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A RISK-BASED METHODOLOGY FOR THE PRIORITIZATION OF RADIOACTIVE SOURCES

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Abstract

The identification of the types of radioactive sources that should be protected from adversary use is likely the most important consideration when preparing regulations for and implementing a radioactive source security program. Such identification is dependent on radionuclides in use and radioactivity thresholds as required by the regulatory body. The IAEA categories used for this purpose represent particular safety scenarios based on deterministic effect consequences. They, therefore, do not consider the likelihood of encounter of a threat actor with a radioactive source of such consequence, the other part of the risk equation.

A downselect methodology has been developed that is useful to identify source types presenting the greatest threat. This is a six-step process that identifies such sources and applications for prioritization of security measures. The results provide a technical basis necessary for development of regulation and design and implementation of source security programs by a state or entity.

1. INTRODUCTION

The need for security for radioactive sources was identified by the IAEA as important prior to 1998. In that year, the first conference, *Safety of Radiation Sources and Security of Radioactive Materials* too place in Dijon France [proceedings]. At that conference, presentations were given on a series of accidents involving sources over the previous few decades, accidents being the focus. Illicit trafficking was also identified as having occurred and of importance. Radionuclides of concern were not identified at this time, but over the next decade applications of sources that could present a risk of accidental or purposeful exposure were identified.

In 2000, the IAEA published a report documenting an effort to categorize radioactive sources based on perceived consequences of accidental use [1]. Such categorization was based on injury to exposed individuals, but it was recognized that economic, social, and political consequences were also possible. Injury scenarios included:

- External exposure to an individual from a source in very close proximity
- External exposure from unshielded source (involving several individuals)
- Exposures following rupture of source casing

The categorization at this time was applied to source applications, loosely related to amounts of radioactivity. The categories identified and applications are shown in Table 1. Control measures for each category were provided, but generally addressed safety administratively and not security.

In 2003 this system was re-designed to include the concept of the *D-value* [1]. These *dangerous quantities* are described as "radionuclide-specific activity levels for the purposes of emergency planning and response."

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Categories were re-defined as shown in XREF to those codified in the *IAEA Code of Conduct on the Safety and Security of Radioactive Sources* currently in use [2].

Table 1: Source categories as initially promulgated by the IAEA

Category	Application
Category 1	Industrial radiography
	Teletherapy
	Irradiators
Category 2	HDR brachytherapy
	Fixed industrial gauges involving high activity sources
	Well logging
	LDR Brachytherapy
Category 3	Fixed industrial gauges involving lower activity sources

Table 2: IAEA categories based on A/D and applications

Category	Application	Activity ratio (A/D)
Category 1	Radioisotope thermoelectric generators	A/D ≥ 1000
	Teletherapy	
	Irradiators	
	Fixed, multi-beam teletherapy	
Category 2	Industrial gamma radiography	1000 > A/D ≥ 100
	High/medium dose rate brachytherapy	
Category 3	Fixed industrial gauges	10 > A/D ≥ 1
	Well logging gauges	
Category 4	Low dose rate brachytherapy (not Category 5)	1 > A/D ≥ 0.01
	Thickness/fill-level gauges	
	Portable gauges	
	Bone densitometers	
	Static eliminators	
Category5	LDR brachytherapy eye plaques and permanent implants	0.01 > A/D ≥ EQ
	X ray fluorescence devices	
	Electron capture devices	
	Mossbauer spectrometry	
	PET checking	

These categories have allowed for the development of safety and security protocols worldwide, allowing for continuing safe use of radioactive sources.

The current IAEA category system does have shortfalls. Being based on D-values as described, the category thresholds do not account for security aspects of source trafficking and pernicious use. IAEA TECDOC-1191 stated that there were important effects not addressed such as economic, social, and political consequences. Economic consequences themselves could be significant at Category 3 or lower amounts. The system also does not include a prioritization of sources for security measures, addressing only the broad categories described.

2. DOWNSELECT BASIS AND METHODOLOGY

The IAEA category system has been codified in the United States of America within regulations promulgated by the U.S, Nuclear Regulatory Commission. This includes requirements for security of sources depending on the IAEA category level. These regulations increase source security nationwide by requiring users to implement safety protocols. However, as in the IAEA code of conduct do not allow for identification of sources of particular risk or other prioritization. As such, a downselect methodology has been developed.

The downselect methodology is a seven step process as shown in Table 3. The process begins with identification of all known nuclides. For this step. The *LiveChart of Nuclides* tool of the Nuclear Data Section of the IAEA [3]. The number of nuclides in that database at the time of analysis in 2019 was 3283 nuclides.

Table 3: Six steps in downselect process

Step	Action	Remaining # Nuclides
Step 1	Consider all nuclides	3283
Step 2	Eliminate stable nuclides	3038
Step 3	Eliminate all with T < 36 days	214
Step 4	Eliminate all with specific activity > 1700 kg/GBq (100 lb/Ci) T > 68 million years	173
Step 5	Eliminate all without some global production	66
Step 6	Eliminate all without known medical or industrial use	39
Step 7	Eliminate all but category 1, 2, high category 3 amounts available as single source	5

Since this is an analysis of radionuclides, the next step is to remove those that are stable. The 245 stable nuclides were deleted from the full list leaving 3038 radionuclides.

The following two steps comprised an analysis of the radiological half-life. The limits placed on those two steps were somewhat subjective. The first was a consideration of the rate of decay. If a radionuclide decays too quickly, its usefulness as a radiological threat is much reduced. The subjective decision point for this threshold that was used in this analysis was 36 days or approximately one tenth of a year. This point was chosen because all exposure from the source would occur in one year or less, after which the source has effectively decayed away. The vast majority of radionuclides are eliminated in this step as shown in Figure 1.

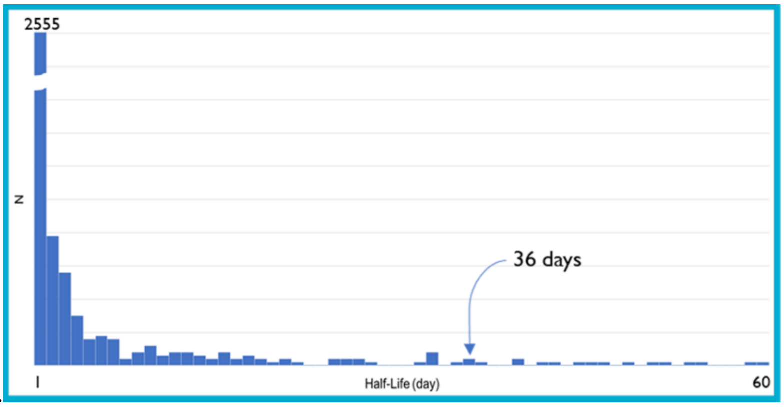

Figure 1: Histogram of binned radiological half-lives of the set of 3038 radionuclides

Step 4 was a consideration of the mass needed to incorporate into some type of radioactive device that would then have to be transported to a target location. As a primarily American activity, the limit chosen was based on pounds of weight per curie of activity and set at 100 lb/Ci, approximately 1700 kg/GBq. Since specific activity can be calculated directly from the radiological decay constant, ($\ln 2/T_{1/2}$), a threshold in terms of half-life can be calculated. This half-life is approximately 68 million years. This step removed 41 additional radionuclides leaving 173.

The next two steps considered availability of sources. Step 5 involved a literature search for radionuclides that are currently produced globally. This included those produced in research reactors and cyclotrons, medical uses, and available for purchase. A further 107 were discarded in this step, reducing the number to 66. Step 6 removed any that were not used in industrial or medical activities. The 39 radionuclides retained are more likely to be available to the general public.

Not all radionuclides being produced and available for purchase are available such that a single source or device containing sources has enough activity for use in a radiological dispersal device. The parameter considered for this step is the protective action guide promulgated by the U.S. Environmental Protection Agency for relocation of members of the public of 20 mSv in the first year of exposure. Single sources or devices with multiple sources which, if distributed, could result in a dose of this magnitude were retained, with all others removed. This step resulted in the final five radionuclides retained. These sources are shown in Table 4.

Table 4: Radionuclides remaining after downselect analysis with applications

Radionuclide	Application	Nominal radioactivity
Ir-192	Industrial radiography	6 TBq
Se-75	Industrial radiograph	6 TBq
Cs-137	Blood and medical irradiators	100 TBq
Co-60	Panoramic irradiators	400 TBq/rod
Am-241	Well logging	600 GBq

3. CONCLUSIONS

The results of this analysis were in no way unexpected. As indicated in Table 1, irradiator and radiography were identified early on in the timeline of consideration of safety and security of radioactive sources as within the non-quantitative Category 1 and well-logging in Category 2. International efforts in the security of these radionuclides has been ongoing for two decades.

The radiography market is slowly but continually changing. The use of Se-75 has become more prevalent because the energies of emitted gamma rays are lower, but can be used for similar applications as that for Ir-192. Safety protocols for Se-75 are reduced from those for Ir-192, so for those states that require significant controls for radiography sources, Se-75 use is increasing. However, the use of Ir-192 reduces the time required for exposures, so its use remains considerable [4].

There is reduction in some irradiator applications, particularly blood irradiation but also irradiators used for medical research. These irradiators are being replaced with alternative technology methods such as x-ray irradiators or, in some cases, non-radiological alternatives. Technologies such as the use of ethylene oxide and electron beam are used as an alternative to Co-60 panoramic irradiators [4]

A periodic reanalysis using this methodology is useful to identify if emerging applications of particular sources increases the prevalence of the existing radionuclides of concern or if there are other radionuclides not previously identified need to be identified and secured.

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