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Introduction to Twenty-First Century Health Physics

1.1

Overview of Twenty-First Century Health Physics

History has the unfortunate habit of repeating. Significant events of a given classification (e.g., accidents, natural disasters, and conflicts over natural resources) reoccur and are often influenced by available technology. For example, wars continue to be waged, but their scope and destructive power are amplified by technology. The development of nuclear technology and the fabrication of nuclear weapons continue to influence world events and health physics concerns as the twenty-first century unfolds.

1.2

Health Physics Issues, Challenges, and Opportunities

The twentieth-century power reactor accidents at Three Mile Island Unit 2 and Chernobyl Unit 4 revealed weaknesses in the management and regulation of nuclear reactors. Unfortunately, the nuclear accident *hat trick* was achieved in the twenty-first century with the accident involving Fukushima Daiichi Units 1, 2, 3, and 4. This most recent accident reveals additional structural weaknesses in nuclear regulation and management that involve fundamental licensing basis issues. The legacies of Three Mile Island and Chernobyl remain, and final cleanup actions for these sites either are delayed until facility decommissioning or are ongoing. The decade cleanup duration of Three Mile Island is dwarfed by the projected 40–100-year recovery effort for Fukushima Daiichi. Associated with these three accidents are issues involving environmental impacts, stakeholder concerns, regulatory changes, licensing impacts, and financial implications. These issues are addressed in this book and have a profound influence on health physics activities associated with these accidents and the subsequent expansion of nuclear power generation.

In a similar fashion, the terrorist attacks of the twentieth century culminated in the 11 September 2001 events involving the World Trade Center in New York and the US Pentagon. These attacks spawned significant concerns regarding the

escalation of terrorist events to include a variety of attacks including those utilizing radioactive materials and nuclear weapons. Technology has once again opened a door to an escalation of attack profiles that significantly affect the health physics profession.

The nuclear fuel cycle has successfully enriched uranium for reactor fuel and weapons production and reprocessed spent nuclear fuel to recover uranium and plutonium. Historically, the enrichment process required large facilities because diffusion and centrifuge technologies are relatively inefficient processes for uranium enrichment. The advent of advanced centrifuge technology and laser isotope separation makes the uranium enrichment step considerably more efficient and permits smaller facilities to be constructed and operated. These facilities are easier to conceal than the large centrifuge and gaseous diffusion plants. This presents the opportunity for a clandestine enrichment facility to produce weapons-grade uranium. Advanced technologies, particularly laser uranium enrichment, present a twenty-first-century nuclear proliferation concern.

In a similar manner, reprocessing technology has successfully recovered plutonium, and this technology is well known. The expansion of nuclear power facilities offers the possibility for the diversion of spent fuel that could be reprocessed and the recovered plutonium diverted toward weapons production or terrorist purposes.

On a more positive note, nuclear medicine has advanced and improved diagnostic and therapeutic techniques. The capability to localize the absorbed dose has improved, and additional radiation types are being utilized to target tumors. Proton and heavy ion therapy techniques are becoming more common, and the initial studies using antiprotons have been published. The use of nanotechnology and internal radiation-generating devices in cancer therapy applications is in development for the selective delivery of absorbed dose.

The advancement of nuclear medicine techniques increased the average absorbed dose delivered to the public. An increased use of nuclear materials in commercial products and their inadvertent entry into scrap metal used in consumer products offer additional challenges. Public concerns regarding the use of nuclear power generation and the effects of major accidents have been heightened by the Fukushima Daiichi accident and its sensationalism by the media and antinuclear groups.

Public interest and the involvement of stakeholder groups in nuclear licensing have also increased following the Fukushima Daiichi accident. Events involving radioactive materials and their associated media attention suggest that the interest of the public in radiation-generating technologies and radioactive materials will likely increase. The media presents a significant challenge because its perspective is often influenced more by emotion and sensationalism than scientific reasoning and knowledge.

Heightened public concern, media presentations that sensationalize events, increasing political pressure and influence, and active stakeholder involvement in nuclear projects suggest that the twenty-first-century regulatory environment will be dynamic and challenging. These elements affected the US fuel repository at

Yucca Mountain and led to a temporary suspension of construction and operating licenses for new power reactors related to fuel storage environmental concerns and the associated legal issues. There has also been significant regulatory action following the Fukushima Daiichi accident that affects existing plants and those facilities under design and construction. The twenty-first century will likely offer a challenging health physics environment with considerable emphasis on postulated power reactor release scenarios, assumed accident severity, and the definition of credible design basis events.

The twentieth century saw a maturation of the health physics profession and its scientific basis, and the twenty-first century will require additional scientific training for health physics professionals to meet the significant challenges posed by advanced technologies. These challenges include continued debate over the fundamental regulatory assumption regarding the linear-nonthreshold (LNT) dose–response hypothesis, applicability of hormesis to the human species, evaluation of doses to reference plants and animals and their inclusion in environmental assessments and regulations, and the inclusion of occupational dosimetry and environmental doses into assessments of the biological effects of ionizing radiation.

National and international organizations continue to foster sustained development and standardization, but they run the risk of becoming decoupled from applied health physicists over issues such as the LNT hypothesis and environmental protection. Instrumentation advances will permit the enhanced detection of a variety of ionizing radiation types over a wide range of energies, and these detectors will find their incorporation into consumer products such as cell phones and enhance the detection of illicit nuclear materials.

Health Physics: Radiation-Generating Devices, Characteristics, and Hazards reviews emerging and maturing radiation-generating technologies that will affect the health physics profession. It is hoped that this review will foster additional research into these and supporting areas.

Health physics is a dynamic and vital field and has an exciting future. The topics addressed in this text encompass energy generation, medical applications, fuel cycle technologies, consumer applications, public exposures, and national defense. However, significant challenges will likely arise as new technologies expand the use of radioactive materials and radiation-generating devices, failures of existing technology occur, terrorist attacks expand to include radioactive materials or nuclear weapons, and old paradigms fall.

There is an intimate linkage between the health physics profession and the expansion of nuclear technology and nuclear-related events. This linkage will manifest itself in traditional fields and possibly in new areas including the response to public space tourism and nuclear terrorism. Communications with stakeholders and the public are essential to counter misinformation and hysteria that often accompanies media reports of nuclear-related events. The twenty-first-century health physicist must be technically capable and able to communicate information to the public in a commonsense manner that is understandable to a group with limited scientific knowledge. It will be an exciting time, but a

time filled with challenges. The following areas are judged by the author to be representative of future health physics challenges, and these topics are further explored in this book:

- Generation IV fission power reactors
- Low earth orbit tourism by the public
- Advanced nuclear fuel cycles incorporating laser uranium enrichment and actinide transmutation
- Radiation therapy using heavy ions, exotic particles, internal radiation-generating devices, and antimatter
- Public radiation exposure
- Radioactive dispersal and improvised nuclear devices
- Nuclear accidents
- Evolving regulatory considerations

1.3

Forecast of Possible Future Issues

Table 1.1 summarizes a selected set of twentieth-century and early twenty-first-century events that are used to forecast events that may have health physics relevance. For example, the occurrence of the Three Mile Island and Chernobyl reactor accidents suggested that future accidents are likely and have occurred at Fukushima Daiichi. However, the cause of a future accident is not predicted by the recurrence of these events. An examination of the events is summarized in Table 1.1 suggesting possible causes for a future nuclear event which include natural events such as an earthquake, rare natural phenomena, military action, terrorism, technology failure, management failure, human error, an unrelated industrial accident, economic failure, and social disruption. The 2011 Fukushima Daiichi accident was caused by an earthquake and subsequent tsunami. The predictive power of the aforementioned approach is speculative. However, it does suggest possible twenty-first-century health physics events having the potential for significant environmental releases of radioactive materials and associated public doses.

Given the history of humankind, twenty-first-century wars are likely. With the expansion of the use of nuclear technology, these wars could include a nuclear exchange between nations and a military attack or intentional sabotage of a nuclear facility.

Terrorist events have continued into the twenty-first century including the 11 September 2001 attacks in the United States and the 2004 Madrid and 2005 London transportation bombings. Terrorist attacks on a nuclear facility are possible twenty-first-century radiological events. Other terrorist events with radiological consequences include the use of nuclear weapons, intentional dispersal of radioactive materials into a populated area, intentional contamination of water supplies, and contamination of food supplies.

Table 1.1 Selected significant twentieth-century and early twenty-first-century events.

Event	Event type	Possible twenty-first-century health physics event extrapolation
1906 San Francisco earthquake and fire	Natural event—massive earthquake	Massive earthquake damaging a nuclear facility
1908 Tunguska explosion in Siberia	Unknown cause, possibly a meteorite strike Impact energy equivalent of about 15 MT of TNT ^a)	Rare natural event damaging a nuclear facility
1914–1919 World War I	International armed conflict	Military attack on a nuclear facility
1918 Spanish flu pandemic	Epidemic	Epidemic affects staffing and disrupts nuclear facility operations
1929 stock market crash	Economic disruption	Economic event disrupts nuclear facility operations
1930s to early 1940s Great Depression	Economic collapse	Worldwide economic collapse disrupts nuclear facility operations
1939–1945 World War II	International armed conflict	Military attack on a nuclear facility
1945 nuclear bombing of Hiroshima and Nagasaki, Japan	Nuclear attack	Nuclear exchange between nations or terrorist nuclear event in a major city
1950–1970s Space Race	Development of long-range rockets and space exploration	Nuclear missile attack Public space tourism
1960s political assassinations in the United States	Disruption of government	Social unrest disrupts nuclear facility operations
1965 Northeast US and Canada blackout	Disruption of electrical energy supply	Loss of off-site power for a nuclear facility
1972 Munich Olympics massacre	Terrorist attack	Nuclear terrorism
1976 earthquake hits Tangshan, in northeastern China	Natural event—massive earthquake	Massive earthquake with significant loss of life affects nuclear facility operations
1979 Three Mile Island nuclear accident	Power reactor accident with minimal release of radioactive material	Major power reactor accident
1981 Israeli military successfully attacks and destroys the Osirak nuclear reactor in Iraq	Military attack on a nuclear power facility	Major power reactor accident following a military attack
1984 massive poison gas leak in Bhopal, India	Major industrial accident	Major industrial accident affects nuclear facility operations

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Table 1.1 (Continued)

Event	Event type	Possible twenty-first-century health physics event extrapolation
1986 Chernobyl nuclear accident	Power reactor accident with significant release of radioactive material	Major power reactor accident
1986 Space Shuttle Challenger explosion	Technological and management failure	Failure of safety and management systems disrupts nuclear facility operations
1987 Goiania, Brazil, contamination event	^{137}Cs orphan source contaminates homes and individuals, resulting in four fatalities	Radiological dispersal device is utilized in a terrorist attack
1989 Northeast United States, Canada, and Sweden experience a power blackout caused by a solar flare	Disruption of electrical energy supply	Loss of off-site power for a nuclear facility
2001 New York City and Pentagon terrorist attacks	Terrorist attack	Nuclear terrorism including a direct attack on a nuclear facility
2003 Space Shuttle Columbia accident	Technological and management failure	Failure of safety and management systems disrupts nuclear facility operations
2003 Northeastern and Midwestern United States and Ontario, Canada, blackout caused by a solar flare	Disruption of electrical energy supply	Loss of off-site power for a nuclear facility
2004 Madrid commuter train bombing	Terrorist attack	Nuclear terrorism including a direct attack on a nuclear facility
2005 London underground train and double-decker bus bombings	Terrorist attack	Nuclear terrorism including a direct attack on a nuclear facility
2005 Hurricane Katrina floods New Orleans, kills nearly 2000, and damages critical infrastructure	Massive storm disrupts a major city and surrounding areas	Loss of power and critical infrastructure support to a nuclear facility Flooding a nuclear facility
2009 terrorist attack occurred at Fort Hood in Texas. A US Army major and psychiatrist fatally shot 13 people and injured more than 30 others	Insider terrorist attack by a member of the operating organization	Trusted employee becomes a terrorist and sabotages a nuclear reactor to create severe core damage and release of fission products to the environment

Table 1.1 (Continued)

Event	Event type	Possible twenty-first-century health physics event extrapolation
2011 Fukushima Daiichi nuclear accident	Massive earthquake and tsunami causes a power reactor accident involving multiple units with a significant release of radioactive material	Major power reactor accident involving multiple units caused by a natural event
2012 Hurricane Sandy storm surge floods New York City and neighboring areas	500-year storm surge disrupts city services	Loss of power and infrastructure support to a nuclear facility Flooding of a nuclear facility
2013 18 m-diameter meteorite explodes over Chelyabinsk, Russia, and injures 1000 people	Impact event corresponding to an energy equivalent of about 1 MT of TNT ^{a)}	Rare natural event damages a nuclear facility
2013 Asteroid DA14 (5.7×10^8 kg) passes within 1.0×10^4 km of the earth	Astronomical near miss with a 2046 predicted return to earth	Rare natural event damages a significant geographical area including infrastructure and nuclear facilities
2013 Typhoon Haiyan devastates the eastern Philippines	The massive typhoon leads to a death toll in the thousands with hundreds of thousands displaced and critical infrastructure destroyed	Massive typhoon disrupts nuclear facility operations
2013 110 TBq ⁶⁰ Co teletherapy source stolen in Mexico	Theft of radioactive material	Stolen radioactive material is incorporated into a terrorist device
2014 Waste Isolation Pilot Plant waste container undergoes an unanticipated chemical reaction and releases americium and plutonium into the environment	Underground geologic waste repository event	Major accident at a high level waste geologic repository caused by the failure of assumed controls and inadequate oversight
2014 Belgian Doel 4 nuclear reactor's turbine is sabotaged and severely damaged	Sabotage of a nuclear power reactor	Sabotage of a nuclear reactor leading to a major accident with severe core damage and an off-site release
2015 Germanwings Airbus A320 carrying more than 140 passengers intentionally crashed by its copilot	Catastrophic act committed by a trusted employee	Trusted employee sabotages a nuclear reactor to create severe core damage and release of fission products to the environment

a) Megatons of trinitrotoluene.

Many aspects of health physics activities are reactive. These reactive aspects include resolution of audit and inspection findings, response to abnormal and emergency events, and development of procedures and programs to meet regulatory requirements. However, the author prefers a proactive approach that challenges accepted assumptions and established practices to address and anticipate future events. For example, the National Council on Radiation Protection and Measurements assumes that improvised nuclear devices will not exceed 10 kT (trinitrotoluene, TNT equivalent). Given the level of technology, availability of weapons information in the open literature, abundance of raw scientific data, proliferation of nuclear materials, and availability of necessary computational tools, the 10 kT design assumption should be expanded to include larger weapons yields to develop bounding plans, procedures, and resource allocation requirements. The 10 kT limit also appears to exclude the possibility of the theft of an existing device from a nuclear power, transfer of a device from a nuclear power to a terrorist organization, or use of proven scientific resources to develop a higher-yield clandestine device.

Other nuclear scenarios that could present twenty-first-century health physics challenges are developed in subsequent chapters and their associated problems. However, to provide a preview of upcoming topics, a series of general problems are provided in this chapter to illustrate possible twenty-first-century events of significant health physics consequences. These problems are based on the events in Table 1.1. They are low-probability, high-consequence events that are often classified as X factors or black swan events.

In the twentieth century, the causes of the Fukushima Daiichi accident would have been classified as X factors. Unfortunately, my Mark-I Crystal Ball is out of service, but past events are often a guide to future events. Therefore, the Chapter 1 solutions are necessarily general and brief. However, considerable additional detail is provided in the subsequent chapters that more fully characterized the consequences of more probable event types.

One way to minimize the consequences of future radiological events is to constantly challenge assumptions, focus on the mitigation of significant events, and have an informed public that understands the risks and benefits of nuclear technologies. Scientific prediction and mitigation of significant nuclear events have not been completely successful, and we must do a significantly better job in the future. That is not an easy task. I hope that this text will motivate additional improvements to minimize the probability and consequence of future radiological events.

The twenty-first century will be an exciting time for the health physics profession. It is the author's desire that this book contributes in some small measure to the education of twenty-first-century health physicists and their understanding of existing, evolving, and emerging radiation-generating technologies. The author also hopes that this text will foster additional effort to improve upon and further develop the topics of this text.

Problems

- 1.1 The 1908 Tunguska explosion in Siberia is believed to have been caused by a meteorite. On 30 June 1908, a meteorite exploded about 10 km above the ground in a sparsely populated region. The blast released about 15 MT of energy and leveled about 2000 km² of forest. Predict the consequences of a Tunguska-type event that explodes in the air within 1 km of the underground Hanford Tank Farms containing fuel reprocessing waste. List the most likely public effects and required health physics actions resulting from this event.
- 1.2 In 1984, a huge poison gas leak in Bhopal, India, led to the death of thousands of people. A storage tank containing methyl isocyanate at a pesticide plant leaked gas into the densely populated city of Bhopal. It was one of the worst industrial accidents in history. Predict the consequences of a Bhopal-type event that occurs in proximity of an operating nuclear power reactor. List the most likely effects and health physics consequences of a Bhopal-style event if the gas cloud covered a nuclear power facility for an extended period.
- 1.3 The North American blackout of 1965 was a significant disruption in the supply of electricity that affected parts of Ontario, Canada, and New England in the United States. Over 30 million people and 207 000 km² were without electricity for over 10 h. Predict the consequences of an extended (e.g., several weeks) power blackout event that occurs at a uranium enrichment facility using lasers and UF₆ gas as the working fluid.
- 1.4 Assume that a terrorist group acquires medical isotopes (i.e., ³²P, ⁶⁰Co, and ¹³¹I) and incorporates them into a dirty bomb. What is the relative hazard of these isotopes if the dirty bomb is detonated in a populated area? How do these hazards affect recovery activities?
- 1.5 A massive solar event has the potential to disrupt the electrical grid for an extended period. If a solar event an order of magnitude larger than the 1859 Carrington event (see Chapter 6) occurred, what is the impact on the capability of a nuclear power reactor to preserve its fission product barriers? Assume the event disrupts the power grid supplying the reactor and its surrounding area for 1 month.
- 1.6 A limited nuclear exchange occurs between two neighboring nations. Each nation has detonated three, 250 kT ²³⁹Pu fission devices over separate, heavily populated targets. You have been requested to advise the population residing outside the immediate blast area. Stakeholders are particularly interested in the radiological effects of fallout. The impacts on the food supply and means to limit the associated effective doses are immediate concerns. From a health physics perspective, what isotopes are of concern, what pathways can these isotopes enter the food chain, and what protective actions can be applied to limit the absorbed dose from these isotopes?
- 1.7 A terrorist group has stolen sufficient ²³⁵U to fabricate a crude nuclear weapon. In the process of constructing the device, the explosive package prematurely detonates, but the weapon does not achieve a significant nuclear yield. What isotopes are of concern? What health physics actions should be implemented to permit reentry into the ground zero area?

- 1.8** A research team has developed a cancer therapy technique using anti- ^{12}C ions. List three challenges to deploying this technology to medical facilities. List three positive aspects of this technology.

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