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I.E.A. CO-OPERATIVE PROGRAMME ON THE ECONOMIC, SAFETY AND ENVIRONMENTAL ASPECTS OF FUSION POWER

COLLABORATIVE STUDY ON THE BACK-END OF FUSION MATERIALS

UKAEA final report – November 2007

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SUMMARY

The back-end of the materials cycle plays a key role in maximising the environmental benefits of fusion power generation. Under the auspices of the International Energy Agency (IEA) a worldwide collaborative study has examined the different options for the management of fusion irradiated material focusing on the EU and US standpoints; this document reports the contribution of UKAEA to this project. Following from earlier European work in the field, the irradiated material inventory in two near-term fusion power plants in the European Power Plant Conceptual Study (PPCS) has been computed and analysed with increasing detail and applying the newest findings in the field of fusion waste management, for the first time for PPCS-B. The suitability of this material to follow the two main management routes envisaged, recycling and disposal, has been estimated and compared in a comprehensive manner, the latter for the first time in this kind of study in the EU.

A novel scheme has been developed providing a coarse but insightful tool to evaluate the technical difficulties of treatments and operations on active material. Results of these analyses highlight the over-conservatism of previous studies; all the material in these plants is suitable for recycling shortly (<1y) after plant shutdown. Furthermore, a few decades of storage suffice for the vast majority to be suitable for undemanding techniques or equipment; however some of this material requires active (but not wet) cooling during its interim storage. Disposal in EU low level repositories has been considered; in decreasing order of amount of material accepted, the cases analysed were Germany (Konrad), UK and France (CSA). In the latter case, rejection of metal streams arises largely due to stringent limits on Nb-94 and C-14 activation products. It is pointed out, however, that all disposal criteria were developed for fission waste and are rather over-stringent and arbitrary for fusion: the need to develop relevant standards for fusion in the EU, in a similar way to the US, appears pertinent. In all cases, release from regulatory control (clearance) for either disposal or reuse depends chiefly on the decay of the Ni-63 activation product. Focus has been given to the assessment of long-lived activity: estimation of the amount and radiotoxicity of secondary wastes generated during recycling operations in PPCS-AB and PPCS-B materials has been made. Both PPCS models produce similar C-14 levels to fission, however mobility is much lower in fusion. PPCS-B performs better in terms of production rate per electrical unit, however an impurity-free PPCS-AB is also a C-14 free plant, whereas PPCS-B is not. Alleviation to these issues is achieved by material choices and strict impurity control prior to service in the plant.

1. INTRODUCTION

In the transition from scientific and technological research to industrial implementation, the fusion community will have important socio-economic and regulatory aspects to address; one of the more subtle ones will be the management of irradiated material. Understanding the particularities and radiological characteristics of fusion irradiated material, and conceiving credible and environmentally acceptable management routes based on up-to-date practices and regulations, are two key elements in the maximisation of the environmental benefits of fusion power as an energy source. Under the auspices of the International Energy Agency (IEA) Co-operative Program on the Environmental, Safety and Economic Aspects of Fusion Power, an international collaborative study on fusion irradiated material has examined the back-end of the materials cycle as an important element in maximising the environmental benefits of fusion power generation. The study analysed the material inventory in fusion power plants and addressed the potential management procedures for active materials following the replacement of components and decommissioning of fusion facilities, [1].

This document reports the UKAEA contribution to this international collaboration. In the last few years, European work in the field produced a first estimation of the active material inventory in a range of power plant concepts, for the first time providing a 2D examination of activation levels, [2]. The methodology used for the analysis of the material was, however, outdated and inconclusive, and the detail of the computational models showed potential to be increased. Follow up studies concentrated in a more realistic assessment based on the latest industrial practices and regulations, more detailed modelling, near-term plant concepts and the envisioning of suitable treatments for some of the material streams, particularly for PPCS-AB, [3].

This more sensible approach provided valuable information and pointed towards important R&D needs and measures to minimise the material inventory and its radiotoxicity. However, the increased detail in the activation analyses remained to be fully applied to PPCS-B, the second of the PPCS plants based on European ITER test blanket module technology. Furthermore, although the suitability for recycling was more realistically evaluated no practical measurement of the technical difficulties posed by the radioactive nature of the irradiated material was made. A scheme facilitating such assessment, even if rudimentary, would be a valuable instrument for the analysis and comparison of the implications of the recycling route for different plant concepts, and provide an insightful tool to evaluate the difficulty of whatever operations were envisaged. In order to overcome previous unpractical classification methods this scheme should be based on actual regulatory guidelines and/or industry experience, such as those gathered in the PPCS follow-up work, [3]. Moreover, it should serve not only to classify the material at specific times but to ascertain storage time requirements for the technical difficulty to be relaxed and processes to become easier or less challenging due to decay of the activity.

Secondary wastes from recycling operations have to date received little attention in European studies in the field. Management routes for long-lived activation products such as carbon-14, generated during operation and concentrated by recycling treatments, need to be addressed; an essential first step is to estimate their quantity and characteristics. Finally, although several factors drive an interest in pursuing the recycling route for fusion materials in the EU its alternative, disposal, should not be categorically disregarded as it has been the tendency in recent years; it might be the most practical option for some material streams. A comparison of the suitability of fusion irradiated material for shallow-land burial, as well as recycling, based on up-to-date regulatory and industrial standards should provide a more complete picture of the management strategy for the back-end of fusion materials.

Summarising, the following aspects of the fusion material back-end have been analysed from an EU standpoint as part of the IEA collaborative study:

(a) detailed activation analysis and material inventory of PPCS-B;
(b) development of a scheme assessing the difficulty of recycling or waste conditioning operations on fusion irradiated material;
(c) revision of disposal regulations in EU repositories;
(d) application of the above to PPCS-AB and PPCS-B, for classification of the inventory at given times, comparison of fusion technology concepts and estimation of storage times, capacity and cooling requirements;
(e) analysis of secondary wastes and long-lived activation products in both models;

2. MANAGEMENT OF FUSION IRRADIATED MATERIAL

2.1 PPCS irradiated material inventory

The bulk of the radioactive inventory in a fusion power plant is the result of the activation of materials under irradiation by plasma neutrons, experienced by all tokamak components to a greater or lesser extent. In-vessel, fuel systems and other components also suffer from surface contamination with tritium. The European Fusion Programme favours the fast deployment of fusion power and is consequently studying near-term power plant concepts, such as PPCS-AB and PPCS-B considered here, [4,5]. These are, in general, large machines designed assuming little extrapolation from current expertise. The actual fine detail of the activation distribution and characteristics is very sensitive to details of plant design and material choices. Previous studies show, however, that a consequence of the above design is a significant portion of the decommissioning stream (i.e. outer, lifetime components) being only very mildly activated and therefore potentially suitable for release from regulatory control after a period of decay. Owing to their position closer to the plasma in-vessel, replaceable components receive most of the neutron fluence and experience greater activation.

PPCS-AB has a liquid lead-lithium breeder while PPCS-B has a pebble bed beryllium multiplier/lithium silicate breeder. From the management point of view, the entire material inventory in these PPCS models can be classified into six different material categories:

(1) steels, further subdivided into (1a) ferritic steels, and (1b) austenitic steels and alloys;
(2) tungsten materials, subdivided into (2a) tungsten-rich alloys (e.g. plasma-facing armours, W+1%La_2O_3 in PPCS-AB divertor) and (2b) tungsten carbide used in PPCS-AB cold shield;
(3) lithium lead;
(4) ceramics, in the form of pebble beds;
(5) zirconium hydride, used in PPCS-B cold shield;
(6) small amounts of other coil materials: epoxy-glass, superconductor strand.

The irradiated material mass to be managed in a fusion power facility is generated in two stages: first during operation, by routine replacement of components such as the blanket, and then during the decommissioning, from the dismantling of lifetime components such as the coils and vacuum vessel. Figure 1 shows the partition of PPCS-AB and PPCS-B material inventory into the aforementioned stages and categories; total masses are ~124,000 and ~51,000 tonnes, respectively, [6]. The large difference arises due to (a) differences in tokamak size and radial builds, and (b) the large mass of LiPb used in PPCS-AB (~35,000

tonnes) compared with the amount of ceramic pebble beds in PPCS-B (~3,000 tonnes). These amounts do not consider buildings and balance-of-plant systems, which can represent up to ~90% of the total amount of material on-site.

There are two main strategies for the management of fusion irradiated material: recycling for reuse (in or outside the nuclear industry) and disposal of the material as waste in repositories (again, nuclear or conventional). The application of each of them is highly dependent on socio-economic, technical and political issues, and in the regulatory framework (hence in national and international conventions).

2.2 Management routes: recycling

In the EU, limited availability and stringent acceptance criteria of land burial facilities, future scarcity of industrial materials and other socio-economic issues drive an interest in pursuing, as much as reasonably possible, the recycling and reuse of materials following their service in a fusion power facility, be this within the nuclear industry or otherwise. A schematic diagram of a fusion materials "closed" back-end strategy, based on maximum recycling, is shown in Figure 2.

The level of detail and radiological criteria employed in the PPCS analyses was insufficient to provide a firm estimation of the recycling potential of the material inventory. Criteria served to quantitatively describe the characteristics of the irradiated material, but did not ensure the feasibility of recycling as did not account for the availability of industrial processes and methods; some have been repeatedly pointed out as unrealistic and severely over-conservative. Results of follow-up work overcame such conservatism and identified suitable industrial processes for some of the material streams. It was realised that radiological criteria were not the key drivers of the suitability of the materials for recycling, and indeed only very high radioactivity levels could prevent recycling operations due to the need of active wet cooling to remove decay heat. Some particular recycling treatments, such as metal melting in nuclear foundries, were seen to have specific levels limiting their applicability, [3]. Table 1 shows the new, relaxed, generic radiological levels for the applicability of recycling, and an example of a more stringent specific one for the particular case of metal melting.

Rather than to radiological criteria, however, recycling of irradiated material is subject to:

- the provision of appropriate and viable industrial treatments and facilities for the material to be processed and conditioned for reuse;
- the existence of a suitable application for the reuse of the recycled product.

Table 1: management routes – recycling (EU standards).

		contact dose rate *mSv/h*	***decay heat rate*** *W/m^3*	***specific activity*** *Bq/kg*	***clearance index*** *CI*	*ref*
clearance (all applications)					<1	[7]
recycling (nuclear applications)	**metal foundry**			<10^{+6}		[3]
	processes t.b.d.	< 10^{+7}	< 2000			[3]
refurbishing (fusion applications)		< 10^{+7} (*)	< 2000			
actively cooled storage (no recycling)			> 2000			

(*) essentially no upper limit to dose rates.

Reuse can be either in nuclear or non-nuclear applications, depending chiefly on the radiological characteristics of the irradiated material:

- if below very stringent radiological levels, the material is released from nuclear regulatory control and reuse is allowed in any industrial application; this is known as "clearance" and is normally achieved only by materials very mildly activated, such as outer tokamak structures (vacuum vessel and coils);
- if above such levels, reuse is only possible in nuclear applications (fusion or otherwise) following recycling treatments.

A generally accepted method to assess the suitability of a material for clearance from regulatory control is via a "clearance index", CI, by application of nuclide-by-nuclide clearance levels to the specific activity of the material from each nuclide. Clearance is granted when CI < 1. The International Atomic Energy Authority (IAEA) and several national agencies periodically issue guidelines for clearance levels, which differ but are developed along similar lines. The 2004 set of values are used in the present study.

Distinction must be made between refurbishment (or *in-situ* reuse) and recycling of materials. In the context of this work, 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 time scale (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), involving greater processing in dedicated facilities. Refurbishment procedures need to occur on-site, possibly within the hot cell, and contribute importantly to the reduction of the mass to be recycled later on. Earlier work showed how the refurbishing of the liquid breeder in PPCS-AB could reduce the amount of this material stream from ~35,000 tonnes to ~ 7,000 tonnes, reducing the operational material inventory by ~40% and the total by ~22% (down to ~96,500 tonnes), [6].

2.3 Management routes: disposal

If for any reason (no application, nuclear or otherwise, found for irradiated material, economic considerations, etc) recycling and reuse cannot be envisaged, disposal in repositories is the alternative management route. Materials for which no reuse is foreseen thus become *waste*. A schematic diagram of a fusion materials "open" back-end strategy, based on disposal, is shown in Figure 3. Three different kinds of disposal can be foreseen:

- when activation is below stringent levels, namely those established for clearance, the waste is considered to be non-active and disposal can be provided for in conventional industrial waste repositories;

Table 2: management routes – disposal (EU standards).

		contact dose rate *mSv/h*	***decay heat rate*** *W/m^3*	***specific activity*** *Bq/kg*	***clearance index*** *CI*	*ref*
non-active waste (conventional repository)					1	[7]
active waste (nuclear repository)	LLW France UK Germany	< 2	< 10	(*) 1.2 10^{+7}		[11] [8] [9]
	ILW		< 2000			[10]
	HLW		> 2000			

(*) LLW nuclide-specific limits for the *Centre de Stockage the L'Aube* (CSA) can be found in reference [11].

- if above clearance but still below certain limits, and consisting mainly of short-lived nuclides, active material can be disposed of as low level waste (LLW) normally, but not always, in near-surface nuclear repositories;
- when not qualifying for near-surface disposal, alternative storage for intermediate level waste (ILW) and high-level waste (HLW) is required, the difference between the two being based upon decay heat generation rates (e.g. deep geological storage).

The boundaries between LLW and ILW, and the definition of "short-lived" activity, are highly dependent on national regulations. The French convention applying to ITER waste, for instance, imposes nuclide-by-nuclide limitations, [11], and so do USA regulations, [12]. UK regulations follow IAEA recommendations, [8], whereas the limits in the Konrad repository in Germany, a deep geological site, only apply to contact dose and decay heat rates, [9]. HLW levels have an international standard in IAEA recommendations, [10]; to date, however, no country has officially endorsed a final solution to the disposal of this waste. Levels are summarised in Table 2.

2.4 Assessing the technical difficulty of operations on active material

In transcending the previous PPCS classification and taking a more practical approach to the management of material, it was established that the absolute feasibility of recycling does not depend strongly on radiological levels (apart from decay heat rates). Active waste classification for disposal, on the other hand, depends entirely on these. Regardless of the route followed, however, an important element in a credible management strategy is to be able to estimate the technical difficulty of recycling or waste conditioning treatments and operations. Detailed radiological data and up-to-date industry practices and regulations can and must be used to:

- ascertain technical details such as cooling, storage time and capacity, transport, shielding and remote handling needs;
- compare the performance of different fusion technologies and power plant concepts;
- estimate time scales for the activity to decay to predetermined levels of relevance to the different processes;

It is difficult to foresee at this stage radiological requirements to the different treatments and processes, mainly due to the fact that these have only been identified for a few material streams following certain routes. It is reasonable to expect, for instance, that it will be possible to process materials meeting nuclear foundry standards in these facilities just like any other nuclear materials, and using the same or similar techniques and equipment. Likewise, material classifying as LLW will be suitable to follow the conditioning procedures foreseen in near-surface repositories. Until the design stage of fusion power facilities is closer to its industrial implementation, however, it is not likely that processes and routes for other materials will be thoroughly developed.

Still, 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 whatever processing is envisaged, be this for recycling or disposal. For this purpose, a rudimentary scheme has been developed based on two main aspects: handling equipment/procedures, and cooling requirements. For handling, three main types are foreseen, [13]:

(a) unshielded hands-on handling by qualified radiation workers, HOH, when contact dose levels are below 10 μSv/h,

Table 3: scheme determining the radiological complexity of operations on irradiated material.

handling (H)	*cooling [C]*	*difficulty*	*score (H+C)*
HOH = 1 SHOH = 2 RH = 3	NONE = 0 DRY = 2 WET = 5	**level 1**	1
		level 2	2
		level 3	3,4,5
		level 4 (no operations possible)	6,7,8

(b) shielded hands-on by qualified radiation workers, SHOH, when contact dose levels are below 2 mSv/h; equipment such as shielded glove boxes can be conceived under this category;
(c) remote handling, RH, when contact dose levels are above 2 mSv/h.

As for cooling requirements, the following levels are envisaged, [14]:

(a) no active cooling needed (only natural ventilation) when decay heat rates are <10 W/m^3;
(b) dry cooling (e.g. active ventilation) when decay heat rates are >10 W/m^3 but <2000 W/m^3;
(c) 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 3 was developed. The rationale behind the scheme is that:

- Level 1 material can be handled hands-on, and requires no cooling whatsoever.
- Level 2 material can be handled using shielded hands-on methods and equipment, and again no cooling is required.
- Level 4 material requires active wet cooling; it is anticipated that no operation on this kind of material is possible.
- Level 3 covers everything in between levels 2 and 4: essentially, material requiring remote handling equipment and/or dry cooling.

The above scheme can be used to ascertain storage times for the activity of the material, and therefore the technical difficulty of treatment processes, to fall within these levels. In parallel to this, comparison of different fusion technology concepts and plant designs can be made via conventional “snap-shot” classification at specific times. This has been applied to the detailed activation results for PPCS-AB and PPCS-B in order to compare the characteristics of the irradiated material inventory in both plants.

2.5 Secondary wastes and long-lived activation products

Even in the unlikely case of recycling the entire material inventory in the plant, some secondary waste generation during the different steps in the recycling process is foreseen; this is represented by the orange arrow flow in the diagram in Figure 2. The main sources of secondary wastes from fusion recycling are foreseen to be:

- Dust and melting wastes (solids), from the separation/segregation and restoration/conditioning operations on the recycled material; amounts of these vary depending on the mechanisms employed, however a conservative estimation is ~5% of the total processed weight, [13].
- Only when de-activation is foreseen: concentrated activation products from chemical or isotopical processing (mainly expected in liquid form).

It is possible to conceive the reintroduction of the former in the recycling process at some stage; the latter, however, requires an alternative route. Previous studies pointed out the significance of carbon-14 ($t_{1/2}$ ~ 5730y) as a potential hazard from fusion power*; it was found to lead to the largest, though still small, external economic cost as a result of its incorporation to the carbon cycle in a full-scale fusion industry, [15]. C-14, as well as other long-lived nuclides, build up within the materials as a consequence of neutron irradiation. C-14 production also occurs in fission power plants through neutron irradiation of the coolant and other materials (H_2O, CO_2, N_2 coatings): between 0.7 (PWR) and 50 (HWR) TBq/GWe.a according to [16].

Artificial long-lived activation may cause concern during operation, due to release of effluents, as well as during decommissioning. In fission, C-14 generally takes gaseous form (CO_2) and is difficult to contain, thus a large fraction of it is released as operational effluents: release values between 0.22 (PWR) and 1.6 (HWR) TBq/GWe.a are reported in the literature, [17]. The vast majority of the C-14 and long-lived activation products in a fusion plant, however, are embedded in the structures; hence it is reasonable to expect that mobility and release fractions during normal operation will be much lower than in fission plants, [18]. The only exception to this would be long-lived activation products in breeder materials, which are either circulated or purged with gas and could lead to effluents during operation.

As for decommissioning, if an “open cycle” is followed limits to the concentration of C-14 and other long-lived nuclides in materials exist today (and will exist in the future) in near-surface burial facilities (e.g. CSA limits, [11]). In a “closed cycle” maximising recycling and reuse, processing operations such as melting could lead to the release of substantial amounts of C-14 and other long-lived activation products. Alternatively, materials could be de-activated and long-lived nuclides concentrated into secondary wastes which would also require disposal. In any case, C-14 and long-lived activation products compromise the benign environmental performance of a fully developed fusion industry, be it in the form of operational releases, repository limitations or concentrated secondary wastes. It is therefore sensible to estimate their amounts and to prospect for materials and choices to minimise production.

3. PPCS CASE: REVISION OF ACTIVE MATERIAL INVENTORY

3.1 Neutron transport and activation modelling

The assumption made during the latest European work in the field was that PPCS-B outer components (cold shield, vacuum vessel and toroidal field coils) would behave similarly to those in PPCS-AB. However the two plant designs differ greatly in dimensions and shielding performance, and therefore this claim is difficult to sustain. The level of detail in PPCS-B activation calculations has now been raised to the same standards as in PPCS-AB. The methodology of the neutron transport and activation computer modelling is summarised here:

- the HERCULES software, [19], developed and maintained at UKAEA Fusion, was employed to develop a geometry model of the plant based on cells resulting from radial layering and poloidal sectioning; the level of detail in outer components was increased, compared to PPCS work, by extra layering and by sectioning the toroidal field coils (TFC) into separate limbs, which for the first time led to real 3D modelling (see Figure 4);

* C-14 occurs naturally in the atmosphere from cosmic ray bombardment of nitrogen in air (N-14(n,p)C-14 reaction); a fusion power plant replicates this process when fusion neutrons impact on nitrogen impurities and other elements in the tokamak materials (e.g. oxygen in water or breeders, via O-17(n,α)C-14).

- the neutron field distribution throughout this model was computed running 6.10^{+7} histories using an MPI parallel version of MCNPv5 in a cluster of 72 dual processors running linux, track length estimation of the neutron flux and cell importance mapping for variance reduction, [20]; results are illustrated in Figures 5a and 5b;
- using MCNP neutron flux results obtained in such way, HERCULES was employed to automate the estimation of nuclide inventories and radiological quantities throughout the geometry by coupling it to the FISPACT code and EAF nuclear data libraries (v2005), [21]; individual materials rather than mixtures were analysed separately.

3.2 PPCS-AB active material assessment

The radiological information of previous PPCS-AB analyses, [6], as well as that of the new PPCS-B calculations, was analysed using the radiological scheme and recycling/disposal categories and guidelines outlined in previous sections. A purpose-built Excel workbook feeding from HERCULES output files automated the classification and analysis procedures. Figure 6 shows a time history of the radiological score according to the scheme in Table 3; Figures 7 to 9 show the classification of the material for waste disposal according to the German, UK and French regulations, respectively. Tables in the Appendix show the partition of these results into the material categories defined in section 2.1.

All results presented here correspond to the scenario in which refurbishment and reuse of the liquid breeder throughout the entire lifetime of the plant is foreseen (total amount of material ~96,500 tonnes). Considering the radiological score, a significant result is that nearly all material in PPCS-AB is suitable for recycling (level 3) very shortly after shutdown (<1y), and only small amounts (<12%) require cooling times of between 1 and 5 years to do so. After 100y only small amounts of material (~9% of the total) have technical difficulty of level 3, consisting mostly of LiPb breeder and plasma-facing tungsten[*]. These materials do not decay to lower levels for several centuries (e.g. ~350y to level 2 for tungsten). Figure 10 shows the cooling times required for PPCS-AB steel structures (categories 1a and 1b) to decay to level 3 and level 2, respectively. There is a marked difference in decay times between inboard and outboard sides and between permanent (decommissioning) and replaceable (operational) components in both cases. Results are in agreement with earlier and more conservative estimations, [22].

The disposal classification according to German limits (Fig. 7), based on contact dose and decay heat rates, is expectedly similar to the radiological scoring and varies strongly with decay time. After 100 years most of the material is considered LLW, the remaining ILW corresponding again to LiPb and plasma-facing tungsten (~9%). In the UK the time dependence is again strong: the stringent activity criterion limits the amount of LLW and increases the ILW to ~41%, mainly due to Ni-63 activity (Fig. 8). Finally, the most stringent criteria are found in France (Fig. 9), where specific limits to long-lived nuclides (mainly Nb-94 and C-14, discussed later) increase the amount of ILW to ~65% and eliminate the time dependence (except for clearance, for which the decay of Ni-63 generated in steels plays a key role in all cases). The clearance share, based on universal IAEA values (2004), is ~21% in all cases (~25% for 1996 levels) and comes in its totality from the decommissioning stage.

3.3 PPCS-B active material assessment

For PPCS-B, Figures 11 to 15, after 100y only ~5% of the material is categorised as level 3, mostly plasma-facing tungsten and ceramic breeder which take a few centuries to decay to

[*] If LiPb refurbishing is not accounted for, after 100y only the plasma-facing tungsten remains as level 3, however the total amount of material is ~124,000 tonnes.

lower levels. Previous studies have shown, however, that in the case of the breeders this is entirely caused by activation of impurities, [6]. Figure 15 shows the cooling times required for PPCS-B steel structures (categories 1a and 1b) to decay to level 3 and level 2, respectively. As for disposal, the amounts of material not meeting acceptance criteria are 5% in Germany, 41% in the UK and 54% in France. The 2004 IAEA levels and refined computer modelling result in a dramatic reduction of the clearance share of this plant from ~22% (1996) to ~1%.

An important consideration is that, in both plants, most level 3 material requires some active (but not wet) cooling; Figures 16 and 17 show the history of the mass requiring cooling for each material category in both models. The vast majority of the operational streams (Eurofer, W) require some sort of cooling for a period of between 10 and 25 years. For LiPb, this time span extends to 25-50 years. As for the decommissioning streams, only WC and some 316ss (from the vacuum vessel) require cooling for up to 10 years.

Despite the small quantities, analysis of the activation inventory points towards Nb-94, and C-14 to a lesser but also important extent, as the main sources of rejection of PPCS-AB and PPCS-B steels and tungsten material streams in the French LLW repository. To date, no CSA limit exists for Pb-205, nor for the majority of long-lived activation products in pure LiPb and Li_4SiO_4; rejection of these materials occurs, however, again due to Nb-94 and C-14 contributions generated by irradiation of impurities. Be-10 is the cause of rejection of the ceramic multiplier in PPCS-B.

4. PPCS CASE: SECONDARY WASTES

According to the above analyses and to estimations made in earlier work, [13], the amounts of secondary wastes generated from the operation of these near-term PPCS plants would be as described in Table 4. Specific activity levels of those wastes generated during segregation and conditioning treatments would be the same as those in the material being processed, hence the proportion of secondary wastes per type of waste would match that of the original material, described in sections 3.2 and 3.3. It is estimated that de-activation processes and concentration of activation products would achieve a 10^3 reduction in mass, with respect to the original material. Quantities and main activation products in secondary wastes from de-activation of PPCS-AB and PPCS-B materials are described in this section. Only nuclides with half-life greater than $t_{1/2} > 500$y were considered.

4.1 Carbon-14

Table 5 presents the amounts of C-14 generated in these two plants from the above contributions based on PPCS activation analyses, [6], and a comparison with PWR and HWR fission data. The main sources of C-14 in PPCS-AB and PPCS-B are as follows:

Table 4: PPCS secondary wastes.

plant model	origin	mass / form	type
PPCS-AB	segregation and conditioning treatments	~4,800 tonnes, solid	LLW and ILW*
	de-activation processes	~95 tonnes, liquid	ILW
PPCS-B	segregation and conditioning treatments	~2550 tonnes, solid	LLW and ILW*
	de-activation processes	~50 tonnes, liquid	ILW

* see sections 3.2 and 3.3.

Table 5: C-14 production in PPCS and typical fission plants (main constituents in bold).

material source	precursor (%wt)	PPCS-AB,TBq	PPCS-B,TBq	PWR [16]*	HWR [16]*
1a, 1b	N (0.03)	1110 (95%)	688 (84%)		
2a, 2b	N (0.0009)	8 (1%)			
3	N (0.0004)	47 (4%)			
4 - beryllium - lithium silicate	N (0.01) **O (54.2)**		70 (9%) 58 (7%)		
water coolant	**O (88.9)**			32 (100%)	1050(47%)
annulus gas system	**N (100)**				1200(53%)
total, TBq total, TBq/GWe.a		1165 26	816 20	32 0.7	2250 50

* extrapolated to 1.5GWe and 30y operation.

PPCS-AB: (1) nitrogen impurities in metals,
(2) nitrogen impurities in LiPb breeder.

PPCS-B: (1) nitrogen impurities in metals,
(2) nitrogen impurities in beryllium and Li_4SiO_4 breeding materials,
(3) oxygen in Li_4SiO_4.

These amounts lead to a production rate of ~26 TBq/GWe.a in PPCS-AB and ~20 TBq/GWe.a in PPCS-B. The smaller blanket thickness and overall plant size of PPCS-B, which would allow expecting a lower production, are to some extent counteracted by the much softer neutron spectrum in the blanket leading to greater generation by means of higher reaction rate, and to an increased production in the shield. These values are within the range of production in fission plants which, as discussed previously, are subject to higher volatility and release fraction than fusion.

Table 6: other long-lived nuclei in PPCS and typical fission plants (main constituents in bold).

source	precursor(%wt)	nuclei	PPCS-AB,TBq	PPCS-B, TBq	PWR,TBq [23]
1a, 1b	**Mo***,Nb (0.001)	Nb-94	38		
	Mn (0.4)	Mn-53	5	10	
	other impurities	several	80	20	
2a, 2b	Mo, Nb (0.05)	Nb-94	2		
	other impurities	several	74		
3	**Pb (98.7)**	Pb-205	377		
		Bi-208	13		
	Mo, Nb (0.001)	Nb-94	1		
	Ar, Ca (0.009)	Ar-39	151		
	other impurities	several	89		
4 - beryllium	**Be (99.4)**	Be-10		5	
	U (0.0032)	several		75	
- lithium silicate	other impurities	several		<1	
UO_2 fuel	**U (88.9)**	FFPP			$1.48\ 10^5$
		Pu-239			$2.50\ 10^4$
		Pu-240			$4.27\ 10^4$
total, TBq			830	110	$2.16\ 10^5$
total, TBq/Gwe.a			19	2.7	4800

* Molybdenum: main constituent in 1b (2.5%wt), impurity in 1a (0.0012%wt).

Table 7: comparison of long-lived (1000y) activity production (C-14 contribution in brackets).

plant model	PPCS-AB TBq (% C-14)	PPCS-B TBq (% C-14)	PPCS-AB TBq/GWe.a	PPCS-B TBq/GWe.a	PWR TBq/GWe.a
impure materials	1995 (58%)	926 (88%)	45	23	4800
pure materials	395 (0%)	73 (79%)	9	1.8	4800

4.2 Other long-lived radionuclides

Regarding other long-lived nuclides, data are summarised in Table 6. The greatest single contributor in PPCS-AB is Pb-205 ($t_{1/2}$ ~15.3 10^6 y) generated in the LiPb breeder. FISPACT data show values of ~377 TBq (i.e. ~8.4 TBq/GWe.a). In PPCS-B there are two contributions arising in the beryllium breeder: (i) Be-10 ($t_{1/2}$ ~ 1.6 10^6 y) from irradiation of Be-9, and (ii) actinides and transuranides, including plutonium, from irradiation of U and Th impurities. Finally, there are also contributions of other long-lived nuclides generated from the irradiation of impurities other than nitrogen in the plant steel structures of both models (e.g. Nb-94). For comparison with fission, a typical 1.5 GWe PWR reactor produces about 3300 TBq/GWe.a of fission products (FFPP) and about 1500 TBq/GWe.a of plutonium, [23].

Because of the nature of neutron-induced transmutation, nuclides having a half-life much greater than the length of the irradiation and relatively small neutron interaction cross-sections build up approximately linearly with irradiation time. Hence, from the point of view of generation of long-lived activity, it makes no difference whether the material is reused (when recycling is pursued) or if it is disposed of and replaced by fresh components. The only difference would be the concentration of this activity per mass of irradiated material, which as discussed earlier may lead to rejection from LLW repositories. It follows that the only way to alleviate the problem is to control the level of the precursors in the first place and therefore, since main constituents cannot be avoided, the level of impurities. Table 7 shows a comparison of the long-lived activity generated in both plants assuming pure and PPCS-grade materials (including impurities). PPCS-B performs better in terms of TBq/GWe.a, however an impurity-free PPCS-AB is also a C-14-free power plant.

5. DISCUSSION

Following from earlier European work in the field the irradiated material inventory in two near-term PPCS fusion power plants been computed and assessed with increasing detail and applying the latest developments in the field of fusion waste management. The suitability of this material to follow the two main management routes envisaged, recycling and disposal, has been estimated and compared in a comprehensive manner. A novel scheme has been developed 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; a scoring table rates the material in levels of increasing difficulty.

This scheme is suitable for either the estimation of interim storage times or “snap-shot” comparison of different concepts at given times, and has been applied to both near-term PPCS models. Results emphasise the over-conservatism of previous studies; all the material in PPCS-AB and PPCS-B appears to be:

Table 8: summary of radiological scoring and disposal potential for PPCS-AB and PPCS-B 100y after plant shutdown, in tonnes (% of the total in brackets).

plant model	level 3	level 2	level 1	ILW Germany	ILW UK	ILW France	clearance
PPCS-AB	8,682 (9%)	62,597 (65%)	25,296 (26%)	8,682 (9%)	39,510 (41%)	62,415 (65%)	20,216 (21%)
PPCS-B	2,509 (5%)	34,370 (69%)	13,248 (26%)	2,509 (5%)	20,541 (41%)	27,668 (55%)	496 (1%)

(i) suitable for recycling shortly (<5y) after plant shutdown;
(ii) after a period of time from a few decades up to 100y, 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); a large share of this material, however, requires active (but not wet) cooling during some of its interim storage time.

Disposal of PPCS-AB and PPCS-B active material in EU low level repositories has been considered. Due to the variety of regulations and acceptance criteria, a selection of cases needed assessment. In decreasing order of amount of material accepted, the cases analysed were Germany (Konrad), UK and France (CSA). In the latter case, rejection of metal streams is largely due to stringent limits on Nb-94 and C-14 activation products. Both of these are generated by impurities (Mo, 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 Ni-63 ($t_{1/2}$~100y) activation product. To maximise acceptance in CSA and clearance of outer components the use of impurity-controlled Eurofer (1a) throughout the plants is recommended (replacing 316ss (1b) in the vacuum vessel and toroidal field coils, where both Mo and Ni are main constituents).

It must 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 over-stringent and arbitrary for fusion-relevant radionuclides, having dubious scientific justification. The development of rigorous fusion-specific disposal criteria in the EU, as done in the US, 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 8 summarises the radiological scoring and disposal results described in this document. 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 (1.45 and 1.35 GWe, respectively). The former is massive and focuses on the provision of heavy shielding in inner, replaceable components to reduce the neutron fluence and maximise the clearance of lifetime, outer ones (up to 21% of the total material after 100y). 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 (nearly half), which might represent a substantial advantage.

Estimation of the amount of secondary wastes 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, carbon-14 being recognised 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 C-14 levels than 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/GWe.y, however an impurity-free PPCS-AB is also a C-14-free plant whereas PPCS-B is not.

The analyses presented here illustrate the main challenges associated with the back-end of the fusion material cycle in near-term plant concepts:

- The time scales, from several decades to 100 years, for the radiological features of irradiated material to decay to levels simplifying the technical difficulty of waste treatment and recycling operations. Appropriate storage and cooling arrangements for such extended time scales and amounts of material are yet to be broadly thought of.
- The build-up of long-lived activation products, and in particular C-14 and Nb-94, which result in undesirable effluents, concentrated secondary wastes and/or failure to meet some stringent repository standards. Careful material selection and impurity control are the main tools to alleviate this issue.
- The need to develop and introduce guidelines for fusion-specific waste regulations, be this clearance or disposal levels.

Moreover, it is desirable to further develop credible industrial processes and facilities for the recycling treatment of such vast amounts of activated material, and in particular metals. Work already done in this direction, [3,6,13], is susceptible to be extended and improved by the study of treatments for all material categories in the PPCS plants, and by an extensive analysis of a few particular cases of interest. It is also desirable to compare the results obtained for the two near-term options analysed here with the more advanced design PPCS-D (based on SiC structures and self-cooled LiPb breeding blanket), in order to confirm or refute C-14 results from earlier work estimating no great advantages from the use of such under-developed technology, [24]. Routes for potential environmental releases should be addressed, particularly for the activity in the breeders and during recycling operations. It is in the best interest of the smooth development of fusion power to address these issues during the conceptual stage of power plants, thereby envisaging a sound back-end strategy based on generally accepted industry practices and regulations.

Acknowledgement

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FIGURES

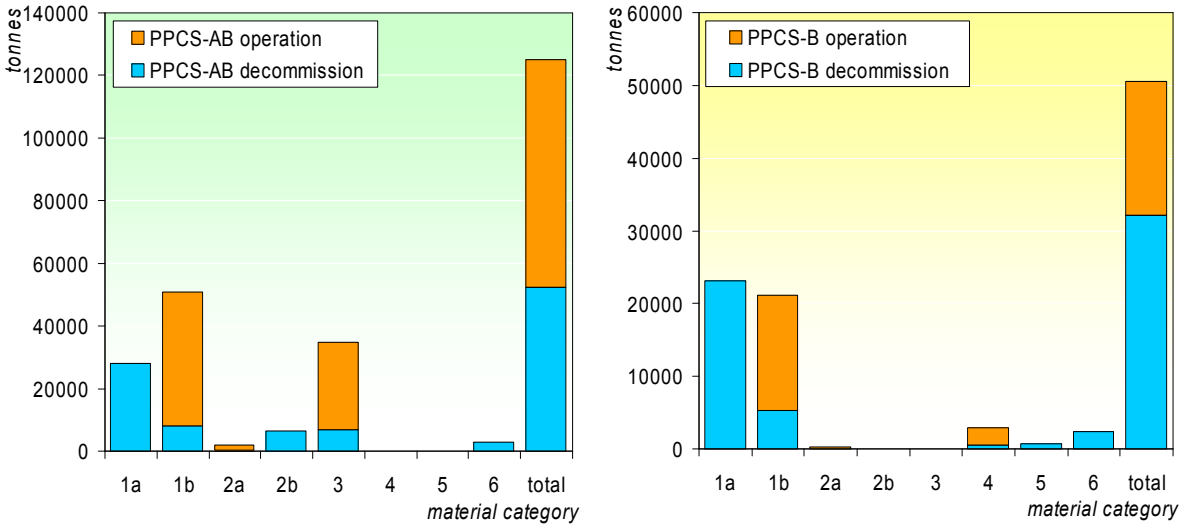

Fig. 1: material inventory in PPCS-AB (left) and PPCS-B (right).

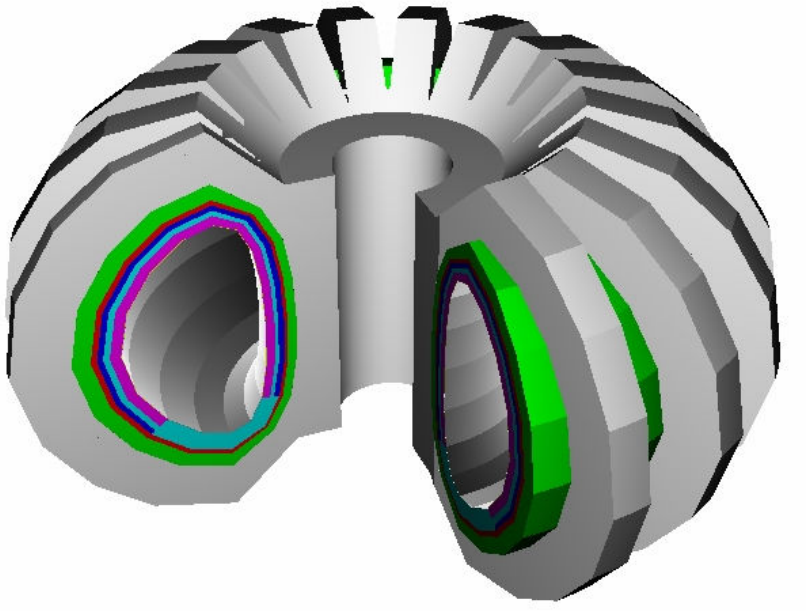

Fig. 4: cutaway of PPCS-B HERCULES geometry for MCNP.

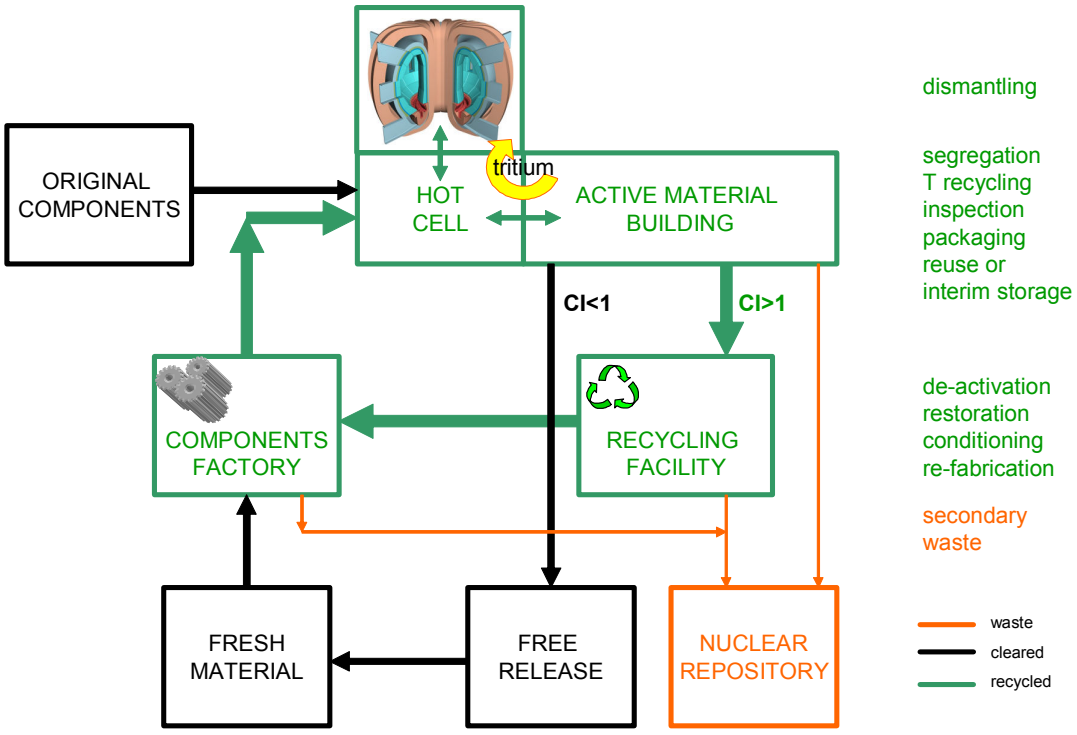

Fig. 2: fusion materials back-end closed strategy.

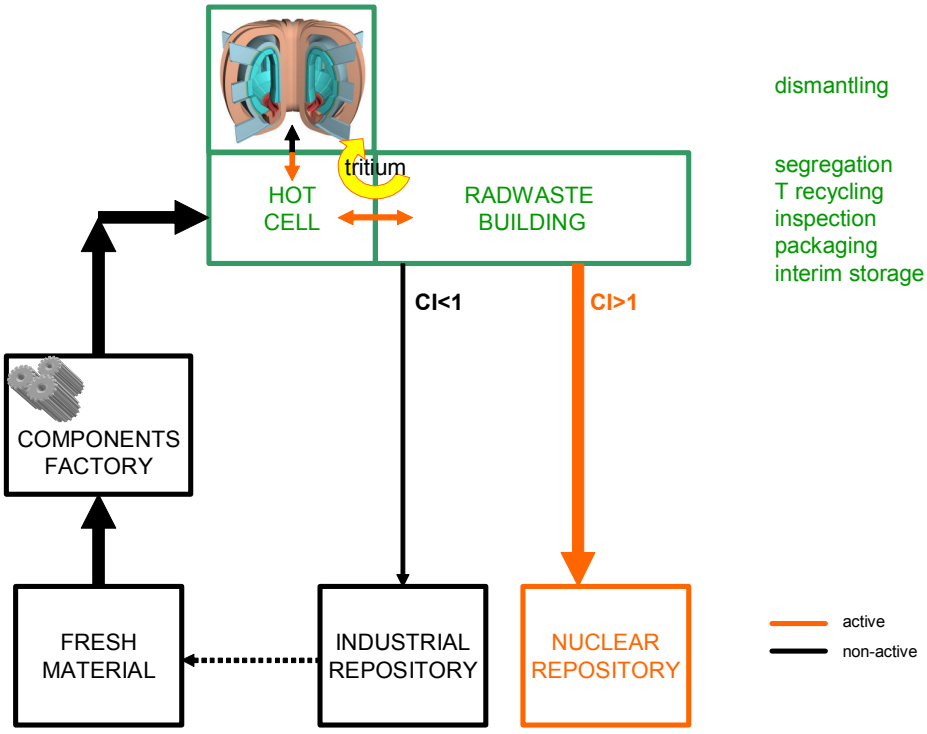

Fig. 3: fusion materials back-end open strategy.

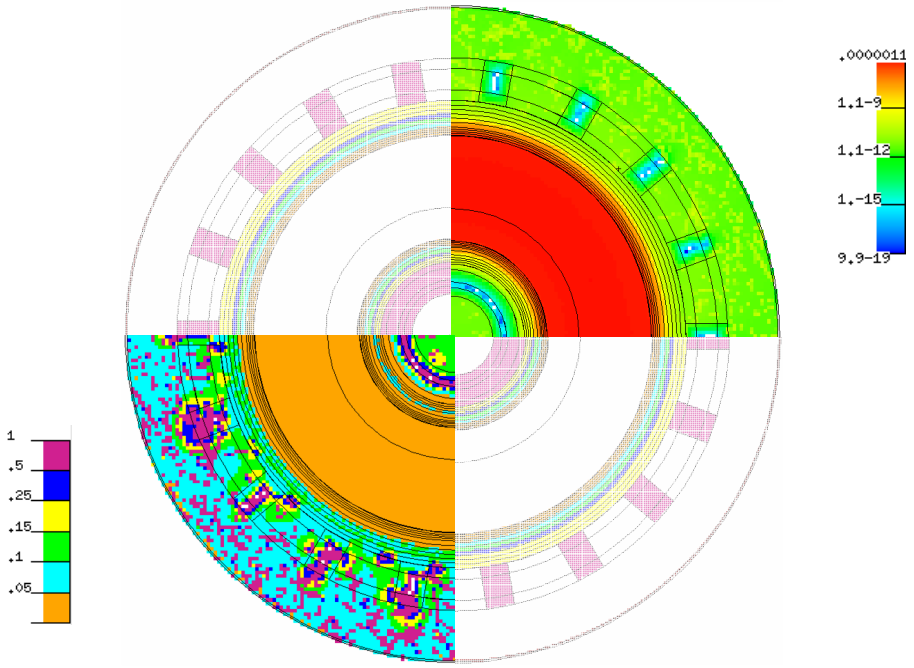

Fig. 5a: radial distribution at midplane of the neutron flux (up) and Monte-Carlo statistical uncertainty (down) throughout PPCS-B.

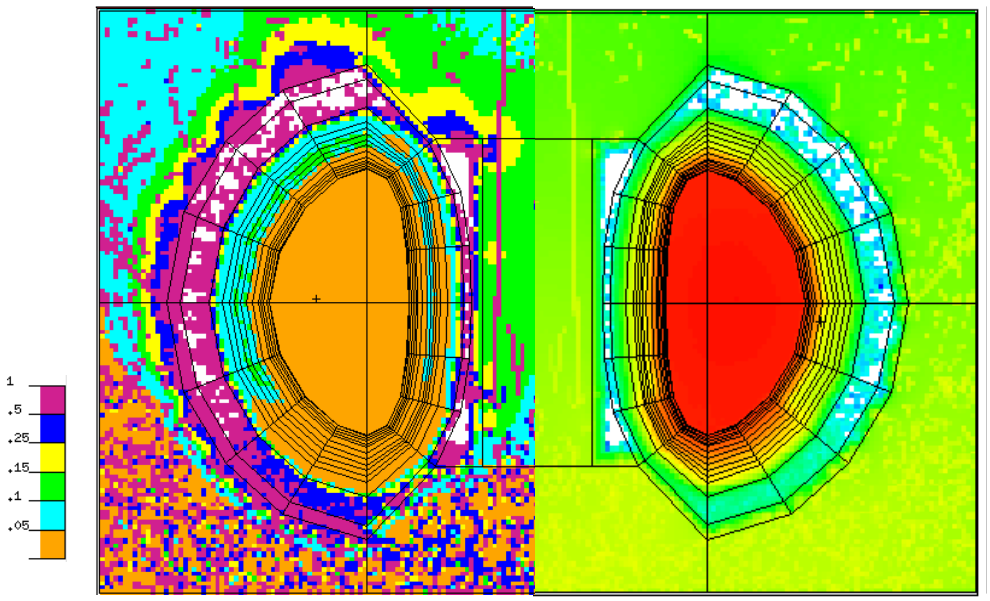

Fig. 5b: poloidal distribution of the neutron flux (right) and Monte-Carlo statistical uncertainty (left) throughout PPCS-B.

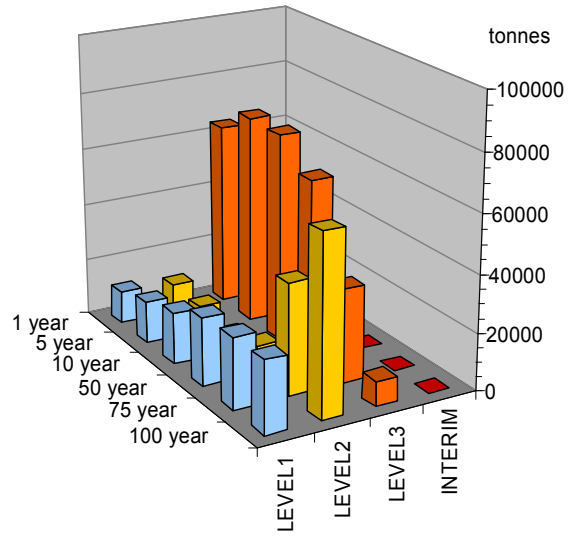

Fig. 6: radiological scoring of PPCS-AB irradiated materials at different times after shutdown.

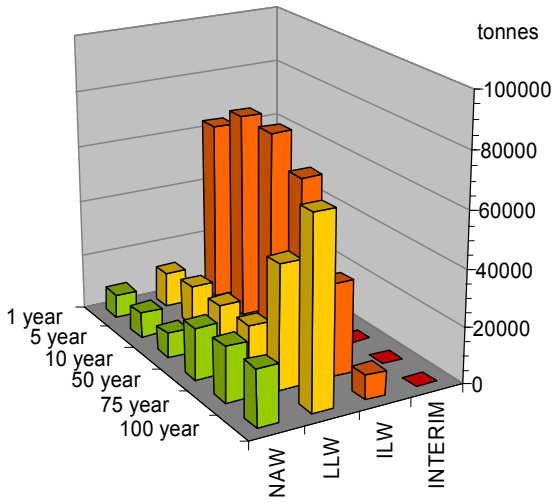

Fig. 7: disposal classification of PPCS-AB materials according to German standards at different times after shutdown.

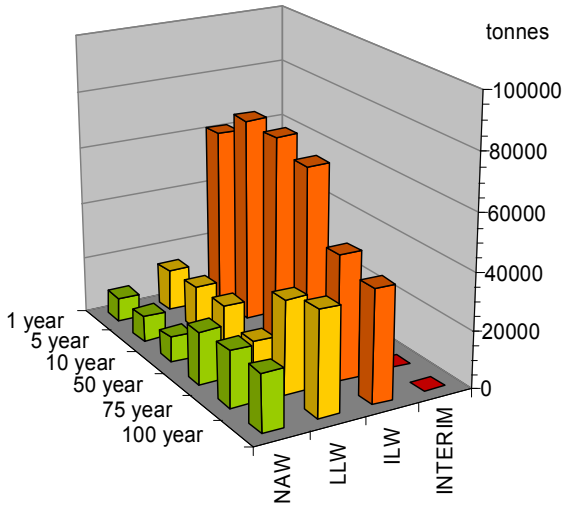

Fig. 8: classification of PPCS-AB materials for disposal according to UK standards at different times after shutdown.

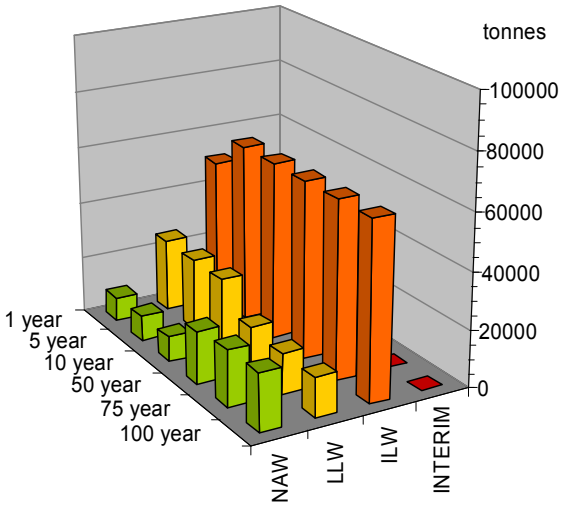

Fig. 9: classification of PPCS-AB materials for disposal according to French standards at different times after shutdown.

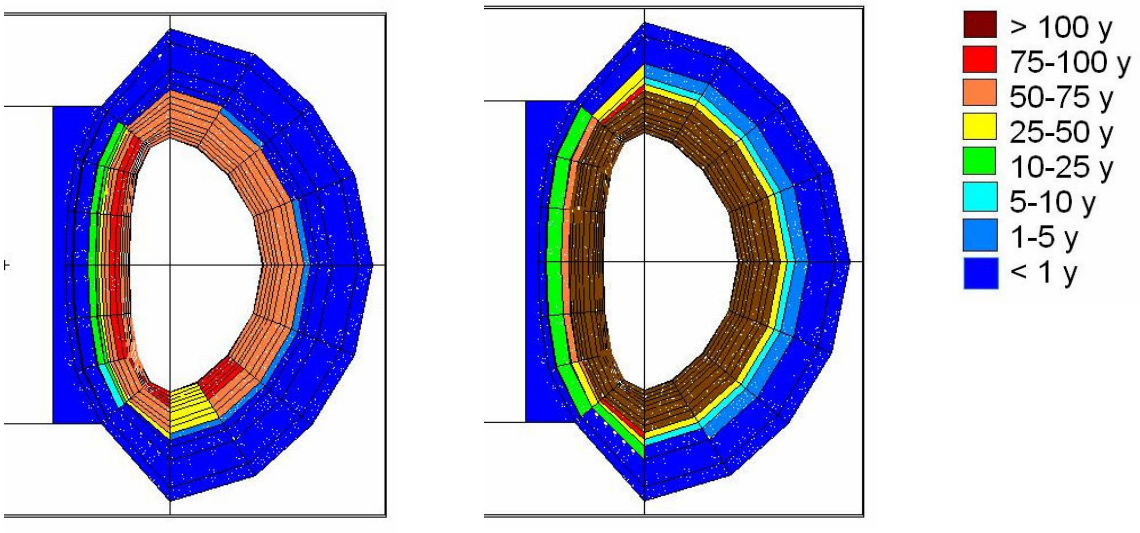

Fig. 10: PPCS-AB poloidal cross-section showing times required for steel structures to decay to level 2 (left) and level 1 (right).

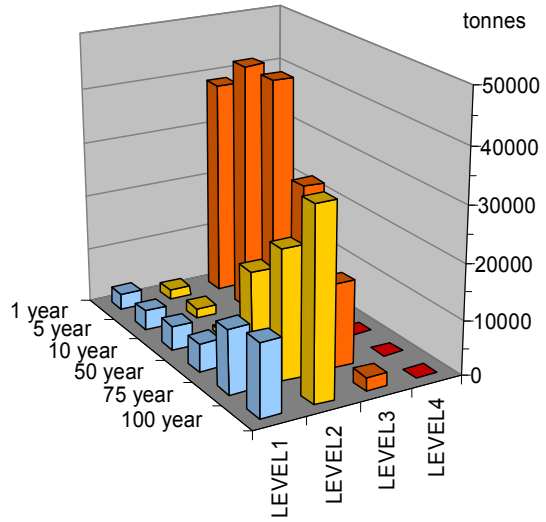

Fig. 11: radiological scoring of PPCS-B irradiated materials at different times after shutdown.

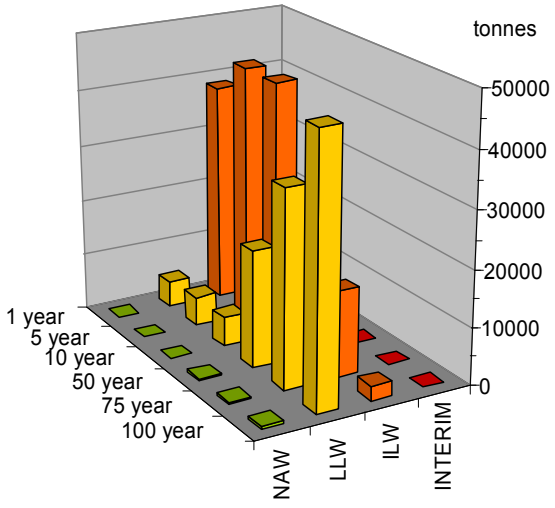

Fig. 12: disposal classification of PPCS-B materials according to German standards at different times after shutdown.

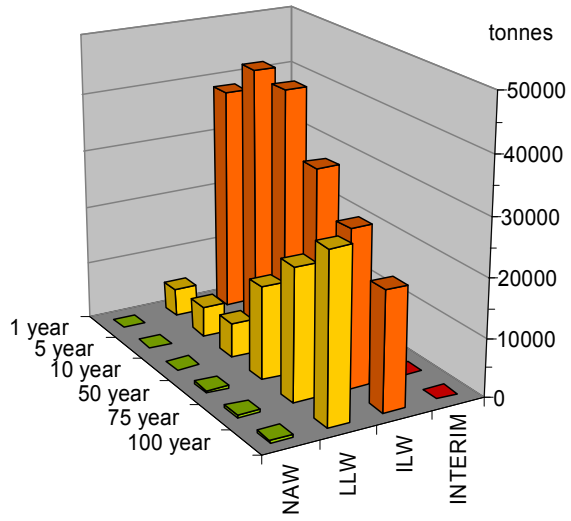

Fig. 13: classification of PPCS-B materials for disposal according to UK standards at different times after shutdown.

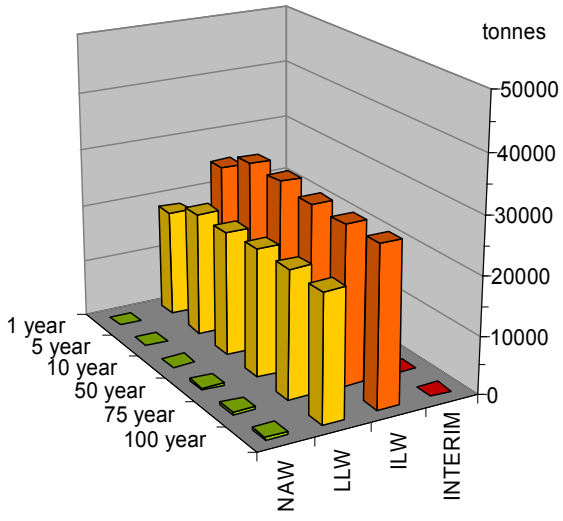

Fig. 14: classification of PPCS-B materials for disposal according to French standards at different times after shutdown.

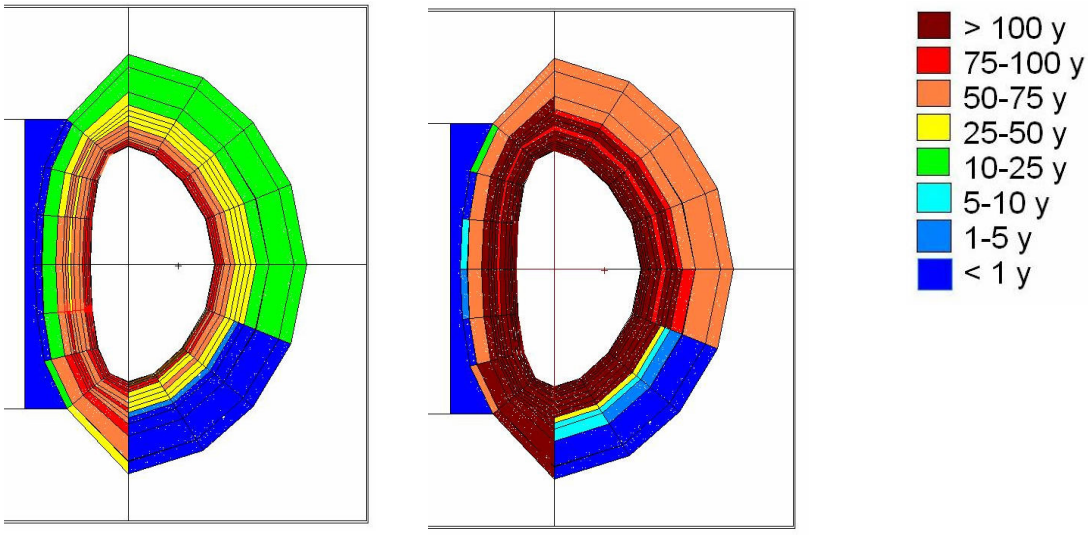

Fig. 15: PPCS-B poloidal cross section showing times required for steel structures to decay to level 2 (left) and level 1 (right).

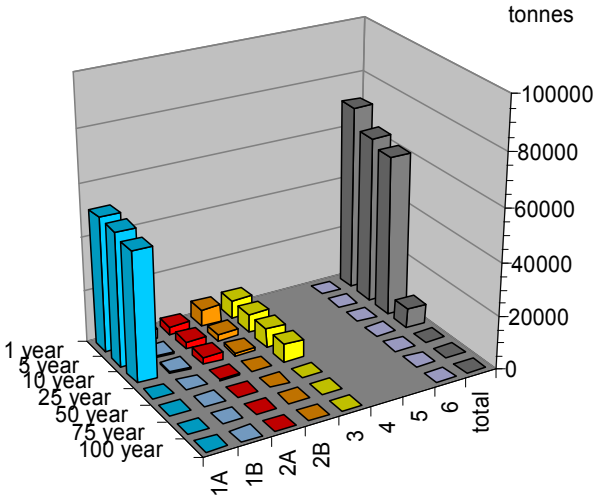

Fig. 16: histories of PPCS-AB material mass requiring cooling per category.

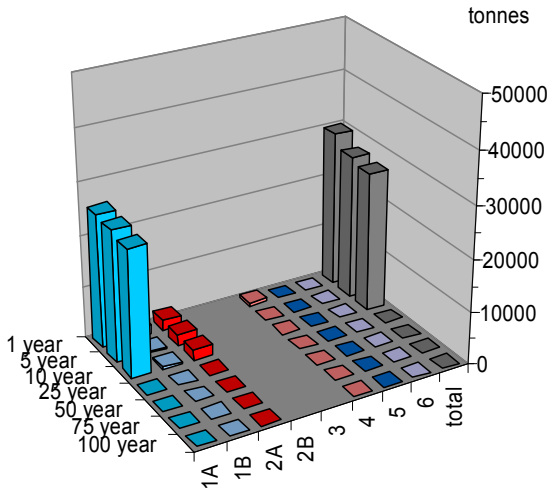

Fig. 17: histories of PPCS-B material mass requiring cooling per category.

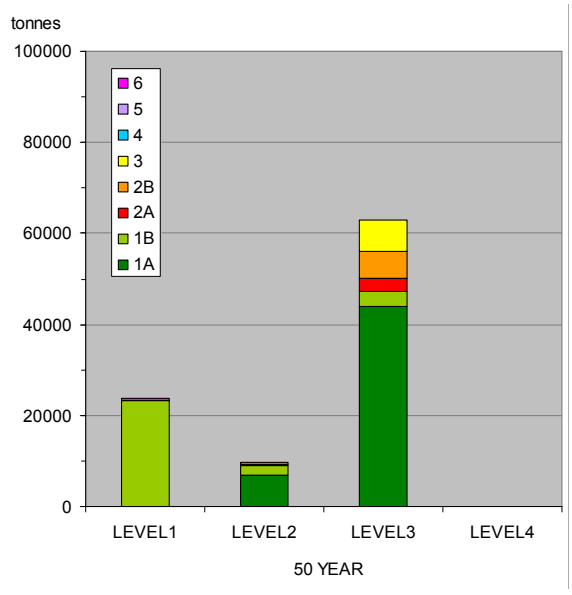

Fig. 18: PPCS-AB material inventory radiological scoring per category @ 50y.

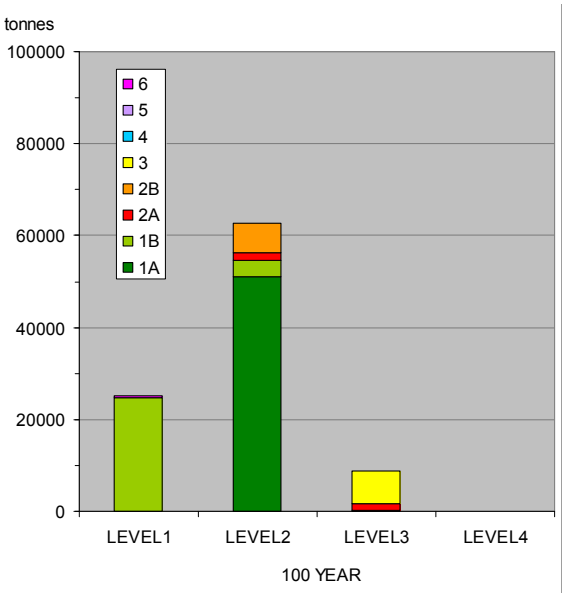

Fig. 19: PPCS-AB material inventory radiological scoring per category @ 100y.

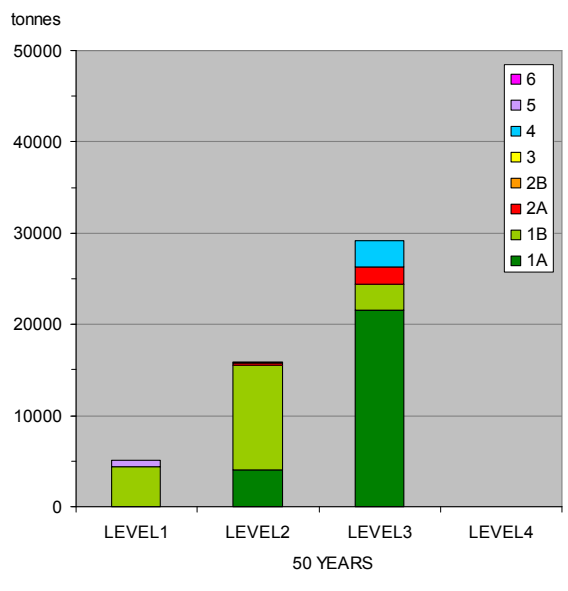

Fig. 20: PPCS-B material inventory radiological scoring per category @ 50y.

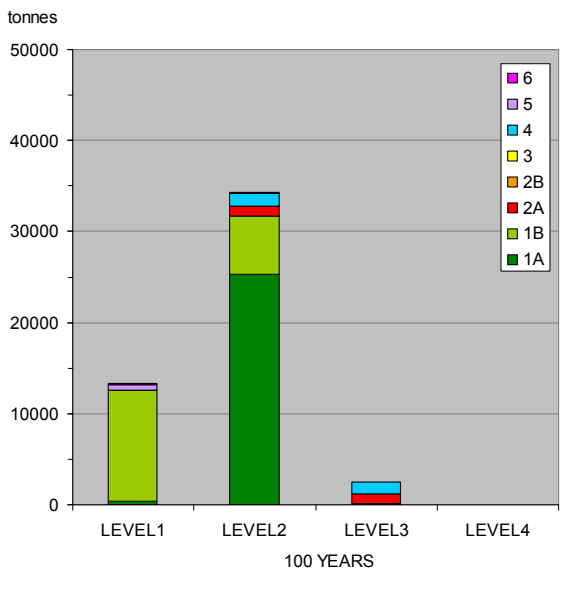

Fig. 21: PPCS-B material inventory radiological scoring per category @ 100y.

APPENDIX:
TABLES OF ACTIVE MATERIAL INVENTORY

Table A1: PPCS-AB material radiological scoring at different times (tonnes).

1 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
LEVEL1	0	10656	0	0	0			523	11179
LEVEL2	0	9681	0	0	0			78	9759
LEVEL3	42168	8314	281	6414	6933			0	64110
LEVEL4	8842	0	2685	0	0			0	11526
totals	51010	28650	2966	6414	6933	0	0	601	96574

5 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
LEVEL1	0	14184	0	0	0			542	14725
LEVEL2	0	8850	0	0	0			60	8910
LEVEL3	51010	5617	2966	6414	6933			0	72940
LEVEL4	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

10 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
LEVEL1	0	17557	0	0	0			572	18129
LEVEL2	0	5681	0	0	0			30	5710
LEVEL3	51010	5412	2966	6414	6933			0	72735
LEVEL4	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

25 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
LEVEL1	0	19117	0	0	0			601	19718
LEVEL2	0	5326	0	0	0			0	5326
LEVEL3	51010	4207	2966	6414	6933			0	71530
LEVEL4	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

50 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
LEVEL1	0	23238	0	0	0			601	23839
LEVEL2	7003	2049	285	405	0			0	9743
LEVEL3	44007	3363	2681	6009	6933			0	62992
LEVEL4	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

75 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
LEVEL1	0	24443	0	0	0			601	25044
LEVEL2	29481	3869	225	5240	0			0	38814
LEVEL3	21529	338	2741	1175	6933			0	32716
LEVEL4	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

100 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
LEVEL1	0	24694	0	0	0			601	25296
LEVEL2	51010	3618	1555	6414	0			0	62597
LEVEL3	0	338	1411	0	6933			0	8682
LEVEL4	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

Table A2: PPCS-AB material classification for German disposal at different times (tonnes).

1 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	8053	0	0	0			382	8435
LLW	0	12284	0	0	0			219	12503
ILW	42168	8314	281	6414	6933			0	64110
INTERIM	8842	0	2685	0	0			0	11526
totals	51010	28650	2966	6414	6933	0	0	601	96574

5 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	8612	0	0	0			404	9016
LLW	0	14422	0	0	0			197	14619
ILW	51010	5617	2966	6414	6933			0	72940
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

10 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	8612	0	0	0			404	9016
LLW	0	14626	0	0	0			197	14823
ILW	51010	5412	2966	6414	6933			0	72735
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

25 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	10169	0	0	0			404	10574
LLW	0	14274	0	0	0			197	14471
ILW	51010	4207	2966	6414	6933			0	71530
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

50 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	18066	0	0	0			455	18521
LLW	7003	7221	285	405	0			147	15062
ILW	44007	3363	2681	6009	6933			0	62992
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

75 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	19557	0	0	0			455	20012
LLW	29481	8755	225	5240	0			147	43847
ILW	21529	338	2741	1175	6933			0	32716
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

100 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	19762	0	0	0			455	20216
LLW	51010	8551	1555	6414	0			147	67677
ILW	0	338	1411	0	6933			0	8682
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

Table A3: PPCS-AB material classification for UK disposal at different times (tonnes).

1 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	8053	0	0	0			382	8435
LLW	0	14471	0	0	0			219	14689
ILW	42168	6127	281	6414	6933			0	61923
INTERIM	8842	0	2685	0	0			0	11526
totals	51010	28650	2966	6414	6933	0	0	601	96574

5 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	8612	0	0	0			404	9016
LLW	0	15493	0	0	0			197	15690
ILW	51010	4546	2966	6414	6933			0	71868
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

10 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	8612	0	0	0			404	9016
LLW	0	15831	0	0	0			197	16028
ILW	51010	4207	2966	6414	6933			0	71530
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

25 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	10169	0	0	0			404	10574
LLW	0	14274	0	0	0			197	14471
ILW	51010	4207	2966	6414	6933			0	71530
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

50 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	18066	0	0	0			455	18521
LLW	3939	6628	0	0	0			147	10714
ILW	47071	3956	2966	6414	6933			0	67340
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

75 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	19557	0	0	0			455	20012
LLW	23454	5137	0	4046	0			147	32784
ILW	27556	3956	2966	2368	6933			0	43779
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

100 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	19762	0	0	0			455	20216
LLW	27723	4933	0	4046	0			147	36849
ILW	23287	3956	2966	2368	6933			0	39510
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

Table A4: PPCS-AB material classification for French disposal at different times (tonnes).

1 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	8053	0	0	0			382	8435
LLW	258	20008	0	5240	0			219	25724
ILW	41910	590	281	1175	6933			0	50889
INTERIM	8842	0	2685	0	0			0	11526
totals	51010	28650	2966	6414	6933	0	0	601	96574

5 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	8612	0	0	0			404	9016
LLW	258	19449	0	5240	0			197	25143
ILW	50752	590	2966	1175	6933			0	62415
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

10 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	8612	0	0	0			404	9016
LLW	258	19449	0	5240	0			197	25143
ILW	50752	590	2966	1175	6933			0	62415
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

25 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	10169	0	0	0			404	10574
LLW	258	17891	0	5240	0			197	23586
ILW	50752	590	2966	1175	6933			0	62415
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

50 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	18066	0	0	0			455	18521
LLW	258	9995	0	5240	0			147	15639
ILW	50752	590	2966	1175	6933			0	62415
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

75 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	19557	0	0	0			455	20012
LLW	258	8504	0	5240	0			147	14148
ILW	50752	590	2966	1175	6933			0	62415
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

100 year	**1A**	**1B**	**2A**	**2B**	**3**	**4**	**5**	**6**	total
NAW	0	19762	0	0	0			455	20216
LLW	258	8299	0	5240	0			147	13943
ILW	50752	590	2966	1175	6933			0	62415
INTERIM	0	0	0	0	0			0	0
totals	51010	28650	2966	6414	6933	0	0	601	96574

Table A5: PPCS-B material radiological scoring at different times (tonnes).

1 year	1A	1B	2A	2B	3	4	5	6	total
LEVEL1	0	2226	0			0	681	21	2929
LEVEL2	0	1606	0			0	0	129	1735
LEVEL3	20847	15013	138			2739	0	65	38802
LEVEL4	4734	0	1926			0	0	0	6660
totals	25581	18845	2064	0	0	2739	681	215	50125

5 year	1A	1B	2A	2B	3	4	5	6	total
LEVEL1	0	2749	0			0	681	21	3452
LEVEL2	0	1673	0			0	0	129	1802
LEVEL3	25581	14422	2064			2739	0	65	44871
LEVEL4	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

10 year	1A	1B	2A	2B	3	4	5	6	total
LEVEL1	0	3656	0			0	681	21	4358
LEVEL2	0	767	0			0	0	145	912
LEVEL3	25581	14422	2064			2739	0	48	44855
LEVEL4	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

25 year	1A	1B	2A	2B	3	4	5	6	total
LEVEL1	0	3800	0			0	681	21	4503
LEVEL2	0	7435	0			0	0	145	7580
LEVEL3	25581	7611	2064			2739	0	48	38043
LEVEL4	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

50 year	1A	1B	2A	2B	3	4	5	6	total
LEVEL1	0	4423	0			0	681	21	5125
LEVEL2	4023	11540	151			0	0	145	15859
LEVEL3	21558	2882	1913			2739	0	48	29141
LEVEL4	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

75 year	1A	1B	2A	2B	3	4	5	6	total
LEVEL1	0	10961	0			0	681	21	11664
LEVEL2	15255	7437	107			374	0	145	23318
LEVEL3	10326	447	1957			2365	0	48	15143
LEVEL4	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

100 year	1A	1B	2A	2B	3	4	5	6	total
LEVEL1	307	12238	0			0	681	21	13248
LEVEL2	25274	6488	969			1492	0	145	34369
LEVEL3	0	119	1095			1247	0	48	2509
LEVEL4	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

Table A6: PPCS-B material classification for German disposal at different times (tonnes).

1 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	0	0
LLW	0	3832	0			0	681	150	4663
ILW	20847	15013	138			2739	0	65	38802
INTERIM	4734	0	1926			0	0	0	6660
totals	25581	18845	2064	0	0	2739	681	215	50125

5 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	4	4
LLW	0	4423	0			0	681	146	5250
ILW	25581	14422	2064			2739	0	65	44871
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

10 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	7	7
LLW	0	4423	0			0	681	160	5264
ILW	25581	14422	2064			2739	0	48	44855
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

25 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	7	7
LLW	0	11234	0			0	681	159	12075
ILW	25581	7611	2064			2739	0	48	38043
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

50 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	366	0			0	0	9	376
LLW	4023	15596	151			0	681	157	20608
ILW	21558	2882	1913			2739	0	48	29141
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

75 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	366	0			0	0	11	377
LLW	15255	18032	107			374	681	156	34605
ILW	10326	447	1957			2365	0	48	15143
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

100 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	485	0			0	0	11	496
LLW	25581	18241	969			1492	681	156	47120
ILW	0	119	1095			1247	0	48	2509
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

Table A7: PPCS-B material classification for UK disposal at different times (tonnes).

1 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	0	0
LLW	0	4084	0			0	681	67	4833
ILW	20847	14760	138			2739	0	147	38631
INTERIM	4734	0	1926			0	0	0	6660
totals	25581	18845	2064	0	0	2739	681	215	50125

5 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	4	4
LLW	0	4423	0			0	681	128	5232
ILW	25581	14422	2064			2739	0	83	44889
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

10 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	7	7
LLW	0	5097	0			0	681	143	5922
ILW	25581	13748	2064			2739	0	65	44196
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

25 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	7	7
LLW	0	11076	0			0	681	159	11916
ILW	25581	7769	2064			2739	0	48	38201
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

50 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	366	0			0	0	9	376
LLW	2509	12540	0			0	681	157	15888
ILW	23072	5938	2064			2739	0	48	33862
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

75 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	366	0			0	0	11	377
LLW	8308	13572	0			0	681	156	22717
ILW	17273	4907	2064			2739	0	48	27031
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

100 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	485	0			0	0	11	496
LLW	14797	13453	0			0	681	156	29088
ILW	10784	4907	2064			2739	0	48	20541
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

Table A8: PPCS-B material classification for French disposal at different times (tonnes).

1 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	0	0
LLW	0	17382	0			170	681	215	18449
ILW	20847	1463	138			2569	0	0	25016
INTERIM	4734	0	1926			0	0	0	6660
totals	25581	18845	2064	0	0	2739	681	215	50125

5 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	4	4
LLW	688	17665	0			2222	681	210	21467
ILW	24893	1180	2064			517	0	0	28653
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

10 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	7	7
LLW	828	17665	0			2222	681	208	21605
ILW	24753	1180	2064			517	0	0	28514
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

25 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	0	0			0	0	7	7
LLW	1564	17665	0			2274	681	208	22393
ILW	24017	1180	2064			465	0	0	27725
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

50 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	366	0			0	0	9	376
LLW	1564	17299	0			2274	681	205	22024
ILW	24017	1180	2064			465	0	0	27725
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

75 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	366	0			0	0	11	377
LLW	1564	17299	0			2331	681	204	22080
ILW	24017	1180	2064			408	0	0	27668
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125

100 year	1A	1B	2A	2B	3	4	5	6	total
NAW	0	485	0			0	0	11	496
LLW	1564	17180	0			2331	681	204	21961
ILW	24017	1180	2064			408	0	0	27668
INTERIM	0	0	0			0	0	0	0
totals	25581	18845	2064	0	0	2739	681	215	50125