RESEARCH APPLICATIONS OF THE HEALTH PHYSICS SURVEILLANCE SYSTEM AT THE AUSTRALIAN NATIONAL MEDICAL CYCLOTRON

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The Health Physics Surveillance System of the National Medical Cyclotron (NMC) operated by the Australian Nuclear Science and Technology Organisation (ANSTO) is being used for the real-time monitoring of cyclotron beam currents, neutron and gamma dose equivalent rate at various important locations, stack effluent discharge and the volume of low level liquid radioactive waste. In addition to the routine health physics monitoring, the Health Physics Surveillance System provided a sound basis of interesting Research and Development applications including the analysis of the cyclotron component cool-down characteristics, estimation of neutron and gamma source terms and the time dependent radiation field mapping near the highly activated cyclotron targets.

1. Introduction

Since July 1991 the National Medical Cyclotron (NMC) has operated a 30 MeV H^- ion Medical Cyclotron (Model: CYCLONE 30, Manufacturer: Ion Beam Applications, Louvain La Neuve, Belgium) for the production of short lived PET (Positron Emission Tomography) and longer lived SPECT (Single Photon Emission Computerised Tomography) isotopes. During routine isotope production operations a thick copper substrate plate electroplated with a thin layer of specific enriched target material is bombarded by a 30 MeV proton beam with a current up to 350 μA. In addition to activating the target, the beam results in the production of an intense flux of evaporation neutrons causing the activation of cyclotron components. In compliance with the mandatory requirements imposed by the regulatory authority, a real-time Health Physics Surveillance System (Watchdog) has been developed to monitor the radiation levels at selected locations. The typical examples include the detection of neutron and gamma dose equivalent rate levels at areas of interest, evaluation of stack effluent release concentrations and the storage volume of the liquid radioactive waste. The basic principle of the original Health Physics Monitoring System, operating since June 1991 was described elesewhere[1].

The Health Physics Surveillance System has also provided a sound basis of the following important Research and Development applications: a) Estimation of the neutron and gamma source terms for copper and water targets required for cyclotron shielding calculations, b) Analysis of the cool-down characteristics of activated cyclotron components and c) Spatial and temporal field mapping of the induced gamma radiation in the vicinity of the activated target irradiation stations. This data is required for the personnel dose minimisation and the planning of preventative maintenance program of the cyclotron beam lines, Faraday-cups and target stations in accordance with the ALARA criterion. This paper highlights the above R&D applications of the Health Physics Surveillance System at the NMC.

2. System Description

The Health Physics Surveillance System consists of fourteen gamma and two neutron area monitors, two gaseous effluent detectors installed in the stack and filter room (not shown) and three low-level radioactive liquid level monitors (not shown). The PET and SPECT targets (acting as Faraday-Cups) were also connected to the system, with a view to monitoring the target currents. The surveillance system incorporates 23 sensors which are connected to a datalogger interfaced to a Personal Computer. The analog signal outputs of the sensors are sampled every second, processed with linearising polynomials residing in the datalogger driver program and stored in a Pentium 133 MHz Personal Computer. The principle of the data acquisition system is shown in Figure 1. The floor plan of the cyclotron facility indicating the location of the radiation monitors is shown in Figure 2.

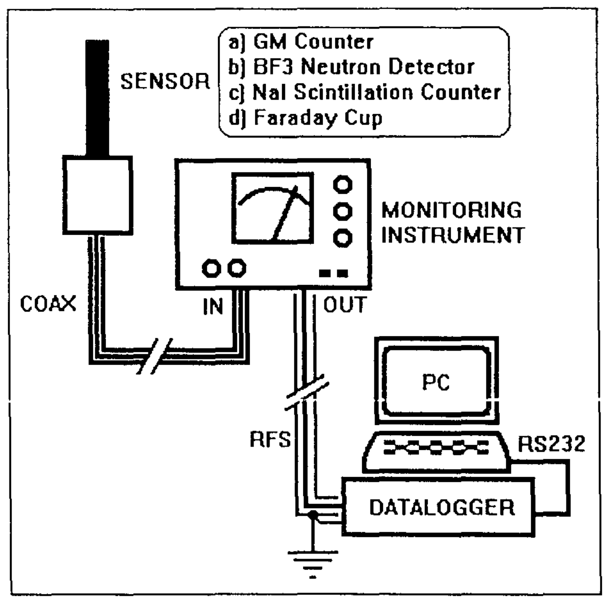

Figure 1: Showing the principle of health physics data acquisition system. The application specific sensors (inset) are connected to the individual monitoring instrument using a coaxial cable (COAX). The analog signal output from the monitoring instrument is linked to the datalogger (in 0-40 mA current loop mode) via a RF-shielded twisted pair cable (RFS). The datalogger is interfaced to the serial port (RS232) of a Personal Computer (PC).

3. Application Examples

3.1 Estimation of Neutron Gamma Source Terms

The neutron/gamma source term [$\mu Sv h^{-1} \mu A^{-1} m^2$] is defined as the dose equivalent rates per unit beam current at 1m from target bombarded with protons.

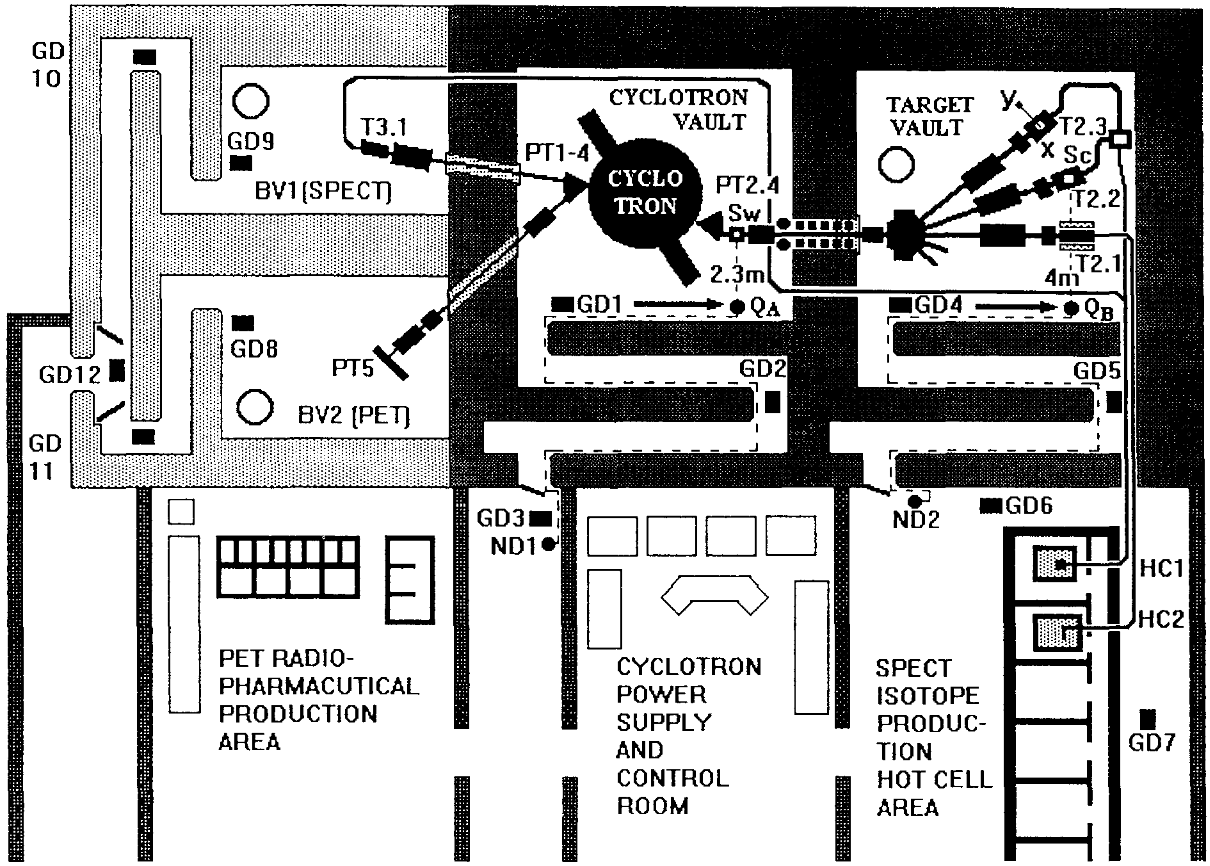

Figure 2: Schematic diagram of the floor plan of the cyclotron facility showing the location of the radiation monitors: GD1 = Gamma Area Monitor in Cyclotron vault, GD2 = Gamma Area Monitor in Cyclotron vault maze, GD3 = Gamma Area Monitor at Cyclotron vault door, GD4 = Gamma Area Monitor in Target vault, GD5 = Gamma Area Monitor in Target vault maze, GD6 = Gamma Area Monitor at Target vault door/Hot cell entrance, ND1 = Neutron area monitor at Cyclotron vault door, ND2 = Neutron area monitor at Target vault door, GD7 = Gamma Area Monitor at the rear of the Hot cells, GD8 = Gamma Area Monitor in new PET beam room (BV2), GD9 = Gamma Area Monitor in new SPECT beam room (BV1), GD10 = Gamma Area Monitor in new SPECT beam room maze, GD11 = Gamma Area Monitor in new PET beam room maze, GD12 = Gamma Area Monitor in the entrance corridor of the new beam rooms.

The source terms[2] are the most important parameters required for the lateral shielding thickness calculations[3] for cyclotron facilities.

The neutron and gamma source terms for copper and water targets were estimated experimentally using the Health Physics Surveillance System as detailed below. A thick copper target plate (S_C) was loaded into the target irradiation station T2.3 in the target vault. A standard neutron REM counter (Model: 05-711EX-Snoopy, Manufacturer: Victoreen, USA) was mounted on a aluminium trolley placed at location Q_B, 4 metres from the copper target Sc and about 1.2m from the floor level. The detector head of the Gamma area monitor GD4 (Model: 808 Gammaguard, Manufacturer: Victoreen, USA) was relocated and positioned next to the neutron

REM counter. The signal output of the REM counter was connected to the neutron monitoring instrument (ND2) located at the entrance of the Target vault using a coaxial cable (dotted lines) as shown in Figure 2. After the sealing of the target vault the copper target plate was bombarded with a narrow well focussed 30 MeV proton beam. The neutron and gamma dose equivalent rates and the corresponding proton beam current on the target (S_C) were simultaneously sampled every minute and stored in the Data Acquisition Computer (Figure 1) of the Health Physics Surveillance System[1].

Later, the experiment was repeated in the cyclotron vault by placing the neutron REM counter and the Gamma area monitor GD1 (relocated) at the spot Q_A, 2.3m from the Faraday Cup Sw. The beam dump of the Faraday Cup constituted a 30 ml water volume flowing behind a 0.1 mm thick Tantalum window, in which the beam is directed. The Faraday Cup was bombarded with a 30 MeV proton beam and the neutron/gamma dose rate and beam current were recorded using the Health Physics Surveillance System as described earlier.

The source term H for the neutron and gamma radiation field produced by the proton bombardment of the thick copper target in the target vault and water target in the cyclotron vault could be given as:

$H = DI^{-1}x^2$ (1)

where, D = neutron or gamma dose equivalent rate [Svh^{-1}]

I = proton beam current [μA]

x = distance between the target and the location of the radiation detector [m], x> 1m

The neutron (H_n) and gamma (H_g) source terms for the thick targets are shown in Tables 1a and 1b respectively. The experimental uncertainties constituted one standard deviation ($\pm 1\sigma$) of 10 different observations.

Table 1a: Neutron source terms (H_n) for thick copper and water targets bombarded with a narrow beam of 30 MeV protons.

Target	I [μA]	d [m]	D_g [Svh^{-1}]	H_g [$Svh^{-1}\mu A^{-1} m^2$]
Copper	0.17 ± 0.003	4	0.015 ±0.002	1.4 ± 0.17
Water	0.15 ± 0.003	2.3	0.009 ±0.001	0.33 ±0.04

Table 1b: Gamma source terms (H_g) for thick copper and water targets bombarded with a narrow beam of 30 MeV protons.

Target	I [μA]	d [m]	D_g [Svh^{-1}]	H_g [$Svh^{-1}\mu A^{-1} m^2$]
Copper	0.17 ±0.003	4	0.0012 ±0.0001	0.11 ± 0.012
Water	0.15 ± 0.003	2.3	0.00113 ±0.0001	0.04 ±0.005

3.2 Analysis of component cool-down characteristics

Intense field of evaporation neutrons with a peak energy of 1.25 MeV is produced during the bombardment of the copper target plate with protons[4]. These evaporation neutrons slow down via multiple collisions with the hydrogen atoms of the water molecules present in the concrete mass of the target vault shielding. These slow neutrons bounce back to the interior space of the vault activating the cyclotron parts, beam tube components and other utilities installed in the irradiation vaults[5]. The Health Physics Surveillance System was used to analyse the complex decay characteristics of the radioactivity induced in the components located in the target vault. This important information should be assessed to determine the optimum cool down period to work commencing, in order to minimise the personnel radiation exposure while handling the activated parts during cyclotron maintenance procedure[6].

After the completion of the weekly routine SPECT isotope production runs lasting ca. 22 hours (Monday afternoon - Saturday morning) the target shuttle carrying the irradiated copper target plate was pneumatically transferred to one of the radio-chemical production hot cells (HC1). The radioactive I-123 produced usually on Monday and Wednesday (ca. 4 hours irradiation per run) in the Target station T2.1 was transferred via a pipeline to the I-123 production plant installed in a dedicated hot cell HC2 (Figure 2). Immediately after the removal of the target shuttle the gamma area monitor GD4 located at the entrance of the target vault was switched on. The gamma dose rate was sampled every minute by the Health Physics Surveillance System for 25 hours (1500 min) and the data was stored. In Figure 3 the gamma dose rates are plotted as a function of elapsed time and shown as the "Cool down curve". The dose cool down curve was unfolded into four unique exponential functions within a least square error ± 2% as follows:

$$D_t = D_0(0.65\exp(-0.693t/T_1) + 0.20\exp(-0.693t/T_2) + 0.06\exp(-0.693t/T_3) + 0.09\exp(-0.693t/T_4)) \qquad (2)$$

where t = elapsed time (minute) after the completion of the target bombardment "shuttle transfer"

D_t = gamma dose rate after the elapsed time t

D_0 = gamma dose rate detected in the target vault by GD4 immediately after the removal of the irradiated target = 9000 μSvh^{-1}

T_1, T_2, T_3 and T_4 represent the half lives of the individual radioisotopes and were calculated to be:

(a): T_1 = 4 min, (b): T_2 = 156 min (= 2.6 h), (c): T_3 = 900 min (= 15 h) and (d): T_4 = 64224 min (= 44.6 d)

By using the half lives the following radioactive species induced in the target vault during the proton bombardment of the thick copper target were identified[7]:

(a): ^{28}Al, (b): ^{56}Mn, (c): ^{24}Na and (d): ^{59}Fe

By substituting the half life data and the value of D_0 the dose "cool down" equation (2) could be rewritten as:

$$D_t = 5850\exp(-1.73\times10^{-1}t) + 1800\exp(-4.44\times10^{-3}t) + 540\exp(-7.70\times10^{-4}t) + 810\exp(-1.08\times10^{-5}t) \qquad (3)$$

The above equation could be used to extrapolate (predict) the gamma dose rate in the target vault at any elapsed time (t min) after the end of routine irradiation schedule (target bombardment).

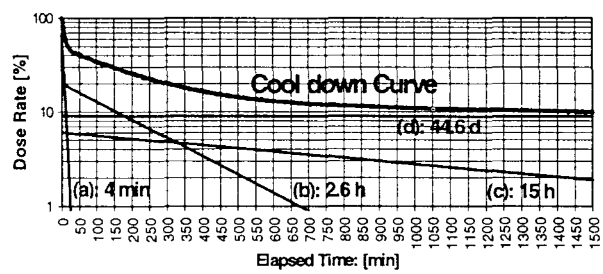

Figure 3: The gamma dose rate in the target vault as a function of elapsed time detected with the gamma area monitor GD4 (Figure 2) is shown. The gamma dose detection began immediately after the removal of the proton irradiated copper target plate from the target vault. The initial value of the dose rate (t = 0) was normalised to 100%.

3.3 Mapping of the induced gamma radiation field

The gamma dose rate in the vicinity of the cyclotron target stations originated from the activated cyclotron components may cause a considerable radiation exposure to cyclotron maintenance personnel while working in the radiation environment of the target stations. Therefore, it becomes imperative to predict the gamma dose at such locations of interest for an optimum planning of the maintenance schedule. The Health Physics surveillance System used in conjunction with measurements made with hand held survey meter to predict the spatial and temporal variation of these dose rates.

As a part of the routine Health Physics Survey, the gamma dose rates at contact (position x) and 50 cm from the target station T2.3 (position y), i.e. two of the work areas with very high gamma dose, were recorded on every Monday morning between 7.30-8.30 hr throughout the observation period "December 1994 - March 1996" using a telescopic gamma monitor (Model DX-2, Manufacturer: Gaertz, Germany). The gamma dose rate prevalent near the target and at the target vault entrance were detected by the gamma area monitor GD4 (Figure 2) interfaced to the Health Physics Surveillance System (Figure 1) and are plotted against the "December 1994 - March 1996" observation period in Figure 4.

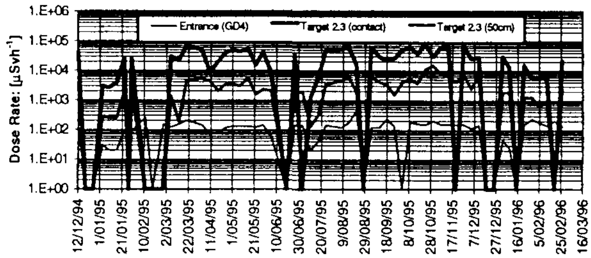

Figure 4: Shows the gamma dose rates at contact (point x in Figure 2) and at 50 cm from the Target Station T2.3 (point y in Figure 2) as well as at the entrance point of the Target vault recorded during the weekly routine Health Physics Survey over the period of 12 December 1994 - 25 February 1996.

It is evident from the "plateau nature" of the gamma dose curves in Figure 4 that the dose rates at contact and 50 cm from the target as well as at the vault entrance remained constant at 40000 μSvh^{-1}, 3000 $\mu Svh^{-1}$and 150 μSvh^{-1} respectively. The gamma dose rate at contact with the target $D_x(t)$ and 50 cm therefrom $D_y(t)$ after the elapsed time t [min] are given as:

$D_x(t) = k_x D_t$ (4a)

$D_y(t) = k_y D_t$ (4b)

where

k_x = (gamma dose rate at contact with Target 2.3) / gamma dose rate at vault entrance

$= 40000\ \mu Svh^{-1}/150\ \mu Svh^{-1} = 267$ (5a)

k_y = (gamma dose rate at 50 cm from Target 2.3) / gamma dose rate at vault entrance

$= 3000\ \mu Svh^{-1}/150\ \mu Svh^{-1} = 20$ (5b)

By substituting the values of k_x (equation 5a), k_y (equation 5b) and D_t (equation 3) in equations 4a and 4b the projected values of $D_x(t)$ and $D_y(t)$ were calculated for the elapsed time periods of 1minute, 1hour, 1, 2, 4 and 8 weeks after the end of the target (T2.3) bombardment and shown in Table 2. The principle of gamma dose prediction in critical work areas in the radiation environment of a commercial Medical Cyclotron is reported elswhere[8].

4. Summary and Discussion

The Health Physics Surveillance System routinely operating since June 1991 at the Australian National Medical Cyclotron has been providing various important radiological data including neutron and gamma dose equivalent rates prevailing at various important locations of the facility, proton beam currents at different cyclotron operating conditions and the stack effluent release rates.

Table 2: Gamma dose rate at contact Dx(t) and at 50 cm Dy(t) from the target station T2.3 (Figure 2) at the elapsed time (t) ranging from 1min - 8 weeks after the end of the target bombardment. The dose extrapolations were calculated using equations 4a and 4b.

Elapsed time: t	Gamma Dose Rate: [μSvh^{-1}]	
	$D_x(t)$	$D_y(t)$
1 min	2.15×10^6	1.61×10^5
1 hour	7.22×10^5	5.41×10^4
1 day	2.61×10^5	1.96×10^4
1 week	1.94×10^5	1.45×10^4
2 weeks	1.74×10^5	1.30×10^4
4 weeks	1.36×10^5	1.02×10^4
8 weeks	8.51×10^4	6.37×10^3

The system was also implemented in various Research activities[9] including the determination of neutron/gamma source terms, prediction of long-term cool down characteristics of activated cyclotron components and the analysis of spatial and temporal gamma dose distribution in the work areas at our 30 MeV Medical Cyclotron facility.

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