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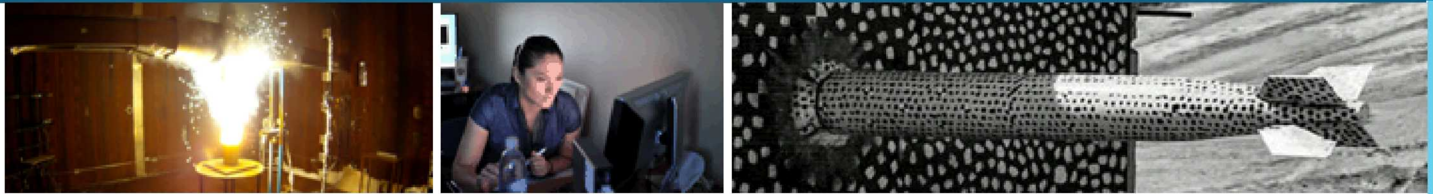
Evaluation of a Potential RDD Risk Posed by Non-Reactor Radionuclide Production Technologies



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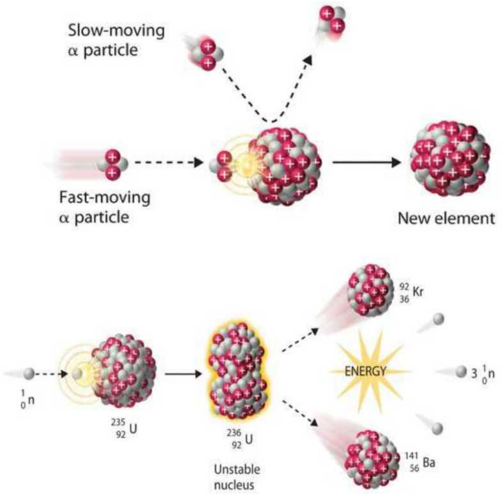
Introduction

- 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
- Some of these radionuclides can be used for malicious purposes
- A full range of non-reactor radionuclide production technologies were evaluated from the standpoint of generating enough material for a radiological dispersal device (RDD)
    - The capabilities, capacities and potential dangers they can pose were 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

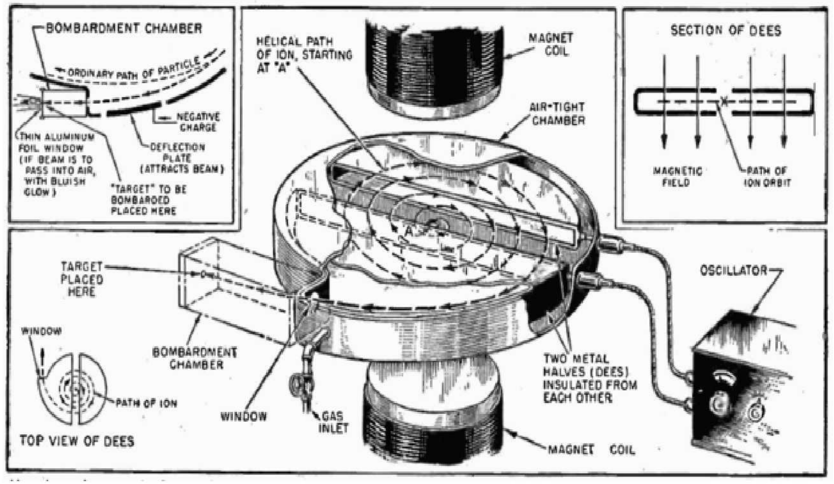
How can we make radionuclides?

Radionuclides are produced via nuclear reactions

- We have to change the ratio of neutrons and protons to get outside of the band of stability
- Usually this is done by bombarding nuclei of stable isotopes by high-energy particles
  - neutrons
  - protons
  - deuterons
  - photons
  - etc.
- Sophisticated devices are needed to create high energy particles and induce nuclear reactions
  - nuclear reactors (neutrons)
  - particle accelerators (charged particles)



Source: https://saylordotorg.github.io/text_general-chemistry-principles-patterns-and-applications-v1.0/s24-02-nuclear-reactions.html



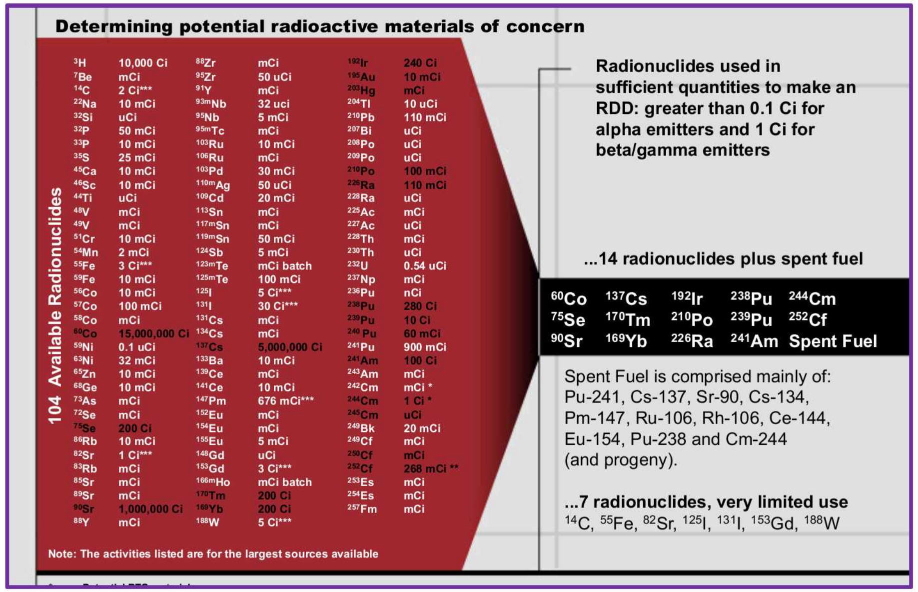
Retrieved November 3, 2014 from Radio-Craft, Radcraft Publications, Springfield, Massachusetts, Vol. 18, No. 9, June 1947 p. 23 on American Radio History archive

Risk Analysis Procedure

Risk is traditionally characterized by

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

In the RDD scenario *consequences* are determined by the radionuclides' characteristics and quantities



Determining potential radioactive materials of concern

104 Available Radionuclides

^{3}H	10,000 Ci	^{88}Zr	mCi	^{192}Ir	240 Ci
^{7}Be	mCi	^{95}Zr	50 uCi	^{195}Au	10 mCi
^{14}C	2 Ci***	^{91}Y	mCi	^{203}Hg	mCi
^{22}Na	10 mCi	^{93m}Nb	32 uci	^{204}Tl	10 uCi
^{32}Si	uCi	^{95}Nb	5 mCi	^{210}Pb	110 mCi
^{32}P	50 mCi	^{95m}Tc	mCi	^{207}Bi	uCi
^{33}P	10 mCi	^{103}Ru	10 mCi	^{208}Po	uCi
^{35}S	25 mCi	^{106}Ru	mCi	^{209}Po	uCi
^{45}Ca	10 mCi	^{103}Pd	30 mCi	^{210}Po	100 mCi
^{46}Sc	10 mCi	^{110m}Ag	50 uCi	^{226}Ra	110 mCi
^{44}Ti	uCi	^{109}Cd	20 mCi	^{228}Ra	uCi
^{48}V	mCi	^{113}Sn	mCi	^{225}Ac	mCi
^{49}V	mCi	^{117m}Sn	mCi	^{227}Ac	uCi
^{51}Cr	10 mCi	^{119m}Sn	50 mCi	^{228}Th	mCi
^{54}Mn	2 mCi	^{124}Sb	5 mCi	^{230}Th	uCi
^{55}Fe	3 Ci***	^{123m}Te	mCi batch	^{232}U	0.54 uCi
^{59}Fe	10 mCi	^{125m}Te	100 mCi	^{237}Np	mCi
^{56}Co	10 mCi	^{125}I	5 Ci***	^{236}Pu	nCi
^{57}Co	100 mCi	^{131}I	30 Ci***	^{238}Pu	280 Ci
^{58}Co	mCi	^{131}Cs	mCi	^{239}Pu	10 Ci
^{60}Co	15,000,000 Ci	^{134}Cs	mCi	^{240}Pu	60 mCi
^{59}Ni	0.1 uCi	^{137}Cs	5,000,000 Ci	^{241}Pu	900 mCi
^{63}Ni	32 mCi	^{133}Ba	10 mCi	^{241}Am	100 Ci
^{65}Zn	10 mCi	^{139}Ce	mCi	^{243}Am	mCi
^{68}Ge	10 mCi	^{141}Ce	10 mCi	^{242}Cm	mCi *
^{73}As	mCi	^{147}Pm	676 mCi***	^{244}Cm	1 Ci *
^{72}Se	mCi	^{152}Eu	mCi	^{245}Cm	uCi
^{75}Se	200 Ci	^{154}Eu	mCi	^{249}Bk	20 mCi
^{86}Rb	10 mCi	^{155}Eu	5 mCi	^{249}Cf	mCi
^{82}Sr	1 Ci***	^{148}Gd	uCi	^{250}Cf	mCi
^{83}Rb	mCi	^{153}Gd	3 Ci***	^{252}Cf	268 mCi **
^{85}Sr	mCi	^{166m}Ho	mCi batch	^{253}Es	mCi
^{89}Sr	mCi	^{170}Tm	200 Ci	^{254}Es	mCi
^{90}Sr	1,000,000 Ci	^{169}Yb	200 Ci	^{257}Fm	mCi
^{88}Y	mCi	^{188}W	5 Ci***		

Note: The activities listed are for the largest sources available

Radionuclides used in sufficient quantities to make an RDD: greater than 0.1 Ci for alpha emitters and 1 Ci for beta/gamma emitters

...14 radionuclides plus spent fuel

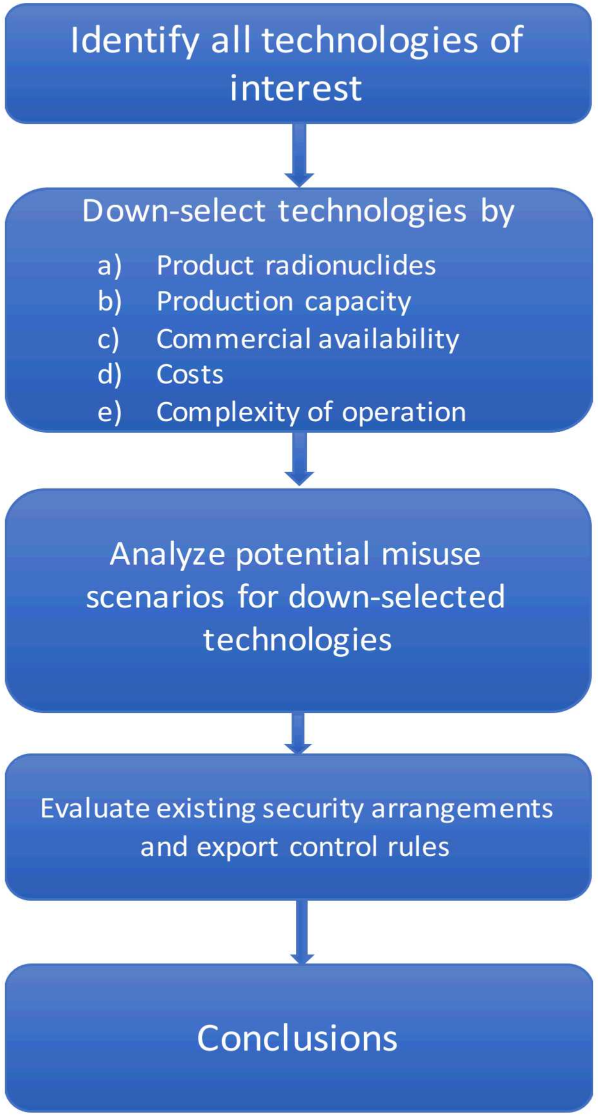
^{60}Co	^{137}Cs	^{192}Ir	^{238}Pu	^{244}Cm
^{75}Se	^{170}Tm	^{210}Po	^{239}Pu	^{252}Cf
^{90}Sr	^{169}Yb	^{226}Ra	^{241}Am	Spent Fuel

Spent Fuel is comprised mainly of: Pu-241, Cs-137, Sr-90, Cs-134, Pm-147, Ru-106, Rh-106, Ce-144, Eu-154, Pu-238 and Cm-244 (and progeny).

...7 radionuclides, very limited use

^{14}C, ^{55}Fe, ^{82}Sr, ^{125}I, ^{131}I, ^{153}Gd, ^{188}W

We evaluated '*probability of event*' through analyzing capabilities of technologies of interest as outlines in the flowchart



Identify all technologies of interest

Down-select technologies by

a) Product radionuclides
b) Production capacity
c) Commercial availability
d) Costs
e) Complexity of operation

Analyze potential misuse scenarios for down-selected technologies

Evaluate existing security arrangements and export control rules

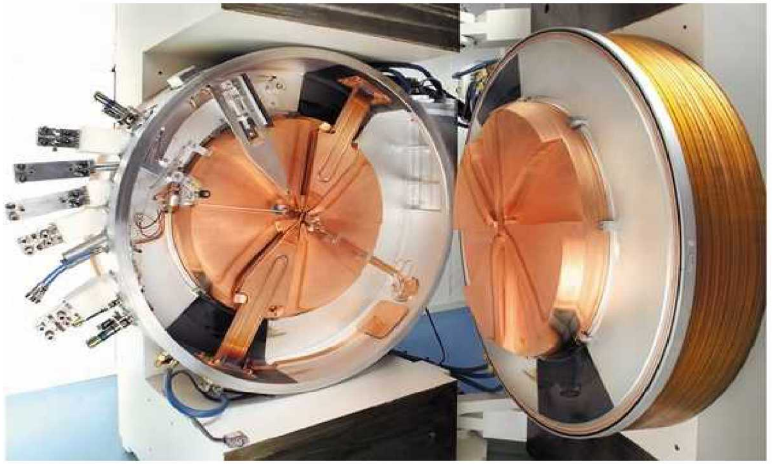
Conclusions

Charged Particle Accelerators - Background

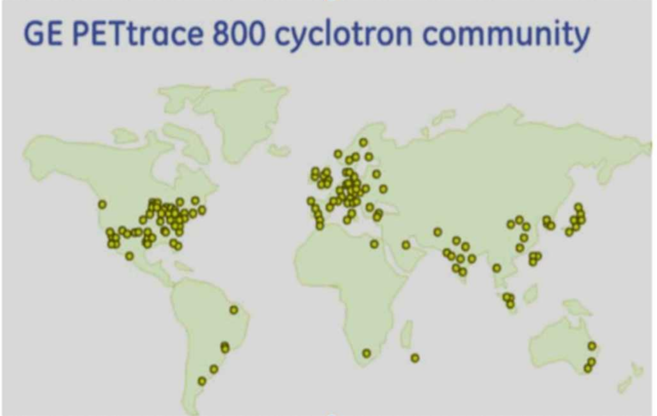
- More than 1200 medical cyclotrons operating around the world (10% increase yearly)
- Variety of benchtop systems commercially available (GE, Siemens, IBA)
  - up to 70 MeV max particle energy
    - more possible product radionuclides
  - up to 2100 μA current
    - higher production rates

Four radionuclides were selected as having potential for misuse:

- Vannadium-48
- Germanium-68
- Yttrium-88
- Actinium-225



source: http://www3.gehealthcare.com.sg/en-gb/products/categories/pet-radiopharmacy/tracer_center_equipment/pettrace_700_series_cyclotron



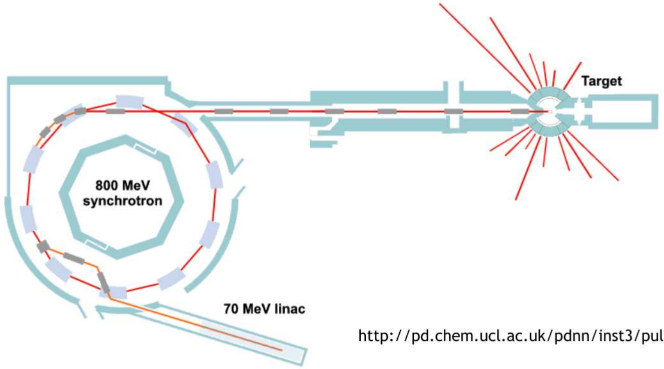
source: P. Schaffer, at al. "Direct Production of ^{99m}Tc via ^{100}Mo(p,2n) on Small Medical Cyclotrons

Downselected Radionuclides	*Production Capacity*	*Commercial Availability*	*Cost*	*Complexity of Operation*	***Overall Risk***
Some	Average	Yes	High ~USD2.6M	High	**Low**

Spallation Neutron Sources – Very Low Risk

Radionuclides can be produced by a capture of neutrons from a spallation neutron source (SNS)

- high-energy protons (100 to 1000 MeV) hit a high Z target (Hg or W) fragmenting the target and liberating multiple neutrons
- neutrons can be thermalized to produce radionuclides



http://pd.chem.ucl.ac.uk/pdnn/inst3/pulsed.htm

Thermal fluence rates of 10^{14} to 10^{16} n/cm^2/sec

Extremely complex and costly (site security)

- *determined to be very low radiological risk*

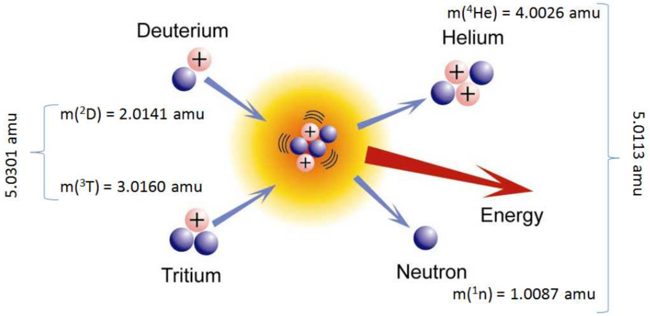
Downselected Radionuclides	*Production Capacity*	*Commercial Availability*	*Complexity of Operation*	*Cost*	***Overall Risk***
Multiple	High	No	Extremely High	Extremely High ~USD1.5B	**Very Low**

Portable Neutron Generators - Background

Typical (fast) neutron output: ~10^8 – 10^{10} n/s
- thermal fluence rate an order of magnitude lower

Multiple radionuclides can be produced in a neutron beam from a neutron generator
- As an example, ^{60}Co production
- Conservative flux estimate 10^{10} n/cm^2/sec

For fluence rate 10^8 n/cm^2/sec, 100 hour irradiation, ^{60}Co yield ~70 μCi



Q = 0.0188 amu x 931.481 MeV/amu = 17.5 MeV
Source: http://www.nuclear-power.net/nuclear-power/nuclear-reactions/

source: Idaho National Laboratory (INL)

Downselected Radionuclides	*Production Capacity*	*Commercial Availability*	*Cost*	*Complexity of Operation*	***Overall Risk***
Multiple	Very Low	Yes	Low ~USD100K	Low	**Very Low**

Conclusions

- A variety of technologies were assessed
  - charged-particle accelerators,
  - spallation neutron sources,
  - neutron generators,
  - x-ray systems, and
  - long-lived parent radionuclide generators
- 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