Proton Therapy Facility

Facility Overview

The XXX is constructing a proton therapy center and installing a Mevion S250 proton Therapy System at the XXX. This facility will be used for treating pediatric and adult cancer patients. The Mevion S250 system is a single room compact accelerator (Fig. 1) employing a passive scattering technology to produce a broad proton beam for clinical applications.

The accelerator structure in the S250 system consists of a 20 ton synchrocyclotron and a 9Tesla superconducting magnet. It will accelerate protons to about 2/3 the speed of light at energy 250 MeV, which can penetrate to a depth of ~35 cm in tissue. The compact design of the Mevion S250 system removes the need for a beam transport system (BTS) and has integrated the energy selection system (ESS) absorber into the field shaping system (FSS). The FSS consists of rough and fine carbon absorbers, a first scatterer made of lead and a second scatterer made of lead and glass. The FSS system takes the narrow full energy beam and degrades the energy to the requested energy and broadens the beam to a clinically useful size with the scatterers. In the generating and delivering of a high energy proton beam, the cyclotron and the associated accessories will become activated as a result of bombardment from the protons and/or neutrons, necessitating an amendment to the XXX existing XXX license. These activated parts will be for possession and storage only.

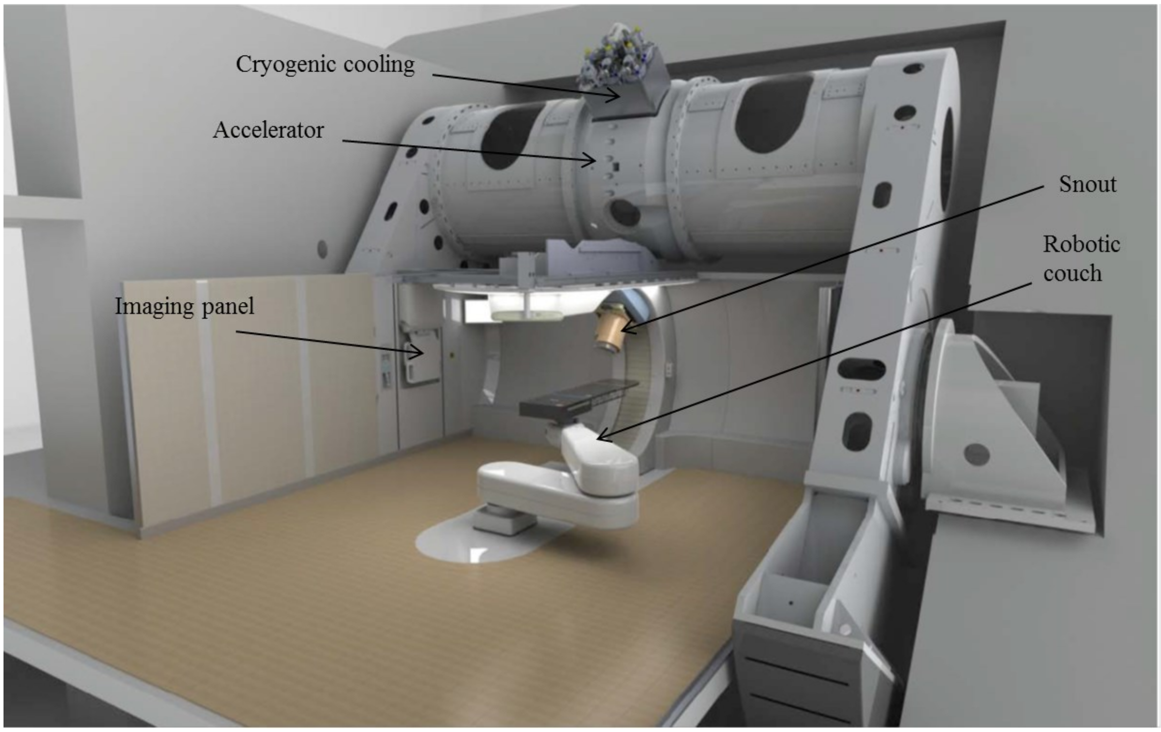


Fig. 1. A cutaway view (with the walls removed) of the Mevion S250 system showing the gantry system, the snout and the robotic couch (Mevion site planning guide).

The cyclotron is made of copper and relatively pure iron. Figure 2 shows our cyclotron in the factory. The design capacity of this unit is 20 nA proton current at extraction, but it will operate typically at lower currents (≤5 nA) clinically. It may be of interest to note that, over the life of this facility, it is anticipated that significantly less than one gram of protons will be delivered to patient.


Figure 2. Cyclotron in factory.

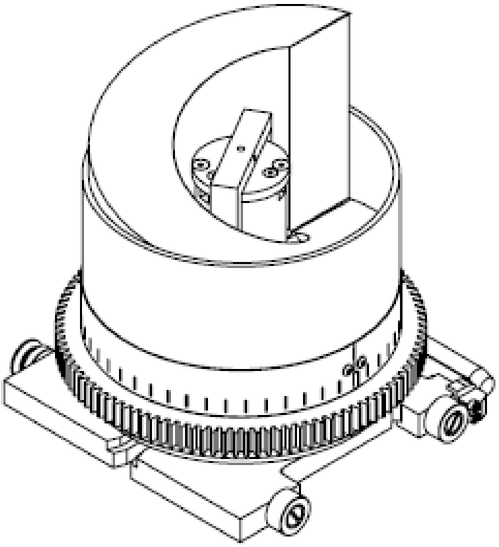
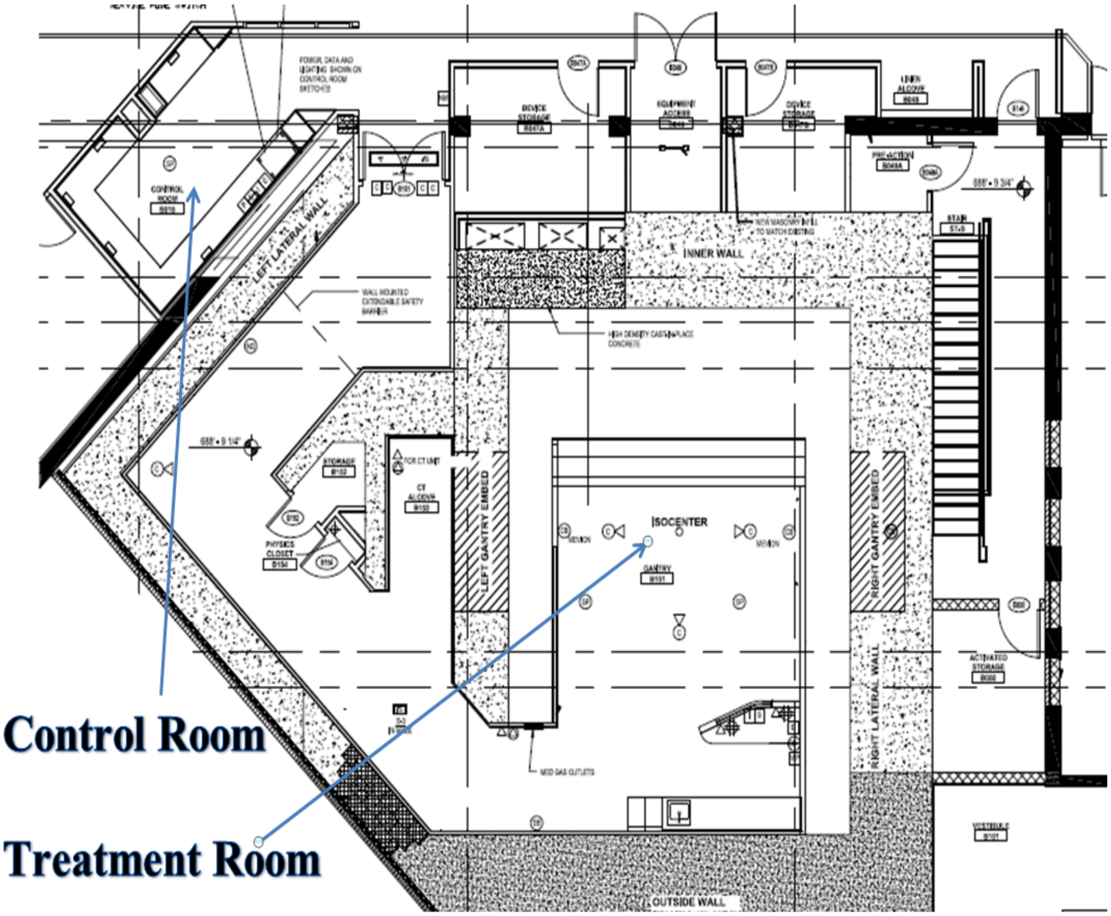


Figure 3. A schematic diagram of high density graphite energy absorber.

Once the protons are extracted from the cyclotron, they are guided to the graphite energy absorber (Fig. 3), which reduces the initially 250 MeV protons to the energy desired for delivery to the patient, between 70 MeV and 250 MeV. The energy is reduced largely through Coulomb interactions in the graphite wedge. This slowing down process can be very inefficient, with <1% loss at 250 MeV to up to >99% loss of the initial protons for the lowest energy. The energy absorber is the largest source of radiation in the proton therapy facility, produced mostly by proton-carbon interactions in the graphite. It is assumed that all neutrons produced in the absorber and scatterers interact in the concrete walls. Figure 4 shows the layout of the facility at XXX. The distance from the isocenter to the lateral concrete walls is 2.8 m. The facility is connected to the XXX Hospital.

The Mevion passive scattering system requires the use of customized brass apertures and plastic (or wax) compensators for each patient for field and isodose shaping. These devices will be activated during their usage in the treatments. Because of the low current and the short irradiation time (~ 1 min/treatment/day for each set of aperture and compensator), the induced activities after the completion of treatment (40 fractions @5 fractions/week) are of the order of a fraction of μCi. These devices will be kept in storage until they have decayed to background radiation levels.

It should be pointed out that concrete contains trace elements of europium and cobalt in less than one part per million concentration but their large thermal neutron cross-sections result in radioactive nuclides with long half-lives, namely ^{60}Co (5.26 years) and ^{152}Eu (13.5 years). An activation analysis has been carried out to estimate the induced activities during the operation of the cyclotron in its life time (30 years) of these two long lived isotopes in the concrete as well as other radioactive nuclides with half-lives more than 120 days that are produced in the cyclotron and the associated accessories. In calculating activation in the cyclotron, it was assumed based on machine specifications that 60% of the protons were lost in the cyclotron, and therefore interacted in the copper and iron. It was also assumed that there is a full load of patients, consistent with the shielding analysis, for a period of 30 years.



Control Room

Treatment Room

Figure 4. Layout of the XXX proton treatment and control rooms.

Activation Analysis

Proton production numbers and energies were determined by assuming a mix of different anatomical treatment sites and volumes. Workload assumptions are 4 patients per hour for 10 hours per treatment day, five days per week and 52 weeks per year, with allowances for additional quality assurance beam time. From these assumptions, the number of protons per year delivered to the patient as well as those lost in the cyclotron and lost in the FSS were calculated.

For the purpose of calculating induced activity, proton interactions in the cyclotron with copper and iron, neutron interactions in the copper, iron, and in the concrete walls from secondary neutrons from the FSS were calculated using the proton loss terms generated in the shielding calculations. Proton loss terms were also used to generate neutron production terms in the FSS.

The proton beam current is highest in locations upstream of the absorber, potentially as high as 20+ nA. The downstream beam current is much lower after passing through the various beam line components (absorber, the range modulator and the scattering foils). An average beam current of 5 nA is used for the activation calculation for the cyclotron and beamline components. The activation inventory is obtained for all activation products with half-lives > 120 days, produced by protons and neutrons on all materials that are present in the proton beam path or in the surrounding areas, including the concrete walls housing the proton accelerator. These radioactive nuclides include[11]: ^{22}Na ($T_{1/2}$=2.6 yrs), ^{49}V ($T_{1/2}$=0.9 yrs), ^{54}Mn ($T_{1/2}$=0.86 yrs), ^{55}Fe ($T_{1/2}$=2.74 yrs), ^{57}Co ($T_{1/2}$=0.74 yrs), ^{60}Co ($T_{1/2}$=5.27 yrs), ^{65}Zn ($T_{1/2}$=0.67 yrs) and ^{152}Eu ($T_{1/2}$=13.5 yrs).

The proton beam irradiation is structured as follows:

- One min irradiation for each treatment
- Four treatments delivered each hour
- One min beam on and 14 min beam off to allow for setup for next irradiation
- 40 treatments delivered in 10 hours
- 14 hours of no beam overnight
- The above steps are repeated for five consecutive days
- Two days of no beam (weekend)
- The above sequence of steps is repeated 52 times/year for 30 years

The total induced activity after 30 years of operation of the cyclotron is given by:

$$
\begin{aligned}
A_{tot} &= S*[\Sigma \exp(-\lambda*15*(m-1))]*[\Sigma \exp(-\lambda*2*24*60*(n-1))]*[\Sigma \exp(-\lambda*(k-1)*7*24*60)] \\
&\qquad *\exp(-\lambda*14*60)*\exp(-\lambda*2*24*60) \\
&= S*[\Sigma \exp(-\lambda*15*(m-1))]*[\Sigma \exp(-\lambda*2*24*60*(n-1))]*[\Sigma \exp(-\lambda*(k-1)*7*24*60)] \quad (1)
\end{aligned}
$$

Where A_{tot} is the total induced activity after 30years of operation of the cyclotron,
S is the induced activity produced in one minute of proton irradiation,
λ is the decay constant of the induced activity,
m, n and k are the running indices in the Σ:

$\Sigma\exp(-\lambda*15*(m-1))]$ where m=1-40 is the total induced activity at the end of the 40th irradiation in a treatment day
$\Sigma\exp(-\lambda*2*24*60*(n-1))$ where n=1-5 is the residual activity in the weekend after 5 days of irradiation and two weekend days of cooling
$\Sigma\exp(-\lambda*(k-1)*7*24*60)$ where k=1-1560 is the contribution to total activity in 30 years (1560 weeks),

For the half-lives of the radioactive nuclides considered in this analysis,
$\exp(-\lambda*14*60)*\exp(-\lambda*2*24*60) =1$.

The induced activity, S, due to one minute of beam-on time per patient is given by

$$S = \varphi*\sigma*N_T*L*(1-\exp(-\lambda*t)) \qquad (2)$$

Where φ is the proton fluence/cm^2/min
σ is the nuclear reaction cross-section in cm^2
N_T is the number of target nuclide =f * N_A, where f is the atomic fraction of the target nuclide and N_A is the Avogadro's number
L is the attenuation length in cm
T is the decay time per fraction (which is 15 min.).

The thermal neutron capture cross-sections and number density of target atoms are obtained from a number of publications[1-7].

The activation in the cyclotron (assuming 60% beam loss as mentioned above) and the beam line components by the 250 MeV proton beams is computed using the empirical equations from Sullivan[1]. This is because the proton activation cross-section data for 250 MeV proton energy as required by Eqn. (2) is lacking in the literature for the elements of interest in the analysis.

The cyclotron consists of mostly copper and almost pure Fe isotopes. The total induced activity from spallation events on medium atomic number elements (such as Cu and Fe) is seen to be independent of half-life and is given by the equation[1]:

$$S = 15* \mathrm{Ln}\ ((T+t)/t) \quad \mathrm{mCi} \qquad (3)$$

where T is the beam-on time and t the beam-off time.

Using the same proton beam irradiation schema as described above, the proton induced activity inside the cyclotron over a 52-week period follows a logarithmic equation:

$$S = 0.1875*\mathrm{Ln}(t') + 0.09327 \qquad (4)$$

where t' is the time in weeks. Equation (4) is independent of Z and half-life. It is used to estimate the proton-induced radioactivities of medium Z nuclides with half-lives longer than 120 days (0.33 yr) in the cyclotron after 30 years of operation: ^{49}V ($T_{1/2}$=0.9 yrs), ^{54}Mn ($T_{1/2}$=0.86 yrs), ^{55}Fe ($T_{1/2}$=2.74 yrs), ^{57}Co ($T_{1/2}$=0.74 yrs), ^{65}Zn ($T_{1/2}$=0.67 yrs). The most probable proton capture reactions to produce these radioactive nuclides inside the cyclotron are (p, γ), (p,α), (p,n), (p,d), (p,t), (p, 2n) and (p, P+He^3). The radioactivity computed from Eqn. (4) is1.48 mCi for each of the medium Z nuclides listed. Thus the total induced activity is 1.48*10 = 14.8 mCi.

Activation of beam line components and support frames which are made of medium Z materials follows the same mechanism as described by Eqn. (3) and (4). The only difference from that of the calculation for cyclotron is that the proton beam current is the extracted beam (5 nA) instead of the beam loss in the cyclotron[11].

The products of proton interactions on carbon in the absorber are H^3, Be^7, C^{10} and C^{11}. $T_{1/2}$ of H^3 = 12.3 years. However, H^3 will not reach activity in the μC range even after 10000 min of continuous irradiation. All the other radioactive nuclides have half-lives in the range 20 sec – 53.4 days and have no significance in the buildup of activity after 30 years of cyclotron operation. Thus the graphite energy absorber does not produce radioactivities of any significance[11].

Heavy elements are more active after short irradiation times than medium elements, but the activity induced in heavy elements decay more rapidly. Thus the activation of heavy elements in the scattering foils and other parts of the cyclotron system will be handled differently from those for medium Z materials[11]. The following equation in Sullivan[1] is employed for heavy elements such as Pb and tungsten:

$$S=20^{*}\left[t^{-0.4} - (T+t)^{-0.4}\right] \quad \text{mCi} \qquad (5)$$

where T is the beam-on time and t the beam-off time.

Tables 1 and 2 summarize the estimated induced activities in the cyclotron system and the concrete walls after 30 years of operation of the cyclotron. Table 3 lists the probably nuclear reactions and the radioactive isotopes produced with half-lives > 120 days in the cyclotron, absorber, beam line components, scattering foils and concrete. Table 4 summarizes the cost estimate for decommissioning.

Table 1. Total proton facility activation after 30 years of cyclotron operation

Summary	
Proton/neutron induced activities	**mCi**
Cyclotron (stored)	14.8
Beamline (stored)	14.0
Scattering foils (stored)	0.7
Concrete	38.9
Total	68.4

Table 2. Five activation products in concrete with half-lives more than 120 days with the highest induced activities after 30 years of cyclotron operation.

Summary		
Proton/neutron induced activities in concrete	**$T_{1/2}$ (yr)**	**mCi**
Co-60	5.7	2.18
Eu-152	13.5	9.39
Na-22	2.6	13.30
Fe-55	2.74	0.35
Zn-65	0.67	13.70
Total		38.9

Table 3. Proton activation products in cyclotron with half-lives > 120 days (0.33 yr) after 30 years of cyclotron operation.

Summary	
Probable proton capture reactons in cyclotron	**$T_{1/2}$ (yr)**
Fe56(p, p+He3)Mn54	0.86
Fe56(p, d)Fe55	2.74
Fe58(p, 2n)Co57	0.74
Fe-57(p, α)Mn54	0.86
Mn55(p, n)Fe55	2.74
Fe57(p, n)Co57	0.74
Mn55(p, d)Mn54	0.86
Fe57(p, t)Fe55	2.74
Fe56(p, γ)Co57	0.74
Cu65(p, n)Zn65	0.67
Total induced activity after 30 years = 14.8 mCi	

In addition to the residual activities of the radioactive nuclides of half-lives >120 days after 30 years of the cyclotron operation as estimated above, there are short-lived isotopes (^{7}Be ($T_{1/2}$=53.2 d), ^{11}C($T_{1/2}$=20.3 m), ^{18}F($T_{1/2}$=110. m), ^{24}Na($T_{1/2}$=15.0 h), ^{46}Sc($T_{1/2}$=83.8 d), ^{48}Sc($T_{1/2}$=43.7 h), ^{48}V($T_{1/2}$=16.0 d), ^{51}Cr($T_{1/2}$=27.7 d), ^{52}MN($T_{1/2}$=5.60 d), ^{53}Fe($T_{1/2}$=8.50 m.), ^{61}Cu($T_{1/2}$=3.33 h), ^{64}Cu($T_{1/2}$=12.7 h), ^{55}Co($T_{1/2}$=17.5 h), ^{56}Co($T_{1/2}$=77.2 d) and ^{58}Co(70.9 d)), which will not contribute to the decommissioning cost, but which may affect the total activity permissible in the RAM license of the facility. These short-lived isotopes are produced as a result of proton or neutron interactions with the cyclotron and its accessories as well as in the concrete walls. Based on the estimations in Appendices A and B, the total activity produced of these short-lived isotopes at the end of a daily operation is less than 100 mCi.

To accommodate this activation as well as the short lived isotopes that will not contribute to decommissioning cost, a radioactive materials license for the possession of 400 mCi is requested to be added to the XXX license for this location.

Decommissioning Costs

The radiological and economic impact of decommissioning charged particle accelerators have been reported in literature.[7,9,10] The intent of decommissioning the proton facility at XXX is to ensure that the activated components are below the specific and absolute activity regulatory limits as specified in XXX. It is anticipated that activated products in the cyclotron will be localized, and that those activated to specific activities above regulatory limits will be isolated and removed[6]. For the purposes of low-level radioactive waste (LLRW) disposal, it is assumed that all 100 kg of copper in the cyclotron, as well as 10% of the iron, will need to be disposed of as LLRW. Further, it is assumed that concrete might need to be saw cut and removed from the walls nearest the cyclotron and disposed of as LLRW. It is assumed that the removal and deconstruction will be performed by personnel overseen by the radiation safety office. Costs for shipping out LLRW, personnel to deconstruct the cyclotron, FSS and radiation safety personnel time at today's estimates were calculated. These estimates can be found on Table 3below. Based on the assumptions listed, the cost is estimated to be less than $350,000.

Table 4. Breakdown of decommissioning cost estimate for the XXX Proton Therapy Center

LLW Cost Assumptions	Cost	
Low Level Radioactive Waste		
Metal	7	($ per lb)
Concrete/rebar	100	($/ft^3)

Cyclotron LLW Disposal Cost			
Copper Density (g/cc)	9		
Iron Density (g/cc)	8		
		Mass Activated (kg)	Cost (@ $7/kg)
Mass of Cu in Cyclotron (kg)	200	200	**$3,080**
Mass of Fe in Cyclotron (kg)	14000	1400	**$21,560**
Percentage of Fe Activated	10		

Concrete LLW Disposal Cost					
Concrete	Width (ft)	Height (ft)	Depth (ft)	Volume (ft^3)	Cost
Northwest Vault Wall	10	10	1.5	150	$15,000
Northeast Vault Wall	10	10	1.5	150	$15,000
Southwest Vault wall	10	10	1.5	150	$15,000
			Total		**$45,000**

Manpower Costs				
Cyclotron Removal Labor Cost	**$100,000**			
Concrete Destruction Cost	**$22,800**			
	Personnel	Hours	Rate ($/hr)	Total cost
Radiation Safety Oversight	2	1000	50	**$100,000**

Sub-Total	$292,440
Contingency (15%)	$43,866

Total Cost	$336,306

References

[1] Sullivan AH. A guide to radiation and radioactivity levels near high energy particle accelerators. Nucl Tech. Publishing, Ashford, Kent, Great Britain.

[2] Williams RG, Gesh CJ, Pagn RT. Compendium of material composition data for radiation transport modeling. Pacific Northwest national Laboratory, PNNL-15870.

[3] Mughabghab SF. Thermal neutron capture cross-sections resonance integrals and g-factors. IAEA Nucl Data section,

[4] Schiekel et al. Nuclide production by proton-induced reactions on elements ($6 \leq Z \leq 29$) in the energy range from 200 MeV to 400 MeV. Nuclear Instruments and Methods in Physics Research B 114(1996) 91-119.

[5] Neutron Activation Cross Section Library, IAEA-TECDOC-1285, April 2002

[6] Dewald, Alfred. Report on the measurement of the activation of the cyclotron accelerator AC250ISC after a first test operation phase, Institure of Nuclear Physics, University of Cologne, Cologne Germany, (August 2011).

[7] Eggermont GX, Buls N, Hermanne A. Decommissioning analysis of a university cyclotron. IAEA Technical Report Series 414, (2003) 3: 338-340.

[8] Agosteo S et al. Double differential distributions and attenuation in concrete for neutrons produced by 100-400 MeV protons on iron and tissue targets, Nuclear Instruments and Methods in Physics Research B 114(1996) 70-80.

[9] Sonck M. et al. Radiological and economic impact of decommissioning charged particle accelerators, European Union P-5-315.

[10] Muckerjee B. Radiation safety issues relevant to proton therapy and radioisotope production medical cyclotrons, Radiation Protection and Environment, (July 2012) 35, 126-134.

[11] Please see Appendix B.

Appendix A

(It has been removed as we have not obtained
permission from the institution to distribute the report)

Appendix B

Guidance Concerning the Production of Radioactive Materials By the Operationof a 250 MeV Cyclotron Incorporated in a Radiation Therapy Device such as the MEVION S250

Mevion Medical Systems, Inc. 300 Foster St, Littleton, MA 01460

State Licensing may require an accounting of long-lived radioactive materials produced by the operation of radiotherapy equipment such as the MEVION S250. In order to assist the applicant for such licenses, Mevion Medical Systems provides the following analysis based on Radioactive Material production in industrial and research accelerators with features similar to the MEVION S250.

Classification of Radioactive Materials consistent with RAM license application Item 5.

a. Element & mass number - Any byproduct material with atomic numbers 1 through 83

b. Chemical and/or physical form - Incidentally Activated Products in a Cyclotron and along the Beam Line, monitoring and test fixtures

c. Maximum amount that may be possessed as a result of clinical use - 25 millicuries per nuclide, 100 millicuries total.

Explanation:

Radioactive material is produced as a result of operation of the Proton Cyclotron. Components of the accelerator and the beam transport line, which see incident protons, may become radioactive. In addition materials that a user irradiates directly with proton beam or indirectly with secondary particles may become radioactive.

The MEVION S250 is an FM Cyclotron design for the external beam radiation of patients at Hospitals.

The MEVION S250 is a nominal 250 MeV cyclotron, which produces a proton beam between 1 and 20 nA depending on patient prescriptions. For calculation of radioactive materials an average beam current of 5 nA may be assumed. The hospital workload model should predict the beam on time per hour of operation. For the purposes of calculating production over time we offer the following usage models.

Patient irradiations total 500 hours per year for a treatment room. The average beam current is 5 nA or 31.25 x 10_9 protons/sec (31 GP/sec) (Gp = Gigaprotons).

The Activity resulting from this operation reported in Item 5c may be calculated as follows:

The PTS-250 beam will be comprised of 250 MeV protons and directed at various beam line components to measure, scatter, degrade, collimate and completely absorb the beam. Within the cyclotron there may be high energy beam losses less than or equal to the extracted beam current. There will be additional shielding materials and the Vault itself, which sees secondary irradiation of energetic and thermal neutrons. The beam will also pass through a meter of air during some tests.

Spallation events will occur when the high-energy protons and neutrons strike nuclei within these materials producing new isotopes and elements, some of which may be radioactive. Thermal neutrons could interact and produce radioactive isotopes through a capture event.

The type and quantity of radionuclides produced depends on:
1- Quantity of protons striking a material
2- Composition of material being struck
3- Production cross section of isotope product
4- Isotope half-life
5- The time the beam is on (T)
6- The time since a given beam irradiation was stopped (t)

I) Activation of cyclotron due to beam internal beam loss – The isotopes we expect to be produced within a 250 MeV cyclotron will be consistent with those produced in high energy accelerator in the past. The products of high energy proton interactions on steel and brass components are principally $_{7}$Be, $_{11}$C, $_{18}$F, $_{22}$Na, $_{24}$Na, $_{46}$Sc, $_{48}$Sc, $_{48}$V, $_{51}$Cr, $_{52}$Mn, $_{54}$Mn, $_{56}$Co, $_{60}$Co, $_{65}$Zn. For products with half lives from 10 minutes to 2 years, the total induced activity from spallation events on medium atomic number elements such as iron and copper is seen to be independent of half-life and is well represented by the equation

$$S = 2.4\ x\ 10^{-4}\ \Phi\ \ln(T + t)t \qquad \mathrm{Bq/g}$$

(Sullivan Equation 4.19)[1]. Where S is the activity per gram of irradiated material produced for a proton flux of Φ in protons/second (p/s), T is beam on, and t is beam off times. A flux equal to the extracted beam may be lost inside the cyclotron on medium atomic number elements, with Φ = 31 Gp/s over the area A of material where beam is lost. The mass irradiated is = ρ·A·l and Φ·A=31 Gp/s $cm^!$, Therefore:

$$S = 7.5\ x\ 10^{-2}\ \mathrm{Ln}\ (T + t)/t * \rho \cdot l\ \ \mathrm{GBq}$$

All the materials have a ρ < 9 g/cc and the depth of irradiated material is less than the proton stopping distance of 8 cm. We also convert to Curie (Ci) from 1 Ci=37GBq.

$$S = 15\ \ln(T + t)/t \qquad mCi$$

During commissioning a long individual irradiation may be 5 minutes and the Vault would be entered 1 minute after the radiation ends.

$LONG\ SINGLE\ IRRADIATON\ S = 25\ mCi$

Executing a 5 minutes irradiation followed by a 10 minute off period 30 times during a work day:

$AFTER\ FIRST\ 15\ MINUTES\ S = 6\ mCi$

$AFTER\ 30\ MINUTES\ S = 6 + 2.5 = 8.5\ mCi$

$AFTER\ FIRST\ 7.5\ HOURS\ 30\ irradiations\ S = 20\ mCi$

A single cyclotron test period could be 60 days of 150 minute irradiation each day:

$AFTER\ FIRST\ DAY\ (16\ hours\ off)\ S = 2\ mCi$

$AFTER\ TWO\ DAYS\ S = 2 + 1 = 3\ mCi$

$AFTER\ 60\ DAYS\ (\ 150\ hours\ of\ irradiations)\ S = 8\ mCi$

Summary I) There will be 25 mCi or less of Activity within the Cyclotron.

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[1]

A.H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Accelerators, Nuclear Technology Publishing, Kent, England, 1992

II) Activation of collimating components after beam exit – Within the scattering system a fraction of the beam is scattered out of the transmitted beam and stopped by Brass or Steel collimators. The system will transmit on average 40% of the beam leaving 3 nA or 20 Gp/s directed onto the collimators. Activation of these components follows the same formalism as the cyclotron medium atomic number material in I. The flux difference reduces the total activity to 17.5 mCi or less.

Summary II) There will be 17 mCi of activity on beam line components which intercept the scattered beam.

III) Activation of lead in scattering foils after beam exit – During scattering system testing the entire beam will pass through components attached to the cyclotron containing lead layers in the beam path. The average lead thickness is 15 mm.

Heavy elements do not exhibit the same activation approximation as the medium elements. An empirical formula for lead can be found in Sullivan equation 4.30, with T and t expressed in “days”:

$$S = 1.8\ x\ 10_{!!}\Phi\ [\ _{!!.!} - T + t\ _{!!.!}]Bq/g$$

Since the beam passes through the lead the larger the area encompassing the primary beam, the more the activation. The beam size is 1 cm diameter. The mass of Lead exposed to primary beam, 6.2 Gp/s, will be $M = \rho * A * t = 13.3\ g$.

$$\therefore S = 20.0\ [\ _{!!.!} - T + t\ _{!!.!}]mCi$$

Lead will exhibit a higher activity at short interval but decay faster than the medium number elements.

$LONG\ SINGLE\ IRRADIATON\ time\ on\ T = 5\ min,\ time\ off\ t = 1\ min \rightarrow S = 187\ mCi$

Executing an irradiation 5 minutes irradiation followed by a 10 minute off period 30 times during a work day:

$AFTER\ FIRST\ 15\ MINUTES\ S = 22\ mCi$

$AFTER\ 30\ MINUTES\ S = 22 + 9 = 29\ mCi$

$AFTER\ FIRST\ 7.5\ HOURS\ 30\ irradiations\ S = 47\ mCi$

Calculations up to 60 days of 150 minute irradiation each day:

$AFTER\ FIRST\ DAY\ 16\ hours\ off\ S = 1.3\ mCi$

$AFTER\ TWO\ DAYS\ S = 1.3 + .4 = 1.7\ mCi$

$AFTER\ 60\ DAYS\ (\ 150\ hours\ of\ irradiations)\ S = 0.56\ mCi$

Summary III) There may be 50 mCi of Activity stored on a daily basis on lead components attached to the cyclotron. For periods under 5 minutes temporary activity on these components may be as high as 187 mCi at 1 minute post irradiation. For periods beyond a day the activated components in lead decay to under 2 mCi.

IV) Activation of carbon used as absorber material after beam exit – Within the scattering system the entire beam will pass through components attached to the cyclotron in which carbon intercepts the beam. Average carbon thickness is 10 cm. The products of proton interactions on carbon are ^{3}H, ^{7}Be, ^{10}C, and ^{11}C. Tritium with a half life of 12.3 years will not reach quantities in the μCi range after 150 hours of irradiation. The ^{10}C isotope has a 20 second half life and will exist in mCi quantities for only short periods. From nuclear cross section calculations:

$$S = \phi * \sigma * \rho * l * N_{!} AtomicWt * T\tau * e_{!!/!}\ for\ \sigma = 10\ mbarns$$

$_{7}$Be will be produced in quantities less than 15 uCi after a day and .5 mCi in 60 days. $_{11}$C with its 20 minute half life will exist at 5 mCi after 8 hours and decay quickly.

Summary IV) 5 mCi of activity will exist on carbon components on a daily basis.

V) Activation of aluminum used in frames and supports near the beam line - Aluminum may become activated by spallation reactions with secondary particles, principally neutrons above 20 MeV. These particles are produced when the primary beam interacts with beam line and beam dosimetry compounds, i.e. lead, carbon, water and plastic. The number of secondary neutrons produced per interaction at incident energy of 250 MeV is close to 1 for all materials. The likelihood that a secondary neutron hits one of the aluminum structures is reasonably less than 50%. Activation products in aluminum are limited to $_{18}$F, $_{24}$Na, and $_{22}$Na with half lives of 1.8h, 15h, and 2.6y respectively. Activation from secondary neutron on aluminum has been shown to be less than 30% that of iron for equal irradiation times. Therefore the quantities in I can be reduced by 70% for the reduced cross section and another 50% for the reduced flux. We note that product $_{22}$Na has a long half life

Summary V) There will be less than 4 mCi of activity on aluminum structures near the beam line. Build up of $_{22}$Na with a 2.6y half life needs to be monitored.

VI) Activation of accelerator and vault by thermal neutron capture secondary to proton beam irradiation – The principal materials near an accelerator with a significant thermal neutron activation cross section are:

a. $_{63}$Cu in natural copper
b. Na in concrete
c. Argon in air
d. Zinc in copper
e. Manganese and cobalt in steel
f. Antimony in lead
g. Trace elements in concrete
h. $_{186}$W in tungsten

Of these isotopes produced by thermal neutron capture the largest activity in our operation will be $_{64}$Cu from $_{63}$Cu in copper with a half life of 13 hours. There is 2000 lbs of copper in our magnet which is 70% $_{63}$Cu. The thermal neutron fluence rate can be estimated from[2]

$$\phi_{!!!"\#\$\%} = 1.25Q/S$$

where Q is the fast neutron yield and S is the internal surface area of the vault

The activity from $_{64}$Cu after an 8 hour shift of 30 five minute irradiations is 10 uCi. There is also small amounts of Manganese (<.4%) in the iron shield around the cyclotron which weighs 20 tons. This has a high cross section for thermal neutrons forming $_{56}$Mn with a 2.6 hour half life. This activity is also in the uCi range.

Summary VI) There will be of $_{63}$Cu and $_{56}$Mn at times in the cyclotron structure in uCi quantities.

[2] NCRP Report 144 Radiation Protection For Particle Accelerator Facilities, 2005

VII) Activation of air and water in the vault by high energy protons – The radioactive isotopes ^{14}O, ^{15}O, ^{13}N, and ^{11}C will be produced when high energy beams pass through air or water. All are short lived and for 1 meter of air a 5 minute 5 nA irradiation will produce activities in the uCi range (Sullivan Table 4.11). The beam at times is delivered to a water tank where these same isotopes are produced up to .2 mCi total activity.

Summary VII) There will be short lived radionuclides below 1 mCi. Water used for dosimetry will decay to 10CFR 20.2003, 105 CMR 120.222, and 105 CMR 120.296 Table II levels for disposal in 4 hours.

Total) The accumulation of radionuclides from the above interactions is <100 mCi with peak quantities at the end of a daily operation.

Section	**Maximum Activity**	**Peak Period**
I	**25 mCi**	**Daily**
II	**17 mCi**	**Daily**
III	**50 mCi**	**Daily**
IV	**5 mCi**	**Daily**
V	**< 1 mCi**	**Daily**
VI	**Negligible**	
VII	**Negligible**	
TOTAL	**98 mCi**	**Daily**

Distribution of finished cyclotrons and their components as part of a Proton Radiation Therapy device may contain residual amounts of activity described in ITEM 5. The recipients of these devices are Hospital and Medical Facilities licensed for the use of radiation producing equipment and possession of radioactive materials in accordance with their local state regulations.

Packaging and transportation of product will be in accordance with the regulations 105 CMR 120.770.