LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF–94/054 (P)
26 Settembre 1994

Radiation Protection Problems Around the Positron Converter of the DAΦNE Machine Project

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INTRODUCTION

One of the most important radiation protection problems involved with a high energy particle accelerator concerns the exposure of personnel to β and γ radiations from the components of the machine exposed to primary beams (beam dumps, targets, collimators etc.).

The aim of this paper is to set a scale of amount of activity induced in the DAΦNE positron converter and to calculate the expected photon dose rate.

PACS.: 87.50.N, P Radiation protection

Presented at the
1st Mediterranean Congress on Radiation Protection
5th – 7th April, 1994 – Athens (Greece)

RADIOACTIVATION BY PARTICLE BEAMS

Radioactivity may be induced in solid components, in air and water, to an extent that depends mainly on particle energy, beam power and on the type of material. Activation can be produced in all parts of DAΦNE as electron energies are above the thresholds for activation. Precise thresholds for various activation reactions can be found in literature (Die 88).

When a stable isotope B of a target material is exposed to a high energy particle beam it is transmuted to a radioactive nuclide R which decays with its characteristic disintegration constant λ_R. The rate of accumulation of R, given by the rate of its formation minus the rate of disintegration, may be expressed by the following differential equation:

$$\frac{dN_R}{dt} = \sigma_{B,R}\varphi N_B - \lambda_R N_R \qquad (1)$$

where

φ is the particle fluence rate

$\sigma_{B,R}$ is the activation cross section

N_B is the number of atoms of B present in the target material

N_R is the number of radioactive atoms.

Through the integration of equation (1) the number of radioactive atoms present at the end of the irradiation time t will be given by:

$$N_R(t) = \frac{\sigma_{B,R}\varphi N_B}{\lambda_R}\left(1 - e^{-\lambda_R t}\right) \qquad (2)$$

and the number of disintegrations per second will be given by:

$$A_R(t) = N_R(t)\lambda_R = \sigma_{B,R}\varphi N_B\left(1 - e^{-\lambda_R t}\right) \qquad (3)$$

If the irradiation time t is long compared to the meanlife of the produced radionuclide, the decay rate for this radionuclide has a limit, the so–called saturation activity $A_{RS} = \sigma_{B,R}\varphi N_B$, that depends only on the reaction cross section and on the particle fluence rate. Introducing the elapsed time T_C after the irradiation has been completed, the so–called "cooling" time, eq. (3) becomes:

$$A_R(t, T_C) = \sigma_{B,R}\varphi N_B\left(1 - e^{-\lambda_R t}\right)e^{-\lambda_R T_C} \qquad (4)$$

which represents the activity of the radionuclide R as a function of both the irradiation time t and the cooling time T_C.

The main purpose of these calculations is to give an estimate of the production of induced radioactivity in the materials constituting the positron converter of the DAΦNE Linac, mainly tungsten, copper, iron and cooling water. An accurate approch to the problem would be possible by Montecarlo–codes by which, the geometry, the materials and the physical

phenomena (nuclear reactions, cross sections etc.) could be competely simulated. Nevertheless an exhaustive, conservative and easy approch to the problem is possible assuming the following hypotheses:

1) the positron converter is made only of tungsten, copper, iron and water;
2) the residual radioactivity is mainly induced by neutron photoproduction and photospallation reactions;
3) each reaction leads to radioactive atoms.

The most copious radioactivity reactions are the (γ,n) ones (Swa 79 a). The saturation activity produced by other photoneutron reactions and by all other processes, including photospallation, is assumed to be about 5% of the (γ,n) value (Swa 79 a) for each reaction considered. The radioactivity values calculated under these unfavourable conditions, rarely found in practice, set an upper limit to the amount of radioactivation that is possible.

So it will be sufficient to know the yield of neutrons to know the yield of radionuclides. The photoneutron production rate due to the high energy electron beams incident on a target has been exhaustively treated by Swanson (Swa 79). For infinitely thick targets Swanson gives the following expression for the neutron yield per kW of electron beam power, as a function of the atomic number, disregarding target self–shielding:

$$Y_R = 1.21 \cdot 10^{11} Z^{0,66} \text{ neutrons } s^{-1}kW^{-1} \tag{5}$$

or

$$Y_R = 1.21 \cdot 10^{11} Z^{0,66} \text{ radioactive atoms } s^{-1}kW^{-1}. \tag{6}$$

This expression assumes that only a single target isotope is present, and that all the energy of the electromagnetic shower induced by the incident electron beam is absorbed in the material.

Considering that the real target is made of a natural material and introducing the isotopic abundance F of element considered (Table I) eq. (6) becomes:

$$Y_R = 1.21 \cdot 10^{11} Z^{0,66} F \text{ radioactive atoms } s^{-1}kW^{-1} \tag{7}$$

which represents the saturation activity of the radionuclide considered.

Introducing the factor $R_{\sigma(\gamma,x),\sigma(\gamma,n)}$, that represents the ratio between the saturation activity for the (γ,x) reaction considered and the saturation activity for the (γ,n) reaction, eq. (7) can be rewritten as follows:

$$Y_R = 1.21 \cdot 10^{11} Z^{0.66} F R_{\sigma(\gamma,x)\sigma(\gamma,n)} \text{ radioactive atoms } s^{-1}kW^{-1}. \tag{8}$$

Since $Y_R = A_{RS} = \sigma_{B,R} \varphi N_B$, by replacing this value in equation (4) it can be obtained:

$$A_R(t, T_C) = Y_R\left(1 - e^{-\lambda_R t}\right)e^{-\lambda_R T_C} \tag{9}$$

and in general for cycles of the same type (same irradiation and cooling time) it can be written:

$$A_R(n,t,T_C) = \left[A_R(n-1,t,T_C) + A_R(t)\right]e^{-\lambda_R T_C} \qquad (10)$$

where n is the progressive number of operational cycles.

TABLE I — Materials and nuclear reactions considered.

Target material	Atomic number	Isotopic abundance	Nuclear reaction	Radioactive product
TUNGSTEN				
W–182	74	0.264	γ,n	W–181
W–182	74	0.264	γ,np	Ta–180m
W –183	74	0.144	γ,2n	W–181
W–183	74	0.144	γ,p	Ta–182
W–184	74	0.306	γ,n	W–183m
W–184	74	0.306	γ,p	Ta–183
W–184	74	0.306	γ,np	Ta–182
W–186	74	0.284	γ,n	W–185m
W–186	74	0.284	γ,p	Ta–185
W–186	74	0.284	γ,np	Ta–184
COPPER				
Cu–63	29	0.691	γ,n	Cu–62
Cu–63	29	0.691	γ,2n	Cu–61
Cu–63	29	0.691	γ,n2p	Co–60
Cu–63	29	0.691	γ,sp	Co–58m
Cu–65	29	0.309	γ,n	Cu–64
Cu–65	29	0.309	γ,np	Ni–63
IRON				
Fe–54	27	0.058	γ,n	Fe–53
Fe–54	27	0.058	γ,2n	Fe–52
Fe–54	27	0.058	γ,np	Mn–52m
Fe–54	27	0.058	γ,sp	Sc–46
Fe–54	27	0.058	γ,sp	V–48
Fe–54	27	0.058	γ,sp	Cr–51
Fe–56	27	0.917	γ,n	Fe–55
Fe–56	27	0.917	γ,np	Mn–54
Fe–57	27	0.022	γ,p	Mn–56
Fe–57	27	0.022	γ,2n	Fe–55
Fe–57	27	0.022	γ,2p	Cr–55
Fe–58	27	0.003	γ,np	Mn–56
Fe–58	27	0.003	γ,2p	Cr–56
WATER				
Cooling water*	3.34	1	γ,n	O–15
Cooling water	3.34	1	γ,sp	C–11
Cooling water	3.34	1	γ,sp	H–3
Cooling water	3.34	1	γ,sp	N–13
Cooling water	3.34	1	γ,sp	Be–7

* only oxigen

POSITRON CONVERTER OF DAΦNE

The aim of the DAΦNE machine is to have stored in the main ring two electron and positron beams stored of $1.068 \cdot 10^{13}$ particles per beam, distributed in 120 bunches at 510 MeV.

The positron injection cycle foresees a 250 MeV electron beam of $1.44 \cdot 10^{13} e^{-} s^{-1}$, corresponding to a power of 576 watt, incident on the converter target for 120 s.

The injection is repeated every 4 h (meanlife of the beams in DAΦNE) for an amount of 50 h of operation per year (1500 cycles) (Esp 92).

ACTIVATION OF TUNGSTEN, COPPER AND IRON

The following calculations are obtained from eq.(10) assuming that 150 watt of the incident power of the electron beam are completely absorbed by one of the materials which the converter is made of (Alt 92).

Figures 1, 2, 3 show the results of the calculations of the residual radioactivity relatively to a period of 20 years of continuous operation (30000 cycles) in the above mentioned conditions.

Figures 4 and 5 show the same results for radionuclides with long and short meanlife respectively.

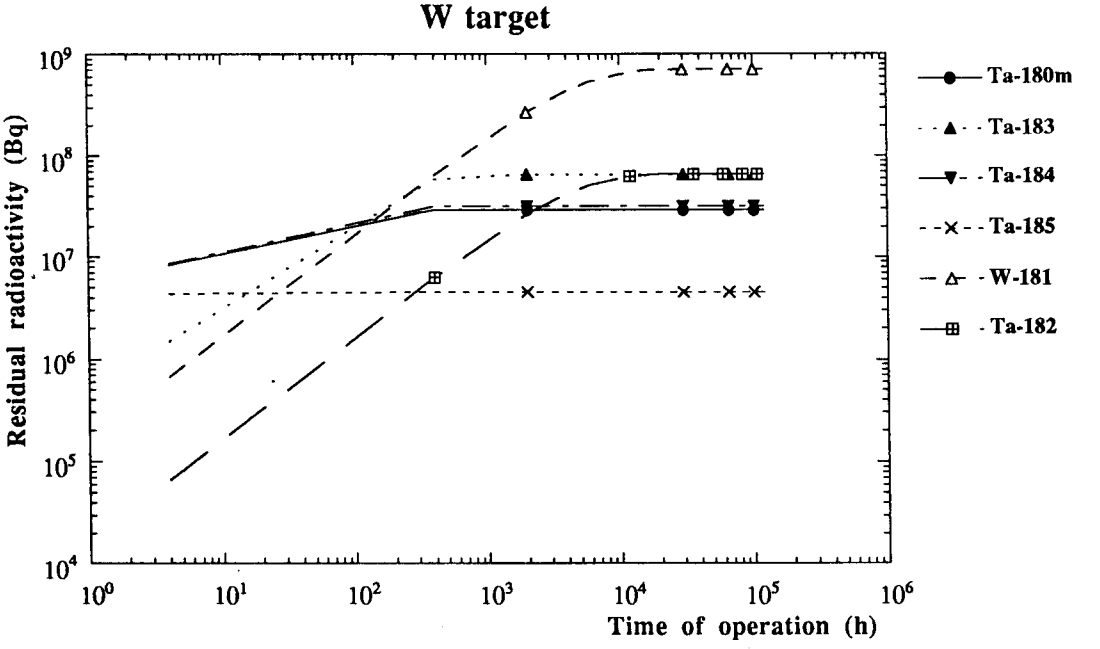

FIG. 1

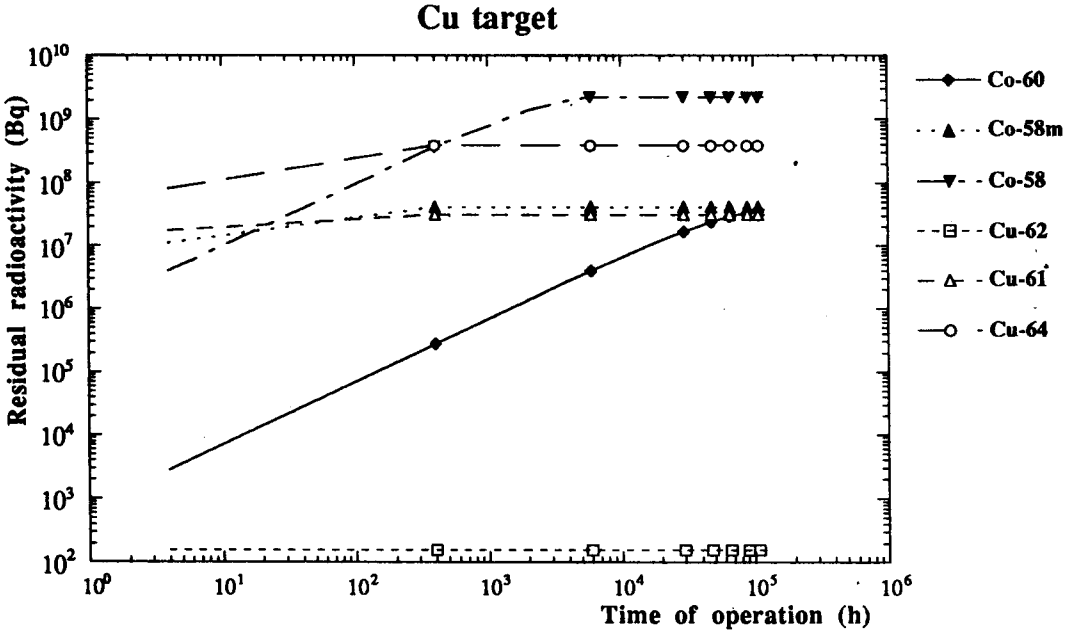
Cu target
Residual radioactivity (Bq)
Time of operation (h)
Co-60
Co-58m
Co-58
Cu-62
Cu-61
Cu-64

FIG. 2

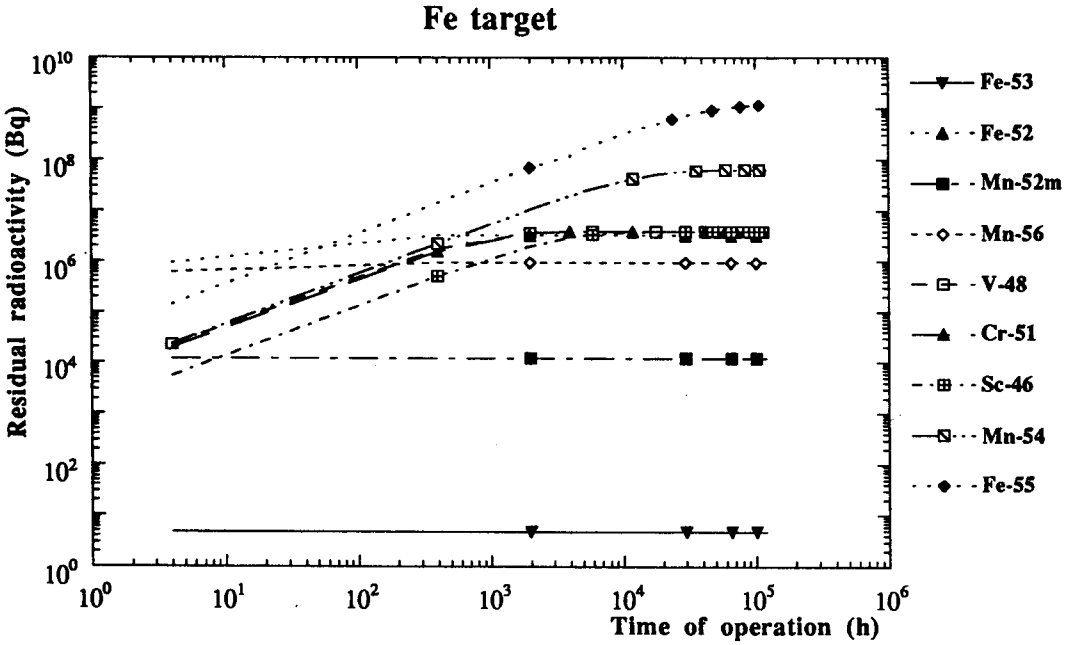
Fe target
Residual radioactivity (Bq)
Time of operation (h)
Fe-53
Fe-52
Mn-52m
Mn-56
V-48
Cr-51
Sc-46
Mn-54
Fe-55

FIG. 3

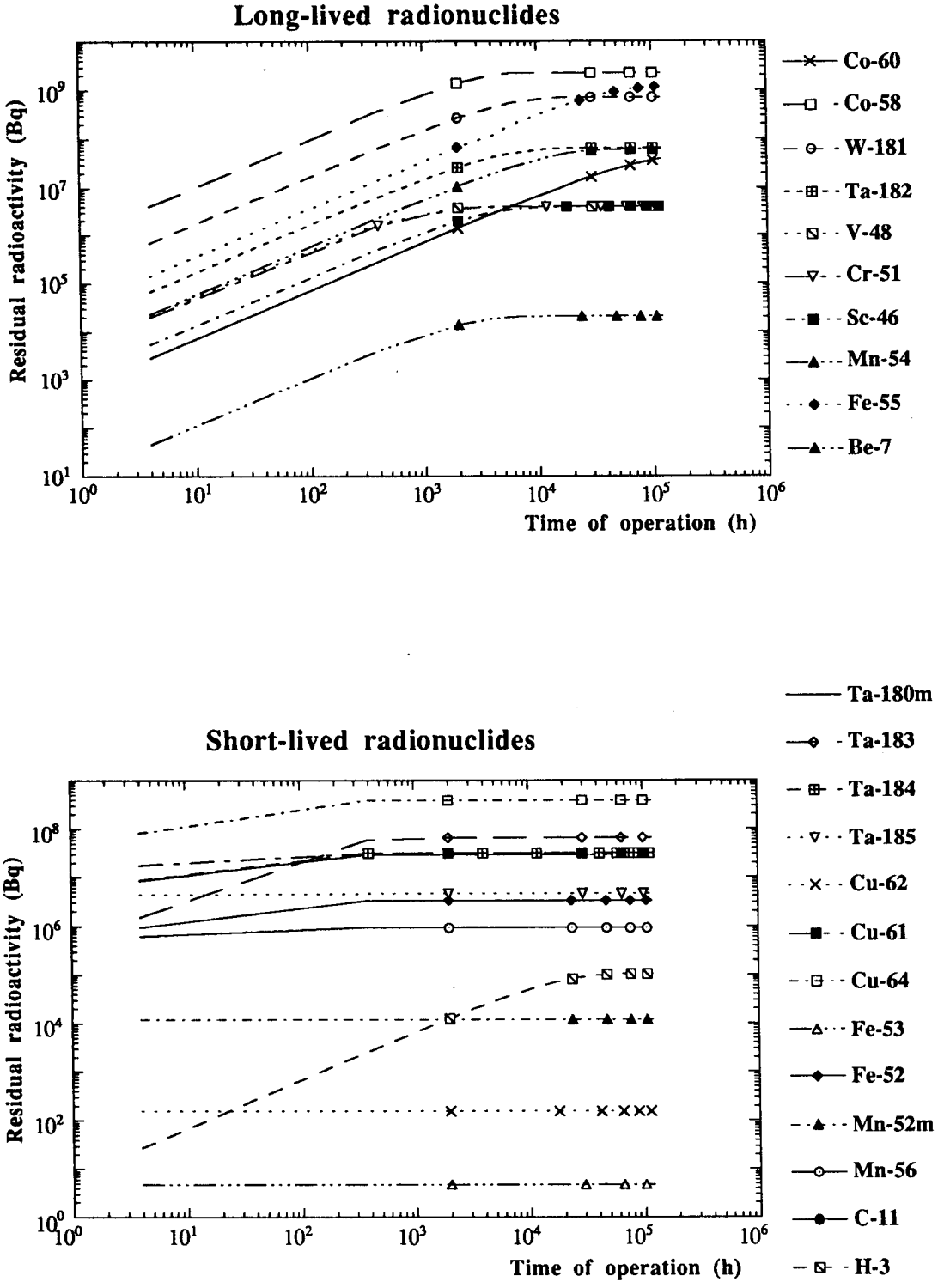

FIG. 5

The greatest contribution to the residual radioactivity, after a long shut–down of the machine, will be due to Mn–54, Ta–182, W–181, Fe–55 and Co–60. These radionuclides,

whose activity is distributed in a range between some MBq and some GBq, will influence the disposition of facilities components. Co–60 and Mn–54 indeed have been the most important radionuclides measured during the decommissioning of accelerators (Phi 86, All 90, Lam 92) and during the recent decommissioning of the Linac–Adone machine (report in preparation).

The short meanlife radionuclides will be determinant in the routine maintenance of the machine, which takes place from the first cycles of operation.

The main contributors to the residual radioactivity will be Cu–64, Cu–61, Ta–183, Ta–184 and Co–58^m.

The activity of these radionuclides, such as the Co–58, daughter of the Co–58^m, reaches an equilibrium value of some GBq after the first 500 hours of operation.

COOLING WATER OF THE POSITRON CONVERTER

The activation of cooling water may be deduced in the same way as for solid material.

In fact being Y_R the number of neutrons per second produced and assuming that such a number is the yield of radioactive atoms of the R type it may be written (Fas 84, Moe 91)

$$Y_R = 1.21 \cdot 10^{11} \cdot Z^{0.66} F \cdot G \cdot R_{\sigma(\gamma,x)(\gamma,n)} \left(1 - e^{-\kappa/\lambda}\right) \text{ radioactive atoms } s^{-1} kW^{-1} \qquad (11)$$

where

F	is the isotopic abundance of the element considered, in this case it is assumed to be all oxygen
Z	is the atomic number, in the case of water it is equal to 3.34 (Sch 73)
G	is the fraction of the power directly dissipated in the cooling water, assumed to be equal to 0.1 (Swa 79a, Moe 91)
$R_{\sigma(\gamma,x)(\gamma,n)}$	is the (γ,x)/(γ,n) saturation radioactivity ratio mentioned above
κ	is the average path length of the beam in water, in the LNF positron converter it is equal to 0.075 m about (Alt 92)
λ	is the average attenuation length for water equal to 0.5 m at energies above 1 MeV (Fas 84).

The change in the number of radioactive atoms in the irradiated volume of the cooling closed loop circuit is given by the following differential equation, that describes the growth and decay of the activity of induced radioisotopes (Hof 88, Moe 91)

$$\frac{dN}{dt} = Y_R - \lambda_R N - \frac{QN}{V} + \frac{QN}{V} e^{-\lambda_R T} \qquad s^{-1} \qquad (12)$$

where Q is the flux of water equal to 41 $m^3 h$ about

V is the volume of the cooling circuit to 0.3 m^3 about

T is the transit time equal to 0.0075 h about (it is the time lapse before the previously activated water returns to the irradiation position; no mixing is assumed).

Eq. (12) can be rewritten as follows:

$$\frac{dN}{dt} = Y_R - \left[\lambda_R + \frac{Q}{V}\left(1 - e^{-\lambda_R T}\right)\right]N \tag{13}$$

and by integration

$$N(t) = \frac{Y_R}{\lambda_R + \frac{Q}{V}\left(1 - e^{-\lambda_R T}\right)}\left\{1 - e^{-\left[\lambda_R \frac{Q}{V}\left(1 - e^{-\lambda_R T}\right)\right]N}\right\} \tag{14}$$

and then

$$A_R(t) = \lambda_R N(t). \qquad 15)$$

The results shown in Fig. 6 have been obtained from eq. (15) assuming a continuous operation period of 20 years (30000 cycles).

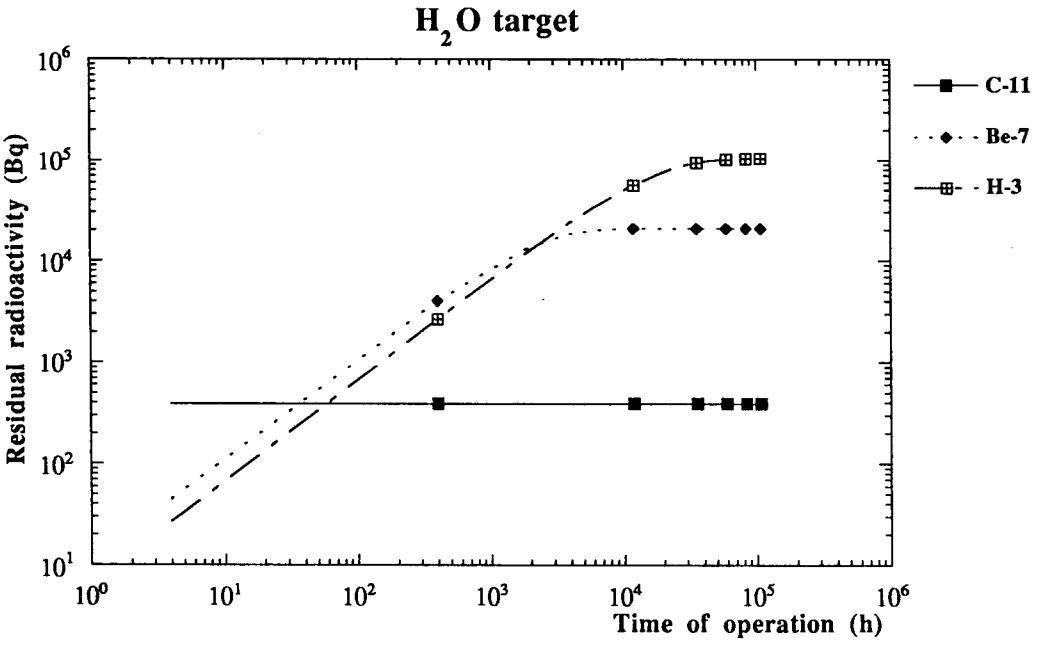

FIG. 6

It can be noted that the residual radioactivity expected in the cooling water does not give particular management problems from a radiological point of view except for H–3, because of its long half life.

Anyway, assuming that the cooling water is accidentally discharged from the 0.3 m^3 closed system the estimated total activity discharged and concentration would be respectively about 0.1 MBq and 0.33 MBq m^{-3}, well below the discharge limits stated in the Italian law (CNEN 80).

EXPECTED DOSE RATES AROUND THE POSITRON CONVERTER

In order to estimate the doses received by people working at the routine maintenance of the installations, the radiation field around the positron target has been characterized by the calculation of the absorbed dose rate in air, $\dot{D}_{air}$, versus the distance from the converter.

$$\dot{D}_{air} = \sum_i \frac{A_R p_i}{4\pi r^2} (\mu_{en}/\rho)_i E_i \qquad (16)$$

where A_R is the activity of the isotope considered as a point source
p_i is the probability of emission of photons of energy E_i
$(\mu_{en}/\rho)_i$ is the mass energy absorption coefficient for air of photons of energy E_i
r is the distance from the source.

Eq. (16) is valid only under charged particle equilibrium (CPE), not reached in the present case. It is still possible to use the mentioned equation under charged particles quasi–equilibrium on condition that a correction factor be applied. Luckily this factor would be 0.5 % for Co–60 (Gr 81) and less at lower energies, thus it was not applied in the present calculations.

Figure (7) shows the total photon dose rate in air, obtained using previous equation (16), at 1 meter from the positron converter. In the first cycles of operation the total photon dose rate is due to the short–lived radionuclides. Beginning from the first year of operation the contribution to the total photon dose rate is mainly due to the long–lived radionuclides.

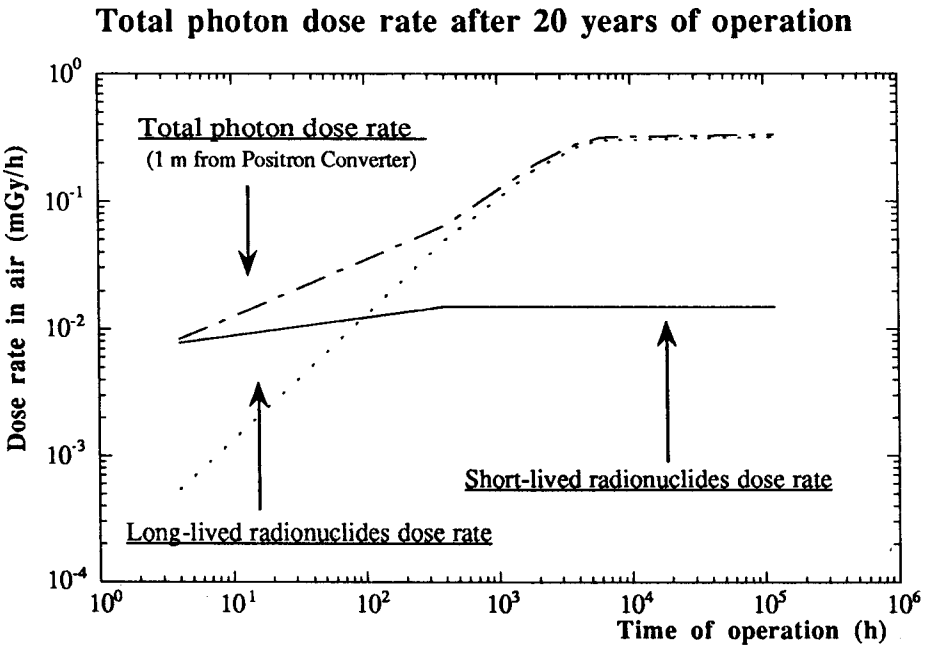

FIG. 7

Of course urgency operations carried out soon after the shut down could involve higher absorbed dose, although always restrained, considering that the opening of the Linac shielding–door should have a 15 minutes delay device, to permit the elimination of the radioactive gases produced.

CONCLUSIONS

On the basis of the calculations shown in this paper, made under quite conservative conditions, the estimated residual radioactivity and related dose rates around the positron converter, should not cause special radiological problems during the DAΦNE operation. No problems are expected from maintenance and decommissioning, since the target and the other components can be easily removed, put into a container and disposed of in long–term storage.

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