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P. Andrew Karam

Radiological and Nuclear Terrorism

Their Science, Effects, Prevention, and Recovery

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P. Andrew Karam
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This book is dedicated to those who got me started and influenced me on this particular path of both service and science:

Fred Byus, Fellow Submariner (retired)
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Foreword

"With a screwdriver." That was how Robert Oppenheimer, the father of the American atomic bomb, answered the question of how a nuclear weapon smuggled into the USA in a crate could be detected. His answer, given in 1946 during congressional testimony, suggested a screwdriver would be necessary to open every crate and look inside. As some experts in the field are aware, Oppenheimer's answer led to the first US report on preventing nuclear terrorism, the so-called screwdriver report, which remains classified.

The number and type of tools we have developed to prevent nuclear terrorism have expanded greatly since 1946. Opening crates with a screwdriver to look inside has certain advantages, but is of course implausible on a large scale. To deal with this challenge, we have created an array of new radiation detector materials and devices that can help to detect illicit nuclear materials. A lightly trained police officer can now use a handheld detector to identify nuclear or radiological materials that only a trained scientist with a laboratory full of equipment could accomplish at the dawn of the nuclear era. Moreover, not far ahead, networked detectors using advanced anomaly detection algorithms will provide a detection capability many times more effective than the same number of individual detectors.

Of course, technology development is the only one element of an overall strategy to prevent nuclear terrorism, and notwithstanding important technical improvements in our capabilities, basic laws of physics will always work against detecting nuclear materials at a distance.

Technology has changed, but so has the risk. Nuclear and radiological materials are now used around the world in a variety of applications. In the early days, just a handful of countries produced nuclear weapons usable materials. The number of counties that possesses nuclear weapons usable material has grown substantially. Though the growth has not been as rapid as some feared, as reflected in JFK's 1963 prediction that in the 1970s "15 or 20 or 25 nations may have these [nuclear] weapons", the growth has continued. And even countries that do not seek nuclear weapons, such as Japan, possess substantial amounts of nuclear weapons usable material in civil stockpiles. Moreover, the technologies useful in the production of nuclear material and nuclear explosives have become much more easily accessible. Finally, with the dissolution of the Soviet Union in 1991, small, but still alarming amounts of material entered into illicit commerce for the first time. What will happen as governments in control of nuclear materials fall or become unstable in future?

Radiological materials are a separate problem—less threatening than nuclear materials, but with a much lower bar for acquisition. Radioactive materials are used widely in industrial and medical applications around the world—in all countries. Sometimes radioactive materials are used in quantities and forms that could be transformed into a significant radiological dispersal device—a so-called dirty bomb. Prior to 9/11, controls on these materials were weak. Since then, several countries, in particular the USA, have engaged in a coherent effort to help secure or replace these sources with non-radioactive alternatives, but the job is far from done.

As illustrated above, both the risk of nuclear or radiological terrorism as well as the technology to address this risk have changed substantially over the past seven decades since Oppenheimer made his screwdriver remark. However, one thing has not changed. And that is the need for practitioners and policy-makers to make decisions with a thorough understanding of the science that underlies nuclear science and technology.

That is why this book by Dr. Karam is so important. Along with a well-crafted curriculum, it can help to prepare the next generation of nuclear specialists in key areas related to nuclear terrorism. Scientists, technicians, politicians and policy-makers need a clear-eyed understanding of the science and the tools we must deploy to deal with these risks. Our ability to prevent a nuclear catastrophe will be based on the skills and knowledge of key decision-makers and implementers. This excellent book will help to facilitate that. It addresses a range of essential topics in the field.

Dr. Karam's work as a scientist and as scientific advisor for the Counterterrorism Division of the NYPD expanding and operating our rad/nuke interdiction system provides an excellent background for this book. He is a respected health physicist with experience in radiological and nuclear emergency preparedness and response. He has extensive teaching experience at all levels of education and has published widely for both technical and popular audiences. His professional skills have also been recognized by his colleagues; he was asked to participate on committees for the National Academy of Science, the National Council on Radiation Protection and Measurements, and participated in several overseas missions on behalf of the International Atomic Energy Agency and the Health Physics Society.

Seventy years into the nuclear era, no terrorist has successfully exploited the potential of nuclear power. Why is this? Is it because we have developed strong enough protections to prevent terrorists from succeeding? Is it because we have been successful in convincing terrorists that they will not succeed and thus they do not try? Is it because terrorists just are not interested or capable? We just do not know.

We do know that the threat will likely grow. And we know that technology alone cannot prevent nuclear terrorism. It must be integrated into an overall strategy, and the strategy must be adequately resourced. Preventing nuclear terrorism clearly requires a multi-prong effort. The first is to minimize the use of the most threatening materials. The second is to ensure that nuclear and radiological materials are secured at their source. The third is to ensure that we have in place the necessary technology and agreements to support recovery of nuclear or radiological material that may be stolen.

And finally, we need to be prepared to mitigate the effects of an attack through well-defined emergency response and consequence management plans and capabilities.

If we are lucky, we will have time to prepare. Do we have enough time? We may, but we do not have time to waste.

Warren Stern
Deputy Chair, Nonproliferation and National Security

Preface and Acknowledgements

I spent the first part of my adult life in the American Navy—8 years during the final decade of the Cold War, with half of that spent on a nuclear attack submarine. Those years were tense; protests against American nuclear weapons roiled Europe, the Soviet Union shot down a civilian airliner over the Kamchatka Peninsula, and Ronald Regan jokingly announced that he had outlawed the Soviet Union. The submarine I was on spent about two months every year in close proximity to the Soviet Union, following their submarines and collecting intelligence, and they sent ships and submarines to try to find and to follow us. During these years, too, I had the opportunity to make radiation measurements on and near nuclear weapons, giving me an appreciation for not only their destructive power, but also of how difficult detecting them can be. Our primary worry was that there would be a nuclear war between NATO and the Warsaw Pact that could quite possibly kill hundreds of millions of people.

Imagine my surprise when, shortly after I left the Navy, the Berlin Wall fell, followed in the next few years by the Warsaw Pact and the Soviet Union. The future seemed brighter than I could have imagined just a year or so earlier when we were trying to avoid detection by the Soviet Navy.

Fast-forwarding a decade, I have to admit to mild bemusement when some guy I'd sort of heard of—Osama bin Laden—"declared war" on the USA. But then his forces attacked two of our embassies in Africa, followed by a series of smaller attacks and then the attacks of September 11, 2001. And with the latter, my whole world changed.

As a radiation safety officer, my primary concern had been worries that an angry graduate student would dump some radioactive reagents into their supervisor's lunch—something that had happened a number of times at a variety of universities. And suddenly I was worried about terrorists trying to steal our high-activity irradiator sources to use in a terrorist attack—I had to learn about vehicle-borne explosives, how to work with police and fire to thwart or to respond to an attack, how to set up security systems, and any number of things I never expected to need to know about. As time went on, I found myself becoming increasingly immersed in a topic to which I'd never before had to give more than passing attention—I was asked to provide feedback on a proposed Congressional bill to help prevent radiological terrorism, I helped prepare our medical center to respond to a radiological or nuclear attack (or to provide assistance to others who were attacked), I contributed to a few reports on topics related to radiological and nuclear terrorism, and much more. And then things got even more involved.

I spent nearly a decade working for the New York City government, first for the Health Department and then for the Counterterrorism Division of the New York City Police Department (NYPD), getting two more views of this issue. My time at Health was spent working with my staff and with other agencies to develop the department's and the city's emergency response plans; at the Police Department, I continued this planning work as well as working with expanding and operating our rad/nuke interdiction system. During my time with Health and Police, I also spent a fair amount of time in the field, standing by with the Hazardous Materials Response Unit for major events, in the event that there was an attack, performing aerial and maritime interdiction surveys and helping to interpret the various instrument readings when I was with the Police. It is safe to say that the possibility of a radiological or nuclear attack changed the direction of my career and much of my life.

In the last 30 years, the world has grown both more and less dangerous and a lot more confusing. While we no longer worry that the world will be engulfed in nuclear fireballs, we do worry that a single city might; and while we are no longer faced with a relatively monolithic and implacable foe, we are facing a multitude of smaller enemies who, unfortunately, are not tied to a single state or even to a single location—an enemy that has few worries of being destroyed because we might not even know where to find them. Not only that, but our enemies' goals are different than those of the Soviet Union—they do not mind launching "nuisance" attacks with radiological weapons and they do not possess a nation or substantial resources that can be easily targeted for retaliatory attacks. Thus, we find ourselves in a world in which a nuclear attack is plausibly more likely than it was—but is less likely to be the existential threat it once was—and in which a radiological attack is more likely still. Preventing, planning for, or responding to such attacks is a complex matter that involves a sometimes-bewildering array of knowledge and skills; more than any single person can master.

Radiological and Nuclear Terrorism is aimed at a broad range of readers, including radiation safety professionals, emergency response planners, emergency responders, medical professionals, public health officials and the elected and appointed officials who will be managing our preparations for—and response to—any such attacks. My intention is to give each of these groups enough information to help them begin to consider how they would address their own piece of this issue, to provide high-quality references to help them dig deeper (should they wish) and sufficiently broad view of this matter to help them to understand how their own work falls into the overall "big picture" of both preparation and response. Hopefully, too, having a broad understanding of this matter will help to appreciate the problems faced by others and the work that these others are doing.

I have wanted to write a book like this one for over a decade. When I first started thinking about it, I was convinced I could do it well—and every year I learn more, I do more, and I realize how little I actually knew when this thought first crossed my mind. My goal—my hope—is that this will be a fairly comprehensive reference on a topic that is, and that, unfortunately, is likely to remain timely for some time to come. I hope that you will find it useful—at the same time, I hope you never need to use it.

Finally, there are far too many people who have helped me with this than I can properly thank. First and foremost is Anneliese Kersbergen of Springer; Anneliese gave me the opportunity to write this book, and she has exhibited unflagging patience, support and a sense of humor, all deployed as appropriate. Others who have helped with information, encouragement, reviews, support and moreover the years—with this book and in this area include (in no particular order other than alphabetical)—with my sincere apologies to those who I failed to mention due to CRS (a condition my wife has noticed and labeled—Can't Remember Stuff):

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Michael Riggio
Robert Ullrich
Yuichi Yokoyama

Brooklyn, NY, USA

P. Andrew Karam

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Chapter 1
Introduction

In a 1954 interview described in author Bob Considine's biography of General Douglas MacArthur [1] the General was describing his plans for winning the Korean War. They included dropping "30–50 tactical atomic bombs" on North Korea's military and then contaminating the land "…from the Sea of Japan to the Yellow Sea—a belt of radioactive cobalt. It could have been spread from wagons, carts, trucks and planes. It is not an expensive material. It has an active life of between 60 and 120 years. For at least 60 years there could have been no land invasion of Korea from the North. The enemy could not have marched across that radiated collar I proposed to put across Korea's neck." While MacArthur obviously never implemented his plan, it certainly captures some of the essentials of both nuclear and radiological weapons—using the sheer destructive power of the former and the long-term "staying power" of the latter to destroy an enemy and to deny them use of an area of land for an extended period of time. Those considering using such weapons in radiological attacks are likely making the same type of assessment.

Something else that can be inferred from this interview is that MacArthur lacked a detailed understanding about the biological effects of radiation and the amount that would be required to sow such a large area with enough radioactive cobalt to make the area unsafe for several decades. This, too, reflects a mentality that has been carried forward for more than a half-century—that radiation is uniquely dangerous and that only a small amount is sufficient to cause grave danger. The fact that it is not—and that so few actually understand this fact—could well be the most damaging aspect of radiological terrorism, not to mention our response to radiological or nuclear accidents (e.g. Fukushima) and their aftermath. In fact, this lack of information—among members of the public, the medical community, politicians, emergency responders, public health officials, and many more—was among the factors prompting this book.

In Part I of *Radiological and Nuclear Terrorism* we will review some of the fundamental science of radiation; it's basic properties, how it affects our health, and how we detect it. This fundamental information will inform the rest of the book, helping the reader to understand the scientific context surrounding many of

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the questions that must be answered in trying to avert, respond to, or recover from a radiological or nuclear attack.

Part II will discuss radiological weapons—how they work, their possible health and physical effects, and how the use of radiological weapons might affect society. And in Part III we will explore the same aspects of an attack using nuclear weapons. Both of these will use the science presented in Part I to help the reader to understand the topic and, more importantly, to understand what the actual—not imagined or feared—impact of such an attack might be. In particular, if such an attack does occur it's important to understand what these weapons can—and cannot—do if we are to be able to plan and to respond appropriately.

From here, we move on to some more applied topics. Part IV uses what we have learned about radiation instruments and about these weapons to discuss how an attack might be stopped before it can even take place. This interdiction activity is what many call the "Left of Boom" phase (meaning the activities that take place on an imaginary timeline *before* something explodes). And in Part V we explore how to use the preceding information to help inform an effective response to a radiological or nuclear attack—one designed to provide for the public safety while also keeping emergency responders safe.

Finally, in Part VI we will use what has been discussed to help to determine how to recover from such an attack. And, in spite of fears to the contrary, there is no reason why such a recovery cannot be accomplished—Hiroshima and Nagasaki, after all, are thriving cities today, and there is no reason to believe that even nuclear terrorism would leave a modern city permanently uninhabitable. We can draw upon our experiences from the past, in conjunction with the fundamental science, to help plan recovery efforts from even something as major as an act of nuclear terrorism.

One thing to bear in mind is that there has never been a terrorist attack using radiological or nuclear weapons. There seems to be compelling evidence that terrorist groups have an interest in them and there have been any number of instances of attempted smuggling of radioactive or nuclear materials [2]—but there has never been an attack using them. But even if these weapons are never used by terrorists—or by governments—we can assume that there will be future accidents,small, moderate, or large in scale. The information found in this book is equally relevant for any radiological or nuclear event, deliberate or accidental.

On a personal note, one of our children used to be scared of the dark. In actuality, it wasn't the dark that was frightening—it was what might be lurking in the dark. Similarly, it seems reasonable to assume that it's the lack of good information about radiation and its effects that contributes to much of the fear surrounding it, and this fear makes it a good weapon for terrorizing the public. We can hope that, by helping to spread *good* information, we can help to lessen the fear so that we—as individuals and as a society—might give radiation the respect it deserves, but not unwarranted and inappropriate terror (Figs. 1.1 and 1.2).

Fig. 1.1 Hiroshima shortly after the nuclear attack (US Army photo)

Fig. 1.2 Hiroshima's "Atomic Dome" today. Author's photo

References

1. Considine R (1964) The long and illustrious career of General Douglas MacArthur. Fawcett Publications, New York City
2. Langewiesche W (2008) The Atomic Bazaar: dispatches from the underground world of nuclear trafficking. Farrar, Straus, and Giroux, New York City

Chapter 2
Types of Radiation and Their Properties

Radiation and radioactivity are physical phenomena that have been well-described by science. An understanding of their physical properties and an appreciation of the relevant science is essential if we are to understand how to evaluate the risks they pose, the measurements we make, recommended safety measures, and so forth. For this reason, we will start with a review of the fundamental science that underlies the field of radiation safety and its applications. In addition, the reader should consider that, in the midst of a radiological or nuclear emergency, it might not be necessary to develop precise calculations—quick estimate is often good enough, with more detailed calculations coming when the emergency phase is over. At times, a rough answer that comes quickly can be more useful than a precise answer that arrives hours or days later. Finally, please note that this is a quick review of the basic concepts and is not intended to be comprehensive or in-depth; those interested in a more in-depth understanding of the topic should consider an introductory textbook (e.g., [1, 2], among others).

2.1 What Radiation and Radioactivity Are

Radiation, to a physicist, is nothing more—or less—than the emission of energy by an object and the transmission of that energy to a different location. A toaster does this; a toaster emits thermal radiation that is transferred to a piece of bread. To most members of the general public, radiation is a dangerous and mysterious phenomenon that glows, mutates, and kills. What the public thinks of as "radiation" is more specifically referred to as "ionizing radiation"—radiation that carries with it enough energy to strip an electron from an atom to create a pair of ions where there had previously been an uncharged atom. It is this process of ionization that can initiate the chain of events that can lead to health problems. The threshold energy for causing an ionization is about 5 electron volts (eV); for photons this corresponds

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to a wavelength of about 250 nm, which is solidly in the ultraviolet (UV). Thus, any photon radiation that is more energetic (shorter wavelength) than UV will be ionizing, while visible light and longer-wavelength radiation (including radio frequencies) is non-ionizing.

In addition to high-energy photons, ionizing radiation also includes charged particles (alpha and beta radiation) and uncharged particles (neutrons). Each type of radiation has its own physical properties that affect the manner in which it interacts with matter and within our bodies and that determines the instrument(s) used for detection as well as our radiation safety practices. These are described in more detail below.

2.1.1 Alpha Radiation

Alpha particles are relatively massive charged particles given off by heavy and unstable atoms. Alpha radiation is very damaging to living cells because of its relatively high mass and electrical charge. These same factors cause alpha radiation to lose energy quickly in tissue, with the result that alpha radiation cannot penetrate more than several microns into tissue; less than the thickness of the dead cells of the epidermis. Thus, as long as alpha radiation is neither inhaled or ingested and as long as open cuts and scrapes are covered, alpha radiation is harmless. Internally, however, alpha radioactivity is highly dangerous; the Russian spy Alexander Litvenenko was killed by ingesting very small amounts of alpha-emitting polonium (Po-210)—about as much as a single grain of salt. While there is no need for protective equipment to avoid tissue damage, protective clothing will prevent skin contamination that might later transfer to food or to other objects. In addition, respiratory protection will reduce the risk of accidental inhalation and covering open cuts, scrapes, and other injuries will reduce the risk of absorption into the blood stream.

Table 2.1 summarizes some important information about alpha radiation.

2.1.2 Beta Radiation

Beta particles are electrons or positrons—small, light particles—given off by radioactive atoms. Any element can have nuclides that give off beta radiation. Beta radiation is less damaging to living cells than alpha radiation, but beta particles penetrate more deeply into human tissue—up to about 1 cm. Accordingly, external beta radiation cannot damage internal organs, but high levels of beta contamination can produce skin burns ("beta burns") unless decontaminated quickly. Heavy clothing (e.g. firefighters' turnout gear and heavy gloves) will protect the skin from most beta radiation, and workers should wear respiratory protection if beta-emitting radioactivity might be airborne.

While beta radiation is normally in the form of negatively charged electrons, some neutron-deficient radionuclides emit positrons—the antimatter equivalent of

Table 2.1 Information about alpha radiation

What will emit alpha radiation	• Nuclides with high atomic number and high atomic mass (e.g. Am-241, Ra-226, U-235, etc.) • Smoke detectors, gas lantern mantles, welding rods, some rocks, nuclear weapons, some radioactive sources
Detectors and instruments	• Geiger Mueller "pancake" probes, alpha probes
Health effects	• Some alpha emitters are also toxic heavy metals (e.g. uranium) • No health effects from external alpha radiation • **Can be very harmful if inhaled or ingested**
Protective equipment	• Respiratory protection if activity is airborne • Cover open cuts, scrapes, and other wounds, gloves
Levels of concern[a]	• Greater than 10,000 cpm on the ground • Greater than 1000 cpm on the bare skin • Airborne alpha activity
Other comments	• Some alpha emitters (e.g. Am-241, Ra-226) also emit gamma radiation • The former Russian spy Alexander Litvenenko was killed by adding trace amounts of alpha-emitting polonium to tea

[a]Note that readings in Tables 2.1, 2.2 and 2.3 are given in cpm (what the instrument reads) and not in dpm (the activity that is actually present) to simplify comparison with the instrument being used. The count rates provided here are for a "pancake" type GM detector at a distance of about 2 cm from the surface being surveyed. Other detectors will produce different readings

Table 2.2 Information about beta radiation

What will emit beta radiation	• Any element can have beta-emitting nuclides • Many laboratory nuclides (e.g. H-3, C-14, P-32, S-35) • Newer self-luminous watch dials and some self-illuminating exit signs
Detectors and instruments	• Geiger counters (e.g. GM pancake probe) • Beta scintillation probes • Liquid scintillation counter (in the laboratory)
Health effects	• External beta radiation cannot expose internal organs • May cause shallow burns (beta burns) if bare skin is contaminated • Can expose internal organs if inhaled or ingested
Protective equipment	• Anti-contamination clothing (including heavy gloves if possible) to reduce skin contamination • Respiratory protection (if airborne) • Cover open cuts, scrapes, or wounds
Levels of concern*	• Greater than 100,000 cpm on the ground • Greater than 10,000 cpm on the skin
Other comments	• Many beta-emitters also emit gamma radiation (e.g. I-131) • There have been several instances of laboratory workers trying to poison co-workers with beta-emitters such as P-32 • Positron emission will be accompanied by 511 keV gamma radiation from electron–positron annihilation

*See comment to Table 2.1

Table 2.3 Information about gamma radiation

What will emit gamma radiation	• Industrial and medical nuclides emit gamma radiation (e.g. F-18, Co-60, Se-75, I-131, Cs-137, Ir-192, etc.)
Detectors and instruments	• Sodium iodide-type detectors (e.g. PRD, RIID, sodium iodide detector, etc.) • Ion chamber (to measure dose rate)
Health effects	• External gamma radiation can expose entire body (including internal organs) • Exposure to high dose in a short time can cause skin burns • Prolonged exposure to eyes can cause cataracts
Protective equipment	• Anti-contamination clothing to reduce skin contamination • Respiratory protection (if airborne) • Cover open cuts, scrapes, or wounds
When to worry	• Gamma dose rates greater than 100 μR/hr (1 μGy/hr) indicates the likely presence of radioactive materials • Gamma dose rates greater than 2 mR/hr (20 μGy/hr) might require a boundary to exclude members of the public • Gamma dose rates greater than 100 mR/hr (1 mGy/hr) might require dosimetry to enter • Gamma dose rates greater than 1 R/hr (10 mGy/hr) should be entered only if necessary • Gamma dose rates greater than 100 R/hr (1 Gy/hr) can be dangerous
Other comments	• Many gamma-emitting nuclides also emit alpha or beta radiation • Only gamma radiation will penetrate many packages or containers—other forms of radiation may also be present when opening a package, container, or vehicle emitting gamma radiation

electrons. When positrons are emitted they will encounter electrons and the electron and positron will annihilate each other, emitting two gamma rays, each with an energy of 511 keV.

Table 2.2 summarizes some important information about beta radiation.

2.1.3 Gamma Radiation

Gamma rays are photons, similar to the photons emitted by electric lights; the primary difference is that, like x-rays, gamma rays possess sufficient energy to pass through objects. Since gamma radiation can pass through the entire body, it can expose internal organs to radiation dose. Protective clothing will protect against skin contamination, respiratory protection will protect against inhalation and ingestion, and good work practices (e.g. time, distance, and shielding) will help to reduce radiation exposure. Due to the higher energy of gamma radiation (compared to x-ray photons), gamma radiation cannot normally be shielded by using lead aprons as is done with the

Table 2.4 Properties of neutron radiation

What will emit neutron radiation	• Neutron sources (soil gauges, well-logging sources, AmBe, and Cf-252 neutron sources) • Operating nuclear reactors • Particle accelerators (research, medical) • Nuclear weapons (low level)
Detectors and instruments	Neutron detectors (Helium-3, BF3, and others)
Health effects	• External neutron radiation can expose the entire body (including internal organs) • Many neutron sources also emit alpha radiation
Protective equipment	• Anti-contamination clothing to reduce skin contamination • Respiratory protection (if airborne) • Cover open cuts, scrapes, or wounds
Levels of concern	• Any sustained neutron dose rate above natural background levels should be investigated
Other comments	• Background neutron levels will vary widely • Different instruments will have different background neutron levels • Neutron levels can increase somewhat when near large structures (called the "ship effect") on the water or on land

lower-energy x-ray radiation. Table 2.3 summarizes some important information about gamma radiation.

2.1.4 Neutron Radiation

Neutrons are subatomic particles that are given off during nuclear reactions such as nuclear fission or from radioactive sources comprised of beryllium mixed with an alpha-emitting radionuclide (e.g. Am-241 and beryllium, or AmBe). Neutrons are highly penetrating and will pass through most solid materials; they are best shielded by using hydrogen-rich materials (e.g. water, plastic) and neutron-absorbing elements such as boron. Bombarding materials with neutrons can cause them to become radioactive. Due to their higher mass, neutrons are much more biologically damaging than are beta particles or gamma rays; neutron absorption can also cause materials to become radioactive. Table 2.4 summarizes some important information about neutron radiation.

2.1.5 Radioactivity Units

Radioactivity is measured in terms of the number of radioactive decays (also referred to as "disintegrations") an amount of radioactive material (a radioactive source) undergoes each second. The international unit, the Becquerel (Bq), is the amount of a radioactive material that undergoes 1 decay in one second. As with other SI units, modifiers (k, M, m, and so forth) are used to reflect multiples or fractions of a Bq (e.g. 25,000 Bq = 25 kBq).

In addition to the SI unit, there are places in which the “traditional” unit of the Curie (Ci) remains in popular, if not in official, use. One Ci is that amount of a radioactive source that undergoes 37 billion decays in one second, so 1 Ci = 37 GBq.

It is important to note that the amount of radioactivity present in a source is not necessarily related to the physical size of the source. One gram of Ra-226, for example, contains about 1 Ci (37 GBq) of activity, one gram of Co-60 contains over 1000 times as much radioactivity, and one gram of U-238 contains less than a millionth as much radioactivity. Thus, 1 g of U-238 is radiologically harmless, 1 g of Ra-226 must be handled with caution, and 1 g of Co-60 can pose a risk to life and health with only several minutes of exposure. This is why the relative risk posed by a radioactive source can only be evaluated by making radiation measurements or through calculation (if sufficient information is available).

If one knows the half-life of a radionuclide and can calculate the number of radioactive atoms in a sample then it is possible to calculate the amount of radioactivity present in that sample using the law of radioactive decay: $A = \lambda N$ where A is the number of decays per unit of time and N is the number of atoms. The decay constant (λ) is the fraction of atoms that decay in a given amount of time and is equal to $\frac{\ln(2)}{t1/2}$ where $t_{1/2}$ is the nuclide’s half-life. The amount of radioactivity per gram is referred to as the specific activity.

2.1.6 *Radioactive Decay Calculations*

When an atom of Co-60 has decayed, the progeny nuclide (Ni-60) is non-radioactive. This means that radioactive decay reduces the number of radioactive atoms and, as the number of radioactive atoms decreases so does the decay rate. In other words, the amount of radioactivity decreases with time. The magnitude of this decrease can be calculated fairly easily using the equation $A_t = A_0 \times e^{-\lambda t}$ where A_0 and A_t are the original and decayed activity (respectively), λ is the decay constant, and t is the time between A_0 and A_t. Decay can also be calculated using the number of elapsed half-lives: $A_t = A_0 \times 2^{-x}$ where x is the number of half-lives that have elapsed.

Example: calculating the specific activity of Co-60

- The number of atoms of Co-60 in one gram is 6.022×10^{23} atoms per mole/59.934 g of Co-60 per mole = 1.005×10^{22} atoms of Co-60 per gram.
- The decay constant for Co-60 = ln(2)/5.27 years = 0.1315 yr^{-1}.
- So the decay rate of 1 g of Co-60 = 1.005×10^{22} atoms of Co-60 × 0.1315 yr^{-1} = 1.32×10^{21} decays per year.

- Since there are about 3.156×10^7 s in a year, this comes out to about 4.2×10^{13} decays per second, or about 42 TBq.

There are a number of measurements whose change can be calculated in this same manner. Contamination levels, for example, are a measure of the amount of radioactivity per unit area (e.g. decays per second or decays per minute in a 100 cm^2 area); as the contaminating radionuclide decays, contamination levels will drop steadily. In a medical setting, for example, it is not uncommon to see contamination from Tc-99 m, a nuclide with a half-life of only about 6 h. With so short a half-life it often makes sense to simply lock the door to the room and let the contamination decay away over the space of a few days than it does to devote resources towards decontamination.

Example: calculating the decay of a Co-60 source

A radioactive materials licensee was cleaning out storage cabinets and found a 25-year-old Co-60 source with an original activity of 500 mCi (18.5 GBq). The licensee, not wanting to overpay for the source's disposal, needed to calculate the decayed activity of the source.

$$A_t = A_0 \times e^{-\lambda t}$$

We know from the previous example that the decay constant for Co-60 is $0.1315\ \text{yr}^{-1}$ (from the previous text box) so the calculation is:

$$A_t = 18.5\,\text{GBq} \times e^{-\left(0.1315 yr^{-1}\right) \times (25 yr)}$$

The decayed activity was calculated to be 0.691 GBq, or 691 MBq—considerably lower than the original activity and much less expensive to dispose of.

Similarly, as we will see in the next section, the radiation dose rate from a beta or gamma source depends on the amount of radioactivity present; as these source decay to lower activities the radiation dose rate drops as well. Thus, the radioactive decay equation can be used to calculate the reduction in radiation or contamination levels over time.

2.2 Radiation Dose and Dose Rate Determinations

When considering the health effects of radiation exposure the single most relevant fact is the amount of radiation dose a person, animal, or organ has received. Some