Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Principal Safety Requirements of Radioactive Waste Management for Future Fusion Power Plants in Korea

Doo-Hee Chang*, Sun-Ho Kim
Nuclear Physics Application Research Division, Korea Atomic Energy Research Institute, Daejeon 34057, Korea
**Corresponding author: doochang@kaeri.re.kr*

1. Introduction

Beyond the ITER device, the development of K-DEMO fusion reactor toward the commercial fusion power plants is planned to support the future national massive and clean energy requirements in Korea [1, 2]. The important issues related to the safety and security of fusion reactors are the amount of activated material of different composition and shape that is produced inside the reactor vacuum vessel as a consequence of the interactions between plasmas and materials [3]. Although the products of the D-T fusion reaction (helium and neutrons) are not radioactive, energetic fusion neutrons of 14.1-MeV from D-T fusion reactions are absorbed and captured by structural materials and fluids surrounding the core plasmas. The 14.1-MeV high-energy neutrons can transmute some elements the structural materials and produce radioactive isotopes. These materials belong principally to the in-vessel components (e.g. blanket, shield and divertor of a tokamak fusion plant).

Furthermore, a small percentage of the D-T fuel is consumed and some tritium (the one not reacting with deuterium and not extracted from the plasma chamber) could escape and contaminate the plasma facing components by various mechanisms (diffusion, implantation and co-deposition). Hence, the major issue of fusion radioactive waste handling is not only linked to the safe and environmentally friendly management of activated materials, but also to the detritiation and treatment of contaminated components [4]. The principal safety requirements of radioactive waste management are reviewed shortly for future fusion power plants in Korea, such as K-DEMO and commercial fusion power plants.

2. Radioactive Waste Management

In this section, some of the integrated approach to radioactive materials management are summarized for the basic principal guidance of Clearance, Recycling, and Disposal processes in the future fusion devices [5].

2.1 Environmental Features of Fusion Device

Fusion devices, although being nuclear installations, have certain characteristics as to make them environmentally friendly devices. Prior to analyzing the management scheme of fusion activated materials, it is worthwhile to highlight what makes fusion energy safe and environmentally attractive compared to other nuclear energy sources [4]:

- There is no nuclear chain reaction
- A small amount of fuel circulates (order of grams) in the reaction chamber which maintains the D-T reaction for only few seconds
- The power density in a fusion reactor is much lower than that of fission reactors and it can be limited by design in such a way to moderate the consequences of most severe accidents
- The main radioactive inventory is generated by neutron activation of plasma surrounding components. This activation process depends strongly on the type of irradiated materials and the careful choice of material constituents

These and other factors corroborate the hypothesis that fusion power, with a safety oriented design and a smart choice of its constituting materials, can be “intrinsically safe” with very low probability of severe accidents (and even in case of accident, without important impact on the surrounding population) and minimal environmental impact.

2.2 Comparison with nuclear fission radioactive waste management

The differences exist between fission and fusion in terms of fuels, reaction products, activated material type, activity levels, half-life, radiotoxicity, etc. The quantity of activated material originating from the fusion power core is larger than that from the fission core (per unit of electricity produced). The main differences between fission and fusion waste are related to their radiotoxicity (much higher in fission for waste originating from the fuel cycle) and waste form for their final disposal. When recycling is conceived, fission has a large share of highly radioactive and radiotoxic liquid secondary waste from spent fuel reprocessing, which has to be solidified by cementation or vitrification. Fusion waste in terms of volume is mostly solid and does not require those processes in extensive way.

Fusion solid waste also requires treatment (decontamination, detritiation, cutting, compacting) and conditioning (stabilizing e.g. by grout, packaging, etc.) which will generate some secondary waste requiring solidification. It is worthwhile to mention that tritiated water at low tritium concentration will be produced as well from the Fuel Cycle Systems requiring treatment and in some cases conditioning. Most importantly, the fusion generated waste is not intrinsic to the fusion reaction, and therefore is more controllable. Thus, providing prudent and intelligent selection of materials and processes (avoiding noxious impurities), fusion reactors can avoid generating high level and long-lived waste streams. This is probably the most important difference between fusion and fission radioactive waste, and this will have an important impact on their management.

2.3 Clearance

"Clearance" (unrestricted release from regulatory control) means that the material complying with the requirements defined by the national regulatory authorities can be handled as if it contains no radioactivity significantly higher than naturally occurring. Under this option, solid material can be reused without restriction, recycled into a consumer product, or disposed off in any industrial landfill. The clearance limits for selected radionuclides encountered in fusion applications, according to the standards and guidelines cited are shown in Table 1.

Table 1: IAEA, U.S., Russian, and EU clearance limits (in Bq/g) for some fusion-relevant nuclides

Nuclide	IAEA (IAEA, 2004)	United States NUREG-1640 (US-NRC, 2003) (steel / Cu / concrete)	Russia (NRB, 2009; OSPORB, 2010) (general / metals / MSSA)	European Union EC RP 122 (EC-RP, 2000)
^{3}H	100	526 / 1e5 / 152	100 / - / 10^{6}	100
^{14}C	1	313 / 4.17e4 / 83	1 / - / 10^{4}	10
^{22}Na	0.1	0.238 / 8.33 / 0.0417	0.1 / - / 10	0.1
^{40}K	10	2.94 / 153.8 / 0.526	10 / - / 100	1
^{41}Ca	-	47.6 / 9.1e3 / 13.9	-	-
^{45}Ca	100	5e3 / 7e4 / 909	100 / - / 10^{4}	100
^{53}Mn	100	1.14e4 / 7.1e5 / 6.67e3	100 / - / 10^{4}	1000
^{54}Mn	0.1	0.625 / 23.26 / 0.118	0.1 / 1 / 10	0.1
^{55}Fe	1000	2.17e4 / 2.33e5 / 4.76e3	10^{3} / - / 10^{4}	100
^{59}Fe	1	0.476 / 22.7 / 0.114	1 / - / 10	0.1
^{58}Co	1	0.588 / 28.57 / 0.133	1 / - / 10	0.1
^{60}Co	0.1	0.192 / 9.1 / 0.035	0.1 / 0.3 / 10	0.1
^{59}Ni	100	2.17e4 / 3.57e5 / 4.76e3	100 / - / 10^{4}	100
^{63}Ni	100	2.13e4 / 1.85e5 / 4.76e3	100 / - / 10^{5}	100
^{64}Cu	100	-	100 / - / 100	-
^{94}Nb	0.1	0.333 / 11.5 / 0.059	0.1 / 0.4 / 10	0.1
^{99}Mo	10	-	10 / - / 100	1
^{99}Tc	1	6.25 / 1.05e3 / 1.64	1 / - / 10^{4}	1
^{108m}Ag	-	0.345 / 18.18 / 0.0588	-	0.1
^{110m}Ag	0.1	0.192 / 10.3 / 0.0357	0.1 / 0.3 / 10	0.1
^{125}Sb	0.1	1.41 / 62.5 / 0.23	0.1 / 1.6 / 100	1
^{152}Eu	0.1	0.455 / 16.4 / 0.083	0.1 / 0.5 / 10	0.1
^{154}Eu	0.1	0.455 / 16.67 / 0.071	0.1 / 0.5 / 10	0.1
^{182}Ta	0.1	0.435 / 16.95 / 0.091	0.1 / - / 10	0.1
^{192}Ir	1	0.91 / 52.63 / 0.172	1 / - / 10	0.1
^{186}Re	1000	-	1000 / - / 1000	100

2.4 Recycling

The recent development of advanced radiation hardened remote handling tools encouraged many fusion designers to apply the recycling option to all fusion components that are subject to extreme radiation levels: very high levels near the plasma and very low levels at the bio-shield. Recycling processes includes storage in permanently monitored facilities, segregation of various materials, crushing, melting, re-fabrication and some other processes.

Aiming to define the recycling features in the context of a fusion-oriented approach to the back-end of the fusion materials cycle, the following recycling handling categories have been proposed:

- HOH (Hands-On Handling). Contact dose rate (DR) <10 μSv/h.
- S-HOH (Shielded Hands-On Handling). Contact DR < 2 mSv/h.
- RH (Remote Handling). Contact DR >2mGy/h, it can be dealt with by remote handling equipments, without active cooling: decay heat is <2000 W/m3.
- ACM (Active Cooling Material). This requires active cooling and it is unlikely that any recycling operations can be performed until its decay heat decreases to levels not requiring active cooling, hence interim storage with cooling is the only option available.

The EU study exemplified these by the categories in Table 2.

Table 2: EU Recycling Routes for Fusion Radioactive Materials

<table>
<tr><th>Limit</th><th colspan="2">< 10 μSv/h</th><th colspan="2">< 2 mSv/h</th><th>< 2,000 W/m³ (> 2 mGy/h)</th></tr>
<tr><td>Handling</td><td colspan="2">HOH</td><td colspan="2">SHOH</td><td>RH</td></tr>
<tr><td>Categories</td><td>Clearance</td><td colspan="2">Recycle in Foundries (1)</td><td colspan="2">Processes to Define</td></tr>
<tr><td>Limit</td><td>CI < 1</td><td colspan="2">< 1,000 Bq/g</td><td colspan="2">< 2,000 W/m³ (decay heat)</td></tr>
</table>

CI : Clearance Index
HOH : Hands-On Handling
SHOH : Shielded Hands-On Handling
RH : Remote Handling

(1) For metals

2.5 Integrated active fusion material management strategy

In order to overcome previous classifications and propose realistic routes and management processes for the materials, a distinction has been made between the Regulatory Route (unconditional clearance, conditional clearance, no-clearance) and the Management Route (recycling/re-use, disposal) as summarized in Table 3.

Table 3: An integrated approach to fusion radioactive materials management

Regulatory Route	Management Route	
	Recycling/Reuse	Disposal
Clearance (unconditional)	**Outside the nuclear industry.** All final destinations are feasible [*this can be after a certain decay storage time) this can happen within a licensed facility until specific conditions are met to allow clearance (i.e. in melting facilities to produce metal ingots)*]	In a landfill (*for urban, special or toxic waste, depending on chemical toxicity of the waste*)
Conditional Clearance	**Within the nuclear industry** or in general industry for specific applications. Continuous regulatory control. [*Examples include: building concrete rubbles for base road construction or as an additive for manufacturing new concrete buildings; or metal used for making shielding blocks and containers*]	In special industrial (and/or toxic) landfill
No-clearance (No-release)	**Within the nuclear industry** (it can be direct reuse, **or after processing**)	In a licensed repository for radioactive waste (after an interim storage if applicable)

The integration of the recycling and clearance processes in fusion power plants is at an early stage of development. The principal elements of the recycling/clearance process are depicted in Fig. 1 [6].

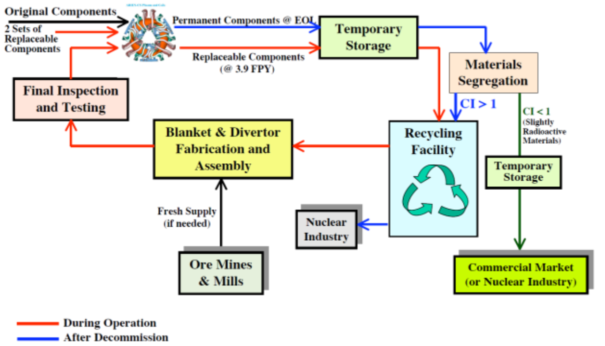

Fig. 1. Diagram of recycling and clearance processes.

We might predict the following steps by examining the various management step of fusion material at the back-end:

1. After extraction from the power fusion plant core, components are taken to the hot cell to disassemble and remove any parts that will be reused, separate into like materials, detritiate, and consolidate into a condensed form. This is probably one of the most challenging steps
2. Ship materials to a temporary storage onsite (or to a centralized facility) to store for several years
3. If the Clearance Index (CI) does not go down to unity in less than e.g. 100 y, transfer the materials to a recycling center to refabricate remotely into useful forms. Fresh supply of materials could be added as needed
4. If the CI can go down to unity in less than e.g. 100 y, store the materials for 1-100 y then release to the public sector to reuse without any restriction.

Due to the lack of experience, it is almost impossible to state how long it will take and how it will cost to refabricate the replaceable components (blanket and divertor) out of radioactive materials. This is probably the key element for defining a complete waste management strategy. In addition, many efforts should be put on developing these technologies. The minimum time that one would expect is one year temporary storage and two years for fabrication, assembly, inspection, and testing. All processes must be done remotely with no personnel access to fabrication premises.

3. Critical Issues for Disposal, Recycling, and Clearance

3.1 Critical Issues for Disposal

We provided the most critical disposal issues facing the international fusion community:

- Large volume to be disposed of equal or in excess of 8,000 cubic meters
- High disposal cost (for preparation, packaging, transportation, licensing, and disposal)
- Limited capacity of existing LLW (low level waste) repositories
- Need for fusion-specific repositories designed for T-containing activated materials or perform detritiation
- Need for specific activity limits for fusion LLW issued by legal authorities
- Political difficulty of building new repositories
- Tighter environmental controls
- Radwaste burden for future generations
- Immediate or deferred dismantling?

3.2 Critical Issues for Recycling

We identified several critical issues for the international fusion community to examine with dedicated R&D programs in key areas:

- Development of radiation-resistant RH equipment (> 10,000 Sv/h)
- Large (and economical) interim storage facility with adequate heat removal capacity
- Impurity detection and removal mechanisms below current levels.
- Dismantling and separation of different materials from complex components
- Energy demand for recycling process
- Forecasting the cost of recycled materials
- Treatment and complex remote re-fabrication using radioactive materials
- Radiochemical or isotopic separation processes for some materials, if needed
- Efficiency of detritiation system
- Quantity of materials for disposal? Volume? Radwaste level?
- Properties of recycled materials? Any structural role? Reuse as filler?
- Aspects of radioisotope and radiotoxicity build-up by subsequent reuse
- Recycling plant capacity and support ratio
- Acceptability of nuclear and fusion industry to recycled materials
- Management of secondary waste
- Recycling infrastructure

3.3 Critical Issues for Clearance

The clearance-related issues that need further assessment include:

- Discrepancies between the various clearance standards
- Impact of missing radioisotopes on CI prediction
- Need for official fusion-specific clearance limits issued by legal authorities
- Large (and economical) interim storage facility
- Clearance infrastructure
- Availability of clearance market.

4. Conclusions

It is very important to define clearly the parameters governing the management procedures for radioactive materials following the change-out of replaceable components and decommissioning of future fusion facilities, such as K-DEMO toward commercial fusion power plants, in Korea. In that respect, recycling and clearance (i.e. declassification to non-radioactive material) still play the role as the two recommended options for reducing the amount of fusion waste, while disposal as LLW could be an alternative route.

Therefore, the parameters that govern the back-end process of the fusion materials cycle should be clearly defined for the future fusion facilities in Korea. A new fusion-specific approach for the entire back-end cycle of fusion materials is also required. It takes into account the evacuation routes for the waste and materials, the handling difficulties, as well as the critical issues and challenges facing three options: recycling, clearance, and disposal. This approach strategy includes all the procedures necessary to manage radioactive materials from fusion facilities, including the removal of the components from the device to their re-use through the recycling and clearance, or to the disposal of the waste in shallow and deep underground repositories. Such an approach strategy requires further refinement, approval of the national authorities, and more important a dedicated R&D programs to address the identified critical issues. Thus, it allows a complete attention to most of the parameters involved in such a complex management system. Furthermore, it allows investigating and comparing different plant designs and material compositions, based on their environmental effects.

REFERENCES

[1] M. Kwon, Present and Future of Fusion Energy Development, World Green Energy Forum, Gyeong-ju, 18 November, 2010.

[2] K. Kim, K. Im, H. Park, Y. K. Oh, Y. S. Kim, Recent Fusion Activities of Korea toward DEMO, TOFE 2016 (Philadelphia, 2016/08/22-25), 23 August, 2016.

[3] L. A. Poggi, A.Malizia, J. F. Ciparisse, et al., A novel integrated approach for the hazardous radioactive dust source terms estimation in future nuclear fusion power plants, Heliyon 2, pp.e00184-1~16, 2016.

[4] Luigi Di Pace, Laila El-Guebaly, Boris Kolbasov, et al., Chapter 4. Radioactive Waste Management of Fusion Power Plants (in Radioactive Waste, edited by Dr. Rehab Abdel Rahman), ISBN 978-953-51-0551-0 (Published Online), 25 April, 2012.

[5] M. Zucchetti, L. Di Pace, L. El-Guebaly, et al., The back-end of fusion materials cycle: Recycling, Clearance and Disposal, Fusion Science and Technology, Vol. 56, pp.781-788, 2009.

[6] L. El-Guebaly, Evaluation of disposal recycling and clearance scenarios for managing ARIES radwaste after plant decommissioning, 8th IAEA TM on Fusion Power Plant Safety, Vienna, Austria, 10-13 July, 2006.