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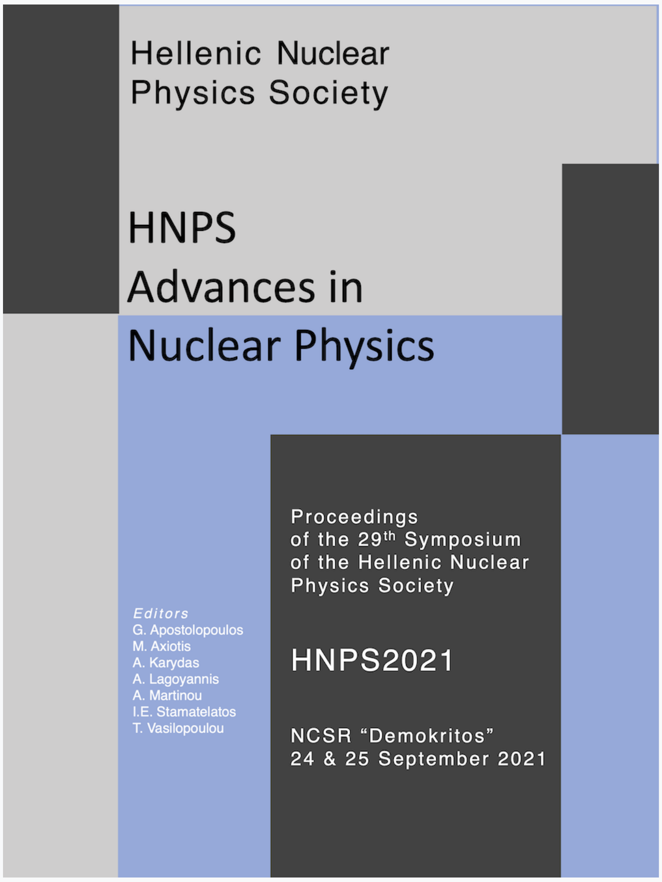

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Practical Guidance for Radiological Risk Assessment in Educational and Research Laboratories

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Abstract Using ionizing radiation, even in educational and research laboratories, is based on the triplet of principles of justification, optimization and dose limits. These principles are applicable to the risk assessment that follows the identification of hazards in specific applications of ionizing radiation. In this work, a practical procedure for the development of risk assessments is provided for the majority of research and educational practices, which include the use of unsealed and sealed radioactive sources and apparatus with tubes producing ionizing radiation. In addition, an example of radiological hazard of fire is analyzed, in order to classify the severity of such risk on radioactive materials and sources. The severity of the hazard and consequently of the risk, the probability of the hazard to occur and the detectability of the occurrence are analyzed and combined to yield a risk classification, which induces the manageme nt of the measures taken for the emergency preparedness and response. The proposed methodology considers worst case scenarios of external exposure, inhalation and ingestion [1] and compares the doses with criteria like the annual dose limits or the reference band of 20 – 100 mSv [2], in order to initially classify the hazards and therefore the severity on the risk assessment procedure. The results indicate low or medium severity of the risks for most of the educational and research applications. Moreover, specifically the radiological hazard of fire for the public and the first responders is not high due to the relatively low or moderate activities in use. Nevertheless, application of the principle of optimization reduces even more the risks with the appropriate measures, like: controlled access, fire detectors and extinguishers, secure storage and keeping of records.

Keywords Radiological Risk, Hazard, SRS, HASS, Unsealed Radioactive Source

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INTRODUCTION

The radiological risk assessment, in respect of occupational and public exposure, is a requisite for the authorization of a practice. Authorization means registration or licensing of a practice [3]. Radiation protection experts give competent advice on matters relating to compliance with applicable legal requirements and therefore, inter alia, prepare prior risk assessments and relevant written procedures for their laboratories. This work presenting some simplified steps on the direction of developing risk assessment. The practices involving radiological hazards in research and educational laboratories are related with the use, storage, transport and disposal of radioactive sources, materials and waste. Also, the use of tubes producing ionizing radiation are considered in radiological risk assessments. The plethora of educational and research practices can be classified, for the objective of this article, in practices with Sealed Radioactive Sources (SRSs); Unsealed Radioactive Sources (UnSRSs); and tubes emitting X-rays or other particle beams. Some examples of practices is useful to be mentioned: (a) irradiator with High Activity Sealed Source (HASS); (b) set of SRSs with activities a bit higher than the exemption levels [3]; (c) radiolabeling of chemical compounds and administration of radiopharmaceuticals to laboratory animals; and (d) X-ray tube for radiography of samples, like

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sediment-carrots or even animals.

In the early 90s, IAEA establishes the International Nuclear and Radiological Event Scale (INES) as an aftermath of the Chernobyl accident occurred in 1986. INES is a tool for communicating the safety significance of nuclear and radiological events to the public. Events are rated, in terms of severity, in 7 levels as it is depicted in Fig.1. Accidents are major importance events and incidents are lesser importance events.

Fig. 1. Schematic of the 7 levels rating of the nuclear and radiological events. The events are classified in accidents and incidents [4] (Reproducing with permission by IAEA).

In this work, only incidents are considered, because the total activities of the research and educational practices taken into account cannot cause so serious events as accidents. Even though a thorough analysis of hazards and associated risks should be conducted for workers, first responders and members of the public.

Several methods of risk assessment are in use [5]. One analytical method is Failure Modes and Effects Analysis (FMEA) which prioritizes the risk of each hazard (or failure) utilizing its severity, probability and detectability. In other words, hazards are prioritized according to how serious their consequences are, how frequently they occur, and how easily they can be detected. The objective of FMEA is to reveal the actions needed to eliminate or reduce risks, starting with the highest-priority ones.

FMEA prompts radiation protection experts to review, evaluate, and record the following:

- Distinct processes in the practice that involve ionizing radiation
- Failure modes (What could go wrong?)
- Failure causes (Why would the failure happen?)
- Failure effects (What would be the consequences of each failure?)

FMEA is utilized during design of practices to prevent hazards, and during ongoing practices whenever changes are scheduled. Ideally, FMEA begins during the earliest conceptual stages of design and continues throughout the whole practice that involves radiological risks. During the FMEA process, current knowledge and actions about the risks are recorded, for use in continuous improvement.

INVENTORIES, PRACTICES AND METHODS

Four main scenarios of inventories and the relevant practices are under investigation for the present work, all of them located in the basement of an old building of a research institute:

A) An irradiator with Co-60 High Activity Sealed Sources (HASS) and activity 185 TBq;

B) A set of SRSs with activities a bit higher than the exemption levels [3]. These SRSs are stored in a drawer of a bench and are used in γ-spectroscopy educational experiments;

C) UnSRSs for radiolabeling of chemical compounds with and administration of radiopharmaceuticals to laboratory animals;

D) An X-ray tube for industrial radiography of samples installed in a research laboratory.

For all the above cases, the Radiation Protection Officer or the Radiation Protection Expert with the consultation of the workers, should identify the relevant hazards. Hazards compatible with above cases (A) to (C) are: flood, fire, uncontrolled access and theft. Especially for case (A) an additional hazard is for the shutter to remain accidentally open (mechanical or electrical failure) and for case (C) skin contamination, inhalation and ingestion. Hazards compatible with case (D) are: uncontrolled access and mechanical or electrical failure causes beam-on incident.

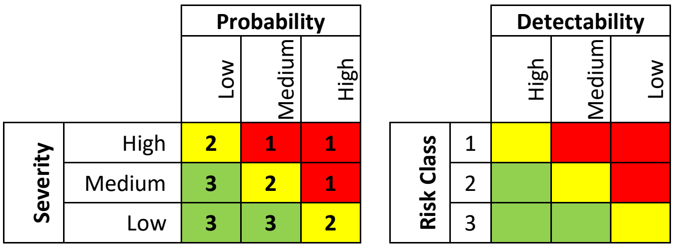

Fig. 2. Generic risk assessment classification method. Left: Risk class: Red=1, Yellow=2, Green=3. Right: Risk Priority: Red=High, Yellow=Medium, Green=Low.

A synopsis of the method for evaluating the risks can be seen in Fig.2. The 1st step (left schematic of Fig.2) classifies the risk, taking into account its severity and probability of occurrence. Severity may include sub-factors, like the exposure of workers or members of the public; the number of persons that been exposed; and the consequent failures that may be implied to the over-all chain-process of the practice. For instance, the severity of unauthorized use of an X-ray tube by a member of the public should include the number of the people exposed accidentally; their accidental exposure; and the failure of the forthcoming processes of the laboratory, in case the X-ray tube overheats and fails. Weighted contribution of the above should considered, as the severity of human exposure to the beam is higher than the severity of the failure of the forthcoming processes. Thus, a normalized equation could be built, combining those sub-factors. For the specific instance a suggested equation could be:

$$S = \frac{5 * E(\%) + 5 * \mathrm{N} + \cdots + \mathrm{F}(\%)}{5 + 5 + \cdots + 1} \qquad (1)$$

Where S is the severity of the risk, taking values from 1 to 100. E(%) is the percentage of the derived from the incident effective dose, to the dose limit. The dose limit could be equal to: 1mSv, valid for the public; 20mSv, valid for occupational exposure; 100mSv, valid for the workers in emergency situation. N is the number of persons exposed, considering that no more than 100 persons might be exposed. F(%) is the percentage of failures that may be occurred to the forthcoming processes, due to the incident. 5 and 1 are weighted factors in the scale 1 to 5. Finalizing this 1st step, the class of the risk is yielded by the product of the risk severity with its likelihood of occurrence.

The 2nd step (right schematic of Fig.2) of evaluating the risks takes into account the aforementioned classification of the risk and its likelihood of detection, in order to yield the Risk Priority Number (RPN). This number indicates the priority to be given to the confrontation of each relative risk. In this way, the available resources of the laboratory could be managed in more justifiable manner, targeting the reduction of RPN of each risk with a three-step procedure. Firstly, reduce high priority risks to medium priority risks; secondly reduce medium priority risks to low priority risks when possible; and at last, accept the remaining risks.

RESULTS AND DISCUSSION

Applying FMEA to the above mentioned (A) to (D) practices results to a systematic evaluation of the risks. The results for some of the above-mentioned hazards are analyzed here.

Risk of flood has medium probability for all the cases because they are installed in the basement. Despite that, the severity of such hazard differs from radiological point of view. In ascending order: The X-ray tube may get damaged, but no radiological effect will occur. The irradiator may get damaged as well, but its HASSs will remain in their position, inside irradiator shielding. The SRSs set stored in a drawer of a bench may be moved away from their initial position due to their small mass, but even if they are lost, their activities are too low for considering high exposure to members of the public or workers. The UnSRSs may diluted into the flood or moved away from their initial position, so the probability of surface contamination is high. Obviously, the detectability of a serious flood that may affect the above inventories is high. Therefore, applying the method of Fig.2, the 1st risk priority may be given to (C), the 2nd to (B), the 3rd to (A) and the 4th to (D). This means that if an appropriate empty room is available at the upper floors of the building, priority for the moving should be given to the laboratory of (C). This initial simplified outcome for the radiological risk of flood should be combined with other aspects, such as the cost of retrieving the HASSs from a possibly damaged by the flood irradiator. Then the priority for (A) should be set higher. In addition, other preparedness measures, like the installation of mechanical pumps or some kind of engineered barriers should be considered to prevent the rise of the waterline. In this manner, every additional measure decreases the probability of occurrence or the severity of the flood.

For a single case, like case (C), several distinct processes must be examined for their relevant risks. Table 1 shows such risk assessment, which can be done for every multi-process case, comparing the priorities of risks concerning a specific practice. The final rows show how severity, probability and detectability affected, after taking measures to reduce RPN factors.

For the risk of fire, one has to take into account not only the case of radioactive material catches fire, but also the rising of temperature in the room to the point that the radioactive material may be sublime and dispersed into the air of the room. Considering scenarios with some flammable materials been stored in adjacent rooms, the risk of fire has medium probability of occurrence. For case (B): two SRSs, one Cs-137 and one Co-60 with activities 37kBq each one, are stored in the wooden drawer of a bench; and for case (A): the irradiator room containing some flammable materials (e.g. Styrofoam boxes), so the initial probability of fire is high. The severity can be calculated by equation (1). During the fire a release of radioactive material may be happen. The percentage of the affected radioactive material which may be dispersed is higher for case (C) where the sources are unsealed. The SRSs of case (B) are more vulnerable than the well confined HASSs of case (A). In fact, the probability for the fire to surpass the thick shielding of the irradiator and reach the HASSs is negligible. Despite that, rising of temperature for long time into the room may give rise to the temperature of the HASSs, due to induction. Considering that the radioactive plume occupies homogeneously the room [6] and a person inhales a minor part of the radioactive plume, its dose can be estimated roughly using the reference values of Delacroix et al [1] for inhalation dose. For instance, in case of radiolabeled with P-32 samples, assuming that 10% of their total activity of 30MBq are dispersed into the plume due to fire and a person inhales 2% of that plume, the dose is: $0.02\times3\cdot10^{6}$Bq$\times1.1\cdot10^{-9}$Sv/Bq=0.066mSv. Respective calculations can be done for every radioisotope, percentage of release and percentage of inhalation and for combination of different radioisotopes. In the upper part of Table 2, the radionuclide; the inhalation dose factor [1]; the rate of the plume which is inhaled by a person; the rate of the initial activity dispersed into the plume; and the initial activity of the sources, per each practice of interest, are shown. Taking into account these elements, the effective dose to the dose limit rate (exposure (%)) is calculated. In addition, given for all the cases, that two workers and one member of the public are exposed to the radioactive plume and failure to the chain-process (F) is 100%, the severity is calculated in the middle part of Table 2. In the lower part of Table 2, the changes in probability and detectability of the risk and the consequent decrease of RPN, based on actions and measures, like removal of flammable materials; controlled access; fire detectors; and extinguishers, are presented.

Radiological hazard due to fire for case (D) can be considered not applicable, due to the absence of radioactive material to be dispersed. Nevertheless, electrical or mechanical failures may be occurred to the X-ray system or the room shielding may be affected after a fire in the installation, so the appropriate inspections should be conducted. Also the detectability in this case is considered 1 (instead of 10 for the other cases), because there is no need for specific inspections, like smear test, to reveal any dispersion of radioactive material.

The detectability of fire usually is high. Once again, the product of severity, probability and detectability determines the priority of each case. Removal of the flammable materials, controlled access, presence of fire detectors and extinguishers are measures that can been taken for the reduction of probability or severity of the radiological risk of fire.

Hazards like theft; irradiator shutter remaining accidentally open; skin contamination; ingestion; mechanical or electrical failures can be analyzed similarly, in order to prioritize the relevant radiological risks. Radiation Protection Experts or Officers, via interviewing experienced personnel and inspecting equipment and procedures, can reveal hazards which are not obvious for specific practices.

CONCLUSIONS

Taking into account the subjectivity of conceiving realistic scenarios, and relations of factors affecting severity of risk, probability of occurrence and detectability of event, Radiation Protection Officers and Experts should interview experienced personnel, inspect equipment and procedures, in order to reveal no-obvious hazards and to decrease the above-mentioned subjectivity, for specific practices. In this context, the proposed method can be utilized for assessment of radiological risks. Taking into account the examples analyzed in this work, approximate risk analysis can be attained for a plethora of practices involving ionizing radiation in research and educational laboratories.

Risk of flood and fire are presented as two examples of analysis that can be applied to many other radiological risks. In addition, an example of risk assessment for a multi-process practice presented, to make clear that comparison of different risks associated with a specific practice is attainable, prior or during its implementation.

Appropriate measures, like controlled access; fire detectors and extinguishers; secure storage; and keeping of records, lead to optimization of safety and security of most of the practices applying in research and educational laboratories.

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Table 1 (see next page): An example of multi-process practice, involving one or more failures for each process. Examined practice: UnSRSs for radio-labeling of biological samples. Processes: Bring in the radioisotope into laboratory; Storage of radioactive substances; Carrying radioactive substances for using or measurement; Using (dispensing; labeling, measurement); Waste disposal. 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 100mSv for workers in an emergency situation and the dose limit of 1mSv for members of the public, respectively.

Steps in the Process			Bring in	Storage	Carry	Using #1	Using #2	Waste Disposal
Failure			Contaminated Package	Uncontrolled access	Contamination at public areas	Contamination at controlled areas	No use of shielding	Exceeding clearance levels
Failure Causes			No Inspection (Optical, Detector)	Irrelevant personnel in storage room	Storage room or counter located away from laboratory	Derogations in using instructions	Lack of information about radiation protection	Inappropriate management, no measurements on exit
Failure Effects			Contamination, Unjustified exposure	Unjustified exposure	Contamination, Unjustified exposure	Contamination, Unjustified exposure	Unjustified exposure	Unjustified exposure of the public
Severity	Failures	to chain-process (%)	80	60	80	80	10	1
	Workers	exposure (%)	0,2	0	0,2	0,2	16	0,2
		# persons exposed	1	0	1	1	1	1
	Public	exposure (%)	20	20	20	1	10	20
		# persons exposed	2	1	2	1	1	10
		Severity (%)	9	8	9	5	7	7
Likelihood of Occurrence (%)			2	4	2	10	3	3
Likelihood of Detection (%)			20	40	10	10	10	70
Risk Priority Number (RPN)			373	1257	187	457	214	1570
Actions to Reduce Severity, Occurrence of Failure or Increase Detectability			Transporter should comply with license terms	Labeling packages with the sign of radioactivity	Guidance for unpacking	Guidance for Using procedures	Lectures to personnel periodically	Records for closing and exit of bags
			Optical Inspection	Exclusive use of the storage room	Watertight box for transport	Lectures to personnel periodically	Lectures to newcomers	Measurements on exit of bags
			Inspection with Contamination detector	Guidance to irrelevant personnel	Look for closer location of storage or counter room	Lectures to newcomers		
				Lockers				
				Record keeping				
Severity	Failures	to chain-process (%)	80	60	80	80	10	1
	Workers	exposure (%)	0,2	0,2	0,1	0,1	8	0,2
		# persons exposed	1	0	1	1	1	1
	Public	exposure (%)	20	20	2	1	10	2
		# persons exposed	2	1	1	1	1	2
		Severity (%)	9	8	5	5	5	1
Likelihood of Occurrence (%)			1	1	1	3	2	1
Likelihood of Detection (%)			5	20	10	10	10	70
Risk Priority Number (RPN)			47	158	48	152	79	90

Table 2: An example of assessing and comparing the risk of fire for different practices. Upper (Blue) part: Elements for calculating the exposure. Middle part: Risk assessment for the initial conditions of each practice. Bottom part: RPN reduction after applying the above actions and measures taken for optimization of safety and security.

Practice	**Isotope**	**Inhalation dose (Sv/Bq)**	**Part of plume inhaled**	**Activity in plume / Initial Activity**	**Initial Activity (Bq)**
Irradiator HASSs	^{60}Co	7,1E-09	0,02	0	1,85E+14
SRSs	^{137}Cs, ^{60}Co	6,70E-09	0,02	0,001	3,70E+04
Unsealed Sources	^{32}P	1,1E-09	0,02	0,1	3,00E+07

Practice			Irradiator HASSs	SRSs	Unsealed Sources	X-ray tube
Severity	Failures	to chain-process (%)	100	100	100	100
	Workers	exposure (%)	0,00E+00	4,96E-06	6,60E-02	0
		# persons exposed	0	2	2	0
	Public	exposure (%)	0,00E+00	4,96E-04	6,60E+00	0
		# persons exposed	0	1	1	0
		Severity (%)	5	5	7	5
Likelihood of Occurrence (%)			60	60	50	50
Likelihood of Detection (%)			10	10	10	1
Risk Priority Number (RPN)			2857	3286	3532	238
Actions to Reduce Severity, Occurrence of Failure or Increase Detectability			Fire Detectors / Alarm	Fire Detectors / Alarm	Fire Detectors / Alarm	Fire Detectors / Alarm
			Extinguishers	Extinguishers	Extinguishers	Extinguishers
			Controlled Access	Controlled Access	Controlled Access	Controlled Access
			Removal of flammable materials			
Severity	Failures	to chain-process (%)	100	100	100	100
	Workers	exposure (%)	0,00E+00	4,96E-06	3,30E-02	0,00E+00
		# persons exposed	0	2	2	0
	Public	exposure (%)	0,00E+00	4,96E-04	6,60E-01	0,00E+00
		# persons exposed	0	1	0,5	0
		Severity (%)	5	5	6	5
Likelihood of Occurrence (%)			15	20	17	17
Likelihood of Detection (%)			3	3	3	0
Risk Priority Number (RPN)			238	365	307	26