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EVALUATION OF A POTENTIAL RDD RISK POSED BY NON-REACTOR RADIONUCLIDE PRODUCTION TECHNOLOGIES

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Abstract

Most of the radionuclides used for industrial or medical applications cannot be found in nature and must be produced artificially by bombarding targets with nuclear particles. Presently, nuclear reactors are the main technological means for producing radionuclides. Charged-particle accelerators and other radionuclide-producing technologies are significantly less costly, and can be easily acquired by a hospital or an industrial enterprise. In the paper, a full range of non-reactor radionuclide production technologies are evaluated from the standpoint of generating enough material for a radiological dispersal device (RDD). The capabilities, capacities and potential dangers they can pose are assessed. A wide spectrum of technologies was analyzed, such as charged particle accelerators, spallation neutron sources, neutron generators, and electron beam x-ray systems. It was found that currently non-reactor radionuclide technologies present a low to very low risk.

1. INTRODUCTION

Most radionuclides used for industrial or medical applications cannot be found in nature and must be produced artificially by bombarding targets with nuclear particles. Presently, nuclear reactors are the main technological means for producing radionuclides, as they provide superior neutron fluence rates, long-term operational stability for materials activation and fissioning, and a wide range of possible nuclear reactions, which translates into high production rates and a large number of possible radionuclides that can be produced. The main disadvantages associated with using reactor technology for radionuclide production are the extremely high capital costs and remote locations from hospitals or industrial installations where radionuclides are used. Charged-particle accelerators and other radionuclide-producing technologies are significantly less costly, and can be easily acquired by a hospital or an industrial enterprise. At the same time, charged-particle accelerators are only capable of producing a certain set of radionuclides and presently cannot replace reactors for the production of many radionuclides. Their production capacity is also limited compared to nuclear reactors. Most accelerator facilities are being used to produce small quantities of short-lived radionuclides that are generally considered not to be radiological dispersal device (RDD)-useable. It is important to note that recently, new commercial systems have been developed that are capable of accelerating charged particles up to 70 MeV, which is a theoretical limit for cyclotrons and until recently could only be achieved on large industrial machines. Combined with higher currents, which translate into higher production capacity, these devices potentially could be used to produce longer lived radionuclides in significant quantities.

A significant effort has come about in the past several years to replace some traditional radiation sources with alternative technology devices for the purposes of enhanced safety and security. There have also been significant developments in radionuclide production technologies. Some of these new technological advances provide capabilities for undeclared or covert generation of radionuclides that potentially could be used to build an RDD. In addition, some of the radionuclides that were not considered as RDD risk due to relatively low world-wide inventory or short radiological half-life could now pose a higher risk than previously identified.

2. RISK ASSESSMENT FOR RADIONUCLIDE GENERATION TECNOLOGIES

2.1. Risk Analysis Procedure

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Risk analysis for this study was based on the common definition of risk as a product of the probability of an event and its consequences.

$$Risk = Probability\ of\ Event \cdot Consequences$$

When an RDD scenario is considered, the consequences are determined by the specific radionuclide(s) that was used, its quantity and the size of contaminated area. Quantities considered dangerous were calculated using Turbo FRMAC software [1] and based on the US Environmental Protection Agency (EPA) 0.02 Sv (2 rem) relocation protective action guides (PAG) criteria [2].

'Probability of event' in this case is a relative term which was assessed on a 'low' to 'high' scale, rather than by quantifying it. This assessment was based on understanding the capability of various technologies to produce significant quantities of RDD-useable radionuclides in a reasonable period of time. It was determined by the risk analysis of various radionuclide production technologies using the following procedure. First, all potential technologies of interest were identified. After the full list was compiled, all technologies were evaluated based on the number of parameters, such as product radionuclides, production capacity, commercial availability, costs and complexity of operation. A set of potential misuse scenarios was applied to the technologies that were identified as a potential RDD risk. Based on the outcome of the scenario analysis, the conclusions were drawn on the overall risk posed by radionuclide production technologies.

2.2. RDD Threat Posed by Charged Particle Accelerators

Charged particle accelerators are gaining more popularity and are growing significantly in numbers. Accelerators are presently used to supply radionuclides for medical, diagnostic, and industrial purposes. Cyclotrons were the first accelerators used for this purpose and they continue to dominate the radionuclide production market. There are approximately 1200 cyclotrons around the world and data shows that this number is growing by about 10% annually [3].

The two main requirements for producing radionuclides using a charged particle accelerator are: the beam energy must be higher than the reaction threshold, and the beam current must be sufficient to produce a useable quantity. More than 50 radionuclides can be produced using accelerators [4]. A majority of those radionuclides are short-lived and are not suitable for use in an RDD for that particular reason. Nevertheless, for the completeness of this evaluation, all radionuclides produced by charged particle accelerators were analyzed. The analysis process included the following steps. First, the full of list radionuclides was compiled and those with a half-life longer than seven days were extracted. For this selected group, the EPA 0.02 Sv (2 rem)PAG concentrations were then calculated using Turbo FRMAC. This allowed for an understanding of how much material would be needed to build a 'significant RDD'[1]. Next, an understanding on how much time would be needed to produce a significant amount of material. This was done by calculating production rates based on nuclear reactions and required incident particle energy and reaction cross-sections.

$$A = \sigma \cdot I/e \cdot l \cdot \rho \cdot N_a/M \cdot \left(1 - e^{-\lambda t}\right) \tag{1}$$

where:

- A – activity produced
- σ – reaction cross-section at a specific energy
- I – beam current in amps
- e – electron charge in coulombs
- l – target thickness in cm
- ρ – target density in g/cm^3
- N_a – Avogadro's number
- M – molar mass in g
- t – irradiation time in seconds
- λ – product radionuclide decay constant

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[1] Here 'significant RDD' is considered to be a device capable of contaminating 1 km^2 to the levels equal or higher than the 0.02 Sv (2 rem) PAG criteria.

For further analysis it was necessary to specify a 'reasonable time period' for an adversary to produce a significant quantity of a radionuclide to be used in an RDD. Based on discussions with experts, a 'reasonable time period' was selected of no more than 96 hours. The main consideration was an amount of time during which a potential insider adversary could possibly gain sole access to a facility over a long, four-day holiday weekend.

Production rate calculations were based on an assumption of 700 μA current, which is a typical value for modern devices. Expected production rates were then compared to a 'significant RDD' quantity for each radionuclide. If the production rates for a particular radionuclide were within 90% margin from the 'significant RDD' quantities, this radionuclide was further analyzed.

Using this methodology, four radionuclides were selected for further investigation: ^{48}V, ^{68}Ge, ^{88}Y and ^{225}Ac. Some important properties of the selected radionuclides are summarized in the following sections.

2.2.1. Radionuclide Characteristics: Vanadium-48

Production. Vanadium-48 is produced from ^{48}Ti (73% natural abundance) using a ^{48}Ti(p,n)^{48}V reaction with a required proton energy of ~17MeV. Naturally occurring titanium is considered to be the best choice for target material [5] [6].

Common Uses. This radionuclide is considered as an alternative to ^{68}Ge for PET-scan procedures. It has a strong annihilation emission, which makes it a good candidate for this application. A fairly short half-life makes transportation challenging and requires a production capability for ^{48}V to be located close to consumers.

RDD Usability. Vanadium-48 has a half-life of 16 days and 50% of its decay is by positron emission. It has two high-yield, high-energy gamma rays at 984 keV and 1312 keV [4]. The f_1 value[2] for ^{48}V is 0.01. The quantity for a 'significant RDD' based on the 0.02 Sv (2 rem) PAG relocation limit for ^{48}V is 4.48 TBq (121 Ci). Vanadium is a silvery-white metal and it has excellent corrosion resistance at room temperature. Its gamma radiation emission and low internal dose coefficient means that ^{48}V poses a primarily external exposure threat. With the added consideration of a fairly short half-life, complicated accelerator targetry (i.e. target design) and separation chemistry, producing ^{48}V using an accelerator is not an attractive RDD scenario.

2.2.2. Radionuclide Characteristics: Germanium-68

Production. Germanium-68 is produced through an alpha reaction on natural zinc, ^{nat}Zn(α,x)^{68}Ge, or by proton reaction on either natural gallium, ^{nat}Ga(p,x)^{68}Ge, or more often ^{69}Ga, ^{69}Ga(p,2n)^{68}Ge, with a required proton energy of ~30MeV. Target manufacturing and post-irradiation reprocessing is a complicated process, requiring significant expertise and special equipment. The process is well described in IAEA TRS no. 468 [4].

Common Uses. Germanium-68 is mainly used as a calibration source for PET. The decay of ^{68}Ge to ^{68}Ga makes ^{68}Ge a useful long-lived, positron-only source for use in PET instruments. It can also be used to generate ^{68}Ga on an ion exchange column, which can then be used in biomedical experiments [4].

RDD Usability. Germanium-68 decays into ^{68}Ga via electron capture with no additional emissions. However, it is in equilibrium with its daughter ^{68}Ga, which has a significant intensity of annihilation photons (178.28%) and a gamma-ray at 1077.3keV at 3.22% intensity. The quantity for a 'significant RDD' based on the 0.02 Sv (2 rem) relocation PAG for ^{68}Ge is 1.25 TBq (33.9 Ci). The f_1 value for ^{68}Ge is 1.0. However, complicated target manufacturing and reprocessing makes ^{68}Ge not an attractive RDD material.

2.2.3. Radionuclide Characteristics: Yttrium-88

Production. Yttrium-88 is produced from ^{88}Sr via the ^{88}Sr(p,n)^{88}Y reaction at proton energy of ~15MeV [4].

Common Uses. Mostly used as a substitute for ^{90}Y in development of cancer tumor therapy.

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[2] f_1 value - fractional absorption in the gastrointestinal tract is the fraction of an ingested element absorbed directly into body fluids.

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RDD Usability. Yttrium is a silvery metal chemically similar to lanthanides. Yttrium-88 decays into ^{88}Sr via electron capture. The decay is accompanied by two major gamma-rays at 898 keV and 1836 keV with intensities of 94.4% and 100% respectively. The quantity for a 'significant RDD' based on a 0.02 Sv (2 rem) PAG relocation limit is 888 GBq (24 Ci). The f_1 value for ^{88}Y is 0.0001

The source isotope of ^{88}Sr is the naturally-occurring, stable and the most abundant (82.58%) isotope of strontium. Strontium is fairly easy to purchase and is commercially sold as food supplement. Therefore, it is easy to obtain the source material to produce ^{88}Y. However, complicated target manufacturing and reprocessing makes ^{88}Y not an attractive RDD material.

2.2.4. Radionuclide Characteristics: Actinium-225

Production. There is only one favorable reaction for the production of ^{225}Ac on an accelerator: ^{226}Ra(p,2n)^{225}Ac at proton energy of ~16.8MeV [4].

Common Uses. Actinium-225 is used for radioimmunotherapeutic applications using alpha emissions to target cancer cells.

RDD Usability. The quantity for a 'significant RDD' based on the 0.02 Sv (2 rem) relocation PAG for ^{225}Ac is 1.50 TBq (40.4 Ci). This limit is fairly low primarily because ^{255}Ac is a precursor for a decay chain where most of the emissions associated with the decay chain are alpha-particles. There are also a few significant gamma-rays produced shown in Table 1. The f_1 value for ^{225}Ac is 0.0005, therefore alpha particle emission is not going to present a serious threat for this radionuclide.

TABLE 1. SIGNIFICANT GAMMA-RAY ENERGIES ASSOCIATED WITH ^{225}AC DECAY CHAIN [4]

Radionuclide	Gamma-ray energy, keV	Yield, %
^{225}Ac	99.8	1.00
^{221}Fr	218.12	11.18
^{213}Bi	440.45	25.94
^{209}Tl	465.14	1.9

Since the most effective way to produce ^{225}Ac is irradiation of ^{226}Ra it would make little sense for an adversary to go through the extra steps of making ^{225}Ac instead of just using ^{226}Ra itself. For this reason, it is suggested that production of ^{225}Ac for RDD construction to be considered a low threat pathway.

2.2.5. Charged particle accelerator summary

RDD Threat: Based on the analysis above, the conclusion is that charged particle accelerators pose a low RDD threat. An overwhelming majority of the radionuclides produced by these devices are short-lived and therefore not practical for RDD construction. Production of the selected four accelerator-produced radionuclides is considered a low threat pathway due to both complex accelerator targetry and chemical separations which would be required to produce significant quantities of these radionuclides.

2.3. RDD Threat Posed by Linac-Based High-Energy Photon Sources

High-energy photons can be used to induce nuclear reactions. Currently, the use of this method for radionuclide production is limited. There are certain contstraints associated with this technique. However, for ^{99}Mo generation through the ^{100}Mo(γ,n)^{99}Mo reaction [7], these possible limitations are not significant. The radiation range of a high-energy photon (between 10 and 30 MeV) in ^{100}Mo is ~10 mm, is significantly longer than the range of a proton of the same energy. Consequently, the effective target thickness is much larger for photo-neutron reactions compared to proton-induced reactions [7]. NorthStar Medical Radioisotopes, LLC, is constructing the first facility in the US for non-reactor production in Beloit, Wisconsin [8].

RDD Threat: Molybdenum-99 is not considered to be a high threat as an RDD useable material due to a short half-life of 66 hours.

2.4. RDD Threat Posed by Spallation Neutron Sources

Spallation neutron sources (SNS) have the capability to produce a full range of radionuclides that can be produced using nuclear reactors. These devices are also capable of producing high neutron fluence rates (comparable to nuclear reactors), which means they can produce large quantities of material in a fairly short period of time. However, this technology is extremely expensive (on the order of billions of dollars) and complex. For example, SNS at Oak Ridge National Laboratory took five years to construct with overall costs of $1.4 billion [9]. Currently, there are only 11 SNSs in eight countries (see Table 2) and all of them are a part of large government facilities with high levels of physical protection and security arrangements. Operation of these devices is extremely complex, requiring multiple operators to be present at the same time, which would make an insider's misuse extremely difficult.

TABLE 2. SPALLATION NEUTRON SOURCES AROUND THE WORLD

Location	Name
Switzerland	Swiss Spallation Neutron Source (SINQ)
Switzerland	CERN: n-TOF facility
USA	ORNL SNS
USA	LANL LANSCE
China	China Spallation Neutron Source (CSNS)
UK	Rutherford Appleton Laboratory, ISIS
Sweden	European Spallation Source (ESS)
Japan	Japan Proton Accelerator Research Complex (JPARC)
Canada	TRIUMF: UCN facility
Russia	Neutron Complex of the INR RAS

RDD Threat: Based on this analysis, it was determined that the risk posed by SNSs is extremely low due to complexity of operation and high levels of physical protection and security at the sites hosting these devices.

2.5. RDD Threat Posed by Neutron Generators

Neutron generators are primarily used for research and industrial purposes. From the standpoint of radionuclide production, the basic capabilities of neutron generators are the same as those of nuclear reactors. The main difference is the production scale because of the much smaller neutron fluence rates produced by neutron generators, quantities of materials that can be produced are significantly smaller compared to nuclear reactors. Most of the commercially available systems allow the production of up to 10^{10} n/s. For comparison, neutron beams of up to 10^{13}-10^{14} n/cm^2/s can be produced in nuclear reactors. In addition, generator produced neutrons have high energies (2.5 or 14 MeV depending on fusion reaction used), which means that a significant portion of the output will be lost during a thermalizing process.

Capabilities: Typical neutron tubes generate 10^6 neutrons/pulse and pulse 100 times per second to yield 10^8 neutrons/s. Higher neutron output rates (10^{11} neutrons/s) can be achieved in some larger units. Several neutron generators with neutron outputs ranging from 10^7 to 10^{14} neutrons/s have been developed [10].

Applications: Neutron generators can effectively be used for elemental analysis with neutron activation analysis and prompt gamma neutron activation analysis techniques. They are also effective for analysis of hidden materials by neutron radiography. Traditional neutron generators have been shown to be effective for applications including borehole logging, homeland security, nuclear medicine and the online analysis of aluminium, coal and cement. Potential applications in landmine detection, cargo screening, archaeology, and isotope production have also been proposed. The availability of a new generation of low-cost neutron generators offers the opportunity for professional and technical training at universities and at research institutes for physicists, chemists, nuclear engineers, biologists, radiologists and health physicists. More detailed information about applications and use of neutron generators can be found in the IAEA report, *Neutron Generators for Analytical Purposes* [11]. A list of select commercially available devices with manufacturer declared neutron output levels is compiled in Table 4.

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As neutrons produced by both D-D and D-T reactions have high energies, to activate any materials or to produce radionuclides, neutron thermalization and collimation would be needed. This moderation would decrease flux and typically produces a high gamma radiation background.

RDD threat: According to calculations, neutron generators do not pose a serious RDD threat because it would take multiple weeks and even years to produce a useable quantity of radioactive material. As an example, in a best-case scenario about 26 kBq (0.7μCi) of ^{60}Co can be produced with a neutron generator in one hour. With a significant RDD at 410 GBq (11 Ci) for ^{60}Co, it would take more than 10 million hours to generate enough material. Typical operational lifetime for a neutron generator is on the order of 2000 hours.

2.6. RDD Threat Posed by Long-Lived Parent Radionuclide Generators

Long-lived parent radionuclide generators do not produce new radionuclides through nuclear reactions, unlike other devices described in this report. These generators rely on a simple radioactive decay process; short-lived daughters are generated over time from a long-lived parent and then chemically separated to prepare a specific dose for diagnostic or therapeutic purposes. All radionuclides that are produced by these generators are short-lived with half-lives on the order of minutes to hours. Therefore, the only RDD threat that may be potentially posed by these devices is the parent radionuclide itself, and they should be treated simply as radioactive sources for further analysis.

Market analysis of long-lived parent radionuclide generators showed that initial quantities of parent radionuclides in generators are fairly small, usually less than 40 GBq (1 Ci). Such quantities are sufficient to produce needed amounts of the daughters. In addition, smaller quantities of parent radionuclides reduce the requirements for shielding of these devices.

RDD threat: The simple decay process that is employed in radionuclide generators and small quantities of parent radionuclides present in these devices leads to a conclusion that they present a very low RDD threat.

3. FACILITY MISUSE SCENARIOS AND SECURITY ARRANGEMENTS

This chapter describes potential ways to misuse non-reactor radionuclide production facilities for the purpose of producing RDD-useable materials. It is important to address these scenarios; even though technologies assessed were determined to pose low RDD threat, it is not zero. The main categories of scenarios are listed as follows:

a) stealing 'normal' product from a facility
b) using a facility to produce extra material
c) misusing a facility to produce a radionuclide which is not a 'normal' product
d) purchasing equipment for the sole purpose of production of RDD-useable material

Scenario A – Stealing. This scenario is feasible only for facilities that produce RDD-useable materials directly. This condition significantly limits the number of potential facilities of interest, as most charge-particle accelerators produce small quantities of short-lived radionuclides for medical purposes. This scenario would be a concern for facilities producing ^{48}V, ^{68}Ge, ^{88}Y and ^{225}Ac.

Scenario B – Producing Extra Material. Similarly, to Scenario A, this scenario can only be of concern at facilities producing RDD-useable material.

Scenario C – Facility Misuse. In this scenario, a facility would be misused by an insider to produce radionuclides that are not a typical product of that facility. For a majority of commercial turn-key systems, changing target material, configuration, and charged particle beam characteristics could be a significant undertaking that would require sophistication and expertise that can typically only be provided by manufacturers. These systems are sophisticated and are usually fine-tuned for production of specific radionuclides. In addition, beam use time is at a premium and accelerators are typically unusable when they are down for maintenance.

Scenario D – Equipment Purchase. In this scenario, a piece of equipment would be purchased and concealed for the specific purpose of producing RDD-useable radionuclides. Although export control rules are not in place to prevent a potential adversary from purchasing such equipment, the high price tag on the order of several million dollars and level of knowledge and sophistication needed to operate it make this route for acquisition of RDD-useable material a very low probability.

3.7. Security Arrangements at Facilities

Security arrangements are usually minimal at medical particle accelerator facilities. There are no special requirements and rules for physical protection of such facilities. Security at facilities is driven by the high economic value of the devices and product inventory and not by danger these materials can pose.

3.8. Export Control Regulations

Currently, accelerator technologies and other non-reactor radionuclide production technology control regulations are not included into any export-control list. The Nuclear Suppliers group (NSG) list, also known as INFCIRC/254, refers to accelerator technologies only as they apply to electromagnetic isotope separation and 'pulsed electron sources' used in the x-raying of nuclear implosion tests [12].

According to IAEA guidelines, neutron generators that are included in the NSG list must have the following characteristics: 'Neutron generator systems, including tubes, having both of the following characteristics:

— Designed for operation without an external vacuum system; and'
— Either
  - 'Utilizing electrostatic acceleration to induce a tritium-deuterium nuclear reaction; or
  - Utilizing electrostatic acceleration to induce a deuterium-deuterium nuclear reaction and capable of an output of $3x10^9$ neutrons/s or greater.' [13]

No other radionuclide production technology was found in international export control regulations.

4. CONCLUSIONS

In this study, analyses of a potential RDD threat posed by non-reactor radionuclide production technologies were performed. A variety of technologies — charged-particle accelerators, spallation neutron sources, neutron generators, x-ray systems and long-lived parent radionuclide generators — were assessed. It was found that, at present, most of these technologies do not pose any significant radiological threat due to a variety of reasons specific to each device type. Nevertheless, technology is constantly developing and changing rapidly and periodic re-assessment of the risks posed by non-reactor radionuclide production technologies is recommended.

Most accelerator-produced radionuclides are not suitable for building a 'significant RDD' due to short half-lives, complex targetry, and product extraction procedures. However, four accelerator-produced radionuclides were identified that could potentially be used in an RDD (^{48}V, ^{68}Ge, ^{88}Y, ^{225}Ac). After thorough investigation, it was determined that the attractiveness levels of these four radionuclides that would motivate an adversary to produce them using charged particle accelerators are low.

Spallation neutron sources can produce almost all the same radionuclides as nuclear reactors. However, those devices are large and extremely expensive (on the order of billions of dollars) and are usually housed by large national research institutions that provide significant physical protection. In addition, SNSs require complex arrangements for operation, such as sophisticated start-up procedures requiring multiple operators, which would further complicate any attempts of misuse.

Neutron generators can produce a variety of radionuclides through neutron activation. Neutron output generated by those devices is not sufficient for production of significant quantities of radiological materials. It would take on the order of thousands to millions of hours to generate a quantity suitable for a 'significant RDD'.

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