well as for accidents.

The underlying framework for the Atomic Energy Act as well as for the Radiation Protection Act includes expert commission recommendations, national and international standards, rules of the Nuclear Safety Standards Commission (Kerntechnischer Ausschuss – KTA) and further rules. They are applied based on case-by-case considerations and a graded approach with respect to the fundamental safety objective (International Atomic Energy Agency 2006).

An important complementary administrative tool is the “Checklist of documents for licensing of radiation facilities”

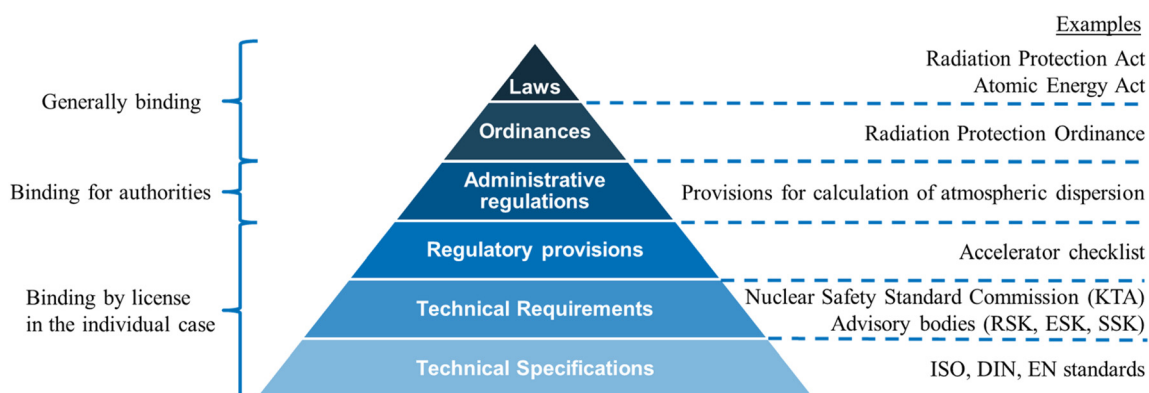


Figure 1: German scheme of existing rules and regulations.

(Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2003), initially developed for accelerators and now also applied to other facilities. It provides a structured approach for topics to be covered in the safety report as the main characteristics of the facility: its construction, radiation protection measures, radioactive waste management and decommissioning. The checklist provides guidance for different types of licences as defined by the Radiation Protection Act: construction licence, test operation licence and operation licence. Fusion facilities share operational characteristics with accelerators, including the generation of neutrons and activation products, making the checklist a suitable starting point for the licensing of fusion facilities.

In general, fusion facilities need licences according to sections 10 and 12 of the Radiation Protection Act (Federal Republic of Germany 2017) for construction, operation and handling of radioactive material. Further safety requirements relevant for fusion facilities are defined in the Radiation Protection Ordinance, if significant amounts of radioactive materials above 10^7 times the weighted exemption values defined for each radioisotope are handled. This level defines a starting point for further safety considerations, cf. Section 6.

3 Licensing of Wendelstein 7-X

W7-X, the world's largest stellarator plasma facility, was built in Greifswald, Germany, and has been operating since December 2015. Table 1 shows basic technical data of W7-X. The planned annual neutron production of up to $3 \cdot 10^{19}$ results from the deuterium-deuterium fusion reaction leading to a maximum licensed release of $2 \cdot 10^{11}$ Bq of tritium.

W7-X was licenced under the German radiation protection law. The licensing process covered a construction licence, an operation licence for the facility and a licence for handling radioactive material (Sieg 2015). The competent authority supervises the operation of W7-X in an ongoing process.

The application for a construction licence was submitted in October 1996 by IPP to the responsible radiation protection licensing authority, for a schematic timeline cf. Figure 2. A construction licence was required according to section 15 under the Radiation Protection Ordinance at this time for “plasma facilities, which could generate more than $1 \cdot 10^{12}$ n in 1 s”. The construction licence was granted in December 1997. The construction process took almost 18 years to complete the facility, which was due to technical challenges of the first-of-its-kind stellarator of this size and technical parameters. Key issues of the construction licence and corresponding reviews were shielding, groundwater activation,

Table 1: Selected technical data of Wendelstein 7-X.

General	
Type	Stellarator
Max. toroidal magnetic field strength	3 T
Torus major diameter	15.2 m
Heating systems	
Electron cyclotron resonance heating (ECRH)	10 MW (steady state)
Neutral beam injection (NBI) phase I	7/10 MW (H^0/D^0)
Phase II	14/20 MW (H^0/D^0)
Ion cyclotron resonance heating (ICRH)	2–12 MW
Neutron parameters	
Max. neutron rate	$6 \cdot 10^{15}$ n/s
Max. annual neutrons	$3 \cdot 10^{19}$ n/a
Limits for radioactive effluents with air	
Tritium	$2 \cdot 10^{11}$ Bq/a
Noble gases (mainly Ar-41)	$2 \cdot 10^{10}$ Bq/a
Further radionuclides	$4 \cdot 10^7$ Bq/a
Radioactive material	
Activated and contaminated material	$\leq 10^{10}$ times exemption value

and, based on preliminary assumptions, radioactive effluents, basic event considerations and corresponding prevention measures. The erection of shielding walls and installations, especially the quality of shielding material properties, was intensively supervised by the authority.

- In May 2014, IPP applied for an operation licence and provided a safety report which followed in principle the recommendations for radiation facilities (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2003) adjusted to the needs of the stellarator W7-X. A review process by the independent reviewer on behalf of the licensing authority started in November 2014 and especially covered the following areas and topics:
 - Monitoring and control of neutron rate and neutron flux
 - Monitoring and control of gamma- and n-dose rate
 - Monitoring and control of liquid and gaseous effluents
 - Shielding and activation
 - Public dose assessment including calculation of atmospheric dispersion of radioactive release
 - Safety and radiation protection relevant system, e.g. for interlock control and management
 - IT-systems relevant for monitoring and documentation,
 - IT security
 - Radiation protection organisation and supervision
 - Operation manuals and documentation

- Procedures relevant for safety and radiation protection
- Safety and radiation protection relevant structures, systems and components (SSC), including control of heating and ventilation systems
- Deterministic accident analysis, especially loss of barrier functions, pressure release, quench resistance
- Waste management and decommissioning preparation.

Based on the safety assessment review report and the on-site inspection report of the independent reviewer as well as on its own considerations, LAGuS granted the operation licence in 2015 (Sieg 2015). The licence defines a wide frame for W7-X operation and allows an ongoing process of subsequent updates and upgrades of W7-X beginning with operation systems required for hydrogen plasma up to the full-scale operation systems for maximum performance with deuterium and maximum neutron rate. This approach allows for a learning process for optimal balance of an adequate safety and radiation protection with scientific progress.

4 Status of international regulatory approaches

Approaches for regulation of fusion facilities are under discussion in several countries and partially already decided on. The following section gives an overview on some countries, where projects or regulations have most been progressed.

The first advanced tokamak experimental demonstration fusion facility, ITER, is licensed under French law. It is treated as a so-called “basic nuclear facility” under Article L593-2 of the Code de l’environnement. As such, it falls under the regulatory authority of ASNR which applies its technical regulation based on fission-facilities in a goal-oriented way with modifications towards the specificities of fusion (Barabaschi et al. 2026).

The most advanced tokamak demonstrator projects, SPARC (Hamade 2025) and BEST (International Atomic Energy Agency 2025), are located in the U.S. and China, respectively. U.S. law treats fusion facilities as particle accelerators and applies its by-product materials framework, following Section 11(e)(3)(B)(i) of the U.S. Atomic Energy Act and 10 CFR Part 30. For that purpose, the U.S. Atomic Energy Act has been amended by a definition of “fusion machine”. Consequently, U.S. fusion regulation focuses on the handling of radioactive material (especially tritium and activated materials), rather than directly regulating the facility. The U.S. NRC has recently published the proposed amendments to its technical regulation (Office of the Federal Register 2026).

The current regulatory approach in China covers fusion facilities as category I radiation facilities with neutron generation above $1 \cdot 10^{12}$ neutrons per second with a pulse duration of at least 1 s. Facilities using tritium and generating neutrons up to $1 \cdot 10^{20}$ per second and having an annual production of less than $1 \cdot 10^{25}$ neutrons would need an environmental impact assessment and a radiation application license and are required to use “nuclear technology” (Wang

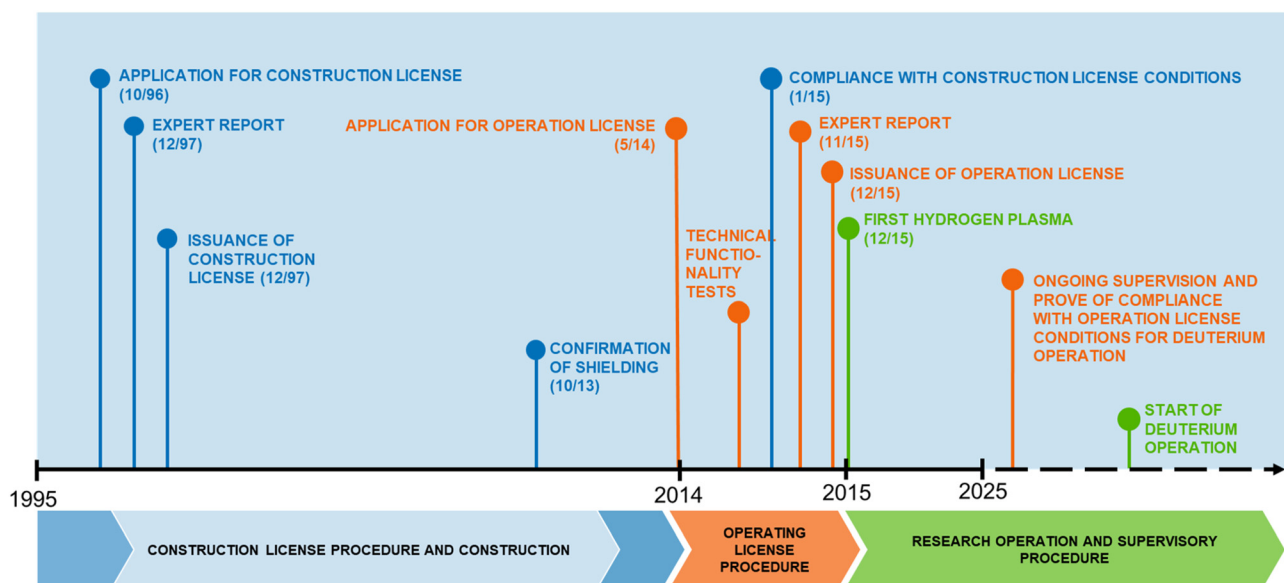


Figure 2: Licensing schedule of W7-X (timeline schematically only).

2025). The Russian regulation is planning to distinguish between fusion reactors using also fissionable material and fusion installations using fusionable materials only (Polianskii et al. 2025). Fusion installations would be treated as radiation sources up to a generation of $1 \cdot 10^{20}$ neutrons per second and $1 \cdot 10^{26}$ neutrons generated in lifetime and for a tritium inventory below a not yet finally defined threshold value. Above these thresholds, fusion facilities are part of nuclear installations. The rules are under preparation for a document with general provisions for fusion facilities (Polianskii et al. 2025).

The UK – currently home of JET and future home of STEP – was one of the first countries to take action regarding fusion regulation. Regulatory changes specified that a fusion facility is not a nuclear installation in the sense of the Nuclear Installation Act. UK law treats fusion the same way as any other major industrial facility, such as chemical plants, with environmental law and radiation protection law being applicable. As such, the competent regulator is not the Office for Nuclear Regulation, but the Health and Safety Executive (HSE) and the respective environmental agency (UK Government 2026).

5 Development of a fusion regulatory approach in Germany

As indicated above, fusion devices in Germany – especially the existing research devices such as W7-X and ASDEX Upgrade – are regulated under radiation protection law. In fact, as highlighted above, the Radiation Protection Act already allows today the licensing of fusion facilities, including commercial power plants, under a radiation protection regime. The licensing process for such facilities or plants would correspond to the one described in Section 3 for W7-X. However, as only “plasma facilities” are mentioned explicitly in the Radiation Protection Act, we propose to add the term “fusion facilities” as part of “plasma facilities” to the definitions in Section 5 para. 2 of the Radiation Protection Act to give absolute clarity that all kinds of fusion facilities are covered by this act including power plants.

Furthermore, the threshold for a construction licence as defined in the Radiation Protection Act already considers different pulse time scales (as ICF generates extremely short neutron pulses with a much higher neutron rate than MCF) as it defines a neutron rate of $1 \cdot 10^{12}$ neutrons within 1 s (German “je” instead of “pro”) which can be understood as the number of neutrons averaged over 1 s.

The German regulatory framework relies on specific nuclear rules for fission facilities such as KTA rules and

special safety requirements (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection 2022). Similar rules do not exist for radiation protection applications. Instead, for facilities under radiation protection law, selected rules for nuclear fission are applied on a case-by-case approach considering the fundamental safety functions and national and international radiation standards. One specific gap has been identified in our analysis: the German calculation rules for DBA (Design Basis Accident) exposure scenarios (German Commission on Radiological Protection 1994) has no calculational rules for tritium exposure. For fusion facilities this gap needs to be closed.

For fusion facilities, there are no specific national standards yet. In the last year, a few new international fusion standards have been published or are under preparation (German Institute for Standardization 2026). The most relevant for designing a fusion facility with respect to safety is ISO 16646:2024 (International Organization for Standardization 2024), which describes requirements for “Fusion installations – Criteria for the design and operation of confinement and ventilation systems of tritium fusion facilities and fusion fuel handling facilities” and also includes other radioactive sources and potential non-radioactive hazards. The standard defines the scope of application for “tritium inventories higher than a range of 10–100 g”. This covers a wide range from potential demonstrators with only a few grams of tritium above that range up to fusion power plants with a tritium inventory of several tens of kg. The safety methodology applied is very close to that applied for fission facilities, since it encompasses all safety levels of the defence-in-depth concept (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection 2022; International Atomic Energy Agency 2016c) including “design extension conditions” as well as deterministic and probabilistic safety assessments. However, there is limited information to support a graded approach in an inventory range across several orders of magnitude.

The German Radiation Protection Ordinance introduces a threshold of 10^7 times the exemption value for non-sealed radioactive sources for considerations regarding a) design basis accidents and b) for preparation of emergency measures. However, there is no further guidance on how to apply these requirements. The Radiation Protection Ordinance refers to potential “general administrative provisions” in which, “taking into consideration the probability of damage occurring and of multiple exemption values for sealed and non-sealed radioactive sources”. Yet, this document was never created.

Therefore, we analysed in more detail the applicability of such an approach for fusion facilities based on the

Radiation Protection Act and the development of a graded approach (International Atomic Energy Agency 2014; International Atomic Energy Agency 2016a). This approach is based on a hazard comparison between different nuclear and radiation applications, cf. Section 6.

As facilities where radioactive materials are handled, produced and stored, safety principles generally apply to fusion research facilities and future fusion power plants, as stated by the IAEA in its Fundamental Safety Principles (International Atomic Energy Agency 2006). These include that ‘people and the environment, present and future, must be protected against radiation risks’. To achieve the corresponding goals, fundamental safety functions are required. In fission power plants fundamental safety functions are (a) Control of reactivity, (b) Removal of heat and (c) Confinement of radioactive material (International Atomic Energy Agency 2016b). Due to the physical and technological differences between nuclear fission and fusion, control of reactivity is not an issue in fusion facilities. “Removal of heat” is not an individual safety function for fusion facilities, although loss of cooling can be a trigger for certain events depending on the actual design of a fusion facility. However, compared with fission facilities, no large core melting with similar severe consequences is possible. Finally, confinement of radioactive material and radiation protection are the fundamental safety functions applicable to fusion facilities. The radioactive inventory consists mainly of tritium and activated materials. It may be present in various physical and chemical forms.

Based on the well-known ALARA principle, the regulation should support an optimisation process considering the “likelihood of an incurring exposure, the number of people exposed and the magnitude of their individual doses” which “should all be kept as low as reasonably achievable, taking into account economic and societal factors” (International Commission on Radiological Protection 2007).

6 Hazard potential

Three relevant aspects of the hazard potential for future fusion power plants are discussed in the following subsections: safety, radioactive waste and non-proliferation.

6.1 Safety

6.1.1 Radioactive inventory

The German Radiation Protection Ordinance defines limits for the preparation of safety measures as 10^{10} times the exemption level for sealed radioactive sources and 10^7 for

other, non-sealed inventories. Exemption values in the European Union are described in directive 2013/59/EURATOM (Council of the European Union 2013). Their definition is based on the de-minimis-concept considering different exposure scenarios relevant for radioactive sources with low activities (Dymke 2002).

We compared inventories for different applications in terms of exemption values as possible metric: for industrial and medical use (blue), for fission applications (green) and for fusion-relevant inventories (pink), cf. Figure 3.

Selected values of the metric are given in Table 2. The publication (Motzkus et al. 2012) gives typical and maximal values for the activities of High-Activity Sealed Radioactive Sources (HASS) for 2012 in Germany. The HASS with the largest ratio of its activity relative to the exemption level, a Cs-137 source installed in an irradiation device, was selected for the comparison. Figure 3 also shows the inventory of the radiological accident in Goiânia (International Atomic Energy Agency 1988). For the inventory of a nuclear power plant, the activities of a reactor core 24 h after shutdown were used (German Commission on Radiological Protection 2004). The total source term has a weighted ratio of 15 orders of magnitude relative to the exemption levels. The single nuclide with the largest ratio to its exemption level is Xe-133. One of the most important nuclides for the longer-term consequences of nuclear accidents is Cs-137 with a ratio of 9 orders of magnitude compared to its exemption level. Also shown are inventories of different research reactors (Travleev, to be published; Ullah et al. 2009; Rätty et al. 2020) and of used fuel elements inside a cask for interim storage (Peiffer et al. 2011).

For fusion facilities, currently only estimates of the radioactive inventories are available from published literature. They are based on ITER and DEMO, i.e. tokamaks only. For tritium, the licensing limit of ITER is 4 kg (French Republic 2012). With respect to activation products, in Mertens et al. 2019; Mertens 2019 the inventory of Po-210 is estimated with about 1 g for fusion power plants using lead as neutron multiplier. In Lukacs and Williams (2020) 1,000 kg of dust is assumed inside the vacuum vessel. The calculated W-185 content in the dust is $3.7 \cdot 10^{16}$ Bq. Figure 3 shows different estimates of the dust inventory from the literature (Raskob et al. 2000; Raskob, to be published; Lukacs and Williams 2021). Additionally, simulation data are shown for the inventory of activated corrosion productions (ACP) in the coolant system of a DEMO design outside the bio-shield of the vacuum vessel (“out-of-flux region”) (Terranova et al. 2022) and, based on simulations for ITER (Carloni et al. 2024), of the ACP inventory inside the bio-shield (“in-flux region”).

The metric for different inventories is shown in Table 2. The largest activity to exemption level ratio for HASS is about

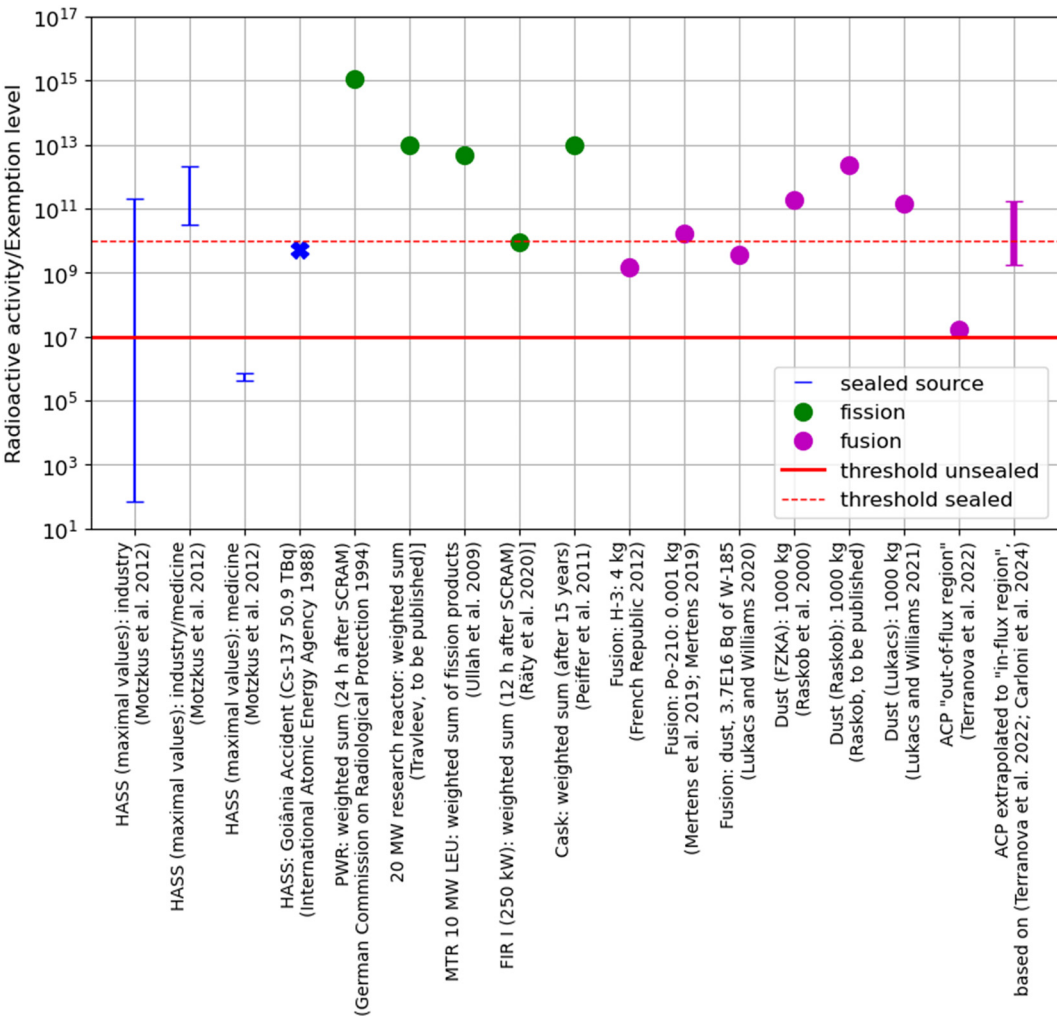


Figure 3: Radioactive inventories for industrial and medical applications (blue), for nuclear (fission) applications (green) and for fusion relevant inventories (pink) in terms of exemption values. The lower line indicates the 10^7 -times the exemption value (threshold for sealed sources), the upper line the 10^{10} -times the exemption value (threshold for unsealed sources).

Table 2: Ratio of radioactive inventories and exemption values for different applications.

Type	Nuclide	Mass (kg)	Inventory (Bq)	Exemption level (Bq)	Ratio (–)	Sealed
HASS	Cs-137	–	$4.4 \cdot 10^{16}$	$1 \cdot 10^4$	$4.4 \cdot 10^{12}$	Yes
PWR	Xe-133	–	$7.3 \cdot 10^{18}$	$1 \cdot 10^4$	$7.3 \cdot 10^{14}$	No
	Cs-137	–	$3.0 \cdot 10^{13}$	$1 \cdot 10^4$	$3.0 \cdot 10^9$	No
	Total	–	$1.9 \cdot 10^{20}$	N.A.	$1.12 \cdot 10^{15}$	No
Fusion	H-3	4.0	$1.44 \cdot 10^{18}$	$1 \cdot 10^9$	$1.44 \cdot 10^9$	No
	Po-210	0.001	$1.74 \cdot 10^{14}$	$1 \cdot 10^4$	$1.74 \cdot 10^{10}$	No
	W-185	(0.1)	$3.7 \cdot 10^{16}$	$1 \cdot 10^7$	$3.7 \cdot 10^9$	No

W-185 part in 1,000 kg of dust.

two orders of magnitude above the threshold for sealed sources in Germany (10^{10} times exemption value) requiring the preparation of safety measures in Germany. For a nuclear power plant, the regulation of safety measures is based on the Atomic Energy Act and not on the thresholds cited

above. However, assuming the criterion from the latter one, the ratio of activities to exemption levels would be about eight orders of magnitude above the threshold for an unsealed source (10^7 times exemption value). For radioactive inventories of fusion facilities, as discussed above, the ratios

are estimated up to roughly five orders above the threshold for unsealed sources.

The data are showing that the available inventory of fusion facilities in terms of exemption values likely lies between facilities regulated by the radiation protection regulatory framework and nuclear power plants, little lower than research reactors.

6.1.2 Nuclide composition and exposure scenarios

To get a better understanding of the applicability of exemption values as a basis for a hazard metric, it is helpful to take a deeper look into typical nuclide compositions of fusion facilities and into exposure scenarios relevant for nuclear fusion facilities.

Beyond tritium, the nuclide composition of radioactive material inside the vacuum vessel consists mainly of activated structural materials such as first wall, blanket and divertor materials. If activated material in the breeder blanket (cf. Park and Pereslavitsev 2021; Stankunas et al. 2019) could be treated as an independent source which does not act together with other materials in the vacuum vessel, the inventories could be counted separately. However, this precondition needs to be proven, further consideration would be required in an additional step. Here we focus on materials

related to components in the vacuum vessel as given in the literature.

Main candidates are corrosion products and tungsten wall material as it is currently planned for ITER as a first wall armour. A detailed analysis performed in Lukacs and Williams 2021 gives the nuclide composition of such products in dust shown in Table 3. Furthermore, we added the exemption values and the relative contribution of each radionuclide to the utilization of the exemption values as a weighted sum for comparison. The main contributors in terms of exemption values are W-187, Ta-182, Re-188, W-185, Re-186 and W-181. The contribution of the remaining nuclides is below one per-mille only. It is also worth noting that all major contributing radionuclides have half-lives ranging from several hours to 121.1 d (W-181) only. The radionuclides with significant half-lives (Co-60 and Ta-179) contributing with 0.01 % to the exemption value and with 0.02 % to the nuclide vector.

In a next step the metric was analysed in terms of release during normal operation and under accident conditions based on a comparison of relative exposures for Cs-137, a radiologically relevant fission radionuclide, and for tritium and W-185 representative for fusion relevant radionuclides in dust. Although other radionuclides have lower exemption values, the contribution of W-185 to the nuclide vector compensates for this effect. In a future recalculation, we plan a more comprehensive comparison considering

Table 3: Nuclide composition of dust expected after one year of full operation of DEMO according to Lukacs and Williams (2021) and its contribution to nuclide vector and relative exemption value.

Radionuclide	Specific release [Bq/g]	Nuclide vector [%]	Exemption value [Bq]	Relative contribution to exemption value [%]	Half-life
W-187	1.04E+11	65.39 %	1E+06	74.02 %	23.7 h
W-185	3.72E+10	23.39 %	1E+07	2.65 %	75.1 d
Re-186	1.97E+09	1.24 %	1E+06	1.40 %	3.7 d
Ta-182	1.67E+08	0.10 %	1E+04	11.89 %	114.4 d
Re-188	1.19E+09	0.75 %	1E+05	8.47 %	17 h
W-181	1.43E+10	8.99 %	1E+07	1.02 %	121.1 d
Ta-183	6.40E+07	0.04 %	1E+06	0.05 %	5.1 d
Co-60	1.27E+06	0.00 %	1E+05	0.01 %	5.27 a
Re-184	1.99E+07	0.01 %	1E+06	0.01 %	38 d
Ta-184	4.33E+07	0.03 %	1E+06	0.03 %	8.7 h
Ta-179	2.74E+07	0.02 %	1E+07	0.00 %	1.82 a
Ag-110m	3.72E+05	0.00 %	1E+06	0.00 %	249.8 d
Co-58	1.14E+06	0.00 %	1E+06	0.00 %	70.86 d
Ta-186	6.40E+07	0.04 %	1E+05	0.46 %	10.5 min
Mn-54	2.57E+05	0.00 %	1E+06	0.00 %	312 d
Total	1.59E+11	100.00 %		100.00 %	
H-3	(3.6E+14)		1E+09		12.3 a
Cs-137			1E+04		30.1 a

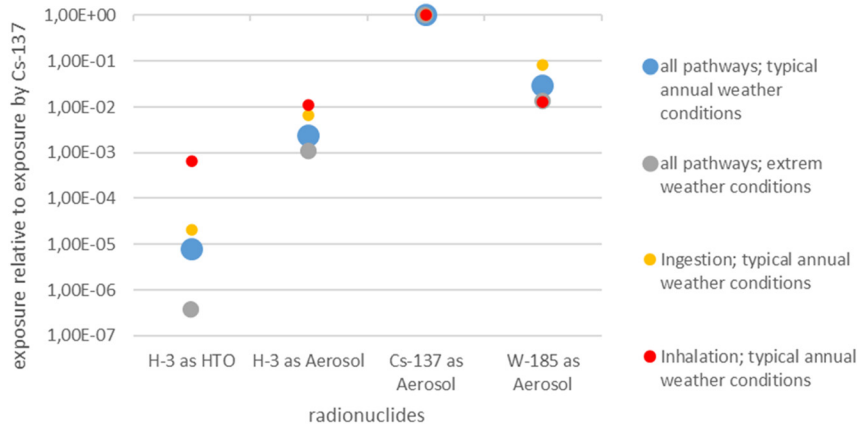


Figure 4: Normal operation exposure of different radionuclides relative to the exposure of Cs-137.

more radionuclides and end points (exposure pathways and scenarios). For tritium we considered two forms: tritium as water and as gas/aerosol. If the exemption values are an appropriate measure for the hazard potential, then the relative exposure should follow those relations.

We assumed a continuous emission of the radionuclides and performed a calculation using a Lagrange dispersion model software ARTM (Richter et al. 2025) combined with a dose model software DARTM (Pattantyús-Ábrahám 2025) considering the German regulations for prospective exposure calculations during normal operation. Although, we considered an 80 m stack, a flat terrain and a 100 m site boundary, this kind of comparison of relative dose contributions is not expected to be very sensitive to those parameters, at least for the aerosols which are always treated equally in the dispersion model. As weather conditions we selected a typical year from German weather statistics as well as extreme weather conditions to check the sensitivity.

In Figure 4 the exposure in terms of effective dose for the sum of all exposure pathways for both weather scenarios (large circles) and for ingestion and inhalation pathway (small circles) for tritium as water and aerosol (International Commission on Radiological Protection 2012) and for W-185 in relation to the exposure due to Cs-137 under the same exposure pathways is shown.

The relative exposure of tritium as water depending on the exposure pathway and weather conditions varies over more than three orders of magnitude. The relative value calculated for typical weather conditions and the sum of all exposure pathways is $1 \cdot 10^{-5}$, the same as the ratio of exemption values for Cs-137 and tritium. This is also valid for the ingestion pathway which dominates the total exposure. However, for inhalation and extreme weather conditions the deviations are significant. For tritium as aerosol, the contribution relative to Cs-137 is two orders of magnitude higher than for tritium as HTO. For W-185, the relative

exposure is of the order of $1 \cdot 10^{-2}$ or larger, which is of the same order of magnitude as the ratios of the exemption values of W-185 and tritium. In summary, the relative doses over all exposure pathways for tritium as HTO and W-185 compared to Cs-137 follow somehow their exemption values. We can conclude, that for normal operation condition the exemption values can reflect the relative hazard of the radionuclides.

It is also worth to note that although the half-life of the contributing radionuclides in the dust is quite short compared to Cs-137, the contribution to the dominating ingestion pathway in a model with continuous release and subsequent chronic ingestion is significant.

The situation is changing, if we regard short term releases as they are typical for incidents and accidents. For the short-lived radionuclides of the dust, the ingestion dose decreases significantly compared to Cs-137. The short-lived radionuclides do not contribute significantly to the ingestion pathway compared to Cs-137. On the other hand, exposure scenarios related to the transition of a cloud, i.e. inhalation, submersion, are now dominant for the total exposure. This is consistent with the results in Lukacs and Williams (2021). We plan to perform further calculations based on the DARTM model adapted to short-term exposure.

Our preliminary conclusion is that the short-lived radionuclides provide a very different result compared with the typical fission accident pattern: Since the typical radionuclide spectrum of fusion facilities does not include longer lived radionuclides, short-term exposure pathways are more relevant than longer term pathways including ingestion. The exemption values may provide an adequate representation of accidental inhalation doses, whereas for ingestion it tends to overestimate the radiological relevance of fusion nuclides. Further analysis is required, especially considering tritium in other chemical/physical form.

6.1.3 Neutron rate and thermal power

Another parameter could be relevant to be considered in the regulation: the neutron rate or fluence. The former is proportional to the thermal power; the latter is proportional to the energy output. In Germany only a threshold of $1 \cdot 10^{12}$ neutrons in 1 s for a construction license is defined. In other countries, $1 \cdot 10^{20}$ neutrons per second (Polianskii et al. 2025; Wang 2025) and $1 \cdot 10^{25}$ neutrons accumulated per year (Wang 2025) or $1 \cdot 10^{26}$ neutrons accumulated in the lifetime (Polianskii et al. 2025) are under consideration for a graded regulation (International Atomic Energy Agency 2014, 2016a). Generally, the neutron rate or fluence is a measure for activation and tritium inventory in the vacuum vessel. However, selection of materials as well as different technologies with different burnup-rates could lead to very different inventories at the same neutron fluence. Thus, we prefer a metric which is technologically neutral as it is based on the inventory.

On the other hand, neutron rate or thermal power of a fusion facility could be an appropriate metric for environmental impact analyses, at least for a power reactor. Alternatively, the neutron fluence or thermal energy delivered could be a useful metric. The German Environmental Impact Assessment (EIA) Act currently does not require an EIA for any fusion facility. With respect to further impacts beyond radiological aspects, for larger plants an EIA might be necessary.

6.2 Radioactive waste

For future fusion power plants, the aim is to produce no or only small amounts of long-lived radioactive waste. According to recent studies, significant volumes of radioactive materials will nonetheless be produced through activation by neutrons or diffusion of tritium into structural materials. These radioactive materials will differ significantly from those resulting from nuclear fission power plants, both in quantities as well as radionuclide content. Significant amounts of radioactive materials will arise from steels and other metallic materials, concrete, dust, and blanket-concept-dependent breeding and neutron multiplier materials.

Research on how to minimise the volume of radioactive materials that will have to be disposed of as intermediate- (ILW) or low-level waste (LLW) is ongoing. One approach is based on material selection and development, e.g. avoiding impurities in structural materials that would lead to long-lived nuclides through neutron activation. Another way is the development of highly efficient detritiation techniques to remove and recover tritium from materials.

It is often foreseen to store materials aboveground for around 50–100 years, so short-lived radionuclides may decay. If radioactive materials are then compliant with regulations and not declared waste, they may be reused and recycled. Otherwise, they will need to be disposed of. In Gilbert et al. 2017, the authors apply current UK waste classification to European DEMO concepts. They show how waste volumes for different breeding-blanket concepts would develop over time, both during operation and decommissioning. While after shutdown the amount of waste that can be classified as nonactive and LLW rises over time, on the order of 10,000 tonnes of ILW will remain after 100 years. Even 1,000 years after shutdown, hundreds to thousands of tonnes of ILW would remain.

Whereas in some countries LLW may be disposed of in near-surface repositories, all radioactive waste in Germany will be disposed of in geologic repositories. Waste resulting from breeding blankets in EU-DEMO in currently foreseen concepts could not be stored in the German repository Konrad for LLW and ILW due to their expected tritium and C-14 contents (Caruso et al. 2022). Besides potential problems with the nuclide content, current capacities for LLW and ILW repositories in Germany will likely not be sufficient for the large volumes of waste arising from future fusion power plants. These potentially arising waste volumes will need to be accounted for in future planning of fusion facilities, storage facilities and repositories.

6.3 Non-proliferation

Nuclear fusion facilities are associated with three categories of potential proliferation risks: The neutrons could be used to produce fissile materials such as plutonium from fertile source materials such as natural or depleted uranium. Although fusion reactors do not contain nuclear material during routine operation, deliberate modifications (introduction of fertile target material in the blanket or coolant) would enable a new “plutonium route” available to states seeking a nuclear weapons option. Since fusion power plants generate considerable amounts of neutrons, large quantities of plutonium could potentially be produced. Even quantities of source material that can be exempted from safeguards (<10 t natural uranium) (Englert and Harrington 2016) could yield significant plutonium production per year (>8 kg/a). Due to the characteristic hard neutron energy spectrum in a typical fusion blanket, the bred plutonium would be of weapon-grade with a very high content of Pu-239 even after long irradiation times (Ball et al. 2025; Diesendorf et al. 2023; Franceschini et al. 2013; Glaser and Goldston 2012). It should, however, be possible to verify without difficulty whether

Neutron rate or thermal power could be used as a threshold for a mandatory EIA. It should be a level of 100 MW thermal or more, we propose 300 MW_{thermal}. For smaller facilities, a pre-assessment of environmental impact could be performed. Both need to be regulated in the German Environmental Impact Assessment Act (Federal Republic of Germany 2021).

Figure 5 summarises the preliminary proposals and gives preliminary values as indicators for further discussions. Based on the analysis above, for fusion facilities in the near term only minor modifications of the German radiation protection framework are recommended including the adaptation of Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2003 into a more specific “checklist for licensing of fusion facilities” and clarifying the necessity and scope of preparational measures for accidents and emergencies. For future fusion power plants, more significant adaptations might be required, which shall be investigated accompanying fusion development.

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