THE BACK END OF THE FUSION MATERIALS CYCLE

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Within the framework of the International Energy Agency, an international collaborative study on fusion radioactive waste has been initiated to examine the back end of the materials cycle as an important stage in maximizing the environmental benefits of fusion as an energy provider.

The study addresses the management procedures for radioactive materials following the changeout of replaceable components and decommissioning of fusion facilities. We define this as "the back end" of the fusion materials cycle. It includes all the procedures necessary to manage spent radioactive materials from fusion facilities, from the removal of the components from the device to the reuse of these components through recycling/clearance, or to the disposal of the waste in geological repositories.

Fusion devices have certain characteristics that make them environmentally friendly devices; minimization of long-lived waste that could be a burden for future generations is one of these characteristics.

Recycling and clearance procedures and regulations have been recently revised, and the effects of these revisions on back-end fusion materials are examined in the paper. Finally, an integrated approach to the management of back-end fusion materials is proposed, and its application to three fusion reactor designs is discussed.

KEYWORDS: *fusion power plants, radioactive waste management, recycling*

Note: Some figures in this paper are in color only in the electronic version.

I. INTRODUCTION

Within the framework of the International Energy Agency Co-operative Program on the Environmental, Safety and Economic Aspects of Fusion Power, an international collaborative study on radioactive waste has been initiated to examine the back end of the materials cycle as an important stage in maximizing the environmental benefits of fusion as an energy provider.

The deuterium-tritium (D-T) fuel cycle offers an easy way to reach ignition and therefore is currently considered to be a preferred energy source for first-generation fusion facilities.[a] Fusion materials become radioactive after service in fusion devices because of two main reasons: neutron-induced radioactivity and contamination with tritium. This study addresses the management procedures for radioactive materials following the changeout of replaceable components and decommissioning of fusion facilities. We define this—using the same terminology as for fission power plants—as "the back end" of the fusion materials cycle. It includes all the procedures necessary to manage spent radioactive materials from

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[a]Some fusion specialists hope to switch in the future from D-T to a more advanced (more environmentally friendly, neutron-depleted) fuel cycle.

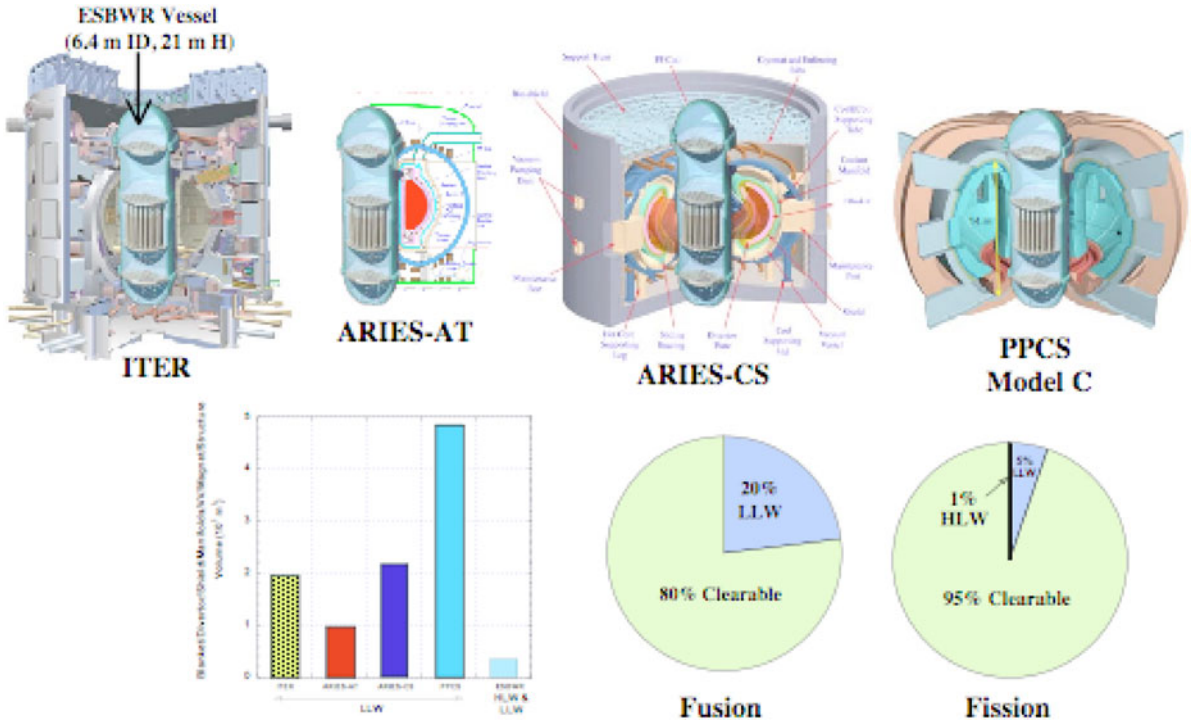

Fig. 1. Comparison between selected fusion devices and vessel of advanced fission reactor. Reading labels is not important, and the figure is just to show a schematic scale.

fusion facilities, from the removal of the components from the device to the reuse of these components through recycling/clearance,[1] or to the disposal of the waste in geological repositories.

We will not focus much on the comparison between fusion waste and fission spent fuel as it has been done in many previous studies. Fusion waste can be best compared with fission decommissioning waste: They both stem from neutron activation of inner structures of the reactor and/or contamination processes. Excluding the fission spent fuel and long-lived radionuclides, differences between fission and fusion are not significant, since the material type (structural materials, mainly steels) and its radiotoxicity are almost the same. However, fusion produces much more activated material than fission. To put matters into perspective, we compared ITER, the advanced ARIES tokamak (ARIES-AT), a compact stellarator (ARIES-CS), and the European Power Plant Conceptual Study (PPCS Model C) to the Economic Simplified Boiling Water Reactor (ESBWR)—a Gen-III$^+$ advanced fission reactor.[2] Figure 1 displays the notable difference in sizes and a typical classification into high-level waste (HLW), low-level waste (LLW), and clearable materials that contain traces of radioactivity. In fact, this activated material volume problem is not new and has been recognized by the fusion program since the early 1970s. The main advantage of fusion power is that it generates no long-lived radionuclides and the overall radiotoxicity of the radioactive waste is much lower than that of fission spent fuel.

I.A. The Attractive Environmental Features of Fusion

Fusion devices, although being nuclear installations,[b] have certain characteristics that make them environmentally friendly devices. First, 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. In other words, the radioactive inventory in any fusion device can be effectively reduced by a clever selection of the materials' alloying elements and impurities. In fusion reactors there is not a chain reaction as in fission plants. Indeed, there is a very small amount of fuel in the reactor only to maintain the D-T reaction for a few seconds. Moreover, a fusion reactor does not contain plutonium, other transuranics, uranium, or strongly radiotoxic fission products like ^{131}I and ^{137}Cs. Also, its power density is much lower than that of fission reactors, and it can be limited by design in such a way as to moderate the consequences of

[b]This is not necessarily true from the legal viewpoint. For instance, according to Russian Law on Atomic Energy, fusion power facilities are not nuclear installations, but radiation sources.

even the severest conceivable accidents. 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 catastrophic accidents and minimal environmental impact. We define these attractive features as the "intrinsically safe" characteristics of fusion.

I.B. The Question of Nuclear Weapon Proliferation Relevance of Fusion Power Plants

Nuclear weapon proliferation relevance 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.[3] However, using the D-T reaction, two main proliferation aspects have to be addressed:

1. Tritium is a proliferation-relevant material. However, the focus of the Non-Proliferation Treaty (NPT) is on substances and technologies that are related to U and Pu bombs. Fusion-related materials are out of the scope of the NPT.

2. The presence of intense neutron fluxes may bring their use to irradiate uranium in order to breed plutonium through a fertilization reaction. It would also be possible to breed another fissile material, ^{233}U, through the irradiation of thorium.

Concerning the first point, however, safeguards against the diversion of tritium are quite easy to implement in the case of a nuclear fusion device. Tritium will be present in a sizable amount (a few kilograms) only in a few systems, for instance, the tritium purification, storage, and injection systems. This may raise proliferation concerns. However, there is a continuous and extremely detailed monitoring system for tritium in particular in every fusion plant. Recording of such measurements can be easily kept under control by the inspection authority. 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 safeguards because one would be looking for fissile or fertile material in an environment where few quantities or none 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.

I.C. Previous Results of Back End for Fusion Power Plant Studies

Ever since the late 1990s, the three scenarios for managing fusion active materials (disposal, recycling, and clearance) have been applied to selected U.S. and European fusion power plant studies[2,4–9]: ARIES (Ref. 10) and PPCS (Ref. 11). The recycling and clearance 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[12] (IAEA) and other national nuclear agencies.[13–16] Most radioactive materials generated during fusion power plant operation are activated solid metallic materials from the main machine components and concrete from the biological shield, assuming liquid tritium breeders (such as LiPb, Li, and Flibe) are refurbished for reuse by future fusion devices. The dominant radioactive material mass stream is generated during the decommissioning stage (if we include the bioshield), but a significant amount—as far as radioactive inventory is concerned—is also produced during routine blanket and divertor replacements. 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 long period (up to 100 yr) of interim storage is anticipated. The remaining 20% of the active materials could be disposed of as LLW or preferably recycled using a combination of advanced and conventional RH equipment. Most fusion active materials contain tritium that could introduce serious complications to the recycling process. A detritiation treatment prior to recycling is imperative for fusion components with high tritium content. It is in most cases compulsory to fulfill the requirements for LLW disposal—an alternate approach to recycling/clearance.

I.D. Revision of Clearance and Recycling Concepts and Limits

Clearance criteria and/or regulations have been recently issued by national and international institutions like the IAEA (Ref. 12), the U.S. Nuclear Regulatory Commission[13] (NRC), the European Commission[14,15] (EC), and the Russian National Commission on Radiological Protection[16] (RNCRP). The NRC has not yet issued an official policy on the unconditional release of specific materials. Herein, the proposed annual doses for 115 radioisotopes, including six of natural origin, reported in the NUREG-1640 document,[13] will be referred to as the proposed U.S. limits. The clearance levels proposed in 1996 by IAEA (Ref. 17) were never endorsed by all IAEA member states. Intensive scientific and political activity was undertaken during the years between 1996 and 2004 to define a set of clearance levels that could be accepted by the IAEA member states and thus publish them in an IAEA Safety Series document. This resulted in the 2004 report[12] that defines a set of clearance levels for 277 radionuclides. On the other hand, the recycling levels, as commonly used in most European fusion studies, were based on a rough derivation from a summary of

waste category levels that were extended and extrapolated to some sort of a recycling classification. This classification, based only on contact dose rate levels, which are useful for a first approach to conceptual design features, did not consider actual recycling possibilities. Indeed, it appeared that the dose rate level was not the only constraint for recycling and that the processes, activity content, and decay heat removal had to be considered in parallel with the type of material and components to be recycled.[6,18] The first overall study in this direction has been carried out in Europe.[19] A comprehensive list of critical issues has been compiled for the three approaches: disposal, recycling, and clearance.[2] A dedicated research and development (R&D) program should address these critical issues in order to optimize the waste management scheme further.

These revisions and their consequences will be examined in this paper. A new radioactive materials management strategy, based on the studies mentioned above, will be proposed.

II. CLEARANCE

II.A. General Definition

"Clearance" (unconditional, unrestricted release) means that the material is handled as if it is no longer radioactive. Under this option, solid material can be reused without restriction, recycled into a consumer product, or disposed of in any industrial landfill. The compliance with the limits 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 making railroad tracks. Another example is related to building concrete rubble that could be used for road construction or as an additive for manufacturing new concrete. In other words, conditional clearance is a restricted release of slightly radioactive material from regulatory control under certain conditions, in particular for its first reuse. What is mostly considered as "conditional release" is the clearance from regulatory control providing certain paths of reuse are guaranteed (and followed up). Germany has this kind of regulation (it is almost the only country). But, this is rather difficult to implement and requires a very extensive follow-up of the materials, which could dramatically increase the price of recycling.

"No release" from regulatory control means that the material, once it leaves the originating facility, must be sent to a nuclear disposal facility or interim storage facility, or remain under regulatory control. It can be recycled and reused in the same or another nuclear facility. And, this can be with or without subsequent treatment, e.g., decontamination, separation of materials, etc.

An example of unconditional release occurs at Studsvik Radwaste (Sweden). Studsvik has a regulated melting oven. The main intent is to release slightly activated materials. Sweden has developed the necessary regulation and released tons of metals during more than 10 yr. But, if the molten metal has too much activity to be released directly, Studsvik offers an interim storage for the ingots of up to 20 yr (now reduced to 10 yr), after which the metal must be released (i.e., the calculations must prove that a decay of 20 yr is sufficient to reach the release values). Otherwise, the molten metal is sent back to the owner as radioactive waste, with the secondary waste of the process refractory bricks, filters, and slag. This kind of delayed release is not considered as "conditional release" by the industry and regulators but as a sort of delayed release.

II.B. Is Conditional Clearance a Viable Option?

In the United States there is very limited support for the unconditional clearance that allows slightly radioactive solid materials to enter commerce for unrestricted recycling and reuse, no matter how restrictive the clearance standards might be. No support for the clearance option exists in the steel and concrete industries. In the 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. Examples include shielding blocks for containment buildings of licensed nuclear facilities, concrete rubble base for roads, deep concrete foundations, nonwater supply dams for flood control, etc. Such slightly contaminated materials have been released since the early 1980s and continue to be released in the United States 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 United States 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, 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 the control and monitoring of the

first reuse of the material that has to be performed, increases the cost of the material management. The German authorities have included a sort of conditional release in their regulation.

II.C. Public Acceptance of Clearance and Recycled Materials

Even though the fusion community and nuclear industry favor some form of clearance standards, many industries and environmental groups do not support clearance that unconditionally allows slightly radioactive solids to enter the commercial market, no matter how restrictive the clearance standards might be. Many industries adopted a "zero tolerance" policy, expressing serious 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 because of public fear. 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 a high degree of control by the nuclear regulatory agencies.

On the other hand, the environmental groups tend to share the following perceptions:

1. The nuclear industry's true intent is economic, that is, to enable recycling of large amounts of contaminated materials, which will benefit no one but the nuclear industry.

2. Multiple effects are possible from a release that is recycled into numerous sources for public use, and these effects have not been well characterized yet.

3. Releases of radioactive materials cannot be tracked or controlled in a way to protect the public health and safety.

4. The concept of buildings made with radioactive materials exposing people to radiation greater than background exposure is contrary to the charter of the nuclear regulatory agencies.

There is no uniform or harmonized regulation on clearance in the European Union[2] (EU). Although the EC has published several guidelines on clearance of materials from regulatory control, each European country can issue its own regulation (see, for example, Ref. 20). Since the 1990s and following the ongoing decommissioning program and projects, several countries have already issued regulations on clearance, and projects have cleared materials in industrial quantities (mostly metals and concrete rubble):

1. Sweden was among the first to apply clearance on metals and installed a "nuclear" furnace in its research center Studsvik. The Swedish regulation allows not only clearing of materials but also treating (smelting) metals from abroad and clearing them, providing the material can be released within 10 yr; the decay storage and subsequent release are carried out at Studsvik.

2. Germany has a rather complex and complete set of regulations for conditional and unconditional release. With several large decommissioning projects (like the Greifswald EWN, Stade, Gunremmingen A, Kahl, etc.), the amount of cleared material already amounts to the thousands of tons.

3. Spain started industrial clearance of metallic material, with its Vandellos decommissioning project. It must also be noted that there is a convention signed between the Spanish government and the steel industry for enhancing the acceptance of cleared materials by the steel recyclers.

4. Belgium has also introduced clearance levels into its regulation and has cleared thousands of tons of steel and concrete from the BR3 and Eurochemic projects.

5. Italy also applies clearance on a case-by-case basis.

The 10 μSv/yr (1 mrem/yr) dose standard for cleared solids per practice that is widely accepted by the IAEA, U.S., Russian, and EU organizations is very small in comparison with the allowable annual dose limit for the public (1 mSv/yr). According to the United Nations recommendations, the radiation dose above background level to members of the public from radiation sources other than medical exposures should not exceed 1 mSv/yr (100 mrem/yr). This means the 10 μSv/yr dose limit for cleared solids represents 1% of the total allowable excess dose, $<$0.5% of the radiation received each year from natural background sources (2.4 to 3.6 mSv/yr), and significantly less than the amount of radiation that we receive from our own body from radioactive ^{40}K (0.18 mSv/yr), from routine medical procedures (0.55 mSv/yr), for living in a brick house (70 μSv/yr), or for flying across the country (25 μSv). Clearly, the unrestricted release of materials with slight levels of radioactivity can be accomplished with negligible or no risk to the public health and safety.

At this writing, environmental and consumer groups in the United States remain concerned with radiation effects on public health despite the economic benefits of clearance. However, professional societies (such as the American Nuclear Society) associated with the nuclear industry support clearance. As clearance is highly desirable for both fission and fusion facilities in order to free the repositories for more radioactive materials, we urge the national and international organizations to continue their efforts to convince industrial as well as environmental groups that clearance of slightly radioactive solids can be conducted safely with no risk to the public health. We support the notion that absolutely prohibiting the release of all solid materials that contain a small amount of radioactivity is unreasonable because zero

radioactivity does not exist in nature—every substance has a minute amount of radioactivity.

II.D. Review of IAEA, U.S., Russian, and EU Clearance Guidelines

The clearance guidelines and standards developed since the early 1950s are documented in a set of reports published by the NRC in the United States[8,13]; the IAEA in Vienna, Austria[12]; the EC Radiation Protection (RP) 122[c] (Refs. 14 and 21); and the Russian Government.[16,22] The most recent attempt by the NRC in 2003 declared that materials with low concentrations of radioactivity could be deregulated. The NUREG-1640 document[13] contains estimates of the total effective dose equivalent (EDE) [from which the clearance index (CI) can be derived] for 115 radioisotopes for steel, copper, aluminum, and concrete-based wastes. The annual doses reported in the NUREG-1640 document[13] will be referred to as the proposed U.S. limits because the NRC has no official policy yet on the unconditional release of slightly activated materials.

In 1996, the IAEA prepared an interim report[17] on recommended clearance limits for solid materials for 1650 radionuclides of interest to fission and fusion applications. In 2004 the IAEA published revised clearance standards[12] for more than 277 radionuclides, claiming to take into account the U.S. NUREG-1640 document and other European evaluations. The 257 radionuclides have an artificial origin, except T, ^{7}Be, and ^{14}C, which can be either artificially produced or naturally produced by cosmic rays. The allowable concentration for the remaining 20 radionuclides of natural origin (such as ^{50}V, ^{113}Cd, ^{180}Ta, etc.) is 1 Bq/g, except for ^{40}K (10 Bq/g) (Ref. 12).

The Radiation Safety Regulations (NRB-96) (Ref. 23) were in force in Russia since 1996 and contain a list of clearance limits (in Bq/g) for 295 radioactive nuclides and two natural elements (U and Th). These clearance limits (with minimally significant specific activities) were computed so that an annual individual effective dose did not exceed 10 μSv. In 2000, this document was replaced by NRB-99 (Ref. 16), prepared by a working group of the RNCRP that consisted of Russian and Belarusan specialists. In the new regulations, the list of the clearance limits remains practically invariable. It contains 296 nuclides and two naturally radioactive elements. These clearance limits are not in contradiction with the 1996 IAEA document[17] but are in general higher than those given in Ref. 12. Moreover, "Basic Sanitary Regulations Ensuring Radiation Safety,"[22] which has been in force in Russia since 2000, contains a list of permissible specific activities (clearance limits) of 14 basic long-lived radioactive nuclides for unrestricted use of metals. These clearance limits also are higher than those given in Ref. 12, but the discrepancy is essentially less.

The EC RP 122 document[14] was issued in the year 2000 and aimed to explain the concept of clearance and exemption and to discuss their practical use from the perspective of the overall regulatory control scheme. The concept of clearance is very close to the concept of exemption, but the two concepts relate to different stages of regulatory control. The mechanism of exemption is used to avoid unwarranted regulatory efforts. Therefore, the term means that the whole practice is exempt from the reporting requirement (indirectly, the concept is applicable to waste generated by such practice), i.e., does not enter the regulatory system as opposed to clearance where materials originating from a controlled practice, but satisfying clearance requirements, are released from further regulatory oversight.[15] With regard to the concept of clearance, the documents introduced the notion of general clearance and the notion of specific clearance to define specific conditions under which materials can be released from regulatory control. Levels for general clearance were provided for 197 radioisotopes.

There is a widespread agreement between the NRC, IAEA, RNCRP, and EC organizations on the primary dose standard and the negligible risk the cleared materials present to individuals. Even though all the standards under consideration recommend an annual dose of 10 μSv as the basis for clearance of solids from regulatory control from one practice, we observed a notable difference between the most recent clearance limits for the 115 and 277 radionuclides developed by the NRC and IAEA, respectively. The difference is lower when comparing the clearance levels developed for the 198 radionuclides by the EC (Ref. 14) and the corresponding values by IAEA. Furthermore, numerous fusion radioisotopes with $T_{1/2} \geq 10$ yr are missing from the U.S., IAEA, and/or EC standards and should be included in future evaluations. These missing radioisotopes include, but are not limited to, ^{10}Be, ^{26}Al, ^{32}Si, ^{91,92}Nb, ^{98}Tc, ^{113m}Cd, ^{121m}Sn, ^{150}Eu, ^{157,158}Tb, ^{163,166m}Ho, ^{178m}Hf, ^{186m,187}Re, ^{193}Pt, ^{208,210m,212}Bi, and ^{209}Po. In the Russian guidelines[16] these radioactive nuclides are also absent, except ^{212}Bi, which is given in conditions of its secular equilibrium with daughter isotopes.

The U.S. 2003 technical study[13] did not address nuclides with half-lives $<$30 days or gases (such as Ar and Kr) since they would not likely remain in the materials removed from nuclear facilities. Short-lived progenies (such as ^{108}Ag, ^{121}Sn, ^{137m}Ba, ^{208}Tl, ^{212}Pb, ^{210}Bi, and ^{209}Po) are assumed to be in secular equilibrium with their

[c] Reference will be made here to RP 122; however, other reports by the EC exist, such as RP 112, RP 113, and RP 114, which are rather specific. RP 112 is "Radiological Protection Principles Concerning the Natural Radioactivity of Building Materials," RP 113 is "Recommended Radiological Protection Criteria for the Clearance of Buildings and Building Rubble from the Dismantling of Nuclear Installations," and RP 114 is "Definition of Clearance Levels for the Release of Radioactively Contaminated Buildings and Building Rubble." RP 122 is more general: "Guidance on General Clearance Levels for Practices."

long-lived parents and are thus included in the analysis of the parents.

The EC RP 122 document[14] was also based on scenario analysis assuming the same radiological protection criteria for individual effective dose <10 μSv/yr to define the exemption levels. This trivial dose has to be guaranteed at the moment of release, keeping in mind that two factors help mitigate the radiological risks: (a) spontaneous or technological dilution and (b) decay.

The dose calculations to derive the clearance levels include the following steps:

1. choice of scenarios
2. definition of pathways of exposure
3. choice of parameter values
4. calculation of individual doses per unit activity concentration (per unit surface concentration for direct reuse)
5. identification of the limiting scenario and pathway
6. Reciprocal individual doses yield activity concentrations corresponding to 10 μSv/yr, rounded to a power of ten.

The IAEA study[12] was based on a set of exposure scenarios, including direct radiation, inhalation, and ingestion, and also took into account some of the national studies (including the U.S. study). However, the IAEA and NRC standards do not agree on the limits for many radioisotopes because different approximations are used to compute these limits and different exposure scenarios are selected to model the doses. For instance, the U.S. study incorporated realistic modeling of the current U.S. industrial practices as well as current data on the living habits in the United States in order to minimize unnecessary conservatism in the dose estimates. Figures 2 and 3 display the ratios of the proposed 2003 NRC limits for steel and concrete to the 2004 IAEA limits, while Table I lists the clearance limits for selected radioisotopes encountered in fusion applications. It should be mentioned that the IAEA and EC RP 122 standards have a better agreement for ~92% of the radioisotopes. The ratio between the two clearance levels is not greater than an order of magnitude for most radionuclides (see Fig. 4).

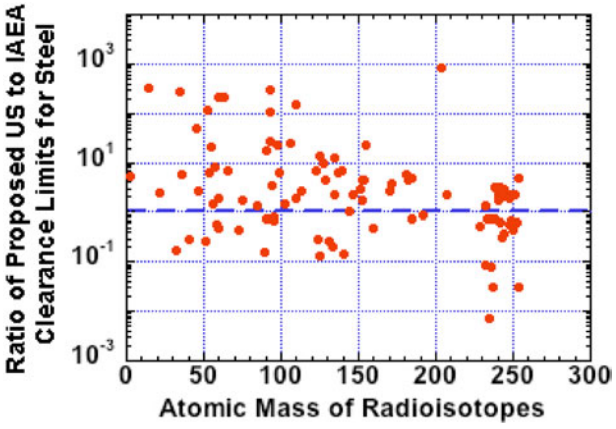

Fig. 2. Ratio of 2003 U.S. steel clearance limits to 2004 IAEA steel clearance limits.

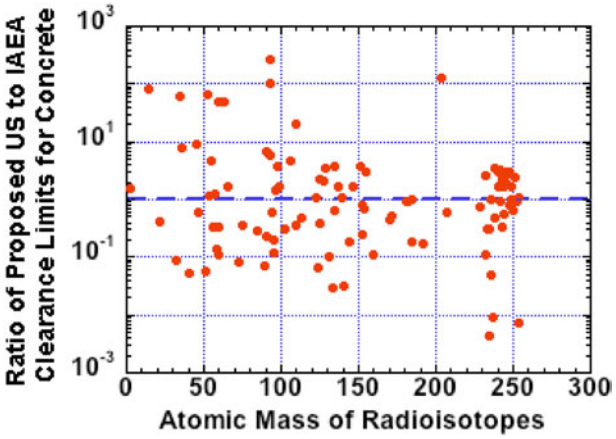

Fig. 3. Ratio of 2003 U.S. concrete clearance limits to 2004 IAEA steel clearance limits.

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

II.E. Proposal for Simplified Procedures to Calculate Self-Consistent Set of Clearance Limits for Fusion-Specific Nuclides

As already mentioned, clearance criteria and/or regulations have been recently issued by national and international institutions, like the IAEA (Ref. 12), NRC (Ref. 13), Russia (Refs. 16 and 22), and EC (Ref. 14). The following procedures are proposed to determine a set of fusion-relevant clearance limits:

1. If the nuclide has a limit defined by IAEA, NRC, Russia, or EC, adopt one consistent set of limits as the reference guideline to evaluate national designs.

2. In absence of national standards, use the IAEA evaluation for all components and constituents.

3. If a specific radioisotope has no limit, follow the rule defined by each organization to define new limits for all missing radioisotopes, expanding the original

TABLE I

IAEA, U.S., Russian, and EC Clearance Limits (in Bq/g) for Some Fusion-Relevant Nuclides

Nuclide	IAEA (Ref. 12)	United States (Ref. 13) (Steel/Cu/Concrete)	Russia (Refs. 16, 22, and 23)	EC RP 122 (Ref. 14)
^{3}H	100	526/1E5[a]/152	10^{6}	100
^{14}C	1	313/4.17E4/83	10^{4}	10
^{22}Na	0.1	0.238/8.33/0.0417	10	0.1
^{40}K	10	2.94/153.8/0.526	100	1
^{41}Ca	—	47.6/9.1E3/13.9	—	—
^{45}Ca	100	5E3/7E4/909	10^{4}	100
^{53}Mn	100	1.14E4/7.1E5/6.67E3	10^{4}	1000
^{54}Mn	0.1	0.625/23.26/0.118	10	0.1
^{55}Fe	1000	2.17E4/2.33E5/4.76E3	10^{4}	100
^{59}Fe	1	0.476/22.7/0.114	10	0.1
^{58}Co	1	0.588/28.57/0.133	10	0.1
^{60}Co	0.1	0.192/9.1/0.035	10	0.1
^{59}Ni	100	2.17E4/3.57E5/4.76E3	10^{4}	100
^{63}Ni	100	2.13E4/1.85E5/4.76E3	10^{5}	100
^{64}Cu	100	—	100	—
^{94}Nb	0.1	0.333/11.5/0.059	10	0.1
^{99}Mo	10	—	100	1
^{99}Tc	1	6.25/1.05E3/1.64	10^{4}	1
^{108m}Ag	—	0.345/18.18/0.0588	—	0.1
^{110m}Ag	0.1	0.192/10.3/0.0357	10	0.1
^{125}Sb	0.1	1.41/62.5/0.23	100	1
^{152}Eu	0.1	0.455/16.4/0.083	10	0.1
^{154}Eu	0.1	0.455/16.67/0.071	10	0.1
^{182}Ta	0.1	0.435/16.95/0.091	10	0.1
^{192}Ir	1	0.91/52.63/0.172	10	0.1
^{186}Re	1000	—	1000	100

[a]Read as 1.0×10^{5}.

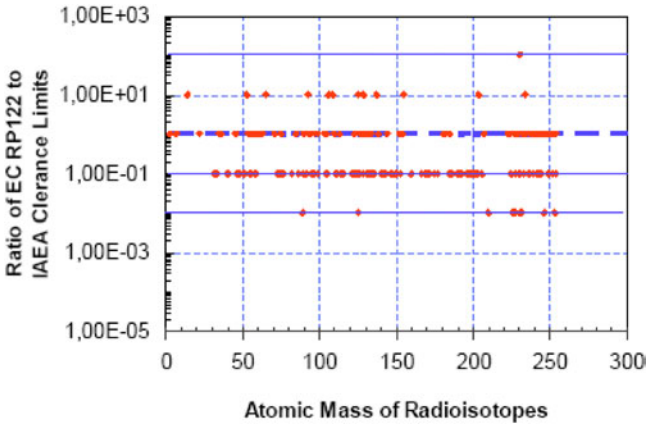

Fig. 4. Ratio of 2000 EC RP 122 clearance limits to 2004 IAEA steel clearance limits.

IAEA, NRC, Russia, or EC list to include all radioisotopes of interest to fusion application. For IAEA in particular, the clearance levels could be evaluated with a fitting formula[17]:

$$L_i = \min\left\{\frac{1}{E_\gamma + 0.1E_\beta}, \frac{ALI_{inh}}{1000}, \frac{ALI_{ing}}{100\,000}\right\} \quad (\text{Bq/g or Bq/cm}^2) \ ,$$

where

E_γ, E_β = maximum gamma and beta energies emitted by the nuclide, respectively (MeV)

ALI_{inh}, ALI_{ing} = annual limits of intake for inhalation and ingestion, respectively (Bq).

4. Borrowing and combining limits from different standards should be avoided because widely different scenarios have been used to develop these standards.

5. It is highly recommended to evaluate any fusion design with both national and IAEA clearance standards and highlight the impacts on fusion designs of the major differences in the various clearance evaluations.

6. Urge national and international organizations to revise their limits and issue fusion-specific, official clearance guidelines.

Clearance is also possible for nonhomogeneous components, such as the magnets, if an appropriate segregation process is carried out. Materials from the same component can be separated and treated accordingly.

III. RECYCLING

Numerous fusion researchers investigated the recycling option in the late 1980s and 1990s, focusing on selected materials or components, then examining almost all fusion components in the late 1990s and 2000s. The recent development of advanced radiation-hardened RH 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 bioshield. Recycling processes include storage in continuously monitored facilities, segregation of various materials, crushing, melting, and refabrication.[19,24] Fusion plasma-facing components are highly radioactive and require special shielding during handling and transportation. Some may even need cooling for several days to remove the decay heat. Most fusion activated material contains tritium that could introduce serious complications to the recycling process. Detritiation treatment prior to recycling is assumed for fusion components with high tritium content.

III.A. Brief Review of Previous Approaches to Recycling of Fusion Materials

The European PPCS, which was completed in 2004 (Refs. 11 and 25), adopted the same waste management strategy as the earlier Safety and Environmental Assessment of Fusion Power[26] (SEAFP), applying both clearance and recycling criteria to the disposition of active material.[27] The clearance limits applied in the PPCS were those recommended by IAEA in 1996 (Ref. 17). If a material could not be clearable, it had to be either recycled or disposed of in repositories.

In the U.S. ARIES studies,[10] the technical feasibility of recycling is based on the dose rate to advanced RH equipment capable of handling 10 000 Sv/h or more.[2] Essentially, the dose determines the RH needs [hands-on handling (HOH), conventional, or advanced tools] and the interim storage period necessary to meet the dose limit. Besides the recycling dose, other important criteria include the decay heat level during reprocessing, economics of fabricating complex shapes remotely, the physical properties of the recycled products, and the acceptability of the nuclear industry to recycled materials.[2]

In most studies, some simple criteria based on contact dose rate levels were proposed to allow for a first classification of the materials. It must be pointed out that such criteria, based solely on radiological parameters such as contact gamma dose rate, should be revised and are probably not sufficient for classifying the materials for recycling purposes. Reviews of remote procedures currently used within the nuclear industry suggest that some criteria have been unduly conservative. For example, remelting of waste from fission power plants has already been carried out on material with a contact dose rate of 120 mSv/h (Ref. 28). Much higher dose rates (up to 10 000 Sv/h) are present in routine operations in the reprocessing of fission reactor fuel.

The conservative radiological criteria applied to EU power plant studies for recycling suitability should be revised. The 2 mSv/h dose limit for shielded HOH (SHOH) seems appropriate, as this corresponds to the acceptance criteria in some existing melting facilities[24] and is related to the transport limits. Recycling practicability depends not only on these radiological criteria, however. The possibility of waste reprocessing and isotope separation systems being available on the industrial scale, for fabrication of new components, as well as the economic viability of these processes, will ultimately determine the extent of fusion materials recycling.

III.B. Lessons Learned from Fission Recycling Experience

One can note here that currently fission spent fuel is reprocessed in hot cells with complete RH systems. These activities involve the treatment of materials presenting dose rates of up to 1500 Sv/h. Much higher dose rates are present in routine operations in the reprocessing of spent fuel in vitrification facilities. Contact dose rates of 3000 to 10 000 Sv/h exist at the outside surfaces of cylinders during operations such as weighing, welding, cleaning, contamination monitoring, and transfer to flasks.[5,29] While treatment of fission materials has no direct relevance to the recycling of fusion materials, its success gives confidence that advanced RH techniques could be developed for the recycling of radioactive fusion components.

One should not forget that to remove the components from tokamaks, use of RH systems is foreseen.[11,25] The RH needs for recycling are expected to be less stringent than the removal of tokamak components and their in-vessel handling even under normal circumstances. Indeed, the proximity of the RH system to the radioactive source can be different, but nevertheless, for decoupling and disassembling the tokamak components, similar proximity must be used. The current developments for RH inside tokamaks (even for ITER) are also leading to the development of radiation-resistant components and equipment.

In the United States, the Department of Energy has operated small-scale constrained releases of mildly radioactive materials to the nuclear industry throughout the 1990s. An unexpected benefit of the scrap metal melting process was that the slag tends to collect some of, or a

majority of, the radionuclides. When the slag was removed from the melt of steel shielding containers at the Idaho National Laboratory (INL), the resulting ingots contained only very low levels of radioactivity.[30] The slag would be sent to LLW disposal but at a greatly reduced volume. Further tests showed that millwright composition adjustments after slag removal in the foundry produced metal alloys with properties very similar to, or equal to, those of fresh alloys. Moreover, recycling cask shielding to fabricate 100 tonnes of lead bricks for the U.S. nuclear industry indicated a cost savings relative to disposal in LLW repositories. These experiences prove the technical and economical feasibility of recycling metals within the U.S. nuclear industry.[30]

At present, a reasonable recycling experience exists worldwide within the fission industry. With the renaissance of nuclear energy, it seems highly likely that recycling technology will continue to develop at a fast pace to support the mixed-oxide fuel reprocessing system and the Global Nuclear Energy Partnership (GNEP). Fusion has a much longer timescale than 30 yr. Developing its long-term recycling strategy, fusion will certainly benefit from the ongoing fission recycling experience and related governmental regulations.[31]

III.C. Reuse (Refurbishment) and Recycling: Two Complementary Approaches

It is important to point out at this stage the distinction between refurbishment and recycling of materials. In the fusion context, the former term is used to describe conditioning for immediate reuse (e.g., in the next batch of blanket modules) or at least after a short time compared with the recycling timescale (e.g., in a later batch) and involves little or no processing. The latter, on the other hand, refers to conditioning for later reuse in the nuclear industry in general (fusion or fission). Recycling generally involves greater processing in dedicated facilities, whereas refurbishment procedures need to occur on-site, possibly within the plant's hot cell. More importantly, refurbishment contributes to the reduction of the mass to be recycled later on, such as in the case of the PPCS-AB and ARIES LiPb breeder that exceeds 5000 tonnes. Even if not significantly contributing to the material inventory, some streams may also be candidates for refurbishment because of their strategic value (Li, Be, W) (Ref. 6).

III.D. Example of Material Reprocessing: Vanadium Alloys

One can say that the reprocessing of fission spent nuclear fuel in a "closed" fuel cycle is also a recycling process. At present, the only commercial technique for reactor fuel processing, adopted by radiochemical plants throughout the world, is the extraction (PUREX) process, in which U and Pu are extracted from HNO_3 solutions with tributylphosphate. This technology has no restrictions for contact dose, specific activity of material, or decay heat density. Radiochemical plants process fuel within a period varying from ~270 days to ~5 yr after its discharge from fission reactors, when the fuel reaches a specific radioactivity of 5 Ci/g of heavy metal (200 GBq/g) (Ref. 32).

A similar technology was proposed for reprocessing of the scarce and costly vanadium alloy after its use as a structural material in a fusion reactor developed in Russia.[33] Unfortunately, PUREX is inapplicable to the V-Cr-Ti alloy because V cannot be extracted from a HNO_3 solution with tributylphosphate. Therefore, it was decided to use another well-known extraction solvent—the di-2-ethyl-hexyl-phosphoric acid[34] (D2EHPA).

It was determined that the reprocessing of the V-Cr-Ti alloy will take place after 12 full yr of operation and 20 yr of cooling after reactor shutdown. Specific activity of the alloy (determined by impurities) by that time will be ~4 MBq/g, i.e., 4 to 5 orders of magnitude less than in the case of nuclear fuel reprocessing. In both cases, the capacity of the reprocessing plant is some hundreds of tonnes per year. The goal of reprocessing is purification of macrocomponents (U + Pu or V + Cr + Ti) from microcomponents (fission products or activation products).

A conceptual model for the radiochemical processing of the V-Cr-Ti alloy was developed and tested experimentally in laboratory conditions with activated specimens. The tests have shown that the purification of the V-Cr-Ti alloy main components, enabling their subsequent 95% hands-on recycling within the nuclear industry, can be achieved using a 50-step extraction cascade. The remaining 5% of the alloy would be disposed of as LLW.

A preliminary technical and economical analysis has shown that the radiochemical processing is more attractive economically than V-Cr-Ti alloy burial as solid radioactive waste.[34] This analysis takes into account the cost of the RH reprocessing and the disposal cost of 5% of the material as LLW.

To analyze the economic expediency of such a radiochemical processing, the two alternative technological solutions for handling the V-Cr-Ti alloy—processing versus burial—were compared economically.[35] The burial process chart is represented in Fig. 5.

It was assumed that the capacity of the processing plant (or, in comparison, the flow of the alloy to the storage facility) would be 400 tonnes/yr. The economic feasibility of the alternative processes was assessed based on the estimated payback period, that is, the length of time necessary for the positive cash flows generated by the sales of products or services to recoup the initial investment. When assessed from this perspective, the solution with the lesser payback time is preferable. To determine the payback period, we preset a profitability level enabling a normal operating industrial and economic activity.

The commercial prices of vanadium (traded in the form of oxides) depend largely on the production scale

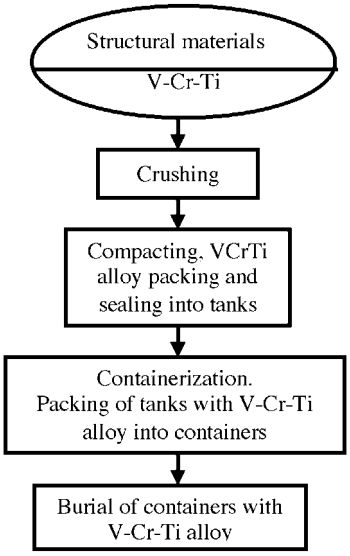

Fig. 5. Schematic diagram of a V-Cr-Ti alloy treatment using a containerization and subsequent long-term storage of solid radioactive waste

and market demand and can vary in a wide range. Also, much depends on product quality. According to Ref. 35, the price of V_2O_5 for 97% purity was US$25/kg, while for 99.99% purity it was US$4000/kg in 1998 prices. However, the information from different sources is inconsistent. For our purposes, we used two V_2O_5 prices: US$250/kg and US$10.5/kg.

To assess the investment needs for the two alternative V-Cr-Ti alloy handling projects, we used data on analogs and aggregated values, as well as expert estimates, with allowance made for the construction-related costs.

It was assumed that all the radiochemical reprocessing operations would be performed in one building with a volume of 60 000 m^3. The cemented compound, loaded into safe 1-m^3 concrete containers, would be placed in an aboveground storage facility (24 000 m^3). The containers would arrive at the storage facility at a rate of 120/yr.

The no-processing alternative would require storing of the alloy in sealed 200-ℓ tanks inside concrete containers accommodating four tanks each. Each year, the storage facility would receive 330 ferroconcrete containers. The construction volume of the facility would be 80 000 m^3.

Table II summarizes the technical and economic characteristics of the two V-Cr-Ti alloy handling alternatives. Metal extraction in the reprocessing operation was assumed to be ~95%. Conversion of U.S. dollars into Russian rubles (RUR) was performed at the Russian Federation Central Bank's exchange rate as of the fourth quarter of 2002 (US$1 = 30 RUR).

These figures suggest that the reprocessing alternative is much more attractive economically than the burial of spent V-Cr-Ti alloy parts. Even at the V_2O_5 price of

TABLE II

Technical and Economical Characteristics of V-Cr-Ti-Alloy Radiochemical Processing and Container Burial Alternatives

Characteristic	Unit of Measure	Alternative	
		Radiochemical Reprocessing	Container Burial
Mass of V-Cr-Ti alloy	t/yr	400	400
End product (V_2O_5, Cr_2O_3, TiO_2)	t/yr	380	—
Total investment of constructing and mounting work	10^6 RUR	21.0	5.1
	10^6 RUR	8.8	2.9
Alloy handling service costs	10^6 RUR	102.6	37.6
Standardized profit (25%)	10^6 RUR/yr	25.7	9.4
Cost of end product			
At US$250/kg	10^6 RUR/yr	3040	—
At US$10.5/kg	10^6 RUR/yr	128	—
Standardized profit plus cost of end product			
At US$250/kg	10^6 RUR/yr	3066	9.4
At US$10.5/kg	10^6 RUR/yr	153	9.4
Payback period at the cost of end product			
At US$250/kg	yr	0.2	13
At US$10.5/kg	yr	4	13

US$10.5/kg, the initial investment in the radiochemical reprocessing project is returned in 4 yr, while in the burial alternative, the payback time is 13 yr, regardless of the V_2O_5 price.

However, this technical and economic evaluation is preliminary. The uncertainties precluding a more definitive assessment are the price of V_2O_5 and the fact that the proposed radiochemical reprocessing has only been tested in laboratory, under static extraction conditions and using modeling solutions.

III.E. The Question of Choosing Between Recycling and Disposal

For the various fusion concepts, reprocessing of active materials appeared technically attractive and was judged to be, in many cases, a necessary requirement to control the radioactive waste stream. The economic aspects have to be taken into account in deciding the suitability of recycling. Even though there are several studies that prove with an adequate margin the economic advantages[30,33] as well as the public safety and health benefits[36] of recycling/reuse versus disposal, it is also fundamental to ascertain the acceptance of the recycled materials by the envisaged receiver. The cost-savings demonstration in recycling lead shielding bricks at INL versus disposal in U.S. LLW repositories[30] promotes the recycling process. For instance, the estimated cost of LLW disposal of the lead was approximately US$2.27/kg (US$5/lb) while the approximate cost of recycling was US$1.95/kg (US$4.3/lb), which included fabrication into brick shapes. Therefore, there was a cost savings in recycling versus disposal and the savings of disposal volume. The cost to purchase brand new shielding bricks rather than obtain recycled bricks was estimated to be US$46 per brick, so there was the savings of not requiring the purchase of new bricks.

Another supportive example mentioned above is the Russian study indicating vanadium alloy reprocessing is economically more attractive than disposal.[34]

A dedicated study,[37] carried out in the frame of the PPCS relative to the subtask on "Waste Generic Issues," dealt with two main questions:

1. Which would be the best approach for materials recycling and reuse?

2. Which should be adopted: on-site facilities or centralized ones?

The work identified the factors that are important in the development of a suitable fusion power waste recycling/reuse and clearance strategy, for which seven different scenarios of management of the back end of the fusion material cycle were developed and studied, introducing some economic considerations as well. These scenarios range from doing very little refurbishment/reprocessing to doing the maximum refurbishing/reprocessing that is practical, in the order of decreasing sociopolitical concern. It also considers performing various refurbishing/reprocessing activities on-site and off-site. A helium-cooled, pebble-bed ceramic blanket was used to provide the basis for estimating material quantities and to compare the various options. It has been assumed that the reactor blanket (including the divertor) will be divided into 12 ring segments and each ring segment comprises 167 discrete blanket modules (2000 modules per reactor). The economic analysis was based on costs that were given as a percent of the total cost of a new set of in-vessel components (IVCs) (blanket modules plus divertor cassettes), which was assumed to be equal to €1 billion. The price of blanket materials such as beryllium, lithium, and titanium was simply assumed to be €100/kg for all three materials. The reprocessing cost of breeder materials was assumed to be €500/kg (Ref. 38), implying that reprocessing would only be economical if the reduced cost of waste disposal, storage, and transportation compensated for the cost of the reprocessing facility. The current price of tritium was assumed to be €25 million/kg. Then, taking into account a plant life of 50 yr and a frequency of IVC replacement of 5 yr, a single plant will require nine IVC replacements. The last set of IVCs is kept inside the tokamak until the plant is decommissioned. The results of the economic analysis are summarized in Table III.

The lifetime replacement cost is given as unity in Table III, and all other costs are given as a fraction. Therefore, for option 1, which requires nine new sets of IVCs, the lifetime replacement cost is €9 billion. The lifetime replacement cost is given as unity, and all other costs are given as a fraction. For example, the option 1 lifetime disposal cost is €5.2 billion, or 0.578 of the IVC lifetime replacement cost (5.2/9). As shown in Table III, the storage option (option 1, which simply foresees building the storage of IVCs on-site until plant decommissioning) gives a total cost that is 69% higher than the least-expensive option (option 5). Option 5 instead foresees building an on-site IVC refurbishing facility, a module detritiation facility, a module refurbishing facility, and a residual materials storage facility (with no shipment off-site). The weakest element of this analysis is the quantification of the unit cost for reprocessing neutron multiplier and breeder materials, which at the moment is difficult to forecast. The assumed cost of €500/kg is based on estimates of unit costs for reprocessing fission reactor fuel. At any rate, the conclusions of this comparative study on economic factors of merit are as follows:

1. IVC refurbishing could possibly cost more than new IVCs because of the radiation environment; however, it will be economically advantageous to refurbish because of lower storage, transportation, and disposal costs, but primarily the latter.

2. The cost of reprocessing is a key factor influencing the final economic result. The assumed price for

TABLE III

Lifetime Costs of IVCs as Fraction of Lifetime Replacement Cost

Option	Replacement Cost	Storage Cost	Transportation Cost	Disposal Cost	Material Reprocessing Cost	Total Cost
1	1.00	0.145	0.058	0.578	0	1.78
2	1.10	0.028	0.011	0.113	0	1.25
3	1.10	0.028	0.011	0.113	0	1.25
4	0.98	0.014	0.028	0.057	0	1.08
5	0.98	0.014	0.006	0.057	0	1.06
6	0.98	0.003	0.006	0.013	0.22	1.27
7	0.98	0.003	0.001	0.013	0.22	1.26

reprocessing (€500/kg) might not justify materials reprocessing, even considering the money savings for storage, transportation, and disposal (socioeconomic and environmental issues are not taken into account).

3. Tritium recovery from the blanket modules is expected to be economical at today's tritium price (€25 million/kg). For lower tritium unit price (i.e., €15 million/kg), it might be uneconomic to detritiate the blanket modules (no tritium control and accountancy and safety issues considered).

4. Without IVC refurbishing, the operational IVC waste will far exceed the decommissioning waste.

5. Several operating strategies are available for significantly reducing both the quantity of IVC waste and the total cost associated with IVC replacement, storage, transport, and disposal.

6. Future fusion power plants will have to be constructed as multiunit plants, possibly four or more units per site.

In other cases, however, even though reprocessing seemed technically feasible for specific components of the inertial fusion energy system, the disposal scheme emerged as the preferred option for the target materials for economic reasons.[39] Recycling the target materials with an RH process tends to double the cost of electricity, which is unacceptable. Nevertheless, the disposal option, which seems to be more appropriate for specific components/materials, implies the siting and licensing of disposal repositories for LLW, which also have problems of public acceptability, as will be discussed later.

III.F. Important Radioactive Quantities To Be Limited: Contact Dose Rate, Decay Heat, Radioactivity Concentration

To study the recycling possibility of fusion materials, various properties and quantities have to be examined and/or limited. First the potential recycling processes (e.g., melting of metals, or sintering for powder metallurgy, machining, crushing of concrete, etc.) have to be considered, and the various intrinsic radiological properties of the materials have to be limited. For the sake of simplicity, it is interesting to summarize the principal quantities to be limited and analyzed in advance. The contact dose rate (at 1 m for instance) is surely an important factor as it determines the possibility to intervene with hands-on or with limited shielding. At very high dose levels ($\gg$10 000 Sv/h), this can influence or even impede the use of remotely controlled tools or instrumentation. Another important aspect is the total, nuclide-specific radioactivity concentration. Indeed, this feature can condition the possibility of reuse of materials, the acceptability by the potential recycling market, the regulatory constraints, and the safety aspects, as this concentration can strongly impact the risk of airborne or transferred radioactive contamination. Moreover, this concentration would also influence the level of radioactivity of the secondary waste produced and the type of waste avoidance if the material can be recycled. Also, the decay heat is indeed an important parameter. It specifies the active cooling needs for storage and further treatment for the highly activated parts of the plant. This aspect is more important for the component removal itself, as the active cooling need can lead to complex removal and handling technologies. A first approach to this aspect was carried out in a European Fusion Development Agreement study.[20]

III.G. The Handling Question: Hands-On, Simple Shielded, and RH Approaches

Aiming at defining the recycling features in the context of a fusion-oriented approach to the back end of the fusion materials cycle, the following types of handling techniques for recycling criteria were proposed following a comprehensive EU survey of recycling experience in the nuclear industry[20]:

1. *HOH*: This technique is applied to the material that has a contact dose rate below 10 μSv/h and can be easily handled by radiation-exposed workers.

2. *SHOH*: This technique is applied to the material that has a contact dose below 2 mSv/h and can be treated with simple shielding requirements by radiation-exposed workers. Glove boxes are a primary example of the type of equipment required by material falling into this category.

3. *RH*: This technique is applied to the material that has a contact dose rate above 2 mSv/h and can be dealt with by RH equipment used by radiation exposed workers, without the need of active cooling; the decay heat is therefore below 2000 W/m^3.

4. *Active Cooling Material*: This material 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 (estimated to be $\sim$2000 W/m^3); hence, interim storage is the only option available.

One of the main tasks of the latest EU study in this field[20] 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 recycling "routes" and "radiological requirements" such as handling, cooling, transport, etc. Recycling 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 IV (Ref. 20). Recycling 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 as follows:

1. For the unconditional clearance, the CI must be lower than unity.

2. For the conditional clearance, this would depend upon local regulations.

3. For the recycling in foundries, one can for the moment take an activity limit of 1000 Bq/g.

4. 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[40] to override these classification criteria with a scoring scheme, rating the difficulty of operations on active material. The radiological scoring goes beyond the requirements for the contact dose and includes other aspects (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.[19,24] The scheme can be used to compare fusion technology concepts through "snapshot" classifications at given times and to ascertain cooling time requirements for different components/materials.

Regardless of the route followed, an important element for a credible management strategy is to be able to estimate the technical difficulty of recycling or waste conditioning treatments and operations.

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

1. unshielded HOH by qualified radiation workers when contact dose levels are below 10 μSv/h

2. SHOH by qualified radiation workers when contact dose levels are below 2 mSv/h; equipment

TABLE IV

EU Recycling Routes for Fusion Radioactive Materials

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

such as shielded glove boxes can be conceived under this category

3. RH when contact dose levels are above 2 mSv/h.

As for cooling requirements, the following levels are envisaged:

1. no active cooling needed (only natural ventilation) when decay heat rates are <10 W/m^3
2. dry cooling (e.g., active ventilation) when decay heat rates are >10 W/m^3 but <2000 W/m^3
3. wet cooling (e.g., actively cooled storage pond) when decay heat rates are >2000 W/m^3, coinciding with the definition of HLW.

Based on these three handling and cooling requirement levels, the scoring scheme illustrated in Table V was developed in Europe. The rationale behind the scheme is as follows:

1. Level 1 material can be handled hands-on and requires no cooling whatsoever.

2. Level 2 material can be handled using shielded hands-on methods and equipment, and again no cooling is required.

3. Level 3 covers everything between levels 2 and 4: essentially, material requiring RH equipment and/or dry cooling.

4. Level 4 material requires active wet cooling; it is anticipated that no operation of this kind of material is possible.

It is proposed to use the above scheme in future assessments of active materials, particularly in EU fusion power plant designs, to ascertain storage times for the activity of the materials and therefore the technical difficulty of treatment processes according to these scoring levels. In parallel to this assessment, a comparison of different fusion technology concepts and plant designs can be made via conventional snapshot classification at specific times. This has already been performed for the PPCS near-term power plant concepts.[40]

III.H. The Routing Question: Recycling Outside Nuclear Industry, Recycle Within Nuclear-Specific Foundries, and Other Recycling Scenarios Without Melting

Besides the radiation protection aspects given above, the EU recycling study and approach have 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 examined, mostly for metals and materials to be removed from the tokamak core and the immediate surroundings. For material with sufficiently low activity to be freely released or conditionally released (see Sec. II), classical ways of recycling (often using remelting of the metal components) can be envisaged. 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 levels. Depending on their license, these foundries can accept plus or minus contaminated or activated materials. But, up to now the levels of accepted and licensed activity have remained very low (on the order of hundreds of Bq/g). Other recycling scenarios without melting also have to be considered, for instance, refractory metals (like tungsten), where normally powder metallurgy is the current industrial process, or components that can be reused without demolition (e.g., tanks, pumps, piping) if they are still in good physical shape but could be reused 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.

TABLE V

EU Scheme Determining Radiological Complexity of Operations on Irradiated Materials

Handling (H)	Cooling (C)	Difficulty	Score ($H + C$)
HOH = 1	None = 0	Level 1	1
SHOH = 2	None = 0	Level 2	2
RH = 3	Dry = 2	Level 3	3,4,5
	Wet = 5	Level 4 (no operations possible)	6,7,8

III.I. Technological Challenges Facing Recycling in Future Fusion Industry

It is important to develop advanced rad-hard RH equipment that can handle 10 000 Gy/h (10 000 Sv/h) or more. This equipment is already needed for removing the replaceable components from the vacuum vessel (VV) and moving them to the hot cell. The proposed high doses are not far from the present technology; e.g., in ITER some RH will have to withstand 1500 Gy/h (and even 15 000 Gy/h) with a total dose of 5 to 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 (nonclearable) materials in special facilities in order to separate noxious radionuclides is another challenge. The outcome of this operation is a small quantity of concentrated radioactive waste, plus a processed material that may be either "clearable" or "nonclearable, to be recycled within the nuclear industry," if the separation process is feasible 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 for fusion activated waste, apart from the small volumes required to store the secondary waste, is very attractive and worth pursuing.

IV. RADIOACTIVE WASTE

We would like to propose in this section a comprehensive definition of the fusion radioactive waste classification, based on two categories: low- and intermediate-level waste (LILW) and HLW. We consider the LILW disposal option as an alternative to recycling/clearance. Note that many countries do not have the LILW category. Therefore, the approval of this proposal requires an extensive review process by the legal authority in each country followed by an official endorsement. Let us first briefly summarize what is meant by LILW, in general terms, as defined by the IAEA, in the United States, in some European countries (Italy and France), and in Russia.

IV.A. IAEA Definition of LLW and LILW

The IAEA has tried to define the various categories of radioactive waste.[41] To be accepted by all member states, the definition remains rather general and somewhat vague but nevertheless gives some guidance on the waste classification. LILW contains activity levels above clearance levels and thermal power below $\sim$2 kW/m^3. A separation is made between short-lived and long-lived waste, based on the concentration of alpha-emitting radionuclides. This separation is set at 30-yr half-life. The HLW is also defined as waste with thermal power above $\sim$2 kW/m^3 and long-lived radionuclide concentrations exceeding limitations for short-lived waste.[41] In the absence of national regulations, these definitions could be used as the basis for the LILW and HLW classifications.

IV.B. U.S. Definition of LLW

The U.S. waste is classified based on where it comes from, while in most other countries the waste is classified according to its effects (e.g., the thermal power). LLW is generated anywhere radioisotopes are produced or used—in nuclear power industries, university research laboratories, manufacturing and food irradiation facilities, and hospitals. LLW contains virtually no alpha emitters and can easily be disposed of in a dry engineered landfill. For regulatory purposes, the U.S. LLW is classified into three classes (A, B, and C) according to the activity concentration and types of radioisotopes. For each type, there is a specific disposal requirement according to the NRC 10CFR61 document[42] so that the waste is disposed properly and safely. Class A is the least hazardous type of waste. The LLW containers are placed 8 m or more deep in the ground. An intrusion barrier, such as a thick concrete slab, is added to class C waste trenches. Class A LLW is intended to be safe after 100 yr, class B after 300 yr, and class C after 500 yr of active institutional control. At present, there is no LILW category in the United States. The intermediate-depth disposal has not received much attention over the past 25 to 30 yr despite the fact that it could provide a comparable degree of isolation as deep-geological repository with less effort and cost.[43]

The ARIES fusion designs[10] evaluate the volumetric average waste disposal rating (WDR) for a fully compacted waste using the most conservative waste disposal limits developed by Fetter et al.[44] for fusion radioactive waste and by NRC 10CFR61 (Ref. 42) for fission, medical, and industrial radioactive waste. The NRC waste classification is based largely on radionuclides that are important to fission facilities. In a fusion system, the isotopes are different because of the different materials being considered and the different transmutation products that are generated. In the early 1990s, Fetter et al. performed analyses 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 NRC 10CFR61. Although Fetter et al.'s calculations carry no regulatory acceptance, they are useful because they include fusion-specific isotopes. The ARIES approach requires all components to meet both the NRC and Fetter et al. limits until the NRC develops official guidelines for fusion waste.

By definition, the WDR is the ratio of the specific activity (in Ci/m^3 at 100 yr after shutdown) to the allowable limit summed over all radioisotopes. For all ARIES designs, we evaluate the WDR based on both the Fetter et al. and NRC limits and report the highest value. A WDR < 1 means LLW and a WDR > 1 means HLW. A WDR < 0.1 indicates the waste may fall under the class A LLW category.

IV.C. Italian Definition of LLW

Italian regulations deal with National Laws on radioactive materials[45] and with Technical Guides from the Italian nuclear regulatory committee [ENEA's "Guida Tecnica 26" (Ref. 46) and others]. The waste is classified into three categories ("I Categoria" = First category = LLW, "II Categoria" = Second Category = intermediate-level waste (ILW), and "III Categoria" = Third Category = HLW) 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 the details, the boundary between the second and third categories, for activated metallic materials, is a concentration of 370 Bq/g for long-lived nuclides ($T_{1/2} > 100$ yr), 37 000 Bq/g for medium-lived nuclides (5 yr $< T_{1/2} <$ 100 yr), and 37×10^6 Bq/g for short-lived nuclides. This limit deals with waste that has been conditioned and treated for disposal.

Concerning clearance, a recent regulation has been issued in Italy[47] concerning the "Allontanamento" (Italian word for "clearance") of solid radioactive spent materials. 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 <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 following criteria must be respected: $\Sigma_i(C_i/C_{li}) < 1$, where C_i is the mass (Bq/g) or superficial (Bq/cm^2) concentration of the nuclide i and C_{li} is the concentration limit. Moreover, both limits (in terms of specific and superficial activity) must be respected.

Recycling in Italy is permitted for cleared materials only.

IV.D. French Definition of Waste Categories

The waste classification in France[48–50] is managed by the French Agency for the Management of Radioactive Waste (ANDRA). This applies to ITER waste. There are four different types of waste (see Table VI):

1. TFA (Très Faible Activité) or very low-level waste (VLLW)
2. FMA (Faible et Moyenne Activité) corresponding to low and short-lived (<31 yr) ILW
3. MAVL (Moyenne Activité à Vie Longue) corresponding to long-lived (>31 yr) ILW
4. HAVL (Haute Activité à Vie Longue) corresponding to long-lived (>31 yr) HLW, with thermal effect.

IV.D.1. VLLW 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 has been the final disposal for VLLW (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 nuclide class (depending on the nuclide radiotoxicity).[51] This radiological acceptance index in storage ["Indice Radiologique d'Acceptabilité de Stockage" (IRAS)] is defined as

TABLE VI

ANDRA Classification

<table>
<tr><th></th><th>Very Short Lived (<100 days)</th><th>Short Lived (≤31 yr)</th><th>Long Lived (>31 yr)</th></tr>
<tr><td>VLLW</td><td rowspan="4">Management by radioactive decay</td><td colspan="2">Surface disposal facility (Morvilliers)</td></tr>
<tr><td>LLW</td><td>Surface disposal facility at the Aube repository</td><td>Subsurface disposal facilities for waste containing Ra and graphite under study (law 2006-739 of June 28, 2006)</td></tr>
<tr><td>ILW</td><td>Tritiated waste under study, law 2006-739 of June 28, 2006.</td><td>Waste management solution under study, law 2006-739 of June 28, 2006</td></tr>
<tr><td>HLW</td><td colspan="2">Waste management solution under study in the framework of law 2006-739 of June 28, 2006</td></tr>
</table>

$$\Sigma \frac{A_i}{10^{C_i}} ,$$

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 two following conditions: IRAS index < 1 and IRAS index of the different packages within the batch lower than 10. For acceptance in the CSTFA, the activity of selected nuclides has to be evaluated and declared if their specific activities are higher than the declaration threshold. Sometimes, it is not necessary to try to determine the actual activity of a package. As a matter of fact, it is allowable to provide a global specific activity to a package, if it is possible to demonstrate that this leads to a conservative declaration. This leads to the use of "Limite de Déclaration Forfaitaire par radionucléide" (LDF), i.e., the overall declaration threshold. More details are given in Ref. 51. TFA criteria for some fusion-relevant nuclides are given in Table VII.

IV.D.2. LLW 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 (Ref. 52), 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 need to be fixed with a matrix having containment properties. Otherwise, a blocking matrix can be used to allow waste immobilization.

FMA criteria for some fusion-relevant nuclides are given in Table VII. Waste containing Be, which is chemically toxic, must be identified and quantified as soon as the mass concentration of Be is higher than 10 ppm in heterogeneous waste and 6 ppm in homogeneous waste. The maximum tritium degassing rate for packages stored in CSA is 2 (Bq/g)/day because of occupational radiation exposure.

IV.D.3. ILW Criteria

The waste, which cannot be stored as FMA or TFA, has been considered as MAVL waste since no acceptance criteria have 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 on radioactive waste has been voted: "programme relatif à la gestion durable des matières et des déchets radioactifs" (program related to durable management of materials and radioactive waste), which describes the objective of such a storage site.[53]

IV.E. Russian Definition of Waste

According to the Russian Basic Sanitary Regulations Ensuring Radiation Safety,[22] there are liquid, solid, and gaseous radioactive wastes. Liquid radioactive waste includes organic and inorganic liquids, pulps, and slimes that are not subject to further utilization and have specific

TABLE VII

French TFA and FMA Criteria for Some Fusion-Relevant Nuclides

Nuclides	Half-Life (yr)	TFA Criteria			FMA Criteria		
		TFA Class	Declaration Threshold (Bq/g)	LDF (Bq/g)	Declaration Threshold (Bq/g)	Maximum Activity Limit (Bq/g)	Embedding Threshold (Bq/g)
^{3}H	1.23E+01[a]	3	1	10	10	2.00E+05	7.40E+03
^{14}C	5.73E+03	3	0.1	1	10	9.20E+04	3.70E+03
^{54}Mn	8.55E−01	1	0.1		10	3.60E+08	3.70E+04
^{59}Ni	7.60E+04	3	10	100	0.1	1.10E+05	3.70E+03
^{60}Co	5.27E+00	1	0.1		10	1.30E+08	3.70E+03
^{63}Ni	9.90E+01	3	10		1	3.20E+06	3.70E+03
^{93}Mo	3.01E+03	3	0.01	0.1	0.001	3.80E+04	
^{94}Nb	2.00E+04	1	0.1		0.1	1.20E+02	
^{99}Tc	2.11E+05	3	0.01	0.1	0.02	4.40E+04	
^{110m}Ag	6.84E−01	1	0.1		10	1.20E+08	2.00E+04
^{152}Eu	1.33E+01	1	0.1		1	7.50E+07	3.00E+04
^{154}Eu	8.60E+00	1	0.1		1		
^{192m2}Ir	2.41E+02	1	0.1		1		

[a]Read as 1.23×10^{1}.

TABLE VIII

Specific Activity (Bq/g) of Different Russian Categories of Liquid and Solid Radioactive Wastes

Category	Beta Emitters	Alpha Emitters Except Transuranium Nuclides	Transuranium Nuclides
LLW	$<10^3$	<100	<10
ILW	10^3 to 10^7	10^2 to 10^6	10 to 10^5
HLW	$>10^7$	$>10^6$	$>10^5$

activities of radioactive nuclides exceeding "intervention threshold" at intake with water, given in NRB-99 (Ref. 16), more than ten times. Solid radioactive waste includes materials, goods, equipment, biological objects, soil, and hardened liquid radioactive waste that are not subject to further utilization and have specific activities of radioactive nuclides exceeding clearance limits (minimally significant specific activities).[16] Solid materials with unknown composition of radioactive nuclides are considered as radioactive waste if their specific activity 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 depending on its specific activity as given in Table VIII.

In the case when different radioactive nuclides relate to different categories, the waste relates to the highest category. Gaseous radioactive waste includes radioactive gases and aerosols that are not subject to further utilization and have activity concentration per unit volume exceeding permissible average annular volume activity given in NRB-99 (Ref. 16). Effective dose rate for population caused by radioactive waste, including stages of its storage and transportation, should not exceed 10 μSv/yr.

IV.F. Proposal of Generalized Definition of LILW for Fusion

National and international regulations have different definitions for LILW. They mainly deal with radioactivity concentration, contact dose rate, and/or decay heat. We could define LILW as that material for which disposal has been decided as a management route and that fulfills some specific requirements. In particular, the following U.S. and EU requirements may be defined for LILW of fusion materials:

1. *United States*: The LLW must meet the shallow-land burial requirements according to the U.S. regulations: NRC 10CFR61 (Ref. 42) and Fetter et al.'s fusion extensions.[44] The WDR should not exceed unity. There is no LILW category in the United States at the present time.

2. *European Union*: The material must fulfill the requirements for LILW as defined by IAEA, with thermal power below $\sim$2 kW/m^3 (see IAEA definition in Sec. IV.A) and no long-lived waste (i.e., $T_{1/2} < 30$ yr) above a certain limit.

All the materials for which the LLW/LILW definition does not apply are HLW. It is highly radioactive and, therefore, requires active cooling and special shielding during handling and transport.

IV.G. Assessment of LILW Disposal Environmental Impact

As an alternative, but less environmentally attractive, route to recycling for fusion, a set of specific sites for LILW disposal is considered here, and the environmental impact is assessed. Disposal in shallow land or underground repositories must provide an efficient containment to prevent any leakage of radioactive species to the biosphere. Two main scenarios of potential radioactive contamination are examined in this study:

1. inadvertent intrusion in the repository, after the period of institutional control, conservatively assumed to last 50 yr
2. long-term migration of radioactive nuclides due to natural degradation of the waste container through interactions with the surrounding environment causing a release of radionuclides to the biosphere.

A computational model was set up to assess the dose to population from the waste disposal site in case of intrusion and containment degradation (hereon called "degradation"). The GENII computer code[54] was utilized. Well drilling is considered as the possible intrusion scenario, and release of radionuclides to wells via groundwater is therefore the selected environmental access point. Details for both scenarios are reported in footnote d. The total EDE to the intruder was evaluated for activated

[d]The following details were adopted for a drilling intrusion scenario. The inventory was disposed after 50 yr of cooling; intrusion begins after another 50 yr. Loss of institutional control occurred just before the beginning of the intrusion. The inadvertent intruder is the drilling worker. He makes a drilling hole (with 305-mm diameter) on the surface of the repository site, where the waste is 100 m below ground level. The waste package degradation immediately and totally occurs. The repository considered here is of the underground type. The intruder is assumed to be irradiated for 1 working week; 40 h to plume exposure (due to resuspension, external irradiation, and inhalation pathways), 40 h to contaminated ground external irradiation, 40 h to groundwater external irradiation. Concerning the degradation scenario, a waste package lifetime equal to 500 yr has been assumed. Waste repository characteristics are the same specified for the intrusion scenario. The very long-term dose evaluated for the maximum exposed individual derives from all exposure pathways (including ingestion).

TABLE IX

An Integrated Approach to 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 nonnuclear 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. Materials must be subject to continuing regulatory control. Examples include building concrete rubble 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 a direct reuse or after processing. The former is defined as refurbishment.)	In a licensed repository for radioactive waste (after interim storage if applicable).

waste arising from in-vessel structures of a PPCS plant model that adopts a martensitic steel structure and Li17-Pb83 breeder. Results show that the intruder dose is rather small (1.26 mSv per event). It is dominated by europium activation products (^{152}Eu and ^{154}Eu), which contribute to $>75\%$ of the total.[e]

Concerning the waste package degradation scenario, long-lived nuclides turned out to be dominant. Maximum doses occur at a very long time after disposal—at a time when package degradation has caused some nuclide migration up to the surface, from one side, and some undecayed long-lived nuclides exist yet, from the other. A maximum dose of 1.5 μSv/yr is the result of the assessment, which is much lower than the 10 μSv/yr considered as trivial by the IAEA.

V. INTEGRATED ACTIVE MATERIALS MANAGEMENT STRATEGY

Given all the above considerations, an integrated activated materials management strategy is proposed. It divides the materials according to the regulatory route (unconditional clearance, conditional clearance, no clearance) and the management route (recycling/reuse, disposal), as summarized in Table IX.

The integration of the recycling and clearance processes in fusion power plants is at an early stage of development. Figure 6 depicts the essential elements of the recycling/clearance process. Examining the various steps, one could envision the following:

1. After extraction from the power 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. Materials are shipped to a temporary storage onsite (or to a centralized facility) to store for several years.

3. If the CI does not reach unity in, e.g., <100 yr, the materials are transferred to a recycling center to refabricate remotely into useful forms. Fresh supply of materials could be added as needed.

4. If the CI can reach unity in, e.g., <100 yr, the materials are stored for 1 to 100 yr then released to the public sector to reuse without any restriction.

Because of the lack of experience, it is almost impossible to state how long it will take to refabricate the

[e]Europium, like other impurity elements, was added to the standard steel composition in the activation analysis in order to take into account the question of impurity activation. If europium is not included in the composition, then the intruder dose falls down to $\sim$0.3 mSv per event.

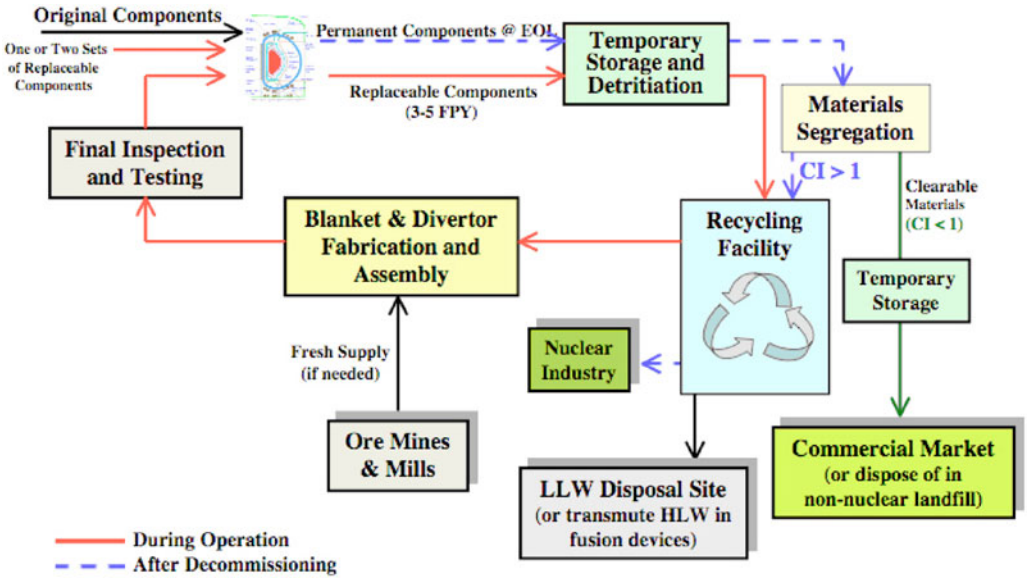

Fig. 6. Diagram of recycling and clearance processes.

replaceable components (blanket and divertor) out of radioactive materials. The minimum time that one would expect is 1 yr of temporary storage and 2 yr for fabrication, assembly, inspection, and testing. All processes must be done remotely with no personnel access to fabrication facilities.

VI. FUSION CYCLE BACK END FOR THREE SELECTED STUDIES

To demonstrate the applicability of the waste management scenarios to fusion radioactive materials, we applied all three approaches (disposal, recycling, and clearance) to selected fusion studies:

1. a proposal of experimental fusion device (Ignitor)
2. two selected power plants from the U.S. ARIES project and the EU PPCS studies.

We started the analyses by applying the existing national standards to all three designs and then examining the impact of the international IAEA standards. These analyses demonstrate the technical feasibility of recycling and clearance and provide evidence regarding their vital role in minimizing the radioactive waste volume of fusion designs. It is pertinent to mention that these analyses were performed before (or even in parallel with) the development of the newly proposed integral approach. In the future, we intend to apply the proposed new approaches and assess their implications for the radioactive waste management of selected fusion power plants. Minor changes are expected to the final results reported herein for Ignitor, ARIES, and PPCS.

VI.A. Ignitor Approaches and Results

Ignitor is a proposed compact high-magnetic-field tokamak aimed at studying plasma burning conditions in D-T plasmas.[55] Ignitor has a major radius of 1.3 m, a minor radius of 0.47 m, an elongation of 0.87 m, a peak plasma temperature of 12 keV, a peak plasma density of 10^{21} ions/m^3, and a maximum fusion power of 90 MW. Pulses at different power levels are planned, with either D-D or D-T operation, distributed over a global operation time of 10 calendar yr. The tokamak main components consist of a molybdenum first wall (FW) (compact metal volume of 2 m^3), an Inconel 625® VV (4.4 m^3), a Cu-based toroidal magnet (12.2 m^3), and an AISI316 machine structure (named "C-Clamp," 24 m^3). The Ignitor experimental reactor operation lifetime will be divided into two phases. In the first phase, aneutronic plasmas will be used, while tritium and neutron activated materials will be present, but at a moderate level, in the second phase. Classification of Ignitor radioactive materials and components is given in Table X. All the Ignitor materials can be declassified to nonradioactive materials (clearable materials) or recycled within the nuclear industry, after a relatively short interim decay time. Concerning recycling, the HOH limit is fulfilled by all the materials (FW, magnets, and part of the structure), except for the vessel material. Part of the structure and the cryostat can be classified as clearable material.

VI.B. ARIES Approaches and Results

The ARIES team recognizes the value of recycling and clearance as an effective means to control the volume of fusion activated material, second to waste

TABLE X

Classification of Ignitor Radioactive Materials and Components

Component	Material	Classification	Necessary Decay Time	Volume (m^3)
VV	Inconel 625® alloy	Shielded recycling or LLW	60 yr	4.4
FW	Molybdenum	Hands-on recycling	10 yr	2
Magnet	Copper	Hands-on recycling	60 yr	12.2
C-clamp structure	AISI 316 steel	Hands-on recycling (40%), clearance (60%)	40 yr	24
Cryostat	Composite material	Clearance	20 yr	1.1

minimization by design. Recyclable and clearable materials are not labeled waste. This means the volume of waste that any fusion power plant will generate is influenced by the adequate choice of materials and design and the implementation of the recycling and clearance approaches in the design from the beginning. Over the years, the ARIES team has been moving forward to underscore its commitment to activated material minimization by clever design, applying more advanced technology and physics operating regimes. For instance, the focus on ARIES compact devices contributed significantly to the twofold to fourfold decrease in activated material volume between the most recently developed power plants and previous designs delivered prior to 1995.

As an illustration of the environmental benefits and impact of the recent activated material management approaches, we applied all three scenarios (disposal, recycling, and clearance) to the most recent U.S. magnetic fusion energy power plant: ARIES-CS—a compact stellarator with a net electric power of 1000 MW(electric) and 7.75-m average major radius, approaching that of tokamaks. The dual-cooled LiPb/ferritic steel/He blanket protects the shield for the entire plant life [40 full-power years (FPY)]. The blanket and shield help protect the manifolds and VV, and all four components protect the superconducting magnets for their lifetime. The neutron wall loading (NWL) averages 2.6 MW/m^2. Based on the 5.3 MW/m^2 peak NWL, the FW, blanket, and divertor will be replaced every 3 FPY. The details of the radial dimensions, compositions, alloying elements, and impurities are all given in Ref. 56.

ARIES-CS generates only LLW that requires near-surface, shallow-land burial because all fusion materials are carefully chosen to minimize the long-lived radioactive products. This is not unique to stellarators as most tokamaks employing low-activation materials exhibit similar features. Table XI identifies the class A and C components according to the U.S. classification at 100 yr after shutdown. The VV and externals are less radioactive than the IVCs, to the extent that they qualify as class A LLW, the least hazardous type of waste. Excluding the clearable components (cryostat and bioshield), ~70% of the waste (blanket, shield, divertor, and manifolds) is class C LLW. The remaining ~30% (VV and magnet) would fall under the class A LLW category.

TABLE XI

ARIES-CS Class A and Class C LLW and Clearable Components

Structure	Class C LLW	Class A LLW	Could be Cleared?
FW/blanket/back wall	✓		No
Divertor system	✓		No
Shield/manifolds	✓		No
VV		✓	No
Magnet			
Nb_3Sn	✓		No
Cu stabilizer		✓	✓
JK2LB steel		✓	✓
Insulator		✓	✓
Cryostat		✓	✓
Bioshield		✓	✓

We applied the recycling approach to all ARIES-CS components. Here, the technical feasibility of recycling is based on the dose rate to the RH equipment. Essentially, the dose rate determines the RH needs (HOH, conventional, or advanced tools) and the interim storage period necessary to meet the dose rate limit, while the presence and quantity of tritium and activated dust determine the confinement needs. Besides the recycling dose rate, other important criteria include the decay heat level during reprocessing, economics of remotely fabricating complex shapes, the physical properties of the recycled products, and the acceptability of the nuclear industry to recycled materials. All the ARIES-CS components can potentially be recycled using conventional and advanced RH equipment that can handle 0.01 Sv/h (or 0.01 Gy/h, a thousandfold the 10 μSv/h absolute hands-on dose rate

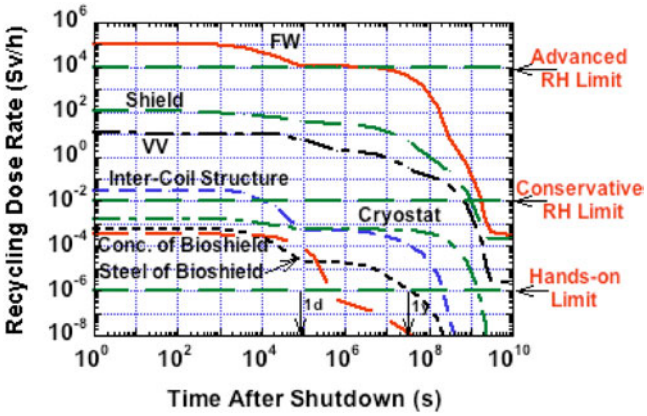

Fig. 7. Reduction of ARIES-CS recycling dose rate with time after shutdown.

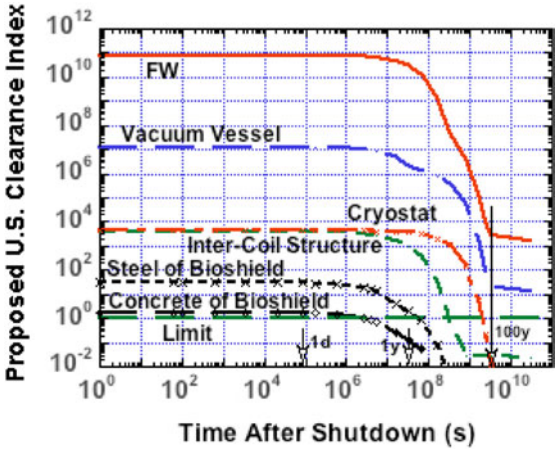

Fig. 8. Decrease of CI of ARIES-CS components with time after shutdown.

limit) and high dose rates of 10 000 Sv/h (10 000 Gy/h) or more, respectively. Applying the as-low-as-reasonably-achievable principle, the 1 μSv/h hands-on design limit considered throughout the ARIES studies is a factor of 10 below the absolute limit of 10 μSv/h.

The variation with time of the recycling dose rate shows a strong material dependence (see Fig. 7). The ARIES-CS FW, made of modified F82H ferritic steel, is an integral part of the blanket. It is shown in Fig. 7 as a separate component to provide the highest possible dose rate to the RH equipment. The average FW/blanket dose rate is an order of magnitude lower. No further dose rate buildups are expected for up to 50 yr following the FW/blanket replacement because of the reuse of these components after numerous life cycles as the dose rate is a flux-dependent response function. At longer time after blanket replacement (>80 yr), impurities start playing a key role, and the multiuse of recycled blanket materials will increase the dose rate. In recent years, many plasma physicists called for attaching 1- to 2-mm W tiles to the FW to enhance the plasma performance. The W exhibits slightly lower recycling dose rates than a steel-based FW. Manganese-54 (from Fe) is the main contributor to the dose rate of ferritic steel–based components (FW, blanket, shield, manifolds, and VV) at early cooling periods (<10 yr), while impurities have no contribution to the recycling dose rate for short cooling periods. Storing the FW/blanket temporarily for several years helps drop the dose rate by a few orders of magnitude before recycling. This analysis indicates that developing advanced recycling tools helps relax the stringent constraints imposed on fusion material impurities. In fact, this is an important choice: either stringent requirements for impurities or for advanced RH equipment.

For the ARIES-CS design as well as for almost all tokamaks, the clearance indices for all internal components (blanket, shield, manifolds, and VV) exceed unity by a wide margin even after an extended cooling period of 100 yr (refer to Fig. 8). Niobium-94 is the main contributor to the CI after 100 yr. Controlling the 3.3-wppm Nb and 21-wppm Mo impurities in MF82H helps the CI approach unity. In the absence of impurity control, the IVCs should either be recycled or disposed of in repositories as LLW.

Since the ultimate goal is to separate the constituents of any component for recycling or clearance, the ARIES approach for handling the cleared components (CI < 1) is to reevaluate the CIs for the constituents.[7] The entire component could have a CI < 1, but the individual constituents may not (and vice versa), requiring further segregation of the active materials based on constituents rather than components. Examining ARIES-CS magnet constituents confirms the impossible clearance of the Nb_3Sn superconductor (because of ^{94}Nb from Nb). The remaining magnet constituents can be cleared, however, within 100 yr. The inconsistencies in the ^{14}C, ^{54}Mn, and ^{63}Ni clearance standards (refer to Table I) result in a wide variation in the required storage period (based on the NRC and IAEA clearance guidelines) for the Cu stabilizer, the coil structure, and the mild steel of the bioshield.[30]

The 2-m-thick external concrete building (bioshield) that surrounds the torus represents the largest single component of the decommissioned radioactive waste. Fortunately, the bioshield along with the 5-cm-thick cryostat and some magnet constituents qualify for clearance, representing ~80% of the total active material volume. We developed another approach to deal with sizable components, such as the bioshield. It should be segmented and reexamined.[7] As such, the bioshield was divided into four segments (0.5 m each), and the CIs were reevaluated for the constituents (85% concrete, 10% mild steel, and 5% He by volume). Our results indicate that the innermost segment has the highest CI, while the outer three segments meet the clearance limit within a few days after

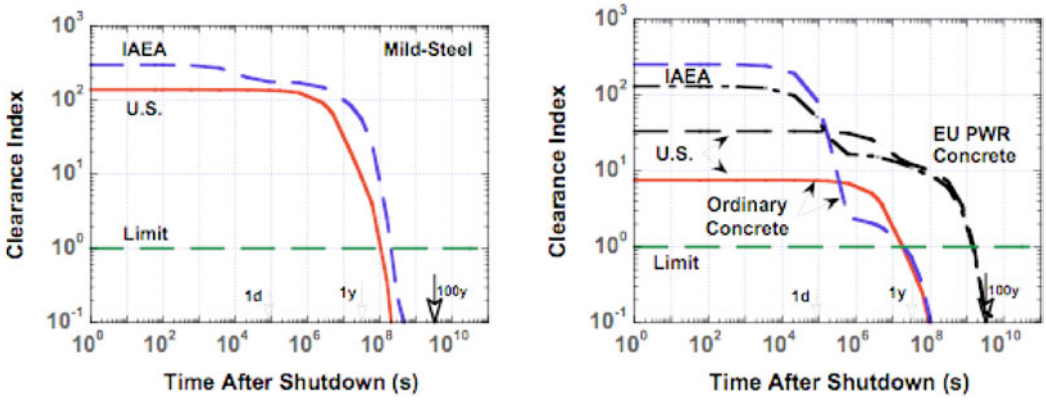

Fig. 9. Comparison of NRC and IAEA CI for constituents of innermost segment of bioshield.

shutdown. It is probably impractical to clear the bioshield after a few days as it is an essential part of the building infrastructure and cannot be dismantled before all internal components are removed.

The mild steel is a major contributor to the CI of the bioshield if used to reinforce the Type-04 ordinary concrete, although its volume fraction is only 10%. A variation was studied that mainly affects the cooling period. Another concrete with a more comprehensive list of constituents and impurities based on data from the European pressurized water reactor[24] (PWR) was considered, and the results are shown in Fig. 9. Compared to Type-04 ordinary concrete, the EU PWR concrete calls for a much longer cooling period (~50 yr) mainly for the CI of ^{152}Eu to drop below one. This finding is in general agreement with Ref. 24.

VI.C. PPCS Approaches and Results

An important conclusion of past PPCS studies based on the former criteria was that for all four plant models, and the fifth one added in follow-on studies, if full use is made of the potential to recycle materials, then after 100 yr there would be no material requiring permanent repository disposal,[57] except for a small amount of secondary waste from reprocessing. Whether or not such recycling operations would be feasible and economically viable for all candidate materials had yet to be determined. In other words, the recycling and clearance strategy would appear to have great potential for fusion, since its application could reduce the amount of radioactive waste to be disposed of; SEAFP and PPCS studies have in fact shown that between 30 and 50% of the activated material could be cleared (excluding the bioshield, which was not assessed in these studies), and between 50 and 70% could be recycled.[11,57,58]

Reference 40 describes the results of the most recent fusion waste studies in the European Union. Following from earlier work, the irradiated material inventory in two PPCS near-term models (PPCS-AB and PPCS-B) has been analyzed with increasing computational detail and taking into account the newest findings in the field. The suitability of this material to follow the recycling and disposal routes has been estimated and compared in a comprehensive manner. The proposed novel scoring scheme for the evaluation of the technical difficulty of operations on active material is applied (refer to Table V), providing a coarse but insightful tool to evaluate the technical difficulty of recycling or waste conditioning operations due to the active nature of the material. Two main parameters were used: contact dose rate, describing handling difficulty, and decay heat rate, describing cooling needs; the scoring table rates the material in levels of increasing difficulty. This scheme, defined in Sec. III.G, is suitable for either the estimation of interim storage times or snapshot comparison of different concepts at given times and has been applied to both near-term PPCS models. Results emphasize the overconservatism of previous studies; the following appears to be true for all the material in PPCS-AB and PPCS-B:

1. It is suitable for recycling with RH techniques shortly after plant shutdown (<5 yr).

2. After a period of time from a few decades up to 100 yr, the vast majority can be treated with undemanding techniques or equipment (91% in PPCS-AB and 95% in PPCS-B in difficulty levels 1 and 2)—refer to Table V; a large share of this material, however, requires active (but not wet) cooling during some of its interim storage time.

Therefore, the vast majority of tokamak components and materials in the PPCS plants have very low handling difficulties (in or below the SHOH category) after a convenient decay time of the order of decades following plant shutdown. Only small amounts (a few hundred tonnes) of plasma-facing tungsten and breeders still require specific RH mechanisms after this timescale.

Disposal of PPCS-AB and PPCS-B active material in EU low-level repositories has also been considered.

TABLE XII

Summary of Radiological Scoring and Disposal Potential for PPCS-AB and PPCS-B 100 yr After Plant Shutdown*

Plant Model	Level 3	Level 2	Level 1	ILW Germany	ILW United Kingdom	ILW France	Clearance
PPCS-AB	8682 (9%)	62 597 (65%)	25 296 (26%)	8682 (9%)	39 510 (41%)	62 415 (65%)	20 216 (21%)
PPCS-B	2509 (5%)	34 370 (69%)	13 248 (26%)	2509 (5%)	20 541 (41%)	27 668 (55%)	496 (1%)

*In tonnes (percent of total in parentheses).[40]

Because of the variety of regulations and acceptance criteria, a selection of cases needed assessment. The cases analyzed were Germany (Konrad), the United Kingdom, and France (CSA). In the latter case, rejection of metal streams is largely due to stringent limits on ^{94}Nb and ^{14}C activation products.[f] Both of these are generated by impurities (Mo and Nb) in the original material; therefore, control of those prior to service would enable the suitability of large amounts of irradiated material for this repository. Release from regulatory control (clearance) depends vastly on the decay of the ^{63}Ni ($T_{1/2} \sim 100$ yr) activation product. To maximize acceptance in CSA and clearance of outer components, the use of impurity-controlled Eurofer throughout the plants is recommended (replacing Type 316 stainless steel in the VV and toroidal field coils, where both Mo and Ni are main constituents).

It should be pointed out, however, that all disposal criteria in EU regulations were developed using fission waste standards and in particular that those based on nuclide-specific limits are overstringent and arbitrary for fusion-relevant radionuclides, having dubious scientific justification. The development of rigorous fusion-specific disposal criteria in the European Union, as done in the United States by Fetter et al.,[44] could serve as a precedent and guide for regulatory bodies introducing fusion into their framework, as well as assist in the development of materials for fusion.

Table XII summarizes the radiological scoring and disposal results obtained during the course of this work. From the material management stance, PPCS-AB and PPCS-B illustrate two different options in near-term fusion power plant design with very similar plasma performance and electrical output power [1.45 and 1.35 GW(electric), respectively]. The former is massive and focuses on the provision of heavy shielding in inner, replaceable components to reduce the neutron fluence and maximize the clearance of lifetime, outer ones (up to 21% of the total material after 100 yr). The latter is a more compact design with less shielding and therefore less clearance potential (only ~1%) but also with much less material to recycle or dispose of (nearly half), which might represent a substantial advantage.

Another important conclusion of the EU study was the great benefit obtained from a stringent impurity control of the materials facing the plasma or close to the neutron source.[6,20] The level of the impurity content in some materials had a very strong influence on their final specific activity, contact dose rates, and related radiological quantities, and therewith on their aptitude to be recycled. Traces of impurities (Ag, Sm, U) in some materials prior to irradiation in PPCS plants were seen to dramatically change the handling category at the recycling timescale (from HOH to RH in the case, for instance, of ceramic breeders and multipliers a few decades after plant shutdown).

Finally, a last important topic to be looked at is the presence and amount of long-lived radionuclides (e.g., ^{14}C, ^{94}Nb, ^{36}Cl, etc.) in the activated parts. These long-lived isotopes accumulate in the irradiated materials and compromise the benign environmental performance of fusion power plants. They are produced as secondary waste from recycling operations and should meet the concentration limits for land burial facilities. It is therefore important to estimate the amount of these isotopes and devise material and design choices to minimize them.[g]

Estimation of the amount of secondary waste generated during the recycling operations in PPCS-AB and PPCS-B material has been made. Focus has been given to the assessment of long-lived activity production, ^{14}C being recognized as the most problematic type. Alleviation to this is again provided by strict impurity control of the materials prior to service in the plant. In production terms, both PPCS models perform at similar ^{14}C levels to fission plants; however, mobility is much lower in fusion, and releases are likely to be well below fission standards. PPCS-B performs better in terms of TBq/GW(electric)yr; however, an impurity-free PPCS-AB is also a ^{14}C-free plant whereas PPCS-B is not. Table XIII summarizes the

[f] This is providing that a detritiation treatment has been carried out. For instance, CSA limits are not fulfilled from a large quantity of LLW of ITER.

[g] They can even lead to consideration of a further category of recycling route, which is the conditional recycle, for instance, reuse in activities where no supplementary irradiation can occur (e.g., for radioactive waste packaging and shielding).

TABLE XIII

Comparison of Long-Lived ($T_{1/2} > 1000$ yr) Activity Production in Near-Term PPCS Models*

Plant Model	PPCS-AB TBq (% ^{14}C)	PPCS-B TBq (% ^{14}C)	PPCS-AB TBq/GW(electric)yr	PPCS-B TBq/GW(electric)yr	PWR TBq/GW(electric)yr
PPCS-grade materials	1995 (58%)	926 (88%)	45	23	4800
Pure materials	395 (0%)	73 (79%)	9	1.8	4800

*The ^{14}C contribution is in parentheses.

amount of long-lived activity generated in the near-term PPCS models and illustrates how controlled impurity levels help limit the amount of long-lived isotopes that is produced. A succinct comparison with a typical fission plant is also given.

VII. CRITICAL ISSUES FOR DISPOSAL, RECYCLING, AND CLEARANCE

It has been shown in Sec. VI that fusion does not produce HLW but generates very few long-lived radionuclides that are well contained within activated metals. Most fusion materials could potentially be recycled or cleared, providing the necessary studies and developments are carried out. To enhance prospects for a successful waste management scheme, we identified the key issues and challenges for disposal, recycling, and clearance. It should be mentioned that as a step forward, the ongoing EU R&D program[19,59] is currently tackling some of these issues, allowing further optimization of the waste management scheme and enhancing the possibility of recycling and clearance as much as practically possible. The EU study comprises a review of the present situation and state-of-the-art recycling methods for typical materials and components of fusion plants based on current European conceptual design studies. It focuses attention on R&D issues to be addressed in order to recycle as much material as possible in a safe, economical, and environmentally attractive manner. The conclusion of this first study is that the solutions and the routes to follow should be developed as soon as possible in order to tackle this important issue as it arises. Moreover, if recycling is foreseen, processes for reuse and refabrication have to be made on an industrial scale.

VII.A. Disposal Critical Issues

Several critical issues for the disposal option can be identified based on the outcome of numerous power plant studies and the assessment of disposal situations in several countries. Note that identifying a common basis for a universal repository seems impossible because of the great diversity in technical and geological repository settings, and in disposal requirements (specific radioactivity, contact dose rate, and decay heat level). Nevertheless, we provided the most critical disposal issues facing the international fusion community:

1. large volume to be disposed of ($\geq$8000 m^3)[h]
2. should dismantling be immediate or deferred?
3. high disposal cost (for preparation, packaging, transportation, licensing, and disposal)
4. limited capacity of existing LLW repositories
5. need for fusion-specific repositories designed for T-containing activated materials or for performing detritiation
6. need for specific activity limits for fusion LLW issued by legal authorities
7. political difficulty of building new repositories
8. tighter environmental controls
9. radioactive waste burden for future generations.

VII.B. Recycling Critical Issues

There is no doubt within the fusion community that recycling has a key role to play to help minimize the large volume of fusion active materials. However, some argue recycling could result in substantial technological difficulties, while others positively claim the environmental benefits far outweigh any adverse effects. On the economic side, a recent Russian study concluded that recycling of a specific type of material (based on vanadium alloy) is less costly than disposal[33] (refer to Sec. III.D). Furthermore, there was a cost-savings demonstration in recycling lead shielding bricks versus disposal in U.S. LLW repositories.[30] On the technology side, a reasonable recycling experience exists within the fission industry. The processes include storing in continuously monitored facilities, segregation of various materials, crushing, melting, and refabrication. So far, the evidence in support of recycling within the nuclear industry is compelling and will be augmented by the growing international effort in support of the GNEP activities. This means we should

[h]This quantity pertains to a 1-GW(electric) fusion power plant.

embrace this opportunity and pursue the fusion recycling development and studies despite the lack of detail on how to fully implement the recycling process now in our designs. In order to provide a broader perspective of the relevant issues involved in the recycling process, we identified several critical issues for the international fusion community to examine with dedicated R&D programs in key areas:

1. development of radiation-resistant RH equipment (>10 000 Sv/h)
2. large (and inexpensive) interim storage facility with adequate heat removal capacity
3. impurity detection and removal mechanisms below current levels
4. dismantling and separation of different materials from complex components
5. energy demand for recycling process
6. cost of recycled materials
7. treatment and complex remote refabrication of radioactive materials
8. radiochemical or isotopic separation processes for some materials, if needed
9. efficiency of detritiation system
10. Are there any materials for disposal? What is their volume? What is their radioactive waste level?
11. What are the properties of recycled materials? Is there any structural role? Can they be reused as filler?
12. aspects of radioisotope and radiotoxicity buildup by subsequent reuse
13. recycling plant capacity and support ratio
14. acceptability of nuclear industry to recycled materials
15. management of secondary waste
16. recycling infrastructure.

VII.C. Clearance Critical Issues

Clearance is highly desirable to minimize the radioactive waste assigned for near surface disposal. Even though the IAEA, European Union, and Russia have published guidelines on clearance of materials from regulatory control, the United States issued its own regulations, which vary widely. The NRC, IAEA, and others should develop universal clearance standards for all radioisotopes of interest to fusion applications and continue their efforts to convince industrial as well as environmental groups that clearance of slightly radioactive solids can be conducted safely with no risk to the public health.

The number of fission reactors reaching the age of 40 yr will rapidly increase after 2010, peaking beyond 2020. Today, the fraction of reactors with more than 20 yr of operation is 75%, while the average age is ~24.3 yr (Ref. 60). This means the decommissioning of nuclear power plants will grow rapidly during the next few decades, generating mainly metallic and concrete materials that are mostly slightly contaminated or noncontaminated. Therefore, we predict a significant increase in the management activity of slightly radioactive fission wastes before 2050. This strongly suggests the development of a dedicated clearance policy in the near future to manage such sizable materials on the national and international levels.[i] The issue of clearing materials from future fusion facilities should be included in this process as well.[61] There is a unique opportunity for the fusion community to get involved in this process and develop a fusion-specific clearance policy, considering the synergies between fission and fusion decommissioning of slightly activated/contaminated materials.

An enormous quantity of slightly contaminated/activated materials, from the decommissioning of an entire generation of nuclear fission facilities, is expected to peak toward the end of the next decade or two. Their management will push the issue of clearance of slightly contaminated/activated material for most and the issue of recyling for some. This offers a great opportunity for the fusion community to take part in the process and develop a clearance policy, considering the similarity between fusion waste and fission decommissioning waste.

Other clearance-related issues that need further assessment include

1. discrepancies between the various clearance standards[8]
2. impact of missing radioisotopes on CI prediction
3. need for official fusion-specific clearance limits issued by legal authorities
4. large (and inexpensive) interim storage facility
5. clearance infrastructure
6. availability of clearance market.

VIII. CONCLUSIONS

This study addresses an integrated approach to the management procedures for active materials following the changeout of replaceable components and decommissioning of fusion facilities. We define this as the

[i] In fact, an increase in the amount of clearable materials already took place during the 1990s, when more and more nuclear power plants came to shutdown and decommissioning. This has lead to the publication of the IAEA safety guide RS-G-1.7 (Ref. 12). As the industry is already dealing with the current clearance levels and asking for stability, however, we believe such a change is difficult to happen in the next few years, at least in Europe.

"back end" of the fusion materials cycle. The attractive environmental features of fusion are put into evidence, and the question of proliferation relevance of fusion power plants is briefly discussed.

Reference is made to previous U.S. and European 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 LLW. Just recently, both clearance and recycling concepts and limits have been revised by national and international organizations. These revisions and their consequences have been examined in this paper and the references therein. More importantly, a new radioactive materials management strategy has been proposed for the clearance, recycling, and disposal approaches.

Concerning the clearance approach, the following may be stated:

1. Different options are available: unconditional clearance, conditional clearance, and no-release materials. Conditional clearance seems to be a viable option in the absence of a clearance market.

2. The problem of public acceptance of clearance and thus recycled material has been addressed: how to improve the actual market for cleared and then recycled materials.[j]

3. Experience gained from the clearance of radioactive waste in Germany, Sweden, Spain, and Belgium is useful.

4. A brief review of the IAEA, U.S., Russian, and EU clearance guidelines, highlighting the similarities and differences, has been carried out.

Concerning the recycling approach, the following may be stated:

1. A brief review of previous approaches to recycling of fusion active materials has been carried out.

2. Lessons learned from the fission experience must be used: hot cell performance and operations with highly radioactive materials.

3. Reuse (refurbishment) and recycling are two complementary approaches.

4. The recycling cost may not be prohibitive.

5. For certain materials, reuse is a solution to minimize active materials inventory and the cost of producing new materials.

6. 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.[30]

7. The question of choosing between disposal and recycling has been addressed.

8. Economic aspects have to be taken into account in deciding the feasibility of recycling.

9. Contact dose rate, decay heat rate, and radioactivity concentration are important radioactive quantities to be limited.

10. Concerning the handling question, hands-on, simple shielded, and RH approaches have been considered.

11. Concerning the routing question, recycling outside the nuclear industry, recycle within nuclear-specific foundries, and other recycling scenarios without melting are viable approaches.

12. The question of reprocessing of radioactive (nonclearable) materials in special facilities in order to separate noxious radionuclides has been addressed. The output of this operation is a small quantity of concentrated radioactive waste, plus a processed material that may be either clearable or nonclearable that can be recycled within the nuclear industry.

Concerning the geological burial approach, we considered two waste disposal categories: LILW and HLW. It was recognized that fusion does not produce any HLW. Disposal as LILW could be an alternative approach but is a less environmentally attractive route to recycling/clearance. At present, the intermediate-depth disposal has not received much attention in many countries. The approval of the LILW category requires the endorsement of national authorities.

Given all the above considerations, an integrated activated materials management strategy has been proposed in Europe: It divides the active 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. Moreover, an approach to the technical difficulty of recycling or waste conditioning, based on a scoring system, depending on the handling and cooling requirements of the components and materials, completed the approach to make it a really integrated system.

In conclusion, we clearly define the parameters that govern the back end of the fusion materials cycle. A new fusion-specific approach for the entire back-end cycle of fusion materials is necessary. Our proposal is a comprehensive one: It considers the evacuation routes for the waste and materials, the handling difficulties, as well as the critical issues and challenges facing all three approaches: recycling, clearance, and disposal. Such an

[j]Fusion will benefit greatly from the experience gained during the decommissioning of fission reactors. The dilemma is whether to dispose of the materials as radioactive waste with the associated problems of finding new repository sites or to clear all slightly activated materials. This stresses the importance of educating the public and soliciting its support for recycling and clearance.

approach requires further refinement, approval of the national authorities, and a dedicated R&D program to address the identified critical issues. Nevertheless, it allows a complete consideration of most of the parameters involved in such a complex materials management system. Also, it allows investigating and comparing different designs and material compositions in view of their impact on the environment.

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