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AEROSOL AND DUST RADIOACTIVITY IN THE HALLS
OF HIGH-ENERGY ACCELERATORS

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ABSTRACT

In the halls of high-energy accelerators radioactive dust normally found is produced mainly by natural erosion and by wear or work of radioactive machine parts. This paper lists the main radionuclides which could be present in the loose radioactivity. They are produced by spallation, fission and capture reactions of primary and secondary particles with the machine components.

From measurements made at the CERN 28 GeV/c Proton Synchrotron, the main radionuclides found in dust are: ^{54}Mn , ^7Be , ^{51}Cr , ^{59}Fe and ^{48}V with an average relative concentration of about 50%, 25%, 7%, 9% and 9% respectively. The quantity and the $(\text{MPC})_a$ of these radionuclides were taken into account and rules of general interest are finally proposed for the evaluation of the hazard from loose radioactivity near high-energy accelerators.

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1. INTRODUCTION

High-energy accelerators require frequent maintenance work. The radiation hazards for persons working on maintenance in the machine halls are:

- a) activated machine parts causing external β - γ radiation,
- b) activated dust and aerosols causing internal contamination,
- c) activated gases causing external plus internal contamination.

Case a) has already been discussed in various papers ^{1,2,3,4,5}). The problem of airborne radioactivity (case c) produced at high-energy accelerators was dealt with in a previous paper ⁶). In the present paper the production of radioactive aerosols and dust and the hazards involved shall be studied.

Radioactive dust is produced from activated machine parts by normal erosion or mechanical wear. Dust in the accelerator halls is also activated when it is in suspension in the air or when it is deposited on the machine components. However, experience shows that the principal radioisotopes found in dust are those produced from the constituents of the machine parts.

The principal radionuclides which can be produced in the machine parts are enumerated hereafter; also the results accumulated through various experiments at the 28 GeV/c CERN Proton Synchrotron (CPS) are given. These results and the conclusions drawn can be considered valid for all types of high-energy proton accelerators.

The hazard deriving from the presence of these radionuclides in the dust at the machine hall is studied and subsequently compared to other radiation risks.

2. ESTIMATION OF THE RADIONUCLIDES IN DUST

Radionuclides in the accelerator halls are mainly produced by spallation processes from high-energy particles, by thermal neutron capture and by fast neutron reactions with the components of the accelerator body.

An exact calculation of all radionuclides produced and their relative amount at a certain time, is very complicated, perhaps impossible owing to the fact that this would imply an extensive knowledge of many parameters such as fluxes of particles, possible reactions and relative cross-sections, amount and distribution of parent isotopes, etc... However, some simplifications introduced in the calculation (see Appendices A and B) enable us to estimate these quantities.

Table 1 lists the main radionuclides which are expected to be found in the CPS after a few years running and some hours after machine stop. Also included in the table are the reactions which produce the radionuclides, and the accepted cross-sections for the reactions. The calculated specific activities of the radionuclides are listed in column 9 of the table. The assumptions made for this calculation refer to the CPS, but with some minor modifications they can be adapted to any proton accelerator of energy up to some 100 GeV, which is constructed with similar technical features. It can be drawn from table 1 that a total activity of some 600 Ci - the largest part (90%) produced in the magnets and vacuum chamber - is expected to be found in the CPS shortly after machine stop. This value is more than one order of magnitude higher than the value calculated using a different method, by Barbier and Cooper⁵⁾ for the CPS, after one day cooling down. Barbier and Cooper take into account only the activity produced by very high-energy particles whereas the present calculations show that the activity produced by fast and thermal neutrons is about 90% of the total activity.

Column 11 of table 1 lists the ratios of the calculated activity of the radionuclides to their maximum permissible concentration in air⁷⁾, relative to ^{54}Mn .*) This figure gives a picture of the relative hazard of the different radionuclides at an accelerator like the CPS. It has not a general significance like, for instance, the relative hazard of Morgan et al.⁸⁾, but it will be used for the analysis of the results.

3. EXPERIMENTAL PROCEDURE

Measurements of the radioactivity of dust in air and of dust from the surface of machine parts are made on a routine basis at the CERN accelerators. For the collection of the dust in air, a filter paper of the Fourestone A type was used through which the air was pumped. The pumping time depended on the density of dust in the air but did not exceed 1 hour. The dust was also collected from the surfaces by wiping a standard surface (100 cm^2) with an oiled filter paper. The filters were measured with a 2" diameter end-window β - α counter having $80\text{ }\mu\text{g/cm}^2$ window thickness, and with a γ spectrometer with a 3"x3" NaI crystal.

Many samplings carried out, 1 to some 100 hours after machine stop, have shown that γ spectra of dust in air and in the smear test are similar. In figure 1 typical γ spectra of a smear test measured at 12 hours and at 110 days after machine stop are shown.

The specific activity of the sample is evaluated from the α - β counting. This specific activity depends on the time interval between machine stop and the measuring time. A typical β -decay curve is shown in figure 2. For the air samples the natural Radon activity is taken into account in evaluating the specific activity.

The decay of γ activity of certain highly active smear tests has also been followed up for about one year.

*) in the following we shall call this ratio "relative hazard for accelerators".

4. EXPERIMENTAL RESULTS

From the spectral and decay measurements, the main radio-isotopes present in the dust of the accelerator hall with half-lives giving rise to a potential hazard were identified and are shown in table 2. The percentage activity of the isotope given in column 2 is the ratio of the isotope activity to the total activity of the five main isotopes at machine stop (the total activity at machine stop is, of course, much bigger due to the presence of short-lived radionuclides). This percentage is an average from various measurements; it can, of course, change from one sample to another depending on the point of sampling, the latest operation conditions of the machine, etc...., however, the values indicated in the table should be considered a good average. In the table also the corresponded calculated values from table 1 are given. The agreement between the experimental and calculated results is in general satisfactory. A discrepancy exists on the relative quantities of beta emitting radionuclides, which could be attributed to the simplifications introduced in the calculation. The ratio of beta to gamma emitters is useful for the routine evaluation of the hazards; for this practical purpose we propose to use the experimental values. If a particular material is irradiated during the machine operation, the radionuclides found as loose radioactivity will obviously be mainly radionuclides produced by this particular material.

5. ANALYSIS OF THE RESULTS

The number of radionuclides which have been found in substantial quantity is very small as compared to the number of possible radionuclides.

Table 1 shows a large production of ^{55}Fe , ^{56}Mn and ^{24}Na which have not been found so far in the measurements. This could be explained by the following reasons:

- a) ^{55}Fe decays by electron capture with emission of X-rays of about 5.6 keV; γ -ray spectrometers with a NaI crystal do not allow the detection of these low-energy lines.

- b) ^{56}Mn has a half-life of 2.6 hours. Ten hours after machine stop the quantity of ^{56}Mn present will be reduced by a factor of about 15. In addition, the γ line of ^{56}Mn (845 keV) is so close to that of ^{54}Mn (840 keV) that it is very difficult to separate them. Anyway, the presence of ^{56}Mn does not influence the hazard owing to its short half-life and to its $(\text{MPC})_a$ being higher than that of ^{54}Mn .
- c) The activity of ^{24}Na is reduced by a factor of ten 48 hours after machine stop, consequently its presence in the evaluation of the hazard can be neglected.

The figures of column 11 of table 1 and the results of the measurements indicate that ^{54}Mn should be considered as the most dangerous radioisotope for internal contamination at high-energy proton accelerators.

A multiple of its maximum permissible concentration in air can be used as a safety value for hazard evaluation when no analysis of the collected dust is made.

Any objections due to the presence of ^{22}Na , ^{60}Co and ^{46}Sc [having a $(\text{MPC})_a$ lower than that of ^{54}Mn], and due to the specific activity of ^{55}Fe and ^{56}Mn (expected to be higher than that of ^{54}Mn), can be disregarded for the following reasons:

The fact that the relative hazards for accelerators of these radionuclides are lower than 1, indicates that the ratio of the expected quantity of radionuclides to that of ^{54}Mn is lower than the ratio of the respective $(\text{MPC})_a$'s. This means that, for the radionuclides with $(\text{MPC})_a$ lower than the $(\text{MPC})_a$ of ^{54}Mn , the activity produced is so low that its contribution to the hazard is included in that of ^{54}Mn when the $(\text{MPC})_a$ of ^{54}Mn is considered. The same applies for radionuclides produced in larger quantities than ^{54}Mn but for which the $(\text{MPC})_a$'s are larger than that of ^{54}Mn .

The activities of ^{22}Na , ^{60}Co and ^{46}Sc have to be smaller than that of ^{54}Mn since their production cross-sections with

Mn, Fe and Cu present in large quantities in the machine parts (see Appendix A) are much smaller than those for the production of ^{54}Mn (see table 1). Besides, the γ spectra also did not show large quantities of these radionuclides.

^{45}Ca being a pure β -emitter of relatively low energy is difficult to identify; assuming that the concrete of the machine creates an important quantity of dust, ^{45}Ca should be present in notable quantities due to the high cross-section (630 mb) of thermal neutron capture of ^{44}Ca [$^{44}\text{Ca}(n,\gamma)^{45}\text{Ca}$]. About 0.4% of the concrete will consist of this particular isotope (isotopic abundance in natural Calcium: 2%). But, if this were true, ^{22}Na , which is easily distinguishable in a γ spectrum, would also be found. ^{22}Na is produced in concrete from Al (4%) and Na (0.5%) (see Appendix A). The production rate of ^{22}Na from Al and Na by high-energy particles and fast neutrons equals approximately the production rate of ^{45}Ca from ^{44}Ca by thermal neutrons if the given elementary quantities and the respective particle fluxes were considered. ^{22}Na is in fact found in the γ spectrum but in such a small quantity that the presence of ^{45}Ca can also be considered negligible as compared to ^{54}Mn . It has also to be taken into account that the (MPC)_a of ^{54}Mn is higher than that of ^{45}Ca . The quantity of ^{45}Ca found from β -decay measurements was also negligible. Moreover the significant presence of ^{59}Fe shows that the origin of the general dust is not due only to the concrete and this confirms our statements.*) The specific radioactivity of the ferric materials (especially for the vacuum chamber) is much higher than that of the concrete because they are exposed to much higher high-energy particle fluxes; consequently their contribution to the specific activity of dust should be more important.

From many series of routine smear tests it was found that smear radioactivity follows up the patterns of the induced β - γ radioactivity. The patterns of induced radioactivity show maxima near the targets and beam loss regions. Figure 3 shows isoactivity curves from smear tests

*) (As already mentioned the calculated contribution of ferric materials to the total radioactivity of the machine is about 90%.)

in a target region; these curves are also typical for external β - γ activity. This demonstrates that the smear test reproduces mainly erosion products from machine parts and dust activated on the spot.

6. CONCLUSIONS

Nuclides emitting only γ -rays contribute about 70%-80% to the measured total radioactivity in the machine hall. Thus, if the specific β activity of a sample is multiplied by a factor 4 a good estimation of the total specific activity of the sample should be obtained.

For general routine purposes, it is proposed that the $(MPC)_a$ of the ^{54}Mn ($4 \times 10^{-8} \mu\text{Ci/cm}^3$) should be used as general $(MPC)_a$ when no special analysis of the sample is made. This avoids excessive over-estimation introduced by the use of $(MPC)_a$ for unknown radioisotopes and yet gives a safety over-estimation of about a factor 4 as compared to the hazard which would be calculated if a mixture of radionuclides were supposed such as that of table 1, and an over-estimation factor of about 3 for a mixture such as that of table 2.

A proposal was made⁹⁾ to cover the most exposed machine parts with marble which would reduce the induced radioactivity; though this should prove successful for the external β - γ exposures, on the other hand, it would create an important contribution of ^{45}Ca to the loose radioactivity produced from ^{44}Ca present in substantial quantity in the marble, and also owing to the greater possibility of erosion of the marble as compared to iron or steel. Thus, the reduction of external β - γ activity could result in a higher potential hazard for internal contamination.

Levels of a total specific radioactivity in the air up to $80 \times 10^{-12} \mu\text{Ci/cm}^3$ have been measured in the machine halls about one

hour after machine stop in regions where the average β - γ external dose-rate was of the order of few rem/h. These levels are about 500 times lower than the proposed $(MPC)_a$.

In smear tests, levels up to $5 \times 10^{-3} \mu\text{Ci}/\text{cm}^2$ have been measured in places where the external β - γ dose-rate at 20 cm rises up to values of some rem/h; these contamination levels are still below the MPC for the contamination of materials¹⁰⁾.

The previous values show that the potential hazard due to internal contamination is small compared to that from external exposure.

This is also demonstrated by the fact that wholebody counting of several persons more frequently employed on machine maintenance who had a quite high accumulated dose from external radiation, did not show the presence of any internal contamination. The measurements were carried out in the wholebody counter of the 'Institut de Radium' in Geneva.

In spite of the fact that internal contamination has not been found so far in persons and that smear tests or air measurements do not normally show high contamination levels, a potential hazard exists in the machine and it is possible to find highly activated machine parts. Consequently, the hazard for internal contamination should be followed up in parallel with the danger from external radiation.

The value of the parameters used for the calculation of the induced radioactivity at the CERN Proton Synchrotron are given. The following table indicates the composition of the main machine parts.

Table
Composition of the main CPS parts

Concrete shielding		Magnets		Coils		Vacuum chamber (Fluginox 130 stainless steel)	
Compon.	% weight	Compon.	% weight	Compon.	% weight	Compon.	% weight
CO ₂	12.33	Fe	99.6	Al	100	Fe	48
H ₂ O	3.09	C	0.06			Ni	35
SiO ₂	46.72	Mn	0.3	(Cu)	(100)	Cr	15
Fe ₂ O ₃	2.02	S	0.025			Ti	2
MnO ₄	0.055	P	0.01			Mo	traces
Al ₂ O ₃	6.72	⁵⁹ Co	0.0054				
CaO	25.38						
MgO	1.43						
K ₂ O	1.00						
Na ₂ O	1.07						
SO ₃	0.25						

Relatively small quantities of other materials, such as lead, copper, wood, plastic, etc... are used in the accelerator; their presence can be ignored if compared to the weight of the shielding and magnets.

The dimensions and weights of those CPS parts considered in these calculations, are given below.

- a. Vacuum chamber has the highest specific radioactivity in the accelerator. Has a roughly elliptical section of 150 mm and 74 mm axes, 2mm thickness and 628 m length. Total surface: $4.6 \times 10^2 \text{ m}^2$. Total volume: $\sim 1 \text{ m}^3$. Total weight: ~ 8 tons.
- b. Magnets 100 units of 30 m^2 surface, 3.8 m^3 volume and 30 tons weight each.
- c. Concrete for a first approximation of the 'active' surface of CPS concrete one should consider a cylinder of 6 m diameter and 628 m length, i.e. $1.25 \times 10^4 \text{ m}^2$ surface. To this surface should be added 20% when taking into account the surface of the corridors and the largest sections. The total surface will then be $1.5 \times 10^4 \text{ m}^2$. The active volume should be calculated on the basis of 10 cm thickness because the first 10 cm of concrete contribute 80% of the total induced radioactivity²³⁾. Then, the total 'active' volume is about $1.5 \times 10^3 \text{ m}^3$ and the total weight 4.5×10^3 tons, assuming a concrete average density of 3 g/cm^3 .
- d. The coils of the magnet units of the CPS are made of Al and weigh about 1.1 tons for each magnet, i.e. 110 tons in total. If Cu is used as an alternative, the total equivalent weight will be 230 tons. Table 1 takes into account this alternative.

Explanations of Table 1 and of the restrictions
applied for its compilation

Column 1

The main radionuclides produced from the reactions of very high-energy protons and neutrons and fast and thermal neutrons with the principal machine components are listed. The following restrictions have been applied:

- a. only radionuclides with half-life between about 1 hour and up to 20 years are considered;
- b. only radionuclides present at a percentage higher than 0.01% are indicated.

Columns 2 and 3

Half-life and decay mode of the radionuclides.

Column 4

Parent isotopes - the following elements in the machine have been considered:

C, O, Na, Mg, Al, Si, P, K, Ca, Ti, Cr, Mn, Fe,
Co, Ni, Cu (as an alternative to Al).

The letters between brackets indicate the origin of the element.
S = shielding, M = magnets, coils, vacuum chambers.

For the spallation reactions producing radionuclides with an atomic mass lower than that of Fe, only the iron was considered as being the heaviest parent element. This is justified by the following:

- i) the quantity of iron is much bigger than that of elements with $Z > 26$;
- ii) the cross-sections of spallation reactions with iron are higher than those with elements of $Z > 26$.

For similar reasons, for spallation products with atomic mass much lower than that of the parent element, only the iron has been taken as parent element.

Column 5

Type of reaction. Many types of particles with different energies are produced in the accelerator giving rise to many types of reactions with machine elements. Reactions with a cross-section $> 1 \text{ mb}$, were chosen, with the exception of Fe present in important quantities in the machine.

Columns 6, 7 and 8

These give the cross-sections used in the calculations, the corresponding energy and the reference, respectively. The criteria for the choice of cross-sections were the maximum values in the case of thermal and fast neutrons. The choice of one cross-section for the reactions with very high-energy particles is more difficult: on one hand, the maximum of σ moves towards high energies as the mass difference parent-product increases and, on the other hand, the average energy at this part of the spectrum is about 100 MeV. However, in this part of the spectrum, the maximum value of σ found in the region of about 100 MeV was used. For many spallation reactions where no experimental values were found for σ , the cross-section was calculated using the Rudstam formula¹⁴⁾. The calculations were made at 100 MeV energy for products close to the parent elements and at 1000 MeV energies for products far from them.

Column 9

Induced activity - indicates the total quantity of radioisotopes produced by the aforesaid reactions from the quantities of parent elements as indicated in Appendix A.

For the calculation the average activating particle fluxes in the CPS hall were assumed to be the following:

$2 \times 10^5 \text{ n cm}^{-2} \text{ s}^{-1}$ of thermal neutrons,
 10^6 " of fast neutrons,
 2×10^5 " of very fast particles.

Column 10

Maximum Permissible Concentration in the air for the critical organs, for insoluble forms and for an exposure of 40 h/week as stated by ICRP.

Column 11

The ratio of the calculated induced activity to the $(\text{MPC})_a$ in relation to ^{54}Mn , i.e.

$$\frac{\text{induced activity of the radionuclide}}{(\text{MPC})_a \text{ of the radionuclide}} \times \frac{(\text{MPC})_a \text{ of } ^{54}\text{Mn}}{\text{induced activity of } ^{54}\text{Mn}} .$$

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TABLE AND FIGURE CAPTIONS

Table 1 : List of the main radionuclides produced by the interaction of primary and secondary particles from a high-energy proton accelerator with the principal materials in the machine. For explanations of the table see Appendix B.

Table 2 : List of the main radioisotopes found from spectral and decay measurements in dust of the CPS.

Figure 1 : Typical γ spectra at 12 hours^{a)} and 110 days^{b)} after machine stop.

Figure 2 : Typical β decay from a few minutes to 10 days after machine stop.

Figure 3 : Isoactivity patterns from smear tests near a target region at the CPS.

Table 1

Radio-nuclide	Half-life	Decay mode	Parent isotope (machine part)	Production reaction				Induced activity (Ci)	(MPC)	Relative hazard for accelerators
				Type of reaction	Cross-section (mb)	Energy (MeV)	Reference			
$^{22}_{11}\text{Na}$	2.6 y	β^+, γ	$^{23}_{11}\text{Na}(\text{S})$	(n,2n)	70	20	(12)	2.05	9×10^{-9}	2.4×10^{-1}
			$^{23}_{11}\text{Na}(\text{S})$	(p,pn)	70.8	50	(11)			
			$^{23}_{11}\text{Na}(\text{S})$	(p,pn)	31	6,000	(11)			
			$^{24}_{12}\text{Mg}(\text{S})$	(p,2pn)	62.7	50	(11)			
			$^{27}_{13}\text{Al}(\text{M})$	(p,spal.)	20	100	(13)			
			$^{40}_{20}\text{Ca}(\text{S})$	(p,spal.)	4	1,000	(14)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p,spal.)	0.02	340	(11)			
$^{60}_{27}\text{Co}$	5.2 y	β^-, γ	$^{59}_{27}\text{Co}(\text{M})$	(n, γ)	37×10^3	th.	(12)	0.41	9×10^{-9}	4.8×10^{-2}
			$^{60}_{28}\text{Ni}(\text{M})$	(n,p)	140	13	(12)			
			(*) $^{63}_{29}\text{Cu}(\text{M})$	(n, α)	40	13	(12)			
			(*) $^{63}_{29}\text{Cu}(\text{M})$	(v,spal.)	59	100	(14)			
			(*) $^{65}_{29}\text{Cu}(\text{M})$	(p,spal.)	18	100	(14)			
$^{44}_{24}\text{Sc}$	84 d	β^-, γ	$^{48}_{22}\text{Ti}(\text{M})$	(p,2pn)	138	100	(14)	0.52	2×10^{-8}	2.75×10^{-2}
			$^{54}_{24}\text{Cr}(\text{M})$	(v,spal.)	13	100	(14)			
			$^{55}_{25}\text{Mn}(\text{M})$	(p,spal.)	5.7	170	(11)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p,spal.)	3.2	340	(11)			
$^{54}_{25}\text{Mn}$	300 d	EC, γ	$^{55}_{25}\text{Mn}(\text{M})$	(n,2n)	1.1×10^3	18	(12)	38	4×10^{-8}	1
			$^{54}_{26}\text{Fe}(\text{M})$	(n,p)	500	6	(12)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p,2pn) (n,p2n)	42	130	(21)			
$^{59}_{26}\text{Fe}$	45 d	β^-, γ	$^{58}_{26}\text{Fe}(\text{M})$	(n, γ)	1.2×10^3	th.	(12)	0.69	5×10^{-8}	1.4×10^{-2}
			$^{59}_{27}\text{Co}(\text{M})$	(n,p)	80	14	(12)			
			$^{60}_{28}\text{Ni}(\text{M})$	(n,2p)	10	100	(**)			
			(*) $^{63}_{29}\text{Cu}(\text{M})$	(v,spal.)	~ 1	300	(14)			
$^{59}_{27}\text{Co}$	71 d	EC, β^+, γ	$^{59}_{27}\text{Co}(\text{M})$	(n,2n)	700	14	(12)	0.396	5×10^{-8}	8.3×10^{-3}
			$^{58}_{28}\text{Ni}(\text{M})$	(n,p)	600	6	(12)			
			$^{60}_{28}\text{Ni}(\text{M})$	(v,2pn)	360	100	(14)			
			(*) $^{69}_{29}\text{Cu}(\text{M})$	(p,spal.)	~ 90	~ 200	(14)			
(*) $^{65}_{30}\text{Zn}$	245 d	EC, β^+, γ	$^{65}_{30}\text{Zn}(\text{M})$	(p,n)	750	10	(22)		6×10^{-8}	
$^{48}_{23}\text{V}$	16.1 d	EC, β^+, γ	$^{52}_{24}\text{Cr}(\text{M})$	(p,spal.)	41	100	(14)	1.64	6×10^{-8}	2.9×10^{-2}
			$^{55}_{25}\text{Mn}(\text{M})$	(p,spal.)	13	170	(11)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p,spal.)	10	340	(11)			

Radio-nuclide	Half-life	Decay mode	Parent isotope (machine part)	Production reaction				Induced activity (Ci)	(MPC) _a	Relative hazard for accelerators
				Type of reaction	Cross-section (mb)	Energy (MeV)	Reference			
$^{59}_{27}\text{Co}$	77.3 d	$\text{EC}, \beta^+, \gamma$ (*)	$^{59}_{27}\text{Co}(\text{M})$	(p, spal.)	33.4	100	(14)	0.0072 (neglig.)	?	?
			$^{58}_{28}\text{Ni}(\text{M})$	(p, 2pn)	59	100	(14)			
			$^{60}_{28}\text{Ni}(\text{M})$	(p, spal.)	18	100	(14)			
			$^{63}_{29}\text{Cu}(\text{M})$	(p, spal.)	3	100	(14)			
$^{32}_{15}\text{P}$	14.3 d	β^-	$^{31}_{15}\text{P}$	(n, γ)	190	th.	(12)	1.76	8×10^{-8}	2.2×10^{-2}
			$^{32}_{16}\text{S}$	(n, p)	380	11	(12)			
			$^{39}_{19}\text{K}(\text{S})$	(p, spal.)	3	100	(14)			
			$^{40}_{20}\text{Ca}(\text{S})$	(p, spal.)	2	100	(14)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p, spal.)	3.1	10^3	(15)			
$^{45}_{20}\text{Ca}$	164 d	β^-	$^{44}_{20}\text{Ca}(\text{S})$	(n, γ)	700	th.	(17)	0.78	10^{-7}	8.2×10^{-3}
			$^{48}_{22}\text{Ti}(\text{M})$	(p, spal.)	15	100	(14)			
			$^{52}_{24}\text{Cr}(\text{M})$	(p, spal.)	1.5	100	(14)			
			$^{55}_{25}\text{Mn}(\text{M})$	(p, spal.)	1.1	170	(11)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p, spal.)	0.56	340	(11)			
$^{43}_{19}\text{K}$	22.4 h	β^-, γ	$^{44}_{20}\text{Ca}(\text{S})$	(n, pn)	2.6	14	(16)	0.082	?	?
			$^{56}_{26}\text{Fe}(\text{M})$	(p, spal.)	0.4	340	(11)			
$^{42}_{19}\text{K}$	12.4 h	β^-, γ	$^{41}_{19}\text{K}(\text{S})$	(n, γ)	1.3×10^3	th.	(17)	0.51	10^{-7}	5.4×10^{-3}
			$^{40}_{20}\text{Ca}(\text{S})$	(p, spal.)	75	100	(14)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p, spal.)	0.07	340	(11)			
$^{52}_{25}\text{Mn}$	5.6 d	$\text{EC}, \beta^+, \gamma$	$^{55}_{25}\text{Mn}(\text{M})$	(p, 3np)	16	170	(11)	2.12	10^{-7}	2.23×10^{-2}
			$^{56}_{26}\text{Fe}(\text{M})$	(p, spal.)	13	340	(11)			
$^{24}_{11}\text{Na}$	15 h	β^-, γ	$^{23}_{11}\text{Na}(\text{S})$	(n, γ)	400	th.	(12)	26.4	10^{-7}	2.8×10^{-1}
			$^{24}_{12}\text{Mg}(\text{S})$	(n, p)	195	14	(12)			
			$^{27}_{13}\text{Al}(\text{M})$	(n, α)	~ 120	12	(13)			
			$^{27}_{13}\text{Al}(\text{M})$	(p, 3pn)	~ 10	100	(13)			
			$^{40}_{20}\text{Ca}(\text{S})$	(p, spal.)	3	1,000	(14)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p, spal.)	1.5	1,000	(15)			
$^{48}_{21}\text{Sc}$	44 h	β^-, γ	$^{48}_{22}\text{Ti}(\text{M})$	(n, p)	64	14	(12)	0.076	10^{-7}	8×10^{-4}
			$^{52}_{24}\text{Cr}(\text{M})$	(p, spal.)	3	100	(14)			
			$^{55}_{25}\text{Mn}(\text{M})$	(p, spal.)	0.7	170	(11)			
			$^{56}_{26}\text{Fe}(\text{M})$	(p, spal.)	0.45	340	(11)			

Radio-nuclide	Half-life	Decay mode	Parent isotope (machine part)	Production reaction				Induced activity (Ci)	(MPC) _a	Relative hazard for accelerators
				Type of reaction	Cross-section (mb)	Energy (MeV)	Reference			
⁵⁷ Co	270 d	EC, γ	⁵⁵ Co(M)	(p, p2n)	65	53	(11)	0.27 (0.17)	2 × 10 ⁻⁷	1.45 × 10 ⁻³
			⁵⁸ Ni(M)	(n, pn)	500	14	(12)			
			⁵⁸ Ni(M)	(p, 2p)	32	370	(18)			
			⁵⁹ Ni(M)	(p, spal.)	102	100	(14)			
			Cu(M)	(p, spal.)	14.7	3,000	(11)			
⁵⁸ S	87 d	β ⁻	³⁹ K(S)	(p, spal.)	33	100	(14)	1.3	3 × 10 ⁻⁷	4.5 × 10 ⁻³
			⁴⁰ Ca(S)	(p, spal.)	18	100	(14)			
			⁵⁶ Fe(M)	(p, spal.)	0.23	340	(11)			
³³ P	24.4 d	β ⁻	³⁹ K(S)	(p, spal.)	7	100	(14)	0.44	?	?
			⁴⁰ Ca(S)	(p, spal.)	4	100	(14)			
			⁵⁶ Fe(M)	(p, spal.)	1	1,000	(14)			
⁴⁷ So	3.4 d	β ⁻ , γ	⁴⁸ Ti(M)	(n, pn)	12.4	14	(12)	0.52	5 × 10 ⁻⁷	1.1 × 10 ⁻³
			⁵² Cr(M)	(p, spal.)	7	100	(14)			
			⁵⁵ Mn(M)	(p, spal.)	5.7	170	(11)			
			⁵⁶ Fe(M)	(p, spal.)	3.2	340	(11)			
⁶⁵ Ni	2.6 h	β ⁻ , γ	⁶⁴ Ni(M)	(n, γ)	1.5 × 10 ³	th.	(17)	(neglig.) (0.39)	5 × 10 ⁻⁷	
			⁶⁵ Cu(M)	(n, p)	22	14	(12)			
⁵⁶ Mn	2.6 h	β ⁻ , γ	⁵⁵ Mn(M)	(n, γ)	13 × 10 ³	th.	(12)	105.5	5 × 10 ⁻⁷	2.2 × 10 ⁻¹
			⁵⁶ Fe(M)	(n, p)	120	14	(12)			
			⁵⁷ Fe(M)	(n, pn)	6	14.8	(12)			
⁵⁵ Fe	2.6 y	EC	⁵⁴ Fe(M)	(n, γ)	2.6 × 10 ³	th.	(12)	385	10 ⁻⁶	4 × 10 ⁻¹
			⁵⁶ Fe(M)	(n, 2n)	440	14	(12)			
			⁵⁵ Mn(M)	(p, n)	10	50	(**)			
			⁵⁷ Co(M)	(p, spal.)	68	100	(14)			
³¹ Si	2.6 h	β ⁻ , γ	³⁰ Si(S)	(n, γ)	103	th.	(16)	0.59	10 ⁻⁶	6.2 × 10 ⁻⁴
			³¹ P	(n, p)	125	5	(12)			
			³⁹ K(S)	(p, spal.)	1.7	100	(14)			
			⁴⁰ Ca(S)	(p, spal.)	1	100	(14)			
			⁵⁶ Fe(M)	(p, spal.)	1	1,000	(14)			
⁶⁴ Cu	12.9 h	EC, β ⁺ , β ⁻ , γ	⁶³ Cu(M)	(n, γ)	3.8 × 10 ³	th.	(12)	(51)	10 ⁻⁶	
			⁶⁵ Cu(M)	(n, 2n)	1.1 × 10 ³	16	(12)			
			⁶⁵ Cu(M)	(p, pn)	108	82	(11)			

Radio-nuclide	Half-life	Decay mode	Parent isotope (machine part)	Production reaction				Induced activity (Ci)	(MPC) _a	Relative hazard for accelerators
				Type of reaction	Cross-section (mb)	Energy (MeV)	Reference			
⁷ Be	53 d	EC, γ	¹² C(S)	(p, spal.)	25	50	(13)	27.4	10 ⁻⁶	2.9 × 10 ⁻²
			¹⁶ O(S, M)	(p, spal.)	10	1,000	(19)			
			²³ Na(S)	(p, fr.)	10	1,000	(19)			
			²⁷ Al(M)	(p, fr.)	8	1,000	(20)			
			²⁸ Si(S)	(p, fr.)	9	1,000	(19)			
			⁴⁰ Ca(S)	(p, fr.)	9	1,000	(19)			
			Fe(M)	(p, fr.)	12	2,800	(15)			
⁴¹ Ar	1.8 h	β ⁻ , γ	⁴¹ K(S)	(n, p)	81	14	(12)	0.225	2 × 10 ⁻⁶	1.2 × 10 ⁻⁴
			⁴⁴ Ca(S)	(p, spal.)	6.7	100	(14)			
			Fe(M)	(p, spal.)	0.75	1,000	(14)			
⁵¹ Cr	27.8 d	EC, γ	⁵⁰ Cr(M)	(n, γ)	16 × 10 ³	th.	(12)	4.9	2 × 10 ⁻⁶	2.6 × 10 ⁻³
			⁵² Cr(M)	(n, 2n)	280	14	(12)			
			⁵⁵ Mn(M)	(p, spal.)	98	100	(14)			
			⁵⁶ Fe(M)	(p, spal.)	30	130	(21)			
⁵⁷ Ni	36 h	β ⁺ , γ	⁵⁸ Ni(M)	(n, 2n)	65	20	(12)	0.04	?	?
			⁶⁰ Ni(M)	(p, p3n)	10	100	(**)			
			⁵⁵ Ni(M)	(p, pn)	50	400	(11)			
			⁶³ Cu(M)	(p, spal.)	1	100	(11)			
		(*)						(neglig.)		
²⁴ Mg	21.3 h	β ⁻ , γ	²⁹ Si(S)	(n, 2p)	10	100	(**)	0.285	?	?
			³⁰ Si(S)	(n, 2pn)	2	130	(11)			
			³¹ P	(p, spal.)	0.2	130	(11)			
			⁴⁰ Ca(S)	(p, spal.)	1	100	(14)			
			⁵⁶ Fe(M)	(p, spal.)	1	1,000	(14)			
⁴³ Sc	3.9 h	β ⁺ , γ	⁴⁸ Ti(M)	(p, spal.)	11	100	(14)	0.327	?	?
			⁵² Cr(M)	(p, spal.)	6	100	(14)			
			⁵⁵ Mn(M)	(p, spal.)	3.4	170	(11)			
			⁵⁶ Fe(M)	(p, spal.)	2	340	(11)			
⁴⁴ Sc ⁴⁴ Sc	2.4 d 4 h	γ β ⁺ , EC, γ	⁴⁸ Ti(M)	(p, 3p3n)	63	100	(14)	0.33	?	?
			⁵² Cr(M)	(p, spal.)	6	100	(14)			
			⁵⁵ Mn(M)	(p, spal.)	3.4	170	(11)			
			⁵⁶ Fe(M)	(p, spal.)	2	340	(11)			

Radio-nuclide	Half-life	Decay mode	Parent isotope (machine part)	Production reaction				Induced activity (Ci)	(MPC) _a	Relative hazard for accelerators
				Type of reaction	Cross-section (mb)	Energy (MeV)	Reference			
$^{45}_{22}\text{Ti}$	3.1 h	EC, β^+	$^{46}_{22}\text{Ti}(\text{M})$	(n,2n)	225	20	(12)	0.6	?	?
			$^{52}_{23}\text{Cr}(\text{M})$	(p,spal.)	2.7	100	(14)			
			$^{54}_{26}\text{Fe}(\text{M})$	(p,spal.)	3.7	340	(11)			
$^{49}_{23}\text{V}$	330 d	EC	$^{50}_{23}\text{Cr}(\text{M})$	(n,p)	277	14	(12)	1.7	?	?
			$^{54}_{23}\text{Cr}(\text{M})$	(p,2p2n)	178	100	(14)			
			$^{55}_{25}\text{Mn}(\text{M})$	(p,spal.)	30	100	(14)			
			$^{54}_{26}\text{Fe}(\text{M})$	(p,spal.)	10	340	(11)			
$^{57}_{27}\text{Co}$	18 h	β^+, γ	$^{59}_{27}\text{Co}(\text{M})$	(p,3p3n)	15	100	(11)	(neglig.)	?	?
			$^{58}_{28}\text{Ni}(\text{M})$	(p,2pn)	7.6	100	(14)			
			$^{60}_{28}\text{Ni}(\text{M})$	(p,spal.)	2.3	100	(14)			
		(*)	$^{63}_{29}\text{Cu}(\text{M})$	(p,spal.)	1.4	190	(11)	(0.011)		

*) The Cu is introduced in the table as an alternative with Al for the coils of magnets. The radioactivity produced by its presence is not taken into consideration in the final results, but is indicated between brackets.

**) Authors' estimation.

Note: For the radioactive fragments emitted from the nuclei following the interaction by high-energy particles, only the ^7Be was considered here since the maximum permissible concentration (MPC) of ^3H is very high. The mechanism of fragmentation explains the high production cross-section of ^7Be from elements far from it. The ^7Be was found in the dust (see text) and it is easier to understand its large presence by fragmentation from heavy parent elements rather than its production from ^{12}C and ^{16}O .

Table 2

Radio-nuclide	Decay mode	Average measured quant.(in %)	Concentration from Table 1	
			Spec.activ.	% (*)
⁵⁴ Mn	EC, γ	~ 50	38	52
⁷ Be	EC, γ	~ 25	27.4	38
⁵¹ Cr	EC, γ	7	4.9	7
⁵⁹ Fe	β^- , γ	~ 9	0.7	< 1
⁴⁸ V	β^+ , γ	~ 9	1.6	~ 2

*) Percentage to the total activity of the five radio-isotopes.

Fig.1

Fig. 3