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1. Introduction

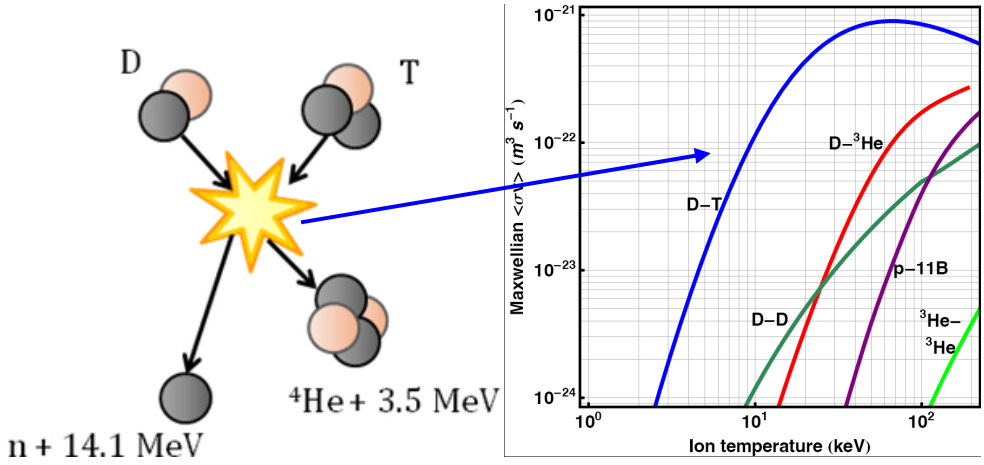
This chapter outlines the attractive environmental features of nuclear fusion, presents an integral scheme to manage fusion activated materials during operation and after decommissioning, compares the volume of fusion and fission waste, covers the recycling, clearance, and disposal concepts and their official radiological limits, and concludes with a section summarizing the newly developed strategy for fusion power plants.

As fusion plays an essential role in the future energy market providing an environmentally attractive source of nuclear energy (Ongena & Van Oost, 2001), it is predictable that there will be tens of fusion power plants commissioned worldwide on an annual basis by the end of the 21st century. The ability of these fusion power plants to handle the radioactive waste stream during operation and after decommissioning suggests re-evaluating the underground disposal option at the outset before considering the environmental impact statement needed for licensing applications. Adopting the 1970s preferred approach of disposing the activated materials in geological repositories after plant decommissioning is becoming difficult to envision because of the limited capacity of existing repositories, difficulty of building new ones, tighter environmental control, and radwaste burden for future generations. Alternatively, fusion scientists are currently promoting a new strategy: avoid underground disposal as much as possible, implement at the maximum extent the recycling of activated materials within the nuclear industry, and/or the clearance and release to commercial markets if materials contain traces of radioactivity. This strategy requires a major rethinking and strong R&D program, hoping all fusion developing countries will be strongly supportive of the proposed recycling and clearance approaches.

Ever since the development of nuclear fusion designs in the early 1970s, most of the related studies and experiments have been devoted to the deuterium (D) and tritium (T) fuel cycle – the easiest way to reach ignition and the preferred cycle (feasible with current technology) for the first generation of fusion power facilities. Nevertheless, the stress on fusion safety has stimulated worldwide research on fuel cycles other than D-T, based on advanced reactions with a much lower neutron level. The focus of this chapter is on fusion power plants fuelled with D-T where the reaction can be expressed as follows:

$$ {}_1^2\mathrm{D} + {}_1^3\mathrm{T} \rightarrow {}_2^4\mathrm{He}\,(3.5\ \mathrm{MeV}) + {}^1\mathrm{n}\,(14.1\ \mathrm{MeV}) \tag{1} $$

Fig. 1(a) shows a schematic of the D-T fusion reaction, while Fig. 1(b) compares the D-T reaction with other potential fusion reactions according to their reaction rate [1].



(a) (b)

Fig. 1. (a) D-T fusion reaction
(from http://en.wikipedia.org/wiki/File:Deuterium-tritium_fusion.svg)
(b) Fusion reaction rates
Courtesy of J. Santarius (University of Wisconsin, USA)

[1] The field of plasma physics deals with phenomena of electromagnetic nature that involve very high temperatures. It is customary to express temperature in electronvolts (eV) or kiloelectronvolts (keV), where 1 eV = 11605 K. That derives from the equivalence energy-temperature expressed by the Boltzmann constant k = 1.3807 × 10^{-23} J·K^{-1}, which corresponds to 8.6175 × 10^{-5} eV/K, as 1 eV = 1.6022 × 10^{-19} J. Hence 1 eV = 1/ 8.6175 × 10^{-5} = 11605 K

As noted, the D-T reaction rate peaks at a lower temperature (about 70 keV, or 800 million Kelvin) with a higher value than other reactions commonly considered for future fusion devices with advanced fuel cycles. Deuterium can be easily extracted from seawater while tritium can be produced through neutron interaction with lithium (a readily available light metal in the earth's crust). Although the products of the D-T fusion reaction (helium and neutrons) are not radioactive, neutrons are absorbed/captured by structural materials and fluids surrounding the plasma. The 14.1-MeV energetic neutrons can transmute some elements of 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[2] 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 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.

2. The attractive environmental features of fusion

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:

- There is no chain nuclear 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, indeed, 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 (Gulden at al., 2000). These attractive features are defined as the "intrinsically safe" characteristics of fusion.

3. Comparison with nuclear fission radioactive waste management

As noticed, 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

[2] A tokamak is a toroidal device that employs magnetic fields to confine the plasma in the shape of a torus.

unit of electricity produced) (El-Guebaly et al., 2008). 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. However, fusion solid waste too 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.

Nuclear weapon proliferation issue of a nuclear device – such as a tokamak-based fusion power plant - needs to be thoroughly addressed. If future fusion power plants can utilize advanced fuel cycles (such as D-^{3}He, or ^{3}He-^{3}He), the fuel cycle will practically be tritium-free. However, using the D-T reaction, two main proliferation aspects have to be addressed:

1. Tritium is a weapon proliferation relevant material. However, the emphasis of the NPT (Non-Proliferation Treaty) is on fissionable substances and technologies that are related to U and Pu bombs, as the Treaty excludes fusionable materials.
2. The presence of intense neutron fluxes may bring their use to irradiate uranium in order to breed plutonium. It would also be possible to breed another fissile material, ^{233}U, through the irradiation of thorium.

Concerning the second point, a possible proliferation-relevant technique could involve an infrequent replacement of a tritium-breeding blanket with modules breeding fissile-fuel. In a fusion power plant it would be much easier to enforce safeguard because one would be looking for fissile or fertile material in an environment where few quantities of it or not at all should be present, in contrast to looking for small discrepancies in the large inventories of a fission power plant. To conclude, the proliferation relevance of a tokamak-based fusion power plant would pose solvable problems from the safeguards viewpoint.

4. Previous results of back end studies for fusion power plants

Ever since the late 1990s, some studies have been carried out at international level to analyse waste management issues related to operation of future commercial power plants, focused on the three scenarios for managing fusion active materials: disposal, recycling, and clearance (i.e. declassification to non-radioactive material). They have been applied to selected U.S. and European fusion power plant studies: SEAFP (Raeder (ed.), 1995), ARIES (El-Guebaly, 2007), and PPCS (Maisonnier et al., 2005) (mostly tokamak-based designs, with the sole exception on ARIES-CS – a compact stellarator[3]). In general, these

[3] A stellarator is a device using only external magnetic coils to confine hot plasma and to sustain a controlled nuclear fusion reaction

studies estimated the amount of potential radioactive waste generated by the fusion power plants of different design concepts and their share amongst the different potential routes of management. These studies made use of classification and categorization approaches and management schemes similar to those of fission waste management. As a general conclusion, it was possible to outline the feasibility of recycling and clearance in extensive way.

These approaches became more technically feasible in recent years with the development of radiation-resistant remote handling (RH) tools and the introduction of the clearance category for slightly radioactive materials by the International Atomic Energy Agency (IAEA, 2004) and other national nuclear agencies (US-NRC, 2003; EC-RP, 2000; 2003; NRB, 1996). A great deal of the decommissioning materials (up to 80%) has a very low activity concentration and can be cleared from regulatory control, especially when a duration period (up to 100 y) of interim storage is anticipated (US-NRC, 2003). The remaining 20% of the active materials could be disposed of as low level waste (LLW) or preferably recycled using a combination of advanced and conventional RH equipment. Most fusion active materials contain tritium that could introduce complications to the recycling process. A detritiation treatment prior to recycling is, then, imperative for fusion components with high tritium content (El-Guebaly et al., 2008).

5. Revision of clearance and recycling concepts and limits

"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 main requirement for the unconditional clearance is that the Clearance Index CI must be below unity. CI is given by the following relationship:

$$\mathrm{CI} = \sum_i \left(A_i \Big/ L_i \right) \tag{2}$$

where A_i is the specific activity of a nuclide after storage, L_i is the clearance limit and i represents the different nuclides contained in the material.

The clearance concepts and limits have been under development since the early 1950s. In 1996, the IAEA prepared an interim report [TECDOC-855 (IAEA, 1996)] on recommended clearance limits for 1650 radionuclides of interest to fission and fusion applications. However, these recommendations were never endorsed by all the IAEA member states. Solely Russia included 297 of the limits recommended by the IAEA interim report into its Radiation Safety Regulations of 1996 (NRB, 1996) as "minimally significant specific activities" (MSSA). These regulations were revised twice in 1999 and 2009 (NRB, 1999, 2009), but the MSSA values were not changed, although the number of the radionuclides and natural radioactive elements covered by these regulations was increased up to 300.

A set of documents on the same topic was published by European Commission (EC) (EC-RP, 2000, 2003) and U.S. Nuclear Regulatory Commission (NRC) NUREG-1640 (US-NRC, 2003). IAEA published in 2004 the revised clearance standards (IAEA, 2004) for 277 radionuclides, claiming to take into account the U.S. NUREG-1640 document and European Commission evaluations. The majority of the new clearance limits recommended by the IAEA were notably lower (down to 4 orders of magnitude for some radionuclides) than the values proposed in 1996 by the TECDOC-855 (IAEA, 1996).

All the standards under consideration take the limit for the annual individual effective dose of 10 μSv as the basis for clearance of solids from regulatory control. Nevertheless, a difference by 1-2 orders of magnitude between the last clearance limits recommended by the IAEA and U.S. NRC is observed for many radionuclides. Some clearance limits differ even by 3-4 orders of magnitude. Discrepancy between values offered by the IAEA and EC is less (not greater than an order of magnitude for most radionuclides).

The recent Russian sanitary regulations (OSPORB, 2010) approved in 2010 have introduced into practice, along with MSSA corresponding to the IAEA recommendations of 1996 (IAEA, 1996), clearance limits coincident with the values recommended by the IAEA in 2004. There are no restrictions for utilization of materials and products (except foodstuffs, drinking water and fodder) if clearance index is below unity. The materials with specific activity between the clearance limit and MSSA can have limited use if the annual individual effective radiation dose at their utilization will not exceed 10 μSv. If the utilization of such materials is impossible or inexpedient, they should be disposed of in non-radioactive industrial landfill type facilities. The document (OSPORB, 2010) also contains clearance limits for some long-lived radionuclides in metals (intermediate between general clearance limits and MSSA).

The clearance limits for selected radionuclides encountered in fusion applications, according to the standards and guidelines cited are shown in Table 1.

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

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)
^{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

Table 1. IAEA, U.S., Russian, and EC clearance limits (in Bq/g) for some fusion-relevant nuclides (partly taken from TABLE I of ref. Zucchetti et al., 2009)

The disagreement between clearance limits in different standards and recommendations is due to the choice of different scenarios to model the effective individual dose rates and different approximations adopted to compute the clearance limits from the effective dose rates. For instance, the U.S. studies incorporated realistic modeling of the current U.S. industrial practices and current data on the living habits in the United States in order to minimize unnecessary conservatism in the dose rate estimates.

Consistency of the clearance standards is certainly desirable, particularly for materials that may end up in the international market. However, given the complexity of the scenarios used to develop the clearance standards with so much efforts having gone into these studies over the past 25 years, it seems unlikely that additional, reasonable effort will be able to reduce dramatically in the short run the differences and explain the technical reasons for the major disagreements.

Recycling includes storage in permanently monitored facilities, segregation of various materials, crushing, melting, refabrication and some other processes (Massaut et al., 2007).

In the European Power Plant Conceptual Study (PPCS) (Maisonnier et al., 2005) a simplified categorization of active material recycling criteria was used. A conclusion of the PPCS analysis was that for all five considered plant models[4] (Models A, B C, D and

[4] All five of the plant models PPCS A to D and AB are based on the tokamak concept. PPCS Model A and Model B are based on limited extrapolations in plasma physics performance compared to the design basis of ITER. In PPCS A and PPCS B, the blankets are based, respectively, on the "water-cooled lithium-lead" and the "helium (He) cooled pebble bed" concepts, studied in the European fusion program. Both concepts are based on the use of a low-activation martensitic steel. PPCS Model C and

AB) , if a full use of the potential to recycle radioactive materials is made, there would be no material requiring permanent burial after a decay storage period from a few decades to 100 y, except for a small amount of secondary waste from reprocessing (Forrest, 2005). In other words, the recycling and clearance strategy would appear to have great potential, since its application could strongly reduce the amount of radioactive waste to be disposed of. The vast majority of radioactive materials (87% in PPCS Model AB and 84% in PPCS Model B) can be cleared or recycled with low handling difficulties after a medium term duration decay period. Only small amounts (a few hundred tons) of plasma-facing tungsten and breeders will require specific remote handling mechanisms. Whether or not such recycling operations would be feasible and economically viable, for all the candidate materials had yet to be determined.

In the U.S. ARIES studies (ARIES Project), the technical feasibility of recycling is based on the dose rate to advanced RH equipment capable of handling at 10 kGy/h or more (El-Guebaly et al, 2008). Such dose rates are present at routine operations in the reprocessing of fission reactor fuel and at the outside surfaces of radioactive goods during their weighing, welding, cleaning, contamination monitoring, and transfer to containers. Corresponding equipment for fusion applications is now under development, since it is needed for removing the replaceable components from the vacuum vessel of the International Thermonuclear Experimental Reactor (ITER), being under construction now in the south of France, and moving them to the hot cell.

A comprehensive survey of remote procedures in the nuclear industry was performed in the framework of an international collaborative Study on the Back End of the Fusion Materials Cycle (SBEFMC) carried out under the auspices of the International Energy Agency (IEA) and documented in ref. (Zucchetti et al., 2009). Some participants of this study found that the remote handling criterion used in the PPCS was unduly conservative. They did not ascertain the upper limit of the dose rate for the RH feasibility, stating that the only upper limit for the RH feasibility seems to be the decay heat density (2 kW/m^3) and active wet cooling needs.

In this study it was assumed that:

- no active cooling is needed (only natural ventilation) when decay heat density is <10 W/m^3;
- dry cooling (e.g. , active ventilation) is required when decay heat density is >10 W/m^3 but <2 kW/m^3;
- active wet cooling (e.g. actively cooled storage pond) is necessary when decay heat density is >2 kW/m^3, coinciding with the definition of high-level radioactive waste.

Model D are based on successively more advanced concepts in plasma configuration and in materials technology. Their technology stems, respectively, from a "dual-coolant" blanket concept (He and lithium-lead coolants with steel structures and silicon carbide (SiC) insulators) and a "self-cooled" blanket concept (lithium-lead coolant with a silicon carbide structure). In PPCS C the divertor is the same concept as for Model B. In the most advanced concept, PPCS D, the divertor is cooled with lithium-lead like the blanket. PPCS Model AB is a combination of the concepts for Model A and B, in detail it is based on He-cooled lithium-lead blanket and He-cooled divertor. The blanket is based on the use of EUROFER as structural material, of Pb-17Li (Li at 90% in 6Li) as breeder, neutron multiplier and tritium carrier, and of helium as coolant.

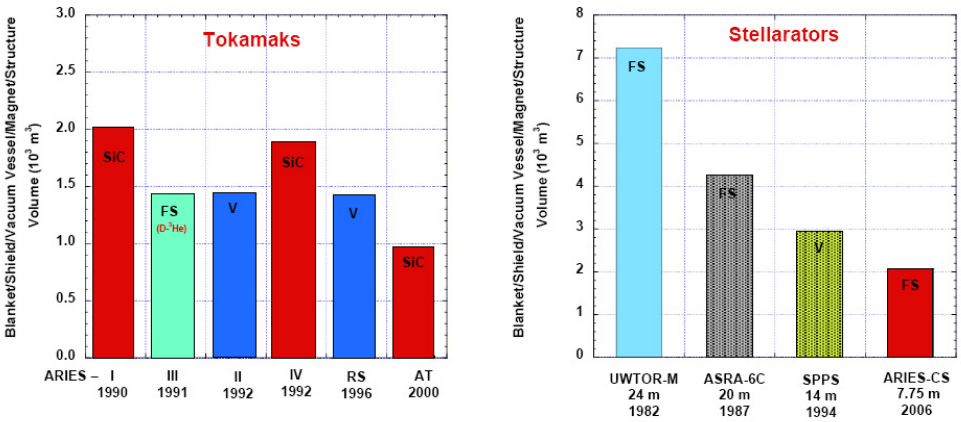
Participants of the SBEFMC expressed doubt that any recycling operations can be performed until the decay heat density decreases to levels not requiring active cooling; hence, interim storage in this case is the only option available. Another conclusion of this study was that for the recycling in foundries, one can for the moment take an activity limit of 1 kBq/g.

The above-considered criteria for feasibility of remote recycling are useful only for the first approach to conceptual design features. They do not show actual recycling expediency, since the processes to be used, type of material and component, economics of fabricating remotely complex forms, and the physical properties of the recycled products also affect the recycling advisability. Furthermore, the acceptability of the recycled materials to nuclear industry has to be considered in parallel with contact dose rate, decay heat and activity content levels.

6. Radioactive material generated during the fusion power plant life cycle

As fusion is expected to play an essential role in supplying clean, environmentally-friendly energy in the second half of the 21st century, the ability of power plant designers to keep up with the persistent demands of controlling the radwaste stream becomes extremely important for fusion as well as for fission. Fusion generates only low level waste (LLW) that requires near-surface, shallow-land burial, if clearance or recycling would not be feasible, as all materials are carefully chosen to minimize the long-lived radioactive products.

Fig. 2 displays the reduction in the fusion power core (FPC) volume over the past 2-3 decades by clever designs that apply more advanced technology and physics operating regimes. The volumes include the actual volumes of power core components (from plasma facing components up to magnets), excluding the bioshield.



SiC = silicon carbide composite structure; V= vanadium alloy structure; FS = ferritic steel structure

Fig. 2. Evolution of fusion power core (FPC) volumes for U.S. tokamaks and stellarators developed over the past 30 years (actual volumes of power core components, no compactness, no replacements).

As noticed, the tokamak volume was halved over 10 y study period, while the stellarator FPC volume dropped by 3-fold over 25 y study period. Most of these designs were developed in the US by the ARIES team (ARIES Project). Other fusion institutions in Europe and Japan delivered several tokamak designs over the past decade.

To put matters into perspective, Fig. 3 compares the volumes of FPCs of ITER (ITER Project), the advanced tokamak ARIES-AT (Najmabadi et al., 2006), the European PPCS Model C (Maisonnier et al., 2005), the Japanese VECTOR tokamak (Nishio et al., 2004), and the compact stellarator ARIES-CS (Najmabadi et al., 2008) to the fission core and vessel of the Economic Simplified Boiling Water Reactor (ESBWR), a GEN-III+ advanced fission reactor.

In recent years, fusion designers have paid more attention to the waste management issues associated with the sizable volume of activated materials discharged from fusion power plants. Specifically, they have striven to minimize the activated materials volume problem, not only by developing advanced designs, but also by reshaping the fusion radwaste management scenario, maximizing the reuse of activated materials through recycling and clearance, avoiding the disposal option.

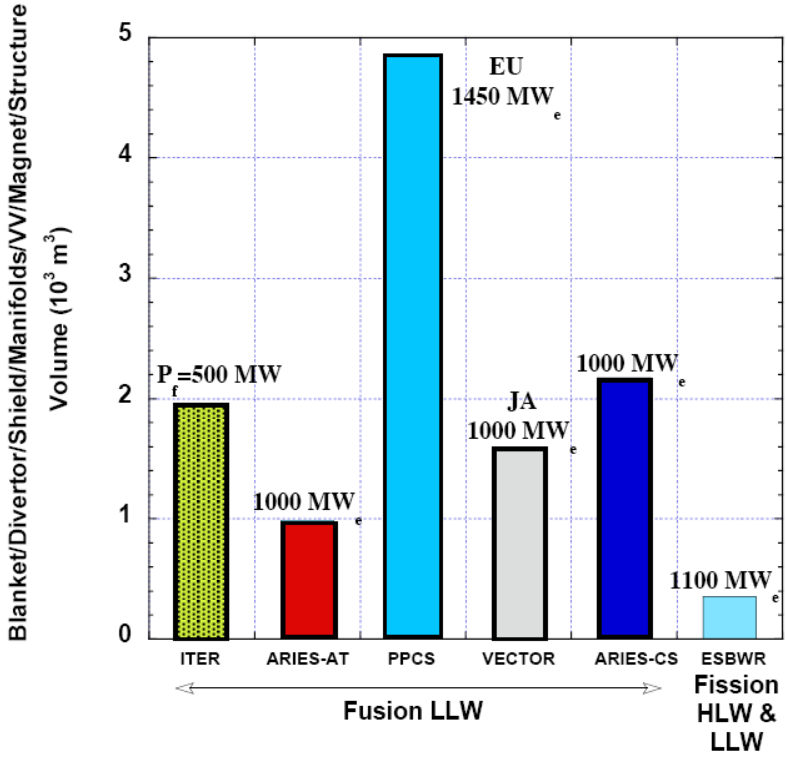


Fig. 3. Volume of fusion power core. Economic Simplified Boiling Water Reactor (ESBWR) fission core and vessel included for comparison (taken from Fig. 1 of ref. El-Guebaly et al., 2008)

Another source of activated materials is the biological shield. As in the fission plant, it surrounds the power core to essentially protect the public and workers against radiation. It is made of 2-3 -m thick steel-reinforced concrete and constructed to withstand natural phenomena, such as earthquakes, tornados, floods, and an airplane crash. Being away from the plasma source, the bioshield is subject to low radiation level in fusion facility and contains very low radioactivity. Since burying such a large volume of slightly activated materials in underground repositories is impractical, the US-NRC and IAEA suggested the clearance concept where such components could temporarily be stored for the radioactivity decay, then released to the commercial market for reuse as shielding blocks for containment buildings of licensed nuclear facilities, concrete rubble base for roads, deep concrete foundations, non-water supply dams for flood control, etc.

Most of the radioactive materials generated during fusion power plant operation are activated solid metallic materials from the main machine components (blanket, divertor, shield, vacuum vessel, and magnets) and concrete from the bioshield. Liquid breeders (such as LiPb, Li, etc.) are normally refurbished for reuse during operation and in future power plants. Even though the dominant radioactive material stream is generated during the decommissioning phase (if one includes the bioshield), a notable amount – as far as radioactive inventory is concerned - is also produced during plant life by routine blanket and divertor replacements. This replacement is necessary due to neutron-induced damage to structural components operating under a 14-MeV neutron flux and due to the need to refurbish the ceramic breeding materials if used in the blanket.

7. Clearance and recycling as viable options for managing activated materials from fusion power plants

Clearance and recycling of structural materials are viable for fusion as the half-life of most radioisotopes contained in such a potential waste can be limited to about 5-10 years, meaning that after a period of about 100 years the radioactivity drops down to one millionth of its initial value. A clever choice of constituents and alloying elements can strongly limit the effects of neutron activation, reducing the concentration of long-lived isotopes (Zucchetti et al., 2007). On the other hand, most fusion active materials contain tritium that could introduce serious complications to the recycling process. Thus a detritiation treatment prior to recycling is imperative for fusion components with high tritium content, as written previously, or in alternative to fulfill the waste acceptance criteria for LLW disposal, if recycling might not be feasible. This excludes the need for deep underground repositories.

7.1 Clearance issues for activated material from fusion power plant

The issue of clearance of fusion radioactive materials is associated to two main aspects:

a. **The definition of clearance levels** which, including radionuclides specific to fusion, should be accepted, as far as possible, at the national and international levels; currently, there is already a certain movement in this direction, as the IAEA guidelines (IAEA, 2004) have been accepted by the Member States (but are not applied as such in the different countries);

b. **The public acceptance of cleared materials**. Even though the fusion community and nuclear industry favor some form of clearance standards, many industries and environmental groups do not allow slightly radioactive solids to enter the commercial market, no matter how low the clearance levels might be. Some European countries and Russia have nevertheless introduced this concept in their regulations.

From the operative point of view the clearance can be divided in:

- Clearance (unconditional, unrestricted release);
- Conditional clearance.

Unconditional clearance means that the material is handled as if it was no longer containing radioactive species above natural or insignificant level. Under this option, the material can be reused without restriction, recycled into a consumer product, or disposed of in any industrial landfill. The compliance with the limits for the clearance levels defined by the national regulatory authorities must be verified.

Conditional clearance means that the material may be recycled or the component reused in a specified application and subject to continuing regulatory control until specific conditions are met to allow unconditional clearance. For example, slightly radioactive metal released under conditional clearance can be melted in licensed melting facilities to produce metal ingots for using them for making railroad tracks or nuclear casks. Another example is related to fabricate concrete rubble that could be used for road construction. In other words, conditional clearance is a restricted release of slightly radioactive material from regulatory control under certain conditions, in particular for its first re-use. What is mostly considered as "conditional release" is the clearance from regulatory control providing certain paths of reuse are guaranteed (and followed up).

In the U.S. there is very limited support for the unconditional clearance, no matter how restrictive the clearance standards might be. No support for the clearance option exists in the steel and concrete industries. In absence of such a clearance market, the conditional clearance represents a viable option – an alternative to disposal. In this conditional clearance category, the slightly radioactive materials are not recycled into a consumer product, but rather released to dedicated nuclear-related facilities under continuing regulatory control or to specific applications where contact for exposure of the general public is minimal. Such slightly contaminated materials have been released since the early 1980s and continue to be released in the U.S. under existing practices on a case-by-case basis using existing NRC guidance and a specific provision contained in the facility's license. While the conditional clearance process has been ongoing in the U.S. for a few decades, a more formal and uniform process would be highly desirable in particular prior to the decommissioning of operating fission reactors. Three facts support this argument: the limited capacity of existing LLW repositories, the political difficulty of building new ones, and the rising cost of geological disposal with tighter environmental control.

From the European perspective (in Europe several countries already apply unconditional clearance for materials coming from decommissioning of fission reactors and nuclear facilities), the conditional clearance is an interesting option, as it can relax the conditions under which materials can be released. Nevertheless, its application is complicated by the fact that

the regulatory control, or at least a control and monitoring of the first re-use of the material has to be performed. That increases the cost of the material management.

Some industries adopted a "zero tolerance" policy, expressing concerns that the presence of radioactive materials in their products could damage their markets, erode public confidence in the safety of their products, and negatively affect their sales. On the other hand, however, some industries would support a restricted use scenario in which cleared materials would be limited to selected purposes (e.g., nuclear facilities or radioactive waste containers) and subject to control by the nuclear regulatory agencies.

There is no uniform or harmonized regulation on clearance even in the European Union. Although the European Commission (EC) has published several guidelines on clearance of materials from regulatory control, see for example Ref. (EC-RP, 2000), each European country can issue its own regulation. Since the 1990s several countries have already issued regulations on clearance and projects have cleared materials in industrial quantities (mostly metals and concrete rubble) for their decommissioning program and related projects, The effective dose limit of 10 μSv/y (1 mrem/y) per practice for cleared solids was adopted in these cases. It is widely accepted by the IAEA, U.S., Russian and EU organizations, it is very small in comparison with the allowable annual dose limit for the public (1 mSv/y). According to the United Nations recommendations, the annual effective radiation dose above background level to members of the public from radiation sources other than medical exposures should not exceed 1 mSv (100 mrem). That means the 10 μSv/y dose limit for cleared solids is 1% of the total allowable excess dose, < 0.5% of the radiation received each year from natural background (2.4-3.6 mSv/y), and significantly less than the amount of radiation that we receive from radioactive ^{40}K located in our own body (0.18 mSv/y), from routine medical procedures (0.55 mSv/y), from living in a brick house (70 μSv/y), or from flying across the U.S. (25 μSv).

7.2 Recycling issues for activated material from fusion power plant

Pursuing recycling of fusion materials has two main justifications: one is environmental, to limit the amount of waste to be disposed of in repositories, and the other is economical and resources-related, to meet the need for a more efficient and effective use of natural resources including expensive materials (Be, V, W, etc.) envisaged for future fusion power plants.

Recycling levels used in previous EU studies (Raeder (ed.), 1995; Maisonnier et al., 2005) were based on a coarse derivation from a summary of waste categories levels (Rocco & Zucchetti, 1998) extended/extrapolated to a recycling classification, based only on contact dose and decay heat rate levels. Although useful for the first approach of conceptual design features, it did not take into account actual recycling feasibility. Indeed, it appeared that dose rate levels were not a severe constraint for recycling and that the activity content and decay heat removal had to be considered in parallel with the type of material and components to be recycled (Massaut et al., 2007, Pampin et al., 2007). At present, the fission spent nuclear fuel is reprocessed in hot cells with complete remote handling systems and active cooling. These facilities can handle materials with dose rates of up to 1500 Gy/h. Moreover, to remove the components from any tokamak, it is foreseen to use remote handling systems. Advanced radiation-hardened remote handling equipment is available in the fission industry and can be applied to fusion materials recycling. The remote handling

needs for recycling are normally less stringent than the ones for removal and handling components in the plant.

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/m^3.
- 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.

One of the main tasks of the latest EU study in this field (Ooms, 2007) was to overcome the previous classification and propose realistic routes and management processes for the materials of the PPCS plants, which would assist the design process of fusion plants and provide guidelines for important R&D needs. Distinction is made between "routes" and "radiological requirements" for handling, cooling, transport, etc. "Routes" define actual, applicable management paths and processes to treat the activated and tritium contaminated materials. Radiological requirements reflect limitations posed by the radioactive nature of the materials. The EU study exemplified these by the categories in Table 2.

Limit	< 10 μSv/h	< 2 mSv/h	< 2000 W/m^3
Handling	HOH	SHOH	RH
Routes	Clearance	Recycle in foundries (1)	Processes to define
Limit	CI < 1	< 1000 Bq/g	< 2000 W/m^3

(1) For metals

Table 2. EU management routes for fusion radioactive materials (taken from Table 1 of ref. Zucchetti et al., 2008)

Management routes were generically categorized in clearance (unconditional and conditional), recycling in foundries (this applies only to metals) and more complex recycling for which the processes still have to be defined and/or developed, providing the decay heat remains below 2000 W/m^3.

Specific levels can be set for these three main categories, but further descriptions are given in the next sections:

- For the unconditional clearance, the Clearance Index (CI) must be lower than unity
- For the conditional clearance, this would depend upon local regulations
- For the recycling in foundries, one can for the moment take an activity limit of 1000 Bq/g
- For the other recycling possibilities, the only limit seems to be the decay heat and active cooling needs limit.

More recently, it has been proposed (Pampin & O'Brien, 2007) to override these classification criteria with a scoring scheme, rating the difficulty of operations on active material. The radiological scoring overcomes the requirements for the contact dose and includes other aspects (e.g.: cooling at the moment, more if necessary in the future). It is based on actual requirements and procedures such as handling (contact dose rates), cooling (decay heat rates), routes, and the radiological levels derived from EU work reviewing industrial experience (Massaut et al., 2007; Ooms & Massaut, 2005). An important element for a credible management strategy is the capability to assess the technical difficulty of recycling or waste conditioning treatments and operations, despite of the route pursued.

It is desirable the capability to assess and compare the radiological characteristics of the irradiated materials, evaluate generic technical hitches posed by their radioactive nature, and ascertain storage decay times, facilitating the processes envisaged for recycling or disposal. For this purpose, a rudimentary scheme has been developed based on two main aspects: handling equipment/procedures, and cooling requirements.

For handling, three main types are foreseen:

a. Unshielded hands-on handling by qualified radiation workers, HOH, when contact dose levels are below 10 μSv/h
b. Shielded hands-on handling by qualified radiation workers, SHOH, when contact dose rates are below 2 mSv/h; equipment such as shielded glove boxes can be conceived under this category
c. Remote handling when contact dose levels are above 2 mSv/h.

As for cooling requirements, the following levels are envisaged:

a. No active cooling needed (only natural ventilation) when decay heat power is < 10 W/m^3
b. Dry cooling (e.g. active ventilation) when decay heat power is > 10 W/m^3 but < 2000 W/m^3
c. Wet cooling (e.g. actively cooled storage pond) when decay heat power is > 2000 W/m^3 – coinciding with the definition of HLW.

Besides the radiation protection aspects given above, the EU recycling study and approach has also addressed the potential routes for the recycled materials. Indeed, even if the material can be handled hands-on or remotely, it makes no sense to go further if no processing routes can be found for this material even without evaluating the economic attractiveness and the potential market. Addressing the routing issue, various scenarios have been analyzed, mostly for metals and materials to be removed from the tokamak core and the immediate surroundings. For material with sufficiently low activity to be unconditionally or conditionally released, usual ways of recycling (often using remelting of the metal components) can be foreseen. Once freely released or conditionally released, the material can follow the existing industrial recycling streams, providing some monitoring of its use for conditional clearance. For material above the release limits, or material for which the measurement of characteristics is difficult, or material for which the treatment would act as a decontamination process (like metal melting for detritiation for instance), recycling within the "nuclear regulated" foundries is currently used at the European and international level. Depending on their license, these foundries can accept plus or minus contaminated or

activated materials. So far, the levels of accepted and licensed activity remain very low (on the order of hundreds of Bq/g). At any rate, melting helps to homogenize the activity concentration, overcoming the problem of activity measurements on piece of equipments with complex geometries. Other recycling scenarios with no melting have to be considered as well. For instance, refractory metal (like tungsten) components, made by powder metallurgy process, whether they are still in good condition, might be re-used within the nuclear industry. Other recycling scenarios can also be developed for exotic materials, like the (liquid or solid) breeder materials. The same approach can also be expected for the superconductor material. But all these approaches need to be investigated and developed in more detail.

It is important to develop advanced rad-hard RH equipment that can handle components presenting dose rates up to 10000 Gy/h (10000 Sv/h) or more. This equipment is already needed for removing the replaceable components from the vacuum vessel of a tokamak and moving them to the hot cell. The proposed high dose rates are not far from the present technology; e.g. in ITER design some RH equipment will have to withstand 1500 Gy/h (and even 15000 Gy/h) with a total dose of 5-10 MGy. Such a high dose rate is reached in fusion power plants within a few years after blanket/divertor replacement and arises mostly from radionuclides originating from the main materials and alloying elements, not from impurities.

The question of reprocessing of radioactive (non-clearable) materials in dedicated facilities in order to separate noxious radionuclides is another challenge. The result of this operation is a small quantity of concentrated radioactive waste, plus a processed material that may be either "clearable" or "non-clearable, to be recycled within nuclear industry", if the separation process is viable and effective.

The development of methods to reprocess the activated alloy to extract radiotoxic nuclides is a long and complicated task, but the possibility to eliminate the need for numerous repositories, so minimizing the burden for future generations, apart from the small volumes required to store the secondary waste, is very attractive and worth pursuing.

Examining several fusion designs revealed that the internal components (blanket, divertor, shield, and vacuum vessel) are not clearable even after an extended cooling period of 100 y (El-Guebaly et al., 2008, Zucchetti et al., 2009). Controlling the Nb and Mo impurities in the low-activation steel stucture may help clear the outer vacuum vessel components. Fortunately, the bioshield (that represents the largest single component of the decommissioned radwaste) along with some magnet constituents qualifies for clearance, especially when a long period (up to 100 y) of interim storage is anticipated. This represents a great deal of the decommissioning materials (70-80%). The remaining 20-30% of the active materials could be recycled using a combination of advanced and conventional remote handling equipment (El-Guebaly et al., 2008; Zucchetti et al., 2009).

8. Radioactive waste classification

The radioactive waste classification differs appreciably in different countries. Below it is given a brief summary of different waste classifications adopted in some countries, but starting with the IAEA recent classification, as it is an international guideline.

8.1 IAEA classification

The IAEA developed and published in 2009 a safety guide containing general scheme for classifying radioactive waste that identifies the conceptual boundaries between different classes of waste and provides guidance on their definition on the basis of long term safety considerations (IAEA, 2009). Six classes of radioactive waste are considered as the basis for the classification scheme in this safety guide:

1. Exempt waste (EW) that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes as described in Ref. (IAEA, 2004). In reality, however, once such waste has been cleared from regulatory control, it is not considered as radioactive waste any more.
2. Very short-lived waste (VSLW) that can be stored for decay over period of up to a few years and consequently cleared from regulatory control. In general, VSLW contains radionuclides with half-lives of the order of 100 days or less.
3. Very low level waste (VLLW) that does not need a high level of containment and isolation and is suitable for disposal in near surface landfill type facilities with limited regulatory control (e.g. soil and rubble with low levels of activity concentrations). In terms of radioactive waste safety, a radionuclide with a half-life of less than about 30 years is considered to be short-lived. Concentrations of longer lived radionuclides in VLLW are generally very limited.
4. Low level waste (LLW) that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities.
5. Intermediate level waste (ILW) that may contain long-lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional control can be relied upon (in some countries up to around 300 years). Therefore, ILW requires disposal at depths of the order of tens meters to a few hundred meters. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.
6. High level waste (HLW) with levels of activity concentrations high enough to generate significant quantities of radioactive decay heat or with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred meters or more below surface is generally recognized option for disposal of HLW.

Contact radiation dose rate is not used to distinguish waste classes in the new IAEA classification scheme. The guide assumes that detailed quantitative boundaries taking into account broad range of parameters may be developed in accordance with national programs and requirements.

8.2 U.S. classification

The Nuclear Regulatory Commission has established classifications for waste generated by nuclear power industries, university research laboratories, manufacturing and food irradiation facilities, and hospitals. Low and high level wastes are classified according to the activity concentration and types of radioisotopes. For each level, there is a specific disposal

requirement according to the US-NRC 10CFR61 document (US-NRC, 1982) so that the waste is disposed properly and safely. At present, there is no low and intermediate level waste (LILW) category in the U.S.

For nuclear power plants, the NRC classification is based largely on radionuclides that are important to fission facilities. In a nuclear fusion system, the isotopes are different because of the different materials being considered and the different decay products that are generated. In the early 1990s, analyses (Fetter et al, 1990) were performed to determine the Class C specific activity limits for all long-lived radionuclides of interest to fusion using a methodology similar to that used in 10 CFR 61. Although Fetter's calculations carry no regulatory acceptance, they are useful because they include fusion-specific isotopes. The ARIES approach requires all components to meet both NRC and Fetter's limits for LLW until the NRC develops official guidelines for fusion waste.

8.3 Russian classification

According to the Russian Basic Sanitary Regulations Ensuring Radiation Safety (OSPORB, 2010), radioactive waste includes matters, materials, mixtures and products that are not subject to further utilization and in which $\Sigma_i(A_i/\mathrm{MSSA}_i) > 1$, where A_i is specific activity of a technogenic radionuclide i and MSSA is minimally significant specific activities, as defined in previous paragraph 5. The waste with unknown radionuclide composition is considered as radioactive if the total specific activity of technogenic radionuclides in them exceeds 100 Bq/g for beta emitters, 10 Bq/g for alpha emitters, and 1.0 Bq/g for transuranium radioactive nuclides. There are three categories of radioactive waste: low level waste (LLW), intermediate level waste (ILW) and high level waste (HLW) depending on their specific activity as given in Table 3. In the case when different radioactive nuclides relate to different categories, the waste relates to the highest category.

Category	Tritium	β Emitters	α Emitters except Transuranium Nuclides	Transuranium Nuclides
LLW	10^6-10^7	$<10^3$	<100	<10
ILW	10^7-10^{11}	10^3-10^7	10^2-10^6	10-10^5
HLW	$>10^{11}$	$>10^7$	$>10^6$	$>10^5$

Table 3. Specific activity (Bq/g) of different categories of liquid and solid waste (OSPORB, 2010)

8.4 Italian classification

Italian regulations deal with national laws on radioactive materials and with Technical Guides from the Italian nuclear regulatory committee ("Guida Tecnica n. 26" – Technical Guide No. 26 - and others). The waste is classified into three categories (the first category = low level waste, the second category = intermediate level waste, the third category = high level waste) on the basis of the radioisotope characteristics (half-life and radiotoxicity) and concentration limits, and considering the possible options for final disposal. Without going into details, the boundary between the second and third category, for activated metallic

materials, is a concentration of 370 Bq/g for long-lived nuclides ($t_{1/2}$ > 100 y), 37000 Bq/g for medium-lived nuclides (5 y < $t_{1/2}$ < 100 y) and 37x10^6 Bq/g for short-lived nuclides. This limit deals with waste that has been conditioned and treated for disposal.

A regulation concerning the *"allontanamento"* (Italian word for "clearance") of solid radioactive spent materials has been issued in Italy recently. This regulation is necessary for the ongoing decommissioning activities of four Italian fission reactors. Concentration limits are issued for each relevant nuclide, however, they may be partially summarized – for our purposes – as follows: a non-alpha-emitter metallic material may be cleared, if its specific activity is less than 1 Bq/g (including tritium). For materials other than metallic and concrete, the limit is 0.1 Bq/g. For concrete, the limit is almost halfway, depending on the type of nuclides. These limits are applicable if only one nuclide is present in the waste, otherwise the criterion $\Sigma_i(A_i/L_i) < 1$, where A_i is the mass (Bq/g) or superficial (Bq/cm^2) activity concentration of the nuclide i, and L_i is the related activity concentration limit, must be respected. Both mass and superficial specific activity limits must be met. Recycling in Italy is permitted for cleared materials only.

8.5 French classifcation

The waste classification in France (LOI 739, 2006; Décret 357, 2008) is managed by the French Agency for the Management of Radioactive Waste (ANDRA). There are four different types of waste:

- TFA (Très Faible Activité) or very low level waste;
- FMAVC (Faible et Moyenne Activité, Vie Courte) corresponding to low and short-lived (< 31 years) intermediate level waste;
- MAVL (Moyenne Activité à Vie Longue) corresponding to long-lived (> 31 years) intermediate level waste;
- HAVL (Haute Activité à Vie Longue) corresponding to long-lived (> 31 years) high level waste, with thermal effect.

Very low level activity (TFA) waste criteria

It should be mentioned that the French regulation does not recognize the clearance concept. Therefore, it was decided to create a category for VLLW and an evacuation route for this category of wastes. The Centre de Stockage TFA (CSTFA) at Morvilliers is the final disposal for Very Low Level Waste (TFA) since summer 2004. There are also specific tritium thresholds to be respected such as: tritium specific activity lower than 1000 Bq/g and tritium degassing rate lower than 200 Bq/m^3/day and 10 Bq/m^3/day, for HTO and HT, respectively. The acceptance of a batch of waste depends on an index considering the nuclide specific activity and the nuclides class (depending on the nuclide radiotoxicity). This radiological acceptance index in storage ("Indice Radiologique d'Acceptabilité de Stockage" (IRAS)) is defined as:

$$\sum \frac{A_i}{10^{C_i}} \tag{3}$$

Where A_i is the specific activity of the nuclide (in Bq/g) and C_i is the nuclide class (0, 1, 2, 3), depending on the nuclide radiotoxicity.

A waste batch can be accepted if it complies simultaneously with the 2 following conditions: IRAS index < 1 and IRAS index of the different packages within the batch lower than 10.

Low Level Activity (FMA) Waste Criteria

FMA waste is disposed of in surface repositories. The Centre de Stockage de l'Aube (CSA) is the current final disposal for this type of waste. For acceptance in the CSA the activity of selected nuclides has to be evaluated and declared if their specific activities are higher than the declaration threshold. Waste containing nuclides above the embedding threshold needs to be fixed with a matrix having containment properties. Otherwise, a blocking matrix can be used to allow waste immobilization.

The maximum tritium degassing rate for packages stored in CSA is 2 Bq/g/day due to occupational radiation exposure.

Intermediate Level Activity (MAVL) Waste Criteria

The waste, which cannot be stored as FMA or TFA, has been considered as MAVL waste since no acceptance criteria has yet been defined, except a decay heat per package limited to 13 W. Studies are currently performed, in France, to define the best strategy for MAVL management. Geological disposal is one of the possibilities studied. A recent law has been voted on radioactive waste: "Programme relatif à la gestion durable des matières et des déchets radioactifs" (program related to durable management of materials and radioactive waste) and describes the objective of such storage site.

High Level Activity (HAVL) Waste Criteria

High level waste is stored temporarily in tanks before being calcined in the form of a powder and then incorporated into a molten glass.

As prescribed by article 3 of the June 28th 2006 Planning Act (LOI-739, 2006), ANDRA is developing, as in the case of MAVL, a 500-metre deep disposal concept for HAVL. The outcome of this study is the commissioning of a repository by 2025 in Meuse/Haute-Marne, subject to government approval and after a public debate. Pending the commissioning of the deep repository, HLW is stored at production sites, La Hague (AREVA), Marcoule (CEA) and Cadarache (CEA).

9. Integrated active fusion material management strategy

Given all the above considerations, 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/reuse, disposal) as summarized in Table 4. Recycling/reuse "routes" define actual, applicable management paths and processes to treat the activated (and tritium contaminated) materials. Radiological requirements reflect limitations posed by the radioactive nature of the materials. The rationale of the proposal is matching handling categories with feasible recycling routes for fusion radioactive materials.

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)

Table 4. An integrated approach to fusion radioactive materials management (taken from Table IX of ref. Zucchetti et al., 2009)

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. 4. At any rate, by examining the various management step of fusion material at the back end, one might predict the following steps:

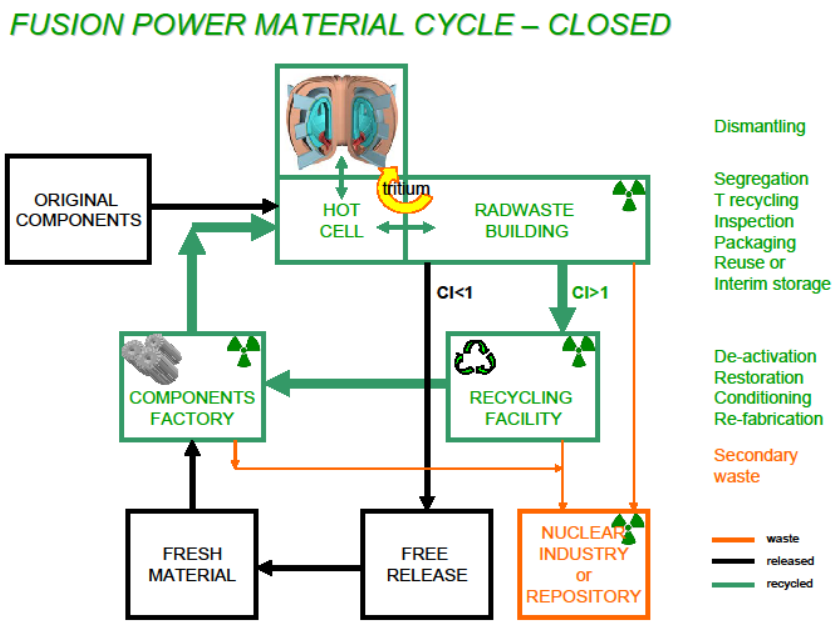


Fig. 4. Diagram of recycling and clearance processes (taken from Fig. 2 of ref. Massaut et al., 2007)

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.

10. Conclusions

In summary, the need for a study on fusion radioactive waste arose to examine the "back-end of the fusion materials cycle" as an important stage in maximizing the environmental benefits of fusion as an energy provider.

An integrated approach to the management procedures for active materials following the change-out of replaceable components and decommissioning of fusion facilities has been proposed. The attractive environmental features of fusion have been put into evidence, and the question of proliferation relevance of fusion power plants has been briefly analyzed.

The reference is towards previous European and U.S. assessments of the back-end for fusion power plant studies, stressing this important result: most materials can be cleared or recycled, and/or disposed of as low level waste. More significantly, a new radioactive materials management strategy has been proposed for the clearance, recycling, and disposal approaches.

Concerning the clearance:

- Two alternatives are feasible: unconditional clearance, conditional clearance. Conditional clearance seems to be a viable option in the absence of a market receiving unconditional clearance materials.
- The problem of public acceptance of clearance and thus recycled material has been analyzed: how to improve the confidence of actual market towards cleared and then recycled materials ?
- Experience gained from the clearance of radioactive waste in Germany, Sweden, Spain, and Belgium might be considered useful.
- A brief review of the IAEA, U.S., Russian, and EU clearance guidelines, highlighting the similarities and differences has been performed.

Concerning the recycling approach:

- A brief review of previous approaches to recycling of fusion active materials has been presented.
- Lessons learnt from the fission experience related to hot cell performances and operations with highly radioactive materials must be used.
- For certain materials, re-use is a solution to reduce active materials inventory and the cost of producing new materials.
- The melting process tends to decontaminate the melt, segregating the slag, dust, and fumes. After slag removal and composition adjustments, the metal alloys could have properties very similar to, or equal to, those of fresh alloys.
- Economic viability of recycling has to be considered in deciding its put in practice.
- Contact dose rate, decay heat rate, radioactivity concentration are important radioactive quantities to be reduced.
- Hands-on, simple shielded and remote handling approaches for handling activated materials, have been discussed.
- Recycling outside the nuclear industry, recycling within nuclear-specific foundries, other recycling scenarios without melting as viable approaches, to answer the routing question, have been considered as viable options.
- The question of reprocessing of radioactive (non-clearable) materials in special facilities in order to separate noxious radionuclides has been mentioned. It is probably the key aspect to be developed in the near future.

Given all the above considerations, an integrated activated materials management strategy has been proposed: it divides the fusion activated materials according to the Regulatory Route (unconditional clearance, conditional clearance, no-clearance) and the Management Route (recycling/reuse, disposal) with a matrix linking the two routes. Furthermore, an approach to the technical difficulty of recycling or waste conditioning, adopting a scoring system, depending on the handling and cooling requirements of the components and materials, completed the approach.

In conclusion, the parameters that govern the back-end of the fusion materials cycle were clearly defined. A new fusion-specific approach for the entire back-end cycle of fusion materials is required. The proposal is for a comprehensive one: it takes into account the evacuation routes for the waste and materials, the handling difficulties, as well as the critical issues and challenges facing all three options: recycling, clearance, and disposal. This approach includes all the procedures necessary to manage radioactive materials from fusion facilities, from the removal of the components from the device to their reuse through recycling/clearance, or to the disposal of the waste in shallow underground repositories. Such an approach requires further refinement, approval of the national authorities, and more important a dedicated R&D program to address the identified critical issues. Nevertheless, it allows a complete attention to most of the parameters involved in such a complex management system. Also, it allows investigating and comparing different plant designs and material compositions, in view of their environmental impact.

As a matter of fact, it is important to clearly define the parameters governing the management procedures for radioactive materials following the change-out of replaceable components and decommissioning of fusion facilities. 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.

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