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LICENSING CRITERIA FOR PARTICLE ACCELERATORS CATEGORIZATION

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ABSTRACT

From the international experience of research centers in various parts of the world, where there are particle accelerators of various sizes and energies, it was found that operating energy of particle accelerators is one of the parameters used by categorization models in the licensing of these radiation facilities, and the facility size is an important aspect to be considered in this model. A categorization based on these two key parameters is presented, also taking into account the kinds of accelerated particles and radiation produced, the operating related technology and the possible applications concerned. The categorization models of national nuclear authorities of five countries are reviewed, emphasizing the contribution of Brazil, and the new model proposed is also based on the experience of these countries, modified by those two parameter discussed above: facility size and operating energy of particle accelerators. Later, some changes are suggested, considering risk factors and safety features related to these facilities, emphasizing some analytical tools commonly used in nuclear facilities and chemical plants, such as: risk-informing decision making, layer of protection analysis (LOPA) and safety integrity levels (SIL), the two latter ones having its origin in the broader concept of system safety. We also discuss the problem of scarcity of reliability data (common in the analyses involving risk factors and safety), due to security concerns and other factors, being the possible alternative solutions the use of generic databases and the adoption of reference facilities that provide partial data publicly.

1. INTRODUCTION

This paper discuss a new categorization model proposal regarding licensing of radiation facilities, aiming to fill the gap of IAEA model [1] concerning radiation generating equipments (RGE). Two key parameters are considered: the facility size and the operating energy level, emphasizing large particle accelerators. Motivated also by the fact that there are no licensing standards that establish a categorization pattern which meets the specific needs of these facilities, the currently accepted model is revised, based on the experience of five countries: Brazil, Canada, India, Argentina and Spain.

2. NUCLEAR LICENSING MODELS

2.1. Regulatory Authorities Experience

2.1.1. Brazil

The Brazilian standard [2] adopts a categorization pattern for particle accelerators and RGE in general, by dividing these facilities into four groups (energy bands), until the maximum level of 50 MeV.

Each group must meet the specific requirements of its licensing stage, and the most critical group (7-D) must meet all of the steps, as well as the groups ranked immediately below are exempt from these steps, as shown in Table 1.

Table 1: Licensing of particle accelerators and RGE – Brazilian categorization model [2]

Standards groups	Energy bands	Licensing stages[a]						
		ST	CT	PC	CM	OP	MD	DC
7-A	E ≤ 100 keV	-	-	X	-	X	-	X
7-B	100 keV < E ≤ 600 keV	-	-	X	-	X	-	X
7-C	600 keV < E ≤ 50 MeV	-	X	X	-	X	X	X
7-D	E > 50 MeV	X	X	X	X	X	X	X

a. ST – Siting; CT – Construction; PC – Procurement of accelerator items; CM – Commissioning; OP – Operation; MD – Modifications of the safety issues; DC – Decommissioning.

Table 2: Licensing of particle accelerators and RGE – categorization models from other countries

Country	Categorization	Energy Band	Ref.
Spain	1st Category[a]	[c]	[8]
	2nd Category	E > 200 keV	
	3rd Category	E ≤ 200 keV	
Argentina	Class I	E > 1 MeV	[7]
	Class II	E ≤ 1 MeV	
India	[b]	E > 10 MeV	[5, 6]
		E ≤ 10 MeV	
Canada	Subclass IB	E > 50 MeV	[3, 4]
	Class II	E ≤ 50 MeV	

a. Particle accelerators are not normally considered 1st category facilities by the Spanish regulatory authority, unless when they are capable of generating radiation beams of high energy fluence or very large inventories of radioactive substances (not quantified by standards), as to cause significant radiological impacts; b. No specific classification; c. Energy level not defined.

2.1.2. Other countries

In Canada, the facilities are categorized into two groups, and such as Brazil, it also adopts the level of 50 MeV to differentiate the categorization groups [3, 4]. In India, particle accelerators are grouped according to their applications, operating related technology and the risks concerned, based on an energy level of 10 MeV [5, 6]. In Argentina [7] this level is lower and in Spain [8] it is not clearly defined. The most important information concerning the categorization models from these countries are shown in Table 2.

2.2. Categorization Parameters

As we begin the discussion of particle accelerators categorization models, as to their size and energy level, we find other parameters such as: kinds of particles accelerated and radiation produced, beam power, workload, technology employed in the acceleration process and particles paths, all possible applications concerned, and the risk inherent to their operations, among other possibilities [9, 10, 11, 12, 13, 14, 15].

2.2.1. Based on facility size

Referring to the experience of some countries, especially regarding the rules and guides from their regulatory authorities and other supporting institutions, like in the United States [9, 16, 17] and India [6, 18] and as seen by international scientific community represented by the IAEA [19, 20], we learn that these facilities can be divided into small, mid and large sizes, based on some specific features.

Table 3: Primary categorization of particle accelerators and RGE concerning equipment/facility sizes [6, 9, 16, 17, 18, 19, 20]

Equipment or Facility Sizes[a]	Equipment or Facility Characteristics
SE ME LE	Small, midsize and large equipment that not necessarily characterize a facility
SF	Facility where usually mid and large sized equipment are used and there must be at least one room or compartment to house the particle accelerator
MF	Facility where large sized equipment consisting of one or more modules are normally used and there must be more than one room or compartment to house the particle accelerator and its auxiliary systems and possible experimental areas
LF	Large facility composed of several accelerating stages or modules or consisting of complex arrangements of particle accelerators in several kinds and technologies, requiring specific buildings where their auxiliary systems and several experimental areas are housed

a. SE: small equipment; ME: midsize equipment; LE: large equipment; SF: small facility; MF: midsize facility; LF: large facility.

However, if we take into account some regulatory standards, such as in Brazil [2], this pattern should also be applied to RGE, in that it actually do not represent a facility, but it can take advantage of the same categorization, being subdivided into small, medium and large sizes as well. A primary categorization is shown in Table 3, considering only equipment and facility sizes, according to the characteristics discussed above.

We stress the importance of the parameter “facility size” on the identification of different kinds of particle accelerators, according to their complexity, which makes it easier to understand the standards requirements for each licensing stage of these facilities (see Section 2.1), as well as the energy levels distribution, the next parameter to be discussed.

2.2.2. Based on energy level

In fact, there is no consensus in the literature concerning low, medium and high energy level categorization for particle accelerators, with the rating depending on the situation, for example, the nature of accelerated particles or the technology involved.

Table 4: Occurrence of nuclear interactions according to energy levels of accelerated particles [9, 10, 15]

Energy Band	Electrons	Protons (and ions)
All the energies[a]	Occurrence of Bremsstrahlung[a]	-
≈ 5 MeV[a]	Neutron production in target materials of heavy nuclei[a]	
10 – 20 MeV[a,b]	Neutron production in target materials of light nuclei[a,b]	
< 30 MeV[a]	Giant photonuclear resonance[a]	
> 100 MeV[a]	Electromagnetic cascade[a]	
≥ 140 MeV[a,c]	Photopion emission[a]	Threshold for pion production[c]
< 200 MeV[a]	-	Neutron production in the low energy level[a]
≈ 200 MeV[c]		Threshold for muon production[c]
30 – 300 MeV[a]	Pseudo-deuteron effect[a]	-
≈ 300 MeV[a]	-	More significant pion production[a]
< 400 MeV[c]		Predominance of activation neutrons[c]
≥ 400 MeV[c]		Predominance of spalation neutrons[c]
≥ 500 MeV[a]		Threshold for kaon production[a]
200 – 1000 MeV[a]		Neutron production in the intermediate energy level[a]
≥ 1 GeV[a,c]	Threshold for muon production[c]	Neutron production in the high energy level[a]
		More significant kaon production[a]
10 GeV[c]	-	More significant muon production[a,c]
≥ 100 GeV[a,c]		Threshold for neutrino production[c]
		More significant effects on the nuclear interactions[a,c]
≥ 1 TeV[a]		Occurrence of Bremsstrahlung[a]

a. [9]; b. [10]; c. [15].

NCRP [9] and IAEA [19, 20], although not directly establishing a categorization based on particle accelerator energies, build a similar line of reasoning in reference to some specific levels of energy, as the occurrence of physical phenomena and aspects of radiological protection, with NCRP offering an updated view of these issues in relation to the latter two IAEA publications, in the case of electron [19] and proton [20] accelerators.

We discuss below some parameters relating to particle accelerators, establishing a relationship with their operating energy, emphasizing the following aspects: occurrence of nuclear phenomena, technology used in acceleration and pathway of particles and possible applications of particles accelerated and radiation produced.

2.2.2.1 Phenomena related aspects

Concerning the phenomena, we highlight neutron production and Bremsstrahlung radiation, produced according to the reactions of accelerated particles and a given target (accelerator components, materials in surroundings, etc.), according to the energy range [9].

As the energy level is increased, besides neutron and Bremsstrahlung radiation, other particles less likely than electrons and protons may appear, such as pions, kaons, muons and neutrinos, with implications for radiation protection. Some of the main nuclear phenomena are presented in Table 4, according to the energy levels of particles accelerated, as divided in electrons, protons and ions.

2.2.2.2 Technological aspects

Particle accelerators technology is related to the particle acceleration process and the particle pathway. As to the first aspect, they can be divided in direct and indirect acceleration, or in electrostatic and electromagnetic kinds; as to the second, they can be classified as linear, circular or of spiral path [9, 10, 11, 12].

In general, the evolution of particle accelerators can be divided into five phases: direct-voltage, resonance, synchronous, alternating gradient and colliding beams [20]. The technological evolution of particle accelerators is presented in Tables 5a-e, considering their main variants, as related to technologies involved on acceleration and particle pathway, and according to energy variation.

Table 5a: Particle accelerators technology according to energy levels – high-voltage electrostatic generators and transformers [10, 11, 12, 13, 14]

Energy Band	Technological Variants
0 – 10 MeV	Electrostatic generators and cascade accelerators (simple module)
10 – 50 MeV	Electrostatic generators and cascade accelerators (in tandem)

Table 5b: Particle accelerators technology according to energy levels – linear accelerators [10, 11, 12, 13, 14]

Energy Band	Technological Variants[a]
0 – 10 MeV	RFQ type may reach from dozens of kV to some few MV
10 – 100 MeV	DTL type may accelerate protons at this energy range
100 MeV – 1 GeV	CCL e SC type may accelerate electrons at this range
1 – 50 GeV	SC type may accelerate protons until 40 GeV

Table 5c: Particle accelerators technology according to energy levels – cyclotrons, microtrons and synchrocyclotrons [10, 11, 12, 13, 14]

Energy Band	Technological Variants[a]
0 – 50 MeV	Classic cyclotrons accelerate protons in the maximum range from 20 to 30 MeV
	Circular microtrons may reach the maximum range
50 – 100 MeV	Isochronous cyclotrons of RSC type may reach 80 MeV
100 – 500 MeV	Isochronous cyclotrons of SSC type may reach the maximum range
	Racetrack microtrons may reach hundreds of MeV
500 MeV – 1 GeV	Synchrocyclotrons and isochronous cyclotrons of SSRC type may reach the maximum range
1 – 10 GeV	Isochronous cyclotrons of SOC type and SC may reach dozens of GeV
1 GeV – 10 TeV	Cyclotrons of FFAG type may reach dozens of TeV

Table 5d: Particle accelerators technology according to energy levels – synchrotrons and betatrons [10, 11, 12, 13, 14]

Energy Band	Technological Variants[a]
0 – 500 MeV	Betatrons may reach 300 MeV
500 MeV – 100 GeV	Conventional synchrotrons may reach the maximum range
100 GeV – 1 TeV	Synchrotrons of AG type may reach the maximum range

Table 5e: Particle accelerators technology according to energy levels – colliders, rings and hybrid accelerators [10, 11, 12, 13, 14]

Energy Band	Technological Variants
1 – 10 GeV	Particle factories (mesons, leptons and neutrinos) may operate on this energy range
1 – 100 GeV	Hadrons colliders operate on this energy range; the hadrons-leptons ones, just for electrons
100 GeV – 1 TeV	Hadrons-leptons colliders operate on this range for protons
10 GeV – 10 TeV	Electron-positron colliders operate on this energy range
100 GeV – 10 TeV	Muon colliders operate on this energy range
10 TeV – 1 PeV	The most advanced technologies may use laser and plasma wakefields on this energy range

a. AG: alternating gradient; CCL: cavity-coupled linac; DTL: drift tube linac; FFAG: fixed field and alternating gradient; RFQ: radiofrequency quadrupole; RSC: radial-sector cyclotron; SC: superconductor; SOC: separated-orbit cyclotron; SSC: spiral-sector cyclotron; SSRC: separated-sector cyclotron ring.

2.2.2.3 Applications related aspects

Among the aspects that should be considered in the categorization of particle accelerators, there are several applications in industry, health and research fields. In the case of industrial applications, the most common are related to industrial processing, industrial radiography and safety inspection; in medical applications, to radiotherapy and radiopharmaceuticals production; and in research applications, to synchrotron light sources, spalation neutron sources and accelerators used in high-energy physics [10, 14]. The main social and scientific applications of particle accelerators on these three areas are presented in Table 6, according to energy level variation.

Table 6: Medical, industrial and research applications of particle accelerators according to energy level [9, 10, 12, 14, 15]

Energy Band	Varieties on Applications
	Medical and Industrial
0 – 50 MeV	Most commercially available accelerators, as applied to radiotherapy, industrial processing and industrial radiography, range from 1 to 50 MeV, much below 30 MeV
	Only Medical
50 – 250 MeV	Therapy with protons is applied in the 70 MeV - 250 MeV range
100 – 200 MeV	Therapy with protons and deuterons beams is applied in this energy range
200 – 500 MeV	Therapy with ions is applied from the 400 MeV/nucleon level on
500 MeV – 1 GeV	Therapy with neutrons may reach 1 GeV
	Therapy with pions is forecast to be applied from the 700 MeV level on for proton beams
1 – 10 GeV	Therapy with heavy ions may reach this energy range, normally operating with carbon ions
	Research
1 – 10 GeV	Synchrotron radiation sources normally operate from 2 to 8 GeV
100 MeV – 1 TeV	High intense proton sources, as known by proton drivers, operate in this energy range
	Spalation neutron sources operate in this energy range

2.2.3 Final categorization

The final categorization will take into account the use of all the parameters considered in Section 2.2, as shown in Tables 3-6, taking as a basis the nuclear licensing standards in Brazil [2], by presenting a more complete categorization model, as compared to other countries (see Section 2.1).

The main proposed changes are related to the range from 600 keV to 50 MeV and the energy ranges that can be included from the threshold up to 50 MeV (Table 1). In the first case, we suggest a break in the 600 keV - 50 MeV range in two energy bands: the first, from 600 keV to 10 MeV and the second, from 10 to 50 MeV.

The threshold of 10 MeV builds on the India's experience [18] in addition to assessing some features related to the practical threshold for the activation neutron production (Table 4) and the operating energy range for small facilities, mainly in industry (Table 6). The range from 10 to 50 MeV meets the main medical accelerators: linear accelerators in radiation therapy and cyclotrons for radiopharmaceuticals production (Table 6).

Table 7: Particle accelerators categorization according to facility size and operating energy range

Current Model			Proposed Model		Equipment and Facility Sizes[d]
Standards Groups[a]	Energy Band		New groups[c]	Energy Band	
7-A	E ≤ 100 keV		E1	E ≤ 100 keV	SE
7-B	100 keV < E ≤ 600 keV		E2	100 keV < E ≤ 600 keV	SE / ME
7-C	600 keV < E ≤ 50 MeV		E3	600 keV < E ≤ 10 MeV	LE
7-D	E > 50 MeV		I1	600 keV < E ≤ 10 MeV	SF
b	b		I2	10 MeV < E ≤ 50 MeV	MF
b	b		I3	50 MeV < E ≤ 100 MeV	MF
b	b		I4	100 MeV < E ≤ 1 GeV	MF
b	b		I5	1 GeV < E ≤ 10 GeV	LF
b	b		I6	10 GeV < E ≤ 100 GeV	LF
b	b		I7	E > 100 GeV	LF

a. [2]; b. Brazilian standard categorization groups establish 50 MeV as the maximum level without further groups [2]; c. E1, 2, 3: class 1 equipments (SE), class 2 equipments (SE or ME), class 3 equipments (LE); I1, 2, 3, 4, 5, 6, 7: class 1 facilities (SF), class 2 facilities (low level energy MF), class 3 facilities (intermediate energy level MF), class 4 facilities (high level energy MF), class 5 facilities (low level energy LF), class 6 facilities (intermediate energy level LF), class 7 facilities (high energy level LF); d. SE, ME and LE: small, midsize and large equipments; SF, MF e LF: small, midsize and large facilities.

The second change concerns the inclusion of more subgroups, from 50 MeV, but it should be discussed how many energy ranges may be included to account for large facilities (Table 3), especially those operating at higher energy levels (Tables 5a-e). In the range from 50 to 100 MeV, there are other kinds of applications (Table 6), other acceleration technologies (Tables 5a-e), and there is a higher incidence of midsize facilities (Table 3). However, there are no significant changes in the effects of nuclear interactions, since for electron accelerators, the new level for new effects, such as the electromagnetic cascade, is from 100 MeV (Table 4), with similar situation occurring for protons and ions.

Considering finally the main possibilities of the situations involving the operation of particle accelerators from 100 MeV, it is possible to establish the final categorization, taking into account, in the first instance, the facility sizes and the energy range in which they operate, and second, the other characteristics discussed in Section 2.2. This final categorization is presented in Table 7, based on the main elements established in Tables 3-6, considering the remarks above.

2.3 Comments on Results

Referring to Table 7, it appears that the goals have been met regarding the establishment of a new categorization model for particle accelerators, from reviewing the model adopted in several countries, such as in Brazil [2]. The new model increased the amount of energy ranges, improving the specification of the kinds of particle accelerators, as well as allowing a greater range of applications which are more widespread today.

Taking as a basis the Brazilian standard [2], besides defining the levels above 50 MeV, the gaps were resolved for the standards groups below this value, especially with the creation of intermediate groups, with new energy ranges, from the threshold of 10 MeV. The establishment of new categorization groups for energies above 100 MeV, another major contribution of this work, confirmed the tendency of the scientific community about the definition of low, medium and high energy for these facilities, a fact strongly aided by the parameter "facility size" through flexible distribution of new groups, with the creation of three levels for midsize facilities and three for large facilities, both separately for low, medium and high energy.

On the other hand, it was found that the model obtained is not sufficient to establish a comparative analysis with the IAEA model [1], which considers specific scenarios of radiological accidents, according to the variation of the sources activities and the risks associated with practices, emphasizing the three occurrences with particle accelerators in irradiation industry, as reported by IAEA [21]. Accordingly, we discuss below some alternatives for improving the model, with the adoption of two additional parameters: the hazards inherent in these facilities and the safety systems provided to face these hazards.

2.4 Risk Factors and Safety Features

This new model will be formulated under two analysis bases: experience of facilities with large particle accelerators and nuclear facilities, whose development in this kind of analysis is longer. As for particle accelerators, we will come back to Section 2.1 to discuss the regulators' experience, and other regulatory agencies and consultants in the nuclear field, emphasizing the contribution of AERB [5, 6, 18], DOE [16, 17, 22], NCRP [9, 23, 24], ANSI [25] and IAEA [19, 20]. In the case of nuclear facilities, a recent analytical model will be considered: risk-informing (RI), which originated from the nuclear reactors field and has been expanding its range of applications since then, making use jointly of probabilistic (PSA) and deterministic (DSA) safety analysis [26].

2.4.1 Experience from large particle accelerator facilities

India has two additional criteria for categorization of particle accelerators: the first related to risk classes and the second one to regulatory concessions in the licensing process of these facilities [5, 6]. The risk classes are divided into four groups presented in order of increasing risk severity: I, II, III and IV, based on the potential of generating radiation as well as the risk inherent to their operations, and involve dose levels that facility workers and external population may be exposed to, some doses being considered lethal in the case of class IV [6].

Regulatory concessions are also divided into four groups, presented in descending order of importance: license, authorization, registration and approval, based on the degree of complexity and risk of these facilities, with respect to licensing steps [5]. The identification of particle accelerators by risk class is not very easy to be established, and the regulator granting criterion should be evaluated, since in that case the potentials facilities are listed for each concession group, thus making the identification easier.

DOE [22] did not clearly establish a categorization for particle accelerators, because it is presented based on nuclear reactor and waste treatment facilities, and as such, based on the potential of the radioactive material inventory generated. Radiation facilities (including most particle accelerators) are not easily identified when this criterion is applied, and this fact is not sufficient clarified by other documents with direct application to these facilities [16, 17].

The contribution of NCRP [9, 23, 24], ANSI [25] and IAEA [19, 20] does not necessarily establish categorization criteria, on the other hand, it provides important information regarding different risk sources (radiological and non-radiological) present in particle accelerators, and systems and subsystems responsible for eliminating these risks or reducing their frequency or potential for harm through physical, engineering and administrative provisions. Accordingly, DOE [16, 17] offers the same kind of contribution.

2.4.2 Experience from nuclear facilities

The risk-informing approach (RI) is established within the basis of risk and safety analysis, structured around deterministic and probabilistic models and other factors may be considered. The great dilemma is adapting the metrics and scenarios used by these techniques, based on the experience from nuclear reactors, to the facilities considered to be of lesser risk ranking, for instance, particle accelerators.

Although IAEA [26] recommends this model to non-reactor nuclear facilities (including particle accelerators), in practice, it appears that the methods and techniques associated with these models are oriented to higher risk facilities. However, the graded-approach concept [26, 27] establishes a relationship of proportionality between strict application of criteria and degree of complexity and risk of the assessed installation, greatly simplifying the job of adapting the model of nuclear facilities, which sometimes has a very hard script to fully comply with, as in RI and PSA [27, 28].

Usually, these models could be addressed by means of three kinds of analysis: quantitative (higher risk facilities), semiquantitative (mid risk facilities) and qualitative (lower risk facilities). Thus, it is easy to conclude that the risk and safety analyses of particle accelerators will be conducted through qualitative or semiquantitative techniques, depending on the kind of facility (Tables 5-7).

In this regard, two semiquantitative techniques, LOPA and SIL [29], can be very useful to improve the classification model (previously discussed), since they consider the risk factors and safety features in the analysis. These techniques are more easily and straightforward to apply than fault tree and event tree analyses, for example, commonly used in PSA, the probabilistic hand of RI-based analysis. The deterministic RI-based analysis is conducted primarily by a concept that is the heart of DSA, the defense-in-depth, which in turn bears a great resemblance to the LOPA approach. Now the SIL contribution is very specific for model improvement, to establish a hierarchy of safety integrity levels to facility systems, which summarizes the very meaning of the technique itself.

The greatest difficulty lies in the data for all these techniques, related to the reliability of systems, such as failure rates, frequency of hazardous events, etc., usually treated as confidential information by such plants, increasing the stringency in controlling information as risk increases. The alternative is to use generic data available in different databases, such as those published by IAEA [30] and CCPS / AIChE [29, 31].

In addition, there are facilities that make part of these data available for public consultation, which lets elect some reference facilities, as some of DOE research centers, some European facilities, among other contributions, as brought by ICRP [32], which provides examples of applying PSA to several radiation facilities, including three different kinds of particle accelerators.

Finally, we should comment on the existence of another analytical tool, one of the variations of RI, the risk-informing and safety categorization (RISC) [33], which is precisely the sort criteria employing risk and safety factors in their approach, yet it presents the same problems of adapting metrics and scenarios of analysis parameters, as discussed above for RI and PSA.

3. CONCLUSIONS

The proposed new categorization model of particle accelerators will support future revisions of non-nuclear facilities licensing standards, as in Brazil [2], and will serve as the basis for other works within the approach proposed here, in order to improve the model, as suggested in previous section. However, impasses must be resolved related to metrics and scenarios set in RI, PSA and RISC techniques, beyond the scarcity of reliability data used by these three techniques, as well as for LOPA and SIL, evaluating whether the alternatives presented are sufficient or further research on these topics is needed.

It should also be noted that the knowledge of the characteristics of nuclear interactions in the laboratory is limited [9], which implies that in the future these energy levels may undergo some modifications in the light of technological advances coming from particle accelerators and their new applications that may arise, especially in the fields of new medical therapies, nuclear power generation and waste treatment, extent of use of 3rd and 4th generation of light source synchrotrons and new trends on the exploration of matter with high energy physics. Finally, we consider that these advances will bring new implications regarding risks, new safety philosophies and hence the need to review the licensing models currently set out.

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