Potential exposures in the classification of workers and workplaces in industrial practices

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ABSTRACT

Introduction: A prior safety assessment should be submitted to the regulatory body as part of the licensing process. The mentioned assessment should estimate normal and potential occupational exposures. This study aims to assess the influence of potential exposures on the final categorisation of workers and classification of workplaces. **Methods:** Based on prior radiological evaluations of 92 industrial radiation sources, 56 of them being sealed radioactive sources and 36 being radiation generators, the classifications of workers and workplaces based only on normal exposures were compared with the final classifications that additionally considered the contribution of potential exposures (probability and magnitude). **Results:** Potential exposures changed the categorisation of workers in 31 of the 56 sealed radioactive sources considered (55.4 %) from members of the public to exposed workers of category B and changed the workplace classification from non-classified to supervised area in 32 cases (57.1 %). Regarding X-ray generators, potential exposures changed the categorisation of workers in 5 cases (13.9 %) and the classification of 5 workplaces (13.9 %). **Conclusion:** Potential exposures presented a greater impact on the classification of workers and workplaces involved in the practice of operating equipment that incorporates sealed radioactive sources, due to the greater risk they pose. This was not verified for X-ray generators, where there was a lower magnitude and probability of potential exposures, since most of the generators had engineering controls robust enough to be operated by members of the public and do not present any risk of exposure when switched off.

KEYWORDS: Occupational exposure, potential exposure, sealed source, radiation generator, radiation protection, safety assessment.

1. INTRODUCTION

Ionising radiation sources are used in a wide range of applications in the sectors of industry, energy, medicine, research, education and agriculture, and their application is clearly beneficial. [1-3]

It is known that the ions produced when radiation interacts with living tissues may break chemical bonds and cause biological damage with potential health effects. Therefore, the risk to workers, to members of the public and to the environment arising from these applications must be assessed. [2-5]

Radiation exposure includes both normal and potential exposures. Normal exposures are those expected to occur under normal operating conditions of a radiological facility or practice. On the other hand, potential exposures are not expected to occur with certainty, but they can be predicted since they result from events previously identified as possible incident or accident scenarios, such as equipment failures or operating errors. The correlation between the probability of occurrence of these potential events and their magnitude are important to determine the inherent radiological risk of a practice and to properly classify workers and workplaces. [5,6]

Given the transposition of the Council Directive 2013/59/Euratom of 5 December 2013, to the Portuguese lay in 2018 through the Decree-Law No. 108/2018, potential exposures must be considered in the prior safety assessment of a practice. This assessment is currently required for its licensing. [5]

Potential exposures must be considered in the categorisation of workers and in the classification of workplaces as well.

Individuals can be categorised as members of the public or as exposed workers. Exposed workers can additionally be distinguished between two categories: A or B. These categorisations affect the education and training needed, the frequency of medical surveillance and of individual monitoring, when needed. [5]

Category A includes exposed workers who are likely to receive an annual effective dose greater than 6 mSv, an annual equivalent dose greater than 15 mSv for the lens of the eye or greater than 150 mSv for the skin and extremities. In Category B are the remaining exposed workers not classified as Category A but likely to receive doses higher than the limits for members of the public. The dose limits for public exposure are 1 mSv/year for effective dose, 15 mSv/year for the lens of the eye and 50 mSv/year for the skin. [5]

Workplaces are classified as supervised or controlled areas, or in cases where it is not expected that the effective doses to be incurred in that area may exceed the effective dose limit of 1 mSv/year, the equivalent dose limit of 15 mSv/year for the lens of the eye or the equivalent dose limit of 50 mSv/year for the skin and extremities, workplaces are not classified. [5]

Controlled areas are those where, due to the existing working conditions, it is likely that the exposure to which workers are subjected to annually may exceed effective doses of 6 mSv or equivalent doses of 3/10 of the established dose limits to the lens of the eye, skin and extremities for category A exposed workers. Controlled areas must be physically delimited and have access controls. Supervised areas are those where it is likely that the exposure to which workers are subjected to annually may exceed an effective dose of 1 mSv or an equivalent dose of 15 mSv for the lens of the eye or 50 mSv for the skin and extremities, but are not expected to exceed an effective dose of 6 mSv or an equivalent dose greater than 3/10 of the dose limits set for the lens of the eye, skin and extremities. [5]

This study aims to assess the influence of potential exposures on the final categorisation of workers and classification of workplaces in industrial practices that use sealed radioactive sources and radiation generators by assessing the classifications of workers and workplaces based only on normal exposures and establishing a final one considering additionally the contribution of potential exposures.

2. METHODS

92 industrial radiation sources used in multiple industries such as construction, plastics, paper, steel, food, automotive, among others, were included in this study. 56 of them are category 4 and 5 sealed sources (^{137}Cs, ^{60}Co, ^{241}Am, ^{241}Am:Be, ^{85}Kr, ^{147}Pm, ^{63}Ni) and the remaining 36 are radiation generators (figure 1).

Of the 56 sealed radioactive sources, 4 are portable density/moisture gauges with ^{137}Cs and^{241}Am:Be sources, 5 are gas chromatography equipment with electron capture detectors (^{63}Ni) sources and the remaining 47 are fixed nuclear gauges used to measure level, thickness and density with ^{137}Cs, ^{241}Am, ^{147}Pm, ^{60}Co and ^{85}Kr sources.

3 of the 36 ionising radiation generators, are portable x-ray fluorescence (XRF) spectrometers, 5 are foreign body inspectors, 15 are level inspectors and the remaining 13 perform XRF or industrial radiography in a shielded enclosure.

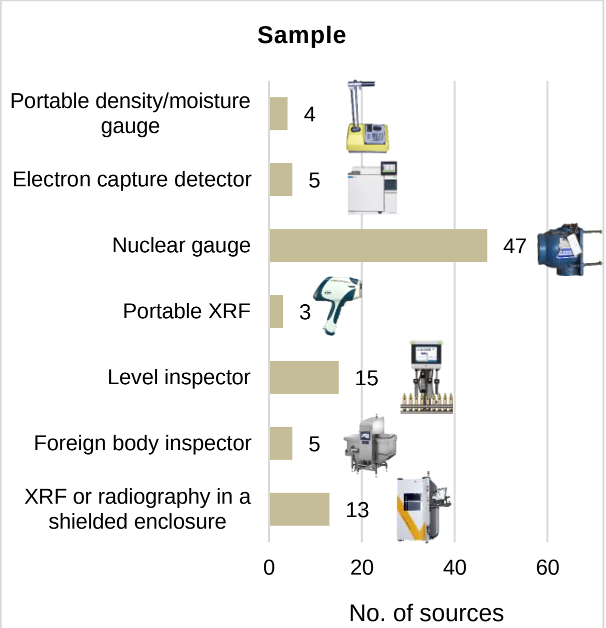

Figure 1 – sample description.

The level of detail of the safety assessment must consider a graded approach according to the magnitude of the possible radiation risks arising from the practice. Therefore, the safety assessment and analysis for category 4 and 5 sealed sources and for these X-ray generators is usually straightforward. [2,7]

Normal exposures were estimated from the workplaces' monitoring and the occupancy declared by the licensee.

Potential exposures were estimated after the potential scenarios were identified. For each scenario, a workplace monitoring was performed, and whenever not possible, numerical simulations were performed. The consideration of potential exposures followed a deterministic approach considering a 100 %

probability of occurrence of the identified scenarios.

In facilities where the risks to workers and members of the public is considered low to moderate, the deterministic approach is followed since the inherent conservatism compensates for uncertainties mainly associated with operating errors and other events of a probabilistic nature, providing an appropriate safety margin. [2]

Normal exposures

The effective doses resulting from the normal operation of facilities with X-ray generators or gamma or neutron sealed sources were estimated with the measurement of the ambient dose equivalent rate $\dot{H}^*(10)$ in the workplaces of human occupancy closest to each source.

$$E = \dot{H}^*(10) \times t \qquad (2.1)$$

Where E is the effective dose and t is the time that workers occupy that workplace annually.

For β^- sources, this monitoring was made by measuring the fluence rate. The fluence rate or flux is the quotient between the number of particles, dN, incident upon a small sphere of cross-sectional area, dA, per unit of time. [8]

$$\dot{\Phi}_\beta = \frac{dN}{dA \times dt} \qquad (2.2)$$

From the determined flux, the absorbed dose rate was computed as follows:

$$\dot{D}_\beta = 5{,}768 \times 10^{-5} \times \dot{\Phi}_\beta \times \mu_\beta^{tissue} \times E_{\beta,avg} \times \left[e^{-\mu_\beta^{air}(\rho x)}\right]\left[e^{-\mu_\beta^{tissue}(0{,}007)}\right] \qquad (2.3)$$

Where $\dot{D}_\beta$ is the absorbed dose rate due to beta particles, $\dot{\Phi}_\beta$ is the fluence rate determined, μ_β^{tissue} is the beta absorption coefficient for tissue, $E_{\beta,avg}$ is the average energy of the beta particles, μ_β^{air} is the beta absorption coefficient for air, ρx is the density thickness of the absorber and the 0,007 value is the density thickness of the dead skin layer. [9]

$$\mu_\beta^{tissue} = 18{,}6 \times (E_{\beta,máx} - 0{,}036)^{-1{,}37} \qquad (2.4)$$

$$\mu_\beta^{air} = 16 \times (E_{\beta,máx} - 0{,}036)^{-1{,}4} \qquad (2.5)$$

The equivalent dose for the skin is then determined as follows:

$$H_{skin} = \dot{D}_\beta \times w_r \times t \qquad (2.6)$$

Where H_{skin} is the equivalent dose for the skin, $\dot{D}_\beta$ is the beta particle dose rate, t is the time that worker occupies that workplace annually and w_r is the radiation weighting factor, which is 1 for electrons.

The results obtained were then compared with the effective dose or equivalent dose limits for the skin and extremities of each category considered – members of the public, exposed workers from category B or A to assess the initial categorisation of workers.

Potential exposures

To estimate the potential exposures, several scenarios were considered for each practice and their probability and duration were discussed with the radiation protection officer.

The following potential scenarios for sealed radioactive sources have been identified:

1. Failure in the following of safety protocols, which can result, for example, in an

exposure to the primary beam with the shutter opened;

2. Fire, explosion, floods, earthquakes;
3. Fall, mechanical shock or crushing damaging the equipment's shielding or increasing the likelihood of a radioactive leakage;
4. Failure of the shutter switching system in a nuclear gauge or of the interlocking of the ^{137}Cs source rod in a portable density/moisture gauge as a result of mechanical shock, rust or lack of cleaning;
5. Loss or theft;
6. Use of the source beyond its recommended working life with potential loss of the source's integrity. [10-16]

The radiation generators' potential scenarios were:

1. Failure in the following of safety protocols, resulting in exposure of one end to the primary beam when accessible or exposure in the product entry zone and closer to the beam;
2. Damages in the shielding of the equipment, increasing leakage radiation due to mechanical shock, earthquake, fire, explosion;
3. Failure of a safety interlock that prevents access to the direct beam when it is being emitted;
4. Failure of an audible or light beam emission alarm;
5. Loss or theft. [10,17-19]

To estimate the exposure from these potential scenarios, measurements were made in the workplaces in conditions that simulate the considered scenarios. When that was not possible, numerical simulations were performed.

In cases where it was necessary to estimate the doses from the exposure to the primary X-ray beam, measures were performed with an adequate equipment, and whenever not possible, numerical simulations where performed as follows:

$$\dot{D} = \dot{D_2} \times \frac{V_1^2}{V_2^2} \times \frac{I_1}{I_2} \quad (2.7)$$

Where D_2 is a known dose rate from a beam of a known voltage, V_{p2}, and a known current, I_2, and V_{p1} and I_1 are the working conditions of the beam that is not reachable.

In cases where it was intended to simulate and estimate the doses due to exposure to the primary beam of a sealed source, the point source approximation was used as follows:

$$\dot{D} = \frac{A \times \Gamma}{d^2} \quad (3.9)$$

Finally, in cases where the sealed sources exceeded their recommended working life established by the manufacturer, the committed effective dose from internal exposure of a 200 Bq activity was determined.

$$E(50) = \sum_j e_{j,inh}(50) \times I_{j,inh} + \sum_j e_{j,ing}(50) \times I_{j,ing} \quad (2.10)$$

Where $e_{j,inh}(50)$ and $e_{j,ing}(50)$ are the committed effective dose coefficient for activity intakes by inhalation and ingestion of a radionuclide, respectively, and $I_{j,inh}$ e $I_{j,ing}$ are the activity values of the radionuclide incorporated. [20]

The doses obtained were added to the normal exposures estimated and compared with the effective dose limits or equivalent dose limits for the skin and extremities for members of the public and for exposed workers form categories A or B.

To determine normal exposures in workplaces, the places of normal occupation and the maximum length of stay declared by the licensee were considered. This estimation followed the methodology used to estimate normal occupational doses. Then, to estimate the potential doses in the workplaces, the permanence of workers in the workplaces closest to each source and a continuous operation of the equipment during the maximum usage time declared by the licensee was considered, which corresponds to a continuous emission of the X-ray beam for the radiation generator and, for sealed radioactive sources, a continuous use of its switch opened. Estimates were made not only in areas usually occupied by workers but also at shorter distances from each source. Finally, these results were compared with the doses likely to be received in the supervised and controlled areas, and a final workplace classification was set.

3. RESULTS AND DISCUSSION

Categorisation of workers

The estimated normal occupational exposures of workers indicated that in 82 of the cases, the workers' doses would be below the limit of 1 mSv/year for members of the public, while for the remaining 10 sources, the estimated normal doses were between 1 to 6 mSv/year, so the assigned category would be exposed worker of category B (figure 2).

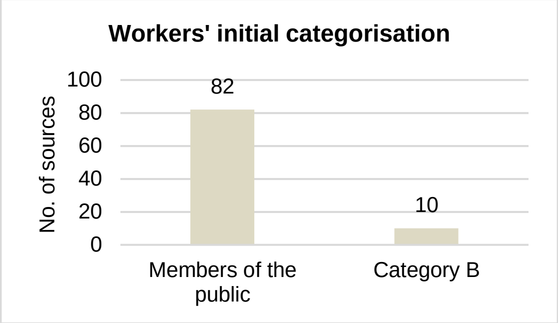

Figure 2 – Categorisation of workers only considering the estimated normal exposures.

The 10 radiation sources whose normal operation exposes their workers to effective doses greater than 1 mSv/year are the 4 portable density/moisture gauges and the 6 nuclear gauges that incorporate ^{60}Co sources. Unlike the remaining sources, portable density/moisture gauges are directly operated, and the normal scenarios include exposures due to their operation, transport and storage. The ^{60}Co sources are installed in production lines that require frequent approach of workers.

Potential exposures changed the categorisation of workers of 31 sealed radioactive sources and 5 of the radiation generators considered from members of the public to exposed workers of category B and (figure 3).

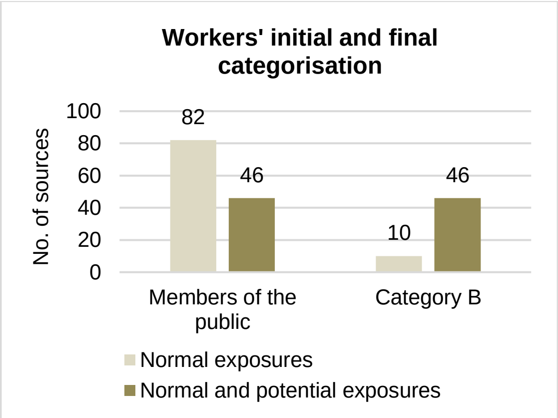

Figure 3 – Final categorisation of workers.

2 of the X-ray generators are portable XRF with accessible primary beam that operates with a voltage up to 50 kV and a current up to 0.1 mA. Their operators' categorisation was changed after considering the increase in the frequency of its use and the irradiation of an extremity of a worker. The other 3 generators are 2 foreign body inspectors and 1 level inspector, that can expose their workers to effective doses greater than 1 mSv/year if their distance to the sources decrease.

Finally, the final categorisation of workers involved in the operation and maintenance of 3 ^{85}Kr nuclear gauges and 28 ^{137}Cs nuclear gauges were changed from member of the public to category B. The potential exposures considered involved:

- an increase in occupancy times in the workplaces near the sources with their shutter opened;
- for ^{137}Cs sources in tanks or vessels, exposure to the primary beam resulting from an entry into those structures without the switch having been properly closed; and
- for sources that had already exceeded their recommended working life, scenarios of loss of integrity were considered.

The classifications were kept as members of the public for workers involved in the operation of the following radiation sources:

- XRF and radiography generators in a shielded enclosure, mainly due to its shielding and safety interlocks;
- The remaining level and foreign body inspectors;
- Electron capture detectors;
- 1 portable XRF with maximum conditions of operation of 50 kV and 0.039 mA;
- Thickness gauges containing ^{147}Pm and level gauges containing ^{241}Am;
- 1 ^{85}Kr thickness gauge.

Classification of workplaces

The figure 4 shows the initial classification of the workplaces where every source operates.

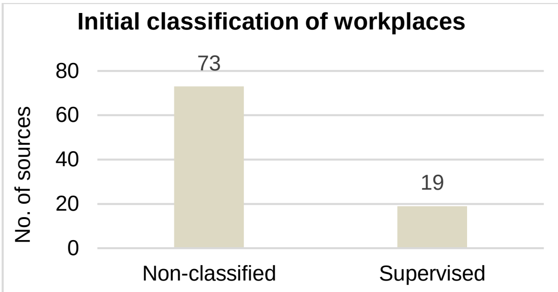

Figure 4 – Initial classification of workplaces based on normal occupancies.

The 19 supervised areas are the ones where 3 nuclear gauges with ^{137}Cs sources, 1 ^{147}Pm nuclear gauge, 1 ^{85}Kr nuclear gauge, 4 portable density/moisture gauges, 6 ^{60}Co nuclear gauge, 2 portable XRF and 2 foreign body inspectors operate.

This is due to the higher dose rates measured and to the greater workload declared by the licensee. The X-ray generators considered operate at higher voltages (foreign body inspectors) or have a high probability of exposure to the primary beam (portable XRF). The nuclear gauges presented higher dose rates due to its higher activity, higher proximity of the operators and even higher operation times.

Figure 5 shows the initial and final classifications assigned to the workplaces of the 92 sources.

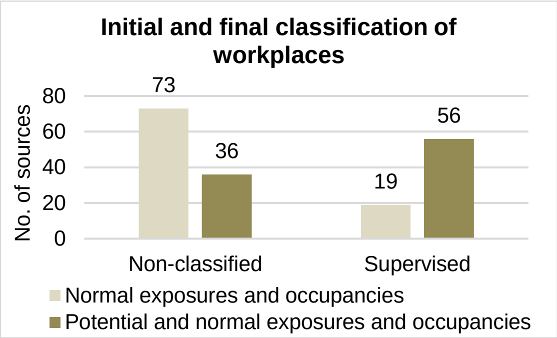

Figure 5 – Initial and final classification of workplaces.

Potential exposures changed the workplace classification from non-classified to supervised area of 37 radiation sources, 32 of them being the sealed sources and the remaining 5 being radiation generators.

The sources were 1 portable XRF, 4 level inspectors, 25 ^{137}Cs nuclear gauges, 2 ^{147}Pm nuclear gauges, 2 ^{241}Am nuclear gauges and the 3 remaining ^{85}Kr sources.

The portable XRF's workplace changed after the consideration of an increase of their use, an increase of the time of each analysis performed, an increase in the number of analysed samples and the potential doses resulting from irradiation of an extremity to the primary beam.

The workplace classifications of the remaining ^{137}Cs sources were changed to supervised areas mainly due to the possible deterioration of the sources' integrity since most of them have already exceeded their recommended working time and that have not been subjected to any wipe tests and also due to a possible increase of the occupancy near the sources.

The remaining ^{85}Kr sources' workplace had their final classifications changed, mainly due to the potential doses that can be incurred at their accessible surfaces with the shutter opened.

The 2 ^{241}Am sources operating in supervised areas had this final classification due to the dose rates measured in contact with the equipment, nearest working areas or near the primary beam. These 2 presented higher potential exposures since their activities are higher (3,7 GBq) compared to the others (1,67 GBq).

3 of the last 4 level inspectors who saw their workplaces' classification being changed, have an accessible primary beam. The other one has a physical structure that prevents primary beam approximation, however, the dose rates measured in contact with the railing where high enough to classify that area as a supervised one considering the permanent occupancy of a worker.

4. CONCLUSION

Potential exposures changed the categorisation of workers in 31 of the 56 sealed radioactive sources considered (55.4 %) from members of the public to exposed workers of category B and changed the workplace classification from non-classified to supervised area in 32 cases (57.1 %). Regarding X-ray generators, potential exposures changed the categorisation of workers in 5 cases (13.9 %) and the classification of 5 workplaces (13.9 %).

Potential exposures presented a greater impact on the classification of workers and workplaces involved in the practice of operating equipment that incorporates sealed radioactive sources, which was due to the greater number of potential scenarios identified, the higher potential doses involved and due to the greater risk they pose.

This was not verified for X-ray generators, where there was a lower magnitude and probability of potential exposures, since most of the generators had engineering controls robust enough to be operated by members of the public, adequate shielding, safety interlocks, emergency stop buttons, safety keys, light signs, and they do not present any risk of exposure when switched off. It was also verified that some of these apparatuses are subjected to regulatory control through registration or exempt from regulatory control in other Member States, where the regulatory framework established is subjected to a graded approach in accordance with the radiation risks associated with facilities and activities. [21]

The Council's Directive 2013/59/Euratom and the Decree-Law No. 108/2018 define potential exposures and indicate that they must be considered in the prior safety assessment of a practice to determine the radiological risk arising from exposure to workers. However, they do not give any guidance on how to take into account the probabilistic nature of potential scenarios, namely human errors and equipment failures. Therefore, it is expected that guidelines for the assessment of potential exposures in multiple practices may be published. Until then, an empirical estimation of the probability of occurrence of each potential scenario is adopted, in order to assess whether potential doses are considered in the final classifications of workers and workplaces or not (deterministic approach).

It is intended to include, in the future, a probability of occurrence for each potential scenario based on findings from the available literature review or, ideally, on annual reports of the notified incidents to be published by the competent authority in radiation protection, as verified by other authorities at the international level. For the potential scenarios with a lack of data available regarding its probability of occurrence, it is intended to adopt a probabilistic distribution, which would consequently lead to a classification of workplaces and workers dependent of an accepted probability of risk.

Guidelines for future work

The inclusion of other sources used in an industrial context and that represent a greater radiological risk is mentioned, namely the irradiation facilities, industrial radiography that does not use self-shielded booths and industrial gammagraphy, can be added to this study.

It would be equally relevant to assess the impact of potential exposures in medical practices with a higher radiological risk such as radiotherapy, which involves generators that operate up to dozens of MeV and nuclear medicine, which involves the manipulation and administration of unsealed sources to patients and where there is a permanent potential for internal and external contamination.

REFERENCES

1. Carvalho FP. A Radioactividade no Ambiente, Radionuclidos de origem natural e artificial. Instituto Tecnológico e Nuclear; Departamento de Protecção Radiológica e Segurança Nuclear: 2000.
2. International Atomic Energy Agency. Safety Assessment for Facilities and Activities. General Safety Requirements No. GSR Part 4 (Rev. 1). 2016.
3. International Atomic Energy Agency. Fundamental Safety Principles, IAEA Safety Standards for protecting people and the environment. Series No. SF-1. 2006.
4. Liu SZ. Biological effects of low level exposures to ionizing radiation: theory and practice. Hum Exp Toxicol. 2010 Apr;29(4):275-81.
5. Diário da República. Decreto-Lei n.º 108/2018. 2018; 232: 5490-5543.
6. International Commission on Radiological Protection. ICRP publication 64. Protection from Potential Exposure: A Conceptual Framework. 1993; 23(1): 1-20.
7. International Atomic Energy Agency. Safety of Radiation Generators and Sealed Radioactive Sources. IAEA Safety Standards Series No. RS-G-1.10. Viena: IAEA; 2006.
8. Turner J. Atoms, Radiation, and Radiation Protection. 3 ed. Oak Ridge: Wiley; 2007.
9. Martin J. Physics for Radiation Protection. 3rd ed. USA: Wiley; 2013.
10. International Atomic Energy Agency. Safety of Radiation Generators and Sealed Radioactive Sources. IAEA Safety Standards Series No. RS-G-1.10. Viena: IAEA; 2006.
11. United States Nuclear Regulatory Commission. Consolidated Guidance About Materials Licenses Program-Specific Guidance About Fixed Gauge Licenses. [Available from: https://www.nrc.gov/docs/ML1618/ML16188A048.pdf]
12. International Atomic Energy Agency. Radiation Safety in the Use of Nuclear Gauges. Specific Safety Guide No. SSG-58. 2020.
13. Endress+Hauser. Radiation Safety and Technical Reference Manual U.S. General and Specific Licensees For Radiation Source Containers FQG61, FQG62. [Available from: https://portal.endress.com/wa001/dla/5000304/5289/000/01/SD00293FEN_1310.pdf]
14. Australian Radiation Protection and Nuclear Safety Agency. Portable Density/Moisture Gauges Containing Radioactive Sources. 2004. [Available from: https://www.arpansa.gov.au/sites/default/files/legacy/pubs/rps/rps5.pdf]
15. United States Nuclear Regulatory Commission. Consolidated Guidance About Materials Licenses. Program-Specific Guidance About Portable Gauge Licenses. 2016. [Available from: https://www.nrc.gov/docs/ML1617/ML16175A375.pdf]
16. Australian Radiation Protection and Nuclear Safety Agency. Australian Radiation Incident Register. Annual Report 1 January 2016 to 31 December 2016. 2017. [Available from: https://www.arpansa.gov.au/sites/default/files/arir2016.pdf]
17. Rios P, Rios D. Estudo de exposições em situações de incidentes envolvendo geradores de raios X de uso industrial. Braz. J. Rad. Sci. 2016: 03-2A; 1-13.

18. Australian Radiation Protection and Nuclear Safety Agency. Summary Of Radiation Incidents: 1 January To 31 December 2009. 2010. [Available from: https://www.arpansa.gov.au/sites/default/files/legacy/pubs/RadiationProtection/arir/arir2009.pdf
19. Australian Radiation Protection and Nuclear Safety Agency. Australian Radiation Incident Register. Annual Report 1 January 2017 to 31 December 2017. 2018. [Available from: https://www.arpansa.gov.au/sites/default/files/arir_-_annual_summary_report_2017_final.pdf]
20. Diário da República. Portaria n.º 137/2019 de 10 de maio. Diário da República. 2019;90:8–10.
21. International Atomic Energy Agency . Application of a Graded Approach in Regulating the Safety of Radiation Sources. IAEA-TECDOC-1974. 2021.