INTRODUCTION

Particle accelerators are not often thought of as potential polluters of the environment. In fact, by comparison with nuclear reactors, they are rather insignificant in their ability to produce radioactivity. However small and insignificant, in this age of growing public concern about radiation safety, it is essential to carefully consider these effects at the design stage particularly when the accelerator need be sited in densely populated areas such as hospitals and universities, or in close proximity to residential areas. It is also necessary to document the radiation field around accelerators by carrying out regular measurements or theoretical estimates in order to properly evaluate the radiological risk associated with a particle accelerator installation.[1-4]

Risk is defined as the probability of occurrence of an undesired event multiplied by the consequences of the event. In the case of radiological risk evaluation, the consequences are exposure to radiation and the undesired events are the hazards, which can lead to unwanted personnel exposure to radiation.[5-11] In recent years, there is a widespread use of particle accelerators of different types and designs for industrial, medical and research purposes. Recently, developed high power accelerators particularly those used for accelerator driven systems (ADS) and the radioactive ion beam (RIB) facilities no longer remain benign research tools for the physicists.[12-15] Since these accelerators are sources of harmful ionizing and non-ionizing radiations, safe operational procedures have to be adopted for them. Depending on the type of various beam material interactions and design of the accelerator the hazard potential differs.[1] A basic understanding of the accelerator operation is essential for a proper implementation of any radiological safety program. The parameters of major importance are the types of particles accelerated, their energy and intensity and the time structure of the accelerated particle beams. We shall proceed to discuss and present a general analysis of radiological risk common to almost all accelerators in operation or being designed. We do this by first identifying the probable hazards and then identifying and analyzing the initiating events leading to such hazards. The ultimate aim is to estimate the frequency of occurrence and radiological consequence of different hazards, which is approached in a qualitative way. Constructing fault trees giving the logical combinations leading to an undesired event can yield quantitative results.[16] However, it’s important to have an understanding of the different hazards in an accelerator, which finally contributes to the radiological risk.

There is a great diversity among accelerator installations and there cannot be a single comprehensive safety
program suitable for all. However, experience suggests some general principles that should be considered and a good accelerator safety program is to be integrated with all disciplines involved in a comprehensive safety program. The integration of safety disciplines is necessary at accelerator laboratories because some desirable aspects of accelerator safety may conflict with other safety needs. Many safety systems are used in the accelerator to enhance both personal and accelerator system safety. From radiological point of view there are both prompt radiation and residual radiation in an accelerator. Air activity increases due to prompt radiation when the accelerator operates for some time. Even after the accelerator is switched off residual radiation exists. Maintenance personnel enter active areas after residual radiation is checked. Ventilation systems ensure that the level of air activity is controlled and maintained within limits. The number of air changes is decided based on the requirement. Safety interlocks are used to ensure that people do not enter in accessible areas when the accelerator is running. Interlocks are also used to protect the accelerator systems from starting only after the required checklists are through. If some beam parameters or safety indicator parameters cross their limits then also safety interlocks take care.

As for the emerging techniques of safety aspects of particle accelerators, one has to focus attention on high energy, high current accelerators now being built for ADS, spallation neutron sources and RIB facilities. In these cases conventional radiation protection techniques are found to be inadequate and new developments are necessary. Absence of charge particle equilibrium poses a serious problem to the so far used techniques of dose measurements. Pulsed radiation field, large dynamic energy range of radiation, interference from the radio-frequency (RF) etc., add to the uncertainty (sometimes large enough to make the results meaningless) of measurements. Formations of hadronic and electromagnetic cascades lead to unconventional safety assessment problems that have to be seriously dealt with.

With the advent of technologically advanced and complex facilities such as accelerator driven subcritical or transmuting systems and RIB facilities, the practitioners of radiation protection face new and unconventional challenges requiring satisfactory solutions. A high energy particle accelerator producing a large number of neutrons by spallation reactions when coupled with a subcritical nuclear reactor to maintain the fissioning process without achieving criticality is known as the accelerator driven subcritical system which can also be used to transmute long lived nuclear waste containing transuranic elements. RIB facilities aim at accelerating ions of unstable (radioactive) elements for studies of exotic nuclei, which will open new frontiers in nuclear physics, nuclear astrophysics, material science and biology.

Both the facilities are based on high energy, high intensity particle accelerators producing large fluence of high energy neutrons, gammas and muons. They initiate hadronic and electromagnetic cascades generating neutron-proton and electron-gamma showers making the radiation environment highly complex spatially and directionally around these facilities. Technological and theoretical developments necessary for a more precise radiation protection practices to cope with such directional, dynamic, pulsed and a mixture of different types of radiation fields are nontrivial in nature and are different from conventional radiological safety requirements. The major radiation safety considerations for these facilities can be broadly classified in two parts:

1. To protect the public from radiation hazards (for which we have to take into consideration skyshine, release of toxic gases in the environment, soil and groundwater activation)
2. To maintain hazards within limits for radiation workers (for this we have to consider bulk shielding, streaming of radiation through ducts and penetrations, induced activity in target, air, cooling water, walls and accelerator structures).

Theoretical results obtained so far indicate that the very high activation of the structural materials in some components will require a detailed study and comparison of the behavior of different materials, namely their remaining activity several years after beam shutdown. The very high dose rates assessed in the computational studies performed also impose stringent requirements in the radiological protection and radiation safety issues associated with the operation and maintenance of these facilities.

Presently, several new RIB facilities are planned, which typically will have three orders of magnitude larger radioactive inventory than already existing facilities. These radioactivities mostly are produced by ion beam irradiation with many kW of power. In the direct production method, protons of about 1 GeV hit different thick targets and produce a broad range of neutron- and proton-rich nuclei by fragmentation or spallation. In the indirect approach, secondary particles like fast neutrons, thermal neutrons or bremsstrahlung photons are generated and then an intense source of neutron-rich fission fragments is obtained by fissioning of uranium or thorium targets. The radioactive ion production target is hot and shows out gassing, but at the same time ionized species are extracted. To safely confine and control the radioactive inventory of this open source special efforts are required.
Considering the complex radiological safety issues in particle accelerators of the modern age, it appears essential to carry out probabilistic safety analysis (PSA) of radiological and other hazards based on hazards and operability analysis and failure mode effect and criticality analysis.[3] Fault Tree and Event tree methods can be used to depict system failure logic, identify different initiating events and analyze the safety systems required under such circumstances.

To carry out radiological safety assessment in particle accelerators with both deterministic as well as probabilistic approach, it is essential to have knowledge of energy and angular distribution of radiations (neutrons, gammas, etc..) emitted during interaction of projectiles (accelerated particles) with various surrounding materials (targets). Such double differential (energy-angle) distributions of emitted radiation are generally known as the “source term.” In the next section we discuss the estimation of this source term in particle accelerators followed by discussions on shielding, interlocks and the probabilistic safety analysis (PSA) including human reliability analysis (HRA).[21]

**ESTIMATION OF THE RADIATION SOURCE TERM**

Accelerated charged particles, except for the singular phenomenon of synchrotron radiation (SR), do not produce radiation unless there is some interaction with matter. The charged particles directly accelerated and otherwise manipulated by the electromagnetic fields within the accelerator, are referred to as the primary particles or beam. If one considers primary particles incident upon a physical object such as a target, the yield of secondary particles is a crucial parameter. Such particle yields, dependent upon both target material and thickness, are reported in terms of particle type, energy and angular distributions. The rate of production of the desired reaction products and their energy spectra is, in general, a strong function of both the emission angle and the incident particle energy.

In an accelerator facility the following situations can contribute as a source of ionizing radiation depending on various beam material interactions:

1. During the acceleration process, a small fraction of the partially stripped ions will lose electrons due to interaction with the rest gas. These ions leave the acceleration path and hit the accelerator structure, thus inducing radiation. During the extraction of the beam in cyclic accelerators, some beam is lost, which when hits the accelerator structure

2. With the help of collimators and scrapers, the extracted beams are sometimes shaped into special geometries. These are strong sources of radiation, which need to be shielded locally by thick iron and concrete walls

3. The target to be experimentally irradiated is an important source of radiation

4. Finally, the beam, which has not undergone any interaction, is dumped into the “beam dump” where all the energy is lost in nuclear reactions and electromagnetic stopping

5. In addition, worst-case scenarios of, e.g., lost beams due to the malfunction of beam optics elements, cause high radiation fields in unwanted locations.

**In electron accelerators**

For photons with energies above the typical binding energy of nucleons (>5-15 MeV), photonuclear interaction generally leads to emission of photoneutrons as well as photo-protons. Photonuclear interaction is mainly the result of three specific processes: Giant nuclear dipole resonance, quasi-deuteron production and decay and intranuclear cascade generated through photopion production. At electron accelerators of all energies, bremsstrahlung photons dominate the secondary radiation field. For primary electron energies above 100 MeV, a description of the radiation field is best approached through a discussion of the electromagnetic cascade. In this process, electrons and photons repeatedly interact, each time losing energy, to replenish their numbers until the degraded electrons are brought to rest by ionization and finally, the photons are attenuated at a rate close to the minimum attenuation coefficient for the material.

Energy distributions of electrons and photons provide the essential information necessary to a complete understanding of dosimetry of high energy electron beams.[3] This is so because the electromagnetic cascade contains electrons and photons of essentially all energies from zero up to the maximum energy possible; however it is the particles of lower energy that dominate the deposition of absorbed dose in matter. The electromagnetic cascade is copiously populated with low-linear energy transfer particles and the quality factor for related absorbed doses is accepted as \( Q = 1.\)[21]

**Photoneutron production**

Giant nuclear dipole resonance results if the energy of the incident photons is close to the binding energy of the nucleons (>5-15 MeV). In this case, photo absorption leads to relative displacement of tightly bound neutrons and protons inside the nucleus, resulting in a giant resonance condition. Absorption of the incident photons excites the nucleus to a higher discrete energy state and the extra energy is emitted in the form of neutrons. Giant resonance neutrons are of low energy (1-3 MeV), with a maximum cross section for their production of
1-2 mb/nucleon. The angular distribution of photo neutrons is assumed isotropic for photon energies below 50 MeV. At incident photon energies greater than 30 MeV, the cross section for giant resonance neutron production decreases rapidly. Above 50 MeV, the predominant nuclear photo absorption mechanism is through quasi-deuteron production and decay. In this process, the incident photon interacts with the dipole moment of a proton neutron pair inside the nucleus. Neutron-proton pairs inside the nucleus are considered nuclear deuterons. Quasi-deuteron production gets its name because the proton-neutron pair or deutron does not leave the nucleus. An incident photon couples directly to the electric dipole moment of the quasi-deuteron in the nucleus causing photodisintegration ($\gamma$, np) of the deutron. A neutron and proton are ejected from the nucleus. The energy range for quasi-deuteron decay neutrons is between 50 and 150 MeV, with moderately high-energy neutrons and protons emitted from the photodisintegration of the quasi-deuteron. The neutron distribution is only moderately peaked in the forward direction. Photo production of pions (photopions) becomes dominant for incident photon energies above 140 MeV, where the primary interaction is expected to be between the photon and a single nucleon and the interaction results in the production of one or more $\pi$-mesons or pions. In heavy nuclei, approximately 80% of the photo produced pions are reabsorbed by the nucleus leading to the development of an intranuclear cascade. High-energy neutrons, as well as protons and pions, are emitted in the intranuclear cascade process.[1]

Muon production

With electron beams, muons become of significance above electron energy of approximately 211 MeV, the threshold of the process in which a muon pair is produced in a pair production process. They can be produced, with much smaller yields, by the decay of pions and kaons, which are, in turn, due to secondary production processes. Such decay muons are more prominent at positive ion accelerators.

In positive ion accelerators

The radiation environment around positive ion (protons, alphas, heavy ions etc.,) accelerators are dominated by neutrons. In fact, nowadays, such particle accelerators are the primary source of neutrons commonly encountered in scientific laboratories. The production and behavior of neutrons at proton and ion accelerators have different characteristics as the energy of the beam particles is increased.[1]

Neutron production

Three nuclear processes are important in determining the yield of particles following positive ion-nucleus interactions: Nuclear evaporation, pre-equilibrium emissions and direct reactions. At low proton energies, the interaction of a proton with a nucleus is best explained by a compound nucleus model, into which the incident particle is absorbed into the target nucleus to create a new compound nucleus. This compound nucleus is in an excited state with a number of allowed decay channels with the entrance channel preferred. As the energy of the incident particle increases, the number of levels available to the incident channel becomes very large. Under these circumstances, the emission of particles is best described by an evaporation process analogous to the evaporation of a molecule from the surface of a liquid. The energy distribution of emitted neutrons can be described by a Maxwellian type equation.

At higher incident energies (above 50 MeV) the development of an intranuclear cascade (including both pre-equilibrium and direct processes) in which an incident proton interacts with individual nucleons, rather than with the nucleus as a whole, becomes important. The angular distribution of the neutrons from this process is forward-peaked rather than isotropic and the neutrons generated are higher in energy. When an energetic particle hits a target nucleus, it initiates a sequence of reactions: Direct, intranuclear cascade, pre-equilibrium, equilibrium, fission and de-excitation through $\gamma$ emissions. All these processes together are known as spallation reaction. In this reaction process, the energetic incident particle splits the target nucleus into multiple fragments with emission of a large number of neutrons.

Muon production

Muons at proton accelerators arise from two principal mechanisms; from pion and kaon decay and from so-called “direct” production. Muon fields are forward-peaked and normally, dominated by those from pion decay (except, perhaps at the highest energies). At the higher energies, there are significant complications in that muon creation mechanisms, in addition to the production of pions and kaons and their subsequent decays, are possible. However, the muons from pion and kaon decay generally, but not universally, represent the most important consideration in practical shielding calculations. The fluence-to-dose conversion coefficient for muons has been determined to be 40 fSv.m$^{-2}$ over the muon energy range from 100 MeV to 100 GeV.

Shielding of particle accelerators

A shield has been defined as a physical entity interposed between a source of ionizing radiation and an object to be protected such that the radiation level at the position of that object will be reduced. The object to be protected
is most often a human being, but can be anything that is sensitive to ionizing radiation (e.g., instruments, electronics etc.) The shielding around particle accelerators is designed to protect personnel from intense fluxes of secondary particles (mostly neutrons) and gamma radiation. Modern accelerators are capable of producing extremely high intensity mixed radiation fields. The goal of efficient accelerator shield design is to attenuate these high radiation intensities to acceptable levels outside the shield and to do so at a reasonable cost and insofar as is practical, without compromising the utility of the accelerator for its designed purpose.

At high energy particle accelerators the design of adequate shielding and techniques of safety assessment becomes complex with increasing beam energy due to the cascade phenomena. A high energy hadron (neutron or proton) interacting with a nucleus generally creates a rather large number of short-lived particles (pions, kaons, etc.), as well as protons, neutrons and nuclear fragments. Another important result of high energy interactions is the production of muons, which for very high energy; high current accelerators might represent a significant shielding problem. The interactions of the high energy beams can also produce significant radioactivation of the beamline components and the surrounding environment.

There are three principal reasons why accelerator and beamline components need to be shielded for radiation protection purposes:
1. To reduce the dose received by personnel during beam-on conditions
2. To reduce exposure to personnel from highly radioactive targets and beam absorbers, etc., and
3. To prevent contamination of the environment by creation of radioactivity in locations outside of areas controlled for personnel protection.

The major issues for the shielding design are bulk shielding, streaming through ducts and openings, skyshine dose away from the accelerator installation and radio activation of accelerator components soil and ground water. Because of the uncertainties in the primary beam loss conditions except in beam dumps and targets, a serious problem in shield design arise and thus only semi-empirical formulas and simplified methods can practically be applied for most of the design study.[12]

Transmission of photons and neutrons through penetrations
All accelerators evidence the need to control the transmission of neutrons by penetrations since all have access ways to permit entry of personnel and equipment as well as penetrations for cables and for RF waveguides. Personnel access penetrations will typically have cross-sectional dimensions of about 1 m × 2 m (door-sized) while utility ducts will generally be much smaller, typically no larger than 0.2 m × 0.2 m. Often the utility penetrations are partially filled with cables and other items and even cooling water in pipes.

Two general rules are required to be followed for all penetrations openings of accelerator shielding:
1. A penetration should not be arranged so that a particle or photon beam is aimed directly toward it. This is needed to assure that the penetrations are transmitting primarily neutrons that result from large angle scattering rather than those arising from the forward peaked neutron radiation fields or from the direct beam
2. For any labyrinth, the sum of the wall thickness between the source and the “outside” should be equivalent to that which would be required if the labyrinth were not present.

Skyshine
Thin roof shielding represents a serious problem that has plagued a number of accelerators. The phenomenon, known as skyshine, is the situation in which the roof of some portion of the accelerator or an associated experimental facility is shielded more thinly than are the sides of the same enclosure that directly view the radiation source. The radiations transmitted through the inadequate roof shielding get scattered by air molecules and come back to the ground level at a distance from the facility. Neutron skyshine, while it is usually “preventable” through the application of sufficient roof shielding, has been encountered at nearly all earlier major accelerators. This has resulted either from lack of consideration at the design stage or from the need to accommodate other constraints such as the need to minimize the weight of shielding borne by the roofs of large experimental halls.

Shielding materials
Because of the size of many modern accelerators, economic considerations typically dominate shielding designs by requiring the use of relatively inexpensive, but less efficient shields. Aside from the need to accomplish the identified goals in radiation safety, in all situations good engineering practices concerning structural properties, appropriate floor loading allowances and fire protection must be taken into account to provide an acceptable level of occupational safety.[13] In general, low atomic number materials are best used for targets, collimators and beam stops at electron accelerators to reduce photon and photo-neutron production, while high atomic number materials are preferred at proton and heavy ion accelerators for these components to reduce neutron production. At energies above 5 MeV
neutrons are produced in most materials. Some materials have superior heat transfer characteristics that enhance reliability and thus can reduce personnel exposures incurred in maintenance activities. We discuss below the advantages and disadvantages of some commonly used shielding materials.

Earth

Earth has many admirable qualities as a shield material besides its low cost. Especially important is that the water it contains enhances the effectiveness of the neutron attenuation. In addition earth is also composed of sufficiently high atomic number elements to be effective against photons. Earth is generally a “crackless” shield, not prone to neutron leakage by “streaming.” The density of earth varies widely, from as low as 1.7 g/cm³ to as much as 2.25 g/cm³, depending upon soil type and water content and its compactness. In general, sandy soils will have lower values of density than heavy clays found in glacial till. Extrusive volcanic soils, on the other hand, can have very low densities. Given this variation, specific knowledge of soil characteristics at the accelerator site is needed for effective shielding designs. Definitive measurements of the water content are also most useful if the shielding of neutrons is the intent and no safety factors are being used.

Concrete

Concrete has obvious advantages in that it can either be poured in place permanently or be cast into modular blocks. Sometimes concrete is used to shield targets, beam stops, etc., in a manner that allows their ready access if the need for maintenance arises. The use of concrete blocks generally requires the overlapping of the blocks to avoid streaming through the cracks. It is sometimes efficient to use a heavy material as part of the aggregate in the concrete recipe. This can increase the density of the material as well as its average atomic number increasing the effectiveness against photons. When shielding neutrons, the water content is quite important because it incorporates almost all of the hydrogen. Under extreme low humidity conditions, the water content of concrete can decrease with time, to as little as 50% of the initial value over a 20 year period. The density of concrete is locally variable. While selecting course and fine aggregates in the constituents of the concrete care should be taken for the presence of elements that can lead to long-lived activation products in the case of neutron shielding. This may lead to the problem of safe disposal of large quantities of radioactive concrete after decommissioning of the accelerator facility. The recent development of self-compacting or self-consolidating concrete (SCC). SCC is a new class of high performance concrete that can fill into restricted sections as well as congested reinforcement structures, without the need of mechanical consolidation and without undergoing any significant separation of material constituents is likely to solve massive bulk shielding construction problems in accelerators or other nuclear installations.

Other hydrogenous materials

Polyethylene, (CH²)ᵢ, is a very effective neutron shield because of its hydrogen content (14% by weight) and its density (about 0.92 g/cm³). In many circumstances, it provides very adequate shielding and is highly efficient due to the high hydrogen content. Thermal neutrons can be captured through the ¹H(n, gamma)²H reaction, which has a cross section of 0.33 barn for thermal neutrons. The emitted gamma-ray has energy of 2.2 MeV that is a somewhat troublesome source of radiation exposure in some situations. The addition of boron can reduce the buildup of 2.2 MeV photons released in thermal neutron capture by hydrogen by instead capturing the thermal neutrons in the boron, by means of the ¹⁰B(n, alpha)⁷Li reaction that has a cross section of 3837 barns for thermal neutrons. In 94% of these captures, the emitted alpha particle is accompanied by a 0.48 MeV gamma-ray. The alpha particle is readily absorbed by ionization while the gamma-ray has a much shorter attenuation length than a 2.2 MeV gamma-ray. Commercially, polyethylene is available that includes additives of boron (up to 32%), lithium (up to 10%) and lead (up to 80%) in various forms. These materials can be useful, if it is necessary, to economize on space and also to accomplish shielding of photons and neutrons simultaneously. Pure polyethylene is flammable, but some of the commercial products available contain self-extinguishing additives. Some of these materials are available in powder form, for molding into a desired shape by the user. Besides polyethylene, boron has been added to other materials to form effective thermal neutron shields. These include other plastics, putties, clays, and glasses to accomplish specific shielding objectives. Plastic materials such as polyethylene can also be subject to significant radiation damage at relative low levels of integrated absorbed dose. The effects upon the structural integrity must be carefully considered in such circumstances.

SAFETY INTERLOCKS

The safety interlock system (SIS) is designed to protect personnel from exposure to radiation present when the accelerator facilities are operating.[18] SIS is a system that ensures certain conditions have been met, in a proper sequence, before the accelerator can be operated, the beam can be injected to the storage ring or a beam line can be used. In addition, any action that could potentially cause accidentally exposure will violate the SIS system and cause a fault. The result of a SIS fault, in an electron storage ring facility, will terminate the booster operation,
cease the injection process and eliminate the entire stored electron beam in the storage ring.

The merit of an appropriate beam interlock system not only increases the degree of protection afforded individuals, but also reduces the technical and administrative burden. The fundamental philosophy is to make sure fail safe operation of the system, and to provide backup functions in the event of failure. SIS in an accelerator facility can be designed following the principles:

1. The system should be fail safe, redundant, unrestrictive and testable
2. Emergency-off and search confirmation buttons should be provided inside the interlock area, and be clearly visible, easily distinguishable, unambiguously labeled and readily accessible
3. Emergency exit mechanisms should be provided in entrance doors of interlock area, even when interlocked. Emergency entry features for interlocked doors are not precluded
4. Clearly labeled status indicators reflecting actual conditions should be provided at entrance doors
5. A reasonable search interval should be provided for each interlock area. An audible and visual warning interval should also be provided before the beam is introduced
6. The main shutter of each beamline should be closed during injection for example in an electron accelerator and the branch shutters (photon shutters) should not be opened before the open of the main shutter
7. Once SIS fault is happened, there should have redundant devices to cease the injection process and dump the entire stored electron beam in an electron accelerator.

**PSA of Accelerators and HRA**

PSA has contributed significantly to the understanding of how best to ensure the safety of nuclear power plants.\[8,11\] By means of PSA, a nuclear power plant, including its safety systems and installations, can be analyzed in its entirety. Such an analysis can yield insights into plant processes and mechanisms and possible interactions between plant systems, both for existing plants with operating histories and for plants still in the design stage. The PSA provides a systematic approach to determining whether the safety systems are adequate, the plant design is balanced, the defense in depth requirement has been realized and the risk is as low as reasonably achievable. These are characteristics of the probabilistic approach, which distinguish it from the deterministic approach.

Since an accelerator does not contain any fissile material inventory like in a nuclear reactor the PSA approach followed here is also different from that in a nuclear reactor.\[8\] It is proposed to identify all possible hazards in the accelerator.\[9\] There are numerous variations in the design of existing accelerators. However, in general an accelerator consists of an ion source, the main accelerator and the target. There are magnet systems, with high voltage and high current power supplies, cooling arrangements, vacuum systems, ventilation systems and safety interlock systems. The accelerator beam is transported to the target using the beam transport system. The material, design and dimensions of the target vary depending on the end use and user requirements, experiments planned and beam to be extracted. Failure of any of the major accelerator systems or essential support systems is expected to result in the shutdown of the accelerator.

For safety analysis, it is profitable to take the approach of hazard identification.\[9\] Their possible causes, severity of impact and adequacy of mitigating measures are required to be studied. Possible hazards in the accelerator may be identified as:

1. Ionizing radiation inside accelerator
2. Ionizing radiation exposure outside accelerator
3. Exposure to hazardous materials
4. Electrical hazard
5. Non-ionizing radiation exposure – RF
6. Environment pollution
7. Fire Inside accelerator Building
8. Fire in equipment and control areas

Each hazard identified can be caused by various initiating events. Maximum impact is for the hazard due to ionizing radiation inside accelerator, which can be due to both prompt and residual radiation or any contamination. Presently, we have restricted our analysis only to hazards due to ionizing radiation inside accelerators.

**Listing of undesirable initiating events**

The following initiating events, which are undesirable and can lead to severe radiological consequences at the site, are identified as follows:

1. Beam losses
2. Target rupture
3. Faulty components causing radiation leak
4. Trapping of persons inside high radiation areas
5. Failure or bypassing interlock facility.

**Beam losses**

An errant beam, if it were to strike an internal component of the machine, could produce a large dose confined to a small angle. This is possible due to human error, malfunctioning of precision instruments or some equipment failure. Improper tuning of the beam can be
possible due to inadequate skill and/or knowledge of the operator. Beam tuning is a multi-parameter optimization problem where several optimal combinations are possible. The combination chosen depends on the operator. If the beam is switched to the wrong beamline it can lead to high radiation at unexpected locations. For complex facilities having many different operating modes and several rooms, tunnels or caves, the beam loss scenarios are difficult to assess and may be different for different operators. In case of any equipment failure, the failure is not monitored, the operator may not be aware of the equipment failure leading to larger beam loss. The effect of any beam loss is the activation of the accelerator parts and shield materials. There will be streaming of a significant amount of radiation through ducts (S-bends) and labyrinths. Workers during maintenance will receive a high dose. There will also be a generation of a large quantity of radioactive waste during decommissioning.

**Target rupture**

The consequence of irradiation of a target by the accelerator beam can result in different toxic radioactive products. It is important to have an idea of the target, experiment being performed and possible radionuclide production after irradiation.[10] This can help in estimating residual dose and monitoring different kinds of radioactivity during and after the experiment. When high beam current is used for experiments, the target rupture probability is also high. This probability would also depend on the target material, its form, design and cooling facility required and available. The effect of target rupture is extensive beam line contamination. Radionuclides produced will contaminate the pump oil and some of it may be released to the air. Several event sequences for the target rupture scenario are possible and the event tree would depend on whether the target is in the air or vacuum, does a beam window exist or not, byproducts of target irradiation are in a closed loop or not etc., Details of target design and experimental procedure is to be scrutinized by competent persons. This will help in planning any special safety measures required. It should be ensured that all users are trained in radiation protection procedures.

**Faulty components causing leak in radiation**

Simple examples are a shield wall plug not closed properly, beam line leak etc.. A sudden vacuum leak occurring would take some time before it is detected. This will produce increasing radiation dose till the chamber filled with air. In a complex accelerator facility, different components of the accelerator, may not work efficiently at the same time. Accelerator components may be damaged or destroyed when power deposition (from radiation) is too high. Inadvertent placing of high Z materials (or Be) in electron/gamma flight path may cause neutrons to be emitted where they are not expected.

**Persons trapped in a radiation area**

The possible situations are:

Maintenance person remaining inside the cyclotron and the accelerator are started. For experiments where low beam current is used, target rupture consequences are low, but generally more people are experimenting here. So the possibility of a person getting trapped is higher. Administrative controls should be used and announcements should be made so that any maintenance person inside the cyclotron can leave the place before it is started. Access control system should be implemented, which will give an online indication of any personnel working, the location and duration of work. Starting of the accelerator should be interlocked with access control.

**Fault tree analysis**

As an illustration, we discuss the technique of FTA in an electron SR facility to quantify the level of safety provided by the hutch search and interlock procedure.[16,18] The hutch is an enclosure with access controlled interlock where experiments are carried out with the SR produced in a high energy electron accelerator.

The first step in this process is to agree on a “top event,” i.e., the failure to be quantified, which for the present example is “Failure to ensure that no personnel are in a certain hutch when X-rays SR are present.” (The hutch chosen is a large one and contains a substantial amount of experimental equipment.) The FTA technique involves defining all the possible sub-events which could independently cause the top event (in this case “person present in hutch when X-ray beam is activated” and “person enters hutch when X-ray beam is present”), then defining the sub-events which could cause these and so on. Eventually “base events” are encountered, which can be quantified without further subdivision; examples are “bulb fails” (in the visual warning display), “relay contact fails and leads to the sign door closed” or “person ignores warning sign.” Hardware failure rates can be derived from recorded failure data or from libraries of data on similar devices. The derivation of human failure rates is a specialization, which involves analysis of the tasks involved and comparison of these to other tasks, which have estimated or measured failure probabilities.

It is usual to draw the Event Tree using a proprietary software package, which then does Boolean reduction on the resultant event logic to derive minimal cut sets (MCSs).[10,16,18] A MCS is a set of base events, which together can cause the top event. The probability of each MCS is the product of the probabilities of the base events within it; while the probability of the top event is the sum of the MCS probabilities. In the typical case like this, the probability of the top event is around $2.6 \times 10^{-8}$ per hutch search. Besides indicating a fairly good level of system
safety, arguably the most useful finding is the relative contribution of the various MCSs, for each of which the percentage contribution to the top event is given within square brackets:

1. The searcher presses the buttons in sequence but makes no attempt to search, AND someone was in the hutch, AND that person does not respond to either the audible search warning or the visual warnings following the search (–either deliberately or due to being unconscious) (77%)
2. As above, but the person in the hutch does not respond because the warnings are not operational (22.5%)
3. A person releases the hutch interlocks and enters and both radiation shutters remain open. This also requires that the hutch door’s electric lock fails to be engaged (0.5%).

These results clearly underline the need to ensure that users are properly trained in the hutch search procedure. They indicate the gain in safety, which can be made by making the warnings failsafe, which should reduce the probability of the second category to the same order of magnitude as the third. They show that the next most likely cause of failure is the simultaneous failure of both shutters to close; this will be mitigated by the implementation of a beam dump on failure of the port shutter.

**Failure or bypassing of interlock facility**

This can lead to the accelerator operating when it should be shutdown. Authorities sometimes tolerate bypassing of some interlock facility. At other times it is due to the over confidence of the operator in their own capability or the capability of the machine. There a large number of interlocks, which need to be tested at regular intervals to ensure that they operate on demand. Bypassing of any interlock can be done only after proper authentication.

**HRA**

Human performance may substantially influence the reliability and safety level of complex technical systems. For this reason, HRA constitutes an important part of PSA. Adequate treatment of human interactions in such studies is one of the keys to understand accident sequences and their relative importance to overall risk.\[10,21\] The main objectives of HRA are:

1. To ensure that the key human interactions are systematically identified, analyzed and incorporated into the safety analysis in a traceable manner
2. To quantify the probabilities of their success and failure
3. To provide insights that may improve human performance. Examples include: Improvements of man-machine interface, procedures and training, better match between task demands and human

This task analyses the human performance associated with the initiating events and subsequent system responses. Human acts to be covered are all those identified during the course of model development as having a potential impact on the structure and results of the models. Usually human performance analysis considers only errors of omission, although some recent developments have been published providing guidance on how errors of commission can be evaluated and modeled in a PSA.\[21\] The evaluation of human performance depends on the complexity and the degree of automation of the technical process. The depth of human performance analysis is driven by the PSA scope and objectives and influences the selection of analysis methodology. HRA can be segregated into two broad categories: Qualitative or quantitative.

**Qualitative HRA**

A qualitative HRA is necessary to identify those possible operator actions which, if not properly performed, will have an adverse impact on the development of the accidents. HRA generally involves the evaluation of tasks within a procedure or sequence, taking into account factors such as the complexity of the task, the conditions under which it is performed and the mental and physical characteristics and limitations of the operator.

Some software tools are available that will calculate a value for a human error. Programs of this kind require the input of parameters that could influence the human error probability, such as the complexity of the operation, availability of instructions, degree of training, time available to carry out the operation, etc., Dependencies between different operators or between different tasks performed by the same operator can significantly affect the overall level of reliability. The safety assessor should therefore take great care to identify dependencies that may exist between different operators, between different errors committed by the same operator, and even between hardware failures and operator action.

**Human task analysis**

The first step in any human error analysis is human task analysis. There are two stages of operation in the accelerator as follows:\[9\]

1. Pre-operation tasks: Before starting of operation, testing of various systems at different periodicities is made along with a checklist to ensure compliance. Difference in work culture and different confidence levels may result in variable approach to the same job by different people.
2. Tasks during operation:
   - Startup beam tuning: For a typical three sector cyclotron there are many trim coils and valley coils to be tuned. Several optimal conditions are possible as beam tuning depends on multiple variables.
   - Switching to required beam line: Here an unintentional error is possible.
   - Maintaining a steady beam on target: There can be beam fluctuations due to lack of stability in power supply. Beam current output may reduce and the quick and easy solution adopted to circumvent the loss is to increase input current, which directly increases the output current. This will lead to more beam loss which is not desirable. Any system degradation or failure will also have an impact on the beam.

   All the above tasks very much depend on the operator. It is recommended that proper system diagnostic tools be used to detect the cause of any beam loss. Though the procedure is the standard time required and accuracy with which the job is done will depend on individual experience, skill and knowledge. When an operator follows a written set of procedures then it becomes a rule-based task and this can lead to faster beam tuning, lower human error and beam losses.[21]

   In all the operational stages some perpetual errors occur as a response to illusions. During prestart up, beam tuning and maintaining steady beam erroneous response may occur under variable situations due to degraded sensory input and misreading of the beam tuning parameters.

   If we take an actual initiating event in an accelerator, beam loss is one of the most important events that depend very much on the operator. The major causes of beam losses are human error or equipment error. If we see the causes of Human error as identified in the fault tree there are three main stages where there can be an error. Firstly the operator has to set the parameters for beam tuning. This he has to do in stages for different stages. After the beam is tuned it is extracted and switched on to the beam line where it is required.

   Any human intervention can reduce or eliminate the impact of any incident in a plant by acting proactively. Further detailed study is required in this area to strike a balance between computerized automation and human intervention levels and limits. In addition to estimations regarding operator error it must be noted that:[21] “However, many accidents have their roots high within the organization. It is the decisions made by those at the top that often influence the safety culture contributing significantly to the preconditions for unsafe acts. In order to understand the causal genesis of an accident, we must “peel the proverbial onion back, layer by layer.”

CONCLUSIONS

With advances in accelerator technology, the radiological and other safety considerations in particle accelerators are increasing. Intense research and development activities including experimental measurements and theoretical analyses are required to cope up with the complex problems prevalent in high-energy, high-current accelerators and ADS.

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