A RADIOLOGICAL SAFETY AND HEALTH PHYSICS DATABASE FOR CYCLOTRONS ACCELERATING PROTONS AND DEUTERONS UP TO 250 MEV

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Abstract
An excess of 230 cyclotrons are at present in operation in many countries of the world. The majority of these cyclotrons are meant for basic scientific and technological research and advanced medical applications, such as the production of short-lived PET and longer-lived SPECT radiopharmaceuticals, as well as radiotherapy of tumours. Intense fields of ionising radiation are produced during the operation of cyclotrons. Today's cyclotron professionals often have to solve a diverse radiological safety and decision-making related tasks, which require a tedious and time consuming reference search and computation of intricate engineering/technical problems. Hence, as a practical problem-solution aid and scientific compendium, a hyperlinked database (NEA-1694 SATIF/CYCLO-RADSAFE) of scientific and technical reference work encompassing all major radiological safety related issues of cyclotrons has been developed. The main goal of this paper is to introduce the latest version of the database to the cyclotron user communities.

INTRODUCTION

Dr. Ernest Orlando Lawrence of the University of California in Berkeley, USA, invented the cyclotron in 1929. From its nascent stage until the 1950s the cyclotrons were the vital instruments of early nuclear physics and the predecessors of modern high-energy particle accelerators [1]. The significance of the radiological safety aspects of cyclotrons was well recognised by early days cyclotron experts. Consequently, they carried out a series of important research work in the relevant fields, which later gave birth to a new vocation; the Accelerator Health Physics [2].

Modern cyclotrons are capable of accelerating protons (^{1}H-) and deuterons (^{2}H-) to a wide-ranging application-specific energy and beam current levels. These machines are now vital to applied science and cutting edge environmental and medical research. There are at present in excess of 230 cyclotrons in operation in the world [3] and about 30 new units are planned (Figure 1). Noticeably, the largest number of cyclotrons operating today belongs to the category of low-energy (E < 20 MeV) machines primarily used for the production of high activities of short-lived medical radioisotopes.

These special types of cyclotron accelerating intense beams of protons (H^-) and /or deuterons (d^-) are known as "medical cyclotron". Most medical cyclotrons are installed in urban hospitals and nuclear medical clinics and are usually open to members of the public, including patients and children. During routine radioisotope production operation of the medical cyclotrons intense fields of gamma rays and high-energy neutrons as well as high levels of gaseous radioactive effluent are generated. Thus, the reign of a sound operational health physics and efficient radiological protection measures are vital to safe operation and public acceptance of medical cyclotron facilities [4]. Obviously, the same operational safety aspects including the amendments for high-energy options are mandatory for cyclotrons operating at higher energies (Figure 1).

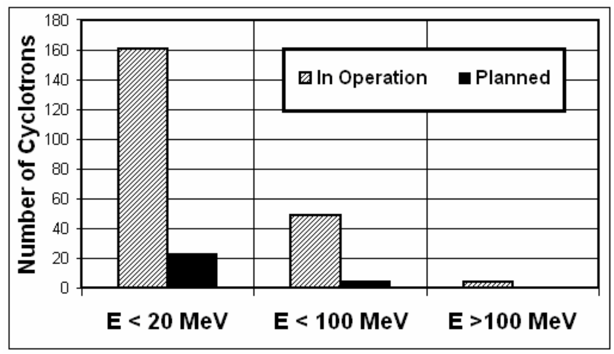

Figure 1. Bar graph showing the number of cyclotrons of different acceleration energy levels presently in operation and under the planning stage.

The modern industrial and medical cyclotron establishments have to comply with the varying work environment and operational conditions, such as: (a) frequent installation of new cyclotron components, (b) dismantling (radio-) activated parts, (c) modification or undertaking of custom design of radiological shielding and (d) management of solid and liquid waste and (e) calculation of accidental radiation exposure.

Specialist knowledge of accelerator health physics and radiation dosimetry is imperative to tackle the above tasks and the responsible officer often has to carry out tedious and time-consuming information research. Hence, as an essential aid to those cyclotron physicists/engineers a hyperlinked information search database [5] concerning all major radiological safety aspects of industrial and medical cyclotrons has been developed. The other major objective of this database is to introduce the valuable early work on radiological safety of cyclotrons to today's radiation protection community [6].

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THE RADIATION ENVIRONMENT

During routine cyclotron operation, i.e. target bombardment for radioisotope production or an unexpected beam loss when the defocused ion beam accidentally hits the internal wall of the beam tube, high levels of prompt neutron and gamma rays are generated. The prompt fast neutrons slow down via multiple scattering with the vault (containment) wall, bounce back to the centre of the vault, thereby activating the cyclotron parts, including the beam tubes, focusing magnets, target (irradiation) chambers, ducts and pipes and other ancillaries. These situations may cause radioactive contamination of skin and whole-body (external) exposure to persons working in the vault. On the other hand, the radioactive noble gas ^{41}Ar (half-life = 1.8 h) produced by the neutron capture (n,γ) reaction with ^{40}Ar present in the vault air may cause whole-body (external) inhalation (internal) radiation exposure.

The prompt gamma and neutron radiation may escape to the external environment through an inadequately shielded cyclotron/target vault, producing direct radiation exposure. In particular, the neutrons penetrated through the vault roof reach a long distance via multiple scattering with the nitrogen and oxygen molecules in air causing low-level exposure via the skyshine radiation. The generic flow chart explaining various major radiation production and corresponding exposure pathways of cyclotrons is shown in Figure 2. The exposure modalities and the associated radiological safety aspects of cyclotrons as described above constitute the main search criteria of a recently published database [5] dealing with the health physics and radiological safety of cyclotrons.

SATIF/CYCLO-RADSAFE DATABASE

The Cyclotron Radiation Safety Database (SATIF/CYCLO-RADSAFE) described in this paper is based on 15 hyperlinked key words (Table 1) dealing with various radiological safety-related issues of a wide range of modern cyclotrons. The key words used in this database are explained below:

Cyclotron classification (key words 1, 2, 3)

The cyclotrons are classified into three energy level categories, a) low-energy cyclotron (E < 20 MeV) for short-lived positron emission tomography (PET) radioisotope production, b) medium-energy cyclotron (E < 100 MeV) for longer-lived single photon emission computer tomography (SPECT) radioisotope production and industrial applications and c) high-energy cyclotron (E > 100 MeV) for radiotherapy of deep-seated tumours. The energy and intensity of the secondary neutron and gamma radiation field produced by a cyclotron primarily depend on the energy of the accelerated ion beam, ion beam species (i.e. proton, deuteron alpha particle) and the atomic weight of the target (beam interaction) material.

Table 1. Showing the keyword ID (KWID) including KW description used in SATIF/CYCLO-RADSAFE database. The number of literature entries for each keyword is also shown.

KWID	Key word description	Entries
1	Low-energy cyclotron (E < 20 MeV)	39
2	Med.-energy cyclotron (E < 100 MeV)	79
3	High-energy cyclotron (E > 100 MeV)	44
4	Shielding material	93
5	Source term	139
6	Monte Carlo (shielding) calculation	36
7	Deterministic (shielding) calculation	43
8	Duct and mazes	21
9	Optimisation technique	8
10	Skyshine	16
11	Dosimetry and Spectrometry	128
12	Radioactive effluent	23
13	Components and shielding activation	31
14	Waste management	19
15	Instrumentation and Control System	10

Shielding Materials and Source-Terms (key words 4,5)

The intensity and energy distribution (spectrum) of a radiation field (generated by beam interaction) at unit distance (1 m) from its production point is defined as a source term. For the purpose of cyclotron shielding calculation one requires the source term and the attenuation characteristics of the shielding material. The most popular shielding material is heavy concrete. However, the shielding attribute of the concrete is enhanced with the inclusion of thermal-neutron absorbing material, such as boron carbide (B_4C). Ultra compact radiation shield made of sophisticated composite materials are now used in self-shielded medical cyclotrons. Evidently, for a reliable shielding design the mechanical and structural properties of shielding material should also be taken into account.

Shielding calculations, Duct & Mazes and Optimisation technique (key words 6, 7, 8, 9)

Monte Carlo (stochastic) simulation and various deterministic (analytical) shielding calculation techniques have been reported. These calculation methods are used to estimate the shielding wall thickness, dimension of various types of mazes and ducts, estimate the skyshine radiation and to optimise the shielding parameters. The availability of fast personal computers with large memory capacity enables the health physicist to simulate dimension of a complex shielding geometry using Monte Carlo (MC) codes. However, the MC code data output may suffer severe pitfalls even in case of minor mistakes in input data including the assignment of shielding geometry. The deterministic shielding calculation methods are based on a simple neutron attenuation model (Moyer Model) producing sufficiently accurate results.

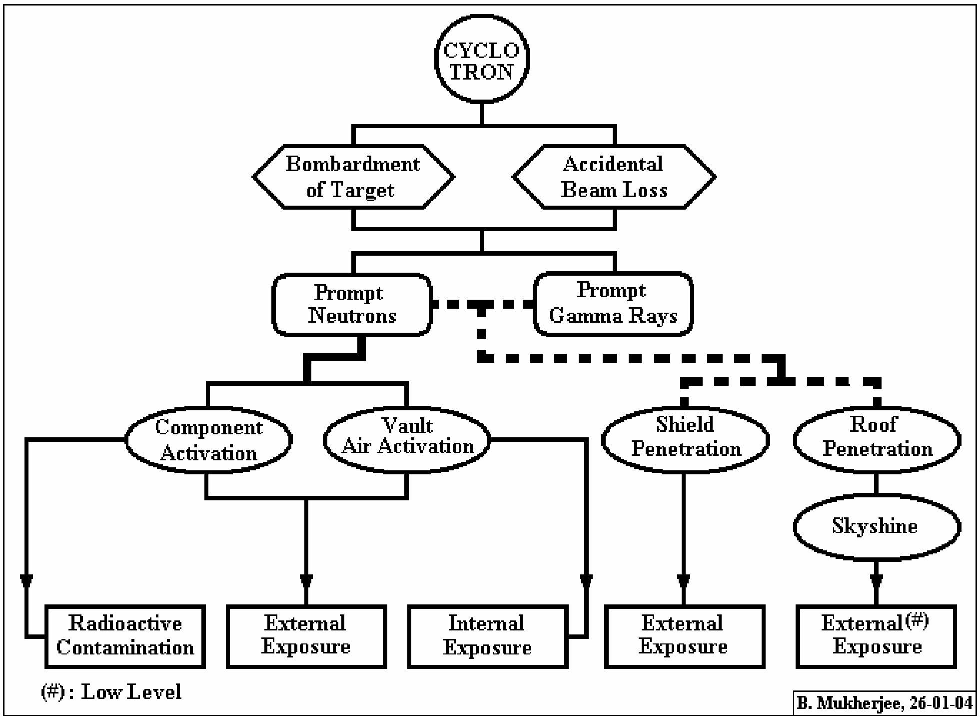

Figure 2. A generic chart showing the radiation production and associated radiological exposure pathways of cyclotrons designated for industrial and fundamental research and medical applications.

Dosimetry & Spectrometry and Skyshine (key words 10, 11)

In the database various computational and experimental methods for the assessment of neutron and gamma dose distribution and the energy spectra of cyclotron-produced radiation fields, including neutron and gamma skyshine have been documented. Such information is vital to determining the efficacy of the radiological shielding of the cyclotron facilities and various radiation safety, public health and exposure analysis related topics.

Radioactive effluent, Activated parts and Waste management (key words 12, 13, 14)

Activities of gaseous radioactive effluent, solid and liquid radioactive waste produced by cyclotrons, in particular the radioisotope production facilities, play a vital role as regards compliance with the radiation safety regulations imposed by the statutory bodies, as well as public acceptance of cyclotron laboratories. The management of radioactive waste plays a crucial role in safe and profitable operation of commercial cyclotrons.

Instrumentation and Control (keyword 15)

Instrumentation and Control systems based on sophisticated microelectronic devices are essential for the monitoring of various operational parameters including the radiation exposure levels of the modern cyclotron. The smart, computer driven radiation, stack emission and effluent monitoring systems are indispensable for assuring the safe and economic cyclotron operation.

SUMMARY AND CONCLUSION

A hyperlinked database (SATIF/CYCLO-RADSAFE) on health physics and radiation safety-related information of a broad range of industrial and medical cyclotrons is available form OECD-NEA Databank. The database includes a large collection of scientific literature of various researchers and technologists over the past forty-year period [6], aiming to provide cyclotron health physicists or engineers with valuable information to solve a myriad of scientific, technical and decision-making problems.

REFERENCES

[1] The Development of High-Energy Accelerators, M.S. Livingston, Ed., Dover Publications, Inc. (1966).

[2] Patterson, W and R.H. Thomas, Accelerator Health Physics, Academic Press, New York (1973).

[3] "Directory of Cyclotrons used for Radionuclide Production in Member States-International Atomic Energy Agency", IAEA-DCRP/CD, ISBM 92-0-133302-1 (2002).

[4] Mukherjee, B., "Radiological Safety and Operational Health Physics of Medical Cyclotrons", Proceedings of the 3rd Int.Conf. on Isotopes (3ICI),Vancouver, Canada, 6-10 September, 1999.

[5] Mukherjee, B., "A Database on Health Physics and Radiological Safety of Cyclotrons 10-250 MeV", NEA-1694-SATIF/CYCLO-RADSAFE: http://www.nea.fr/abs/html/nea-1694.html.

[6] Thomas, R.H., The History and Future of Accelerator Radiation Protection, *Radiat.* Prot. Dosim., 96-4(2001)441.