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Radiological risk assessment method for the interim storage of radioactive materials

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Abstract Safe storage of radioactive materials is based on three universal radiation protection principles. Justification, optimization and dose limits are applicable to the risk assessment, acknowledging the hazards in each procedure of delivery, usage, storage and disposal of radioactive materials. Failure Modes and Effects Analysis method (FMEA) is developed for the risk evaluation of common practices. In this work FMEA is exploited for the radiological risk assessment in practices using radioactive materials. In addition, the radiological hazard of fire is studied, in order to classify its severity for different examples of radioactive materials inventories. The severity of the hazard, the likelihood and the detectability of its occurrence are exploited for classifying the associated risk. Appropriate measures that should be taken for the emergency preparedness and response are taken into account in order to reduce the Risk Priority Number (RPN). Scenarios of external exposure, skin contamination and inhalation are investigated, in order to calculate the received doses, for workers and members of the public. The outcomes of the analysis indicate low or medium severity of the risks for most of the examined practices, especially under the implementation of the appropriate measures, like: controlled access of the facilities, records keeping for delivery, usage, storage and disposal of radioactive materials; presence of fire detectors and extinguishers; and removal of flammable materials from the vicinity of the radioactive materials.

1 Introduction

In respect of occupational and public exposure, the radiological risk evaluation is always a common requisite that has to be included in the safety assessments of interim storage facilities of radioactive sources and materials. Among others, the radiological hazard due to fire is an important factor considered in the radiological risk evaluation [1]. As the stored radioactive materials often get minimum attention by the staff, the probability of occurrence and the severity of radiological incidents may be significant. Therefore radiation protection experts assess the severity, the probability of occurrence and the detectability of each radiological risk and subsequently give competent advices and written guidelines for the staff, in compliance with the respective legal requirements. In this work we are presenting a simplified method for the development of radiological risk assessment at laboratories where radioactive materials are used and stored, considering some practical examples. The probability of radiological impact from fire may be higher for disused radioactive materials (like the old lightning rod heads) and for disused sealed radioactive sources (DSRSs), because of the reduced attention they receive, compared with the ones in use.

Among several methods of risk evaluation, we choosed an analytical method which prioritizes the risk of each hazard utilizing its severity, probability and detectability. Its name is Failure Modes and Effects Analysis (FMEA). FMEA prioritizes the hazards according to how serious their consequences are, how frequently they occur, and how laborious their detection is. The final objective of the presented method is: (a) to prioritize the risks and thus indicate which risk should be confronted first, (b) to reveal the actions needed to eliminate or reduce the risks.

To perform such analysis, the radiation protection experts must interview the associated personnel and record: (a) the distinct processes in the practice under investigation; (b) the failure modes, by answering the question "What could go wrong?"; the failure causes by answering the question "Why would the failure happen?"; the failure effects by answering the question "What would be the consequences of each failure?".

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FMEA is utilized during the design of a practice to prevent hazards, and during the implementation of a practice, whenever changes are scheduled. Ideally, FMEA begins during the conceptual stages of design and continues throughout the whole practice that involves radiological risks.

Two main categories of people may receive doses from these scenarios: first responders, and members of the public such as the inhabitants of a neighbouring area. It is assumed that in case of such an accident workers will follow guidance for evacuation and move to a distance where dose rates will remain at natural background levels. Some workers are designated by emergency plans to serve as first responders. According to 2013/59 Euratom directive the acute or annual dose for first responders and members of the public [2] due to an emergency situation should be kept in the band of 20 to 100 mSv. Specific reference levels should be determined for particular cases, but should not exceed the upper level of this band. In exceptional cases the reference level for workers can be set higher, up to 500 mSv [1]. Thus, the calculated doses are compared with the band of 20–100 mSv.

This band can be considered as an example of generic criteria established for the protection strategy against nuclear and radiological emergencies. Any exceedance of this band is associated with possible increase in the stochastic effects of ionizing radiation, while higher doses on the order of 1 Gy are associated with the deterministic effects of ionizing radiation. The emergency threat categorization (five categories: I, II, III, IV, V) suggested by IAEA [3] is a useful tool for decision-making about actual measures to be applied in specific scenarios and with specific inventories (e.g. evacuation of the affected area or restrictions on contaminated, locally produced food).

2 Inventories and methods

Three examples of inventories are studied to demonstrate the FMEA method adjusted for radiological risk evaluation and a dose calculation method exploiting the Gauss Plume Model (GPM) [4] for incidents of fire:

A. An interim storage of lightning rods with Am-241 and Ra-226 pellets.
B. A centralized interim storage of DSRSs and orphan sources.
C. A radio-labelling laboratory using and storing Phosphorus-32 (P-32).

2.1 Radiological risk assessment

In the present work, two different implementations of the FMEA method are demonstrated. The first one performs an evaluation of the different risks in the discrete processes of a practice. The second one evaluates one specific risk (the example of fire is chosen) for a set of different practices that a research or industrial laboratory might perform.

FMEA can be performed in two steps, which consequently feed each other. The first step considers the severity of the risk and its probability of occurrence. The severity includes factors, like the calculated dose of workers or members of the public; the number of persons who are exposed; and the consequent failures to the following processes chain of the practice. For instance, the severity of fire on a SRSs calibration set should include: the number of the people accidentally exposed, their calculated dose, and the failure of the forthcoming processes in the practice of calibration. The weighted contribution of each factor can be considered for the estimation of the total severity. A normalized equation can be structured for each specific risk, like that:

$$S = \frac{w_E * E(\%) + w_N * \mathrm{N} + \cdots + w_F * \mathrm{F}(\%)}{w_E + w_N + \cdots + w_F}$$

where S is the severity of the risk, taking values from 1 to 100; E(%) is the percentage of the anticipated dose, to the dose limit; N is the number of exposed persons, considering that no more than 100 persons might be exposed; F (%) is the percentage of failures that may occur to the forthcoming processes, due to the incident; $\mathrm{w_E}$, $\mathrm{w_N}$, $\mathrm{w_F}$ are the corresponding weighting factors.

2.2 Doses evaluation due to fire incident

As an example of how each risk is evaluated to feed back the above risk assessment method, a simple and conservative analysis, which covers the worst possible off-site consequences, can be followed, in order to compensate for the uncertainties in the amount of radioactive material burned in a fire incident.

A release which is detained indoors can be assessed by a simplified scenario with realistic assumptions: (a) a portion of the radioactive material is diluted into the plume; (b) the plume is dispersed uniformly into the room; (c) a small portion of the plume is inhaled by the exposed person, until the person realize the fire incident and escape to a safer place. These scenarios can be as complicated as the radiation protection expert deems necessary. For the objectives of this work the above three simple assumptions are used for the indoor dispersion of the plume.

Dispersion of the radioactive cloud in the open air is calculated with the GPM. This model is used often for the assessment of the impact of accidents and also as a tool for the evaluation of safety case and safety assessment reports of nuclear installations by the regulatory authorities [5–7]. The wet deposition as a washout and the dry deposition as a fallout of the radioactive plume is considered for the calculations. Protection by the storage buildings or the storage containers, and fire safety measures and procedures, is not taken into account. This assumption significantly overestimates the release into the atmosphere, therefore can be considered as the worst-case scenario.

The different meteorological conditions are set by the combination of the air speed, the rain density and the stability of the atmosphere surrounding the interim storage facilities. The air speed is set to 1 m/s as the worst case scenario and 3.7 m/s as the average wind speed in Athens [8]. The rain intensity is set to 0 mm/h for the most probable condition of no-rain and 3 mm/h which is the average rain intensity in Athens [9]. For the input atmospheric turbulences, the Pasquill stability classes [10] are exploited. The most probable stability condition in Athens is the D class (i.e. neutral) [11], which imposes a slight entrainment of clear air into the radioactive plume, and the worst-case stability is the F class (i.e. stable).

The existence of steep structures like buildings at the surrounding terrain hinders the air passage and also produces turbulence which generates fluctuation of the deposition of the plume. Therefore, the roughness of the terrain is considered with two modes: rural and urban.

Specifically the GPM uses the following equation, in order to calculate concentration (x) (Bq/m) for every i airborne radioisotope composing the cloud, at x distance from the point of the accidental release, along the central line of the plume as it follows the direction of the wind. Thus, the maximum concentration, compared with other directions, is given by [12]:

$$C^i(\mathrm{x}) = Q^i DF^i(\mathrm{x})$$

where Qi is the release rate (Bq/s) of the ith isotope and DFi(x) is its diffusion factor, given by:

$$DF^i(\mathrm{x}) = \frac{1}{\pi\sigma_y\sigma_z\mathrm{u}}\exp\left(\frac{H_e^2}{2\sigma_z^2}\right)f_{decay}f_{deposition}$$

where H_e is the height of the point of release, u is the wind speed at this height, σ_x and σ_y are the diffusion parameters which are functions of the distance from the release point and the stability category of the atmosphere [10].

For the demonstration of the doses delivered to the first responders and the public by an incident of fire, two examples of inventories are used. Specifically, a centralized interim storage of about 400 DSRSs and orphan sources is used for the demonstration of the dose dependency on weather and terrain conditions. The hypothetical scenario considers a large fire covering the inventory presented in Table 1.The part of the material in terms of activity which released in the plume is 1/100 or 1/1000 depending on the material volatility. For instance the salts of Cs-137 are keener to escape than the metal source of Co-60.

Another example of interim storage with reduced activity by three orders of magnitude is an interim storage of lightning rods with Am-241 and Ra-226 pellets of about 30 GBq total activity. The management of the disused radioactive lightning rods includes removal from their poles and collection at interim storage facilities. Subsequently the radioactive pellets are dismantled and stored in sealed packages. While waiting for the dismantling to occur, a large number of lightning rod heads may be accumulated. As a case study, the fire destroys the full inventory which comprise 520 heads of Am-241 and 25 older heads of Ra-226, with 55 MBq mean activity for each head.

Table 1 The inventory of DSRSs and orphan sources stored in a typical centralized interim storage facility

Isotope	Half-life (years)	Total activity (MBq)	Airborne release fraction
Co-60	5.27E+00	2.20E+07	0.001
Cs-137	3.02E+01	1.57E+05	0.01
Am-241	4.32E+02	5.40E+04	0.001
Sr-90	2.91E+01	1.56E+05	0.01
Ir-192	2.41E+02	5.50E+03	0.001
Ra-226	1.60E+03	5.50E+03	0.001
C-14	5.73E+03	5.50E+03	0.01
Mn-54	8.56E−01	5.50E+03	0.01
Eu-152	1.33E+01	9.00E+00	0.001

3 Results and discussion

In the first subsection are described the components of the effective dose and is presented their relation with the weather and terrain conditions. The next 3 subsections present the overall dose that may be delivered to the first responders and the public for the (A), (B) and (C) inventories, in case of fire. The next subsection combines the previous dose estimation with the FMEA method applied for the risk off fire on the storage of the different (A), (B) and (C) inventories. In the last subsection, FMEA method is performed for the certain practice of (C), in order to prioritize the risks of the different processes of a practice.

3.1 Dose dependency on weather and terrain conditions

The dose which originates by cloud-shine, inhalation and ground-shine of the plume is shown in Fig. 1a–c. Their dependence on weather conditions is indicated with different colors. These are the doses during release of the radioactive plume. In addition, the annual dose from deposition of the radioisotopes on the ground and the relative weather and terrain dependences is presented in Fig. 1d. The centralized interim storage facility is a good example to apply for the different weather and terrain conditions, as its inventory consists of several radioisotopes with total activities high enough to yield doses near the public dose limit.

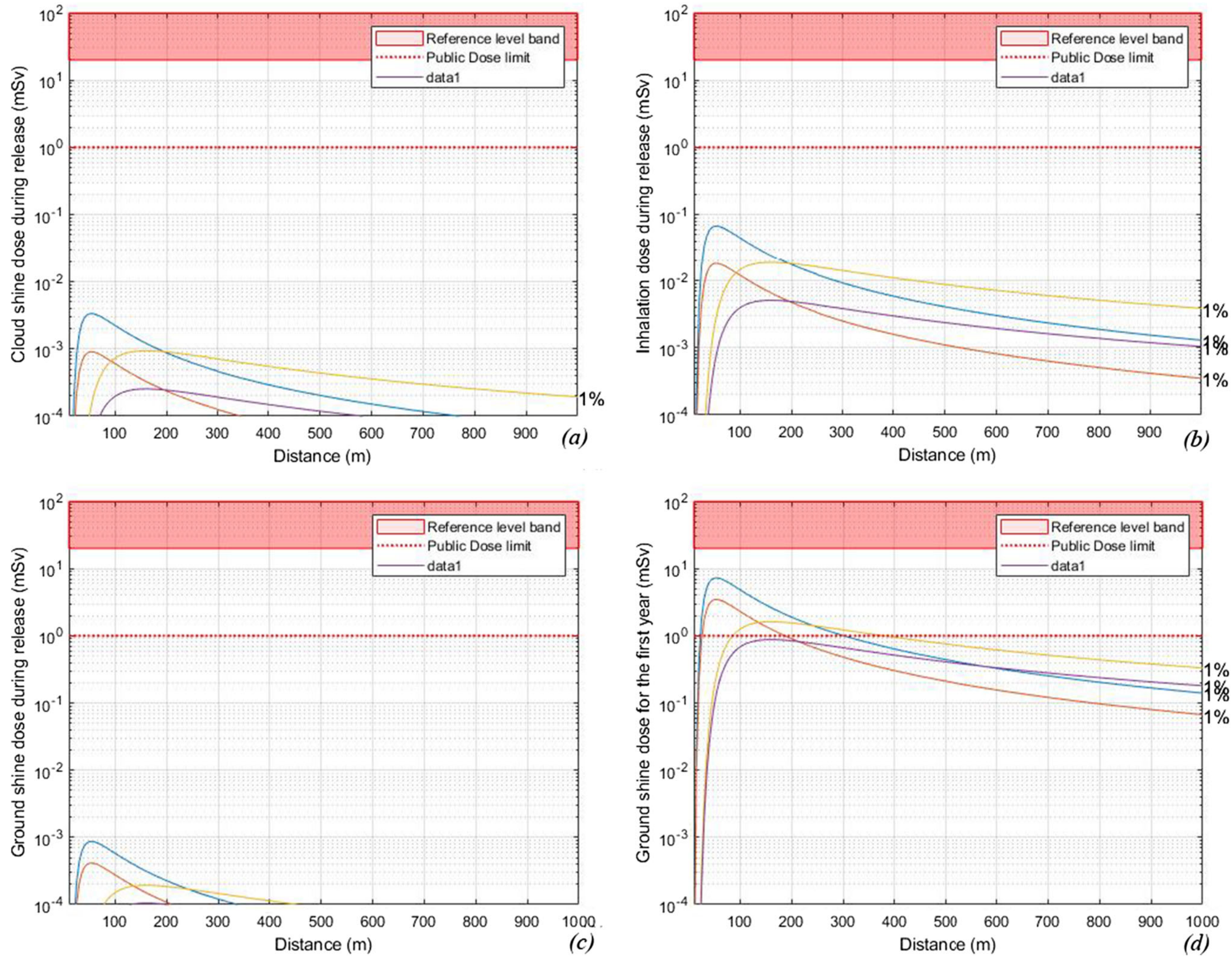

Fig. 1 The dose delivered during the release by: **a** cloud-shine, **b** inhalation, **c** ground-shine. **d** The annual dose delivered by the deposition of the radioisotopes on the ground. Color-lines: Blue = Stability condition: D; Wind speed: 1 m/s. Red = Stability condition: D; Wind speed: 3.7 m/s. Yellow = Stability condition: F; Wind speed: 1 m/s. Violet = Stability condition: F; Wind speed: 3.7 m/s. Rural and urban terrain conditions lead to negligible differences of the curves

Increasing the speed of the wind results in lower dose curves due to faster transport of the cloud at larger distances. More stable atmospheric conditions result in lowering of the peak of the dose curves and greater dose at its tail (i.e. the dose increases at further distances, while stability increases). More stability introduces less fresh, clean air into the radioactive plume. The differences between the dose curves for rain and no-rain conditions are presented in all the figures in the following subsections. Rain occurrence leads to wash-out of the radioactive plume and deposition of the radioisotopes onto the ground surface. The terrain conditions are chosen to be rural, since negligible changes are calculated when urban terrain is chosen.

3.2 Lightning rods

The inventory of the lightning rods as noted above consists mainly of Am-241 pellets and a few Ra-226 pellets, with total activity less than 0.1% of the total activity of the centralized interim storage inventory.

Accumulating the effective dose by cloud-shine, ground-shine and inhalation, during the release and the next 8 h, the dose of the 1st responders can be estimated less than 0.3 mSv for the case of breathing unfiltered air of the radioactive plume. This value decreased by almost six orders of magnitude in the case of breathing with protective apparatus or filters. Ra-226 and Am-241 contribute significantly to inhalation dose, as the organs receiving the highest dose are the lungs and the bone surface, respectively [13]. A moderate rain will not affect significantly the dose compared with the dry weather. The safety zone should set a circle of 100 m radius for the public reference dose level (i.e. 0.3 mSv) to be satisfied [2].

The high contribution of the inhalation dose to the total dose, suggests that, during release, evacuation of an area twice the radius of the safety zone is an efficient measure to decrease the dose to the public lower than 0.1 mSv, assuring that on-time evacuation is possible. For the specific amount of activity, even with no evacuation, the annual dose remains lower than the national reference level for the public (i.e. 0.3 mSv). Nevertheless, for more active inventories, evacuation will be an effective measure for the reduction of the public dose.

The radiological hazard for first responders and members of the public is considered to be readily manageable, based on comparison of the calculated doses with the public dose limit. It is important to highlight the compatibility of the above analysis with the approved national plan for radiological or nuclear emergency response in category III facility [14].

3.3 Centralized interim storage

Accumulating the effective dose by cloud-shine, ground-shine and inhalation, during the release and the next 8 h, the dose of the 1st responders is estimated less than 0.9 mSv. Excluding the possibility of inhalation of radioisotopes with the use of breathing apparatus or full-face masks bearing filters, the calculated dose to first responders is almost two orders of magnitude lower than in the case of unfiltered air breathing. The remaining of the dose consists of the cloud and ground shine and it is by a factor of 1.1 higher for the rain conditions than for the dry weather conditions.

For the public the calculated annual dose is lower than 1 mSv for distances further than 300 m from the release point along the wind direction. Thus, building an outer fence with radius more than 300 m would be an effective measure to limit the public dose below 1 mSv. Consequently, the inhabitants of the surroundings will receive annual effective doses lower than the public dose limit of 1 mSv. If no evacuation takes place during the release of the radioactive plume, the external exposure to the cloud and ground shine and the dose by inhalation for the time of release will be added to the above first year ground shine and the total dose will rise by a factor 1.1. Therefore, it should be under further investigation whether evacuation of the neighbouring urban area needs to occur, as its benefit will be small yet it might give rise to other hazards like traffic accidents. Obviously, the dose will decrease over successive years. Decontamination activities might be also suitable due to the small affected urban area.

3.4 Unsealed radioactive source in biological research laboratory

An example of storage and use of P-32 for radio-labelling biological samples in a biological laboratory is presented to demonstrate the versatility of the method. The ractivity in the storage room is far less than the two previous examples, i.e. 30 MBq. P-32 is a β-emitter and the dose is due to β-particles with peak energy of 1710 keV. Such energetic β-particles have a range of 6.3 mm in plastic materials. Using appropriate factors [5], the dose due to skin contamination and inhalation can be calculated with the assumption that 5% of the total activity of 30 MBq is released in the plume and a person inhales 2% of this radioactive plume. Considering that the firefighters will use their breathing apparatus and protective gloves and uniform, the only persons exposed will be few workers (or even few members of the public) who will run away after inhaling accidently a small part (e.g. 2%) of the radioactive smoke. For such short time of exposure the skin contamination will be negligible. The dose due to the inhalation is calculated to be about 3.3 mSv.

3.5 Evaluation of the fire risk for different industrial and research practices

For the above mentioned practices the fire risk is assessed and the outcomes can be compared to prioritize the practices and to decide which one has to be addressed first. Applying the appropriate safety and security measures and actions reduces the severity of the hazard and the probability of its occurrence and increase its detectability in case of occurrence. Thus the Risk Priority Number (RPN) is calculated again and its values are reduced. The actions can be relevant to severity, occurrence and detectability or to any combination of them. For the presented demonstration each relevant action reduces the values of severity, occurrence and detectability by a factor of 2, but the radiation protection expert can choose different weighting factors derived by specialized studies (Table 2).

The results indicate that the preventive and protective actions has to be implemented firstly for the centralized interim storage facility, then for the lightning rods interim storage and lastly for the radio-labelling research laboratory. Of course the simultaneously implementation of the appropriate actions for all the practices would be preferred, but most of the times economical and administrative reasons force the one-by-one implementation.

3.6 Evaluation of the different risks in the discrete processes of a practice

The majority of the practices are multi-process, involving one or more risks for each process. As an example, the entering and the storage of a package containing P-32 is examined at the premises of a biological laboratory. Also its transfer to the hood for further use and the radioactive waste disposal are examined.

Once again, each relevant action reduces the values of severity, occurrence and detectability by a factor of 2, but one can choose different weighting factors derived by specialized studies. For instance, entering the package containing 30 MBq of P-32 in the premises of the laboratory, includes the risk of bring-in in a contaminated package. The cause could be the lack of inspection of the package visually and instrumentally with a contamination monitor. The effect of this failure probably will be the contamination of workers or members of the public and their unjustified exposure. Some of the

Table 2 Assessing the fire risk for different practices

Practice			Lightning rods	Centralized Interim Storage	Unsealed Sources
Severity	Failures	to chain next process (%)	100	100	100
	Workers	exposure (% of 100mSv)	0.30	0.90	0.03
		# persons exposed	40	40	2
	Public	exposure (% of 1mSv)	0.30	1,00	3.30
		# persons exposed	10	50	1
		Severity (%)	17	27	6
Likelihood of Occurrence (%)			60	40	60
Likelihood of Detection (%)			50	50	10
Risk Priority Number (RPN)			50429	53286	3762
Actions to Reduce Severity, Occurrence of Failure or Increase Detectability			Fire Detectors / Alarm	Fire Detectors / Alarm	Fire Detectors / Alarm
			Extinguishers	Extinguishers	Extinguishers
			Controlled Access	Controlled Access	Controlled Access
			Removal of flammable materials		Removal of flammable materials
Severity	Failures	to chain next process (%)	100	100	100
	Workers	exposure (% of 100mSv)	0.30	0.90	0.03
		# persons exposed	40	40	2
	Public	exposure (% of 1mSv)	0.30	1.00	3.30
		# persons exposed	10	50	1
		Severity (%)	17	27	6
Likelihood of Occurrence (%)			4	5	4
Likelihood of Detection (%)			6	6	1
Risk Priority Number (RPN)			394	833	29

Upper part: Risk assessment for the initial conditions of each practice. Bottom part: Risk Priority Number reduction after applying the above actions and measures taken for optimizing safety and security. Risk Priority Number is the product of Severity, Occurrence and Detection. Severity is a multi-component factor considering failures in the whole chain of the multi-process practice; exposure of workers; and exposure of members of the public, in terms of percentage of the dose limit of 100 mSv for workers in emergency situation and the dose limit of 1 mSv for members of the public, respectively. 100% likelihood of detection means very unlikely for the risk to be detected

actions which can reduce the likelihood of occurrence or optimize the detectability of this risk are: to enforce the licence terms in the procedure of entering the package into the laboratory and to inspect the package visually with the appropriate instrumentation (Table 3).

Therefore, after the implementation of these actions which affects the likelihood of occurrence and the detectability factor their values are reduced by a factor of 1/23 and consequently the RPN is reduced. The comparison of the values of RPN prioritizes the risks and the steps-processes of a practice. For the above particular processes the preventive and protective actions has to be implemented firstly for the radioactive waste management, then for the storage process and lastly for the entering and the transferring of the radioactive material.

4 Conclusions

Conceiving realistic scenarios, and relations of the factors affecting the severity of risk, the probability of occurrence and the detectability of an incident, appears to be quite subjective. Radiation Protection Experts should inspect both equipment and procedures and interview experienced staff, to control the above mentioned subjectivity and to reveal hidden hazards. In this context, the proposed method can evaluate and prioritize the radiological risks for industrial and research practices.

For three different inventories, fire scenarios are analyzed. The higher collective dose (to the first responders and the public) is predicted for the centralized interim storage facility where a large number of DSRSs are stored. The interim storage facility of lightning rods yields relevant effective doses below 0.015 manSv per caput. The practice of unsealed radioactive source of P-32 for radio-labelling activities delivers less than 0.015 manSv. The use of breathing apparatus by the first responders indicates the minimization of the inhalation dose associated with the radioactive plume, by several orders of magnitude. Evacuation of the surroundings during the release of the radioactive plume significantly reduces the dose to the public. Nonetheless, even for the case of no-evacuation, the dose remains at low levels.

Table 3 Examined practice: Unsealed P-32 solution for radio-labelling of biological samples

Step-Processes in the Practice			Entering	Interim Storage	Transferring for use	Waste Disposal
Failure Mode			Contaminated Package	Uncontrolled access	Contamination at public areas	Exceeding the clearance levels
Failure Causes			No Inspection (Visual, Detector)	Irrelevant personnel in storage room	Storage room or counter located away	Inappropriate management, no measurements on exit
Failure Effects			Contamination, Unjustified exposure	Unjustified exposure	Contamination, Unjustified exposure	Unjustified exposure of the public
Severity	Failures	to chain-process (%)	80	60	80	1
	Workers	exposure (%)	0.2	0	0.2	0.2
		# persons exposed	1	0	1	1
	Public	exposure (%)	20	20	20	20
		# persons exposed	2	1	2	10
		Severity (%)	9	8	9	7
Likelihood of Occurrence (%)			6	8	6	7
Likelihood of Detection (%)			20	30	10	60
Risk Priority Number (RPN)			1120	1886	560	3140
Actions to Reduce Severity, Occurrence of Failure or Increase Detectability			Transporter should comply with license terms	Labelling packages with sign of radioactivity	Guidance for Unpacking	Records on wastes bags
			Visual Inspection	Exclusive use of storage room, lockers	Watertight box for transport	Measurements on exit of bags
			Inspection with Contamination Detector	Guidelines to irrelevant personnel	Find a closer location of storage room	
				Record keeping		
Severity	Failures	to chain-process (%)	80	60	80	1
	Workers	exposure (%)	0.2	0	0.2	0.2
		of persons exposed	1	0	1	1
	Public	exposure (%)	20	20	20	20
		of persons exposed	2	1	2	10
		Severity (%)	9	8	9	7
Likelihood of Occurrence (%)			2	1	1	2
Likelihood of Detection (%)			1	8	3	15
Risk Priority Number (RPN)			18	29	18	196

Processes: Entering the package of the radioactive solution into laboratory; storage; transferring the radioactive solution to the hood for use; disposing the produced radioactive wastes. For the scale of likelihood of detection, 100% means very unlikely for the risk to be detected

Therefore, the occurrence of traffic or crowding accidents, should be considered before the decision of evacuation is taken.

The fire risk is presented as an example of analysis that can be applied also for many other radiological risks. In addition, an example of risk assessment for a multi-process practice presented, in order to indicate that comparison of risks associated with different processes of a specific practice is attainable. Appropriate measures, like controlled access; fire detectors and fire extinguishers; secure storage; and records keeping, lead to optimization of safety and security of practices applied in industrial and research laboratories, like the ones presented in this work.

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