

Radiological and Economic Impact of Decommissioning Charged Particle Accelerators

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INTRODUCTION

Currently there are about 250 particle accelerators (not including medical linear accelerators) in operation in the European Union (EU). These are used for radionuclide production, radiotherapy and research.

For biological shielding these accelerators are housed in buildings with thick concrete walls. During the operational life of the accelerator those walls become radioactive over time, just like the accelerator itself and all infrastructures in the irradiation rooms. When considering decommissioning of these accelerators, large amounts of low level solid radioactive waste have to be taken into account. However, practically no data on the type of activation, the level of activation or the depth of activation of the concrete and metallic infrastructure existed. For this reason DG ENV/C3 of the European Commission (EC) launched a research project in 1997 focusing on "The evaluation of the radiological and economic consequences of decommissioning particle accelerators". The contract (B4-3070/97/00024/MAR/C3) was granted to the Cyclotron Department of the Vrije Universiteit Brussel (VUB). The objectives of the project can be summarised in 5 main points: inventory of the decommissioning problem of accelerators in the EU, characterisation of the activation of 3 reference accelerators and their shielding, estimation of dismantling techniques, costs and potential waste volumes evaluation and recommendations for prevention.

INVENTORY OF ACCELERATORS

To estimate the economic and radiological consequences of decommissioning the EU particle accelerator park (not medical), it is necessary to have a correct idea of the total number of accelerators present in the EU, their operational status, their main uses and the corresponding beam loads and beam energies. In addition to these basic data, information on the shielding and the metal infrastructure of the installation allows a more reliable view of the radiological situation of the accelerator and its environment. As the information needed is rather detailed, the institutes themselves were contacted. Based on an extensive survey of the available literature and with the help of the local authorities, a preliminary address list was composed, containing 226 installations. A questionnaire was sent to all the identified installations, containing questions dealing with the 5 topics mentioned in Table I. This questionnaire was also published on the Internet allowing online access and immediate electronic processing of the information supplied. After sending several reminders, a total of 91 accelerator facilities supplied (part of) the information needed. This information was collected in a database from which a number of important conclusions could be drawn.

Table II compares the number of facilities responding to the questionnaire with the total number of facilities located in each country. From this table we conclude that Sweden, Italy and Holland, who have a rather large number of accelerators, have done a serious effort in replying to the questionnaire. On the other hand, Germany and especially France have failed largely in replying to the questionnaire, although together they account for over 50% of the EU-accelerators.

The distribution of the answers to the question on the type of shielding used was the following: no answer 26, fully movable shielding 5, massive shielding walls 28, massive and movable shielding 32. For most of the accelerators using a mixture of massive and movable shielding, the ratio of massive to movable is larger than 1. As a result, it can clearly be stated that massive shielding is used in most cases what can result in additional

Table I. Layout of the questionnaire

	Topic	Description
1	General Information	Deals with general data on the institute, the operator, the reporter and the accelerator.
2	Accelerator Data	Asks for more details on the accelerator characteristics.
3	Irradiation and Activation Data	Probes more in detail to the risks of activation of the infrastructure or shielding using information on the beam history, history of the shielding and composition of the shielding and infrastructure.
4	End of Life of Accelerator and Decommissioning	Checks to what extent the institutes are aware of the consequences of decommissioning a particle accelerator and of the national regulations.
5	Future Plans	Contains information on possible new accelerators.

Table II. Comparison between number of answers received and number of questionnaires sent per country

Country	N° located	N° received	Ratio [%]
Greece	1	1	100
Portugal	1	1	100
Finland	6	5	83
Sweden	11	8	73
Holland	18	12	67
Italy	18	9	50
Denmark	4	2	50
Belgium	15	7	47
United Kingdom	20	7	35
Germany	91	30	33
Spain	4	1	25
France	35	8	23
Ireland	2	0	0
	226	91	40

problems during the decommissioning phase. The database also indicates that Ba, Fe or other heavy elements are seldom used in the walls of accelerators. The effect of long-lived radionuclides produced on these elements is hence minimal.

With respect to activation of the concrete shielding, the metal infrastructure and the machine parts, the information in Table III was supplied. A broad range of values can be noticed, clearly indicating that considerable differences in activation can be expected in the different installations.

Table III. Reported specific activation in concrete and metal parts

concrete (for 3 cyclotrons)	¹⁵² Eu	700	-	12000	Bq/kg
	⁶⁰ Co	80	-	8000	Bq/kg
	⁴⁶ Sc	800	-	900	Bq/kg
metal infrastructure (for 3 accelerators)	⁶⁰ Co	0.10	-	100	kBq/kg
	⁵⁴ Mn	0.09	-	380	kBq/kg
	⁶⁵ Zn	1.64	-	170	kBq/kg
machine parts	⁶⁰ Co	32	-	5000	kBq/kg
	⁵⁴ Mn	0.9	-	1000	kBq/kg
	²² Na	1000	-	10000	kBq/kg
	⁵⁷ Co	0.25	-	100	kBq/kg

The low number of replies received to these questions furthermore indicates clearly the lack of awareness of a long-term waste problem around accelerators. This demonstrates that the problem of decommissioning particle accelerators is strongly underestimated.

Another conclusion from the database is that we are dealing with an ageing accelerator park with a majority of installations in the public or health sector. From several contradictory answers can be concluded that the regulatory framework is generally unknown by users of accelerators. In addition to the underestimation of the problem, the existence of a decommissioning plan is exceptional and almost no institutes foresee provisions.

SELECTION OF 3 REPRESENTATIVE ACCELERATORS

The large number of accelerators in the EU and their variety makes that the activation can only be analysed in detail through a limited number of representative case studies. When excluding the medical linear accelerators used for radiotherapy, the database learns that the accelerators can be subdivided into 4 classes (see Table IV).

Class 1 accelerators do not pose an activation risk as the energy delivered is below the threshold for the large majority of nuclear reactions. Hence the possibly generated secondary particle fluxes are inexistent or very low, producing negligible activation of the shielding. No systematic investigations have been carried out for accelerators in this class.

Class 2 contains the medium energy cyclotrons and linear accelerators, used for research, radionuclide production and radiotherapy. This group represents over 50% of the accelerator park of the EU. As the energy

delivered is high enough to produce activation by secondary particles and as a high particle flux is characteristic

Table IV. Classes of accelerators.

Class	Description
0	Radiotherapy linear accelerators (estimated 1200 machines in the EU, not addressed in the questionnaire, direct contact with manufacturers established, practical decommissioning experience available).
1	Low energy (2-10 MeV) linear and electrostatic accelerators, grouping essentially a score of Van de Graaff, tandem and similar accelerators.
2	Medium energy (10-100 MeV) proton, H ⁺ or multiple particle (including heavy ions) cyclotrons and linear accelerators mainly used for physics research (also injectors) and radionuclide production. As confirmed by the results of the questionnaire this class represents over 50% of the accelerator park in the EU.
3	High energy (100-300 MeV) proton cyclotrons or synchrocyclotrons and high energy linear accelerators (used for basic physics research, frequently as spallation neutron sources generating hence high neutron fluxes and activation). About 6% of the accelerator park.
4	Very high energy synchrotrons and storage rings up to several GeV, used in high energy physics, making up 12% of the accelerator park of the EU.

for these machines, problems with activation of concrete shielding and metal infrastructure can be expected. As a representative of this class, the cyclotron of the VUB was chosen. It is a variable energy multi-particle cyclotron with 43 MeV maximal proton energy for 100 μ A maximal beam intensity. The utilisation of the different irradiation rooms includes semi-commercial radionuclide production and research, yielding a wide range of activation.

In class 3 we find the high energy cyclotrons and linear accelerators used for basic research, frequently as charged particle based spallation neutron source. The 200 MeV electron linear accelerator of the Institute for Reference Materials and Measurements (IRMM/JRC) in Geel (Be) was chosen as representative in this group. The very high neutron production rate around this accelerator will probably yield the upper limit of activation to be expected.

The group of very high energy synchrotrons and storage rings forms class 4. The complexity of these installations and the difficulty to have access to the facilities for an extensive investigation campaign limited the possibility of a real choice for a representative case in this class. Due to the coincidence of our investigation with the start of a local decommissioning study, the large 6 GeV proton synchrotron SATURNE of the CNRS-CEA (Fr) was chosen as representative in this class.

EXPERIMENTAL DETERMINATION OF THE ACTIVATION STATUS

Activation of the Concrete Shielding:

Activation of the concrete shielding is one of the most important problems at decommissioning. Although the principles of activation are well understood, only limited studies on the relation between accelerator characteristics and activation levels are published (1, 2, 3, 4, 5). It was therefore necessary to obtain detailed quantitative information on the radioactivity induced in the concrete shielding. The activation of the concrete shielding is produced by secondary neutrons and photons. These are generated in collisions of the primary particles with the accelerator itself, during the beam transport and through interaction with the target.

At the 3 facilities core samples of the concrete shielding were taken with a boring device using a diamond-drilling tool of 50 mm diameter. The closed circuit of the cooling system of the boring device enabled an almost 100% recuperation of liquid effluents in a tank. The risk of dust contamination or dust intake was low due to the wet drilling process preventing the airborne spread of activity. After a few hours the water in the tank could be separated from the sediment, which has to be disposed of as low activity nuclear waste. All the removed concrete cores were then cut in 5 cm long samples (± 0.2 kg) by a diamond saw. These concrete samples were analysed with a high-resolution γ -spectrometer (HPGe-detector) using correction for self-absorption and measurement geometry. When present, pieces of the reinforcement steel were removed and measured separately.

For the VUB cyclotron a total of 96 drillings were performed. The drilling campaign was concentrated in the accelerator vault and in irradiation room 2, as these rooms have been the most intensely irradiated (78% of the integrated beam load was put on target in irradiation room 2). At the IRMM linear accelerator a total of 61 drill cores were taken, mainly concentrated in the target hall. Due to the very localised beam losses of a synchrotron, only 2 well-defined regions (around the beam extractors) of the shielding of the SATURNE accelerator can be activated. Hence 50 drillings were performed, distributed over these 2 regions.

Table V shows the radionuclides detected in the concrete after γ -spectrometric analysis. The activation

of trace elements of metals (e.g. europium) in sand yield medium lived radionuclides. These are mainly created by neutron capture with high cross sections and by threshold reactions with lower yield. Because of the high ^{151}Eu

Table V. Radionuclides identified in the concrete shielding.

Radionuclide	Possible Reaction	Cross section	Half life
^{152}Eu	$^{151}\text{Eu} (n,\gamma) ^{152}\text{Eu}$	9198 barn	13.33 years
^{154}Eu	$^{153}\text{Eu} (n,\gamma) ^{154}\text{Eu}$	312 barn	8.8 years
^{134}Cs	$^{133}\text{Cs} (n,\gamma) ^{134}\text{Cs}$ $^{134}\text{Ba} (n,p) ^{134}\text{Cs}$	29 barn 9 mbarn at $E_n = 16$ MeV	2.06 years
^{60}Co	$^{59}\text{Co} (n,\gamma) ^{60}\text{Co}$	37 barn	5.3 years
^{46}Sc	$^{45}\text{Sc} (n,\gamma) ^{46}\text{Sc}$	27 barn	83 days
$^{133}\text{Ba}^a$	$^{132}\text{Ba} (n,\gamma) ^{133}\text{Ba}$	7 barn	10.5 years
^{54}Mn	$^{55}\text{Mn} (n,2n) ^{54}\text{Mn}$ $^{54}\text{Fe} (n,p) ^{54}\text{Mn}$	910 mbarn at $E_n = 18$ MeV 590 mbarn at $E_n = 10$ MeV	312 days
^{22}Na	$^{23}\text{Na} (n,2n) ^{22}\text{Na}$ $^{27}\text{Al} (n,2p4n) ^{22}\text{Na}$	40 mbarn at $E_n = 15$ MeV 10 mbarn at $E_n = 25$ MeV	2.6 years
^{137}Cs	$^{136}\text{Ba} (n,\gamma) ^{137m}\text{Ba} \rightarrow ^{137}\text{Cs}$ $^{137}\text{Ba} (n,p) ^{137}\text{Cs}$	0.4 barn 3.7 mbarn at $E_n = 16$ MeV	30 years

^a only detected where “barite” concrete is used

cross section for thermal neutron capture and the long half life of ^{152}Eu , this nuclide is present in large quantities in the activated shielding. At the VUB cyclotron and the IRMM linear accelerator, the highest detected specific activity for ^{152}Eu was 11 kBq/kg, respectively 90 kBq/kg. At SATURNE the 2 most important radionuclides present are ^{133}Ba and ^{22}Na due to the use of barite concrete and concrete with high Na content. A maximal specific activity of 1.8 kBq/kg was measured for ^{133}Ba . These values are considerably higher than the different proposed clearance levels, which are all between 100 Bq/kg and 1 kBq/kg as discussed further in this text.

For the different radionuclides found in the concrete, in-depth activation profiles were drawn. Figure 1 shows such a typical profile from irradiation room 2 of the VUB cyclotron, from which can be concluded that after an activity build-up in the first 15 cm, a quasi-exponential decay of the activity occurs. This behaviour is found for nearly all profiles of both VUB cyclotron and IRMM linear accelerator. The in-depth activation profiles of the SATURNE synchrotron does not show the build-up. In addition to the γ -analysis of the concrete, the tritium content of several samples was determined. Small chunks of concrete originating from the 3 reference accelerators were ground and sieved for this purpose. Samples of 0.1 g were prepared and heated to 1100°C. The water liberated from these samples was mixed with a scintillation liquid. Specific activities for ^3H up to 380 kBq/kg were found and correlate well with the corresponding ^{152}Eu activation. Tritium is probably produced by spallation reactions that frequently occur around high energy accelerators. However further studies are required to obtain a satisfactory explanation for this ^3H -formation in concrete.

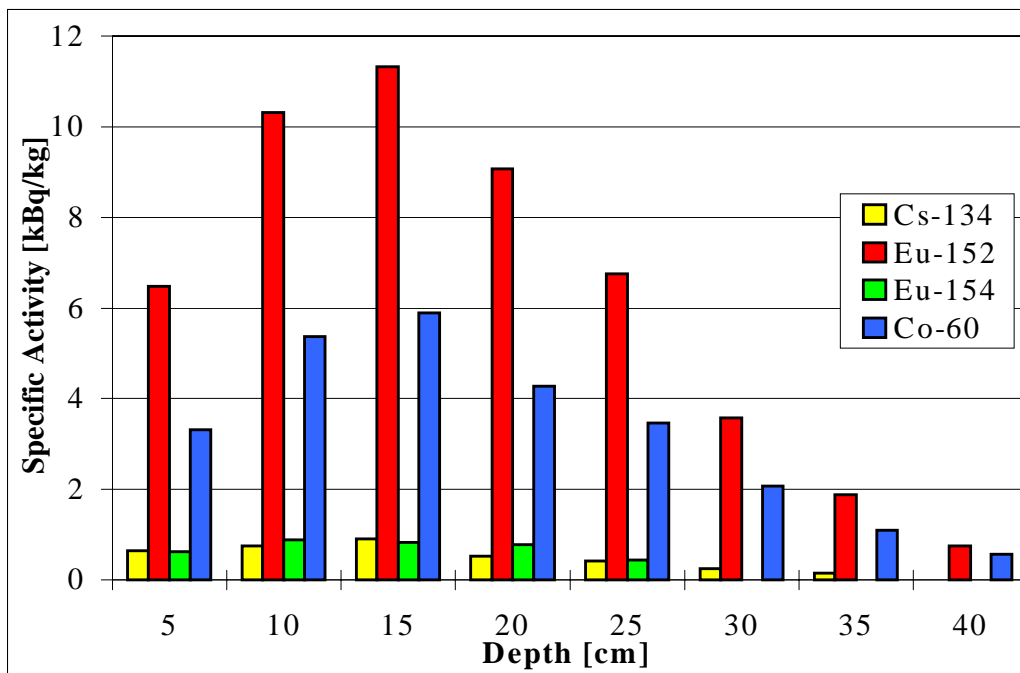


Figure 1. Typical in-depth activation profile (irradiation room 2 - VUB cyclotron).

Activation of Metal Parts:

At all three facilities, a sampling campaign of different kinds of metal parts (aluminium, stainless steel, plain steel, copper, brass and galvanised steel), originating from the accelerator rooms, target rooms and experimental halls, was carried out to investigate the activation. The samples were taken from both the machine itself and the surrounding infrastructure which can be activated by neutrons.

The measurements of the infrastructure parts of the VUB cyclotron show considerable amounts of ^{60}Co , ^{65}Zn and ^{54}Mn with specific activities between 1 and 200 kBq/kg. Most aluminium parts have a specific activity below 1 kBq/kg, while a few parts of steel and stainless steel constructions have a specific activity above 200 kBq/kg.

Attention is drawn to the fact that the yokes of the main magnets and switching magnets, which are made of low Co steel (Co is only present as a possible impurity), are only slightly activated. Highly activated machine parts are the deflector and its support structure and the accelerating Dee structures. Both structures are activated far above 1 MBq/kg and have to be removed as soon as possible after shutdown, nevertheless allowing for decay of short-lived nuclides.

The reinforcement rods of the concrete walls were activated up to 300 kBq/kg. Analogous results were found from the measurements at IRMM and CEA.

Interpolation and 3D distributions:

The final goal of this work is to estimate the total decommissioning cost of particle accelerators. For this purpose information on the activation products is not only needed in the sampling points, but as a 3D distribution over the entire walls of the building and in the depth of these walls. A technique was developed for the extrapolation from a few simple points to an activation distribution over an entire room. This extrapolation technique is based on the conclusion that the main parameters influencing the specific activity $A^i(x, y, z)$ produced by secondary neutrons in a certain point of layer i of a concrete wall are:

- the source-concrete distance for the point of interest $R^i(x, y, z)$;
- the relative number of neutrons able to produce activation $\varphi^i(x, y, z)$ in the direction of interest.

The activity in a layer of concrete $A^i(x, y, z)$ can hence be written as:

$$A^i(x, y, z) = A_0^i \varphi^i(x, y, z) \frac{(R_0^i)^2}{(R^i(x, y, z))^2} \quad (1)$$

where A_0^i is a known activation level in layer i of the concrete (based on the measurement of the core samples) and R_0^i is the corresponding source-concrete distance. Based on the measurements of the other core samples,

discrete values for the function $\phi^i(x, y, z)$ can be calculated:

$$\phi_j^i = \frac{A_j^i (R_j^i)^2}{A_0^i (R_0^i)^2}$$

Assuming a cylindrical symmetry and using a 3rd order polynomial fit, the unknown function $\phi^i = \phi^i(\theta)$ can be found. Based on this result and on (1), the specific activity in any point (x,y,z) of concrete layer i can be calculated. Repeating this for all layers, the activation level in any point of a concrete shielding can be found for every radionuclide of interest.

A typical result of this interpolation is shown in Figure 2. The activation level determines the colour scale code for each voxel at that point. It changes between 0 and 10 kBq/kg. The voxel size was chosen at 10x10x10 cm³. For each wall the highest activation levels are found at the points opposing the neutron source (target). From the figure it is also clearly visible that, instead of the first layer of concrete, the second one contains the highest specific activity, which is fully in accordance with the activation profiles found. Further information on this interpolation scheme can be found in (6). These interpolations yield the input to the cost evaluation procedures.

Medical Linear Accelerators:

Although the activation of and around linear accelerators used for radiotherapy is generally considered very low, the total amount of radioactive waste can be considerable due to the important number of accelerators concerned (>1200 in EU, 300 new accelerators or replacements installed each year in Europe).

Concrete samples were taken from the upper 5 cm of the floor under the treatment table of a medical linear accelerator (20 MeV electrons, 18 MV photons, 15 years of operation), showing no significant activation above background level. It can hence be concluded that the neutron fluxes produced during the operation of this type of accelerator are too low to activate this upper layer of the concrete shielding. Our measurements around the other types of accelerators show that the maximum of activation of the concrete is found at deeper layers. However these measurements indicate that most likely no concrete activation of importance will be found around

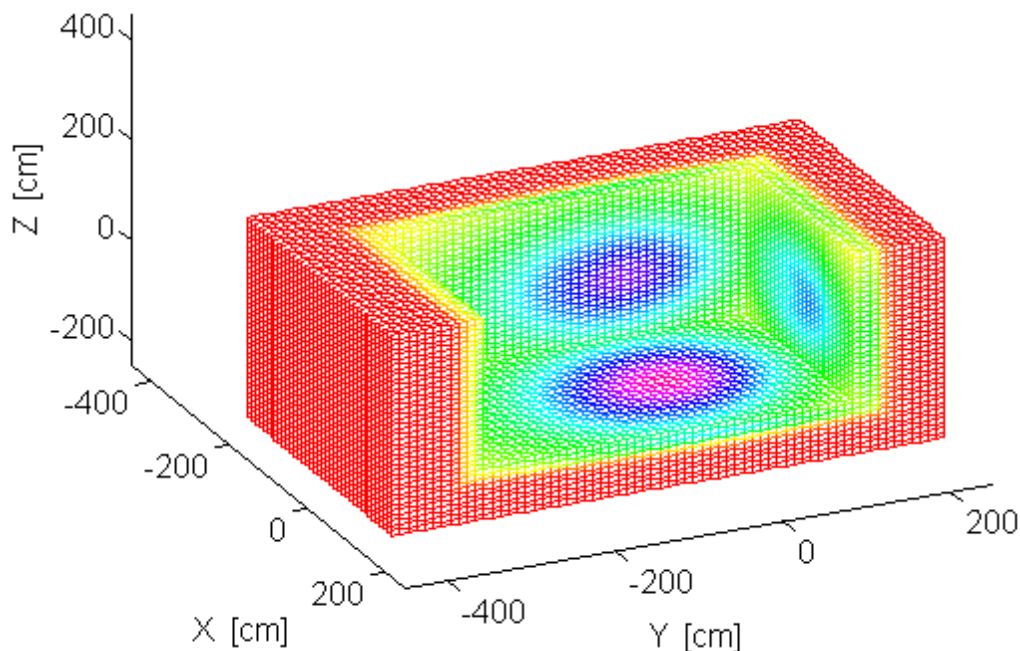


Figure 2. 3D distribution of the specific activity of ¹⁵²Eu in irradiation room 2.

medical linear accelerators. Further details can be found in (7).

To evaluate the activation of machine parts samples were taken from a 23 MeV accelerator. Measurement revealed activation levels up to 26 MBq/kg of ¹⁸¹W and 70 kBq/kg of ⁶⁰Co (both in the conversion target). The relative short half life of ¹⁸¹W would allow release of the material after 5-6 years, but due to the presence of ⁶⁰Co, more than 40 years of cooling time is necessary to bring its value under 300 Bq/kg. Presence of Sb-nuclides in activated lead pieces could drastically increase these cooling times.

Important amounts of ^{110m}Ag were found in the soldering material used in the wave-guides, requiring cooling times of over 100 years. The other materials pose less long term waste problems due to the short half

lives. During the dismantling of the 20 MeV linear accelerator mentioned earlier, a total of 400 kg metal parts was disposed of as (low level) nuclear waste.

DISMANTLING TECHNIQUES

Some remarks on possible techniques for dismantling particle accelerators are presented here. The objectives of these techniques include minimisation of the exposure of personnel and minimisation of the generated amounts of waste. Dismantling techniques should be selected and used so that activated plant and equipment components are removed in a controlled way, avoiding mixing with non-activated wastes where possible. If possible unconditional and conditional recycling are to be preferred to the apparently more simple method of disposal as radioactive waste, not least of all due to economic considerations.

The selection of cutting techniques used for dismantling has to be optimised from the point of view of radiation protection, secondary waste generation and cost-efficiency. The radiological protection requirements to avoid any unnecessary radiation exposure necessitate cutting techniques that allow high cutting speeds, automatic operation or remote control. Simple, proven techniques can also meet these requirements. Therefore, during decommissioning, conventional cutting techniques will be mainly used. These have to be adapted however to the special conditions, such as the confined space and possibilities of transporting the cut-away components.

Moreover, the cutting techniques have to be adapted for the activity levels and materials of the components that are to be cut up. Special attention must be paid in this respect to the avoidance of dust (aerosols) and to their safe containment in cases where they are unavoidable.

A very wide range of techniques is available to allow a clean dismantling of concrete structures, i.e. with the least possible generation of dust: sawing, wire-cutting, circular sawing, chain sawing, drilling, core drilling, cutting with special hydraulic pincers, operated manually on gripper arms and thermal exposure of reinforcing steels by means of electric resistance heating (8).

Where dust and gas formation can be well contained it may be advantageous to use controlled, gentle detonation techniques. This is the case in the vaults of particle accelerators.

COST EVALUATION

With respect to cost evaluations, no conformity exists between the different member states of the EU. There are large differences in labour costs and waste management costs. In addition to this, currently no international consensus on clearance levels exists as both can be seen from Table VI. In Germany, for instance, a strict clearance regulation is in place, using 100 Bq/kg as general clearance level, whereas Great Britain is applying 400 Bq/kg. France has no clearance levels but has a system based on “zoning”, where waste from “non contaminating” zones can be treated as conventional waste, while waste from “contaminating” zones can be eliminated as very low level waste as long as the specific activity is lower than 100 kBq/kg. In addition to this, Germany allows melting of metallic waste in the conventional industry as long as the specific activity remains below 1 kBq/kg. Furthermore there is the basic safety standard of the EC where nuclide specific levels are proposed for exemption, which can be considered an upper limit for all clearance levels in case total quantities are limited. The EURATOM Art. 31 Expert Group has recently provided further guidance.

Table VI. Clearance criteria and labour costs in the EU

	Germany	Great Britain	France
Clearance (γ/β -activity)	0.1 kBq/kg	0.4 kBq/kg *	no clearance; managed as VLLW
Clearance for melting in the conventional industry	1 kBq/kg	-	
Labour cost in industry **	42.25 €/h	22.97 €/h	33.80 €/h
Total Cost in industry ***	55.72 €/h	27.34 €/h	49.28 €/h

* Limits given by the Radioactive Substances Exemption order issued in 1996.

** Values for 1995; the values in ECU have been converted into € by a factor 1.

*** Direct + indirect costs, but without social security paid by the employer.

With all these different situations, a choice of 7 different decommissioning scenarios was made: an immediate dismantling in the French, German and British situations (also using local labour and waste treatment costs), an immediate dismantling with these 3 cost assumptions using the clearance levels recommended by the EC (only for VUB cyclotron) and a deferred dismantling scenario in the British case. In this last case cooling times for the concrete of 70 years (VUB cyclotron), 105 years (IRMM linac) and 75 years (SATURNE) are needed to reach the clearance level applied in UK.

The resulting waste volumes (in tonnes) are presented in Table VII and the total decommissioning costs are found in Table VIII. It can be concluded that:

- the British scenario seems to be the most cost-effective one, not only due to the higher clearance levels, but

- also mostly due to lower labour and waste management costs;
- the French scenario provides much lower costs compared to the German one owing to the fact that the costs for very low-level waste management are assumed to be very low (1/10 of the costs for low-level waste in France and about 1/25 of those costs in Germany). Due to the high amounts of very low level waste in the French scenario, the results of this evaluation could thus be quite different in case of cost increasing for this type of waste in France;
- costs for deferred dismantling are lower than those for immediate dismantling. Nevertheless, this scenario needs to be handled carefully because the costs for long-term safe store depend greatly on the context within which the installation needs to be maintained. The feasibility of maintaining the installation during such long periods under regulatory control within a changing surrounding needs also to be evaluated carefully. Furthermore, the implementation of the EC-recommended exemption system, as an assumption for maximal clearance levels, competes with the deferred scenario from the point of view of decommissioning costs;
- the use of these maximum clearance levels would considerably reduce the costs for decommissioning accelerators due to the very low level of activity in the structures. This illustrates the sensitivity to the adopted clearance levels. This conclusion is specific for accelerators and cannot be extended to other types of facilities where the ratio of very low level waste to other radioactive waste could be quite different.

PREVENTION OF ACTIVATION

The results of the three extensive case studies presented here show that the major part of long lived radionuclides present in the waste around particle accelerators are due to neutron induced reactions. The resulting radiological burden to workers during exploitation of the accelerator and the immense economical consequences of dealing with the nuclear waste at decommissioning asks for important measures to reduce or prevent activation of machine parts, infrastructure or shielding in a cost effective way. The improvement in design of accelerators and changes in the concept of set-ups for lowering the neutron production particularly yield a reduction of activation and of the waste to be disposed off at dismantling. Equally important are measures to minimise the interaction of these neutrons with materials prone to activation. A judicious choice of construction techniques adapted to the specific requirements for zone-wise dismantling of nuclear installations is necessary. Use of local shielding around target stations and modular construction of main shielding walls are recommended options.

In the field of particle accelerators, radiation losses and secondary particle generations are directly linked to beam losses. Of course, the minimisation of beam losses has always been an important design criterion for accelerators. This is not just in view of its decommissioning, but mainly in view of optimising the beam current and of the very important aspect of maintenance. The success of using H⁻ acceleration in a deep valley magnetic structure (large variation between highest and lowest magnetic field along one particle orbit) is exactly based on these factors. Another remark concerns the future of particle accelerators, and in particular of proton accelerators. It becomes more and more evident that future applications of particle accelerators will require strongly increasing amounts of beam power. In such a context it is clear that a very strong reduction of all beam losses is a vital element in the design of new particle accelerators. The passage through a particle accelerator has 3 phases: injection, acceleration and extraction. All 3 phases may be responsible for beam losses, and each needs to be optimised.

Unavoidable radiation losses and generation of spurious neutron fluxes always exist at the collimators, target stations or beam dumps for any type of accelerator. Prevention or diminishing the amount of activated material in the decommissioning waste is however possible by a choice of materials and by adapting the shielding concept.

For a number of applications the use of adapted materials for collimators, beam stops or parts of target holders and irradiation set-ups can greatly reduce the unwanted secondary neutron production. The best example is the replacement of Cu and stainless steel by pure carbon at low energy. The threshold at 18 MeV of the (p,n) reaction guarantees a lower total neutron yield for incident beams up to about 25 MeV proton energy and nearly no long lived activation products. Even at higher energies, the yield of secondary neutrons is always lower for C than for other materials used for the same purpose. A possible negative aspect is the generation of high activities of short lived β^+ emitters limiting rapid access to the vicinity of the irradiated C-parts and the inferior properties concerning degassing and ultimate vacuum. Similar considerations exist for the use of aluminium.

Table VII. Waste volumes for the different scenarios (in tonnes)

	SCENARIO	WASTE	ACCELERATOR		
			VUB	IRMM	SATURNE
I m m e d i a t e	German scenario	LLW concrete	686	1468	612
		LLW metals*	5	27	1.3
	French scenario	LLW	14	28	1.3
		VLLW	2105	3130	1180
	British scenario	LLW	648	850	342
	D e f e r r e d	British scenario	LLW	0.005	6
I m m e d i a t e	German costs, EC-recommended clearance levels	LLW concrete	74	X	X
		LLW metals*	5	X	X
	French costs, EC-recommended clearance levels	LLW	13	X	X
		VLLW	78	X	X
	British costs, EC-recommended clearance levels	LLW	91	X	X

* In the German scenario, radioactive metal is assumed to be molten and recycled in the Siempelkamp facility, which reduces the amount of LLW.

Table VIII. Decommissioning costs for each of the scenarios (in k€)

	SCENARIO	ACCELERATOR		
		VUB	IRMM	SATURNE
I m m e d i a t e	German scenario	7700	16010	6870
	French scenario	4340	6320	1445
	British scenario	3550	4540	1820
D e f e r r e d	British scenario	980	1340	875
I m m e d i a t e	German costs, EC-recommended clearance levels	1545	X	X
	French costs, EC-recommended clearance levels	810	X	X
	British costs, EC-recommended clearance levels	830	X	X

As already mentioned traces of Co, Zn, Ag, Mn, Bi and Eu present in the structural materials result in important amounts of activated decommissioning waste. Minimal quantities of galvanised steel or stainless steel and low Ag content in contacts or solder will guarantee lower specific activity at the end of the operational life of the facility. Replacement by low Co-steel, Al or plastic materials for structural materials is recommended. Attention has to be paid to the type of corrosion protection applied to steel: applications of paints or coatings containing metal traces, which can be activated hence creating possible surface contamination, have to be avoided.

A further possibility in limiting the volumes of activated waste is to reduce the space in which the neutrons can interact with infrastructure and shielding. This can be realised by placing local shielding around the targets or other neutron sources.

If prevention of activation of the main walls of the shielding is not possible, judicious modular construction will limit the volume of activated material and ease the distinction and segregation of nuclear from industrial decommissioning rubble. The main idea is to build all walls (except perhaps the ceiling) in a minimum of two layers. The innermost layer, closest to the neutron-generating target, will act as neutron absorber with little structural function. This part of the wall should ideally be built of modular blocks thick enough to reduce the neutron flux to levels below the critical ones for inducing specific activation higher than the clearance levels. Dimensions should be such that easy removal at dismantling and compliance with regulations for disposal of nuclear waste will be met. The second, mainly structural layer can be executed either in ordinary, massive, reinforced concrete, either in modular blocks. The thickness of this wall can already be reduced in comparison to normal shielding as the first layer, needed for radiation protection, will ensure an important part of the dose reduction. Only γ -rays and neutron beams strongly reduced in energy and flux can reach this wall.

CONCLUSIONS AND RECOMMENDATIONS

The decommissioning of particle accelerators can be considered to be a technical operation without any particular difficulty. In fact, the low level of radioactivity within the structures of the equipment and the surrounding shielding material allows the use of hands-on techniques in a radiological protected area similar to that during maintenance and repairs. No strengthened protective measures are required for decommissioning, except for avoiding the spread of activity during dismantling operations (e.g. use of explosive techniques, special

attention for ^{65}Zn).

The amounts of radioactive waste can however be considerable due to the activation of significant masses of the shielding structures. Consequently, the philosophy of clearance and the levels for clearance largely influence the costs of the decommissioning programme. The sensitivity to the various philosophies and differences in legal and/or recommended values for clearance, has been highlighted in this report through the results of the evaluations. Furthermore, the important differences in labour costs and waste management costs within European countries also influence the results of the economic analysis.

Finally, it needs to be highlighted that the decommissioning costs for accelerators amount to about 50 to 100% of the today's investment costs for such accelerators. This fact has probably been undervalued by the operators of accelerators, which can be illustrated by the results of the questionnaire. More attention for building up financial provisions for the later decommissioning seems to be necessary, even if technological development reduces the beam losses in new facilities, reducing activation in the surrounding biological shielding.

Following recommendations can be made:

- A. Recommendations for management of existing and future accelerator facilities:
 1. Awareness in due time of the problem has to be encouraged so that all information needed for future dismantling is recorded and documented by the operator.
 2. National competent authorities should agree in an international framework on the waste management at decommissioning accelerators. Well-defined quantitative clearance levels accompanied by clear conditions and constraints for application are recommended. The conditions for waste management and disposal for all types of materials should help to respect basic radiation protection and environmental criteria.
 3. Regulatory authorities should enforce preparation of preliminary dismantling plans in an early stage of the accelerator operation.
 4. Mechanisms and funds for provisioning decommissioning costs should be foreseen and enforced.
- B. Recommendations for management, operators and constructors of new accelerator facilities
 5. The optimisation in the use of nuclear techniques and life cycle analysis of concepts of installations and materials used can decrease the future impact of the waste production.
 6. As prevention is always better than curing: adapted technical solutions are recommended for the reduction of source terms, with the implementation of modular construction concepts to limit the waste volumes and costs.

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