COMPONENT ACTIVATION OF A HIGH CURRENT RADIOISOTOPE PRODUCTION MEDICAL CYCLOTRON

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Introduction

During routine operation of medical cyclotrons intense flux of fast neutrons and gamma rays are produced.

The fast neutrons suffer multiple collisions with vault walls, slow down and thermalised.

These fast neutrons as well as the thermals interact with the cyclotron parts causing radio activation.

Activated cyclotron parts pose considerable radiological hazard during maintenance and waste disposal procedures.

In this report the mechanism of cyclotron component activation and the long and short-term prediction of the activities have been analysed.

The relevant important radiological safety aspects are highlighted.

# Introduction (contd.)

Furthermore, modern industrial and medical cyclotron facilities have to deal with a frequently changing work environment and operational conditions like:

a) Installation of new cyclotron components

b) Dismantling of old (radio) activated cyclotron parts

c) Design of new and modification of old radiological shields

d) Dose calculations for routine and emergency cases

In order to cope with the above challenges we have developed a practical operational health physics method to predict the induced activity in important cyclotron building materials, such as Aluminium, Brass, Copper and Steel of high-current commercial radioisotope production cyclotrons.

Cyclotron Radioisotope Production Facility
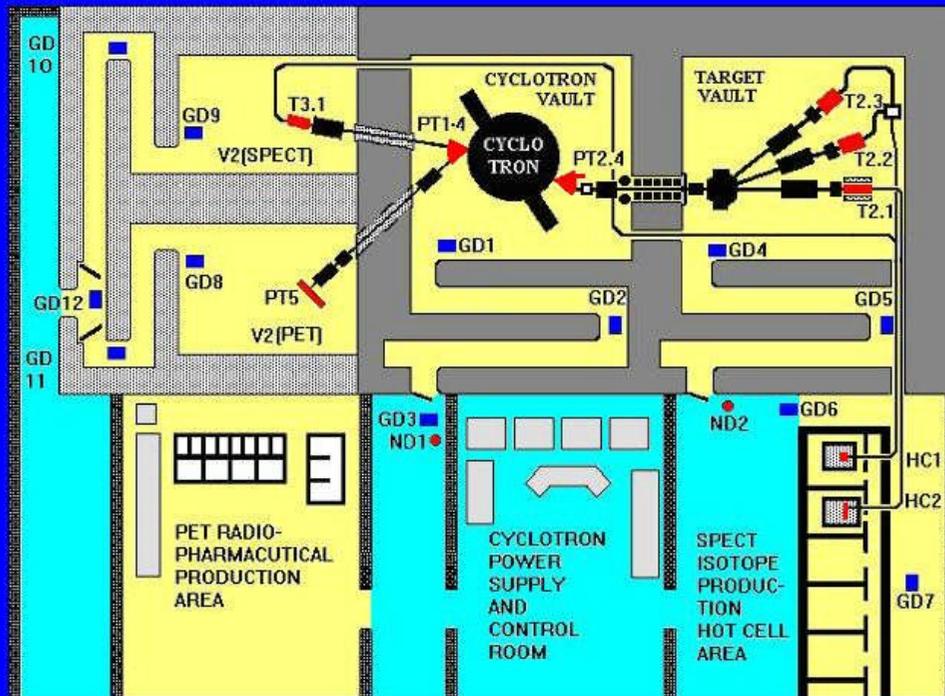
Cyclotron Facility Foot-print

Radioisotope Production Targets

Area Specifications

The 30 MeV H- (Negative Ion) Medical Cyclotron

Materials and Method

Estimation of neutron fluence

Tiny cobalt (^{59}Co, isotopic abundance 100%) palettes (d = 8mm, t = 1mm, w = 447 mg) were wrapped in polyethylene satchel and attached at selected spots of the cyclotron target parts situated in target vault. The locations of the cobalt activation pellets on the cyclotron parts are depicted in Figure below.
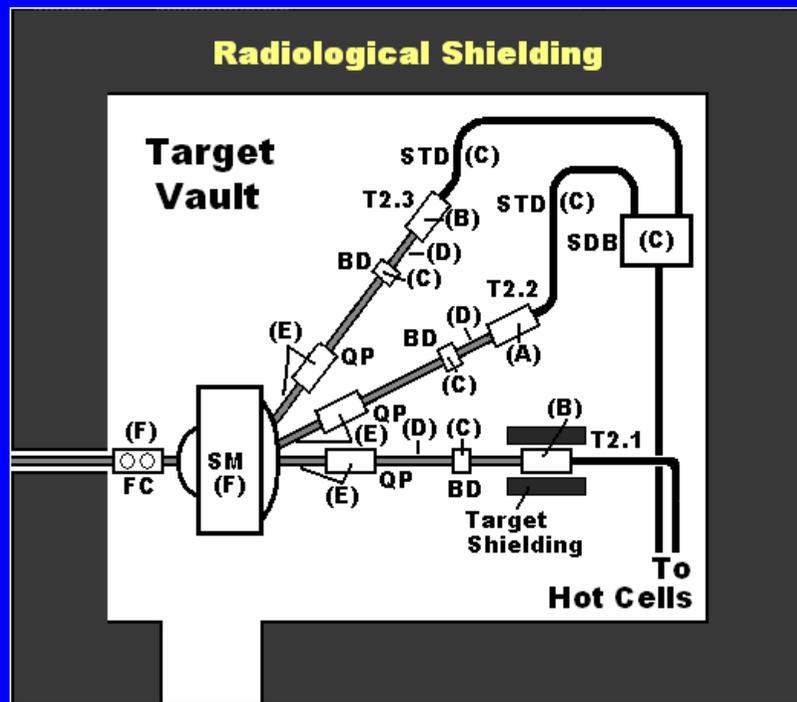
Highlighting the locations of neutron fluence measurement using Cobalt activation pellets:

- **Faraday cup (FC)**
- **Switching magnet (SM)**
- **Quadrupole lenses (QP)**
- **Beam diagnostic ports (BD)**
- **Shuttle transfer duct (STD)**
- **Shuttle distribution box (SDB)**
- **I-123 production target station (T2.1)**
- **SPECT production target stations (T2.2 and T2.3)**

The letters in the "( )" brackets indicate the evaluated neutron fluence category as shown in next figure.

Materials and Method (contd.)

Estimation of neutron fluence (contd.)

The Cobalt pellets were exposed to parasitic neutrons produced during twelve days routine isotope production run. During the entire period the proton current bombarding the targets was monitored in real-time using the Health Physics Watchdog and the data was stored in a database. The results are summarised in Table below.

Date	I (int) : μAh	Irrad. duration: h
1st Week (Mon)	No Run	---
1st Week (Tue)	1200	8.3
1st Week (Wed)	375	10.7
1st Week (Thu)	972	13.1
1st Week (Fri)	1429	8.1
1st Week (Sat)	2157	13.5
1st Week (Sun)	1406	7.4
2nd Week (Mon)	651	6.0
2nd Week (Tue)	1405	7.3
2nd Week (Wed)	1794	12.2
2nd Week (Thu)	1555	11.6
2nd Week (Fri)	1524	13.5
2nd Week (Sat)	1021	6.5
TOTAL	15489	118

Summary of proton bombardment of the cyclotron targets:

- **Total integrated proton current at Faraday Cup = 15489 mAh**

- **proton bombardment duration = 118 h**

- **Location: Target Vault**

- **Target stations monitored in real-time: T2 and T3**

Materials and Method (contd.)

Estimation of neutron fluence (contd.)

The activation pellets were retrieved during the weekly shut down period of the cyclotron removed from the satchel and then assayed using a 95 cm^3 high purity germanium (HPGe) detector interfaced to a 4048 channel MCA after 3 days 72 hours.

The activity of the ^{60}Co in the cobalt pellet produced via the thermal neutron capture reaction ^{59}Co(n, g)^{60}Co was estimated. The areas under the 1.17 and 1.33 MeV photo-peaks of the gamma spectrum were taken into account. The thermal neutron fluence rate F [cm^{-2}s^{-1}] was evaluated using the formula described below:

$$F = Q\,h^{-1}s^{-1}\,N^{-1}\,[1\text{-exp}(\text{-}l\;ti)]^{-1}\,\text{exp}(\text{-}l\;td)^{-1}\,10^{-24} \text{ with } N = Lpkwa^{-1}$$

Q = g-ray count rate of the irradiated cobalt (^{60}Co) pellet (s^{-1})
s = thermal neutron capture cross section for ^{59}Co = 37 barn
N = number of ^{59}Co atoms in the pellet
l = decay constant of daughter product (^{60}Co) = 0.693/T(1/2)
ti = total irradiation time = 118h
td = elapsed time between the end of irradiation and counting begin = 72 h
L = Avogadro's number = 6.02 $\times$ 10^{23} (atoms/mol)
p = elemental fraction (for ^{59}Co, p =1), k = isotopic abundance (for ^{59}Co, k =1)
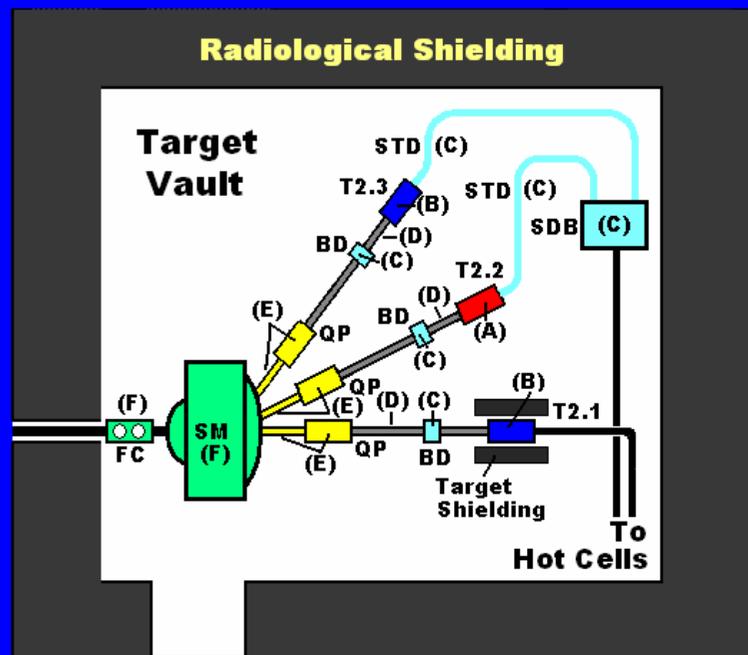w = weight of ^{59}Co pellet = 0.447 g, a = atomic weight of ^{59}Co = 59)
T(1/2) = half life of daughter product (^{60}Co) = 5.6 y

Materials and Method (contd.)

Estimation of neutron fluence (contd.)

The average thermal neutron fluence level categories at the selected cyclotron parts (Figure A) normalised to integrated proton current are shown below (Figure B).

Figure A
Highlighting the locations (colour coded) of neutron fluence measurement using Cobalt activation pellets.
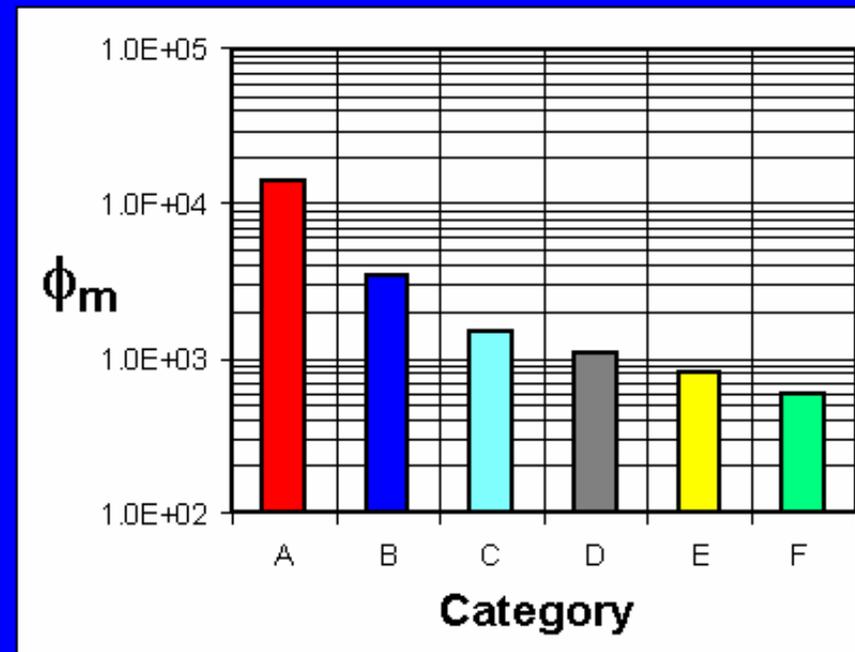
Figure B
Thermal neutron fluence rate f_m [cm^{-2}s^{-1}/mAh] evaluated from the activities of the cobalt pellet are shown with the fluence-level category.

Materials and Method (contd.)

Activity Calculations in Major Cyclotron Building Materials

We undertook a thorough check up of all cyclotron components located in the target vault. The most important building materials are: (a) Copper, (b) Aluminium-type 5083, (c) stainless steel-types 304, 316, (d) Brass-types 83600, 86300. The elemental compositions (percent) of the building materials are summarised in Table below.

Building Material	Copper Pipe	Brass (83600)	Brass (86300)	Steel (304)	Steel (316)	Aluminum (5083)
Al	---	---	7.5	---	---	93
C	---	---	---	0.08	0.08	---
Cr	---	---	---	20	18	0.25
Cu	99.9	84	66	0.35	0.35	0.1
Fe	---	0.3	4	69	70	0.4
Mg	---	---	---	---	---	4.9
Mn	---	---	5	2	2	1
Mo	---	---	---	0.35	3	---
N	---	---	---	0.1	0.1	---
Ni	---	1	1	10.5	14	---
P	0.1	0.05	---	0.45	0.45	---
Pb	---	6	0.2	---	---	---
S	---	0.08	---	0.03	0.03	---
Sb	---	0.25	---	---	---	---
Si	---	0.005	---	0.75	0.75	---
Sn	---	6	0.2	---	---	---
Ti	---	---	---	---	---	0.15
Zn	---	6	28	---	---	0.25

The activities (A [s^{-1}]) generated in cyclotron building materials via thermal neutron capture is given as:

$$A = \mathsf{S_n S_n N_n}[1 - \exp(-\mathsf{I_n}t_i)]\exp(-\mathsf{I_n}t_d)\mathsf{F}$$

$$\mathsf{F} = \mathsf{f_m}\mathsf{I}$$

$\mathsf{S_n}$ = thermal neutron capture cross section for n^{th} element in the cyclotron part of interest

N_n = atom numbers in the nth element

$\mathsf{I_n}$ = decay const. of the nth reaction, t_i = irradiation time [h], t_d = cool down time
F = thermal neutron fluence rate, $\mathsf{f_m}$ = thermal neutron fluence rate of mth category
I = integrated Faraday Cup current [mAh]

Materials and Method (contd.)

A Real Life Example

By applying the above methods we have estimated the activities in 1kg aluminium (Type 5083) "TEST TAG" induced by thermal neutrons in 1 year cyclotron operation :

(a) Total integrated target current of 3.72×10^5 mAh.

(b) The activity product includes all radioactive daughter nuclides generated in the aluminium piece. Samples belong to all six area categories (A, B, C, D, E, F) were taken into account

(c) The results are plotted in Figure shown below
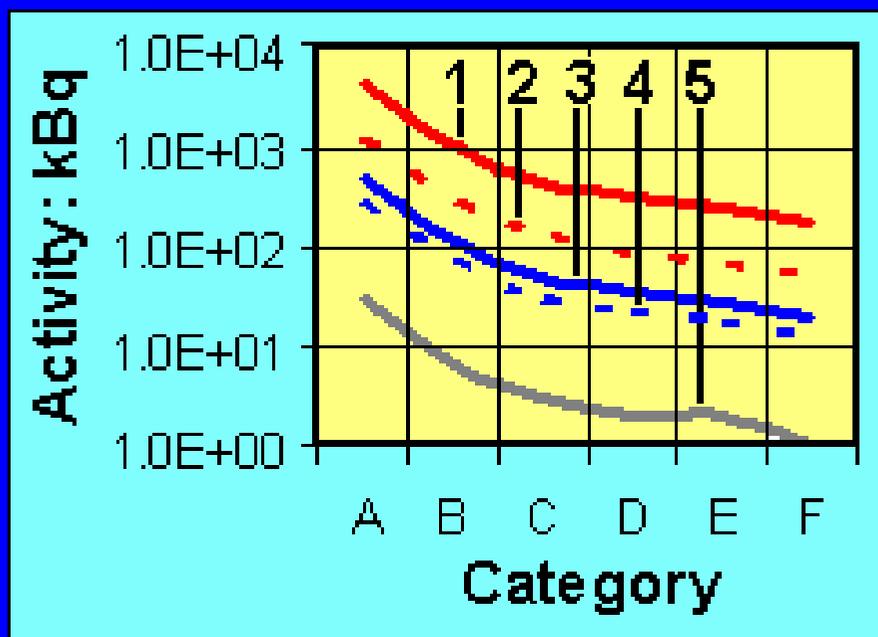
Thermal neutron induced activities of ^{51}Cr (1), ^{65}Zn (2), ^{65}Cu (3), ^{55}Fe (4) and ^{59}Fe (5) generated in 1 year in 1 kg aluminium specimens (Type 5083) placed at selected areas the in the target vault designated by the area categories A, B, C, D, E, F.

Summary and Conclusion

We have developed a simple and user friendly method to predict the induced radioactivity in various parts of high-current radioisotope production cyclotrons.

Tiny cobalt (^{59}Co) activation pellets were placed at selected regions of the cyclotron.

The pellets were retrieved after 2- 4 weeks routine cyclotron operation.

The activities of ^{60}Co generated by thermal neutron capture were assayed using a high purity Ge(Li) detector.

During the entire cyclotron operation period all target currents were integrated using Faraday Cups.

The thermal neutron fluences evaluated from the induced ^{60}Co activity in the pellets were normalised with the integrated Faraday Cup current.

A region specific thermal neutron fluence calibration factor f_m [cm^{-2}/mAh] was established for each location and designated as Category Number A, B, C, D, E and F.

Test Tags made of typical cyclotron building materials like Aluminium, Brass, copper and Steel were placed at location of different Categories.

After a certain cyclotron operation period (ca. 1 year) the activities of the radioactive species induced in the Test Tags were calculated using the fluence calibration Factor f_m and integrated Faraday Cup current as well as assayed using a Ge(Li) detector.

Summary and Conclusion (contd.)

Values of the assayed and calculated activities (decay corrected) of the radioactive species in the Test Tags agreed well with each other.

In this investigation we have ignored the activities caused by fast neutron and proton induced reactions such as, (n, 2n), (n, p), (n, pn) and (p, n), (p, 2n).

These reactions frequently occurs at highly localised zones like the collimators, targets, target windows. The masses of such activated parts are usually quite small.

The method presented in this report is **not** suitable for self-shielded low energy PET cyclotrons, usually operated by nuclear medicine clinics.

On the other hand, this experimental technique is ideally suited for the prediction of component activation of high current commercial medical cyclotrons producing large activities of longer lived radionuclides.

Please visit our poster "Operational Health Physics During the Maintenance of a Radioisotope Production Cyclotron (WEPPRA 07)".

THANK YOU FOR YOUR ATTENTION

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