



**PRODUCTION OF NEUTRONS IN
PARTICLE ACCELERATORS:
A PNRI SAFETY CONCERN**

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A B S T R A C T

In the safety assessment made for the first cyclotron facility in the Philippines, that is the cyclotron in the P.E.T. Center of the St. Luke's Medical Center, the concern on the production of neutrons associated with the operation of particle accelerators has been identified. This takes into consideration the principles in the operation of particle accelerators and the associated production of neutrons resulting from their operation, the hazards and risks in their operation.

The Bureau of Health Devices and Technology (BHDT) of the Department of Health in the Philippines regulates and controls the presently existing six (6) Linear Accelerators distributed in different hospitals in the country, being classified as X-ray producing devices. From the results of this study, it is evident that the production of neutrons from the operation of accelerators, produces neutrons and that activation due to neutrons can form radioactive materials. The PNRI being mandated by law to regulate and control any equipment or devices producing or utilizing radioactive materials should take the proper steps to subject all accelerator facilities and devices in the Philippines such as linear accelerators under its regulatory control in the same manner as it did with the first cyclotron in the country.

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A. BACKGROUND

The Philippine Nuclear Research Institute has faced a strong challenge when it started to regulate and control the first medical cyclotron in the Philippines which was also the first in Southeast Asia. The 2001 Report of Licensed and Unlicensed X-Ray Facilities provided by Bureau of Health Devices and Technology (BHDT) of the Department of Health³ showed that there are a total of six (6) existing Linear Accelerators distributed in different hospitals in the country.

Both cyclotron and linear accelerators belong to the so-called Particle Accelerator, a machine, device, or equipment capable of accelerating electrons, protons, deuterons, or other charged particles in a vacuum and discharging the resultant particulate or other radiation into a medium.

In the safety assessment made for the first cyclotron, the concern on the production of neutrons associated with the operation of accelerators has been identified. This study is therefore intended to understand the principles in the operation of particle accelerators and the associated production of neutrons resulting from their operation, the hazards and risks in their operation. It is also intended to determine the appropriate actions for the protection of the health and safety of workers and general public.

B. DESIGN CONSIDERATION

Particle accelerator is a device or apparatus used in nuclear physics to produce beams of energetic charged particles and to direct them against various targets. Such machines, popularly called atom smashers, are commonly used to observe objects as small as the atomic nucleus in the studies of its structure and of the forces that hold it together. Accelerators are also used to provide enough energy to create new particles. Besides pure research, accelerators have practical applications in medicine and industry, most notably in the production of radioisotopes.

There are many types of accelerator designs, although all have certain features in common. Only charged particles (most commonly protons and electrons, and their *antiparticles*; less often deuterons, alpha particles, and heavy ions) can be artificially accelerated. The first stage therefore in the operation of any accelerator is to produce the charged particles, i.e. an ion source from a neutral gas. All accelerators use electric fields, e.g. steady, alternating, or induced, to speed up particles. Magnetic fields are mostly used to contain and focus the beam. In linear accelerators the particle path is a straight line while in other machines, of which the cyclotron is the prototype, a magnetic field is used to bend the particles in a circular or spiral path.

1. The Linear Accelerator

Linear accelerators (Linac), in which there is very little radiation loss, are the most powerful and efficient electron accelerators. These accelerators can be used to produce higher energies, but will require increasing length.

The largest of linear accelerator is the Stanford University linear accelerator (SLAC), completed in 1957. It is 2 miles (3.2 km) long and produces 20 GeV electrons.

In its simplest form, Linac consists of a series of electrodes. Alternate electrodes are connected electrically to each other, and holes are bored through them to permit the

passage of ion beam. The electric field created by the electrodes exerts a force on the charged particles and accelerates them.

Although simple in concept, Linac has a limited performance due to the constraints on the number of accelerating electrodes it can contain. The particles are limited in the ultimate speed and energy that it can achieve. Figure 1 below shows a simple Linac. In this case, the force is proportional to the change in velocity per unit time. This implies that the velocity of the particle is increasing, so if the electrodes were to be spaced evenly, the particle would travel through the successive spaces in shorter and shorter times until finally it would fall out of phase with the RF accelerating voltage. The machine can be designed, however, so that the electrodes increase successively in length and the *distance* a particle traverses between accelerating gaps increases constantly; the *time* of traversal between gaps is identical.

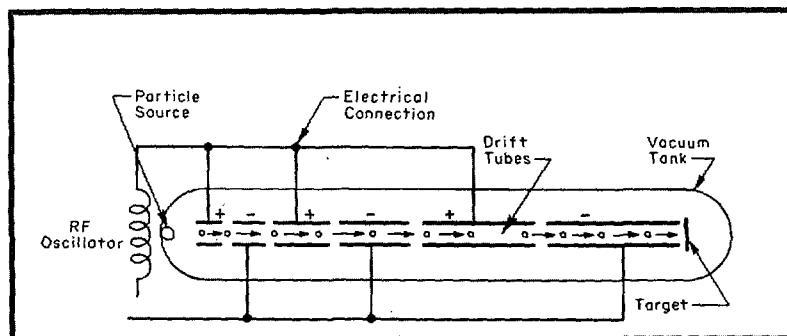


Figure 1. A simple linear accelerator. [Kernan, W. J., *Accelerators*, U.S. Atomic Energy Commission, U.S.A.]. The separation between accelerating gaps, which is the distance traversed by the particles during one half cycle of the applied electric field, becomes greater as the velocity of the particle increases. At any instant, adjacent electrodes carry opposite electric potentials. These are reversed every half cycle.

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velocity of the particle increases. At any instant adjacent electrodes carry opposite electric potentials. These are reversed each half cycle.

The *electron medical accelerators* supported the progress of radiation therapy bringing a dramatic change in the practice of radiotherapy. External beams of high energy electron and X-rays are used routinely for the treatment of deep-seated lesions within the body. To produce X-rays, electrons are accelerated to a proper high energy in medical linear accelerator.

Medical Linacs are available with energies ranging from 4 to 35 MeV. For energies from 4 to 6 MeV the accelerating tube can be made short enough (40 - 80 cm), however, if a high energy beam is required, the tube must be made longer. Most medical Linacs are mounted on a gantry to permit rotation of the unit about the patient (See Figure 2.).

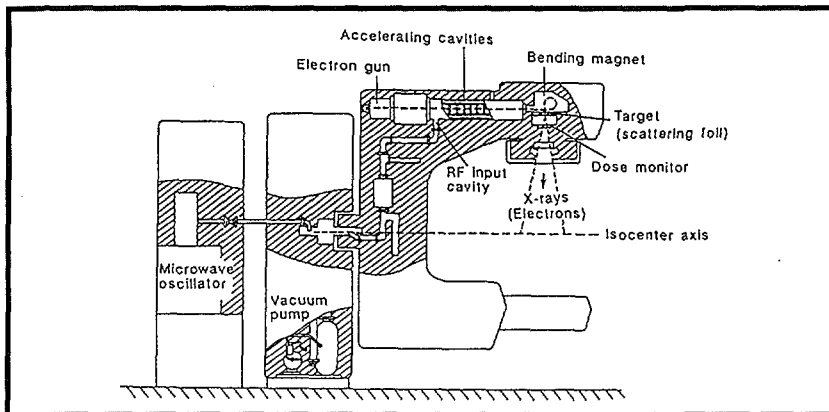


Figure 2. A Medical Linac

2. The Cyclotron

In a *cyclotron*, (also known as *magnetic resonance accelerator*), the particles are made to travel many times around a central point allowing the same particles to traverse the same accelerating electrodes many times over in order to reach the desired very high

speed (energy). Cyclotron accelerates positively charged particles. One particle makes many thousand revolutions until it hits the target. Figure 3 shows the basic principle in the operation of a cyclotron.

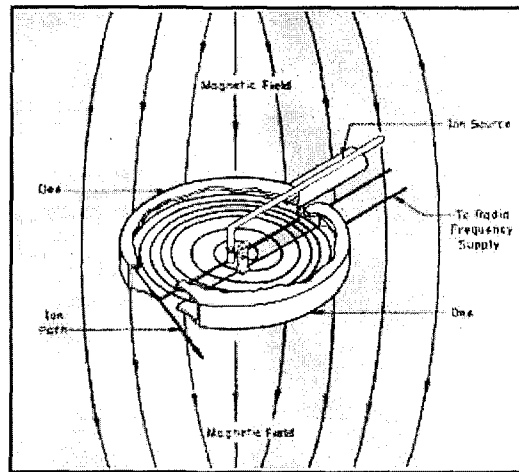


Figure 3. Basic principle in the operation of a cyclotron. Particles injected at the center are bent into circular paths by traveling in a vertical magnetic field. A rapidly alternating horizontal electric field applied between hollow electrodes (dees) accelerates the particles each time they complete a half circle. The particles are extracted and aimed at an external target. The dees are enclosed in a vacuum so that air molecules will not obstruct the motion of the particles.

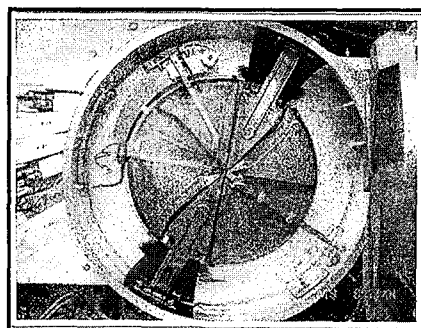


Figure 4. A Medical Cyclotron

Bombardment of the target material by the beam of particles causes a nuclear reaction to take place producing important group of radionuclides that emits positrons which can be used in *Positron Emission Tomography* (PET). Figure 4 shows a medical cyclotron in a PET center.

PET, which uses isotopes produced by a cyclotron, is a three-dimensional medical imaging technology in nuclear medicine. After PET isotope has been administered to a patient, he is then placed within the viewing field of a scanner that images the distribution of the substance in the body. Unlike other medical imaging technologies, PET allows metabolic activities in the tissue and blood flow to be observed.

3. The Synchrocyclotron

The fixed-frequency cyclotron has a limiting factor of inability to compensate for the slowing down of the revolution frequency of protons once they have been accelerated to near the speed of light. In *synchrocyclotron*, the frequency decreases with time to match exactly the slower revolutions of the protons. To attain this, synchrocyclotron is designed to operate in pulsating manner, where protons are accelerated in bursts. Unlike fixed-frequency cyclotron which can continuously accelerate a stream of particles, the synchrocyclotron has to push one group of protons through an entire cycle, from the initial highest frequency to the final lowest one before it can start to accelerate a new group.

4. Synchrotrons

Synchrotrons are used either with positively charged particles or electrons. In these machines, the magnetic field rises in step with the momentum of the particles being accelerated, keeping the particles moving in a circle of virtually constant radius rather than in the widening spirals of cyclotron and synchrocyclotron.

The *proton synchrotrons* operates on cycles of around 0.5 to 10 seconds duration, after which high-energy beam leaves the machine and the system is returned to conditions appropriate for the injection of the next pulse. The cycle is continuously repeated. *Proton synchrotrons* and *electron synchrotrons* operate under almost the same principle. After pre-acceleration, electrons are injected into a vacuum tank inside a ring magnet. The magnetic field then rises as the electrons are accelerated by successive traversals of a high voltage gap.

4. Betatron

Betatron is a machine developed for accelerating electrons. The electrons are injected into a ring-shaped vacuum chamber placed between the pole pieces of a powerful electromagnet in which the magnetizing current is varied. As the magnetic field rises, the changing magnetic flux exerts a force on the circulating electrons, tangential to their motion, and therefore accelerating them in their direction of motion. The magnetic flux and the magnetic field are varied at the desired orbit so that electrons are kept in equilibrium orbit corresponding to the radius of the vacuum chamber. The magnetic field provides focusing effects to keep the beam from striking the walls of the chamber. At the end of the acceleration period, the beam is ejected usually onto a target to make a secondary beam of bremsstrahlung photons. The flux is lowered and the magnet is made ready for the next acceleration cycle. Unlike the cyclotron, the betatron magnet is designed to use alternating current.

C. Neutron Production in Accelerators

1. In Constant-Voltage Accelerators

Some types of tandem Van de Graaff accelerators produce particle energies of about 20 MeV from protons and deuterons and still higher energies from alpha particles and heavy ions. A large number of 14-MeV neutrons were reported to have been produced from small accelerators of this type using deuterons of one or two hundred keV energy.

As beam energy increases, more and more nuclear reactions become possible. An accelerator capable of imparting all energies up to 10 MeV to both protons and deuterons can produce monoenergetic neutrons at all energies up to 27 MeV. For this reason, constant-voltage accelerators are useful in the calibration of neutron radiation instruments.

2. In Positive Ion Accelerators

Positive ion accelerators include the cyclotron, the synchrocyclotron, the proton synchrotron, and heavy ion linear accelerator. As the beam energy increases, neutron production generally increases, and the neutron spectrum spreads over a wide range of energies.

In cyclotron, neutron production takes place only during beam operation. Protons above 10 MeV produces neutrons when striking almost any material. Many neutrons often come from the accelerator itself as well as from the intended target. During cyclotron beam operation gamma is produced aside from neutron radiation. Capture gamma radiation is generated when the neutrons are captured in nuclei and is dependent on the type of nuclei, e.g. boron (approx. 0.3 MeV), hydrogen (2 MeV), iron (approx. 7 MeV). The $p-n$ reaction in the target generates heavy neutron flux around the target during irradiation.

The large number of neutrons associated with these machines entails problems of induced radioactivity in the materials of the accelerator, in dust and in the air of the accelerator and experiment rooms. Neutrons that may penetrate the plastic shield around the targets may produce some radioactivity in the air. A cocktail of radioisotopes are formed in the cyclotron because of neutron activation. Table 1 shows the list of the different isotopes and the nuclear reactions involved. All of these are having different cross-sections and half-lives.

Table 1. Positron Emitters Produced in Cyclotron

Radionuclide	Nuclear Reaction	Description
Oxygen-15 <i>T_{1/2} = 2.05 min.</i>	$^{14}\text{N}(\text{d},\text{n})^{15}\text{O}$	Oxygen-15 is produced by deuteron bombardment of natural nitrogen. Oxygen-15 can be produced as molecular oxygen ($^{15}\text{O}_2$), or directly as carbon dioxide (C^{15}O_2) by mixing the target gas with 5% of natural carbon dioxide as a carrier. Carbon monoxide (C^{15}O) can also be easily produced by reduction of C^{15}O_2 on activated charcoal at 900°C.
Nitrogen-13 <i>T_{1/2} = 10.0 min.</i>	$^{16}\text{O}(\text{p},\alpha)^{13}\text{N}$	Produced by proton bombardment of distilled water and recovered mainly as $^{13}\text{NO}_x$ in aqueous solution. A Devarda alloy is necessary to reduce nitrite and nitrate to $^{13}\text{NH}_3$.
Carbon-11 <i>T_{1/2} = 20.4 min.</i>	$^{14}\text{N}(\text{p},\alpha)^{11}\text{C}$	Produced by proton bombardment of natural nitrogen. A target gas mixture of 2% oxygen in nitrogen will produce $^{11}\text{CO}_2$ and 5% hydrogen and in nitrogen will produce $^{11}\text{CH}_4$. ^{11}CO can be made by reduction of $^{11}\text{CO}_2$ in activated charcoal at 900°C.
Fluorine-18 <i>T_{1/2} = 109.6 min.</i>	$^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$	Produced by proton bombardment of oxygen-18 enriched water. Recovered as a aqueous solution of $\text{H}_2\text{O}/^{18}\text{F}$ -and extracted by ion-exchange chromatography. Ionic ^{18}F can be transferred into an organic solvent and used for stereospecific nucleophilic substitutions.

3. Electron Accelerators

Electron accelerators include circular accelerators such as the betatron and synchrotron and also linear accelerators. The primary radiation hazard is X-rays produced by accelerated electrons striking the target or other material. However, these accelerators can produce large numbers of neutrons from a target due to the (γ,n) reaction occurring in the target. Neutrons are produced in electron accelerators when the electron energy exceeds the threshold for photoneutron production (1.7 MeV for Be, 2.2 MeV for deuterium, and 6-10 MeV for most other nuclei). Figure 5 shows the plot of neutron yield obtained from semi-infinite targets of various materials per unit of incident electron-beam power vs. incident electron energy in MeV.

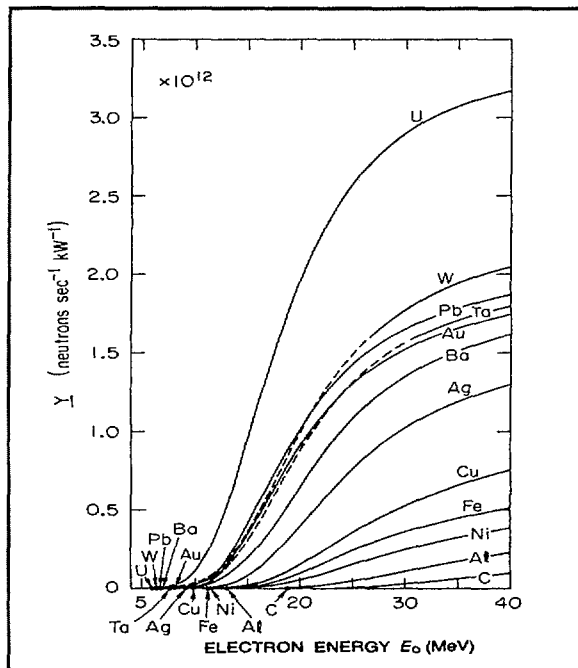


Figure 5. Neutron yields obtained from semi-infinite targets of various materials per unit of incident electron-beam power vs. incident electron energy in MeV. (NCRP No. 79, *Neutron Contamination from Medical Electron Accelerators*, November 1, 1984.)

When a photon produces a neutron through a (γ , n) reaction, the product nucleus may be radioactive and the neutron may be absorbed forming a second radioactive nucleus.

D. SAFETY CONSIDERATION

1. Transport of Neutrons In Accelerator Head

A typical medical accelerator has massive photon shielding around the target which,

when the accelerator is energized, serves to produce a collimated beam of X-rays. Neutrons produced inside the head are approximately isotropic and penetrate the shielding in all directions. The photon shielding material is usually some heavy metal such as tungsten or lead; the head also contains a certain amount of iron and copper in bending magnets. These materials provide good photon shielding since they are all heavy elements.

The shielding and geometry of the head of medical accelerators may be very complicated. Since the head contains many moving and fixed devices, the shielding is never a solid sphere or cube or any other simple geometric configuration. Since the shielding is designed primarily for photons, which are emitted predominantly in the forward direction, the shielding tends to be much thicker and heavier in this direction than in the other directions. Since neutrons are emitted nearly isotropically, this distribution of shielding material may not be a perfect one for protection from neutrons.

2. Transport of Neutrons In Concrete Rooms

Most radiotherapy accelerators are installed in concrete rooms to shield the outside surroundings against radiation. There are various components of radiation from accelerator which have to be absorbed, such as leakage photons, direct-beam photons, scattered photons, and neutrons. The source term for calculating the room shielding is the sum of these four components.

3. Hazards from Neutrons

3.a. Risk to Patients. Neutron production in accelerators used for therapy can result in doses to patients and to operating personnel from direct exposure both to neutrons and to the resulting residual radioactivity.

Specified tissues are to be irradiated to a specified absorbed dose according to a specified time-dose pattern in radiation therapy. Because of the limitations in treatment

techniques, it is impossible to administer the prescribed absorbed dose exclusively to certain tissues. The volume of the patient included within the primary beam which encloses the tissues to be treated is called the treatment volume.

Any absorbed dose the patient receives outside the treatment volume must be considered undesirable. There are several sources of absorbed dose outside the treatment volume in addition to primary beam absorption in overlying and underlying tissues.

- (i) Photons leaking through the head shielding. It varies, but if proper safety procedures are applied, it is usually less than 0.1% useful dose.
- (ii) Photons scattered out of the treatment volume. Integral dose is 5-30 times larger than that produced by 0.1% head leakage.
- (iii) Neutrons originating in the treatment head and leaking through the head shielding. Maximum integral dose equivalent could be about half of that from scattered photons for any therapeutic treatment condition.
- (iv) Neutrons produced in the treatment volume by (γ , n) reactions and then penetrating outside the treatment volume. This has been found to be negligible.
- (v) Radiation due to radioactive isotopes produced in the body. These various components are not completely independent of each other and it is the total risk to the patient which should be considered. This has been found to be negligible.

3.b. Risk to Operating Personnel. The risk to operating personnel may be obtained from the following sources:

- (i) Door Leakage

Most rooms may be adequately shielded against neutron leakage, except at the door. Rooms with inadequately designed mazes and doors, may have a radiation

problem just outside the door. This area may also be occupied by technicians and nurses waiting for the treatment to be completed. The accelerator control console may also be close to the door.

(ii) Activation

When a photon produces a neutron through a (γ, n) reaction, the product nucleus may be radioactive and the neutron may be absorbed forming a second radioactive nucleus. If the resulting radiation levels are significant, they could contribute to the radiation dose of the operating personnel.

The induced radioactivity can develop in the following identified sources:

- Accelerator components and treatment aids.

Parts of the accelerator which are most apt to become radioactive are the target, collimators (if any), field flattener and inside surfaces of the head shielding. These components are well-shielded and would only be a problem when the machine is disassembled for repairs.

- Patient.

While activation of the patient has been observed after radiotherapy there has been no reported dose rates emanating from the activated patient. In all cases, ^{15}O ($T_{1/2} = 2.04$ min) and ^{11}C ($T_{1/2} = 20.3$ min) were the only significant isotopes observed.

- Room walls, ceiling and floor.

The amount of induced radioactivity may vary depending on the source and nature of the cement, sand and aggregate used. Various reactions

are possible which can result in radioactive nuclei, e.g., (γ , n), (n, 2n), thermal (n, γ), (n, p), etc. The magnitude of the activation will be a function of the room size, the neutron yield of the accelerator, the distribution of on-off time, and, perhaps the chemical composition of the concrete.

(iii) Exposures during Installation.

The process of installing a medical accelerator may also cause problems with respect to neutron leakage. Some of conditions may result in higher neutron doses outside the accelerator room such as: machine covers and shielding which are likely to be removed, the alignments which may not be optimized, and higher neutron leakage than specified may occur. In addition, workloads and occupancy factors may come out different from those established for routine clinical work.

E. RELEVANT LAWS and REGULATIONS

The laws which served as the legal framework in the licensing of accelerator facilities are the following:

1. RA 5207 entitled AN ACT PROVIDING THE LICENSING AND REGULATION OF ATOMIC ENERGY FACILITIES AND MATERIALS ESTABLISHING THE RULES ON LIABILITY FOR NUCLEAR DAMAGE AND FOR OTHER PURPOSES, and
2. Presidential Decree (P.D.) No. 480 which is about CREATING A RADIATION HEALTH OFFICE IN THE DEPARTMENT OF HEALTH.

The purpose for the creation and the functions of the Radiation Health Office (RHO) is clearly defined in Section 1 of the P.D, identifying the limitations of RHO and the responsibilities that should fall under the jurisdiction of the Philippine

Atomic Energy Commission (PAEC), which is now PNRI.

Section 1 provides that the equipment and devices involving the application and use of radioactive materials and any equipment or devices producing or utilizing radioactive materials shall fall under regulatory jurisdiction of the Philippine Atomic Energy Commission as provided under R.A. 5207.

The CODE OF PNRI REGULATIONS (CPR), particularly PART 21, Licensing and Safety Requirements for Radioisotope Producing Particle Accelerators shall govern in ensuring the safe operation of the accelerator facility and in the safety of the workers and the environment.

F. RECOMMENDATIONS

It is evident that the production of neutrons from the operation of accelerators, produces neutrons and that activation due to neutrons can form radioactive materials.

It was also clearly stated in Section 1 of P.D. 480 that any equipment or devices producing or utilizing radioactive materials shall fall under regulatory jurisdiction of the PAEC, now the PNRI.

The PNRI is mandated under R.A. 5207 to regulate and control atomic energy facilities and equipment for the protection of the health and safety of workers and general public and to prevent the use of such facilities and equipment for unauthorized purposes.

In view of the above, the PNRI should take the proper steps to subject all accelerator facilities and devices in the Philippines such as linear accelerators under its regulatory control in the same manner as it did with the first cyclotron in the country.

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