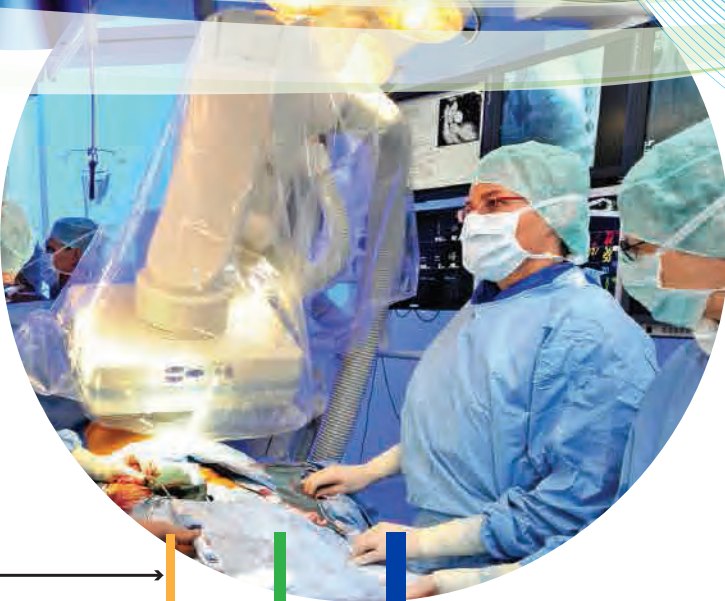


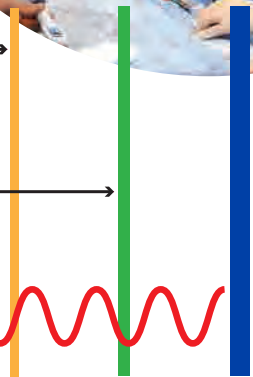
Radiation and Risk: Expert Perspectives



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Radiation and Risk: Expert Perspectives

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Foreword

By Dr. Joxel Garcia, MD, MBA¹

My life as a public health leader has provided me with the opportunity to work on many important and relevant public health issues locally, nationally, and internationally. Among those issues, there is no more fascinating or controversial area of work that I have encountered than the topic of radiation and nuclear energy. It seems that everyone I have met has an opinion about the topic. From the science experts to politicians, from the media to the academicians, even from my childhood friends in the dairy farm town of Hatillo, Puerto Rico, where I was raised, to my educated and prestigious friends in New York City, Washington, DC, and Geneva—every one of them has a “personal expert opinion” about radiation and nuclear energy. People recall the high-profile accidents like Chernobyl in the Ukraine in April 1986 and the more recent Fukushima power plant disaster that followed the earthquake and tsunami affecting Japan in March 2011. Few, though, could describe or place an objective value on the actual benefit to patients and the environment from the use of clean nuclear power instead of fossil fuel-based electricity and from medical treatment of cancer patients with radiation. This selection of papers will provide valuable perspectives on the benefits and risks of nuclear technology from esteemed experts and leaders in the field.

My interest in radiation started as a medical student; I was fascinated by Madame Marie Curie’s life and her groundbreaking work on radiation, especially her interest in its clinical benefits.

As a resident in training and then as a practicing physician, I saw firsthand the clinical benefits of controlled radiation therapy on patients with cervical cancer and other malignancies, as well as the use of radiological tests to screen patients and save lives. As time passed, I had the privilege to serve as the Commissioner of Public Health in Connecticut. That job included working with government and academic peers, public health and safety officers in the state and region, as well as nuclear industry leaders in the support and implementation, if necessary, of the state of Connecticut’s Radiological Emergency Plan, and responding to all transportation, industrial, and research-facility emergencies and incidents involving ionizing radiation. The public health personnel worked closely with the Office of Emergency Management as well as the state’s Department of Environmental Protection and the U.S. Environmental Protection Agency to keep our safety plan up to date and the state well prepared in case of a radiation or nuclear accident.

During that time, I was able to appreciate the work done by our federal regulatory agencies related to nuclear energy, power plants, and medical devices that utilize radiation.

¹ Dr. Joxel Garcia was the 13th U.S. Assistant Secretary for Health and also served as the U.S. Representative to the World Health Organization Executive Board. Currently, Dr. Garcia serves as principal at the International Healthcare Solutions Group and partner at Faunus Global.

I also learned firsthand about the synergistic and collaborative work between industry and government to better protect the populations served, as well as to help produce an efficient and effective alternative to fossil-based fuel. The collaboration and synergy between industry and government has driven nuclear energy innovation and workforce development and strengthened U.S. efforts to address the safety, waste management, and security of nuclear energy.

After I served my state, I went to work for the Pan American Health Organization and the World Health Organization. There I was able to live with, face, and better understand the multiple conflicting, as well as very passionate, views on the topic by people from all segments of society and from various countries in the Pan American region as well as in Asia, Africa, and Europe.

One of my most humbling, and career-fulfilling, experiences was to serve as the 13th U.S. Assistant Secretary for Health (ASH); as the ASH I was the highest public health officer in the United States, and as such I needed to understand how to better protect our nation. One of the lessons I learned was to appreciate the synergistic and collaborative work that the private sector, including industry, research institutions, and academia, provide to our nation in conjunction with federal, state, and local governments. It is that collaborative work that makes our nation better and is an example of how the work on nuclear energy and radiation safety should continue to improve continuously. This document is an example of the collaborative work such improvements require.

My esteemed colleagues will present the reader with objective and science-based information as they help us navigate through some of the most important and timely issues regarding radiation and nuclear energy. The authors are the leading scientists in their respective fields and encompass multiple fields and specialties, including engineering, medicine, health physics, environmental health, and public safety. Their research and academic accolades are matched only by their reputation and experience, which includes firsthand experience with the three most well-known and significant nuclear accidents in history—Fukushima and Chernobyl (the only two classified as a level 7 event on the International Nuclear Event Scale) and the 1979 Three Mile Island accident in Pennsylvania resulting from a partial reactor meltdown.

Mr. Howard Dickson, former president of the Health Physics Society, describes how ubiquitous background radiation is emitted from both natural and human-made radioactive sources and how we are continuously irradiated by sources outside and inside our bodies.

Dr. Richard Vetter, professor of radiobiology and radiation protection at Mayo Clinic, discusses how ionizing radiation serves important purposes in clinical medicine as a diagnostic tool and as therapy.

Dr. Louis Wagner, the chief physicist at the University of Texas Medical School at Houston, explains the important distinction between risk of use and overuse of nonenergy nuclear technology, as well as its distinction in the medical and nonmedical industries.

Dr. Kathryn Higley, from Oregon State University's Department of Nuclear Engineering and a former reactor supervisor, and Ward Whicker, professor emeritus at Colorado State University, make an impressive presentation on the concept that nuclear energy is the only currently available technology that can effectively replace fossil fuel-generated electrical energy. Furthermore, they present the benefits for the environment that could be realized by changing to a mostly nuclear-powered economy.

Dr. Higley presents the central importance of safety to nuclear power design in the United States.

The late Dr. Bernard Cohen, formerly professor emeritus of physics at the University of Pittsburgh, describes the risk ratios and communication aspects of risk assessments.

Dr. Robert Peter Gale of the Imperial College in London and the University of California Los Angeles (as well as a medical consultant involved in the Chernobyl and Fukushima accidents) and colleague Dr. F. Owen Hoffman convey the importance of acknowledging that the uncertainty in our present risk estimates is based on our current knowledge and that this uncertainty may change as our knowledge improves. They argue that this nuanced approach will better inform the public and allow for more intelligent decision making, help build trust between scientists and the public and, more importantly, create more effective communication.

Last, but not least, Dr. Robert Emery, an appointed member of the Texas Radiation Advisory Board and vice president for safety, health, environment, and risk management at the University of Texas Health Science Center at Houston, eloquently describes how the past half century has shown the great value of nuclear energy and the importance of regulatory protocols and effective communication with the public. Furthermore, he convincingly shows that efforts to evaluate and refine current regulations must be steeped in the lessons learned and scientific evidence drawn from past occurrences so that we can continue pursuing the safe and efficient use of radiation.

I am confident you will enjoy the reading these timely articles as you are presented with facts and information needed to understand some of the issues and concerns about nuclear energy and radiation, all in a concise and easy-to-read document.

I will leave you now with words from a two-time Nobel Prize winner (physics and chemistry) and the pioneer in this area, Madame Marie Curie: "Nothing in life is to be

feared, it is only to be understood. Now is the time to understand more, so that we may fear less.”

It has been an honor to provide this foreword.

Very respectfully,

Joxel Garcia, MD, MBA

13th U.S. Assistant Secretary for Health

Former U.S. Representative to the WHO Executive Board

A Primer on Ionizing Radiation

By Howard Dickson¹

Radiation is energy that comes from a source and travels through space and may be able to penetrate various materials in its path. Light, radio, and microwaves are types of radiation that are called nonionizing. The kind of radiation discussed in this document is called *ionizing radiation* because it can produce charged particles (ions) in matter. Ionizing radiation is produced by unstable atoms or high-voltage devices (such as x-ray machines).

Atoms with unstable nuclei are said to be **radioactive**. In order to reach stability, these atoms give off, or emit, the excess energy or mass. These emissions are called **radiation**. In short, radioactive atoms give off—or emit—radiation. The kinds of radiation are electromagnetic (such as x rays and gamma radiation) and particulate (alpha and beta particles).

Radiation Safety

After a century of developing man-made, radiation-producing devices—many of which help support human life—there was a heightened awareness that risks associated with related materials and radiation-based activities had to be evaluated and managed to ensure the safety of the general public. Thus, the multidisciplinary field of health physics was born to fulfill the need to better evaluate and manage radiation safety, and the Health Physics Society was formed shortly after to support all aspects of the profession. The middle of the 20th century marked the time that the U.S. government began responding to the prevalence of man-made radiation with regulatory bodies focused on ensuring public and environmental safety.

Three fundamental radiation protection principles apply to radiation sources and to exposed individuals, in all cases where the exposure is controllable. In general, exposure to natural sources of radiation is controllable only to the limited extent that individuals can choose the location in which they live.

1. The principle of justification: Any decision that alters the radiation exposure situation should do more good than harm. This means that by introducing a new radiation source or by reducing existing exposure, one should achieve an individual or societal benefit that is higher than the detriment it causes.
2. The principle of optimization: The likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal

¹ Howard Dickson is president of Dickson Consulting, LLC, and Web Operations editor in chief for the Health Physics Society. (Correspondence contact: hw dickson1@verizon.net)

factors. This means that the level of protection should be the best under the prevailing circumstances, maximizing the margin of benefit over harm.

The third radiation protection principle is related to individuals and applies only in planned exposure situations.

3. The principle of application of dose limits: The total dose to any individual from all planned exposure situations, other than medical exposure of patients, should not exceed the appropriate limits specified by a regulatory body. Dose limits are determined by a national regulatory authority, such as the Nuclear Regulatory Commission, on the basis of international recommendations and apply to workers and to members of the public in planned exposure situations. Dose limits do not apply to medical exposure of patients or to public exposures in emergency situations.

History of Radiation Protection

Health physics is concerned with protecting people from the harmful effects of ionizing radiation while allowing its beneficial use in medicine, science, and industry. Since the discovery of radiation and radioactivity over 100 years ago, radiation protection standards and the philosophy governing those standards have evolved in somewhat discrete intervals. The changes have been driven by two factors—new information on the effects of radiation on biological systems and changing attitudes toward acceptable risk. The earliest limits were based on preventing the onset of obvious effects such as skin ulcerations that appeared after intense exposure to radiation fields. Later limits were based on preventing delayed effects, such as cancer, that had been observed in populations of people receiving high doses, particularly from medical exposures and from the atomic bomb exposures in Hiroshima and Nagasaki.

During the evolution of standards, the general approach has been to rely on risk estimates that have little chance of underestimating the consequences of radiation exposure. It is important to realize that most of the effects observed in human populations have occurred at high doses and high dose rates. The information gathered from those populations must be scaled down to low doses and low dose rates to estimate the risks that occur in occupational settings.

According to the Environmental Protection Agency's history of radiation protection:

By 1915, the British Roentgen Society adopted a resolution to protect people from overexposure to X-rays. This was probably the first organized effort at Radiation Protection.

By 1922, American organizations had adopted the British protection rules. Awareness and education grew, and throughout the 1920s and 30s, more guidelines were developed and various organizations were

formed to address radiation protection in the United States and overseas.

Radiation protection was primarily a non-governmental function until the late 1940s. After World War II, the development of the atomic bomb, and nuclear reactors caused the federal government to establish policies dealing with human exposure to radiation. In 1959, the Federal Radiation Council was established. The Council was responsible for three things:

1. advising the President of the United States on radiological issues that affected public health
2. providing guidance to all federal agencies in setting radiation protection standards
3. working with the States on radiation issues.²

Following World War II, nuclear regulation was the responsibility of the Atomic Energy Commission, which Congress established in the Atomic Energy Act of 1946 (amended in 1954). The act also made the development of commercial nuclear power possible for the first time in history.

The U.S. Congress chartered the National Council on Radiation Protection and Measurements (NCRP) in 1964 as follows:

To:

1. collect, analyze, develop and disseminate in the public interest information and recommendations about (a) protection against radiation . . . and (b) radiation measurements, quantities and units . . . ;
2. provide a means by which organizations concerned with the scientific and related aspects of radiation protection . . . may cooperate . . . ;
3. develop basic concepts about radiation . . . measurements . . . and about radiation protection;
4. cooperate with the International Commission on Radiological Protection, the Federal Radiation Council, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private,

² <http://www.epa.gov/rpdweb00/understand/history.html>

concerned with radiation . . . measurements and with radiation protection.³

The Energy Reorganization Act of 1974 created the U.S. Nuclear Regulatory Commission (NRC).

Today, the NRC's regulatory activities are focused on reactor safety oversight and reactor license renewal of existing plants, materials safety oversight and materials licensing for a variety of purposes, and waste management of both high-level waste and low-level waste. The NRC also relinquishes to the states portions of its regulatory authority to license and regulate byproduct materials (radioisotopes), source materials (uranium and thorium), and certain quantities of special nuclear materials. Thirty-seven states have entered into agreements with NRC, and others are being evaluated. In addition, the NRC evaluates new applications for nuclear plants.

In 1970 Congress created the Environmental Protection Agency (EPA) and radiation protection became a part of EPA's responsibility. Today, EPA's Radiation Protection Division is responsible for protecting the public's health and the environment from undue exposure to radiation. This is accomplished by setting safety standards and guidelines.

Current radiation dose limits protect workers and the public. Our radiation protection standards embody the extensive knowledge on radiation effects gained through radiobiological and epidemiological research of the last century. Collectively, more is known and understood about the biological effects of radiation than any other toxin or carcinogen. This knowledge applies to animals and the human species of various ages, organs and tissues of differing radiosensitivities, and a wide range of biological endpoints, including cell death, mutations, chromosome aberrations, and carcinogenic transformation. While questions remain on the precise shape of dose-response functions for specific biological effects over a broad spectrum of doses and dose rates for radiations of varying qualities, our understanding is sufficient to establish strong scientific bases for current radiation protection standards. No single hypothesis explains all combinations or mitigating circumstances in radiation toxicology. Further research will enable a greater understanding of natural factors that influence adaptive response and cellular repair of radiation damage.

Natural Background Radiation

Background radiation (which scientists call "ubiquitous" because it is everywhere) is emitted from both natural and human-made radioactive sources. Humans are continuously irradiated by sources outside and inside our bodies. Some naturally occurring radiation comes from the atmosphere as a result of radiation from outer space, some comes from the earth, and some is even in our bodies from radionuclides in the food and water we

³ http://www.ncrponline.org/AboutNCRP/About_NCRP.html

ingest and the air we breathe. Additionally, human-made radiation enters our environment from consumer products and activities such as medical procedures that use radionuclides or x rays and from nuclear power plants used to generate electricity.

Whatever its origin, radiation is everywhere in our environment. Figure 1 depicts the typical distribution of exposure from all sources of ionizing radiation. Natural background radiation is the largest source of radiation exposure to humans (about 50 percent). However, medical sources of radiation exposure are almost as large (about 48 percent). The remaining 2 percent comes from consumer products, occupational exposure, and industrial exposure. A small fraction of this 2 percent comes from the operation of nuclear power plants.

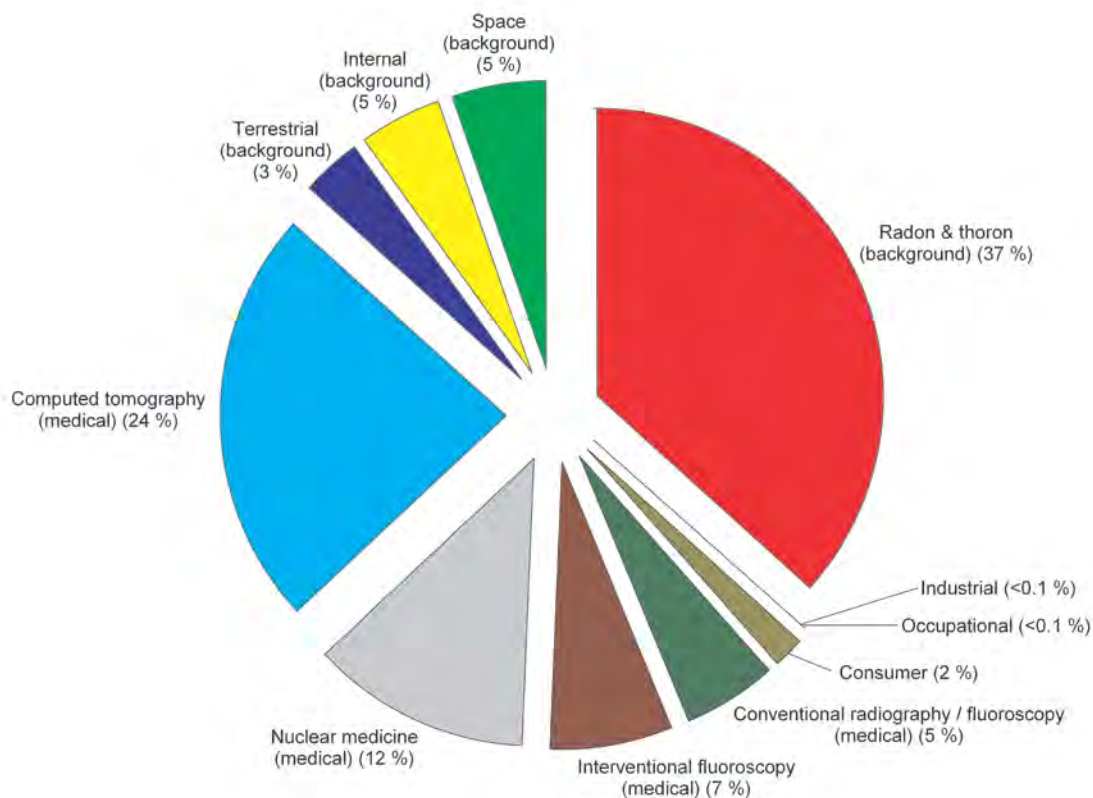


Figure 1. Source distribution for all radiation dose – contribution of various sources of exposure to the total dose per individual in the U.S. population for 2006. Fig. 1.1 from NCRP 160. Reprinted with permission of the National Council on Radiation Protection and Measurements, <http://NCRPpublications.org> (NCRP 2009).

Radiation from Space. Radiation from outer space is called cosmic radiation. Radiation from beyond the solar system has enough energy to generate cosmogenic radionuclides, unstable forms of any nuclide, as it passes through the earth’s atmosphere. Some of this radiation reaches the earth’s surface, with most entering near the poles, where the earth’s

magnetic field is the weakest, and at high altitudes, where the earth's atmosphere is the thinnest. These radionuclides created by cosmic radiation consist primarily of tritium, carbon-14, and beryllium-7.

Radionuclides Originating on Earth. Radiation that originates on earth is called terrestrial radiation. Some elements, such as uranium, that have been present since the earth formed about 4.5 billion years ago decay and produce radioactive isotopes, or radionuclides. They are found around the globe in sedimentary and igneous rock. Radionuclides migrate from rocks into soil, water, and even the air. Human activities such as uranium mining have also redistributed some of these radionuclides.

These radionuclides include the series produced when uranium and thorium decay, as well as potassium-40 and rubidium-87. A past human activity that contributed to terrestrial radiation was atmospheric testing of nuclear weapons. Today, weapons testing is not a significant contributor to airborne background radiation; however, some contamination remaining from previous weapons testing is still detectable at very low levels in surface soil, including cesium-137 and strontium-90. Reactor accidents such as those at Three Mile Island in Pennsylvania (1979), at Chernobyl in Russia (1986), and in Japan (2011) have contributed negligibly to background radiation in the United States.

Radionuclides in the Body. Terrestrial and cosmogenic radionuclides enter the body through the food we eat, the water we drink, and the air we breathe. As with all chemicals, radionuclides are taken in or eliminated by the body during normal metabolism. Some radionuclides are not readily absorbed in the body and are quickly eliminated. Some decay away so quickly they may not have time to accumulate in specific body tissues, but may be replaced through ingestion or inhalation. Others decay more slowly and may concentrate in specific body tissues (such as iodine-131 in the thyroid).

The most significant radionuclides that enter the body are from the earth. Primary among them is radon gas (and its decay products) that we constantly inhale. Radon levels depend on the uranium and thorium content of the soil, which varies widely across the United States. The highest levels are found in the Appalachians, the upper Midwest, and the Rocky Mountain states.

Uranium and thorium (and their decay products), as well as potassium-40, are the main radionuclides in our bodies. These terrestrial radionuclides are in the soil and fertilizers that are applied to the soil, subsequently entering our food and water supply. Most drinking-water sources have very low levels of terrestrial radionuclides, including radium-226, radium-228, and uranium. These radionuclides are found at higher levels in some areas of the United States than others.

Human-Made Sources of Radiation

Medical Sources (48 percent). By far, the major source of human-made radiation is from medical applications. The increase in the medical use of radiation accounts for the largest part of the overall increase in radiation exposure over the decade. However, like natural background radiation, this dose is not evenly distributed across the population. People with health issues receive the majority of the dose, especially older individuals, who receive more diagnostic and therapeutic radiation. Much of the increase in radiation from medical applications is due to advances in technology, especially the increased use of computed tomography (CT). CT scans are the major medical source of radiation and account for half of all medical exposure.

Nuclear Energy Sources (0.1 percent). A relatively minor source of man-made radiation is the nuclear energy industry, which generally uses uranium as fuel to produce about 20 percent of America's electricity. Interestingly, coal-fired plants emit more radioactive particles than nuclear power plants because of natural radioactivity in the coal that is burned, resulting in radioactive plant effluents.

Consumer Products (2 percent). Other sources of radiation include consumer products and uses of natural radioactivity, such as in some smoke detectors, energy-saving compact fluorescent light bulbs, timepieces, ceramics, fertilizers, lantern mantles, and granite countertops.

Dose from Exposure to Radiation

A person receives a dose from the exposure to radiation sources whether outside the body (for example, external radiation from medical x rays) or inside the body (for example, internal radiation from radioactive potassium absorbed by the cells when a person eats food). When scientists describe dose, they use the units of sievert (Sv), one-thousandth of a sievert (millisievert, or mSv), or one-millionth of a sievert (microsievert, or μ Sv). Here in the United States, dose is often referred to in units of rems, which are one-hundredth the dose of a sievert. (*Measurement comparisons and conversions can be found in Appendix 1.*)

Each year, U.S. residents receive an average dose from natural background radiation of about 3.1 mSv (310 mrem). This figure does not include man-made doses, such as from medical procedures, which adds about another 3.1 mSv for a total of about 6.2 mSv (620 mrem) per year.

The NRC is the primary agency for regulating radioactive materials and ensuring public safety. The NRC set a radiation dose limit of 1 mSv (100 mrem) in a year and 0.02 mSv (2 mrem) in an hour for a member of the public from regulated radiation sources; however, the agency excludes natural and medical uses of ionizing radiation. If a member of the public received the entire legal dose limit from regulated man-made sources (a very

rare occurrence), it would still be much less than he or she received from all background sources.

Dose from Space Radiation. In the United States, people receive an average dose from space radiation of about 0.04 μSv (0.004 mrem) in an hour, or about 0.33 mSv (33 mrem) each year. Space radiation dose makes up about 5 percent of the average total dose from all background radiation.

Traveling by airplane can expose people to slightly more space radiation because at high altitudes, there is less atmosphere to shield the incoming radiation. For example, one study found that on a flight from New York to Chicago, travelers would receive an additional dose of about 0.01 mSv (1 mrem).

Dose from Terrestrial Radiation. People living in the United States receive an average dose from terrestrial radiation of about 0.21 mSv (21 mrem) per year.

Fallout from past nuclear weapons testing is not a significant contributor to current radiation dose. The average terrestrial radiation dose (not including the dose from radionuclides in the body, discussed below) is about 3 percent of the average total dose from all background radiation.

Dose from Radionuclides in the Body. Inhaled radionuclides include cosmogenic radionuclides and terrestrial radionuclides that become airborne. Of all sources of background radiation, radon (the radioactive gas emitted by uranium and thorium in soil and rocks) results in the greatest dose to humans. Radon is ever present and occurs at various levels depending on several factors. For example, most would be surprised that due to heavy traces of uranium in the granite and marble used in both the U.S. Capitol and New York City's Grand Central Station, the dose from these buildings is roughly 1.2 mSv (120 mrem) per year (greater than the regulatory limit required of nuclear facilities for exposure to the public).⁴

Indoor radon concentrations, however, are also the most variable dose components, since they depend on the soil the house is built on, how it is built, where in the house radon is measured, and more. Even some granite countertops can contribute to the radon levels in a house, but this contribution is typically very small compared to the radon from the soil under the house. The average dose from all inhaled radionuclides is about 2.3 mSv (230 mrem) per year, which is about 37 percent of the average total dose from all background radiation.

People ingest radionuclides when they eat food grown in soil that contains uranium, thorium, potassium, and rubidium; drink milk from animals fed crops that grow in the soil;

⁴ http://inst.nuc.berkeley.edu/NE104/Lectures/Sources_NE104_Spring12.pdf

and drink water containing dissolved radionuclides. The average dose from all ingested radionuclides is about 0.3 mSv (30 mrem) per year, which is about 5 percent of the average total dose from all background radiation.

Dose from Man-Made Products That Emit Radiation. As mentioned, by far the major radiation dose from man-made products is the result of medical applications. Report NCRP 160 by the National Council on Radiation Protection and Measurements found that medical doses have increased to the point that by 2006, the average individual received 3.1 mSv (310 mrem) per year, almost half of all exposure. This is more than a seven-fold increase in less than three decades, resulting in an increased concern by the medical community and efforts to make sure that these exposures to radiation are medically justified.⁵ The use of CT scans is the major medical source of radiation and accounts for half of the medical exposure.

Consumer products, plus occupational and industrial exposure, which includes the exposure from the operation of nuclear power plants, only contribute about 0.1 mSv (10 mrem) per year (2 percent of the exposure).

Health Effects of Exposure to Radiation

Exposure to high levels of radiation is known to cause cancer and, at very high levels, radiation poisoning and even death. But the effects on human health from very low doses of radiation—such as the doses from background radiation—are extremely hard to determine because there are so many other factors that can mask or distort the effects of radiation. For example, if we compare people exposed to high radon levels to cigarette smokers, the latter group is much more likely to develop lung cancer than nonsmokers. Lifestyle choices, geographic locations, and individual sensitivities are difficult to account for when trying to understand the health effects of background radiation.

A United Nations committee in 2000 concluded that exposure to varying levels of background radiation does not significantly affect cancer incidence (UNSCEAR 2000). In 2006, a committee of the National Academy of Sciences suggested that while there may be some risk of cancer at the very low doses from background radiation, that risk is small (NRC 2006). According to the International Agency for Research on Cancer (IARC), “The impact of low dose radiation on the overall cancer burden is difficult to quantify.”⁶

Still, while the overall risk for radiation-induced cancer is low, it is greater for some types of cancer than others. For lung cancer caused by breathing radon, the EPA estimates that there are as many as 21,000 deaths each year in the United States, which is about 13 percent of all lung-cancer deaths. (Some scientists consider that number as an upper bound

⁵ http://www.ncrponline.org/Publications/Press_Releases/160press.html

⁶ <http://www.iarc.fr/en/research-groups/ENV/index.php>

on the potential deaths from radon exposure.) Of the 21,000 lung cancer deaths from radon inhalation, only 2,900—or roughly 14 percent—are from nonsmokers. Smoking, of course, is the number one cause of lung cancer and secondhand smoke ranks third. The total lung-cancer deaths directly related to smoking (first or secondhand) exceed 190,000 people per year.⁷

There is even some credible scientific evidence that there is a beneficial effect from exposure to low levels of radiation—an effect called *hormesis*. There is no evidence of increased risk of diseases from naturally occurring radiation other than that of cancer.

Total environmental causes and contributors to cancer are difficult to accurately identify, given the varying degrees of exposure any one person may have compared to another based on the time and space in which they exist. Also, in most cases there are combinations of potential cancer triggers that a person is exposed to throughout his or her life in varying degrees and duration. Of course, some catalysts are more easily recognized than others. As the IARC states, “Some agents within this scope of environmental, lifestyle, occupational and radiation-related exposures have already been identified as major causes of cancer, particularly tobacco smoking and exposure to ultraviolet radiation.”

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⁷ <http://www.epa.gov/radon/healthrisks.html>

Growing Importance of Nuclear Technology in Medicine

By Richard Vetter, PhD, CHP¹

Ionizing radiation serves three important purposes in medicine. First, it makes it possible for physicians to diagnose many conditions that would be difficult or impossible to diagnose in any other way. The most well-known use of radiation in medicine is the creation of images of the inside of the human body. Images can be formed in two general ways—by directing x rays through the patient’s body (diagnostic radiology) or by administering radioactive pharmaceuticals to the patient (nuclear medicine imaging).

Second, ionizing radiation is also used to treat cancer by directing intense beams of x rays, gamma rays, or protons directly at the area of the body where the tumor is located. These intense beams are usually produced by large electronic machines called accelerators or cyclotrons, but in some cases a radioactive source is implanted in the tumor either for a short time or permanently. Finally, small amounts of radioactive materials are used in the laboratory to analyze blood and tissue samples or to conduct research.

At some time during our lives, most of us will have a diagnostic radiology or nuclear medicine imaging examination to help the physician evaluate our body. For example, radiology can reveal a broken bone, and nuclear imaging (such as a heart scan) can be crucial in diagnosing a disease. Radiation doses from these exams usually are quite low, but in some cases patients receive higher-than-average doses (Table 1).

During a diagnostic radiology examination, x rays are generated by a machine and directed at the area of the body of interest. Some of the x rays are absorbed in the patient, while others pass through the patient and are captured by an imaging device on the other side of the patient. The imaging device sends information about the captured x rays to a computer that creates an image (radiograph) of the internal structures of the body. The areas of the body most frequently examined by a diagnostic radiologist are arms and legs, chest, and teeth. Radiation doses from these exams are low, usually only a fraction of the dose we receive from background radiation.

Use of one special type of x-ray exam, computed tomography (CT), has increased considerably over the past three decades. Because the radiation dose from a CT exam is higher than a radiograph, it is not used if a radiograph will provide the information needed to make the diagnosis. CT exams have become extremely useful in diagnosing and staging cancer and in evaluating patients with coronary artery disease, but they also serve an important role in diagnosing other diseases, such as acute appendicitis. Therefore, the

¹ Richard Vetter, professor emeritus of biophysics from Mayo Clinic in Rochester, Minnesota, is the agency and congressional liaison for the Health Physics Society.

benefit from CT exams is large compared to the low risk that may result from the radiation exposure.

The procedure that delivers the highest radiation doses in diagnostic radiology is called interventional radiology. This procedure uses x rays to image a specific part of the body, such as the heart, during a procedure that requires the physician to manipulate a probe or other device within the organ of interest. In complicated cases, the organ may receive several minutes of exposure to x rays, compared to a conventional diagnostic radiology exam that delivers x rays in a fraction of a second. Typically, the longest exposure times occur in rare cases when patients require a complicated procedure to correct an internal cardiac-pacing signal.

In nuclear imaging exams, a patient receives a pharmaceutical that has been tagged with a radionuclide (radioactive atom). The pharmaceutical concentrates the radionuclide in particular organs of the body. When the radionuclide undergoes radioactive decay, it emits ionizing radiation, typically x rays or gamma rays, some of which pass through the body and are captured by a large detector placed next to the patient. The detector sends electronic signals to a computer that creates an image of the internal structures of the body. The image shows any abnormality, such as a tumor.

The most common exam performed in cancer patients is a bone scan that will show the location of any tumors that have spread to the bone. Another common nuclear imaging exam performed is a heart scan that will detect areas of the heart where blood circulation is abnormal, such as an area of muscle damaged by a heart attack or an area where blood flow is restricted by a clot or plaque in a coronary artery. The radiation doses from most nuclear medicine exams are comparable to the doses from other diagnostic x-ray imaging procedures (Table 1).

Finally, higher doses of ionizing radiation are used to treat cancer. This technique focuses beams of radiation on the area of the body that contains the cancer cells. This area (a tumor or tissue that contains cancer cells) is exposed to radiation from several directions to minimize the radiation dose to normal tissue and maximize the radiation dose to cancer cells. In addition to receiving a higher radiation dose, cancer cells are more susceptible to radiation and cannot repair the radiation damage as well as normal cells can. Another form of radiation therapy, in which a radiation source is implanted in the tumor, is called brachytherapy.

Even though the medical benefit provided by the information obtained from imaging exams far outweighs any risk to the patient, hospitals take precautions to avoid unnecessary exams and to keep the radiation doses as low as reasonably achievable (ALARA). Under the ALARA principle, the decision to order an imaging exam is based on medical judgment made in the best interests of the patient. The amount of radiation used is

the minimum necessary to make an accurate diagnosis. High quality of the exam is assured by maintaining equipment in the best possible condition and properly adjusting and operating the radiation-generating and imaging equipment.

Table 1. Adult Effective Doses² for Various Radiation Procedures (Mettler 2008)

Radiation Procedure	Average Effective Dose (mSv)
Diagnostic Radiology Exam	
Lumbar spine	1.5
Mammography	0.4
Hip	0.7
Abdomen	0.7
Extremities	0.001–0.005
CT Procedures	
Head	2.0
Chest	7.0
Abdomen	8.0
Pelvis	6.0
Coronary angiography	16.00
Interventional Radiology Procedures	
Coronary angiography (diagnostic)	7.0
Coronary angioplasty	15.0
Pelvic vein embolization	60.0
Nuclear Medicine Imaging Exams	
Brain	7.0
Bone	6.0
Cardiac stress test (^{99m} Tc-sestamibi)	13.0
Cardiac stress test (²⁰¹ Tl-thallium chloride)	40.0
Tumor (¹⁸ F-FDG)	14.0

Health Effects and Risk from Both Energy and Nonenergy Production

Shortly after the discovery of x rays in 1896, scientists observed that people exposed to large amounts of radiation experienced skin damage, and those exposed to many doses of radiation developed tumors several years later. Since then, radiation has been studied extensively and biological effects are well known. Since radiation plays an important part of our lives in the production of energy, diagnosis of medical conditions, and many other applications, it is important that we learn certain basic facts about how radiation affects our bodies.

² Effective dose is a weighted average of the whole-body radiation exposure.

Our knowledge of the health effects of radiation is based on the study of radiation in the laboratory as well as epidemiological studies of populations exposed to high doses of radiation. We know that single exposures to high doses of radiation produce acute effects that scientists call deterministic effects. These effects occur only after the radiation dose surpasses a high dose called the threshold dose. For example, skin reddening observed in some patients who receive radiation therapy occurs only after the radiation dose to the skin exceeds several sievert (Sv), which is nearly 1,000 times the dose to the skin from a chest radiograph. Therefore, in all uses of radiation special care is taken to keep the dose below the threshold dose for deterministic effects unless it would be detrimental to the patient, for example, in certain cancer treatments. Laboratory studies have revealed that these biological effects of radiation are caused by damage to tissue DNA, which results in errors in metabolism of the cells that make up the tissue. In some cases, such as in cancer cells, the DNA damage is so great that the DNA initiates the mechanisms that cause cell death. This is the basis for treatment of tumors with radiation.

When the radiation dose is below the threshold for deterministic effects, the DNA damage is not significant enough to cause errors in metabolism or cell death. In this case, the DNA is able to repair the damage caused by radiation, similar to the way it repairs itself following exposure to other toxic agents. However, epidemiological studies have shown that when people are exposed to high doses of radiation that are below the threshold for deterministic effects, their risk of developing cancer is increased. Since radiation does not produce a unique type of cancer, a cause-and-effect relationship between radiation and a particular cancer cannot be determined by simply examining people who were exposed to radiation. It is also impossible to distinguish a cancer caused by a low dose of radiation from a cancer caused by exposure to some other carcinogen, such as cigarette smoke. Scientists call this type of radiation damage a stochastic effect, which means that the risk of cancer increases as the dose increases. Scientists also assume, but are unable to prove, that cancer caused by high doses of radiation also occurs at low doses of radiation, but at a much lower frequency. Scientists refer to this dose-response relationship as the linear no-threshold (LNT) hypothesis or dose-response model.

Studies of the biological effects of radiation have shown that the LNT hypothesis is not true for deterministic effects. They are observed only after a threshold dose is exceeded. Epidemiological studies of human populations have not been strong enough to determine whether there is a threshold for stochastic effects such as cancer, so scientists assume for purposes of public health that there is no threshold for stochastic effects. It is impossible to prove the LNT hypothesis because people develop cancer from many other causes. Approximately 41 percent of men and women born today will be diagnosed with

cancer of all body sites at some time during their lifetime³ (National Cancer Institute 2011). Epidemiological studies suggest that only a small fraction of 1 percent of these cancers is due to exposure to radiation, including background and man-made radiation.

Discussion of Epidemiological Evidence

Laboratory studies have shown a relationship between radiation-induced DNA damage and the development of cancer. Studies also show that this process does not differ from the process for development of spontaneous cancer or cancers associated with exposure to other carcinogens. Consequently, it is not possible to determine the cause for a particular cancer in a patient. We can only draw an association between the cancer and exposures to carcinogens to surmise the probable cause of cancer. Scientists learn about these associations by studying populations exposed to a probable carcinogen and comparing them to populations that have not been exposed to the carcinogen. These studies are called epidemiologic studies (National Research Council 2006).

The most widely cited epidemiological studies of radiation are the studies of Japanese atomic bomb survivors who were exposed to large doses of radiation from the atomic bombs dropped on Hiroshima and Nagasaki, Japan, in 1945 (National Research Council 2006). The advantages of these populations are their large size (nearly half of the survivors are still alive today), the inclusion of both men and women of all ages, the wide range of estimated doses received by the survivors, and the high quality of the data collected from these populations. The data show that the incidence of cancer increases proportional to the radiation dose from 0.1 Sv (10 rem) upward, suggesting that the LNT dose-response model may be appropriate for doses above 0.1 Sv (10 rem). Although the risk of cancer varies with sex and age of the patient and the type of cancer, the overall estimated risk of cancer based on these studies is 500 cancer deaths per 100,000 individuals exposed to 0.1 Sv (10 rem) of radiation. The number of people expected to die of spontaneous cancer in this population is about 24,000.

A number of medical populations have been studied following their exposure to high doses of radiation, for example, studies of second cancers following radiation therapy (National Research Council 2006). Population-based cancer registries in many countries have allowed scientists to study the probability of a second cancer after treatment of a primary cancer using radiation therapy. In most of these studies, patients received high doses of radiation—40–60 Sv (4,000–6,000 rem)—to the cancerous tissue. Doses to surrounding tissue decreased with distance from the target tissue, allowing scientists to determine the association between tissue dose and frequency of second cancers. Types of cancer treatments studied include cervical cancer, breast cancer, ovarian cancer, testicular

³ National Cancer Institute. Surveillance Epidemiology and End Results, SEER Stat Fact Sheets: All Sites. 2011. Available at: <http://seer.cancer.gov/statfacts/html/all.html>. Accessed 14 February 2012.

cancer, thyroid cancer, and Hodgkin's disease. These studies have shown that in patients exposed to high doses of radiation, the risk of cancer is dependent on the tissue exposed, the sex and age of the patients, and other factors. The risk of these patients developing a second cancer was similar to the risk of cancer in the Japanese population. Additional studies are needed to determine whether there is a risk from exposure to low doses in procedures such as CT scans.

Epidemiological studies of radiation workers exposed to radiation by virtue of the work they do with radiation (for example, radiologists) have been conducted since the 1950s and include workers exposed to diagnostic x rays as early as the 1930s and workers exposed to high concentrations of radioactive materials. These studies are limited by the low radiation doses they typically received. Risk estimates from these studies are variable, with some suggesting no risk while others suggest the risk is similar to the risks to those members of the Japanese population who were exposed to low radiation doses (National Research Council 2006).

Epidemiological studies of populations living around nuclear facilities are limited even more than occupational groups due to the very low doses of radiation they received and by the difficulty in estimating doses to individuals. Thus, most of these studies do not provide an estimate of disease risk. Those studies that did estimate disease risk have found no increased risk of disease associated with radiation exposure (National Research Council 2006).

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Distinguishing Risk: Use and Overuse of Radiation in Medicine

By Louis Wagner, PhD¹

Medical uses of ionizing radiation differ in purpose from industrial uses of ionizing radiation. Principally, the difference in medical and nonmedical industries is that medical exposures of patients are controlled intentional exposures to affect some therapeutic or diagnostic result. Conversely, exposures from all other industries to members of the public are controlled incidental exposures at levels that are usually far lower than the maximum levels allowed by regulation.

Both medical and nonmedical industries result in some radiation exposure to the public. Medicine, however, is by far the leading source of exposure to the population from man-made radiation (Mettler 2007). Nonmedical uses are limited by design to keep radiation exposures to levels well below any that is known to cause any health threat. Medical exposures are designed to be appropriate for the task and by necessity are typically much higher than any incidental exposure from nonmedical industries. But with medical exposures, there is a direct health benefit to the exposed individual. With other industries, the benefits are indirect and include economic and lifestyle benefits.

For workers and members of the public who are incidentally exposed to radiation from industry, the goal is to protect public health while also providing the economic and social benefits of the industry. These social and economic benefits include:

- Produce a supply of electricity
- Provide natural materials from mining
- Supply medical isotopes for diagnosis or treatment
- Verify structural integrity of public works and buildings
- Identify and document works of art

In medicine, the patient is the direct beneficiary. Some examples of major benefits include:

- More effective surgeries
- Shorter hospital stays
- Elimination of many exploratory surgeries
- Better diagnoses of and treatments for cancer
- More efficient treatments after injury
- Better management of stroke patients
- Better management of cardiac conditions

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- Rapid diagnoses of acute life-threatening vascular conditions such as mesenteric ischemia (Furukawa et al. 2009)

The rapid diagnosis made possible by the use of ionizing radiation is a welcome aspect of modern medicine, resulting in the relief of pain, alleviation of suffering, and prolonged and improved quality of life.

Any potential risk associated with the medical uses of ionizing radiation must be weighed against the short-term and the long-term benefits in its use. The goal of medical care is to make sure the benefits to the patient far exceed any putative risks associated with exposure to the radiation. For this reason, the medical profession continues to critically analyze its uses of radiation, ensuring that medical uses are well justified by the need (Furukawa et al. 2009).

There are many examples of professional discourse over the pros and cons of medical uses of radiation. These include uses of x rays for prenatal care and pelvimetry (Campbell 1976; Kelley et al. 1975), publications that are abundantly available of findings relating uses of radiation to treat cancers in patients, introduction of methods to reduce radiation exposures during scoliosis examinations (Gray et al. 1983; Ardran et al. 1980), findings on the inadequate training of physicians in the uses of radiation (Lee et al. 2004), and many more. All these publications are open to the public and indicate a profession freely critiquing itself with the goal that a healthy discourse will foster and encourage improvements in how the profession uses radiation. Only by critical self-examination and self-improvement initiatives can a profession improve its effectiveness.

Mistakes have been made (Shope 1996; Koenig et al. 2001a; Koenig et al. 2001b). Instances of mistakes that led to radiation effects include hair loss from brain perfusion studies and radiation injury to some patients from interventional procedures (that themselves were necessitated by life-threatening conditions). These adverse events are the result of inadequate management of radiation within the medical community. However, the industry is not defined by the occurrence of mistakes, but by the overall improvement in health care and the ability of the industry to correct inadequacies that led to the mistakes (Wagner et al. 1994; Miller et al. 2004; Hirschfeld et al. 2004; NCRP 2009; American College of Radiology 1992; Goske et al. 2010).

For example, early during the findings that radiation delivered to pregnant women might increase the risk of cancer in the children, albeit at relatively low probability, the community of medical professionals opened debate on whether the efficacy of pelvimetry was sufficient to justify its use or whether a limited use of pelvimetry was more appropriate. Ultimately, a limited use prevailed. Today, the movement to better manage radiation exposure of children has led to research into the efficacy of the medical use of computed tomography (CT) in children for diagnosis following traumatic injury (Kuppermann et al. 2009).

Another example of medical industry's dedication to acknowledging and correcting mistakes involves the expanding use of CT in improving the treatment of stroke. These CT studies are known as brain perfusion imaging. At some facilities, the protocols to use CT imaging were not managed appropriately and resulted in excessive exposures to patients, producing hair loss and unnecessarily high radiation doses to the brain. These adverse results were made public when discovered, and the Food and Drug Administration launched investigations immediately, with the full cooperation of medical societies. The outcome was an elevated awareness in the medical community of the need for procedures to assure proper management of CT protocols. This realization led to improved radiation management for a spectrum of procedures, not just brain perfusion studies.

Managing nonmedical radiation exposure to the public focuses on minimizing radiation exposure within the bounds essential to public health.

The risks from medical radiation are so well publicized that some seem to believe medicine is remiss in its use of radiation. A different perspective says that publicizing incidents rapidly exposes weaknesses so they can be more readily corrected. Progress in treating disease and improving health can only be made as long as the medical profession expects it will have to adjust safety procedures to reflect its changing uses of radiation. Only by open acknowledgement of weak areas will medicine have the knowledge necessary to recognize these weaknesses and correct them.

The American Cancer Society recently reported that cancer death rates in the United States have continued to decline over the past two decades (American Cancer Society 2012). The medical community will continue to refine its use of radiation in medical imaging and other nuclear medical technologies for diagnosis and treatment to improve health care and increase our life expectancy.

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Nuclear Energy: The Environmental Context

By F. Ward Whicker¹ and Kathryn Higley²

All forms of energy harnessed to support human activities cause environmental impacts. Coal burning releases air pollutants and carbon dioxide (CO₂) and may cause acid rain. Oil spills damage aquatic and terrestrial ecosystems. Natural gas exploration and production, when not done properly, can harm aquifers. Uranium milling produces radioactive tailings, hydropower alters streams, wind turbines kill birds and bats, and solar panels require disposal of cadmium and other heavy metals and require large land areas. Different ecological impacts can be cited for each of these energy technologies.

Global energy production demands are at an unprecedented scale and growing. As demand for all forms of energy continues to increase to drive economic growth and satisfy universal aspirations for higher standards of living, the environmental impact and costs of various means of energy production must be taken into account.

Many believe that we have the means to significantly reduce the use of coal, oil, and natural gas through the increased use of renewable energy sources such as hydropower, wind, and solar technologies, combined with increased energy efficiencies. While these actions are laudable, most critical studies on this idea find that these technologies are unlikely to ever replace a large percentage of baseline energy needs now met by fossil fuels. Nearly all the feasible sites for damming rivers for hydropower already have been used, and the huge land areas necessary for such massive wind or solar projects is unlikely to ever be available. Wind, solar, and hydropower are weather dependent and cannot be relied upon to produce adequate and reliable levels of base-load electrical power (Dominici et al. 2004; Cravens 2007).

The only available technology that can effectively replace fossil fuel-generated electrical energy is nuclear energy (Deutch and Moniz 2006). Nuclear power yields minor releases of CO₂ to the atmosphere, but only indirectly from obtaining fuel (uranium) and building infrastructure, not from direct electricity generation. The total (direct and indirect) amount of CO₂ released per kilowatt-hour (kWh) of electricity generated by nuclear energy is far lower, by a factor of roughly 50, than fossil-fueled electricity and equal to or lower than other energy sources (Cravens 2007). Furthermore, fossil fuel-powered vehicles release a significant share of CO₂ to the atmosphere. Among other options, hydrogen-powered vehicles offer promise (Tollefson 2010). Nuclear reactors designed to operate at very high temperatures may be able to split water molecules to produce

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hydrogen economically, with minimal release of CO₂ (see http://www.eoearth.org/article/Hydrogen_production_from_nuclear_power).

Deforestation in developing countries from burning biomass to heat or cook not only destroys ecosystems, it also adds to the global problem of CO₂ levels in the atmosphere. Both of these environmental problems could in principle be alleviated in many regions with nuclear energy.

So, while we have the technical means to significantly reduce CO₂ emissions to the atmosphere, the social and political will to do so is problematic. Public acceptance of commercial nuclear power has been hampered in past decades by the testing and use of nuclear weapons, secrecy of the Cold War, poor public education about nuclear topics, and accidents like Three Mile Island, Chernobyl, and Fukushima. In addition, historic use of coal, oil, and gas has given these industries an advantage over other energy industries when it comes to political influence. Communicating the benefits of nuclear energy encounters additional challenges when antinuclear groups exaggerate the dangers of radioactive byproducts and nuclear terrorism.

However, in addition to far lower emissions of CO₂ and other greenhouse gases, there are numerous other benefits of nuclear energy to human health and to the environment. Let's focus on the latter for a moment, namely environmental impacts of nuclear energy in comparison to other technologies. It is essential to base these comparisons on the various environmental impacts per unit of electrical energy obtained (kilowatt-hour). Also, it is important to include all impacts, direct and indirect, of producing a unit of electrical energy, a life-cycle approach.

One can start with the amount of land required to produce energy, including each step in the process (for example, mining, transportation, infrastructure and facility development, waste disposal, etc.). The acreage of land disturbed per kWh of electricity generated is far lower for nuclear energy than for any other method of power generation. This is not surprising, given the incredibly high energy density of uranium, as compared to coal, for example. The energy density of uranium (enriched to about 4 percent uranium-235) is over two million times that of coal (Cravens 2007; see also <http://www.ocean.washington.edu/courses/envir215/energynumbers.pdf>). Producing the same amount of energy requires about 4,600 times more volume of coal compared with the volume required of a typical uranium ore (Hammond 1974). This vast difference in volume of fuel required translates to a comparable difference in disturbed land area. Nuclear power also is a more efficient energy source in terms of land area disturbed per unit of electrical energy produced by a factor of 120 or more (Domenici et al. 2004).

Comparison

While many worry about the highly radioactive wastes from nuclear power generation, the technical means to safely store such material clearly exists. The

fundamental advantage to nuclear waste, compared to coal ash, for example, is the small volume. R.P. Hammond (1974) calculated that if the entire U.S. electrical energy need were met by nuclear reactors, the waste volume resulting from 350 years of production would fit into a cube measuring 200 feet on a side. The comparable volume of coal ash produced to generate an equivalent amount of energy would be more than 1,000 times larger. If the United States continues to rely mainly on coal and other fossil fuels, there will be increasing political pressure to tap reserves in ecologically sensitive areas throughout the United States and Canada. Such reserves include, for example, the Arctic National Wildlife Refuge, offshore areas and pristine lands in the western states, and elsewhere.

Chemical emissions from nuclear power plants are far lower than those from coal-burning plants. For example, coal-fired plants emit, in addition to a long list of toxic chemicals (see <http://www.lung.org/assets/documents/healthy-air/coal-fired-plant-hazards.pdf>), acid rain-producing sulfur dioxide and nitrous oxide as well as mercury, while nuclear plants emit none of these materials (Comby 2001). Coal-fired power plants also emit natural radioactivity (uranium and thorium and their byproducts, as well as potassium-40) found in coal at concentrations comparable to most rocks and soil (Eisenbud and Gesell 1997). Radioactive emissions from nuclear power plants have been shown to be lower than from coal plants, resulting in far lower doses to the public than those from natural background radiation (NCRP 2009) and lower still than those required to cause ecological impacts (Whicker and Schultz 1982).

It is difficult to directly compare environmental impacts of potential large-scale accidents among the different energy technologies. For example, how would one compare the Exxon Valdez oil spill to the Chernobyl accident? Excluding Chernobyl, which was a dangerous reactor design to begin with, there have been no catastrophic accidents from nuclear power generation that have caused significant, recognizable damage to natural ecosystems.³ On the other hand, there are many examples of ecological damage from the many kinds of large and small oil spills, oil storage tank explosions, gas pipeline leaks and fires, and hydroelectric dam failures that caused flooding.

Risk

All sources of energy pose some risk to human health or environmental quality. Many historical facts can be used to argue that nuclear power is much safer than other energy technologies, both for human health and environmental quality. Radiation protection standards for humans, embodied in regulations that U.S. nuclear facilities must adhere to, exceed ample protection for other species and for ecosystems. The world's most serious nuclear accident ever, Chernobyl, caused significant ecological disturbance from

³ Recently some assessments and modeling of soil dose rates surrounding the Fukushima facility have suggested the possibility of impacts close to the site within the deterministic effects range, but longer-term analysis and ground truth data will be required to confirm.

radioactive materials within 10 km or so of the reactor. However, due mainly to evacuation of people living in the area, the diversity of species and overall ecological health was greatly restored through natural succession within a few years after the accident, and the area now has the characteristics of a flourishing wildlife preserve (Mycio 2005; IAEA 2006).

Mining

Uranium mining and milling produce ecological impacts. Land surfaces must be disturbed for mines, storage of overburden piles, roads, milling activities, and mill tailings. However, in recent years a method called in-situ uranium recovery (that involves boring a hole into a deposit followed by pumping in a solution that is then extracted along with the material) has gained favor over large open-pit mines, which drastically reduces the amount of land area disturbed. Uranium mills release chemicals to the atmosphere, and tailings piles and ponds can cause local groundwater degradation and release radon gas as well as resuspended particles to the air. Mill tailings, byproducts of the milling process, contain radium, which decays to produce radon and poses a potential hazard to public health and safety. If left untreated, mill tailings cannot support ecosystems of comparable quality to nearby undisturbed areas. However, these impacts are generally temporary because state and federal regulations require careful remediation of impacted areas. Remediation procedures involve the collaboration of several state and federal agencies and are often highly complex, ensuring that each remediation takes into consideration the specific environmental impacts, location, and regulations involved at a particular site.

Uranium enrichment and fuel fabrication require certain amounts of land and energy, and these processes involve emissions of chemical contaminants and some heat. Nuclear reactors also require land, electrical transmission lines, and infrastructure that use conventional energy sources. Emissions of chemical and radioactive contaminants from modern reactors are extremely low, but large amounts of heat must be released to the environment.

Disposal

Spent nuclear fuel is currently stored at reactor sites in large steel-lined concrete pools or in dry storage casks above ground, since no geological disposal facility is currently available in the United States. Disposal of spent nuclear fuel or high-level radioactive wastes from reprocessing is technically feasible, but politically difficult. Most concepts for high-level waste disposal involve deep geological storage. The environmental impacts of deep geological storage of nuclear waste are likely to be limited because the volume of the waste is extremely small. A road to such a site would be required, as well as limited land surface disturbance at the site for infrastructure and disposal of excavated material. There is potential for deep groundwater contamination many years in the future should waste canisters ultimately leak and should a fraction of the contents be transported by infiltrating water. However, the likelihood of this can be controlled by emerging technologies and

careful site selection, and any human health impacts hundreds to thousands of years into the future can be quantified and mitigated with current knowledge and experience.

Conclusion

Internationally, nuclear energy reactor technology has advanced for several decades, leading to more reliable and safer power generation. For example, advanced designs such as fast neutron reactors, combined with recycling of nuclear fuels, offer significant reductions in uranium ore mining and milling and easier ways of developing effective high-level waste-disposal systems. Spent nuclear fuel from conventional reactors still contains over 90 percent of the potential energy obtainable from nuclear fission of the enriched uranium. Fast neutron reactor designs can utilize most of the remaining energy in the enriched uranium, while simultaneously breeding more fissile material (see <http://www.world-nuclear.org/info/inf98.html>). This combination of increased fuel utilization and fuel breeding in turn would make the environmental advantages of nuclear power even more compelling.

Finally, it is critical to recognize the huge reductions in CO₂ and other greenhouse gases, as well as in land area disturbance, that can be realized from changing to an economy mostly powered by nuclear energy. These facts—and legitimate fears of the impacts of continued fossil fuel consumption—have been recognized by many, including prominent environmentalists such as James Lovelock (Lovelock 2009), noted scientist and author of *The Gaia Theory*; Patrick Moore, a founder of Greenpeace; and Hugh Montefiore, former board chairman of Friends of the Earth.

The overall environmental advantages of nuclear energy significantly surpass those of fossil fuel. Failure to replace, as quickly as possible, coal-, gas-, and oil-burning power plants with nuclear energy is likely to lead to continuing environmental consequences that could result in significant changes in the biosphere and human life-support systems.

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Nuclear Power in the United States: Safety, Emergency Response Planning, and Continuous Learning

By Kathryn Higley¹

The United States has utilized nuclear energy to generate power for more than 50 years. Today there are 104 operating nuclear plants in the United States, consisting of 35 boiling water reactors and 69 pressurized water reactors (Figure 1). These plants produce approximately 20 percent of the electrical power in the United States.

U.S. Operating Commercial Nuclear Power Reactors

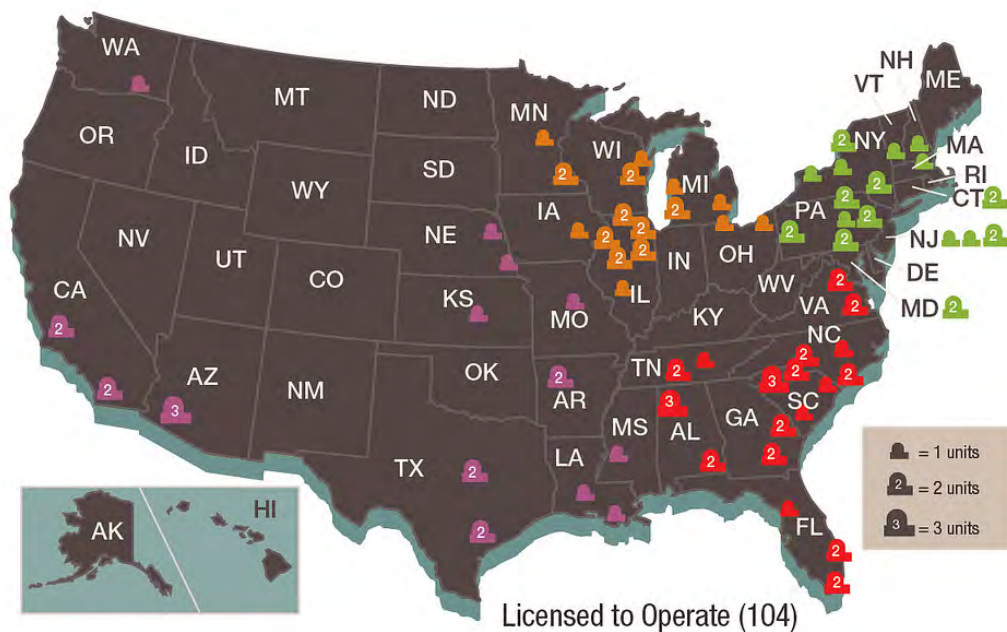


Figure 1. Map of U.S. Operating Commercial Nuclear Power Reactors
(U.S. Nuclear Regulatory Commission, NUREG-1350, Volume 24, August 2012,
<http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/>)

Facility Design and Safety

The production of electrical energy is a high-tech effort—whether it is based on hydropower, solar, wind, coal, natural gas, nuclear, or geothermal resources. And any power-production technology must be operated in a safe fashion. For electricity production using nuclear technology, safety is a cornerstone of power plant design, even going so far as to consider the potential impacts of climate change on the landscape surrounding the facilities (Budnitz 2010; Wan et al. 2010). Reactor design, construction, and operation are

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predicated on the concepts of defense in depth and extremely conservative safety margins. (Rashad and Hammad 2000).

Safety is such an integral part of nuclear power design that it has even resulted in the creation of the field of probabilistic risk assessment (PRA) as an intensely rigorous means to evaluate reactor safety.² PRA provides a systematic structure to examine how components of reactor systems, or other complex designs, interact. This allows quantification of risk and identification of aspects that potentially impact on safety.³

PRA was initially considered an innovative approach to nuclear safety analysis, in that it took a systematic and all-inclusive approach to the problem. Ultimately, it created a fundamental shift in safety design for nuclear plants. PRA work included quantification of risk for specific incidents (Apostolakis and Mosleh 1979) and changed regulation of nuclear power in the United States (Lewis et al. 1979; Keller and Modarres 2005).

In the United States, the U.S. Nuclear Regulatory Commission (NRC) regulates the nuclear power industry.⁴ Its function is very specific—to “ensure the operation of nuclear power plants and other NRC-licensed facilities present no undue risk to public health and safety.” The NRC utilizes a variety of sources and techniques to oversee safe operations of plants under its jurisdiction. For example, it employs independent technical reviewers through the Advisory Committee on Reactor Safeguards. Nuclear facilities also have independent resident inspectors who function as on-site representatives of the NRC to ensure that the plants are run consistent with government regulations.

The Reactor Oversight Process (ROP) is a cornerstone of the NRC’s responsibility to ensure safe facilities. The ROP reviews three specific areas of reactor performance:

- Reactor safety (to prevent facility accidents and/or minimize potential consequences if accidents occur).
- Radiation safety (to protect facility workers and surrounding public from excessive radiation exposure).
- Safeguards (to guard against facility sabotage or unknown security threats).⁵

The purpose of NRC oversight is to verify that a plant operates safely; the NRC also strives to create a culture in which information is shared between operators and regulators, and anyone can raise safety concerns to the highest levels within the organization.

² <http://www.ans.org/pubs/magazines/nn/docs/2000-3-2.pdf>

³ <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/probabilistic-risk-asses.html>

⁴ The NRC, among other responsibilities, also regulates the civilian use of radioactive materials.

<http://www.nrc.gov/reading-rm/doc-collections/nuregs/brochures/br0099/r12/br0099r12.pdf>

⁵ <http://pbadupws.nrc.gov/docs/ML0708/ML070890365.pdf>

Emphasis on routine plant maintenance is intended to keep systems in safe operating condition (NEI 1996). The NRC has created technical requirements that are reviewed and updated periodically (NRC 1997). These are used as a template for plant design and operation and are contained within the Code of Federal Regulations. Inherent within these requirements are engineering concepts such as safety margins, which are applicable to the design, construction, and operation of the plants.

The International Nuclear and Radiological Event Scale (INES) was introduced in 1990 by the International Atomic Energy Agency (IAEA) to enable prompt communication of safety-significant information in case of nuclear accidents.⁶ This scale has seven levels, each 10 times more severe than the preceding one. Assignment of rankings considers if people or the environment are impacted, if barriers restricting radiation release have been breached, and if safety systems have been lost. Events that have no safety significance are not ranked on the scale. Those incidents that are confined within the facility may rank as high as 3, and accidents involving impacts beyond the plant boundary are scored between 4 and 7. In the United States, the only reactor event receiving a ranking was the incident at Three Mile Island, which was assigned a score of 5 because of severe damage to the reactor core.⁷

Preparedness/Withstanding Natural Disasters

The safe operation of nuclear plants is the highest priority for both operators and regulators of nuclear power facilities. Nuclear power plant owners and operators have an obligation to continually evaluate the safety and security of their facilities to ensure that they are able to address evolving or emerging safety concerns. Events that occur at a nuclear plant outside of normal operating parameters are documented, evaluated, and reported to the NRC by the facility owners. External events such as earthquakes or flooding that also may be relevant to the operating safety of nuclear facilities are similarly considered. These events may include something as minor as a sticking valve or new information on seismic events.

The NRC conducts an independent technical evaluation of these variables to make a determination of the appropriate solution to address or resolve a perceived or real problem. This plan of action is then transmitted to the plant owners to incorporate into their operating systems. Safety systems are upgraded as directed by the NRC to address any concerns identified. The process is one of continuous assessment, evaluation, resolution, and improvement (Figure 2).

⁶ <http://www.iaea.org/Publications/Factsheets/English/ines.pdf>

⁷ <http://www.iaea.org/ns/tutorials/regcontrol/appendix/app96.htm?w=1Three+Mile+Island>

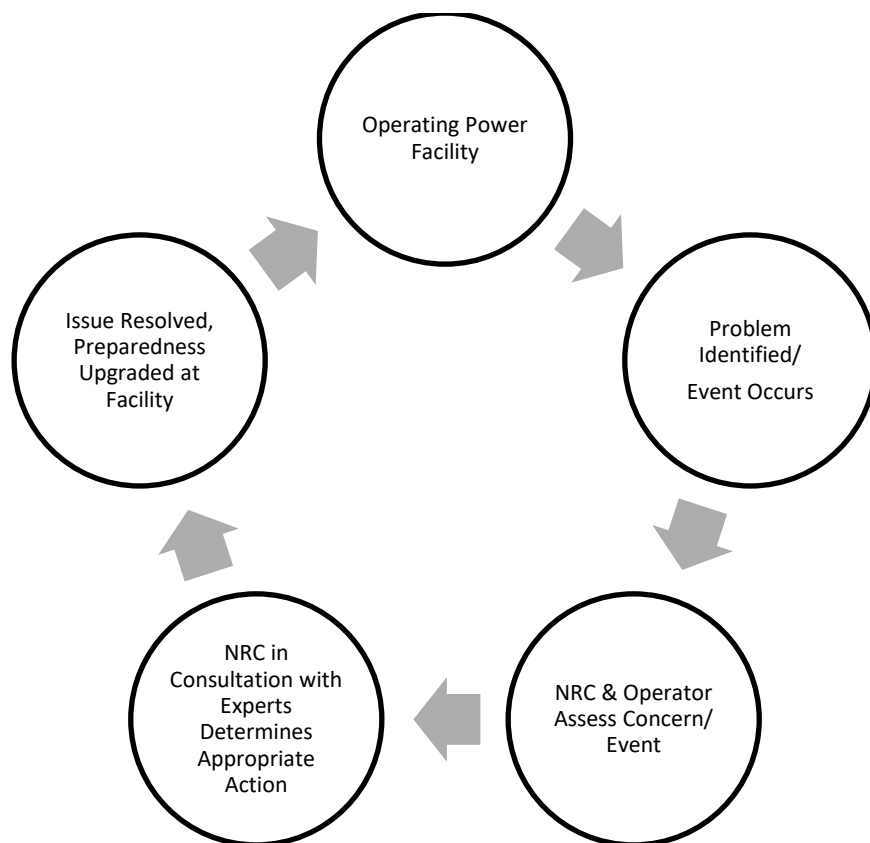


Figure 2. The cycle of continuous safety review and improvement at nuclear facilities

Emergency exercises are routinely conducted at nuclear plants and are regularly coordinated with federal, state, and local response teams. These drills are evaluated by the plant operators and state and local participants and periodically are graded by independent observers on behalf of the NRC. The purpose of each drill is to assess the operator’s (and other participants’) ability to correctly assess and respond to a variety of likely and unlikely emergency situations. The scope of drills is varied so that several aspects of emergency evaluation and response can be challenged at any one time. Drills also provide local, state, and federal agencies an opportunity to look for weaknesses in interagency coordination and cooperation. Results of the drills, including any information regarding potential safety concerns, are shared among participants and reported to the NRC.

Nuclear plant operators also continually assess the potential threat from natural disasters. For example, along the Eastern seaboard of the United States, hurricanes are a common occurrence. Plant operators have plans in place to ensure safe operation, or shutdown, should forecasts indicate landfall of a hurricane in the vicinity of a nuclear plant. Similar plans are in place for earthquakes and floods.

All nuclear power facilities have established emergency planning zones (EPZs) as a means to promote efficient response to potential emergency situations and protect the public as well as the environment. Two distinct EPZs control for exposure:

- A plume exposure EPZ (Figure 3) is meant, in the short term, to provide a method to restrict public exposure to contaminated airborne releases.
- An ingestion exposure EPZ is meant to limit ingestion of contaminated foods and/or water in the long term following an event.

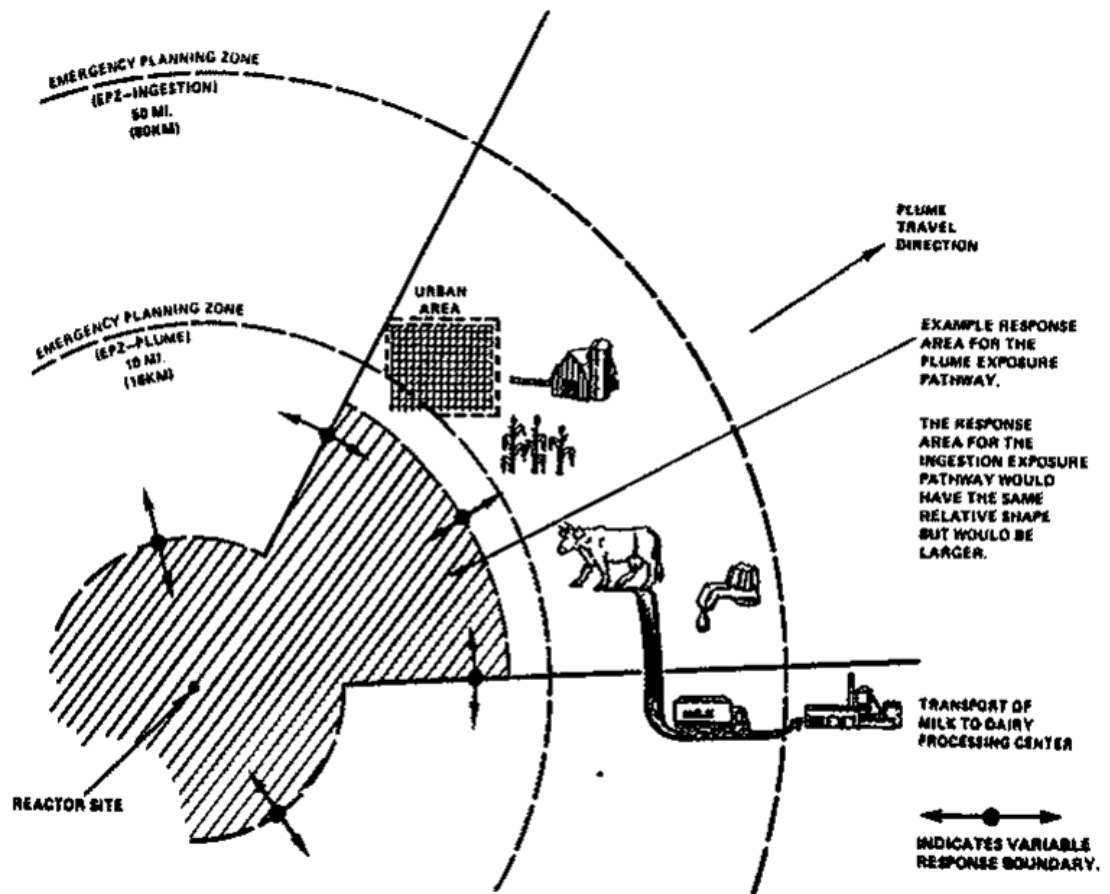


Figure 1 Concept of Emergency Planning Zones

Figure 3. Concept of Emergency Planning Zones (Fig. 1 from NUREG-0654/FEMA-REP-1 Rev. 1)

The EPZs are defined by geographical and demographic characteristics surrounding each site. The plume EPZ extends to a radius of approximately 10 miles from the site, whereas the ingestion EPZ extends up to 50 miles. Each of these EPZs includes procedures to manage exposure through means such as sheltering of the population, evacuation, or use of potassium iodide to block iodine uptake. For the ingestion-exposure EPZ, constraints on food and drinking-water consumption limit dose in the population.⁸

Emergency Planning Zones and Sheltering in Place

Planning for nuclear emergencies requires an understanding of potential accident scenarios and how radioactive releases might move from the plant. Three decades ago, the federal government developed the basis for the EPZ concept (Collins et al. 1978). The EPZ was a conservative, generic, predetermined distance where preselected protective actions could be undertaken when certain triggers (e.g., projected doses) happened. A 10-mile EPZ was created for the early phase of the accident, under the expectation that this would minimize and manage risk.

While the EPZ is described by its radius, evacuating all people within a 10-mile radius is not uniformly beneficial or necessary. Emergency responders would take into consideration how an accident is managed, how the contaminated materials are dispersed, and movement of a resulting plume, among other things. Essentially, the zones are pre-defined to help emergency responders and managers figure out the best way to evacuate people or take other protective actions, but in the event of an accident it is critical to look at the variables affecting contaminants and radiation movement and modify the zone accordingly.

Regardless of the shape of an EPZ, evacuation is not always the necessary course of action. When managing an accident, emergency responders and managers have to strike a balance between minimizing risk of radiation exposure to those in the path of released radiation plumes and the very real, yet sometimes overlooked, risk of evacuating populations. Accident statistics show that there is a potential for loss of life from simply moving people outside of zones (Witzig and Shillenn 1987). Especially with medically fragile patients, as seen with natural disasters such as Hurricane Katrina, taking patients from hospitals and moving them because of perceived or real impending threats may lead to a loss of life (Dosa et al. 2007). For this reason, among others, emergency responders and managers must balance the potential risk of eventual health complications from possible radiation exposure with the very real risk of evacuating designated areas. In some cases, instituting shelter-in-place, or requiring portions of the population to stay within

⁸ <http://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html>

their residence for a specified time, can adequately protect from impending radiation threats while also mitigating additional risks of evacuation.

While 10 miles is the current standard planning zone for evacuation, U.S. regulatory agencies are constantly reassessing the limits based on evolving information and studies. In some instances, agencies engage the public in the discussion about what is appropriate given local variables and look to the industry for additional information on potential risks. Above all, the most knowledge is often gained from lessons learned in previous incidents.

Why Learning from Events Is Integral to Safety at Nuclear Power Plants

A nuclear accident anywhere is an accident everywhere.⁹ The NRC and plant operators study accidents, and other safety occurrences, to determine their applicability and significance to operations. For example, the accident at Three Mile Island (TMI) in 1979 is generally recognized as the most costly reactor accident in the United States. This event, attributed to equipment failure and operator error, resulted in a partial core meltdown, but no loss of life or significant radiation exposures, and led to fundamental changes in how information is shared amongst plant operators and the regulators. Emergency operations procedures were developed and implemented for all U.S. light water reactors as a consequence of this accident.¹⁰ The importance of routine emergency-response drills, and the need for alternate emergency operations facilities, also came out of TMI.

Although Chernobyl occurred outside of the United States, in 1986, it reinforced the significance of containment structures for nuclear plants, incorporating inherent safety features into fuel design, providing thorough safety training for all staff, and thoroughly understanding the environmental transport pathways of radionuclides. Severe accident management guidelines were developed by plant owners as a means to respond to a severe accident.

The criticality event at Tokai-mura in 1999 underscored the importance of regulatory oversight and safety culture, the necessity of adequate worker training, and the importance of having thorough safety reviews when systems are modified¹¹ (Furuta et al. 2000).

The events of 11 September 2001, while nonnuclear in nature, prompted an analysis of nuclear plant operators' ability to respond to beyond-design-basis accidents, such as

⁹ <http://businesstoday.intoday.in/story/mohamed-elbaradei-japan-nuclear-egypt-iaea/1/14318.html>

¹⁰ http://www.anl.gov/sites/anl.gov/files/design_basis_sienicki.pdf

¹¹ <http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2000/secy2000-0085/attachment1.pdf>

aircraft accidents, as well as natural phenomena including tsunamis, tornadoes, earthquakes, and floods (Holt and Andrews 2008).

Fukushima is still being evaluated, but the NRC has already issued guidance to plant operators.¹² Lessons learned include the need to clearly understand the frequency and severity of natural events, to ensure that all facilities can withstand prolonged station blackouts caused by multiple events, and to revisit the margin of safety in plant design. This event also demonstrated the need to adopt universal systems of measurement for radiation protection—to allow for improved communication with our colleagues outside the United States.

Conclusion

Nuclear power plants have been operating for more than 50 years in the United States and now provide a substantial portion of our energy needs. Safety is a fundamental part of plant operation and is managed through a process of continuous assessment, problem evaluation, problem resolution, and improvement. Nuclear plant operations worldwide are examined to determine if there are relevant lessons to be learned and applied to U.S. facilities. The United States has a strong record of nuclear safety due to the emphasis on continuous diligence by the regulator and the operators alike.

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Radiation Risk: Used Nuclear Fuel and Radioactive Waste Disposal

By Bernard Cohen¹³

It is with great pleasure and pride that the Department of Physics and Astronomy at the University of Pittsburgh submits this chapter on behalf of the late Dr. Bernard (“Bernie”) Cohen. Dr. Cohen came to the University of Pittsburgh in 1958 as an associate professor of physics and chemistry and served Pitt and our department in a host of leadership and academic roles throughout his tenure. He officially retired in 1994, but came to the university almost every day to continue with his work until about a month before he died. This chapter is one of Dr. Cohen’s last pieces and is representative of his long career dedicated to the study and awareness of radiation safety. Cohen’s legacy lives on, not only in his many published works, but also within his undeniable impact within multiple fields.

A quick review of natural and man-made background radiation sources and levels will provide a context for assessing the human health risk from used nuclear fuel and high-level radioactive waste.

Background Radiation Exposure

Natural sources of radiation give the average American a total dose of 0.85 mSv (85 mrem) per year, mostly derived from being struck by 15,000 gamma rays per second, a total of 40 trillion gamma rays during a lifetime. The total consists of 0.3 mSv (30 mrem) per year from cosmic rays, 0.2 Sv (20 mrem) per year from natural radioactivity in the ground—mostly from potassium and from uranium and thorium decay products—0.1 mSv (10 mrem) per year from these materials incorporated into bricks, stones, and other building materials derived from the ground, and 0.25 mSv (25 mrem) per year from potassium and other radioactive elements in our bodies. Cosmic-ray exposures increase with altitude, and radioactivity in the ground varies from place to place, causing the total natural radiation exposure to vary from a high of 1.5 mSv (150 mrem) per year in Colorado to a low of 0.6 mSv (60 mrem) per year in the Gulf of Mexico coastal region.

These figures do not include exposure from radon in homes, which gives the average American an average equivalent dose of 2 mSv (200 mrem) per year, with large geographic and even house-to-house variations—the average in Iowa and Colorado is over 6 mSv (600 mrem) per year, and cases have been found where next-door houses have radon levels different by a factor of 1,000.

Man-made radiation gives the average American 3 mSv (300 mrem) per year—1.5 from CT scans, 0.75 from nuclear medicine, 0.4 from interventional fluoroscopy, 0.3 from x rays, etc. Dental x rays give 0.01–0.02 mSv (1–2 mrem) per year, and other x-ray targets give average doses as chest 0.06 mSv (6 mrem), pelvis 0.9 mSv (90 mrem), spine 4.0 mSv

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(400 mrem), and gastrointestinal tract 8 mSv (800 mrem). Residual fallout from nuclear bomb tests 50 years ago still give us about 0.02 mSv (2 mrem) per year. A coast-to-coast airline flight gives passengers about 0.03 mSv (3 mrem). Various other exposures, including those from the nuclear power industry, give the average American about 0.01 mSv (1 mrem) per year—that was the exposure to citizens of Harrisburg, Pennsylvania, from the Three Mile Island accident.

All of these sources combined give the average American an annual dose of 6.2 mSv (620 mrem).

Radioactive Waste from Nuclear Power Plants

The majority of the radioactivity produced in a nuclear reactor is in the uranium fuel rods, which are periodically removed and replaced by fresh fuel, typically after about five years. This radioactive used fuel must be carefully managed and there are many safe approaches to manage this material, including disposal in a specially designed repository. Here, we consider one of the most widely recommended approaches—recovering the energy content still contained in uranium and plutonium through chemical reprocessing for use as fuel for future reactors and incorporating the residue, which contains nearly the entire radioactivity, into glass containers for burial deep underground. How do we know that this glass-encased radioactive waste glass will not impact human health?

Scientists know how rocks behave and there is every reason to expect this glass-rock container for high-level radioactive waste will behave similarly. All ordinary rocks contain radioactive materials, and analyses demonstrate that we can calculate the probability for an atom of these to find its way, via groundwater transport, into our food and water supplies. For rocks at the burial depth of glass-enclosed radioactive waste, this probability is about one chance in a trillion per year. From that we calculate that all the byproducts produced by America's nuclear power plants will eventually cause less than one death per year in the U.S. population. Compare this with the many thousands of deaths per year caused by air pollution from burning coal to produce electricity.

There are several independent methods for confirming this estimate of less than one death per year from spent nuclear fuel. For example, from our knowledge about erosion processes, we can calculate the probability per year for an atom of buried radioactive waste to be dissolved into groundwater (one chance in a billion), and we can trace the various pathways by which it can get from deep groundwater into our food and water supplies—via potable water derived from wells and rivers, groundwater used for irrigating food crops, fish caught from rivers and lakes, etc. Again, this indicates about one death per year over many thousands of years of continuous use of nuclear energy.

These analyses assume that the radioactive waste is buried at locations throughout the United States, whereas the actual locations of waste repositories are carefully selected

by geologists and hydrologists and licensed by the U.S. Nuclear Regulatory Commission to minimize the potential for health impacts. Repository developers take steps to prevent radioactive material from escaping a repository and make plans accordingly to separate people from contaminated water and food. They also adjust waste siting to comply with engineered safeguards provided to minimize dissolution of the radioactivity into groundwater. These safeguards include multiple barriers such as the leach-resistant casing enclosing it and the special clays in which it would be embedded. In addition, low-level radioactive waste—such as filters, water clean-up agents, reactor parts, and contaminated tools—is buried in 20-foot-deep trenches in government-licensed facilities that adhere to elaborate regulatory requirements on packaging and water infiltration control. Analyses indicate that this buried material will cause only a few percent as much human health impact as the high-level radioactive waste.

The cost of high-level radioactive waste management is covered by a tax of one-tenth of a cent per kilowatt-hour of electricity from nuclear energy facilities used by consumers. This tax provides about \$750 million annually for waste management.

Decommissioning

When a reactor is shut down, it is decommissioned by removing the fuel to dry container storage, disassembling the structure and disposing of the radioactive materials (except fuel) as low-level waste, and clearing away any remaining structures. The land is then available for unrestricted use. The first commercial nuclear power plant in Shippingport, Pennsylvania, was decommissioned in this way for a total cost of \$99 million. The eventual cost of decommissioning is included in the charge for electricity during a reactor's operation.

Radiation Risk: Communicating to the Public¹

By Robert Peter Gale, MD, PhD, DSc (hon), FACP,² and F. Owen Hoffman, PhD³

Most people have only a few key questions regarding risks associated with a past or possible future exposure to a potentially harmful substance. Foremost is the deceptively simple question: *What is my risk from exposure to radiation?* Other important issues are: *How certain are you of the risk estimate you are telling me? How does this risk compare to other risks in my life? Is my risk voluntary or involuntary? And, What are my alternatives?* People need this information for many reasons, but especially for informed decision making.

Effective communication of the risk of cancer in persons exposed to ionizing radiation is challenging. Conventional approaches of presenting cancer risks are indirect and typically are point estimates relying on units of dose or concentrations of a radioactive substance in the environment. Information given in this fashion is unlikely to inform most people; worse, it can be misleading. Communication of the potential health consequences of radiation exposure using units of radiation dose also fails to consider that radiation-related cancer risk is highly dependent on the age at time of exposure, remaining life span, exposure to other cancer-causing agents (like smoking), comorbid conditions, and other variables not encompassed in the expression of dose.

The fundamental problem with relying on radiation dose to express cancer risk is that dose is only an intermediate quantity between exposure and risk. When dose is used to express risk, it is typically compared with radiation benchmarks like regulatory dose limits (such as those by the International Commission on Radiological Protection [ICRP] and the Nuclear Regulatory Commission [NRC]), doses associated with natural background radiation, doses from exposure to medical procedures (x rays, CT scans, radioisotope studies) and/or doses at the limits of a statistically significant detection of cancer risks observed in epidemiologic studies, like the Japanese atomic bomb survivors. The implication is that if the estimated dose is below dose or concentration values used for

¹ Adopted from Hoffman FO, Kocher DC, Apostoaei AJ. Beyond dose assessment: Using risk with full disclosure of uncertainty in public and scientific communication. *Health Phys* 101:591–600; 2011. We thank David C. Kocher and A. Iulian Apostoaei for their valuable comments and contributions.

² Gale is visiting professor of haematology at Imperial College, Section of Haematology, Division of Experimental Medicine, Department of Medicine, London, United Kingdom, on the Medical Staff of UCLA Ronald Reagan Medical Center, Los Angeles, California, and a part-time employee of Celgene Corp., Summit, New Jersey. Gale acknowledges support from the National Institute of Health Research Biomedical Research Centre funding scheme.

³ F. Owen Hoffman is president of SENES Oak Ridge, Inc., Center for Risk Analysis. He is a distinguished emeritus member of the National Council on Radiation Protection and Measurements and a consultant to the United Nations Scientific Committee on the Effects of Atomic Radiation.

these comparisons, there should be no cause for concern and that the risk at these dose levels is *acceptable*.

The limitations of using an estimate of dose or a level of radioactivity exposure or concentration as a surrogate for estimating risk may be apparent to some, but is there a better way to express potential cancer-related hazards of radiation exposures to people?

Here are four alternatives:

1. Total lifetime risk of cancer incidence (and/or cancer-related death) regardless of cause.
2. Excess lifetime risk resulting only from additional radiation exposure.
3. Future total lifetime cancer risk for persons exposed in the past and who are currently free of cancer.
4. Total numbers of cancers anticipated in members of an exposed population over their lifetime. For persons previously exposed to radiation who develop a potentially radiation-related cancer, the excess relative risk can be translated into an assigned share.

All of these risk estimates need to be quantified with regard to uncertainty, which includes the following factors:

- Uncertainty in subject-specific absorbed dose estimates to each organ.
- Uncertainty in extrapolating dose estimates into a risk estimate to the individual or to a population.
- Statistical uncertainty in risk coefficients⁴ from epidemiological studies, like those of the atomic bomb survivors, for specific cancer sites.
- Uncertainty in the model used to transfer risk estimates from that seen in atomic bomb survivors to the U.S. population for diseases with markedly different baseline rates between the two populations (for example, breast and gastric cancers).
- Uncertainty in the model and coefficients used to extrapolate the dose-response observed at high doses and high dose rates seen in the atomic bomb survivors to settings where doses are lower and where exposure is prolonged over time and associated with either fractionated or chronic low dose rates.
- Uncertainty in extrapolating risks observed from the atomic bomb survivors who were exposed primarily to an acute, high-energy gamma radiation to other types of radiation exposures.

Effective communication of cancer risk to the public also requires a vital but volatile quantity: trust. Communicating cancer-risk assessments to people by dose estimates and

⁴ A “risk coefficient” is a numerical factor used in estimating the risk of cancer from low-level exposure to radionuclides.

benchmarks without addressing the fundamental issue of cancer risk associated with exposure may lead to a perception that one is censoring information related to risk. Such perceptions of censorship diminish trust, which, once lost, is difficult to regain.

People have *bona fide* concerns about radiation-related cancer risks and deserve direct, credible, and intelligible answers. Information about risk should include uncertainty in risk estimates that reflect current knowledge. Communication of a 95 percent uncertainty range or credibility interval is more informative than a single *best estimate* point value. The upper limit of a 95 percent uncertainty range is indicative of how high the risk might be, whereas the lower limit represents a lower bound estimate of risk. If the upper limit is below a level of risk judged to be *acceptable*, the exposure may be regarded as low priority and no action may be needed. However, if the lower limit is above a level of risk judged to be *unacceptable*, the exposure may be regarded as high priority and may precipitate some form of action to reduce or eliminate exposure or even direct medical intervention.

Some scientists argue there is a threshold in the dose-response relationship of radiation exposure to cancer risk such that there is no risk below a certain dose—usually somewhere between 50 and 200 mSv (5,000 and 20,000 mrem). However, the evidence supporting this assumption is weak. Furthermore, even if the potential for a threshold effect were taken into account in cancer-risk estimation, this effect, in the presence of uncertainty about the true dose response at low doses and dose rates, will have its greatest influence on the lower bound of a 95 percent uncertainty interval and only a minor influence on the upper-bound estimate of risk. This is important because it is the upper bound of uncertainty in the estimate of cancer risk that most concerns the public and that has the greatest implication for compelling action to protect public health. Moreover, arguing for a threshold effect at low doses is difficult without a cogent biological explanation and without convincing evidence that exposure to background radiation is completely risk-free.

As long as background radiation is assumed to be associated with some level of cancer risk, any additional exposure to ionizing radiation, no matter how small, will increase the unavoidable risk associated with background radiation. Finally, arguing for a threshold effect, and therefore a radiation dose associated with no cancer risk, is likely to result in an erosion of public trust and should only be done when there is incontrovertible evidence to support this view. This level of evidence is lacking.⁵

⁵ We recognize many epidemiological studies show no statistically significant excess risk for cohorts exposed to high levels of background radiation (excluding the statistically significant increased risk of lung cancer observed in epidemiological studies on residential exposures to radon decay products). However, these high background exposure studies cannot be used as direct evidence of the absence of cancer risk without supporting mechanistic explanations. Precautionary interpretation of these studies, for purposes of health protection, is that cancer risk associated with exposure to background radiation has not been detected at a

Estimated cancer risks of radiation exposure should be estimated and communicated effectively. The challenge is to place this risk into context such that it can be compared to voluntary and involuntary cancer risks in everyday life (naturally occurring and environmental). Placing risk estimates into context helps people weigh the importance of a cancer risk and decide whether a future exposure is acceptable. Equally important is the ability to compare cancer risk (and uncertainty) with potential alternatives and with potential benefits, such as having a computed tomography (CT) scan.

Information relating the magnitude of a radiation-related cancer risk to other risks is important when communicating with the public. One useful approach is graphical comparisons in the form of risk thermometers. Examples are Figure 1, where we compare cancer risks of different radiation exposures, and Figure 2, where we compare cancer risks of diverse involuntary exposures.

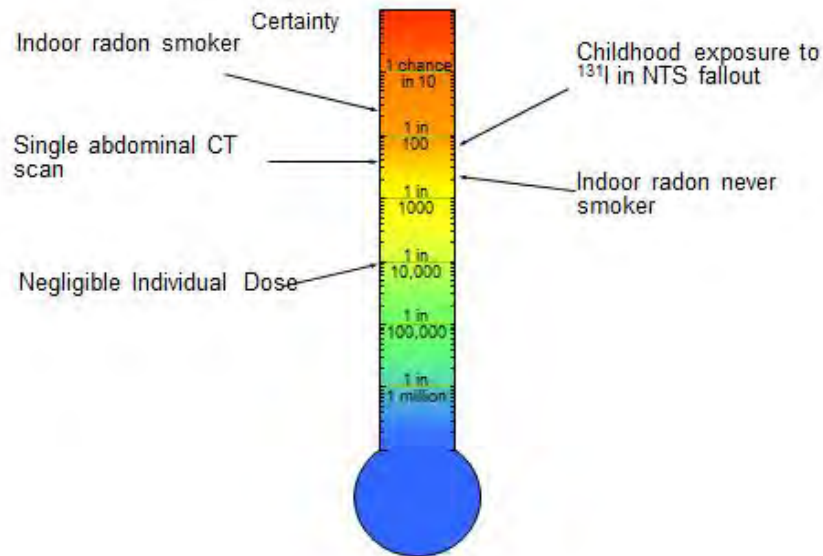


Figure 1. Lifetime cancer risk from exposure to radiation

Original version with references at <http://www.senes.com/BeyondDoseAssessment/figure.1.htm>. Indoor radon levels of 46 Bq m^{-3} ; Nevada Test Site fallout data assume a female born in 1952 receiving a thyroid dose of 0.1 Gy; CT scan in a 50-year-old female; negligible dose is $10 \mu\text{Sv y}^{-1}$ (1 mrem) with a 70-y chronic exposure.

high level of statistical confidence even though the underlying cancer risk is present. Evidence supporting the absence of exposure-related cancer risk at or near background dose levels should be considered when estimating the uncertainty in risk when exposures are below limits of epidemiological detection.

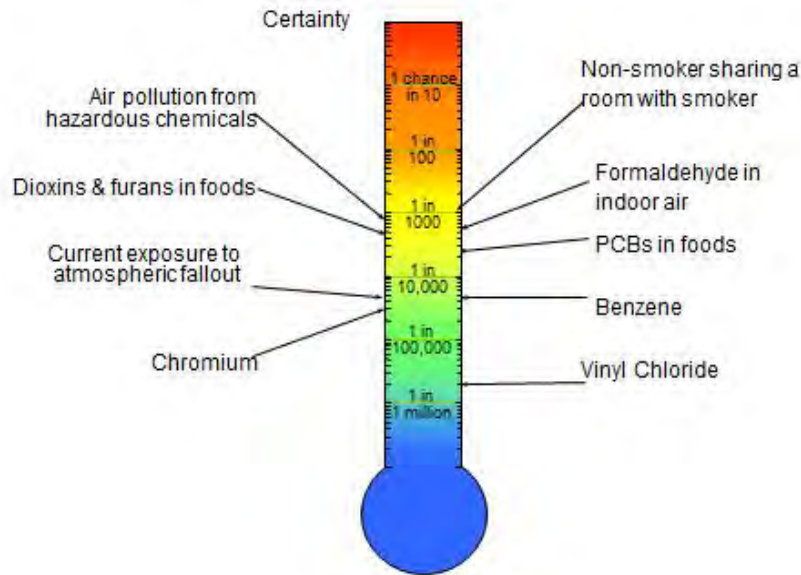


Figure 2. Involuntary lifetime cancer risk for several carcinogenic substances

Original color version and references at www.senes.com/BeyondDoseAssessment/figure.2.htm. Air levels refer to outdoor air in California.

Other information the public wants and needs to know to make informed decisions is not just the cancer risk of radiation exposure but: *What type(s) of cancer we are talking about? How common is this type of cancer absent radiation exposure? At what age is the cancer likely to occur? And, What is my prognosis if I get a radiation-related cancer?*

Consider, for example, nonmelanoma skin cancers, thyroid cancer, and lung cancer, all of which are radiation-related cancers. Nonmelanoma skin cancers are common without exposure to ionizing radiation, easily treated, and unlikely to be fatal. Getting one, especially at an older age, is unlikely to be extraordinarily upsetting to most people. Thyroid cancer is less common absent radiation exposure and may require more extensive therapy, but is also unlikely to be fatal. Finally, lung cancer is relatively common like nonmelanoma skin cancers, but therapy (if given) is most unpleasant, and survival after diagnosis is typically less than six months. The perception of the risk of lung cancer is also likely perceived differently by a young nonsmoker than by an older person who has smoked most of his or her life. When we communicate radiation-related cancer risk to the public, we typically overlook these important considerations. Ways to improve on this situation are complex and continually being developed.

In summary, the direct assessment of cancer risk from radiation exposure, including an expression of uncertainty—rather than indirect assessment of cancer risk using dose or the environmental concentration of a radioactive substance—is more useful to informing the public of the potential importance of past, present, or future radiation exposures. It is especially important to acknowledge that the uncertainty in our risk estimates is based on

our present knowledge and that this uncertainty may change as our state of knowledge improves. This approach will better inform the public and allow for more intelligent decision making. It will also help build trust between scientists and the public, a step essential for effective communication.

After Fukushima: Implications for Public Policy and Communications

By Robert Emery¹

The unique characteristics of radiation have been analyzed and harnessed by science to better the lives of individuals around the world. The beneficial uses of radiation range from the production of energy to improvements in the ability to detect and treat diseases. But like other physical and chemical phenomena—such as compressed gases, electricity, and combustion—if used incorrectly, radiation can cause harm. The scientific community has studied the potentially deleterious effects of radiation for more than a century. This intensive study resulted in regulations and recommendations to control radiation so that the beneficial characteristics can be gleaned, while any associated exposure risks are controlled.

Recent heightened public attention to issues related to radiation exposure in the United States—whether from computed tomography (CT) imaging, airport security scanners, or emissions from nuclear energy facilities—underscores the importance of educating the public about the basis for the radiation protection controls in place and the methods used to incorporate lessons learned from events for continual process improvement. The events associated with the Fukushima reactor complex can serve as a prime example for the basis of discussing this necessary balance.

As one of the few low-carbon methods for producing electricity, nuclear energy has great potential to support the energy needs of societies around the globe while minimizing impacts to the environment. Not unlike other industries, the regulation of nuclear energy is based in part on science, but is also driven by public perception and shaped by notable incidents. Prior to the 2011 Fukushima event, the two most notable nuclear energy facility-related events were Three Mile Island (TMI) in 1979 and Chernobyl in 1986. While the root cause of each event was unique, some common issues have been identified and have been used to improve both regulatory controls and public health response capabilities. These events have also afforded scientists an opportunity to better understand the near-term and long-term implications of various levels of radiation exposure that can help guide factually based policy-making decisions.

The importance of reviewing the lessons learned from TMI and Chernobyl has been catalyzed by the 2011 accident at Fukushima, which has shifted discussions about nuclear energy (and other radiation applications) from their benefits and safe operating history to concerns about overall safety and potential health impact. Now, almost two years after the

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Japanese event, it is important to review in an objective manner the actual impacts of each of these events and to carefully develop approaches to mitigate similar events in the future. It is also critical to put into perspective any actual human health effects that were incurred so that future policies associated with radiation protection are based on the best available scientific knowledge.

The 1979 accident at the TMI facility near Harrisburg, Pennsylvania, was caused by a malfunctioning valve in a cooling system and the inability of plant operators to fully understand and react to the reactor's condition (NRC 2009). The event ranked as a level 5 on the seven-point International Nuclear Event Scale (INES). An INES level 5 signifies an "accident with wider consequences." Both government and industry moved swiftly to contain the situation, ensuring limited radiological consequences beyond the TMI site boundaries. Within five hours of the initial disruption, the regional control office and the U.S. Environmental Protection Agency (EPA) had activated response teams (NRC 2009). Helicopters were engaged to monitor radioactivity in the atmosphere above the facility. As a precaution, all nonessential staff was evacuated from the facility.

Facility operators and response teams believed the core had cooled two days following the event, but ongoing concerns persisted about radioactivity being released from an auxiliary building. Communications between the plant's operators and government officials began to deteriorate. Public concern and media attention increased as groups worked to contain the situation. After two days, the governor of Pennsylvania issued an advisory in an abundance of caution to those most vulnerable to exposure to radiation—pregnant women and young children—to evacuate beyond a 5-mile radius of the facility (NRC 2009).

Within five days of the incident, the TMI 2 facility was stabilized and the threat of any large release of radioactivity was mitigated. Nevertheless, amidst the confusion and apprehension about releases of radioactivity, an estimated 140,000 people evacuated from the area around the facility. In the two decades since the event, more than a dozen epidemiological studies have concluded that the accident resulted in no radiation-related injuries or deaths. In fact, independent, federal, and local government studies of the accident estimate that the average dose to the two million residents in the surrounding area was approximately 0.01 mSv (1 mrem), a minute fraction of the Nuclear Regulatory Commission (NRC) limit for the public (NRC 2009). For comparison, the average person in the United States receives about 6.2 mSv (620 mrem) per year from natural background radiation and medical procedures that use radiation. Following the TMI 2 event, government and industry formed commissions and study groups to investigate how to mitigate similar issues in nuclear plants and to verify the health and safety of the public and plant personnel. In December of 1979, the industry formed the Institute of Nuclear Power

Operations (INPO) to promote and monitor training standards for facility training and operations of commercial nuclear power plants (INPO 2010).

Shortly after, INPO formed the National Academy for Nuclear Training as an accreditation organization for all facility training programs. Still in existence today, INPO continues to serve an essential role in facility safety, as evidenced by unparalleled nuclear plant performance and the absence of significant incidents at the 104 operating reactors in the United States since 1979. In fact, INPO was the model for industry self-regulation in the petroleum industry after the BP Deepwater Horizon accident (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling 2011).

Seven years following the TMI accident, the world experienced a second industrial nuclear power accident, but one that resulted in the release of significant amounts of radioactivity and several radiation-related human fatalities. The 1986 explosions at the former Soviet Union's Chernobyl facility in Ukraine were caused by a combination of the operators' violation of plant operating protocols and faulty Soviet-era reactor design.

In contrast to the response experienced at TMI, Chernobyl plant management failed to report the accident to authorities and local communities for approximately 36 hours. The time between the explosions and government action hindered the ability for local officials to not only assist in monitoring and containing the accident, but to also provide adequate warning to residents of the potential health risks. The Chernobyl event was categorized as a 7 on the INES scale, its highest rating.

Within four months of the incident, 28 reactor staff died due to massive doses of radiation (NRC 2012). By 2004, 19 more had died of causes related to high levels of radiation dose. Procedures for measuring the dosage of radiation varied within the facility, but it is estimated that after the initial explosions, radiation levels in the vicinity of the reactor were more than 2,000 times the annual limit for facility staff. Thousands of individuals were contaminated with radioactive iodine because of the government's delay in providing prudent public health guidance, such as sheltering in place, evacuations, restrictions on the consumption of certain foods, and the use of potassium iodine to prevent the uptake of radioactive iodine in the thyroid (NRC 2012).

The ingestion of radioactive iodine released from the facility through the consumption of cow's milk from local farms has been linked epidemiologically to an increase in thyroid cancers in individuals in the surrounding areas (NRC 2012). While plant management's delay in alerting officials eliminated the chance to avoid short-term contamination of radioactive iodine, the government evacuated all people within an 18-mile radius of the plant within a month. In the long term, scientists are concentrating their attention on mitigating the possible health effects associated with soil contaminated with

cesium-137, which has a half-life of 30 years, and the mental health toll on residents, which resulted in anxiety, depression, and stress-related disorders (NEI 2011).

Unlike the incidents at TMI and Chernobyl, the 2011 Fukushima-Daiichi event in Japan was not caused by or exacerbated by human error, but rather by two exceptional and record-breaking natural disasters. The 9.0-magnitude earthquake that hit the coast of Japan on 11 March led to the automatic shutdown of all the facility's reactors. As planned, emergency cooling systems backed by diesel generators began cooling the reactors. Unfortunately, not long after the earthquake, the site was hit by a powerful tsunami, which damaged the facility's infrastructure and diesel generators and resulted in a loss of power to critical safety systems.

The world watched as the Japanese government, though crippled itself by the massive natural disaster, responded to the accident. In the United States, experts and industry leaders quickly stepped into action. Government agencies, national laboratories, universities, and the U.S. nuclear power industry were monitoring, tracking, and detecting the size of the plume of radioactivity being released from the facilities and conducting self-assessments at all American facilities. Fortunately, most of the released radioactivity dissipated over the Pacific Ocean, with no significant levels reaching American shores. Although the event did not directly affect the United States, the NRC, INPO, and several other agencies and industry groups began reviews and evaluations of all domestic nuclear energy facilities, ensuring that they were capable of withstanding natural disasters.

In the wake of Fukushima, industry and government have agreed on actions that are being undertaken in the near term to further bolster the safety and security of U.S. facilities during severe events (NEI 2012). These steps include:

- Enhancing the ability of nuclear power plants to remain safe during a complete loss of electrical power.
- Improving the plants' ability to monitor water level and temperature in spent fuel pools even during an electric power outage.
- Ensuring enough emergency response equipment and supplies on-site to be able to independently respond to multiple events.
- Safeguarding the emergency equipment from severe conditions.
- Augmenting emergency operating guidelines during and after accidents.

These actions will enhance strict controls and regulations that are in a constant state of evaluation and improvement. Agencies and organizations involved in the continuous quality-improvement review process include the NRC, the National Council on Radiation Protection and Measurements, the Environmental Protection Agency, the departments of Energy and Transportation, and INPO.

Experience gained from previous events indicates that prompt notification of local, state, and federal officials regarding any accident or incident is crucially important in initiating prudent public health responses. As a result of this lesson learned, a requirement exists for notifications to local authorities to occur within 15 minutes of a problem being experienced within a facility. Compliance with this requirement is tested and verified regularly. Requirements also exist to ensure that the maximum public exposure from the entire nuclear fuel cycle is a mere fraction of the amount received naturally.

Above all, these experiences underscore that when it comes to radiation measurement and exposure—whether during routine operation or in times of crisis—communication with and an understanding by the public are essential. However, the scientists, regulators, and policy makers involved in such situations must understand that the science supporting the safety and security of nuclear power is not easily understood by the general public.

To effectively communicate radiation-related information, communicators must first underscore that the entire nuclear industry takes any exposure to radiation very seriously and that any exposures will be assessed within the context of background radiation doses. Communicators also need to clearly articulate what conditions are safe, so that the public can be informed and make personal decisions accordingly.

Coordination among groups providing communications is crucial. Each of the three most significant industry events described above involved some form of miscommunication between facility operators, government regulators, and the public. It is precisely these types of miscommunication that allow for fears and misconceptions about radiation to dominate story lines, often eliciting more apprehension and concern than would be appropriate for the levels of radiation being experienced.

In the early 1950s, when the United States decided that nuclear energy could be used effectively for peaceful endeavors, President Dwight D. Eisenhower commented that “this greatest of all destructive forces can be developed into a great boon for the benefit of all mankind.” With this inspirational goal in mind, American industry and government have worked together to harness this powerful and clean resource through effective design and regulation to improve lives. The past half century has shown the great value of nuclear energy and the importance of regulatory protocols and effective communication with the public. The nuclear power industry must continue to evaluate and refine current regulations based on the lessons learned and scientific evidence drawn from past occurrences and enable these industries to continue pursuing the safe, efficient, and life-enhancing use of radiation.

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Appendix 1: Radiation Units and Measurements

Radiation units and measurements can be confusing for at least three reasons. First, there are different units for measuring how much radiation is being emitted from a source (curie or becquerel) and for how much dose is being received (rad or gray). Second, there are different ways for measuring the amount of radiation received if you are a physicist measuring energy (coulomb per kilogram or C/kg) or a biologist measuring effect (sievert). Third, there are traditional units such as rem (still used in the United States much like we use inches and miles instead of the metric system) and international (SI) units such as sievert.

Also, scientific prefixes may not be familiar to nonscientists. For example, milli indicates 1/1,000th and μ stands for micro or 1/1,000,000th.

	Radioactivity	Absorbed Dose	Dose Equivalent	Exposure
Traditional Units	curie (Ci)	rad	rem	roentgen
SI Units	becquerel (Bq)	gray (Gy)	sievert (Sv)	coulomb/kilogram (C/kg)

Conversion Equivalence

1 curie = 3.7×10^{10} disintegrations per second 1 becquerel = 1 disintegration per second

1 millicurie (mCi) = 37 megabecquerels (MBq)
 1 rad = 0.01 gray (Gy)
 1 rem = 0.01 sievert (Sv)
 1 roentgen = 0.000258 coulomb/kilogram (C/kg)

1 megabecquerel (MBq) = 0.027 millicuries (mCi)
 1 gray (Gy) = 100 rad
 1 sievert (Sv) = 100 rem
 10 microsievert (μ Sv) = 1 millirem
 1 coulomb/kilogram (C/kg) = 3,880 roentgens

Appendix 2: Half-Life of Some Radionuclides

Radionuclide	Half-Life
Americium-241	432.7 years
Beryllium-7	53.3 days
Carbon-14	5,730 years
Cesium-137	30.17 years
Cobalt-60	5.27 years
Iodine-129	15.7 million years
Iodine-131	8 days
Plutonium-238	87.7 years
Plutonium-239	24,100 years
Plutonium-240	6,560 years
Radium-226	1,600 years
Radium-224	3.66 days
Radium-228	5.76 years
Radon-220	54.5 seconds
Radon-222	3.8 days
Strontium-90	29.1 years
Technetium-99	212,000 years
Tritium (Hydrogen-3)	12.3 years
Thorium-232	14 billion years
Uranium-238	4.47 billion years

Bernard L. Cohen (1924–2012)

By David Turnshek, PhD¹

Bernard “Bernie” Cohen, professor emeritus of physics at the University of Pittsburgh (Pitt), died on 17 March 2012. He was born and raised in Pittsburgh, served as a U.S. Navy engineering officer in the Pacific Theater during World War II, completed his undergraduate studies at then Case Institute of Technology, and received a PhD in physics at then Carnegie Institute of Technology in 1950. During the early part of his career, he specialized in nuclear physics. Later in his career, his research areas included health effects of radiation, societal risks and risk aversion, radon levels in homes, and energy and the environment.

During his career, he worked as a group leader for cyclotron research at the Oak Ridge National Laboratory from 1950 until 1958, and then he joined the Pitt faculty as associate professor of physics and chemistry. He was granted tenure in 1959 and was named professor in 1961. He also held adjunct professor appointments at Pitt in chemical and petroleum engineering, radiation health, and environmental and occupational health. He also served as the director of the University’s Scaife Nuclear Laboratory from 1965 to 1978. He served on various national energy committees, panels, and advisory boards. He officially retired in 1994, but came to the university almost every day to continue with his work until about a month before he died.

His publications include six solely authored books, about 135 research papers on basic nuclear physics, plus about 270 papers of various sorts on his “applied” work. He made over 50 TV appearances, including shows with Barbara Walters, William Buckley, Charlie Rose, and Geraldo Rivera. He was interviewed on about 100 radio programs.

He also supervised the measuring of radon levels in about 350,000 homes.

Cohen was elected chairman of the American Physical Society (APS) Division of Nuclear Physics in 1974–1975. He received many awards during his career, including the APS Tom Bonner Prize for Nuclear Physics in 1981, the American Nuclear Society Public Information Award in 1985, and the Health Physics Society Distinguished Scientific Achievement Award in 1992. He was elected to membership in the National Academy of Engineering in 2003.

In a 2005 interview in the radiation safety officer publication *RSO Magazine*, Cohen recommended to the scientific community: “Don’t be enslaved to the linear-no threshold theory of radiation-induced cancer; it is almost certainly not valid and over-estimates the

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risks from low-level radiation. . . . As a nation, we are wasting tens of billions of dollars cleaning up little bits of radiation. The worst thing is that we are largely giving up on nuclear energy because of this.”

Cohen’s legacy lives on, not only in his many published works, but in his undeniable impact within multiple fields.