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Accelerator driven systems from the radiological safety point of view

P K SARKAR[1] and MAITREYEE NANDY[2]
[1]Health Physics Unit, Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700 064, India
[2]Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700 064, India
E-mail: pks@veccal.ernet.in

Abstract. In the proposed accelerator driven systems (ADS) the possible use of several milliamperes of protons of about 1 GeV incident on high mass targets like the molten lead–bismuth eutectic is anticipated to pose radiological problems that have so far not been encountered by the radiation protection community. Spallation reaction products like high energy gammas, neutrons, muons, pions and several radiotoxic nuclides including Po-210 complicate the situation. In the present paper, we discuss radiation safety measures like bulk shielding, containment of radiation leakage through ducts and penetration and induced activity in the structure to protect radiation workers as well as estimation of sky-shine, soil and ground water activation, release of toxic gases to the environment to protect public as per the stipulations of the regulatory authorities. We recommend the application of the probabilistic safety analysis technique by assessing the probability and criticality of different hazard-initiating events using HAZOP and FMECA.

Keywords. Radiation; shielding; accelerator driven systems;, simulation codes; probabilistic safety analysis; failure mode effect and criticality analysis.

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1. Introduction

Radiological safety aspects of accelerator driven systems (ADS) pose some unique challenges to radiation protection and dosimetry. This is mainly due to the sources of radiation that are directional, dynamic, pulsed and a mixture of different types. Technological and theoretical developments necessary for more precise radiation protection practices are non-trivial in nature and are different from conventional radiological safety requirements. We discuss the production of radiation source from high energy proton accelerators used for the ADS, that is complex in space (large fluence gradients), time (duty factor), and composition (e.g., photons, neutrons and muons are the principal components of concern for radiological protection).

Practitioners of health physics who design or review radiation protections around particle accelerators are currently in a dilemma over two facts:

1. Changes in 'acceptable' (no longer 'permissible') legal limit of dose-equivalent that can be received by radiation workers ('occupational dose') ICRP recommendation: 50 mSv/y changed to 20 mSv/y.
2. Doubling of the legal dose-equivalent for neutrons: as a result of reinterpretation of old data from the Hiroshima explosion, the Q-value has been (essentially) doubled all across the neutron spectrum, by the ICRP. This will have the effect of approximately doubling the dose-equivalent, even if the absorbed dose remains the same.

In conventional dosimetry, measurements are done in units of the quantities in which the radiological protection limits are expressed.

In the accelerator environment, measurement of energy and angular distribution of radiations is preferred. This is because:

- Necessary and reliable instruments are available for such measurements.
- Energy and angular distributions of radiations remain invariant but not the dose equivalent quantities (conversion factors have been changed in the past and likely to be changed in the future).
- Dose can be estimated from such data using appropriate conversion factors but not vice versa.

The large dynamic range of neutron/gamma energies, strong interference from other radiations as well as radio frequency waves and pulsed nature of the radiation field make dosimetry in such accelerators significantly different from other well-established, conventional techniques of dosimetry. In an accelerator environment neutron dosimetry is also done for purposes other than radiological protection, e.g., to protect (from radiation damage) certain delicate instruments that are required to be placed close to the beam line for experimental or operational purposes.

2. Radiation environment in proton accelerators

To have knowledge of the radiation environment in any type of accelerator, though measurement is the best choice, it is not feasible to do so for all target and projectile combinations. Therefore, one has to rely heavily on computational procedures. The computational techniques consist of two steps: (i) calculation of the source term for emitted radiations, and (ii) transport of the radiations through shield materials. While radiation transport is a subject more or less standardized, calculation of source terms involves computations using complex nuclear reaction model codes, efficient use of which requires an insight into the mechanisms involved. We give below an outline of the basic processes involved in nuclear reactions at different energies.

2.1 *Nuclear reactions*

When an energetic particle (projectile) approaches another nucleus (target) and if the distance of approach is small so that the nuclear potentials overlap and very strong short range nuclear forces come into play, the projectile experiences the potential of the individual nucleons and nuclear reactions begin. In such cases, if the incident energy is not very high, the following two things may occur:

(i) A particle (ejectile) may be emitted immediately after the first collision between the projectile and the target. This is called single step or direct (DIR) reaction process.

(ii) The projectile may be absorbed by the target nucleus and a composite nucleus is formed. The projectile shares its kinetic energy with the target particles. Ejectiles may be emitted during various stages of this energy sharing process by different mechanisms.

The energy brought in by the projectile is shared by the target particles through two-body interactions. During the initial stages, the energy is shared among only a few particles. Subsequently, the energy is shared among increasing number of particles. Finally, the energy is shared among all the particles. We then say that an equilibrium condition has reached leading to a compound nucleus formation. Emission of neutrons, protons, alphas, deuterons, any other particles or γ-rays from the compound nucleus are known as compound nuclear emission or equilibrium (EQ) emission. Emission of particles or γ-rays from the target + projectile composite system before any equilibrium condition is reached are called pre-equilibrium (PEQ) emissions.

The characteristics of three types of reaction can be outlined as follows:

DIR reactions: Strongly forward peaked, high energy emissions, reaction time $\sim 10^{-22}$ s.

Compound nuclear reactions: Angular distribution is symmetric around 90° centre-of-mass (CM) angle, low energy emissions, reaction time $\sim 10^{-17}$ to 10^{-15} s.

PEQ emissions: Characteristics are in between the direct and compound nuclear reaction. Emissions are forward peaked with significant contribution at back angles.

At sufficiently high incident energies, spallation reactions set in when the projectile splits the target nucleus into multiple fragments with emission of large number of neutrons.

2.2 *Spallation reaction*

Spallation reaction mechanism includes DIR, intra-nuclear cascade (INC), PEQ, EQ emissions and de-excitation through gamma emission, besides multi-fragmentation.

Our study on spallation reactions [1] revealed that the major contribution to neutron emission comes from evaporation + fission of primary fragments and this process is responsible for low energy emission up to about 50 MeV. The non-equilibrium process, on the other hand, contributes up to about 25% of neutron emission and gives rise to high-energy neutrons with energies extending beyond 400 MeV. Angular distribution of neutrons is not highly anisotropic.

We have observed that production of projectile-like and target-like fragments is high. Radioactive gases like tritium, xenon and krypton are produced in significant quantities. Several other long-lived radio-nuclides are also produced.

For the LBE target, production of Po-210 is a major concern.

2.3 *Hadronic cascade*

The hadronic cascade is initiated at proton accelerators when the high energy beam interacts with components to produce neutrons and other particles. The collision of a high energy nucleon with a nucleus produces a large number of particles; pions, kaons, and other nucleons as well as fragments of the struck nucleus. Above 1 GeV and at forward angles, the pions, protons and neutrons can be nearly equal in number.

The neutrons may be classified as either evaporation neutrons or cascade neutrons. Evaporation neutrons originate as decays from excited states of residual nuclei with a few MeV average energy. These neutrons tend to be isotropically distributed. Cascade neutrons are emitted by direct impact and their spectrum extends in energy up to the incident energy following a $1/E$ spectrum.

As the proton kinetic energy increases, other particles, notably $\pi^{\pm}$ and $K^{\pm}$, play roles in the cascade when their production becomes energetically possible.

In general, the neutrons are the principal drivers of the cascade. The ionization range for pions and for protons below 450 MeV becomes roughly equal to the interaction length. Also, any magnetic field that are present which can deflect and disperse charged particles will not affect the neutrons. Furthermore, neutrons are produced in large quantities at large values of emission angles compared with the forward-peaked pions.

To estimate the source term, we have used nuclear reaction model codes like JQMD, FLUKA at high incident energies and ALICE91, EMPIRE2.18 and PRECO2000 at low energies. We have also established and used simple empirical formulations for the source term, up to 200 MeV [2,3].

2.4 *Radiation type*

For the proton energy $E_{\rm p}$ in the range $10 < E_{\rm p} < 200$ MeV, neutrons are usually the dominant feature of the radiation field. The yields are smoother functions of energy due to the lack of resonance and emissions are more forward-peaked. Simple empirical expressions for the neutron yield Y can be described as follows [2]:

$$Y = aE_{\rm p} + bE_{\rm p}^2, \quad \text{for } 25 < E_{\rm p} < 200 \text{ MeV},$$

where a and b are parameters that can be expressed as polynomial functions of target mass numbers.

For intermediate energy (from 200 MeV up to about 1 GeV) proton accelerators, the scenario is as follows:

- Many reaction channels open up.
- The number of protons emitted gradually becomes approximately equal to the number of neutrons.
- At the highest energies the radiation effects of protons and neutrons are essentially identical and both must be taken into account.
- Pre-equilibrium neutrons become much more important than evaporation neutrons.

- The radiation field is more sharply forward-peaked with increasing primary particle energy
- Onset of the spallation process takes place.

ADS is generally operated at energies above 800 MeV and the neutron cost is optimised around 1 GeV. The major radiation safety considerations for the ADS can be broadly classified in two parts:

1. To protect public from radiation hazards which require determination of sky-shine, release of toxic gases in the environment, soil and groundwater activation.
2. To maintain hazards within limit for radiation workers which necessitates bulk shielding, streaming of radiation through ducts and penetrations, induced activity in target, air, cooling water, walls and accelerator structures.

We have attempted to estimate the above quantities mainly by calculations using simplified but reasonably accurate formulations. We have also tried to establish simple empirical formulations from the results of more rigorous calculations (mostly Monte Carlo-based) to enable quick estimation of radiological hazards. A foremost requirement of such calculations is the proper estimation of the radiation environment in the ADS facilities.

3. Radiation shielding

The major issues for the shielding design are bulk shielding, duct streaming, sky-shine and activation. Because of the uncertainties in primary beam loss conditions in different components except in beam dumps and targets, a serious problem in shield design arises. Thus only semi-empirical formulas and simplified methods can practically be applied for most of the design study.

The most important feature of neutron shielding at higher energy accelerators is the fact that the attenuation length becomes almost constant at high energy. As the energy increases, the neutron inelastic cross-sections also increase rapidly until about 25 MeV, then they level off and fall rapidly with energy in the region $25 < E_{\mathrm{n}} < 100$ MeV to a value which becomes independent of energy.

3.1 *Bulk shielding*

Shielding calculations are done using Monte Carlo simulations for complex geometries. For planar bulk shields usually the Moyer's model is employed with modifications. We have obtained simple empirical expressions, based on the Moyer's model, for transmission of flux and dose through concrete shields for neutrons from proton-induced reactions.

For shield geometry as per figure 1, the transmitted dose $H(\theta)$ in the direction θ can be estimated as [4]

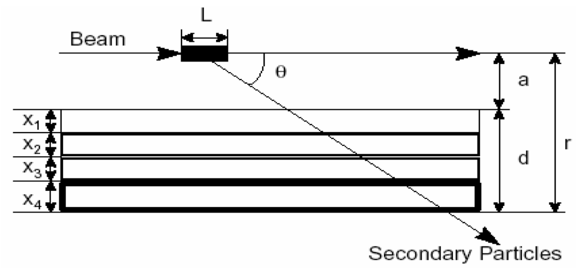

Figure 1. Shield geometry.

$$H(\theta) = \frac{N_\text{p}}{r^2} \int_E F(E)B(E) \frac{\text{d}^2 Y}{\text{d}E\text{d}\Omega} \text{d}\Omega \exp\left[-\frac{d csc\theta}{\lambda(E)}\right] \text{d}E,$$

where N_p is the number of incident protons, F is the flux-to-dose conversion factor, B is the build-up factor, Y is the neutron yield, d is the shield thickness, r is the distance from the source and λ is the attenuation coefficient for the shield material.

In figure 2, we plot the transmitted dose through concrete shields of different thicknesses and also the regulatory limits (horizontal curves) for different distances from the target for 0.2 mA and 2.0 mA proton beam current. The thickness of concrete shield corresponding to the intersection point is the required shield thickness complying with the regulatory constraint.

3.2 *Soil activity*

We have also done soil activation calculations due to neutrons transmitted through the concrete shields for an ADS target located underground. Figure 3 gives a plot of the saturation activities of different soil components at increasing distances in the soil from a 3 m concrete shield where the ADS target (LBE) bombarded by 1 mA proton beam of 1 GeV is placed at 2 m from the inner face of the shield. Our calculations reveal that a shield thickness of about 2.5 m of iron or equivalent is required to keep the soil activation within acceptable limits.

3.3 *Transmission of photons and neutrons through penetrations*

All accelerator facilities need to control transmission of neutrons by penetrations since all have access – ways to permit entry of personnel and equipment as well as penetrations for cables and radio-frequency (RF) waveguides. Personnel access penetrations will typically have cross-sectional dimensions of about 1 × 2 m (door-size) while utility ducts will generally be much smaller, typically no larger than 0.2 × 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 advised for all penetrations of accelerator shielding:

- A penetration should not be arranged so that a particle or photon beam is aimed directly toward it.

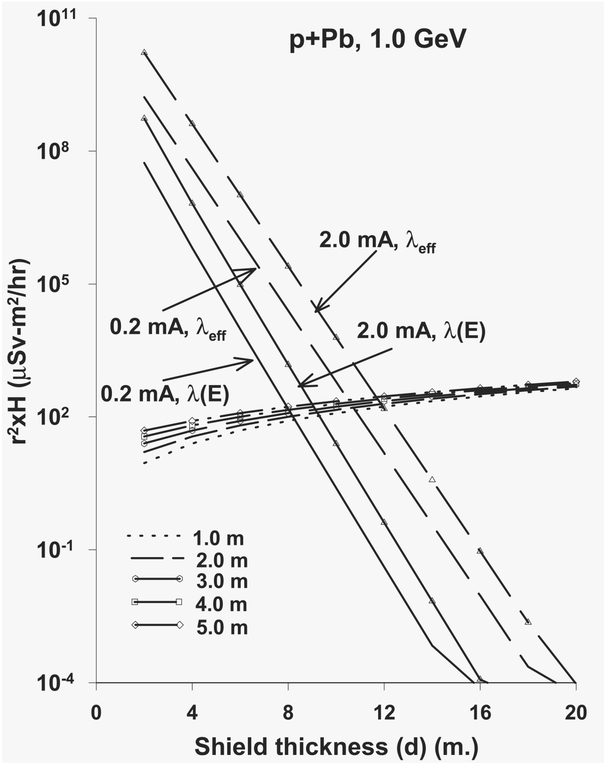

Figure 2. Transmitted dose through different shield thicknesses and the regulatory limits (horizontal curves), both multiplied by r^2 (the square of the distance from the target).

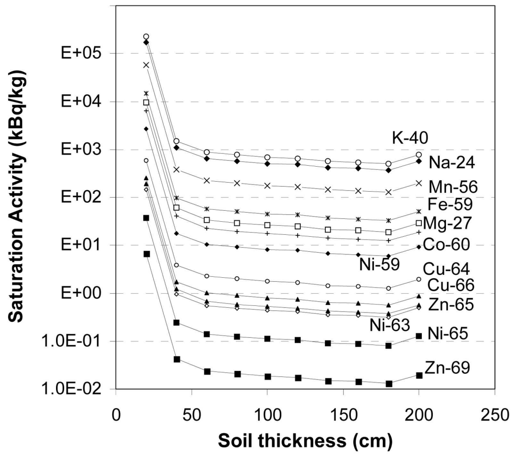

Figure 3. Saturation activity of different radio-nuclides formed by neutrons at different soil thicknesses due to 1 mA protons on LBE.

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.

- 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.

3.4 *Sky-shine*

Thin roof shielding represents a serious problem that has plagued a number of accelerators. The phenomenon, known as sky-shine, 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 penetrating radiations get scattered by air molecules and come back to the ground level at a distance from the facility.

Neutron sky-shine, while it is usually 'preventable' through the application of sufficient roof shielding, has been encountered at nearly all major accelerators. This has resulted either from lack of consideration of it 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.

4. Probabilistic safety analysis

We have also carried out probabilistic safety analysis (PSA) of radiological hazards concerning the ADS based on hazards and operability (HAZOP) analysis and failure mode effect and criticality analysis (FMECA) [5]. Fault tree and event tree methods have been used to depict system failure logic, identify different initiating events and analyse the safety systems required under such circumstances.

5. Conclusions

Based on decades of experience at accelerator laboratories the radiation safety programmes at particle accelerators are emerging with significant improvements. Operational flexibility, such as high beam current and multi-beam capability together with research-oriented requirements from ADS has placed new demands on radiation protection systems. Development of sophisticated computational techniques, particularly those based on Monte Carlo simulations, has made it possible to undertake otherwise intractable calculations. Results of these calculations do serve as necessary adjuncts to experiments where measurements are too difficult or not feasible. Even then, radiation dosimetry at particle accelerators with ADS will be facing problems yet to be resolved satisfactorily. We strongly recommend the use of PSA methodology for safety analysis of the ADS.

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