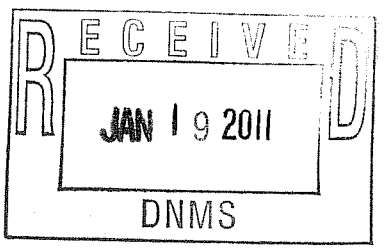
Roldan, Lizette

From: Brian Oyadomari [boyado@queens.org]
Sent: Wednesday, January 19, 2011 10:19 PM
To: Roldan, Lizette
Cc: Torres, RobertoJ
Subject: RE: Update on Financial Assurance - QMC
Attachments: Amendment Letter DN 030-38244.pdf

My apologies for this overdue email. Please find attached Cyclotron License Amendment letter signed by VP.

Thank you,

Brian Oyadomari
(808)547-4884



DECOMMISSIONING PROCEDURES FOR AN 11 MeV SELF-SHIELDED MEDICAL CYCLOTRON AFTER 16 YEARS OF WORKING TIME

R. Calandrino,* A. del Vecchio,* A. Savi,† S. Todde,† V. Griffoni,‡ S. Brambilla,* R. Parisi,* G. Simone,‡ and F. Fazio*

Abstract—The present article describes the decommissioning of a compact, self-shielded, 11 MeV medical cyclotron. A Monte Carlo simulation of the possible nuclear reactions was performed in order to plan the decommissioning activities. In the course of the cyclotron dismantling, cyclotron components, shields, and floor concrete samples were measured. Residual activities were analyzed with a Ge(Li) detector and compared with simulation data. Doses to staff involved in the decommissioning procedure were monitored by individual TL dosimeters. The simulations identified five radioactive nuclides in shields and floor concrete: ^{55}Fe and ^{45}Ca (beta emitters, total specific activity: 2.29×10^4 Bq kg^{-1}) and ^{152}Eu, ^{154}Eu, ^{60}Co (gamma emitters, total specific activity: 1.62×10^3 Bq kg^{-1}). Gamma-ray spectrometry confirmed the presence of gamma emitters, corresponding to a total specific activity of 3.40×10^2 Bq kg^{-1}. The presence of the radioisotope ^{124}Sb in the lead contained in the shield structure, corresponding to a simulated specific activity of 9.38×10^3 Bq kg^{-1}, was experimentally confirmed. The measured dose from external exposure of the involved staff was <20 μSv, in accordance with the expected range of values between 10 and 20 μSv. The measured dose from intake was negligible. Finally, the decommissioning of the 11 MeV cyclotron does not represent a risk for the involved staff, but due to the presence of long-lived radioisotopes, the cyclotron components are to be treated as low level radioactive waste and stored in an authorized storage area.
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Key words: operational topic; cyclotron; accelerators, decommissioned; accelerators, medical

INTRODUCTION

In January 2004, it was decided to shut down the Cyclotron CTI RDS112 after more than 16 years of continuous operation in isotope production at the Nuclear Medicine Department of Istituto di Ricovero e Cura a Carattere Scientifico (IRCCS) San Raffaele–Milano. The more recently published directory of the "Cyclotrons used for radionuclide production in Member States" by the International Atomic Energy Agency (IAEA 1998), listed 40 CTI RDS112 cyclotrons still operating worldwide. The basic machine parameters are:

- Proton beam energy: 11 MeV
- Self-shielded
- Magnet: (a) 3 sector azimuthally varying field; (b) Mean field: 1.8 Tesla
- Radiofrequency (RF): (a) dees number: 2; (b) radiofrequency: 27.2 MHz
- Ion source type: Penning ion gauge (internal)
- Beam size: 10 mm
- Max. beam current (at target level): 50 μA
- Typical performance for ^{18}F: 60 min irradiation at 40 μA yielded about 1,000 mCi
- Typical performance for ^{11}C: 50 min irradiation at 40 μA yielded about 1,000 mCi

The cyclotron was used mainly for the production of ^{18}F by the following reaction: ^{18}O(p,n)^{18}F, using a target of commercially available ^{18}O enriched water (^{18}O > 94%), and for the production of ^{11}C by the reaction: ^{14}N(p,α)^{11}C, using a gaseous target mixture of ^{14}N + 1% O_2. The workload of the cyclotron over the course of its operational life was increased from an initial value of 80 μA h^{-1} wk^{-1} to 180 μA h^{-1} wk^{-1}. Fig. 1 shows the cyclotron workload up to December 2003.

The increased clinical activity of the Positron Emission Tomography (PET) Department (approximately 35 patients per day in 2003) demanded an efficient and reliable radioisotope production system, and consequently the decision was made to replace the original RDS112 with a machine more suitable for the new requirements: the CTI RDS Eclipse. The basic machine parameters are:

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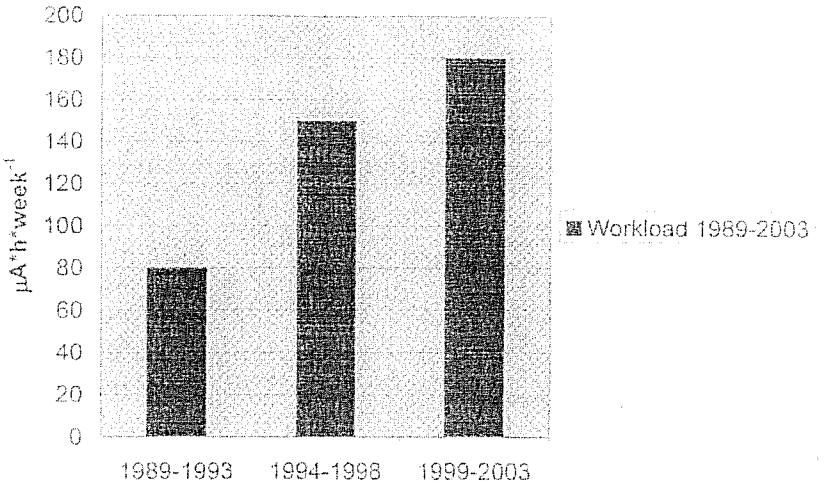

Fig. 1. The cyclotron workload during its life.

- Proton beam energy: 11 MeV
- Self-shielded
- Magnet: (a) 4 sector azimuthally varying field; (b) Mean field: 1.2 Tesla; (c) Valley to Hill gap ratio: 27/1
- RF: (a) dees number: 4; (b) radiofrequency: 72 MHz
- Ion source type: penning ion gauge
- Beam size: 8 mm
- Max. beam current (at target level): 80 μA
- Typical performance for ^{18}F: 60 min irradiation at 40 μA yield about 1,200 mCi
- Typical performance for ^{11}C: 50 min irradiation at 40 μA yield about 1,400 mCi

Due to room and time constraints, the new cyclotron was installed in the same room. Given the difference in concept and facility requirements of the selected CTI RDS Eclipse model it was necessary to confront and resolve a number of problems related to the decommissioning of the old cyclotron, including the partial reconstruction of the cyclotron room.

While several published papers report data concerning the activation of the beam transport components and of the cyclotron vault of high-energy machines or linear accelerators, no data have been found for low energy self-shielded accelerators, despite the fact that this type of cyclotron is currently one of the most suitable and widely used instruments for isotope production (Birattari et al. 1989; Carroll 2001; Eggermont 1995; Kimura et al. 1994; Phillips et al. 1986; Silari 2001; Sonck 1998; Sonck et al. 2000; Urabe et al. 1991).

The present article presents all data and calculations collected concerning the activation level of:

- magnet, extractor body, target;
- shields; and
- walls and floor of the cyclotron room;

as well as data and estimates relative to effective doses for staff involved in the dismantling and rigging of the removed cyclotron.

MATERIALS AND METHODS

The cyclotron was definitively shut down at the end of December 2003. The induction of radioactivity into the cyclotron components and building materials may have originated from:

- direct interaction of the accelerated ion with the cyclotron components (vacuum chamber, dees, extraction channels, stripping foil holder, foils, target); and
- interaction of the proton reaction generated neutrons with all the materials outside the extraction channels, such as shields, vault walls and yoke structure.

The expected activation levels of various components, as reported in literature for high energy machines, are summarized in Table 1 (European Commission 1999). Among these components, the shields and magnet represent 99% (in weight) of the activated parts of the cyclotron, and the evaluation of their radioactive content is mandatory for waste classification, either in the case of storage in an authorized area or of disposal by a licensed company. A suitable storage site located on the hospital premises, but far from the clinical area, was commissioned by our institute for final storage of these large parts. The perimeter walls and ceiling of this storage room were constructed of 30 cm concrete in order to guarantee an external radiation level <0.1 mSv y^{-1}, well below the dose limit of 1 mSv y^{-1} established by

Table 1. Expected activation levels for different cyclotron and shielding components.

Item	Weight (kg)	Expected activity class (kBq kg^{-1})
Magnet	21,020	1.0–200
Targets	10	1.0–200
Ion source	5	1.0–200
Shields	16,000	1.0–200
Vacuum chamber	100	1.0–200
Perimetric walls		0.1–0.4
Cyclotron vault floor		0.1–0.4

international standards for non-exposed populations (ICRP 1991; IAEA 1996). Calculations were performed considering the total stored activity, as stated in Table 1, as a point source located in the center of the room. Room dimensions are 6 × 6 × 3.5 m^3; walls and floor have been coated with epoxy resin in order to obtain a leak proof surface, to prevent dispersion of contaminated liquids into the environment.

Before the beginning of the dismantling of the machine, in order to evaluate the risk for the staff involved, a Monte Carlo (MC) simulation code (MCNPX, MCNP4C2) was adopted to predict the activation of the cyclotron's components: shields (Fig. 2), floor, targets, magnet, and extractor body (Grove 1996; Briesmeister 2000; Hendricks 2001, 2004; McLane 2001; Waters 2002). Simulation codes MCNPX and MCNP4C2 are general purpose Monte Carlo radiation transport codes developed by Los Alamos National Laboratory for modeling the interaction of radiation with the matter. The maximum estimated relative error, defined as one estimated standard deviation of the mean divided by the estimated mean, was 5%. This error is proportional to $N^{-1/2}$, where N is the number of simulated histories and refers only to the precision of Monte Carlo calculation itself.

Subsequent to the definition of the constitutive elements for the various parts of the accelerator, the nuclear reactions generated by the proton beam were analyzed through simulations performed by MCNPX to study the (p,n) reactions occurring in the target and in the extractor body. Elemental analysis of the floor and shield concrete was not performed; therefore, a standard composition was assumed. The evaluation of cross-sections relative to the (p,n) reaction of the considered elements indicated that this is the dominant one for 11 MeV protons (IAEA 2005a, b). Table 2 lists the possible (p,n) reactions generating radioactive elements with half lives greater than 30 d, considering copper as the principal element for the extractor body and tantalium and silver for targets. In addition, activation generated by the secondary neutrons was simulated by MCNP4C2 on the following subsystems: shields, floor, magnet, and extractor body. The shields 4 and 5 have an additional lead absorber surrounding the target region in order to improve the

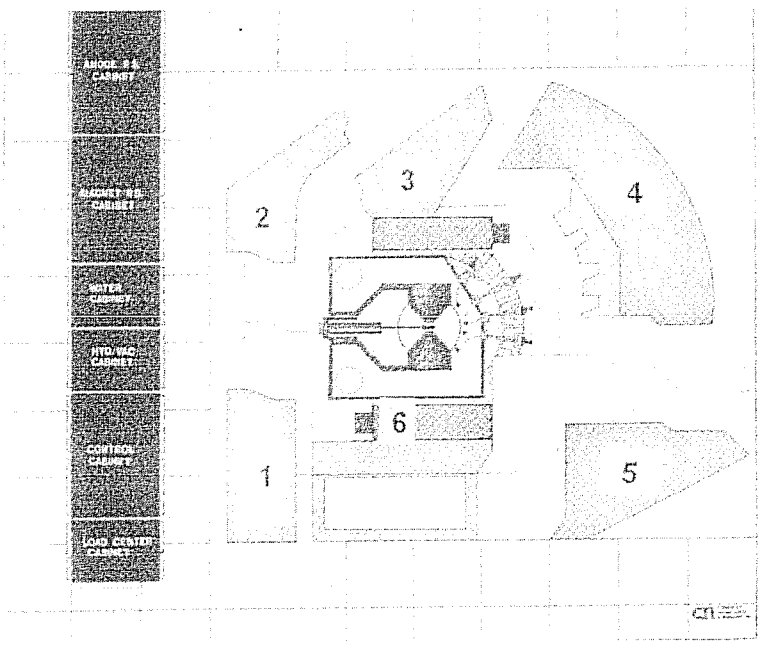

Fig. 2. The cyclotron room layout: 1. Shield 1 (mobile); 2. Shield 2 (mobile); 3. Shield 3 (stationary); 4. Shield 4 (mobile); 5. Shield 5 (mobile); 6. Shield 6 (stationary).

Table 2. Possible (p,n) reactions that generate radioactive elements with half-lives greater than 30 d in the extractor body and targets.

Nuclide	Reaction	Activated element	Half-life
^{65}Cu	(p,n)	^{65}Zn	244.06 (d)
^{109}Ag	(p,n)	^{109}Cd	461.00 (d)
^{181}Ta	(p,n)	^{181}W	121.20 (d)

efficiency of the absorption of the gamma rays generated at the target. The neutron flux energy spectrum and angular distribution were derived from the previous (p,n) reaction. The analyzed reactions were: (n,gamma), (n,p), (n,alpha), (n,d), (n,t) and (n,2n), with a neutron mean energy of 2 MeV. The predicted reactions yielding radioactive isotopes with half-lives greater than 30 d are listed in Tables 3a–d.

Subsequent to the dismantling of the shield, several samples were taken (by drilling holes in selected positions) and analyzed with a Ge-Li spectrometer (EG&G Ortec, 801 South Illinois Avenue, Oak Ridge, TN 37830; GMX2094 energy resolution = 1.77 keV and efficiency = 20% at 1.33 MeV of ^{60}Co), in order to verify the agreement with simulation results. Several of the concrete samples relative to the cyclotron room floor and walls were further analyzed with an HP-Ge spectrometer by the Environmental Protection Agency of Lombardia (EG&G Ortec, GEM28195, energy resolution = 1.84 keV and efficiency = 27.8% at 1.33 MeV of ^{60}Co). Detection efficiency was experimentally determined by measuring multi-gamma calibration sources under the same source-detector geometry as real samples (Knoll 1989; ICRP 1983; European Commission 1998; Debertin and Helmer 1988).

Table 3a. Neutron induced reactions yielding radioactive isotopes with half-life greater than 30 d on shields and floor elements.

Target nuclei	Reaction	Produced radionuclide	Half-life
^{17}O	(n,alpha)	^{14}C	5.73×10^3 (y)
^{41}Ca	(n,gamma)	^{42}Ca	103.00×10^3 (y)
^{40}Ca	(n,p)	^{40}K	1.28×10^9 (y)
^{42}Ca	(n,alpha)	^{39}Ar[a]	2.69×10^2 (y)
^{44}Ca	(n,gamma)	^{45}Ca	1.63×10^2 (d)
^{54}Fe	(n,gamma)	^{55}Fe	0.27×10 (y)
^{58}Fe	(n,gamma)	^{59}Fe	4.46×10 (d)
^{151}Eu	(n,gamma)	^{152}Eu	1.36×10 (y)
^{153}Eu	(n,gamma)	^{154}Eu	0.88×10 (y)
^{59}Co	(n,gamma)	^{60}Co	0.53×10 (y)
^{34}S	(n,gamma)	^{35}S	8.75×10 (d)
^{39}K	(n,gamma)	^{40}K	1.28×10^9 (y)
^{39}K	(n,p)	^{39}Ar	2.69×10^2 (y)
^{39}K	(n,alpha)	^{36}Cl	3.01×10^5 (y)
^{2}H	(n,gamma)	^{3}H	1.23×10 (y)

[a] The trace amount of a gas formed via this reaction is likely to be trapped within the structure of the calcium salt, thus minimizing air contamination.

Table 3b. Neutron induced reactions yielding radioactive isotopes with half-life greater than 30 d on lead in shields 4 and 5.

Target nuclei	Reaction	Produced radionuclide	Half-life
^{204}Pb	(n,gamma)	^{205}Pb	15.10×10^6 (y)
^{206}Pb	(n,2n)	^{205}Pb	15.10×10^6 (y)
^{123}Sb	(n,gamma)	^{124}Sb	60.19 (d)

Table 3c. Neutron induced reactions yielding radioactive isotopes with half-life greater than 30 d on magnet.

Target nuclei	Reaction	Produced radionuclide	Half-life
^{58}Ni	(n,p)	^{58}Co	70.81 (d)
^{58}Ni	(n,alpha)	^{55}Fe	2.70 (y)
^{60}Ni	(n,p)	^{60}Co	5.27 (y)
^{62}Ni	(n,gamma)	^{63}Ni	100.10 (y)
^{62}Ni	(n,alpha)	^{59}Fe	44.64 (d)
^{54}Fe	(n,gamma)	^{55}Fe	2.70 (y)
^{58}Fe	(n,gamma)	^{59}Fe	44.64 (d)
^{59}Co	(n,gamma)	^{60}Co	5.27 (y)

Table 3d. Considered neutron reactions yielding radioactive isotopes with half-life greater than 30 d on extractor body.

Nuclide	Reaction	Activated element	Half-life
^{63}Cu	(n,p)	^{63}Ni	100.10 (y)
^{65}Cu	(n,alpha)	^{60}Co	5.27 (y)

Concerning environmental and staff radiation protection and safety, the decommissioning procedures were scheduled as shown in Table 4 (IAEA 1999). This schedule follows, on the one hand, the logic of initially dismantling the easiest (in terms of the dismantling process) and hottest components (i.e., targets and vacuum pumps) from the cyclotron and, on the other hand, to allow, by means of sampling and measurement, the prior estimation of risk level for involved staff, adjusting the radiation protection requirements to the adequate level. Thus, the dismantling of targets as a whole was initiated. The second step was the sealing of the cyclotron room in order to guarantee the insulation of nearby

Table 4. Decommissioning plan.

Day	Operation
1st–2nd	Dismantling targets, vacuum pumps and cyclotron sealing by CTI engineer
3rd	Preparation and sealing of the demolition areas
4th	Sampling of the perimetric walls for radioactivity content counting
5th	Training course for demolition workers
6th–7th	Partial wall demolition to permit cyclotron removal from the vault
8th	Shield dismantling and rigging outside the vault
9th–11th	Drilling of the floor and packing of demolished blocks for storage as LLRW

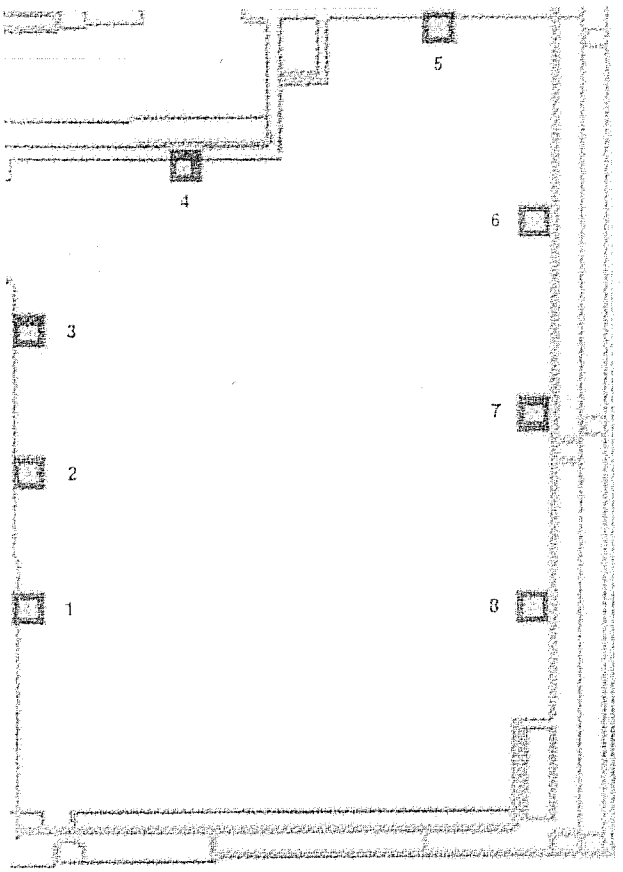

Fig. 3. Cyclotron vault and dosimeter measurement points.

rooms and corridors from ducts, followed by the sampling of the walls and floor concrete in order to predict the risk level for staff involved in subsequent operations. Prior to the initiation of the dismantling operations, a complete training program concerning the safety rules and procedures to be followed during the various phases of the operation was carried out by the Radiation Safety Officer. In particular, as the demolition of the floor area located below the targets was considered the most dangerous phase, the main prescriptions regarding this operation were:

- operating personnel were instructed to wear breathing apparatus (carbon filtered) and sealed suits to prevent radioactive dust inhalation; and
- the use of a suitable drilling tool equipped with a vacuum pump and a dust collection tank was mandatory.

The staff of the Health Physics Department supervised all phases of the decommissioning and collected radiation exposure data for both the environment and operating personnel:

- dose and dose-rate values in the operating room were measured using an organic scintillator probe (AUTOMESS, Daimlerstrasse 27, D-68526 Ladenburg, Germany; 6150 ADB, ZnS-coated) for real time measurement photon radiation (minimum sensitivity 50 nSv h^{-1}, s.d. <15%);
- 8 LiF(Mg,Cu,P) TLD dosimeters, type GR 200 A, without filtration (minimum sensitivity 4 μGy at 1.25 MeV) were positioned on the walls for the entire period necessary for the measurement of the total environmental dose (Fig. 3);
- LiF TLD dosimeters with 2 filters (1 mm Al and 1 mm Cu) were used for workers' dose estimation; and
- daily surface contamination tests on various employed tools (e.g., hammers, drills) as well as external (clothing) and internal (urine samples, spit and nasal mucus) tests for personnel were performed by traditional modalities and measured by means of an Na-I gamma counter (LKB Wallac, Perkin-Elmer, Via Tiepolo 24, 20052 Monza, Italy; energy resolution = 8.4 keV and efficiency = 9% at 661 keV of ^{137}Cs).

RESULTS AND DISCUSSION

Specific activity values, obtained using simulated data averaged over 80 cm with a 10 cm step from the surface of shields and floor, are listed in Tables 5a and 5b. The values obtained from sample measurements performed by both laboratories are also reported for gamma-emitting isotopes. There is a difference of a factor of 25 between simulated and measured activity of ^{152}Eu in shields 4 and 5 (see Table 5a), while the discrepancy is reduced to a factor of 5, for the same radioisotope, in the data collected for the excavated floor (see Table 5b). The simulated data refer to a point 10 cm in front of the sources on the beam axis, while the sample was taken on the same plane, but at 70 cm from the beam axis, for practical reasons. Adjusting for the difference in the positioning between the simulated and measured points, the discrepancy between the data is reduced; therefore, we believe that the prediction of MC code is, in this case, acceptable. In addition, gamma-ray spectrometry has identified the presence of ^{54}Mn and ^{46}Sc both in shields and floor. ^{54}Mn is produced by the (n,p) reaction on ^{54}Fe; Fe impurity is usually present in standard concrete (approximately 10^{20} atoms cm^{-3}) (Birattari et al. 1989; Kimura et al. 1994). While this isotope was not considered in the simulation due to the extremely low cross-section of the reaction (0.386 barn at 4.9 MeV), the abundance of ^{54}Fe in the concrete justifies the experimental data.

The presence of the scandium isotope is evidently due to neutron capture on trace amounts of ^{45}Sc (3.9 ×

Table 5a. Calculated and measured induced activation in shields 4 and 5.

Isotope	Decay	Specific activity (Bq kg^{-1}) Simulated mean over 80 cm	Simulated @ 10 cm	Measured lab 1 @ 10 cm	Measured lab 2 @ 10 cm
^{14}C	EC	$1.63 \pm 0.08 \times 10$	$1.11 \pm 0.05 \times 10$		
^{41}Ca	EC	$2.34 \pm 0.12 \times 10$	$1.58 \pm 0.08 \times 10$		
^{39}Ar	Beta$^-$	$2.80 \pm 0.14 \times 10$	$2.17 \pm 0.11 \times 10$		
^{45}Ca	Beta$^-$	$8.05 \pm 0.40 \times 10^2$	$5.45 \pm 0.27 \times 10^2$		
^{55}Fe	EC	$2.45 \pm 0.12 \times 10^3$	$1.66 \pm 0.08 \times 10^3$		
^{59}Fe	Beta$^-$	$7.62 \pm 0.38 \times 10$	$5.18 \pm 0.26 \times 10$		
^{152}Eu	EC; beta$^+$; beta$^-$	$1.32 \pm 0.07 \times 10^2$	$8.95 \pm 0.45 \times 10^2$	$3.6 \pm 0.20 \times 10$	$3.0 \pm 0.20 \times 10$
^{154}Eu	EC; beta$^-$	$7.56 \pm 0.38 \times 10$	$5.21 \pm 0.26 \times 10$		
^{60}Co	Beta$^-$	$4.80 \pm 0.24 \times 10$	$3.28 \pm 0.16 \times 10^2$	$2.2 \pm 0.14 \times 10$	$2.1 \pm 0.11 \times 10$
^{35}S	Beta$^-$	$4.56 \pm 0.23 \times 10$	$3.08 \pm 0.15 \times 10$		
^{54}Mn	EC			$5.1 \pm 0.05 \times 10$	$5.2 \pm 0.06 \times 10$
Other		$1.67 \pm 0.08 \times 10^{-1}$	$8.28 \pm 0.14 \times 10^{-1}$		

Table 5b. Simulated and measured induced activation in the floor.

Isotope	Decay	Specific activity (Bq kg^{-1}) Simulated mean over 80 cm	Simulated @ 10 cm	Measured lab 1 @ 10 cm	Measured lab 2 @ 10 cm
^{39}Ar	Beta$^-$	$2.96 \pm 0.15 \times 10$	$2.29 \pm 0.11 \times 10$		
^{45}Ca	Beta$^-$	$3.11 \pm 0.16 \times 10$	$2.13 \pm 0.11 \times 10^2$		
^{55}Fe	EC	$9.51 \pm 0.48 \times 10$	$6.54 \pm 0.33 \times 10^2$		
^{59}Fe	Beta$^-$	$3.16 \pm 0.16 \times 10^{-1}$	$2.20 \pm 0.11 \times 10$		
^{152}Eu	EC; beta$^+$; beta$^-$	$4.75 \pm 0.24 \times 10$	$3.21 \pm 0.16 \times 10$	$1.4 \pm 0.06 \times 10^2$	$1.5 \pm 0.05 \times 10^2$
^{154}Eu	EC; beta$^-$	$3.06 \pm 0.15 \times 10^{-1}$	$2.14 \pm 0.11 \times 10$	$1.4 \pm 0.09 \times 10$	$1.9 \pm 0.07 \times 10$
^{60}Co	Beta$^-$	$1.90 \pm 0.09 \times 10$	$1.32 \pm 0.07 \times 10$	$7.3 \pm 0.03 \times 10$	$8.4 \pm 0.03 \times 10$
^{35}S	Beta$^-$	$1.66 \pm 0.08 \times 10^{-1}$	$1.13 \pm 0.06 \times 10$		
^{46}Sc				$2.6 \pm 0.01 \times 10$	$2.9 \pm 0.01 \times 10$
^{54}Mn				$3.5 \pm 0.01 \times 10$	$2.2 \pm 0.01 \times 10$
Others		$1.18 \pm 0.06 \times 10^{-1}$	$8.83 \pm 0.44 \times 10^{-1}$		

10^{17} atoms cm^{-3}) not initially considered in the elemental content of concrete (Kimura et al. 1994). In addition, scandium was not found in the samples of shields; difference in the floor and shields concrete is probably due to the difference in commercially available concrete mixture provided in the U.S. (used for the shields) vs. Italy (used for the floor). The specific activity for lead in shields 4 and 5, which are considered to be the most activated ones, is summarized in Table 6. The isotope ^{124}Sb is produced by (n,gamma) reaction on ^{123}Sb present in lead with an elemental weight abundance of 0.4% (Kimura et al. 1994; Hermanne 1999).

The complexity of the acceleration chamber structure did not allow direct sampling of the magnet structure; therefore, the data of specific activity listed in Table 7 refer only to simulation. However, the magnet surface dose rate was in agreement with data obtained from the Monte Carlo simulation, thus encouraging the continuation of the cyclotron dismantling without further sampling. In Table 8 the simulated data refer only to the copper component of the extractor body, while the measured data also include isotopes from nuclear reactions on other metallic components (screws, etc.), which are part of the extractor body assembly. This justified also the greater measured value of ^{60}Co with respect to the simulated value: in the simulation only the reaction (n,alpha) on ^{63}Cu was considered, while the activity obtained from the sample of the extractor body should include the contribution of the (n,t) reaction on ^{60}Ni, an element present in metallic components. The mismatch between simulated and measured activity of ^{65}Zn is

Table 6. Simulated and measured induced activation in lead in shields 4 and 5.

Isotope	Decay	Specific activity (Bq kg^{-1}) Simulated	Measured lab 2
^{123}Sb	Beta$^-$	$9.38 \pm 0.47 \times 10^3$	$5.5 \pm 0.04 \times 10^3$
^{205}Pb	EC	$1.29 \pm 0.06 \times 10^{-2}$	

Acceleration Chamber

Table 7. Simulated induced activation in magnet.

Isotope	Decay	Specific activity (Bq kg^{-1})
^{55}Fe	EC	$1.14 \pm 0.06 \times 10^3$
^{59}Fe	Beta$^-$	$3.60 \pm 0.18 \times 10$
^{55}Co	EC; beta$^-$	$1.10 \pm 0.06 \times 10^3$
^{60}Co	Beta$^-$	$6.22 \pm 0.31 \times 10$
^{63}Ni	Beta$^-$	$1.29 \pm 0.06 \times 10^3$

Table 11. Measured and expected values of effective dose of the involved staff.

Staff	Number of workers	Working time (d)	Expected mean effective dose (external exposure) (μSv)	Measured mean effective dose (external exposure) (μSv)	Calculated effective dose from intake (μSv)
Engineers	1	2	20	<20	0
Bricklayers	4	12	10	<20	0
Riggers	4	3	10	<20	0
Dismantlers	3	3	10	<20	0

Table 12. Integrated dose on different points of the cyclotron vault.

Point	Integrated dose equivalent H*(10) (μSv)
1	0
2	0
3	0
4	0
5	85[a]
6	15
7	25
8	35

[a] This point was located on the wall bordering the CT-PET scanner room. The high recorded value originates from clinical workload of CT PET.

good agreement with the measured activity as regards the lead samples as well as the surface dose rate of the major cyclotron components. Discrepancies might be explained by taking into account the following considerations:

- There was a lack of detailed information related to the elemental composition of the major building and cyclotron constituents materials (for instance, the concrete used for both the vault and shielding construction or the low copper steel of the magnet coil), as the machine was installed in 1988 and retrieving the above data proved to be difficult; thus, the isotopic ratio of typical, commercially available materials has been considered and used for the MC code modeling, although it was clear that significant differences with the actual composition was of concern. This obviously led to a decreased accuracy in the theoretical estimation of the activation;
- The measured data do not cover the whole cyclotron structure; an extensive drilling campaign was certainly the best way to collect representative samples of the major cyclotron components such as the magnet coil, the yoke structure and the internal vacuum chamber components (e.g., dees, water cooling tubes). However, the need of a suitable, unusual drilling device, together with a strict time constraint, forced us to reduce the sampling to the more easily available cyclotron parts;
- Further, the activity determination of pure beta emitters, due to their characteristic low energy, easily absorbed emissions, required specific analysis techniques that were not readily available in our institute.

In our experience, due to the lack of precise data regarding elemental material composition, beam loss, and historical beam time and conditions, the Monte Carlo simulation data were useful in order to obtain an estimation of the amount of radioactivity involved in each step of the decommissioning procedure, as well as to gain a better understanding of experimental values. Experimental feedback is, however, always mandatory.

As a general conclusion, the decommissioning of a self-shielded cyclotron of 11 MeV, after a 16-y working life, represents no risk for staff involved in its dismantling, when continuously supervised by trained professionals.

The survey and monitoring of the environment and workers, during the dismantling phase, by the health physics staff and by qualified spectroscopy labs, represent a requisite condition for the safe outcome of the procedure.

The presence of residual long-lived activated elements in various parts of the accelerator and the shields is to be taken into account for the classification of waste disposal in accordance with the relevant regulations and national laws. Limits and legal prescriptions currently in force in Italy require the customer to store activated parts indefinitely in authorized areas for radioactive waste disposal.

This aspect should be considered in any facility prior to a decision regarding cyclotron installation.

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Extractor Body: Activated isotopes with half-life greater than 120 days

Reaction	Activated element	Half-life	Specific activity (Bq kg-1)	Weight (kg)	uCi	Appendix B uCi	Ratio (App. B x 10E4)
(p,n)	Zn-65	244.06 (d)	155000	300	1500	10	0.0150
(p,n)	Cd-109	461 (d)	155000	300	1500	10	0.0150
(p,n)	W-181	121.2 (d)	155000	300	1500	10	0.0150
(p,n)	Mn-54	312.3 (d)	319	300	5000	10	0.0500
					Ratio < 1 as specified in 10 CFR 30.35(d) for unsealed form		0.0950

Cyclotron Shields: Activated isotopes with half-life greater than 120 days

Reaction	Activated element	Half-life	Specific activity (Bq kg-1)	Weight (kg)	uCi	Appendix B uCi	Ratio (App.B x 10E4)
(n,alpha)	C-14	5300 (y)	16.3	20000	50	100	0.0001
(n,gamma)	Ca-41	103000 (y)	23.4	20000	50	0.1	0.0500
(n,p)	K-40	1E+09 (y)	25	20000	50	0.1	0.0500
(n,alpha)	Ar-39	269 (y)	28	20000	50	0.1	0.0500
(n,gamma)	Ca-45	163 (d)	5450	20000	3000	10	0.0300
(n,gamma)	Fe-55	2.7 (y)	16600	20000	9000	100	0.0090
(n,gamma)	Fe-59	44.6 (d)	76.2	20000	50	10	0.0005
(n,gamma)	Eu-152	13.6 (y)	895	20000	500	1	0.0500
(n,gamma)	Eu-154	8.8 (y)	75.6	20000	50	1	0.0050
(n,gamma)	Co-60	5.3 (y)	328	20000	200	1	0.0200
(n,gamma)	K-40	1E+09 (y)	25	20000	50	0.1	0.0500
(n,p)	Ar-39	269 (y)	28	20000	50	0.1	0.0500
(n,alpha)	Cl-36	301000 (y)	25	20000	50	10	0.0005
(n,gamma)	H-3	12.3 (y)	25	20000	50	1000	0.0000
	Mn-54	312.3 (d)	1400	20000	5000	10	0.0500
	Other		0.828	20000	50	0.1	0.0500
					Ratio < 1 as specified in 10 CFR 30.35(d) for unsealed form		0.4651

Concrete Floor: Activated isotopes with half-life greater than 120 days

Reaction	Activated element	Half-life	Specific activity (Bq kg-1)	Weight (kg)	uCi	Appendx B uCi	Ratio (App.B x 10E4)
(n,alpha)	Ar-39	269 (y)	29.6	50000	50	0.1	0.0500
(n,gamma)	Ca-45	163 (d)	213	50000	300	10	0.0030
(n,gamma)	Fe-55	2.7 (y)	654	50000	900	100	0.0009
(n,gamma)	Fe-59	44.6 (d)	22	50000	50	10	0.0005
(n,gamma)	Eu-152	13.6 (y)	47.5	50000	100	1	0.0100
(n,gamma)	Eu-154	8.8 (y)	21.4	50000	50	1	0.0050
(n,gamma)	Co-60	5.3 (y)	19	50000	50	1	0.0050
(n,gamma)	S-35	87.5 (d)	11.3	50000	50	100	0.0001
	Sc-46		29	50000	50	10	0.0005
	Mn-54	312.3 (d)	35	50000	5000	10	0.0500
	Others		0.883	50000	50	0.1	0.0500
					Ratio < 1 as specified in 10 CFR 30.35(d) for unsealed form		0.1750

< 120 days

Cyclotron Shields: Activated isotopes with half-life greater than 120 days

Reaction	Activated element	Half-life	Specific activity (Bq kg-1)	Weight (kg)	uCi	Appendix B uCi	Ratio (App.B x 10E4)
(n,gamma)	Pb-205	2E+07 (y)	0.013	20000	50	0.1	0.0500
(n,2n)	Pb-205	2E+07 (y)	0.013	20000	50	0.1	0.0500
					Ratio < 1 as specified in 10 CFR 30.35(d) for unsealed form		0.1000

Magnet: Activated isotopes with half-life greater than 120 days

Reaction	Activated element	Half-life	Specific activity (Bq kg-1)	Weight (kg)	uCi	Appendix B	Ratio (App.B x 10E4)
(n,alpha)	Fe-55	2.7 (y)	11400	21020	7000	100	0.0070
(n,p)	Co-60	5.27 (y)	62.2	21020	50	1	0.0050

(n,gamma)	Ni-63	100.1 (y)	1290	21020	1000	10	0.0100
(n,gamma)	Fe-55	2.7 (y)	11400	21020	7000	100	0.0070
(n,gamma)	Co-60	5.27 (y)	62.2	21020	50	1	0.0050
						Ratio < 1 as specified in 10 CFR 30.35(d) for unsealed form	0.0340

Extractor body: Activated isotopes with half-life greater than 120 days

Reaction	Activated element	Half-life	Specific activity (Bq kg-1)	Weight (kg)	uCi	Appendix B	Ratio (App.B x 10E4)
(n,p)	Ni-63	100.1 (y)	728	300	50	100	0.00005
(n,alpha)	Co-60	5.27 (y)	1090	300	50	10	0.00050
						Ratio < 1 as specified in 10 CFR 30.35(d) for unsealed form	0.00055

Required financial assurance for decommissioning per 10 CFR 30.35(d):

For plated foils, $113000 is required if the calculated ratio divided by 10E10 is greater than 1.
The calculated ratio does not exceed 1, therefore no financial assurance is required for decommissioning the plated foils for the cyclotron.

For activated isotopes in unsealed form, $225000 is required if the calculated ratio divided by 10E4 is less than 1.
The calculated ratio is greater than 0.1 but does not exceed 1, therefore financial assurance in the amount of $225,000 is required for decommissioning the cyclotron facility.