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REGULATORY FRAMEWORK TOWARDS FUSION ENERGY IN GERMANY

Principles and Open Issues

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Abstract

The paper introduces the German project for regulation of future fusion facilities which was started in 2025 and its preliminary results. It shows the existing regulatory framework and based on which fusion facilities such the stellarator type Wendelstein 7-X was licenced. The analysis demonstrates that the German Radiation Protection Law and its subsequent rules and regulations are generally applicable for fusion. However, certain adaptations and clarifications will be required for speeding up fusion power establishment.

1. INTRODUCTION

Germany has a strong track record in research and application on nuclear fusion facilities. With the ASDEX Upgrade tokamak at Garching, the world leading stellarator Wendelstein 7-X at Greifswald, and relevant participation in further international fusion projects such as ITER and EU 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 startups and industrial partners has been growing in Germany, which initiates support programmes, cf. [1, 2]. However, beyond research and technological issues, a key question is how to license diverse fusion facilities ensuring the necessary level of safety and equally supporting the flexibility and openness in a rapidly evolving field. Our research project ReFus focusing on the future regulation of fusion facilities in Germany is dedicated to this topic.

2. THE GERMAN REGULATORY FRAMEWORK

The regulation of nuclear energy forms the foundation to protect life, health and real assets, ensure safety and environmental protection, and compliance with international and national standards. In Germany, the regulatory framework is governed by two primary instruments: the Atomic Energy Act (Atomgesetz, AtG) [3] and the Radiation Protection Act (Strahlenschutzgesetz, StrlSchG) [4]. A system of further regulations, recommendations and rules is arranged hierarchically beneath them. An overview on the principal structure, the binding levels and examples are given in Fig. 1. This regulatory framework forms the current basis for regulation of 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 defines "radioactive material" as "nuclear fuel" and "other radioactive substances", and it focuses on the specific nuclear hazards of nuclear fuel especially of nuclear power plants, nuclear facilities, research reactors and any kind of nuclear fuel treatment, processing and other utilisation. Thresholds for the application of Atomic Energy Act are defined as exemption values, natural occurrence and a proportion of U-233, U-235, Pu-239 and Pu-241 of 15 g or a concentration of those radionuclides of 15 g per 100 kg.

The nuclear fusion process fundamentally differs from nuclear fission, avoiding many of its inherent risks. In nuclear fusion criticality accidents are not possible due to absence of any chain reactions. It typically utilizes fuel that does not contain materials classified as "nuclear fuel" under the Atomic Energy Act's definition of "special fissionable material".

The Radiation Protection Act [4] provides the regulatory framework for protecting individuals and the environment from the effects of ionizing radiation. It governs licensing requirements for the construction and operation of facilities generating ionizing radiation as well as for handling of “other radioactive substances”, such as tritium. Furthermore, fusion facilities are explicitly included under the Radiation Protection Act due to their classification as “installations for the generation of ionizing 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 describes in attachment 2 of the documents, e.g. the safety report required for licensing approval.

Further requirements relevant for fusion facilities are covered in the Radiation Protection Ordinance [5], which includes dose and concentration limits for radioactive effluents, limits for exemption and exclusion, dose limits for worker and public under operation conditions as well as for accidents.

The underlying framework for the Atomic Act as well as for the Radiation Protection Act includes expert commission recommendations, national and international standards, rules of the Nuclear Technical Committee (KTA) and further rules. They are applied based on case-by-case considerations and a graded approach with respect to the protection goals.

An important complementary administrative tool is the “Checklist of documents for licensing of radiation facilities” [6], 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 licenses as defined by the Radiation Protection Act: construction license, test operation license and operation license. Fusion facilities share operational characteristics with accelerators, including neutron generation and activation products, making the checklist a suitable starting point for the licensing of fusion facilities.

In the context of the ReFus project, we are exploring the necessary extensions to the existing German regulatory framework for future fusion power plants, as it is anticipated that their radiological hazards will considerably surpass those of current fusion research facilities.

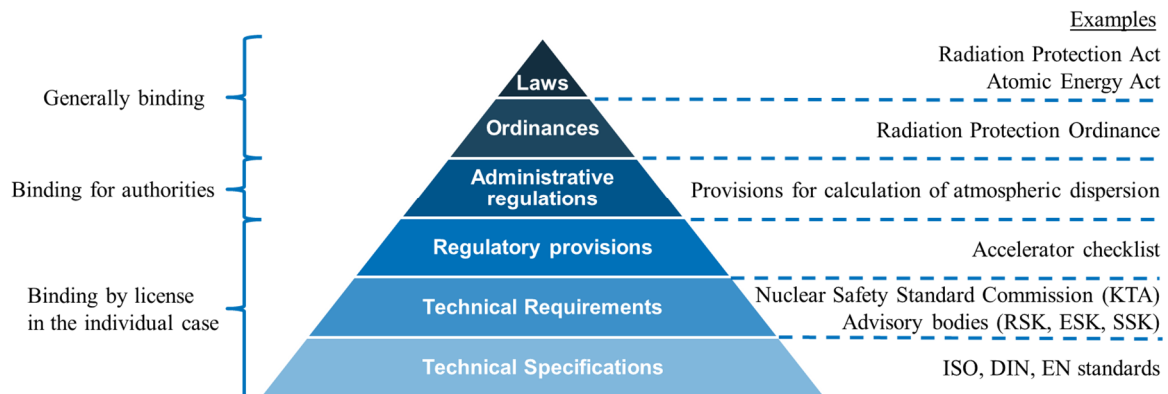


FIG. 1. German scheme of existing rules and regulations.

3. LICENSING OF WENDELSTEIN 7-X

Wendelstein 7-X (W7-X), the world largest stellarator plasma facility, was built in Greifswald, Germany and has been operating since December 2015. Basic technical data of W7-X are given in Table 1. The planned annual neutron production of $3 \cdot 10^{19}$ due to the deuterium-deuterium-fusion reaction results in a maximum release of $2 \cdot 10^{11}$ Bq of Tritium.

W7-X was originally licensed under the German Radiation Protection Ordinance, later superseded by the Radiation Protection Act [4]. The licensing process covered a construction license and an operation license [7] followed by an ongoing supervision process.

TABLE 1. SELECTED TECHNICAL DATA OF WENDELSTEIN 7-X

General	
Type	Stellarator
Max. toroidal magnetic force	3 T
Torus 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 emission 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
Nobel gases (mainly Ar-41)	$2 \cdot 10^{10}$ Bq/a
Further radionuclides	$4 \cdot 10^7$ Bq/a

The application for a construction license was submitted in October 1996 by the Institute of Plasma Physics (IPP) to the responsible radiation protection licensing authority (LAGuS), for a schematically timeline cf. Fig. 2. A construction license 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/s”. The construction license 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. Main subjects of the construction license and corresponding reviews were shielding, groundwater activation, 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.

In May 2014 IPP applied for the operation license and provided a safety report, which followed in principle the recommendations for accelerators [5] adjusted to the needs of the stellarator W7-X. A review process by the independent reviewer on behalf of the licensing authority was started in November 2014 and covered especially 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 license in 2015 [7]. The license 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 a learning process for optimal balance of an adequate safety and radiation protection with scientific progress.

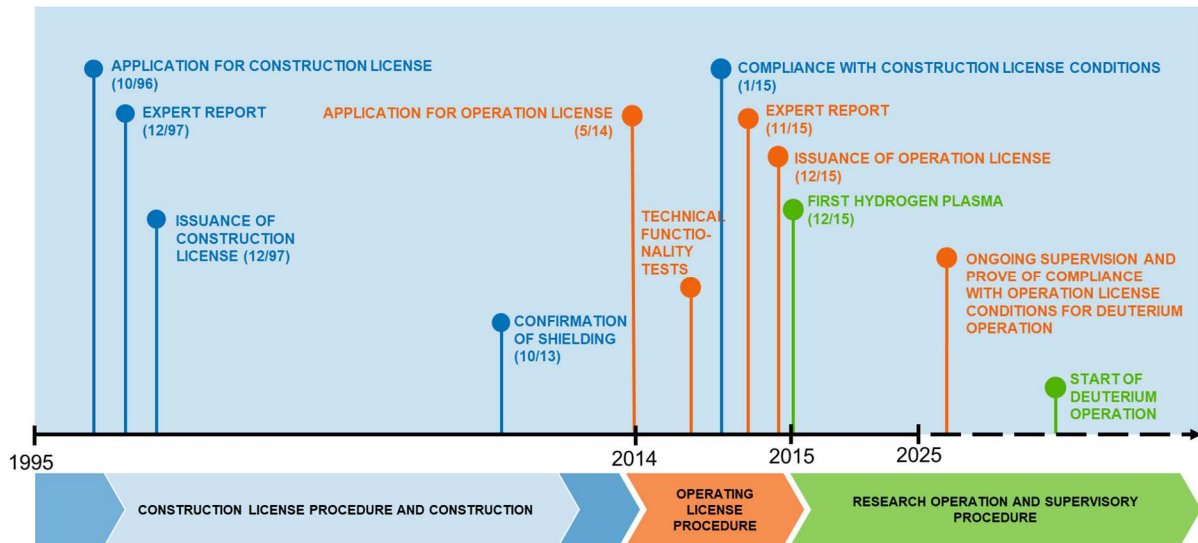


FIG. 2. Licensing schedule of W 7-X (timeline schematically only).

4. FUSION TECHNOLOGIES IN FOCUS

Fusion research in Germany has long been focussed on magnetic confinement fusion (MCF) technologies, with both experimental tokamak and stellarator facilities having been built. Historically, inertial confinement fusion (ICF) research has been dominated by military research, mostly in the US and in France [8]. Only in the last few years research into ICF has become more present in Germany [9].

Current fusion research facilities in Germany are MCF-based and include Wendelstein 7-X, described above, and ASDEX Upgrade. With ASDEX Upgrade being a tokamak, research performed there is then used to inform plans for other research facilities like ITER, EU-DEMO and a possible future fusion power plant based on the tokamak technology. Experiments both at ASDEX Upgrade and W7-X use simple hydrogen or deuterium or a mixture of both as fuel, but no tritium. As a key component of the deuterium-tritium fusion reaction, tritium is indispensable for the operation of ITER and EU-DEMO. Research institutes from Germany are also contributing to ITER and EU-DEMO and especially to the tritium topic including the fuel cycle.

Four start-up companies based in Germany are working on a range of fusion energy technologies: two on MCF using stellarators, two on ICF. The companies are mostly focusing on the deuterium-tritium-fusion reaction, but also other reactions are being considered. Compared to ITER and DEMO, companies set tighter timelines and aim at constructing pilot plants in the 30s to 40s (see e.g. [10]). Besides companies based in Germany, also 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.

5. HAZARD POTENTIAL AND RADIOACTIVE WASTE

Several different aspects of the hazard potential of future fusion power plants are regarded separately. Compared to fission power plants, similar but still distinctly different hazard potentials will arise. They can be split into three groups: safety, radioactive waste and non-proliferation.

5.1. Safety

As facilities where radioactive materials are handled, produced and stored, safety principles as stated by the IAEA in [11] generally apply to fusion research facilities and future fusion power plants.

These include that ‘people and the environment, present and future, must be protected against radiation risks’ [11]. To achieve these goals, fundamental safety functions are required. Fundamental safety functions for nuclear power plants are (a) Control of reactivity, (b) Cooling of radioactive material and (c) Confinement of radioactive material [12]. Due to the physical and technological differences between nuclear fission and fusion, control of reactivity is not an issue in fusion facilities. However, confinement of radioactive material is, and cooling of radioactive material can be, depending on the actual design of a fusion facility. In fusion facilities, the radioactive inventory consists of mainly tritium and activated material. It may be present in various physical and chemical forms.

A metric is proposed to assess the radiological hazard potential of fusion facilities. This metric considers the radiotoxicity of different nuclides and their quantities.

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. The order of magnitude by which the ratio of the activity to the exemption level exceeds the limit value is therefore a possible metric for different facilities with different radioactive inventories.

The proposed metric is based on the inventory of the facilities. It ranks the facilities without considering any safety measures, because its purpose is to indicate whether safety measures are necessary. Considering safety measures in the metric would lead to circular reasoning.

The publication [13] 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. For the inventory of a nuclear power plant, the activities of a reactor core 24 h after shutdown were used [14]. The total source term has a weighted ratio of 8 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 six orders of magnitude compared to its exemption level.

For fusion facilities currently only estimates of the radioactive inventories are available from the open literature. For tritium the licensing limit of ITER is 4 kg [15]. In [17] and [18] the inventory of Po-210 is estimated with about 1 g for fusion power plants using lead as neutron multiplier. In [19] a very conservative estimate of the dust as 1000 kg of W-185 is given.

The calculations of the metric for the different inventories are shown in Table 2. The largest activities to exemption level ratio for HASS is about two orders of magnitude above the limit requiring the preparation of safety measures in Germany. For a nuclear power plant, the regulation of safety measures is based on the Atomic Act and not on the limits above of the Radiation Protection Ordinance. However, assuming the criterion from the latter one, the ratio of activities to exemption levels would be about eight orders of magnitude above the limiting value. For fusion power plants the ratios are estimated to be between two and seven orders above the limiting value.

TABLE 2. METRIC OF RADIOLOGICAL HAZARD

Type	Nuclide	Mass (kg)	Activity (Bq)	Exemption Level (Bq)	Ratio (-)	Sealed	Order of magnitude of exceedance of limit
HASS	Cs-137	-	$4.4 \cdot 10^{16}$	$1 \cdot 10^4$	$4.4 \cdot 10^{12}$	yes	3
PWR	Xe-133	-	$7.3 \cdot 10^{18}$	$1 \cdot 10^4$	$7.3 \cdot 10^{14}$	no	8
	Cs-137	-	$3.0 \cdot 10^{13}$	$1 \cdot 10^4$	$3.0 \cdot 10^9$	no	6
	Total	-	$1.9 \cdot 10^{20}$	n.a.	$1.12 \cdot 10^{15}$	no	8
Fusion	H-3	4.0	$1.44 \cdot 10^{18}$	$1 \cdot 10^9$	$1.44 \cdot 10^9$	no	2
	Po-210	0.001	$1.74 \cdot 10^{14}$	$1 \cdot 10^4$	$1.74 \cdot 10^{10}$	no	3
	W-185	1000	$3.5 \cdot 10^{20}$	$1 \cdot 10^7$	$3.5 \cdot 10^{13}$	no	7

The proposed metric shows that the radiotoxicity of the inventory of fusion power plants likely lies between the radiotoxicity of facilities regulated by the radiation protection regulatory framework and the radiotoxicity of nuclear power plants. Due to the uncertainties as to the design of fusion power plants, it is currently not clear if

their radiotoxicity will be comparable to radiation protection-regulated facilities or if fusion facilities' radiotoxicity will be significantly larger. However, current conservative estimates show that the radiotoxicity of fusion facilities will be lower than that of nuclear power plants.

This preliminary analysis demonstrates that further work is needed to evaluate how safety functions can be implemented in a fusion facility following a graded approach, which will need to be codified in regulations.

5.2. Radioactive waste

For future fusion power plants, the aim is to produce no or only very minor amounts of long-lived radioactive waste. But still significant volumes of radioactive materials could 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 and dust.

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 through 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 to 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.

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 breeder 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 [16]. 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.

5.3. 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 be potentially produced. Even quantities of source material that can be exempted from safeguards (<10 t natural uranium) [20] 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 [21], [22], [23], [24]). It should, however, be possible to verify without difficulty whether uranium or other fertile material such as thorium is being irradiated with neutrons in a fusion plant, since the material should be absent under normal operation.

Additionally, the availability of large quantities of tritium could lead to the material being diverted for military purposes. Only a few grams of tritium are enough to boost the yield of a nuclear weapon, thereby enhancing the efficiency (yield-to-weight ratio) of the weapon and allowing for its minimization. It will be practically impossible to use material accountancy to detect the diversion of a few grammes in a commercial fusion reactor. There are currently no global monitoring measures for tritium equivalent to those implemented by the IAEA for fissile materials, although export controls exist. However, there are calls to establish an adequate monitoring system [25], [26], [27].

Inertial confinement fusion research has clear dual-use potential, as facilities such as the US National Ignition Facility (NIF) and France's Laser Mégajoule (LMJ) were primarily developed for military stockpile stewardship. Although civilian energy applications are now more visible, their experimental data and simulation methods could

enable latent proliferation strategies by virtualizing nuclear testing. Clarifying the boundary between civilian and military applications is therefore essential for assessing the goals of fusion programmes.

Current IAEA safeguards apply only to a limited extent to fusion facilities [28]. A corresponding clarification of the verification regulations for pure fusion power plants would therefore be recommendable for the future use of fusion power plants [29], as appropriate international monitoring measures are inevitable. In addition, methods need to be developed to detect clandestine use.

6. DEVELOPMENT OF A FUSION REGULATORY APPROACH IN GERMANY

In Germany, nuclear and radiological facilities are regulated by the Atomic Energy Act and the Radiation Protection Act. Simplified, the Atomic Energy Act is applicable to nuclear power plants and installations handling nuclear fuel or waste, while the Radiation Protection Act is applicable to all other installations capable of producing ionising radiation as well as the handling of radioactive material other than nuclear fuel.

As indicated above, existing fusion research devices in Germany such as Wendelstein 7-X or ASDEX Upgrade are regulated under the Radiation Protection Act. In fact, the Radiation Protection Act allows already today for licensing 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 Wendelstein 7-X. To give more clarity for future licensing processes, we propose to add the term “fusion facilities” to the definitions in section 5 para. 2 of the Radiation Protection Act.

Furthermore, we are currently analysing the underlying technical regulatory framework for safety, waste management and non-proliferation with respect to its applicability to future fusion power plants and necessary adaptations and extensions. This includes the implementation of a graded approach in safety assessments, the architecture of the underlying technical framework, including codes & standards and guidance on the application of the existing regulatory framework.

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