Health Physics Society

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Plenary Session

"With the belief that nuclear power can be safely employed,
today we see rapidly maturing efforts to build new nuclear power facilities across the globe."

In *Resurgence of Nuclear Power* by PricewaterhouseCoopers, 2010

"The Resurgence of Nuclear Power: Impact on the Health Physics Profession"

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In This Issue

The Resurgence of Nuclear Power

Impact on the Health Physics Profession

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Health Physics News *Associate Editor*

They say a rising tide lifts all boats. If that is so, then what might be the near-term and far-reaching effect on our health physics profession from the resurgence of nuclear power that some have hailed as the "nuclear renaissance?"

Consider for a moment that the scope and scale of nuclear power encompasses much more than just the operation of commercial nuclear reactors to generate electricity—even from the focused perspective of health physics. It includes the exploration and mining for uranium and thorium; the processing and milling of extracted ore; the enrichment and fabrication of nuclear fuel; the licensing, construction, start-up, operation, and ultimate decommissioning of nuclear power plants; the analysis, planning, and preparedness for the possibility of an accident; the packaging, transport, and disposal of low-level radioactive waste; and the management of used nuclear fuel, which might include its own extensive realm of recycling, reprocessing, and nonproliferation.

Consider also that a nuclear renaissance will need a revitalized infrastructure, including academic institutions to train and educate a new workforce and conduct basic and applied research, as well as industries to develop, produce, and deliver new radiation protection instrumentation and equipment, radioactive calibration and test sources, and ionizing and nonionizing radiation technologies for quality control in facility construction, nuclear system component manufacturing, and plant equipment maintenance.

In short, the effect of a resurgence of nuclear power in the area of health physics will be pervasive and profound.

Over the next year, *Health Physics News* intends to publish a series of articles that will explore the various sectors of nuclear energy that, while unique and relatively unfamiliar to our membership at

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(continued from page 1)

large, share the basic science, principles, and methods that are common throughout our profession. To inaugurate the series, this article provides a general overview of nuclear power generation—where it is today and where it's headed tomorrow, environmental considerations, and some challenges and opportunities related to health physics. Future articles will trace each step of the nuclear power fuel cycle in more detail from its extraction from the earth to its ultimate disposition in the earth again.

Nuclear Power—Today and Tomorrow

Sources of Electricity in the United States

Today, there are 104 nuclear power plants generating 20 percent of the nation's electricity at 65 sites in 31 states (Figure 1). These plants provide electricity at a low cost with a high level of reliability. In 2007, average electricity production costs at nuclear power plants were 1.76 cents per kilowatt-hour (Figure 2), and plant capacity factors averaged 92 percent. Capacity factor is the amount of electricity actually generated by a plant in a year divided by the total amount of electricity that could have been generated if the plant had operated 24 hours a day throughout the entire year.

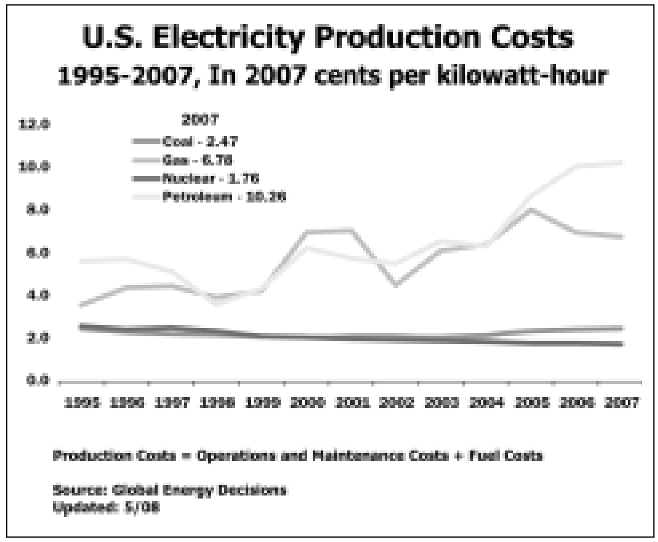

Figure 2

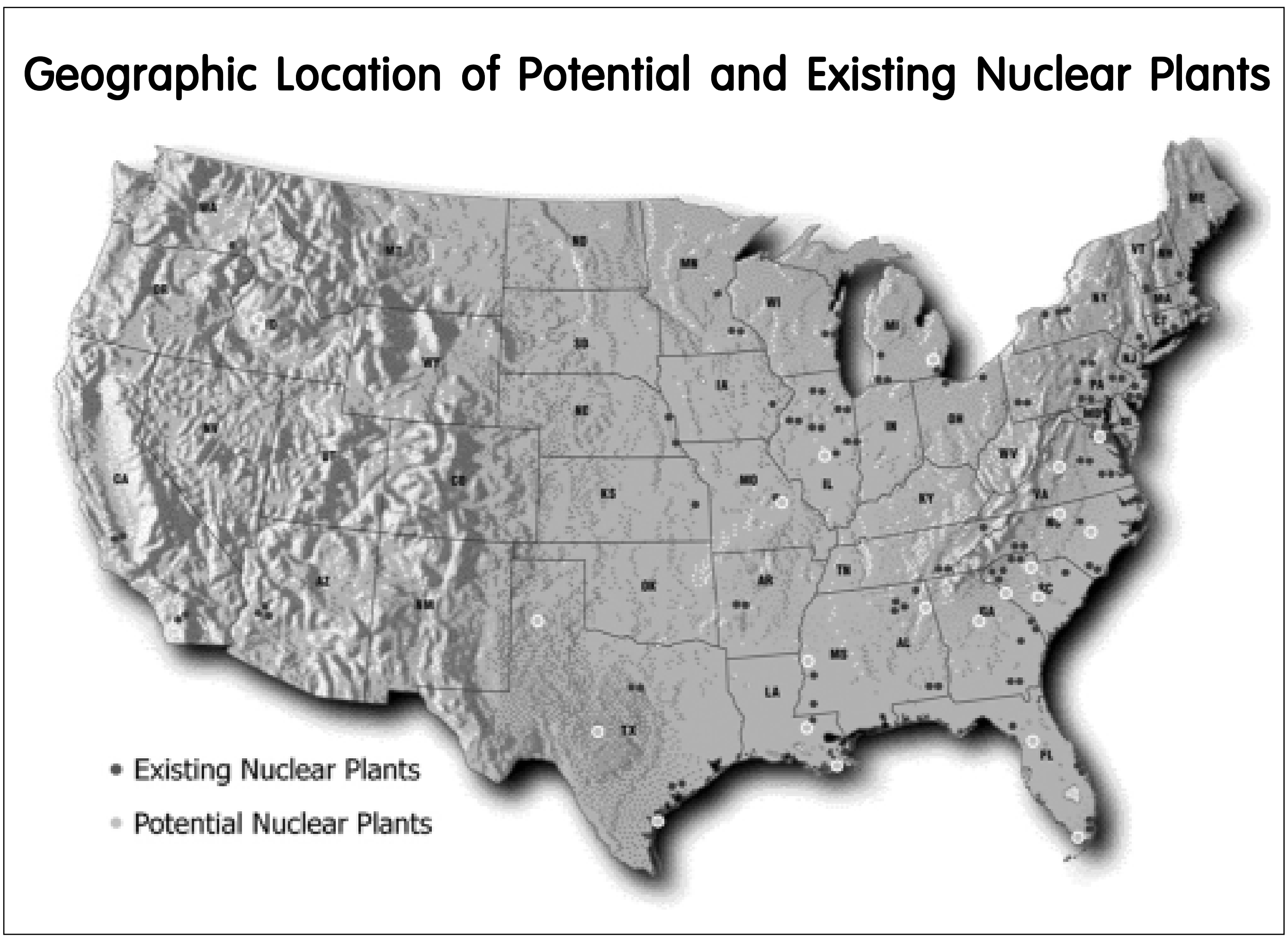

Figure 1

Other sources of electrical generation in the United States include fossil fuels, hydropower, and renewable and other energy sources. Nearly half (49 percent) of the electricity generated in the United States comes from coal, which is also a low-cost power source at 2.47 cents per kilowatt-hour. The average capacity factor for coal-fired plants (71 percent) is second among electrical power sources. The second largest source of electricity generation is natural gas, providing 22 percent of the total generation. Natural gas prices have been volatile over the past decade and production costs in 2007 were 6.78 cents per kilowatt-hour. Oil provides less than 2 percent of electrical generation due mainly to the high production costs (10.26 cents per kilowatt hour in 2007) and extreme volatility in the price of oil.

Hydropower facilities provide 6 percent of electrical generation with low average capacity factors (28 percent). Renewable and other energy sources provide about 3 percent of electrical generation with varied average capacity factors—including wind (30 percent), solar (20 percent), geothermal (75 percent), and biomass (71 percent). To date, these sources of electrical generation have not formed a significant contribution to baseload production due to limitations in regard to reliability, location, and/or power density (i.e., the amount of power that can be generated with a facility's "footprint.")

License Renewal

Nuclear power plants were initially granted licenses to operate for 40 years, based on the level of engineering analysis and limited operating experience at that time. Since then, we have gained several thousand reactor-years of experience and have developed much more informative and robust techniques to evaluate the safety of the plants (e.g., probabilistic risk assessment). In the 1990s, nuclear power plants began submitting applications to extend the licensed period for operation for an additional 20 years.

The Nuclear Regulatory Commission (NRC) review process, termed license renewal, has been continually refined with experience so that today nearly half of the operating reactors (48 plants) have received approval to operate for a total of 60 years. As shown in Figure 3, the majority of the remaining plants either have a license renewal application under review at this time or have formally announced their intent to prepare an application at the appropriate time (typically about 10 years prior to expiration of the original license). The remainder (nine plants) have not yet announced their intention because they still have a significant period of time remaining on their operating licenses and it would be premature to project and assess regional energy needs that far in the future with the associated larger uncertainties.

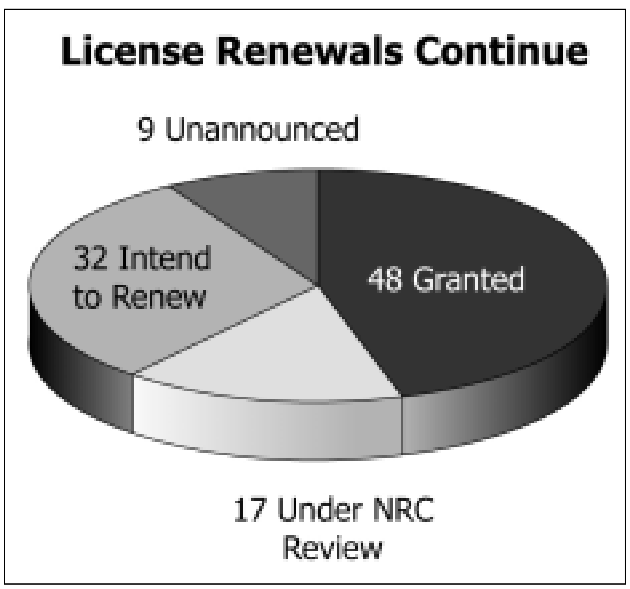

Figure 3

The operating horizon for the current generation of nuclear power plants in the United States now extends to 2030 and beyond. Scientific and engineering research has already begun to assess the possibility of of extending nuclear power plant operating licenses by another 20 years (i.e., a total 80-year operating lifetime).

New Nuclear Power Plants

Over the past 10 years, there has been a rapidly growing interest in building new nuclear power plants in the United States. This interest has been driven by several factors.

First, there is an increasing need for new baseload energy to address not only the increased demand for electricity, but also to offset the retirement of older electricity-generating assets. In the near term, the need for new generating capacity is especially acute in the Northeast, mid-Atlantic, Southeast, South, and Texas. Overall across the nation, the demand for electricity is expected to increase by as much as 25 percent by the year 2030.

Second, increasing concerns about the environment, especially related to climate change, have raised the likelihood of imposing some form of constraints on carbon emissions, which especially challenges the use of fossil fuels as the source of new electricity production. This challenge is compounded by the continued volatility in natural gas prices and the skyrocketing costs of oil.

Third, renewable energy sources are not likely to be able to provide the dramatic increase in reliable, baseload energy necessary to meet a sustained increase in demand for electricity. There is little or no opportunity for developing new large-scale hydropower installations. While it is essential that continued emphasis and support be provided for developing wind and solar power, the inherent limitations on reliability and siting that exist today cause experts to predict that these energy sources cannot deliver more than a small percentage of the new power that will be needed by 2030. Although aggressive energy conservation and improved efficiency in energy use can make a significant inroad into new energy demand, this is not a singular solution.

Finally, the excellent safety record of the nuclear industry, high levels of reliability, and low production costs, along with the lack of greenhouse gas emissions during operation, make nuclear power a much more accepted and desired source of energy for the future. However, new nuclear generating capacity alone is also not sufficient to be "the solution," even under the most optimum of scenarios for new build.

The energy policy for an energy-secure nation in the future that is being advocated by the nuclear energy industry, as well as many others in the energy sector, includes the following:

- Implement energy efficiency and conservation in all phases of electricity generation and use.
- Employ renewable energy sources to the fullest extent possible.
- Maintain an energy portfolio with diverse energy sources.
- Rely on nuclear power as a proven large-scale, emission-free energy source for baseload generation.

The Nuclear Energy Future Is Now

Seventeen companies and consortia are submitting license applications to the NRC to construct and operate as many as 31 new nuclear power plants in the United States. Five applications were submitted in 2007 and 11-15 more are expected by the end of 2008. Also, three new applications have been submitted to the NRC this year for certification of new reactor designs, in addition to the two that have already been certified.

The realistic expectations of industry experts are that the first new nuclear power plant will begin commercial operation in 2017, with a potential for up to 15-20 new plants coming online in the years shortly thereafter.

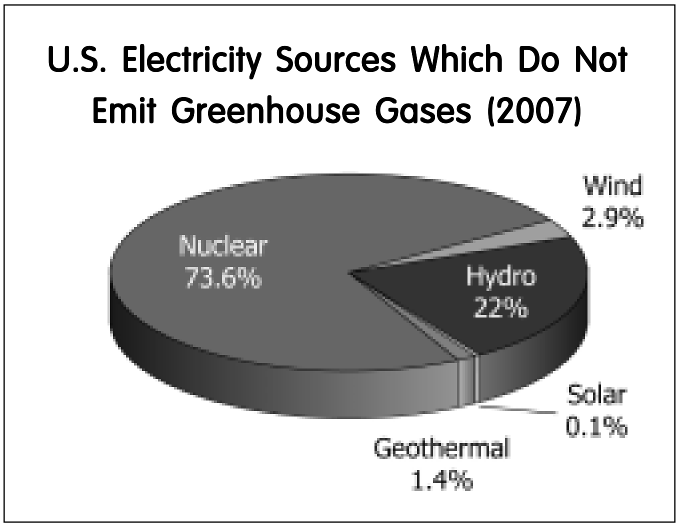

Figure 4

Environmental Considerations for Nuclear Power

One of the strongest arguments for continuing to operate the current fleet of nuclear power plants and to build new plants is the vital role of nuclear power in preventing greenhouse gas emissions, particularly carbon, during the production of electricity. Nuclear power accounts for more than 70 percent among U.S. electricity sources that do not emit greenhouse gases (Figure 4). The remainder is accounted for primarily by hydropower (22 percent), along with an increasing fraction contributed by wind, geothermal, and solar power.

For perspective, in 2006 U.S. nuclear power plants offset nearly 700 million metric tons of CO_2, as calculated from the data of the U.S. Environmental Protection Agency (EPA). Also using EPA data, this amount of CO_2 avoided is equivalent to the total CO_2 emitted by the 136 million passenger cars driven on U.S. roadways.

However, there are some who make the claim that nuclear energy produces significant levels of emissions of greenhouse gases and other pollutants if you consider the entire nuclear life cycle, including mining and milling, fuel fabrication, construction, operation, and ultimate decommissioning. The facts do not bear this out. A life-cycle analysis of the emissions produced by various electricity-generating sources (see Table 1 on page 6) shows that nuclear and hydropower represent the lowest-emitting sources of electricity generation, followed by wind, solar, and biomass.

Radiation Protection at Nuclear Power Plants

Radiation protection at nuclear power plants has proven to be challenging, interesting, and fulfilling for the 2,000 health physicists and technicians who work at 104 operating nuclear power plants in the United States. These radiation protection professionals oversee radiation safety around the clock for more than 100,000 monitored workers who receive measurable occupational radiation dose during operation, refueling, and maintenance of the plants, as well as for the people who live around the plants and the environment. The radiation protection staff also continuously train and participate in exercises and drills to be prepared to address all kinds of contingencies, up to and including postulated nuclear accidents.

Radiation protection organizations at nuclear power plants include health physicists, technicians, and specialists who are extensively trained and qualified to cover a wide range of duties and responsibilities, including radiation monitoring and surveillance, radiation protection job coverage, as low as reasonably achievable (ALARA) planning and radiological engineering, internal and external dosimetry, instrument calibration and maintenance, respiratory protection, decontamination, radioactive material inventory and control, radiological sampling and analysis, radiological effluent monitoring and control, environmental monitoring, radioactive waste packaging and shipment, and emergency preparedness and response.

The types of nuclear power plant workers, and the diverse job functions that they perform, cover a wide range of disciplines, including reactor operations, nuclear, mechanical, electrical, and civil engineering, mechanical and electrical maintenance, instrumentation and control (I&C), chemistry, radioactive waste management, radiography, in-service inspection (ISI), nondestructive examination (NDE), security, training, and quality assurance, as well as skilled craft applications, such as welding, boiler-making, pipefitting, scaffolding, insulating, etc. Plant radiation protection staff must become sufficiently knowledgeable across all of these areas to be able to fully understand the radiological protection aspects related to the work and to provide effective radiation safety support.

Emissions Produced by 1 Kilowatt-Hour of Electricity Based on Life-Cycle Analysis

Generation Option	Greenhouse gas emissions gram equiv. (in CO_2/kWh)	Sulfur dioxide emissions (in milligrams/kWh)	Nitrogen oxide emissions (in milligrams/kWh)	NMVOC (in milligrams /kWh**)	Particulate matter (in milligrams /kWh)
Hydropower	2 – 48	5 – 60	3 – 42	0	5
Nuclear	2 – 59	3 – 50	2 – 100	0	2
Wind	7 – 124	21 – 87	14 – 50	0	5 – 35
Solar photovoltaic	13 – 731	24 – 490	16 – 340	70	12 – 190
Biomass forestry waste combustion	15 – 101	12 – 140	701 – 1,950	0	217 – 320
Natural gas (combined cycle)	389 – 511	4 – 15,000[*]	13 – 1,500	72 – 164	1 – 10
Coal – modern plant	790 – 1,182	700 – 32,321	700 – 5,273	18 – 29	30 – 663

Source: "Hydropower-Internalized Costs and Externalized Benefits," Frans H. Koch, International Energy Agency (IEA)-Implementing Agreement for Hydropower Technologies and Programs, Ottawa, Canada, 2000.

Order of magnitude validation by University of Wisconsin study (August 2002) and WNA Energy Analysis of Power Systems (March 2006)

Table 1

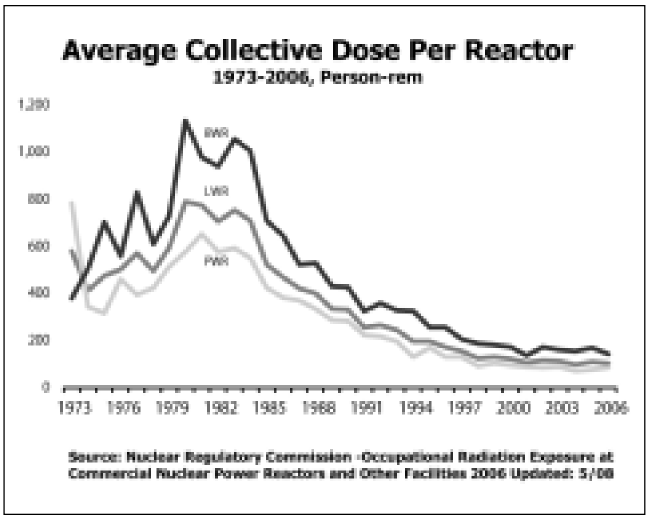

Figure 5

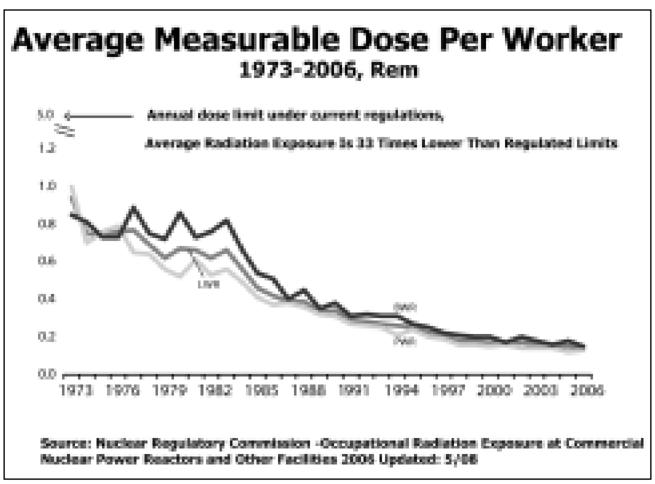

Figure 6

The nuclear power industry work ethic and culture is founded on learning from experience and continuously finding ways to improve performance—especially in regard to radiation safety. Every plant has a well-developed program for maintaining radiation exposures ALARA that involves every level of plant workers, radiation protection staff, site management, and company senior management and executives. Work to be performed in a radiologically significant area is planned, staged, and carried out in a manner that will assure a high degree of radiation and industrial safety and minimize radiation exposures. Following completion of the work, post-job reviews are conducted with the workers to identify lessons learned and plan further improvements for the next time the work is scheduled.

The dose-reduction results that have been achieved through this process of continuous improvement have been dramatic. In the past 25 years, the average annual collective dose per reactor was reduced from 774 person-rem to 106 person-rem, a seven-fold decrease (Figure 5). At the same time, average annual measurable dose per worker was reduced from 660 mrem to 140 mrem, more than a four-fold decrease (Figure 6). In the area of industrial safety, the results have been equally dramatic, with a three-fold decrease achieved in the industrial safety accident incidence rate over the 10-year period from 1997 to 2006, from 0.38 per 200,000 worker hours to 0.12 (Figure 7). For perspective, the incidence rate for office workers in 2006 (1.7 per 200,000 worker hours) was more than 10 times that for nuclear power plant workers.

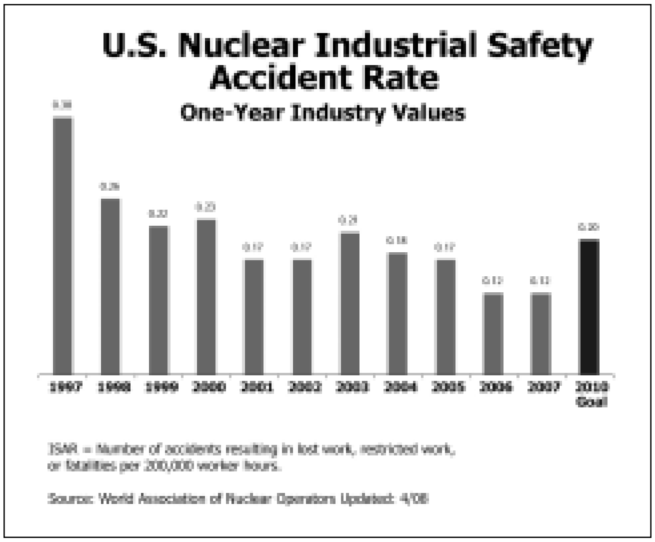

Figure 7

Future Challenges in Radiation Protection

In consideration of the extended operating period of the current fleet of nuclear power plants and in anticipation of building and operating new plants, the nuclear power industry has formed a working group of company executives and radiation protection program managers to develop an industry strategy to address future challenges in radiation protection. The name given to the effort is "RP 2020," to characterize the planning time frame through the year 2020 that will encompass the period in which the first wave of new nuclear power plants is expected to commence operation.

As an initial part of the effort, the working group is building a list of future challenges that should be addressed within RP 2020. While this preliminary list was derived from a nuclear power plant focus, it is apparent that the challenges are likely to be similarly applicable to many sectors within the health physics profession. Three of the challenges are highlighted below, including workforce, standards, and public perception about radiation.

Workforce

The most significant challenge that has been identified is in regard to developing the workforce of health physicists and technicians who will be needed for the next 70+ years at commercial nuclear power plants, which encompasses at least three more generations of new radiation protection professionals. The current situation is reflected in Figure 8, which shows the distribution of the current radiation protection workforce by age. This distribution is being tracked by the Nuclear Energy Institute in a biennial survey that obtains information about the entire nuclear power workforce, not just radiation protection staff.

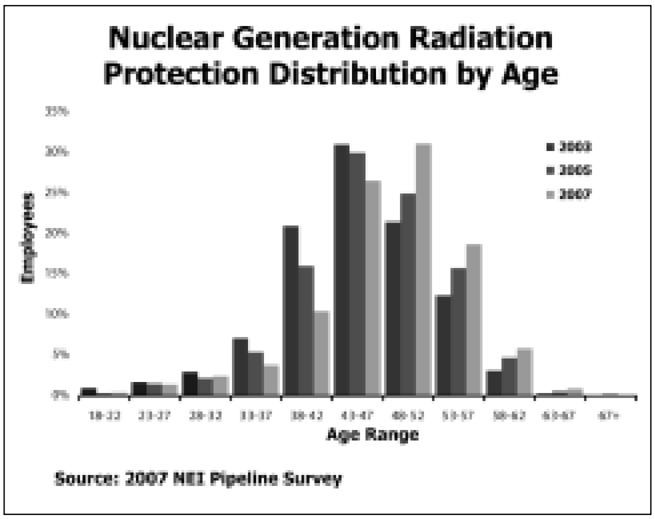

Figure 8

The issue is simple and inescapable: half of the nuclear power radiation protection workforce is 50 years old or older and is likely to retire or leave the industry for other reasons over the next 10 years. At the same time, the entry rate of new radiation protection staff into the industry is on a declining trend, such that only about 10 percent of the workforce is under 40 years old. This means that the nuclear power industry will either need to develop and bring into the workplace more than 1,000 new health physicists and technicans over the next 10 years, or it will need to substantially change how radiation protection is conducted at nuclear power plants in the future, so as not to need as many staff, or both.

In recognition that this challenge extends across the entire spectrum of the health physics profession, the nuclear power industry is partnered with other private and public sectors and the Health Physics Society to develop common solutions. This issue has been the subject of several articles in *Health Physics News* in the past, and a description of the current scale and scope of this effort is best left to an update in a future article on this topic.

Standards

In December 2007, the International Commission on Radiological Protection (ICRP) issued Publication 103, containing its new set of recommendations. In turn, the

International Atomic Energy Agency (IAEA) is updating its basic safety standards for radiation protection (expected to be issued in 2009) to reflect the new ICRP recommendations. Together, these documents will form the basis for the next generation of radiation protection regulations around the world.

Globally, countries and industries utilizing nuclear and radiation technologies are already evaluating how and when they might change regulations to incorporate the new ICRP recommendations and IAEA standards. In the United States, for example, the NRC staff is preparing a paper to be submitted for Commission review in December 2008 that will include various options for pursuing rulemaking to update the agency's regulations.

Such changes will be evolutionary for most countries—in which radiation protection regulations are already based on ICRP Publication 60. In the United States, however, the federal framework for radiation protection is generally based on ICRP Publication 26 for occupational radiation protection and on ICRP Publication 2 for public radiation protection. Therefore, a change to regulations will entail leaping ahead by two or three generations, rather then transitioning from one generation to the next. This will be particularly challenging in regard to dose standards and methodology, not to mention the long-standing differences in the usage of units of dose and activity.

The nuclear industry working group is evaluating the scope of possible changes to NRC regulations with the intent of providing input for consideration by NRC staff in developing its options paper for the Commission.

Radiation Perception

U.S. radiation protection regulations and health physics practices (e.g., ALARA) are based on the assumption that radiation health effects are linearly proportional to radiation dose without a threshold (LNT assumption). Employing that basis, regulatory agencies and licensees have assessed the possibility of public health and safety impacts from gaseous and liquid effluent releases from nuclear power plants as exceedingly small. In fact, the calculated annual maximum dose to a person living next to a nuclear power plant is a millirem or less and the average dose to people living within 50 miles of the plant is calculated as less than 1/100th of a millirem. These assessments are backed up by extensive monitoring and sampling results that are tabulated and submitted annually to the NRC in publicly available reports.

Nevertheless, groups continue to call on the NRC and other agencies to revise their "inadequate" regulations to reflect the LNT (which they already do) and hold up studies that purport to show health effects among populations living around nuclear power plants. Even though public health departments and regulatory agencies repeatedly discredit them, the claims are finding a new platform in license renewal and new plant hearings and are being given ample newspaper coverage and air time in the name of balanced reporting and fairness. It is not surprising that public opinion polls show a modest, but sustained, concern among the general public about radiation from nuclear power plants, as well as from other human-made sources.

The health physics community across all sectors is taking on this challenge, not by perpetuating the debate between proponents and opponents, but by improving the transparency of our radiation safety programs and developing clear, accessible information. This is aimed at providing resources for people to become more informed on their own and to assess for themselves whether they should be concerned about various claims. A recent example of this new approach is the HPS radiation primer, which can be found at www.radiationanswers.org.

Going Forward

The nuclear power industry has defined the mission of RP 2020 as one that will "reshape radiological protection at nuclear power plants." Simply improving the existing programs and processes will ultimately fall short of what is needed to address the challenges described above and others. Examples of strategies that are being developed to help accomplish this include:

- Reform, not just update, radiation protection regulations to become more focused on results, rather than process.
- Significantly reduce radiation fields that are accessed by workers in the plant.
- Improve technologies' utilization to facilitate remote monitoring and worker self-protection.
- Redefine the roles, skills, and qualifications for radiation protection staff.
- Improve worker and public access to radiation protection information.
- Standardize radiation protection practices.

The nuclear power industry strategy for radiation protection, RP 2020, is scheduled to be completed in 2008.

Public Support for Nuclear Energy

Public support for more nuclear energy has been increasing over the past decade, according to national surveys. Those surveys show that support is at an all-time high, with 83 percent of Americans in favor of renewing the licenses of existing plants and 66 percent accepting new reactors being built at the nearest existing nuclear plant (Figure 9). Issues identified by those surveyed as important to their support for nuclear energy include the economy, climate change, energy security, and air pollution.

A survey issued on 6 June 2008 by Zogby International finds that 67 percent of Americans favor building new nuclear power plants in the United States. Respondents in the survey also indicated their preference for the construction of a nuclear power plant in their community over a natural gas, a coal, or an oil plant.

In Summary

The resurgence in nuclear power holds great promise in terms of economic growth, energy security, and environmental protection. But the attendant challenges are also great. Change is sure to come. The question for us is whether we will envision and commit ourselves to achieving a future that we want, or simply let the future happen.

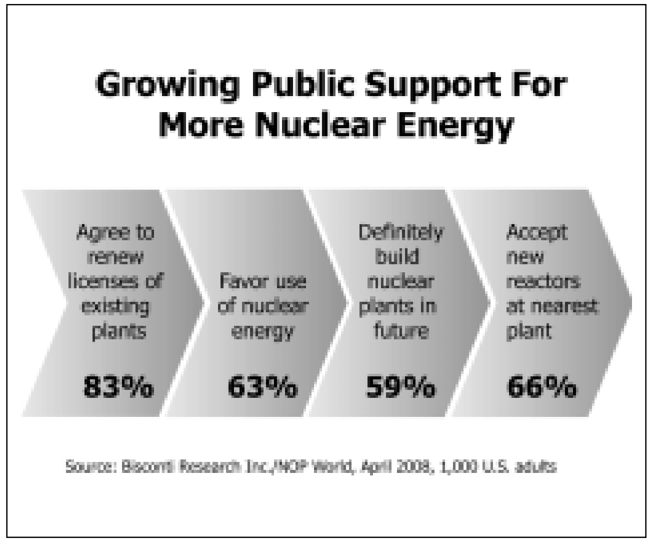

Figure 9

Editor's Note: We will be continuing this series on the resurgence of nuclear power and the impact on our health physics profession in upcoming issues of *Health Physics News*. We welcome experts in the various sectors of nuclear energy to write articles covering the areas discussed on the first page of this story. Contact me at newsed@hps.org or 507-362-4176 for information about content and deadlines.

Ralph Andersen, CHP, is the director of radiation safety and low-level waste management at the Nuclear Energy Institute (NEI) in Washington, DC. He represents the nuclear energy industry to the Congress, the Administration, federal agencies, and other national and international organizations on generic nuclear energy policy matters related to radiological protection, low-level radioactive waste management, and environmental protection.

Ralph and granddaughter, three-year-old Sylvia Rose Wines
Photo by Marlene Andersen

Before joining NEI in 1992, Ralph worked for 20 years in radiation protection, holding such positions as radiation protection manager at the Detroit Edison Company's Fermi 2 nuclear power plant, radiation safety officer and lecturer at the University of Colorado, and principal researcher and associate radiation safety officer at the University of Maryland Medical Center.

Ralph is a member of the Health Physics Society (HPS) Government and Society Relations Committee and an associate editor for *Health Physics News*. He received his BA degree from the University of Maryland and took graduate courses in the Department of Radiation Biology and Radiology at Colorado State University.

Ralph's favorite pastime is going on adventures with his wife, Marlene, and granddaughter, Sylvia.

The Resurgence of Nuclear Power

Impact on the Health Physics Profession

Ralph Andersen, CHP
Health Physics News *Associate Editor*

This is the second in a series of articles in *Health Physics News* that will explore the various sectors of nuclear power that, while unique and relatively unfamiliar to our membership at large, share the basic science, principles, and methods that are common throughout our profession. The first installment (*Health Physics News*, July 2008), presented a general overview of nuclear power generation—where it is today and where it's headed tomorrow, environmental considerations, and some challenges and opportunities related to health physics. This article focuses on the front end of the nuclear fuel cycle, i.e., the uranium recovery industry.

The Uranium Recovery Industry

Steven H.Brown, CHP

Introduction

Uranium recovery encompasses conventional uranium mining and milling as well as in situ recovery techniques (Figure 1) and the recovery of uranium as a byproduct from other processes, such as phosphoric acid production.

Concurrent with the recognition that nuclear-generated electricity must play an increasing role in worldwide energy supply and in consideration of the new nuclear power plants ordered or planned, the demand for uranium needed to fuel these reactors has already outpaced supplies. Accordingly, the price of uranium (typically expressed as $ per pound U_3O_8 equivalent) has increased significantly over the last two years. As a result, numerous new and reconstituted uranium recovery projects are being developed in the United States and in other countries that possess considerable uranium ore reserves (e.g., Canada, Australia, Kazykstan, Mongolia, Namibia, and others).

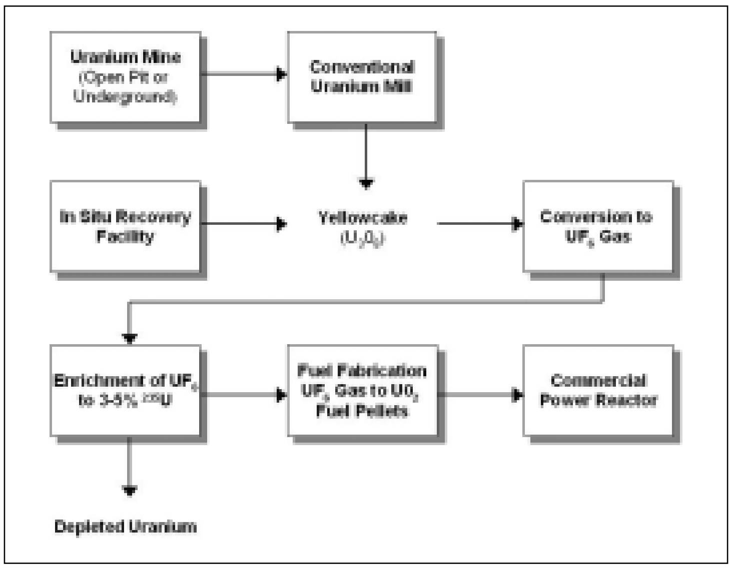

Figure 1. Uranium fuel cycle

Figure 2. U_3O_8 production versus demand
www.uraniumproducersamerica.com/supply.html

This imbalance between supply and demand is depicted in Figure 2. Historical uranium prices are shown in Figure 3 (next page), including the recent significant price increase as a direct result of the supply/demand imbalance. It should be noted that in the United States, our current reactor fleet of 104 operating units, which generate 20 percent of our base-load electricity, requires approximately 55 million pounds of U_3O_8 per year, but only about 4-5 million pounds per year is produced domestically. That is, over 90 percent of our current demand, ignoring anticipated increase in requirements in the near future as new plants come online, must come from foreign sources. Domestic uranium production over the last 10 years reached a low of about two million pounds in 2003 and has been increasing steadily since then.

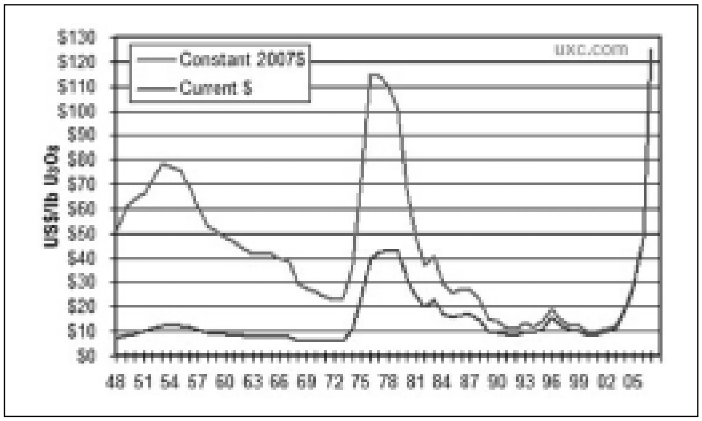

Figure 3. Source: 48-68 U.S./AEC, 69-86 Nuexco EV, 87-Present U_3O_8 Price

History of Uranium Recovery in the United States

In the United States, the mining of ore that contains uranium goes back to the early part of the 20th century. At that time the interest was not in uranium per se, but in other minerals associated with it, namely vanadium and radium. Interest in uranium began in earnest in the years immediately following World War II with the passage by the U.S. Congress of the McMahon Act (more commonly known as the Atomic Energy Act [AEA], signed by President Truman in August 1946), which created the United States Atomic Energy Commission (AEC) and established the U.S. government as the only buyer of uranium (for the nuclear weapons program). The government's uranium ore procurement program sent thousands of prospectors crawling over the "Colorado Plateau" (the four corners area of Utah, New Mexico, Arizona, and Colorado). The AEC developed publications to assist prospectors in this regard (Figure 4). This ore was processed at a number of sites—collectively known as the "MED (Manhatten Engineering District) Sites"—and remediated decades later under the Formerly Utilized Sites Remedial Action programs still ongoing today. AEC incentives ceased in 1962, and mining and milling operations on a much larger scale than those early efforts were

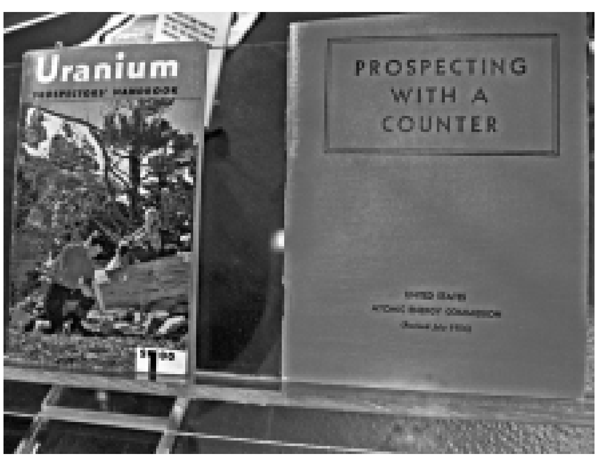

Figure 4. AEC uranium prospecting booklets

established by private companies.

As the commercial nuclear power industry developed in the late 1960s and early 1970s, the federal government was no longer the exclusive buyer of domestically produced uranium. U.S. production and uranium prices peaked in the early 1980s. Shortly thereafter, domestic demand for uranium ore declined as the commercial nuclear power industry fell far short of its expected growth and in response to, and low cost of, much higher-grade Canadian and Australian deposits that began to dominate world markets. Planning and construction of new U.S. commercial nuclear power plants came to a halt and the domestic price of uranium dropped dramatically, and the nation faced an oversupply of uranium despite the fact that demand remained about even through 2003.

As a result of the market conditions described above, the uranium recovery industry will benefit directly from the "nuclear renaissance" of today and into the near future. The U.S. Nuclear Regulatory Commission (NRC) Uranium Recovery Branch estimates that over the next few years, it expects to receive over 30 source material license applications for new and/or upgraded uranium recovery facilities (Camper 2008—see Table 1). Similar new project development is also taking place in the historical uranium recovery districts in NRC Agreement States (e.g., Texas and Colorado).

Facility	Quantity
New ISR* Facility	14
New Conventional Mill	7
Combined ISR-Conventional	1
ISR Expansion	7
ISR Restart	1
Conventional Restart	1
TOTAL	**31**

***In Situ Recovery**

Table 1. New source material licensing actions anticipated by NRC in next few years

Overview of Conventional Uranium Mining Techniques

Conventional mining generally refers to open-pit and underground mining. Open-pit mining is employed for ore deposits that are located at or near the surface, while underground mining is used to extract ore, typically of higher grade (concentration of uranium in the ore expressed as weight percent or ppm), from deeper deposits. Conventional uranium mines are not regulated under the AEA since the raw ore is not considered "source material"[1] under the Act and therefore is not a "licensed material." The health and safety aspects of

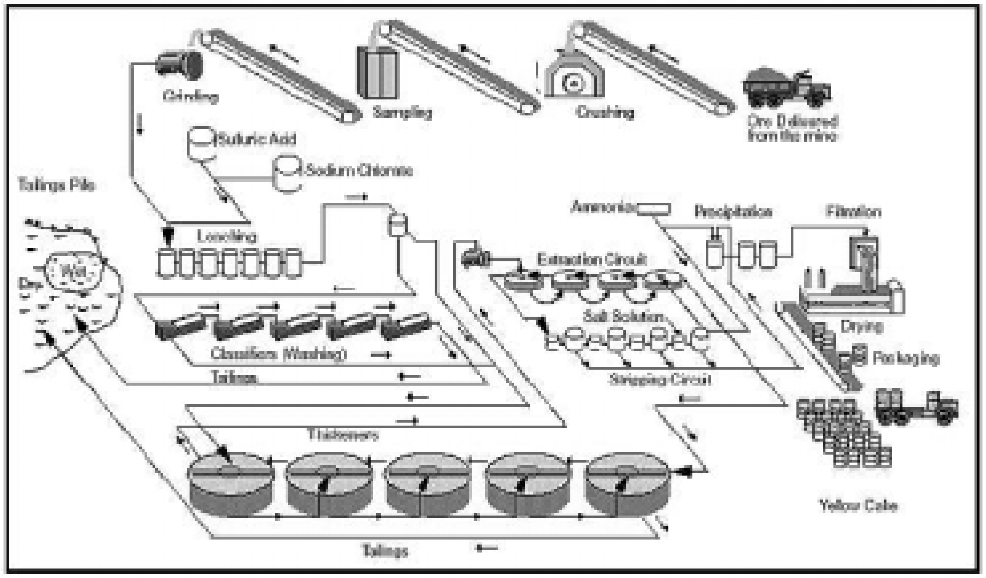

Figure 5. Generalized conventional uranium milling process
U.S. DOE Energy Information Administration

conventional uranium mines are regulated at the federal level by the Mine Safety and Health Administration of the U.S. Department of Labor and by respective state agencies with responsibility for health, safety, and environmental protection associated with mining.

Open-pit mining involves the surface removal of soil and rock overburden and extraction of ore. Open-pit mines are broad, open excavations that narrow toward the bottom and are generally used for shallow ore deposits. The maximum depth of open-pit mining in the United States is usually about 150 meters. Lower-grade ore can be recovered in open-pit mining, since costs are generally lower compared to underground mining. In open-pit mining, topsoil is removed and often stockpiled for later site reclamation (i.e., restoration). Overburden is removed using scrapers, mechanical shovels, trucks, and loaders. In some cases, the overburden may be ripped or blasted free for removal. Once the uranium ore-bearing horizon is reached, the ore is extracted. The extracted ore is stockpiled at the surface or trucked directly to a conventional uranium mill (see below) for processing into the U_3O_8 product (referred to as "yellowcake" due to its typical color).

Deeper uranium ore deposits require underground mining in which declines or shafts are excavated and/or drilled from the surface to access the ore-bearing strata at depth. These deeper deposits may require one or more vertical concrete-lined shafts or declines large enough for motorized vehicles to reach the ore. Stopes (an underground excavation from which ore will be removed in a series of steps) reaching out from the main shaft provide access to the ore. Ore and waste rock generated during mining are usually removed through shafts via elevators or carried to the surface in trucks along declines. As with open pits, the extracted ore is stockpiled at the surface and subsequently transported directly to a conventional uranium mill.

Figure 6. Aerial view—conventional uranium mill complex
Photo courtesy Cotter Corporation

Conventional Uranium Mills

Uranium mills (and in situ recovery facilities [ISRs], see page 12) are "licensed facilities" since they produce source material as defined under the AEA. Accordingly, licensing requirements and management of uranium mills are defined in NRC's 10 CFR 40, *Domestic Licensing of Source Material,* and commensurate requirements of agreement state regulations. The generalized conventional uranium milling process is depicted in Figure 5, and an aerial view showing the "footprint" of a conventional mill and associated tailings (radioactive waste) impoundment is shown in Figure 6.

As shown in Figure 5, the initial step in conventional milling involves crushing and grinding of the raw ore to produce uniformly sized particles. Various mechanical mills grind the rock to further reduce the size of the ore. After the ore is ground and is put in the form of a slurry, it is then pumped to a series of tanks for leaching, either in an acid- or alkaline-based process. The uranium liquor is separated from residual solids and then dissolved into a solvent. These solids are the "uranium mill tailings" which must be managed in large surface impoundments as the major radioactive waste stream of a conventional mill. The uranium is then recovered (stripped) from the solvent-based liquor. The final steps consist of precipitation to produce yellowcake, followed by drying and packaging of the final U_3O_8 product.

A commercial-scale conventional mill processes on the order of 1,000 tons or more of ore per day and produces one to two million pounds per year of U_3O_8. Over 95 percent of the ore mass constitutes radioactive wastes (tailings) and must be permanently impounded at or near the mill site in a highly engineered landfill ("tailings pile or pond"). This material is referred to as "11e.(2) byproduct material" after the AEA paragraph which legally defines it. Radiologically, this material contains 99 percent of the uranium series radionuclides which occurred in secular equilibrium with the ^{238}U parent in the ore body, minus most of the uranium. For an ore grade of a few tenths of a percentage uranium, the tailings would contain an order of magnitude of a few 10s to a few 100s Bq/g of each daughter in equilibrium.

In Situ Recovery Facilities

ISRs (also referred to as in situ leach or uranium solution mining) are rapidly becoming a preferred method around the world for uranium recovery. This is primarily because of lower capital costs, fewer manpower requirements for operations, smaller land-use footprints, and environmental advantages over conventional mines and mills. However, applicability of this technology is generally limited to very specific geological, hydrological, and geochemical conditions. Uranium deposits typically amenable to in situ recovery are usually associated with relatively shallow aquifers, about 30-150 meters subsurface, confined by nonporous shale or mudstone layers. The uranium was transported to these locations over geologic time as soluble anionic complexes by the natural movement of oxygenated groundwater. Deposition occurred in areas where the groundwater conditions changed from oxidizing to reducing, producing what is known as a "roll front deposit."

Accordingly, ISRs are typically used for recovery of uranium at ore grades below that associated with conventional mining (open pits or underground). Typical uranium ore grades associated with ISR roll-front deposits are about 0.1 percent-0.2 percent (1,000-2,000 ppm uranium in the ore). ISRs, like conventional mills, are considered source material facilities under the AEA and therefore must be licensed and operated as such under NRC (e.g., 10 CFR 40) or commensurate agreement state regulations and requirements.

ISR processes in the United States typically involve the circulation of groundwater, fortified with oxidizing (typically gaseous oxygen) and complexing (e.g., carbon dioxide) agents into an ore body (referred to as "the lixiviant"), solubilizing the uranium in situ, and then pumping the solutions to the surface where they are fed to a processing plant (very similar to a conventional mill, without the need for ore crushing, grinding, and leaching). The uranium dissolved in solution returning from underground is first concentrated in an ion exchange circuit, stripped from the ion exchange resin via an elution process and then precipitated into yellowcake, dewatered, dried, and packaged as the final U_3O_8 product in an identical manner as in conventional mills. Figure 7 shows the basic approach to in situ uranium recovery. Figure 8 shows the footprint in an aerial view of a modern ISR.

Since ISRs do not process large volumes of ore (rock), as do conventional mills, conventional-type uranium mill tailings are not generated by these processes. However, ISRs do generate relatively small volumes of 11e.(2) byproduct material related to the need to remove calcium compounds from the process to maintain formation and system permeability and remove impurities. Radium follows the calcium chemistry through the process. Measurements made in the 1970s and early 1980s indicated that 5-15 percent of equilibrium

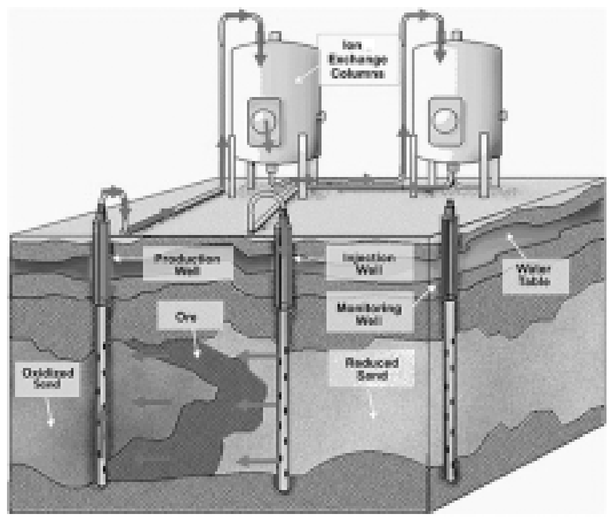

Figure 7. Basic approach to in situ uranium recovery

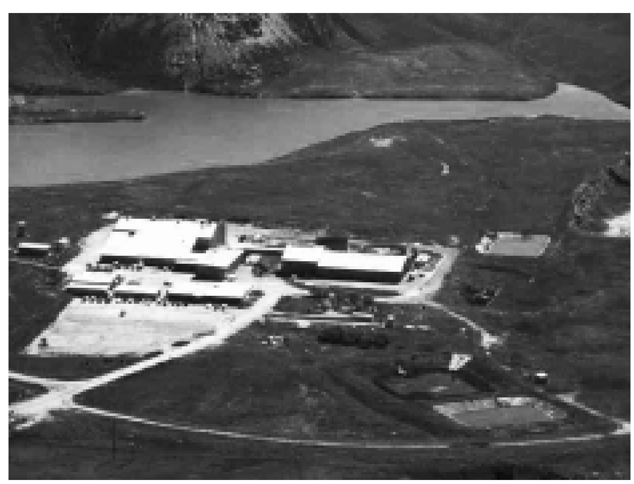

Figure 8. Aerial view—in situ uranium facility
Photo courtesy Wyoming Mining Association

^{226}Ra in the host formation ends up in this material (NMA 2007, Brown 1982). This material must be shipped off-site to a licensed uranium mill tailings impoundment or other licensed disposal facility authorized to accept it. Additionally, due to the need to extract several percent greater volume of solutions for hydrological control than is actually reinjected in the well fields ("over recovery"), large volumes of solutions must be impounded and managed at the surface. In modern designs, these fluids are disposed of via irrigation and/or injected in permitted deep-well disposal systems following treatment.

Another special consideration associated with ISRs that has health physics implications is the manner in which ^{222}Rn gas is evolved by the process. At conventional mills, the "radon source term" is almost exclusively the result of the natural decay of ^{226}Ra in ore bins and the tailings impoundment. At ISRs, it was observed that more than 90 percent of the radon source term results from the dynamic release of radon dissolved in the lixiviant solution as it returns from the underground environment (Brown and Smith 1981). It appears that the temperatures and pressures in situ enhance solubility of radon, and much of the dissolved gas is released when the solutions are first exposed to atmospheric conditions. If this is inside the plant, local exhaust systems deployed at point(s) of release are often required to remove the radon from the work environment, thereby minimizing opportunity for progeny in growth. When inhaled, it is the particulate progeny, not the radon gas itself, that produce the majority of the pulmonary dose.

Additional Uranium Recovery Technologies that May Be Revisited

In the 1970s and into the 1980s, uranium was also recovered as a byproduct of copper and phosphate production. I was the radiation safety officer for a plant that was colocated at the world's largest open-pit copper mine, near Salt Lake City, Utah. Our uranium plant received a portion of the copper recovery circuit liquor and, through ion exchange and subsequent traditional uranium milling processes as described above, produced 150,000-200,000 pounds per year of yellowcake. Similarly, I had corporate radiation protection oversight responsibility for one of the several uranium recovery facilities in the phosphate lands of west central Florida. This facility received a portion of the phosphoric acid production plant stream and, through traditional uranium milling processes, also produced a similar rate of yellowcake. Regarding uranium's well-known occurrence in phosphate rocks, it seems reasonable to assume that uranium companies are again or shortly will be re-evaluating the potential uranium reserves inherent in this material and the associated economic viability of recovery.

Environmental Monitoring at Uranium Mills and ISRs

Comprehensive environmental monitoring programs must be conducted at uranium recovery facilities to (1) establish the preoperational radiological baseline against which potential future impacts can be assessed and (2) demonstrate compliance during operations to public exposure standards (e.g., 1mSv/y per 10 CFR 20.1301) and to ensure effluent releases are maintained ALARA. These programs are typically performed in accordance with NRC Regulatory Guide 4.14 (NRC 1980).

Uranium and, therefore, its progeny are naturally occurring, and levels in environmental media can vary considerably from place to place depending on local geology, hydrology, and geochemistry. Accordingly, measurements are made of direct radiation (cosmic plus terrestrial) and of uranium-series radionuclides in air (long-lived alpha-emitting particulates and radon gas), in surface and groundwater, and in soil, vegetation, and meat, milk, and fish as may be applicable at a given locale. Key elements of the preoperational baseline program are continued during plant operations and also typically include effluent monitoring (radionuclide particulates and radon releases from ventilation systems and yellowcake dryer stacks).

Operational Health Physics Programs at Uranium Recovery Facilities

Uranium Mines: The environment underground potentially exposes workers to two primary sources: (1) internal exposure from inhalation of ^{222}Rn and its short-lived progeny in breathing air (the "radon daughters," ^{218}Po, ^{214}Bi, ^{214}Pb, and ^{214}Po) and (2) external exposure from close proximity to higher-grade uranium ore. Needless to say, ventilation and diligent air sampling programs are critical in maintaining internal exposure ALARA and, in higher-grade mines, occupancy times in some areas underground often must be managed and controlled. As indicated previously, worker health and safety in mines in the United States is regulated by the Mine Safety and Health Administration (MSHA). MSHA regulations currently require documentation of internal exposure (typically in working level[2] months [WLM] of radon daughter exposure relative to a standard of 4 WLM/y) and external exposure relative to a 5 rem/y standard. However, at the present time, MSHA does not require conversion of WLM of exposure to a committed effective dose equivalent (CEDE) nor the addition of internal and external exposure into an expression of the total effective dose equivalent (TEDE). At open-pit mines, internal exposure is usually minimized since excavation is in the open air and dust suppression technology is applied typical of large civil engineering construction projects.

Uranium Mills and ISRs: Operational health physics programs in conventional mills and ISRs are very similar and are generally consistent with any nuclear material facility that produces standard industrial uranium compounds of natural enrichment[3] and include:

- Airborne monitoring for long-lived alpha emitters (uranium, thorium), primarily in ore crushing, drying, and packaging areas including combinations of grab sampling and breathing zone sampling.
- Radioactive material area ingress/egress control programs and surface-area contamination surveillance and control throughout plant areas.
- Respiratory protection programs if necessary, typically only necessary in ore crushing, product drying, and packaging areas.
- Bioassay programs appropriate for the uranium products to which employees are potentially exposed. It must be noted that product-specific solubility characteristics can have metabolic implications for bioassay (NRC 1986; NRC 1988; Eidson and Mewhinney 1980). Higher solubility results in faster pulmonary clearance and, therefore, less pulmonary dose and vice versa. Typically, only urinalysis is performed with in vivo lung counting in response to confirmed intakes above specified action levels.[4]
- Work control and training via formalized procedures.
- Internal audit and quality-control programs to ensure execution of safe work practices, regulatory compliance, and ALARA.
- Airborne monitoring for radon and progeny as dictated by specifics of facility design.
- External exposure monitoring, primarily in areas in which large quantities of uranium concentrates and/or byproduct material are processed, packaged, and/or stored.

Internal exposure is documented by recording the derived air-concentration hours (DAC-hrs) of exposure to long-lived alpha emitters (uranium, thorium, radium), exposure to radon progeny in working level months, and bioassay results. External exposure is documented from TLD results. CEDE resultant from internal exposures and the TEDE as the sum of internal and external exposure are typically calculated using methods described in, e.g., NRC Regulatory Guide 8.30, *Health Physics Surveys in Uranium Recovery Facilities*, 2002.

Over the years, the NRC has issued a number of helpful regulatory guides specific to uranium recovery facilities, providing a solid basis and foundation for "good health physics practice." Typically, the agreement states accept these as appropriate to demonstrate compliance to their own regulations commensurate with, e.g., NRC's 10 CFR 20 and 10 CFR 40. Examples include:

- 8.30 – Health Physics Surveys in Uranium Recovery Facilities
- 8.31 – ALARA Programs at Uranium Recovery Facilities
- 8.22 – Bioassay at Uranium Mills
- 3.56 – Emission Control Devices at Uranium Mills
- 3.59 – Estimating Airborne Source Terms for Uranium Mills

Conclusions—Opportunities for Health Physicists in the Expanding Uranium Recovery Industry

Hopefully, this broad overview above suggests that numerous opportunities for health physicists and radiological scientists are emerging as a result of the rapid ongoing expansion of the uranium recovery industry. Not only are there opportunities to support the health physics and related environmental-assessment and monitoring programs of operating plants, but the preoperational licensing process is arduous and can take several years. During this preoperational period, baseline radiological monitoring programs must be designed and implemented and source material license applications and numerous other permits must be prepared. These regulatory submittals must describe, in some aspects in considerable detail, the intended operational health physics and training programs and provide results of fate and transport modeling efforts to estimate off-site public exposure during operations, radiological design aspects to ensure incorporation of ALARA principles into the facility design and layout and for effluent control, and descriptions of the planned operational environmental monitoring program. After the doldrums of the last 20-plus years, it is again an exciting time at the front end of the uranium fuel cycle.

Footnotes:

[1] In general terms, "source material" means either the element thorium or the element uranium, provided that the uranium has not been enriched in the isotope ^{235}U. Source material also includes any combination of thorium and uranium, in any physical or chemical form, that contains by weight one-twentieth of one percent (0.05 percent) or more of uranium, thorium, or any combination thereof that is processed for its uranium and/or thorium content.

[2] A working level (WL) is the total potential alpha energy dissipated in one liter of air from the decay of the short-lived daughters in equilibrium with 100 pCi/L of radon, equivalent to 1.3 x 10^5 MeV/liter of air; a working level month (WLM) is exposure to a concentration in air of one WL for a working month of 170 hours. It is generally assumed that 1 WLM = 12.5 mSv (1.25 rem) so that 4 WLM/y = 50 mSv (5 rem)/y. Note however, that ICRP 65 (ICRP 1994) equates 1 WLM to 5 mSv (500 mrem), which may be conservative.

[3] Natural enrichment means the mixture of the three naturally occurring isotopes of uranium as it occurs in nature, which is, on a mass basis, 99.3 percent ^{238}U, 0.72 percent ^{235}U, and 0.005 percent ^{234}U. Due to differing half-lives, and therefore different specific activities, on an activity basis these ratios are 48.9 percent ^{238}U, 2.2 percent ^{235}U, and 48.9 percent ^{234}U. By "definition," the specific activity of natural

uranium is 0.67 µCi/g (10 CFR 20, Appendix B, Table 1, footnote 3).

[4] Over my career I have had the opportunity to have been the radiation safety officer at six different uranium recovery facilities that produced products of varying solubility depending on specifics of process chemistry and the drying temperatures used (e.g., Task Group on Lung Dynamics class D/W as well as Y—ICRP 1972). However, modern mill designs dry the final uranium product at much lower temperatures than in the past, producing more soluble products with less potential for pulmonary dose when inhaled (Brown 2008).

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Editor's Note: More detailed information about uranium can be found at http://hps.org/publicinformation/ate/uranium.ppt.

Kathryn and Steve Brown with granddaughter Sydney

Steve Brown, CHP, is president of SHB Inc., a radiological consulting firm in Centennial, Colorado. Since forming his company in early 2007, he has been working as a consultant in the uranium recovery industry supporting mining and engineering companies in the design and licensing of new uranium recovery projects. He was recently appointed chair of the Uranium Committee of the Colorado Mining Association (see *Health Physics News*, July 2008). He recently accepted an assignment to establish an office in the Denver area for SENES, the internationally respected Toronto-based mining and radiological consulting firm.

After several years as a high school chemistry and physics teacher, Steve joined the Uranium Division of the Westinghouse Electric Corporation in 1976 where he was manager of ESH and RSO under six uranium recovery facility licenses. Steve left Westinghouse in 1980 and started a Denver office for Radiation Management Corporation, a health physics consulting firm. Following the downturn in the domestic uranium industry of the early 1980s, Steve worked at DOE's Rocky Flats Nuclear Weapons Plant as a senior nuclear safety specialist. He then joined Dames and Moore as senior radiological engineer at the DOE's West Valley Demonstration Project and subsequently started and managed a DOE and radiological services division for Dames and Moore. In 1992 he joined the International Technology Corporation (acquired by the Shaw Group in 2002) as vice president of DOE programs and was appointed radiological operations manager in 2005.

Steve has been a member of the HPS since 1977, and twice president of the Central Rocky Mountain Chapter (1984 and again for 2008). He was general chair of the HPS's midyear symposium on environmental radioactivity held in Colorado Springs in 1985. He has served on the ABHP Part II exam panel and on many other HPS standing committees over the years. He received an associate degree in radiological health and a bachelor's degree in physics from Temple University and master's degree in physical science from West Chester University. Steve's hobbies include traveling with wife Kathryn, art history (especially the Italian, Flemish, and Dutch renaissance), and hiking and climbing in Colorado's Rocky Mountains. Regarding the "rebirth" of the uranium recovery industry, Steve commented, "Uranium health physics was always my first love (after my wife Kathryn, sons Chad, Joshua, and Sean, and granddaughter Sydney) and I am very excited to be back working in the industry where I started over 30 years ago."

The Resurgence of Nuclear Power

Impact on the Health Physics Profession

Ralph Andersen, CHP
Health Physics News *Associate Editor*

This is the third in a series of articles in *Health Physics News* that will explore the various sectors of nuclear power that, while unique and relatively unfamiliar to our membership at large, share the basic science, principles, and methods that are common throughout our profession. The first installment (*Health Physics News*, July 2008) presented a general overview of nuclear power generation—where it is today and where it's headed tomorrow, environmental considerations, and some challenges and opportunities related to health physics. The second installment (*Health Physics News*, September 2008) presented the uranium recovery industry. This article focuses on the uranium conversion and isotopic enrichment part of the nuclear fuel cycle.*

Uranium Conversion and Isotopic Enrichment

Orville Cypret, CHP, PE

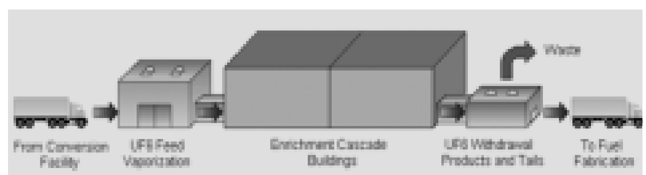
Introduction

Uranium ore is mined from the ground in the chemical form of U_3O_8. After the mining and separation of the nonuranium material from the uranium chemical compound, the material begins the next step in the nuclear fuel cycle. This step, called conversion, is summarized by the Nuclear Regulatory Commission (NRC) (http://www.nrc.gov/materials/fuel-cycle-fac.html) as follows:

> After the yellowcake is produced at the mill, the next step is conversion into pure uranium hexafluoride (UF_6) gas suitable for use in enrichment operations. During this conversion, impurities are removed and the uranium is combined with fluorine to create the UF_6 gas. The UF_6 is then pressurized and cooled to a liquid. In its liquid state it is drained into 14-ton cylinders where it solidifies after cooling for approximately five days. The UF_6 cyclinder, in the solid form, is then shipped to an enrichment plant. UF_6 is the only uranium compound that exists as a gas at a suitable temperature.
>
> One conversion plant is operating in the United States: Honeywell International Inc. (Docket No. 40-3392) in Metropolis, Illinois. Canada, France, United Kingdom, China, and Russia also have conversion plants.
>
> As with mining and milling, the primary risks associated with conversion are chemical and radiological. Strong acids and alkalis are used in the conversion process, which involves converting the yellowcake (uranium oxide) powder to very soluble forms, leading to possible inhalation of uranium. In addition, conversion produces extremely corrosive chemicals that could cause fire and explosion hazards.

The NRC explains the enrichment process as follows:

> The fuel of a nuclear power plant is uranium, but only a certain type of uranium atom can be easily split to produce energy. This type of uranium atom—called uranium-235 (^{235}U)—comprises less than 1 percent by weight of the uranium as it is mined or milled. To make fuel for reactors, the natural uranium is enriched to increase the concentration of ^{235}U to 3 percent to 5 percent.



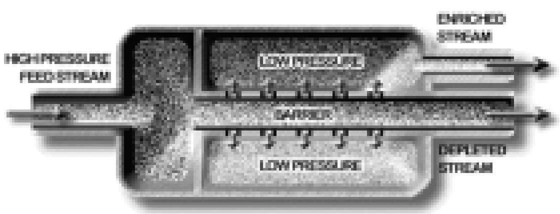
> Throughout the global nuclear industry, uranium is enriched by one of two methods: gaseous diffusion or gas centrifuge. A third method—laser enrichment—has been proposed for use in the United States.

History of Isotope Separation Technology

Various isotope separation processes were investigated in the late 1930s and early 1940s by Harold Urey and others. Immediately prior to World War II, no consensus existed within the scientific community that the fission process could be used to make a weapon. However, this perspective made a radical and rapid about-face in the early 1940s within some of the Allied governments and their associated scientific communities. During the Manhattan Project in World War II, gaseous diffusion became the method of choice for uranium enrichment. The process essentially involves presenting a porous material to gaseous UF_6. The $^{235}UF_6$ will diffuse through the material at a very slightly higher rate than the $^{238}UF_6$. This results in the UF_6 on one side of the porous material having a slightly higher concentration of ^{235}U while the UF_6 on the other side of the porous material has a slightly depleted concentration of ^{235}U.

The first gaseous diffusion plant in the United States, K-25, was built in Oak Ridge, Tennessee. Additional plants were built within a few years at Paducah, Kentucky, and Piketon, Ohio. All used the gaseous diffusion process.

The following graphic is a depiction of a gaseous diffusion stage. Each stage is several feet in length and about half as big in diameter as its length. Buildings housing the cascade are approximately square and about 1,000 feet on each side. Many stages are connected together in series to form a cascade. In the cascade, the enriched stream is fed into the next stage upstream as high-pressure feed material. Thus, each stage provides an incremental amount of enrichment and the cascade, which may consist of several thousand stages, collectively provides substantial isotopic enrichment.



Gaseous Diffusion Stage
Courtesy of USEC, Inc.

The effort required to separate the ^{235}U atoms from the ^{238}U atoms is measured in "separative work units" (SWU). Customers contract with enrichers based on the amount of natural uranium they can supply and the number of SWUs needed to reach their desired product quality and enrichment level. In fact, regardless of the technology used to accomplish the enrichment, the enriched product is purchased based on the number of SWUs it has undergone.

The changing market demand for enriched uranium over the past 20 years or so has impacted the viability of the domestic enrichment enterprise and two of the plants have ceased uranium enrichment operations. K-25 ceased enrichment operations in the mid-1980s and the plant in Piketon, Ohio, ceased enrichment operations in 2001. Only the plant at Paducah, Kentucky, still operates.

Future Technology Developments

Electricity requirements of the gaseous diffusion process are very high. This is the primary reason the process is being phased out and replaced by alternative technologies with lower energy consumption. The second-generation technology currently in use is gas centrifuge. A third-generation technology using lasers to achieve enrichment has been in development for several decades.

Plants using updated U.S. and European gas centrifuge technologies are under construction in the United States. Enrichment plants using European and Russian centrifuge technologies have operated in Europe, Russia, and China for some time.

Isotopic enrichment by gas centrifuge technology involves injecting gaseous UF_6 into a rotor that is spinning rapidly inside a casing. The inner void annulus space between the rotor and the casing is held at a vacuum. The rotor spins and places the contained UF_6 gas under a centrifugal force that results in the heavier $^{238}UF_6$ molecules being preferentially moved closer to the outer wall of the rotor than the lighter $^{235}UF_6$ molecules.

The graphic on the next page schematically represents a centrifuge. The UF_6 gas is injected in the line on the left side of the device; the stream enriched in $^{235}UF_6$ is withdrawn at the top, and the depleted stream is withdrawn from the line on the right side. The casing and rotor (as described above) are shown, as is the motor that spins the rotor.

A countercurrent axial flow may also be induced in the gas inside the rotor which can enhance the separation of the isotopes and result in a concentration of the enriched gas being found at one end of the rotor and a concentration of depleted gas being found at the other end of the rotor. Centrifuges have a large length-to-diameter ratio and spin at very high speeds because the isotopic separation efficiency varies directly with the length of the rotor and its rotational speed.

In terms of enriched product produced per unit of energy consumed, gas centrifuge enrichment technology is more efficient than gaseous diffusion but less efficient than laser enrichment. Two centrifuge designs are currently being fielded in the United States but detailed technical differences between the designs have not been publicly disclosed.

To date, laser enrichment has not been used on an industrial scale to commercially enrich uranium. Laser enrichment is thought to be the most efficient of the enrichment technologies in that it provides the greatest mass of enriched product for the least amount of energy consumed. The technique being considered for commercial deployment is known as the SILEX technology.

The SILEX process is considered classified technology by the United States and Australian governments, so almost no technical details of it are publicly available. However, the process is thought to involve passing gaseous UF_6 through a laser beam. The laser wavelength is tuned to preferentially excite the ^{235}U atoms in the UF_6 molecules. The excited atoms are electrically charged and, when placed under the influence of an electromag-

Gas Centrifuge

Courtesy USEC, Inc.

1. Gaseous UF_6 is fed into a rotor that spins inside a casing.
2. The useful, lighter ^{235}U isotopes remain at the center of the rotor while centrifugal force pushes the heavier ^{238}U isotopes toward the rotor walls.
3. The ^{235}U gas (enriched stream) is extracted at the top.
4. The ^{238}U gas (depleted stream) is extracted at the right.

The process is repeated in several connected centrifuge machines, known as "cascades," until the desired level of ^{235}U is achieved.

netic field, can be deposited on a collecting surface or substrate.

The uranium deposited on the collecting surface will be enriched in very pure ^{235}U. Process losses inherent in this method include less than 100 percent of the gaseous UF_6 being excited by the laser and failure to deposit all the excited atoms on the collecting surface. However, even with these process losses, the technology is reported to be the most efficient isotopic separation methodology available at this time.

Health Physics Considerations

Occupational radiation dose will come from charged particles, i.e., alpha and beta particles, and gamma emissions interacting in both the external and internal exposure pathways. Exposure to radiation from spontaneous fission events is also possible, but the incidence of these events is quite low.

Specific activity of uranium, natural or enriched, is relatively low due to the long half-lives of the constituent isotopes. The specific activity of a mass of uranium, whether natural or enriched, is on the order of 3.7×10^4 Bq (10^{-6} Ci) g^{-1}. It's important to note that the granddaughter of ^{238}U decay, ^{234m}Pa, emits a relatively high-energy 2.29 MeV beta particle. The significance of the ^{234m}Pa decay is that it can result in a surprisingly intense bremsstrahlung photon radiation field in favorable geometry.

Generally before an internal exposure can occur at an enrichment facility, UF_6 must be released from the enclosed process system to the atmosphere. When it is released to open air, UF_6 quickly hydrolyzes with water vapor in the air to uranyl fluoride (UO_2F_2) according to the following equation:

$$2H_2O + UF_6 \longrightarrow UO_2F_2 + 4HF$$

In a facility that uses UF_6, intakes following a release will be of the chemical UO_2F_2, which metabolizes very quickly, is very soluble in body fluids, and has a very short biological half-life. Because the emissions are typically low-energy particles or photons, in vitro bioassay by urinalysis is a typical method for determining the intake mass and estimating the internal dose. It should be noted that the 10 CFR 20 limit on soluble uranium intake is based on mass (10 mg U per week), not dose, due to the fact that the limiting hazard of an intake is the chemical effect of uranium's nephrotoxicity as a heavy metal rather than its consequential radiogenic pathology.

The primary external dose at gaseous diffusion plants comes from charged particles and photons emitted by U and its daughters. Internal dose results from soluble decay progeny that emit charged particles, ^{234}Th and ^{230}Th being major contributors. Both ^{234}Th and ^{230}Th are in the ^{238}U decay chain. Contamination control is the greatest health physics challenge at these plants. Areas requiring radiological control are posted and controlled by the Health Physics Group in accordance with the requirements of 10 CFR 20. Engineered features or respirators are used to minimize internal contamination and workers monitor themselves for radiological contamination when they exit contamination areas.

In a centrifuge plant operating in the United States, the source term for occupational radiation dose is uranium and its daughters. This being the case, the primary source of external occupational dose would be expected to be charged particles and photons emitted from radionuclides in the uranium decay chain. As with gaseous diffusion, the principal source of internal dose is the soluble radionuclides in the uranium decay chain that emit charged particles.

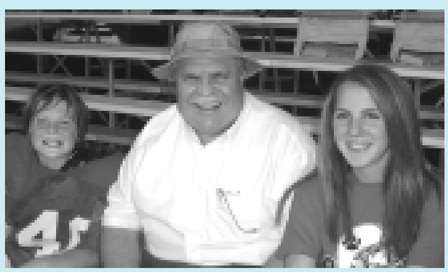
Laser enrichment may present some unique occupational radiological control situations because the feed material can be either metal or UF_6 and the product is primarily ^{235}U deposited on a substrate. Based on what is known about this process, the occupational doses will probably be approximately the same as the doses from centrifuge or gaseous diffusion enrichment plants.

Conclusion

Uranium is currently enriched using the gaseous diffusion and gas centrifuge methods. Beginning in the next decade, uranium may be commercially enriched by using laser enrichment technologies. Gaseous diffusion technology is likely to be used for some time to come but will most likely be gradually phased out as the more energy-efficient technologies become available. The occupational radiation dose considerations are similar for each of these methodologies. Generally, a person's external dose will probably not exceed 5 mSv y^{-1} (500 mrem y^{-1}) and may be much lower. Internal dose will result primarily from alpha-particle emitters in the uranium decay chain. Internal dose from routine operations will probably not exceed a few µGy (mrem) in any given year.

***Editor's Note:** Due to space limitations and security restrictions, many details of these processes are not included in this article.

Orville Cypret, CHP, PE, is employed by the U.S. Enrichment Corporation as the principal health physicist at the Paducah Gaseous Diffusion Plant in Paducah, Kentucky. He received a BS in metallurgical engineering (nuclear option) from the University of Missouri-Rolla (now Missouri Science and Technology) in 1974 and an MS in radiological health from the University of Arkansas in 1990. He is a registered professional engineer and a certified health physicist.



Orville with his grandchildren Gavin and Hannah

Orville worked for Arkansas Power and Light (AP&L) from 1974 until 1992. He was one of two nuclear engineers overseeing the initial approach to criticality of Arkansas Nuclear One-Unit 1 in 1974 and who determined the reactor had achieved initial criticality. He served in several positions while at AP&L in nuclear engineering and health physics. During his time with AP&L, the construction of Arkansas Nuclear-Unit 1 and Unit 2 was completed and both plants were placed into commercial service.

He joined Martin Marietta Energy Services (eventually replaced by the United States Enrichment Corporation) at the Paducah Gaseous Diffusion Plant in 1992 as the dosimetry manager and was named the radiation protection manager in 1993. In this position, he was responsible for the effort to modify the Radiological Protection Program from compliance with Department of Energy rules and expectations to a 10 CFR 20-compliant program in preparation for operation of the plant under the regulatory jurisdiction of the Nuclear Regulatory Commission. As the principal health physicist at the plant, he is responsible for providing technical assistance to the plant management in health physics and nuclear engineering and other project-related activities.

Orville and Dianne, his wife of 35 years, have two adult children, Aaron and Amy, and two grandchildren, Hannah and Gavin. Trips with the grandkids are the way weekends are frequently spent.

Orville's main hobby is amateur radio. He is also a member of the Army Military Affiliate Radio System, a volunteer organization that provides emergency radio communications services to various groups, including the U.S. Department of Homeland Security, the American Red Cross, and the Salvation Army, in times of disaster. Hurricanes Gustav, Hanna, and Ike have kept him very busy this year.

The Resurgence of Nuclear Power

Impact on the Health Physics Profession

Ralph Andersen, CHP
Health Physics News *Associate Editor*

This is the fourth in a series of articles in *Health Physics News* that will explore the various sectors of nuclear power that, while unique and relatively unfamiliar to our membership at large, share the basic science, principles, and methods that are common throughout our profession. The first installment (*Health Physics News,* July 2008) presented a general overview of nuclear power generation—where it is today and where it's headed tomorrow, environmental considerations, and some challenges and opportunities related to health physics. The second installment (September 2008) covered the uranium recovery industry, and the third (November 2008) summarized the uranium conversion and isotopic enrichment processes. This month's article focuses on the fuel fabrication process.

Fuel Fabrication

Allen M. Mabry, CHP

Fuel Fabrication

In the simplest terms, fuel fabrication is the process of transforming refined enriched uranium into finished fuel assemblies suitable for direct placement into the reactor core.

The details that go into that transformation are numerous and diverse. Every component of the fuel assembly—the fuel cladding, the end plugs, the tie plates, even seemingly mundane springs—must be designed and manufactured to meet the demanding environment of a nuclear reactor core.

The uranium itself must be chemically processed, pelletized, sintered into a ceramic, and ground to tolerances of 1/1000ths of an inch.

Then everything must be assembled—the pellets into the cladding, the loaded rods into assemblies—and prepared for shipment to the customer.

A fuel fabrication facility is actually the combination of a chemical processing plant, a components manufacturing plant, a ceramics production facility, and an assembly operation (see Figure 1).

The fuel fabrication process begins with the reconversion of the uranium hexafluoride (UF_6) received from the enrichment facility. Reconversion, also referred to as defluorination, is the process of transforming the UF_6 back to a chemically stable oxide state, essentially reversing the fluorination process that was necessary to facilitate enrichment. The UF_6 is received as a solid in 30-inch-diameter cylinders suitable for connecting directly to the chemical process. Each cylinder contains about one metric ton of uranium. The most common industry method of reconverting uranium hexafluoride to uranium dioxide (UO_2) is the ammonium diuranate (ADU) process, which is a fairly involved multistage chemical process. It requires large centrifuges and reaction tanks, and it produces a high volume of liquid waste that must be treated to remove the fluorides and nitrates, as well as small amounts of uranium.

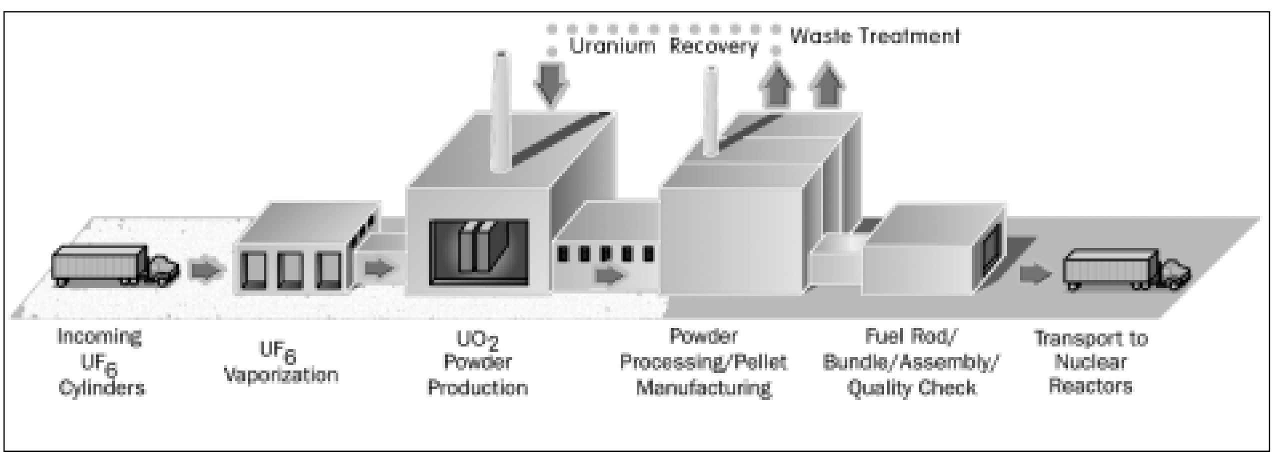


Diagram courtesy of U.S. Nuclear Regulatory Commission

Figure 1. Typical light water reactor fuel fabrication facility

Some fabricators have adopted what is referred to as a dry process, which is much less resource intensive and doesn't generate a liquid waste stream. In fact, the byproduct of the dry process is clean hydrofluoric acid suitable for industrial sale. Both processes rely on a hydrolysis reaction, which is accomplished by heating the UF_6 cylinder to achieve a gaseous state and introducing the UF_6 gas to a vessel where it is mixed with H_2O. The hydrolysis reaction is rapid and exothermic:

$$UF_6 + 2H_2O \longrightarrow UO_2F_2 + 4HF$$

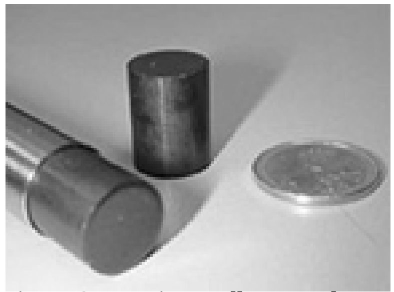


Figure 2. Uranium pellets are shown here next to a coin. One pellet is equivalent to the energy provided by a boxcar of coal or three barrels of oil.

The dry process uses super-heated steam to hydrolyze the UF_6, while the ADU process injects the UF_6 gas into room-temperature water. To complete the dry process, the UO_2F_2 is heated in a reducing atmosphere that strips away the remaining fluoride, resulting in the desired UO_2 powder. The ADU process requires the addition of ammonium hydroxide to precipitate the uranium from solution. The precipitate must be separated by centrifuge and then heated in a reducing atmosphere that removes the remaining fluoride.

Other chemical processes of fuel fabricators are those associated with scrap recovery and waste treatment. These typically involve nitric acid dissolvers, solvent extraction columns, drying ovens, dewatering centrifuges, and various filtration systems. Clearly, chemistry plays a big part in the fabricators' business.

After the finished UO_2 powder leaves the chemical process, it is physically manipulated to achieve the desirable density and particle size for pressing into fuel pellets. Pelletizing operations use high-pressure precision punches and dye cavities to form dense slugs of UO_2. These slugs are then sintered in high-temperature furnaces to form hard, dense ceramic pellets. Typical UO_2 pellets are small cylinders about one cm in length and one cm in diameter (see Figure 2). Individual pellets are loaded into tubular cladding end to end to form a column of fuel. The cladding ends are sealed and welded closed and then assembled with spacers and tie plates to form a finished fuel bundle. Figure 3 illustrates the many components of finished fuel bundles in a boiling water reactor (BWR). A pressurized water reactor (PWR) fuel bundle has basically the same components and complexity.

The fuel fabricators also do more than just manufacture fuel. They provide the fuel design, incorporating the latest technologies for extending the reliability of the fuel, thereby providing longer cycles between refueling and achieving more power per operating cycle. The fabricators also design and manufacture control rods, control rod drives, fuel channels, and reactor components. They provide services such as fuel inspection and core design. Some even have facilities for handling contaminated tooling and equipment used at nuclear power plants by their company's nuclear services and fuel-inspection operations.

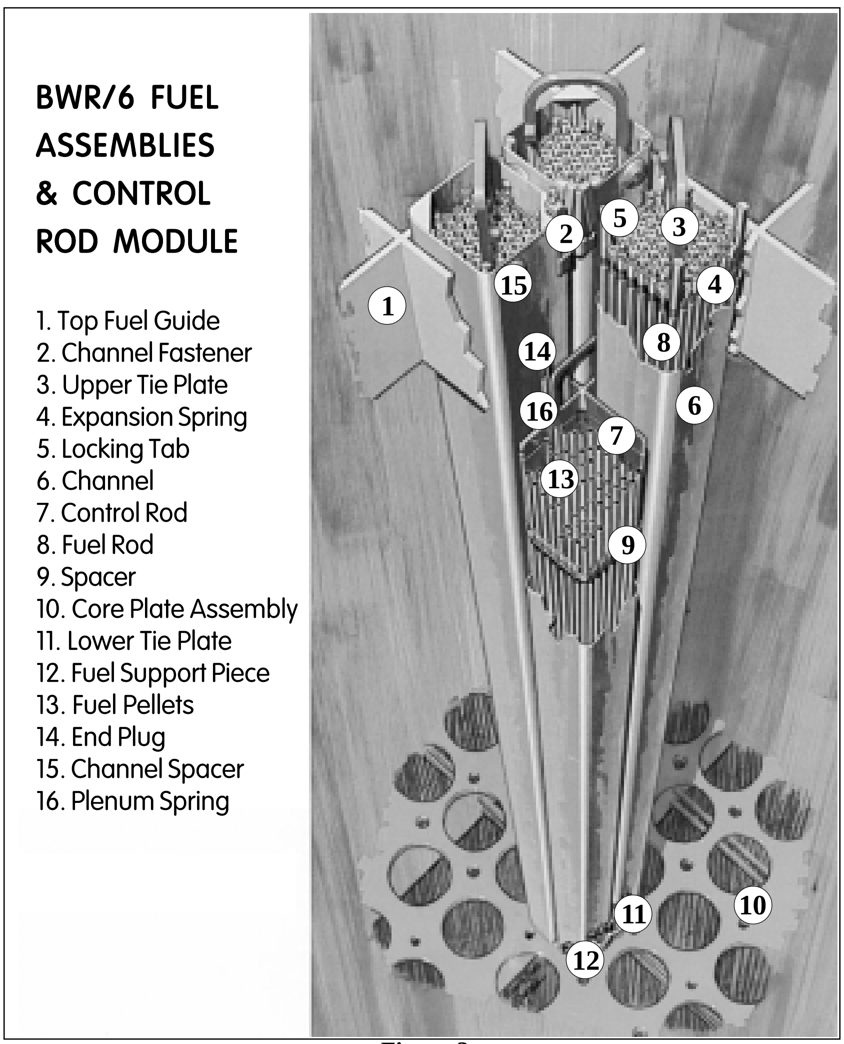


Figure 3

History

Large-scale commercial production of nuclear fuel began in the late 1960s and early 1970s along with the construction of the first commercial nuclear power plants. After working on large nuclear projects for the Department of Defense and the Atomic Energy Commission during and after World War II, large household-name companies like Westinghouse, General Electric, Exxon, and Babcock and Wilcox were well positioned to step into the commercialization of nuclear energy through the design and construction of nuclear power plants, as well as the fuel that would power them. The domestic commercial (nondefense-related) fuel fabrication facilities in operation today are the same facilities started by these companies nearly four decades ago.

Much has changed though. After a long period of rapid domestic growth, the fuel fabrication business was slowed after the last U.S. plants came on line in the 1980s. During the same period, the fuel business had become more and more global, meaning the fabricators had a larger customer base, but the customers had a larger market to shop. This resulted in stiff competition between fabricators and eventual consolidation of businesses.

Today the market has a very global feel, with all of the domestic players now either owned by or affiliated with overseas companies like Areva, Toshiba, and Hitachi. The products offered have also changed over the decades as fuel bundle designs have evolved to achieve higher burnup and longer cycles through the use of higher enrichments, the addition of burnable poisons, and the incorporation of advanced computer modeling of the reactor core thermodynamics and neutronics.

Health Physics

Low-enriched uranium (LEU) is a mixture of uranium isotopes and their short-lived progeny. It is a fairly low-specific-activity material when compared to the material encountered by reactor or medical health physicists. LEU is also a low-dose-rate material. There are photon and electron emissions to consider, but the predominant photon emission energies are less than 200 keV, and the uranium itself is a dense high Z material that provides considerable shielding. In fact, the self-shielding effect results in a dose rate to quantity of material relationship that peaks quickly at less than 0.05 mSv h^{-1} for a few kilograms of uranium (whole-body deep dose at 30 cm) and plateaus as the quantity increases. The shallow dose rate behaves similarly, peaking at about 2 mGy h^{-1} (shallow dose at contact).

The level of enrichment influences the specific activity and consequently the external dose levels. LEU ranges from 1 percent to 5 percent enriched in ^{235}U, with a range of specific activity of approximately 40 to 120 kBq g^{-1}. As the nuclear industry has gradually increased the average enrichment level utilized in the reactor cores, the consequence has been to slightly increase external dose at the fuel fabrication facilities. Another driver of the external dose rate of LEU is the ingrowth of the LEU progeny following the vaporization stage. The vaporization of UF_6 to feed the reconversion process acts as a distillation that purifies the UF_6 as it enters the process, leaving the progeny behind in the cylinder. As time elapses during the processing of the uranium, the short-lived progeny begin to grow back in, reaching full equilibrium in about 100 days. Current business practices that emphasize high turnover rates of inventory result in lower external dose to the workforce as the progeny are not given time to reach equilibrium before the product is shipped. In general the external dose at a fuel fabrication facility is low, with the maximum expected deep dose less than 10 mSv y^{-1} and average deep dose less than 1 mSv y^{-1}.

Conversely, the internal dose due to inhalation of LEU is an important consideration for the fuel fabrication industry. Even though the material is of low specific activity, a very small amount released to the air can create a significant airborne concentration of alpha-emitting uranium isotopes. The enrichment process that increases the amount of ^{235}U also increases the ^{234}U content, which is the primary contributor to LEU alpha activity. The industry increase in average enrichment level mentioned above has increased the average alpha activity of material processed by the fuel fabricators by a factor of two to three during the operating history of the industry, which without changes to the processes would have proportionally increased worker dose.

With an inhalation dose coefficient of 6.8×10^{-6} Sv Bq^{-1}, the insoluble category of uranium (UO_2, U_3O_8) has one of the lowest annual limit on intake values in 10 CFR 20 Appendix B. Keep in mind the fuel fabricators are processing many kilograms of uranium daily, including manual operations requiring workers to handle and manipulate the uranium through the process. As a result, much of the radiation protection activity at a fuel fabricator relies heavily on containment, proper ventilation, contamination control, and respiratory protection.

The health physics monitoring programs are focused on air sampling, contamination monitoring, in-vivo bioassay, and in-vitro bioassay. While internal dose is the main contributor to the total dose of the workforce, another consideration of handling large quantities of LEU is the potential chemical toxicity of the soluble compounds of uranium, e.g., UF_6 and UO_2F_2. In fact, the only nonradiological exposure limit in 10 CFR 20 is the weekly exposure limit of 10 mg soluble uranium.

Fortunately, the radiation protection measures mentioned above are equally effective at limiting exposure to these compounds, and the health physics monitoring of radiological conditions conservatively bounds the chemical toxicity concerns.

As with most health physics programs, there is overlap and shared responsibility with the other health and safety and environmental-protection disciplines. LEU processing intermingles the radiological work environment with hazardous chemicals and heavy machinery. The effluent monitoring programs and controls have radiological considerations as a primary component. The programs and controls to prevent accidental criticality of the fissile material have significant radiological implications. To a lesser degree, the emergency preparedness, fire safety, security, and special nuclear material safeguards programs all have radiological aspects or considerations as well.

The Future

The future challenge for fuel fabrication is not just an increase in demand for fuel to supply new reactors as a result of a nuclear expansion. Certainly the increased number of finished fuel assemblies needed to support the proposed new plants domestically and internationally will necessitate expansion of manufacturing capacity, but the larger challenge will be adapting to the demand for new fuel types that incorporate higher enrichments, reprocessed uranium, and mixed oxide fuel.

From a health physics perspective, adapting to the new fuel types means manufacturing processes will need to be engineered to accommodate higher dose rates and higher specific-activity materials, and future monitoring programs will need to adapt to the increased external exposure hazard, the greater internal exposure potential associated with higher alpha-activity fuels, and the monitoring challenges presented by transuranics and mixed fission products not currently found in virgin uranium.

Uranium Terminology Simplified

Virgin—natural, i.e., no isotopic separation or irradiation has taken place.
Refined—chemically and physically processed to separate it from the uranium ore.
Enriched—processed to increase the weight fraction of the isotope ^{235}U.
Reprocessed—recovered from irradiated fuel, has fission product and transuranium element contaminants.
Mixed Oxide Fuel (MOX)—uranium fuel with fissile plutonium added to it.
Low-Enriched Uranium (LEU)—has a lower than or equal to 20 percent concentration of ^{235}U.
High-Enriched Uranium (HEU)—has a higher than 20 percent concentration of ^{235}U.

Allen Mabry, CHP, is the radiological safety program manager at the Global Nuclear Fuel – Americas, LLC, fuel fabrication facility in Wilmington, North Carolina, where he has been since joining General Electric (GE) in 1992.

He is also the radiation safety officer for the site byproduct material licenses, which include facilities for handling highly radioactive tools and components used at nuclear power plants.

Before coming to GE, Mabry was a health physicist with the North Carolina agreement state program.

He began his career in health physics at the University of North Carolina (UNC) radiation safety office.

Allen and Susan Mabry

Mabry serves on the North Carolina Radiation Protection Commission and chairs the commission’s committee on low-level radioactive waste.

He is active in the Health Physics Society (HPS), currently chairing the Internal Dosimetry for Uranium standard working group, and is a past president of the HPS North Carolina Chapter.

He also leads the very informal but long-standing Uranium Users Group, which is comprised of professional health physicists from the uranium fuel fabrication industry.

He received his BA (chemistry) and MS (radiological hygiene) degrees from UNC.

Allen and his wife Susan enjoy living at the coast, spending most of their spare time boating and fishing. They are also huge Tarheel fans, and during the fall of the year when the UNC football team is playing at home, they can usually be found in Kenan Stadium cheering for the home team.

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In This Issue

The Resurgence of Nuclear Power

Impact on the Health Physics Profession

Ralph Andersen, CHP
Health Physics News *Associate Editor*

This is the fifth in a series of articles in *Health Physics News* that provide an overview of nuclear power so that the effect of a resurgence of this energy source on the profession of health physics can be anticipated. The first four installments (*Health Physics News* July, September, and November 2008 and January 2009) presented an overview of nuclear power generation, the uranium recovery industry, the uranium conversion and isotopic enrichment processes, and the fuel fabrication process. This month's article is the first in a two-part story on the history, status, and outlook for nuclear power in the United States. The upcoming second part will focus on how health physics is fully integrated across all aspects of nuclear power plant design, construction, startup, operation, emergency preparedness, and decommissioning.

History, Status, and Outlook for Nuclear Power in the U.S.

"The more important responsibility of this atomic energy agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind. Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world."

— Address by President Dwight D. Eisenhower to the 470th Plenary Meeting of the United Nations General Assembly on Tuesday, 8 December 1953

(continued on page 3)

The Resurgence of Nuclear Power

(continued from page 1)

In his "Atoms for Peace" address to the United Nations General Assembly more than 50 years ago, President Eisenhower set the stage for the creation of the International Atomic Energy Agency and launched a global effort to "help solve the fearful atomic dilemma—to devote its entire heart and mind to finding the way by which the miraculous inventiveness of man shall not be dedicated to his death, but consecrated to his life."

Following passage of the Atomic Energy Act, the AEC began promulgating regulations and writing internal procedures necessary to license commercial nuclear power plants.

The following year, the U.S. Congress passed the 1954 Atomic Energy Act, which opened the door for the first time for commercial industry to participate in "the development and utilization of atomic energy for peaceful purposes." The act expanded the role of the Atomic Energy Commission (AEC) beyond its ongoing weapons program to also promote beneficial uses of nuclear materials and create regulations to protect public health and safety against radiation hazards. Thus, the AEC was mandated to carry out a dual mission of promoting the use of nuclear technology while also assuring its safety.

Creating a Regulatory Framework

Following passage of the Atomic Energy Act, the AEC began promulgating regulations and writing internal procedures necessary to license commercial nuclear power plants. The AEC developed a two-step licensing process. In the first step, a company would provide the AEC a detailed safety analysis for the design and operation of a proposed power reactor. After review and acceptance of the company's safety analysis, the AEC would issue a construction permit to allow the company to build the plant. When construction was completed and the AEC had assured that all of the safety requirements had been met, then the AEC would issue a license for the company to load fuel and operate the reactor.

At the outset, the AEC understood that some technical data regarding the reactor design or operating procedures would not be fully developed and available at the time of submittal of applications for construction permits. The two-step licensing process gave AEC the flexibility to issue conditional permits for construction if the application included sufficient information for the Commission to conclude with "reasonable assurance" that the plant could be constructed and operated without undue risk to public health and safety.

In parallel to creating a licensing framework, the AEC promulgated regulations for radiation safety in 1955 that went into effect in 1957. In doing so, the AEC drew upon the recommendations of two expert organizations, the International Commission on Radiological Protection (ICRP) and the National Committee on Radiation Protection (NCRP—later renamed National Council on Radiation Protection and Measurements), to set "maximum permissible dose" limits for nuclear workers and the public. Prior to the Atomic Energy Act, the AEC had already employed the NCRP occupational dose limits at its own facilities, and the agency carried over the same limits into its regulations for workers at commercial facilities. In its new regulations, the AEC also adopted the ICRP recommendation that public dose limits be set at one-tenth of the occupational dose limits.

In carrying out its mandate for promoting nuclear energy, the AEC conceived a program in which the government and industry would jointly pursue the development and deployment of commercial nuclear power plants. The purpose of the program was to engage the industry in demonstrating that nuclear power was technically and economically feasible within a competitive energy market. The AEC, through its national laboratory program, would sponsor necessary research and development efforts, while the industry would finance the construction and operation of the plants. The AEC would also provide the nuclear fuel on a subsidized basis for use by the commercial power plants, with ownership of the fissionable materials ultimately being retained by the government.

First Power Reactors

The initial response by industry to the AEC proposal for joint projects was mixed. Three companies stepped forward to participate in the joint demonstration program, while two other companies announced plans to construct and operate nuclear power plants outside of the joint demonstration program. Although the AEC was positive about getting these responses, the congressional joint committee providing oversight of the atomic energy program was not. The Democrats on the committee, led by Senator Albert Gore and Representative Chet Holifield, pushed legislation to direct the AEC to construct six different pilot reactor types to advance commercial nuclear energy "at the maximum possible rate," but the legislation narrowly failed to pass. Subsequently, other companies weighed in with plans to proceed on their own, and since the time of the demonstration project reactors, nuclear power plants have been funded, owned, and operated by the utility companies.

Reactor Designs

A. Existing Operating Plants
- BWR – Boiling Water Reactor—GE
- PWR – Pressurized Water Reactor—Babcock & Wilcox, Westinghouse, and Combustion Engineering

B. New Designs – (New Acronyms; Some New Players)
- ABWR – Advanced BWR—GE
- AP-1000 – Advanced PWR—Westinghouse
- ESBWR – Economic Simplified BWR—GE-Hitachi
- EPR – European Pressurized Reactor—AREVA
- US-APWR – US Advanced PWR—Mitsubishi

A number of different reactor technologies were represented among the plants licensed and operated in the first decade of commercial nuclear power in the United States. This includes what became the mainstays of the U.S. nuclear power plant fleet, the boiling-water reactors (BWRs) and the pressurized-water reactors (PWRs) (see A in the Reactor Designs synopsis above) as well as other types of reactors, including a pressure-tube heavy-water reactor, a high-temperature gas-cooled reactor, an organically cooled and moderated reactor, a graphite-moderated reactor, and a liquid-metal fast breeder reactor. Following the diversity of reactors that were operated briefly in the early days, only one other power reactor type (i.e., besides BWRs and PWRs) has been operated commercially in the United States—Fort St. Vrain, a high-temperature helium-cooled reactor loaded with uranium-thorium fuel blocks, which operated in Colorado from 1976 to 1989.

Rapid Buildup

By the early 1960s, 14 nuclear power plants were operating or under construction. But the reactors were generally not economically competitive with other energy sources. However, in the mid- to late 1960s, several factors emerged that had the effect of greatly improving the economics and desirability of building new nuclear power plants to meet the rapidly increasing demand for electrical energy in the United States. First, one of the primary vendor companies for nuclear power plants, General Electric (GE), introduced the concept of a "turnkey" plant that involved delivery of one each fully-constructed, ready to operate, nuclear power plant for a fixed cost. The idea was that the buyer utility would only need to turn the key to start up and operate the reactor. The first reactor ordered and constructed under this concept was the 515 megawatt Oyster Creek BWR that began operation in New Jersey in 1969 (and continues to operate today). The turnkey approach became a more common practice that greatly accelerated reactor orders.

A second factor involved changes in power distribution contracts within the United States, in which reserve power from one plant or utility could be more readily sold and distributed elsewhere within the country. This pooled power concept shifted the economics in favor of large-base-load generating units that could produce and sell power year-round. This helped to facilitate construction and startup of a new generation of much larger nuclear power plants than had previously been placed into operation. In fact, the design capacity of the plants expanded rapidly from a 200-500 megawatt range to more than 1,000 megawatts. This helped to offset the substantial capital costs involved in constructing a nuclear power plant versus the lesser costs of constructing nonnuclear generating stations. However, the design and operational complexities involved in doubling or tripling the capacity of a power reactor were proving to be exponential, rather than linear.

A third factor that influenced a shift to increased use of nuclear power was the emerging concern over air pollution. Coal plants were viewed as a major contributor to air pollution, which led to increased costs in the form of required pollution control systems. This helped bring nuclear power closer to a head-to-head economic position with coal-fired power plants.

As a result of these and other fundamental economic and social changes, 68 nuclear power plants were ordered in the three-year period of 1966-1968. In the ensuing decade, estimates of up to 400 nuclear power plants in the United States were becoming commonplace and the catch phrase of the day was that nuclear-generated electricity would become "too cheap to meter."

Nuclear Regulatory Commission

During the late 1960s and early 1970s, there were a myriad of construction and operating license applications submitted, extensive licensing reviews by an ever-growing regulatory staff, and numerous adjudicatory hearings under the Atomic Safety and Licensing Boards, all of which produced new and evolving technical issues and a growing public interest and concern about reactor safety. Underlying this was an increasing uneasiness among legislators and the public about the dual mandate of the AEC to both promote and regulate nuclear energy.

With a backdrop of the oil embargo and energy crisis that unfolded in the early 1970s, President Richard Nixon asked Congress to consider the creation of a separate agency to oversee the licensing of nuclear power plants that would not be conflicted with a promotional mission.

This request was made with the idea that such an independent agency could better and more directly address the emerging public confidence issues and thereby actually facilitate licensing of the plants. The Congress responded by passing the Energy Reorganization Act of 1974, which had the effect of splitting the AEC into the Energy Research and Development Administration (which later morphed into the Department of Energy) and the Nuclear Regulatory Commission (NRC).

The NRC took over the licensing and regulatory oversight responsibilities previously carried out by the AEC, not only for nuclear power plants, but also for the rapidly increasing number of radioactive materials licensees. In the first few years following creation of the new agency, considerable effort was expended on administrative and organizational matters, as well as redefining the scope and processes for activities that had previously been part of the multifaceted mission of the AEC. Perhaps the most unique and interesting aspect of this period was the evolution of an institutional culture and values that were intensely focused on nuclear safety, material safeguards, and the protection of public health and the environment. This transformation became fully realized with the occurrence of a major reactor accident at Three Mile Island.

Three Mile Island

In the early morning of 28 March 1979, Unit 2 of the Three Mile Island (TMI) nuclear power plant in Pennsylvania automatically shut down when a main feedwater pump (which supplies water to the reactor) stopped running. As the pressure and temperature inside the reactor vessel increased, a pressure relief valve opened and water and steam were released out of the reactor into a receiving tank (as designed).

However, when the pressure and temperature came down to a point where the relief valve should have automatically closed, the valve stuck open, allowing water and steam to continue to flow out of the reactor. This equipment malfunction was not indicated correctly by the instrumentation in the plant control room. In fact, the operators in the control room received an indication that the relief valve was closed and that water was being pumped into the reactor.

What followed was a series of events that, when compounded by the misunderstanding of plant conditions by the reactor operators, ultimately resulted in a loss of cooling water to the reactor core and a partial melting of the fuel rod cladding and uranium fuel. All of the fuel was damaged. 700,000 gallons of reactor cooling water ended up overflowing into the basement of the reactor building and into tanks in the auxiliary building, contaminating them. In addition, a small amount of radioactivity was released into the atmosphere during efforts to relieve the pressure in the reactor containment building.

The accident at TMI caused no injuries or deaths, and at least a dozen epidemiological studies that have been conducted since the accident have indicated no discernable health effects among the population around the site. The reactor core and damaged fuel have been removed from TMI Unit 2 and the reactor facility has been placed into monitored storage and Unit 1 continues to operate and generate electricity. It is planned that both reactor facilities will be decommissioned jointly when Unit 1 eventually completes its licensed operating lifetime.

The accident at TMI profoundly changed the nuclear energy industry and the NRC. All aspects of plant design, operations, and equipment reliability related to nuclear safety were substantially upgraded. Expanded capabilities were put in place for accident prevention and mitigation, radiation monitoring and dose assessment, and emergency preparedness, including greatly enhanced training, drills, and exercises to test and improve each plant's ability to respond to off-normal and accident conditions. In addition, the nuclear industry formed the Institute of Nuclear Power Operations (INPO) to provide independent evaluation and oversight of plant nuclear and radiation safety, as well as to foster continuously improving standards of performance.

The installation of major modifications to plant safety systems, structures, and components resulted in a marked increase in occupational dose in the years following the TMI accident (1979-1985). However, the resulting challenges had an overall positive effect of facilitating the development of more effective approaches to maintaining exposures as low as reasonably achievable (ALARA), which was greatly enhanced by implementation of the INPO programs for evaluation and sharing of operating experience.

For its part, the NRC permanently increased the level and detail of regulatory requirements, oversight, and interactions with licensees. A significant follow-up action was the NRC Health Physics Appraisal Program, in which the NRC sent teams of agency health physicists to 48 nuclear power plants to perform detailed assessments of the adequacy of radiation protection programs and to determine whether TMI lessons learned were being effectively implemented. The extensive interactions between NRC and the nuclear industry during the appraisal program also had the effect of indelibly highlighting the key importance of the qualifications, training, roles, and responsibilities of the plant radiation protection staff and further bolstering industry efforts to reduce occupational radiation exposure.

The dramatic positive impact of the TMI accident and its aftermath on nuclear power plant radiation protection is illustrated in Figure 1.

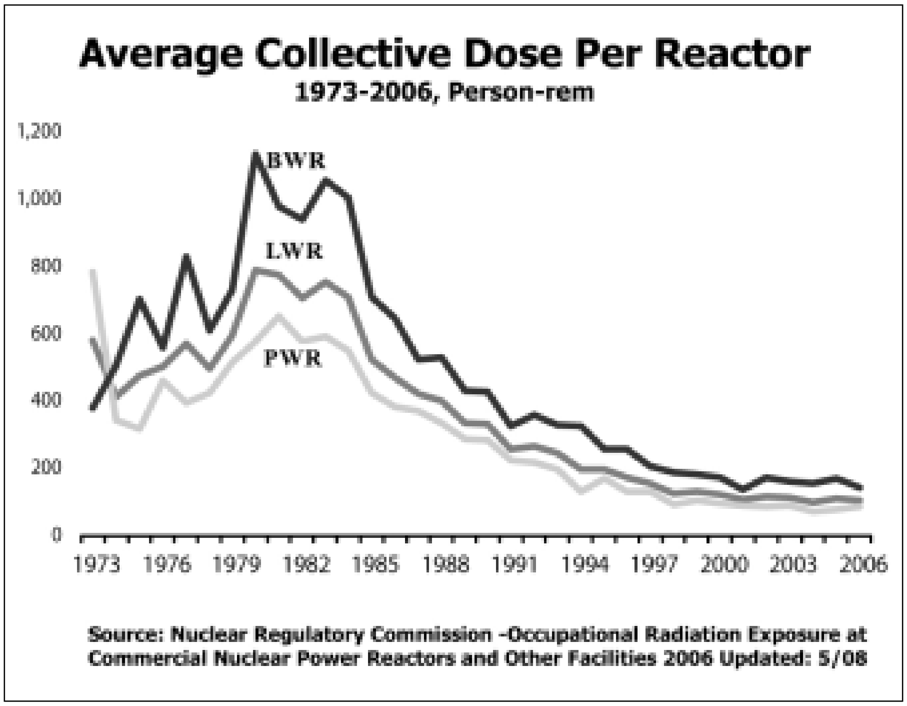

Figure 1

Post-TMI

In the post-TMI era, licensing of nuclear power plants became much more complex, controversial, and uncertain. The addition of major plant modifications and new programs and procedures, as well as constantly changing requirements, endless contentions in licensing, and frequent delays in regulatory decision making helped skyrocket the costs of constructing and licensing into the billions of dollars per plant. As a result, some companies slowed or delayed construction of partially built plants, while others cancelled their plants altogether. Nevertheless, the licensing process for most plants continued, albeit at a snail's pace.

The last nuclear power plant to go into operation was Watts Bar Unit 1 in Tennessee, which was issued an operating license on 7 February 1996. Recently, the Tennessee Valley Authority reinitiated the licensing process for the nearly completed Watts Bar Unit 2 reactor and is considering resumption of construction on two units at the Bellafonte site in Alabama.

License Renewal

In March 2000, the NRC began to approve 20-year renewals of nuclear power plants' 40-year operating licenses. This allows those plants that have compiled detailed applications and undergone rigorous review to operate for a total of 60 years. Since then, the NRC has approved license renewals for 49 nuclear reactors. To date, the owners of 99 of the 104 operating nuclear units have decided to pursue license renewal, and more are expected to follow suit (see Status of Plants synopsis below). The net effect of license renewals is expected to extend the average operating lifetime of the current reactors until about 2040, followed by a decade of decommissioning. This would mean that two more generations of health physics staff and other nuclear workers will be needed to support the existing nuclear power plants—i.e., even without building new plants.

Power Uprates

Nuclear power plants are licensed by the NRC to operate at a set maximum power level for which the safety of the plant has been demonstrated by analysis provided in the license application. Utilities may apply to the NRC for a license amendment to operate at an increased power level if they can show that the plant can operate safely at the higher level. Such changes are called power uprates, which may be accomplished by more precise analysis or by actual modifications to the plant with corresponding power uprates of one to 20 percent.

Since the 1970s the NRC has granted more than 120 power uprates for a total of 5,640 megawatts, which is roughly equivalent to building five new nuclear power plants.

Status of Existing Plants and New Plant Applications in the United States

Existing Plants

- 104 currently operating units (20 percent of the nation's electricity)
- 99 reactors for which the decision has been made to pursue license renewal
- 49 reactors already approved for license renewal
- More expected to follow suit

New Plants—COL Applications Submitted

- 26 reactors
- 17 applications (number of sites)
- 13 to be colocated at existing sites
- 4 to be at new sites

Decommissioning

At the end of its operating life, a nuclear power plant's reactor is shut down for the final time and the plant enters into decommissioning. The decision to permanently shut down can be the result of reaching the end of the operating period allowed by the license, or the plant may be shut down earlier for economic or other reasons. Following the final shutdown of the reactor, the licensee must offload all of the fuel from the reactor and certify to the NRC that the fuel has been removed. At that point, the licensee is no longer authorized to reload the fuel or restart the reactor.

Nuclear power plant licensees have three options for decommissioning a plant prior to seeking termination of the license. The licensee can proceed directly to DECON, in which all of the radioactive components and materials are decontaminated and/or removed for disposal. Once decontamination or removal for disposal has been completed, the licensee enters into a license termination process with the NRC, in which the licensee must demonstrate that radiation doses to members of the public resulting from any residual radioactivity at the facility will be less than 25 mrem per year and ALARA. Once a license is terminated, then the facility can be released for unrestricted use. (There are other regulatory criteria for restricted-use options, but these options have not been used to date at nuclear power plants.)

This would mean that two more generations of health physics staff and other nuclear workers will be needed to support the existing nuclear power plants—i.e., even without building new plants.

A second option is for the licensee to place the facility in protective storage, SAFSTOR, for up to 60 years, which allows much of the radioactivity to decay away prior to entering into DECON.

A third option, ENTOMB, involves encasing radioactive structures, systems, and components in a long-lived matrix, such as concrete, for an extended period of time with the intention of allowing the remaining radioactivity to decay to levels that are suitable for termination of the license with little or no additional decontamination. The ENTOMB option has been retained in regulation, but has not been implemented in either detailed regulatory guidance or in practice.

Under the present NRC regulations for decommissioning, 10 nuclear power reactors have been successfully decommissioned and their licenses have been terminated. Fourteen reactor units are currently in SAFSTOR or are undergoing active decommissioning.

Current Status

Today, 104 nuclear power power plants are providing about 20 percent of the nation's electricity. Plant performance is being sustained at a high level, with new records being set for electrical output and capacity factor, while production costs remain the lowest among sources of electrical generation in the United States. Indicators of nuclear safety performance show a continuously improving positive trend and collective and individual radiation doses to workers are at an all-time low.

Among other factors, consolidation of ownership and operating responsibility into large generating companies has been a major contributor to the current high levels of plant performance. These companies have the organizational depth, financial resources, and economy of scale to achieve significant improvements to performance. The number of nuclear generating companies overall has been reduced by about half since 1999.

New challenges continue to arise and be met, such as the replacement and refurbishment of aging components, comprehensive programs for inspection, testing and mitigation of metallurgical issues, and significantly enhanced and refocused security plans for responding to potential threats in the post-9/11 era. Other issues are being managed effectively, but are still in search of lasting solutions, such as used nuclear fuel management, volatility in uranium prices, and low-level radioactive waste disposal.

In sum, the age of nuclear power that began with several small and diverse reactors more than 40 years ago has reached full maturity. Nuclear power is now fulfilling much of its long-sought promise for safe, reliable, and economic energy produced in a manner that is protective of the environment. Although new challenges arise and are being met, the stage has been set for the next chapter—new plants.

Outlook for New Plants

Several factors have converged to foster a new interest in expanding the use of nuclear energy in the United States. The demand for electricity continues to increase. The costs and supplies of other fuel sources continue to be uncertain. Concerns about clean air and climate change continue to grow. And the deterioration of the economy has given focus to new programs to revitalize the nation's infrastructure and create lasting well-paying jobs. In the energy sector, nuclear power cuts across all of these factors in a big way.

New Plant Licensing Process

In response to the Energy Policy Act of 1992, the NRC created an improved one-step licensing process for new plants that includes issuing combined construction and operating licenses (COLs), as illustrated in Figure 2. Most importantly, the new process places the regulatory reviews, resolution of issues, and ultimate approval at the front end—prior to the outlay of significant expenditures. Thereby, the process minimizes regulatory risk, while still providing proper review and ample opportunity for public involvement.

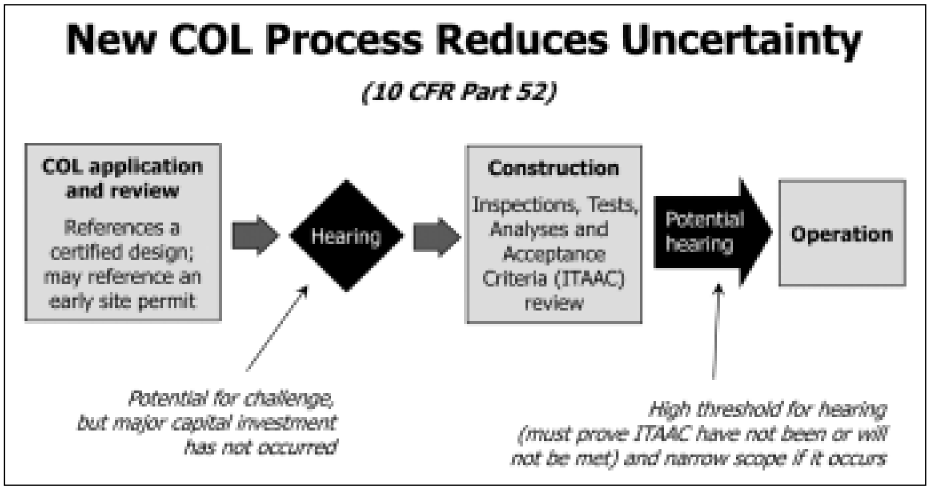

Figure 2

New Reactor Designs

Five new reactor designs either have been certified or are currently under regulatory review (see B in the Reactor Designs synopsis on page 4). The new designs reflect evolutionary enhancements to the existing reactors, e.g., by reducing the overall number of pumps, valves, and other components; employing passive safety features that rely on natural processes (e.g., gravity); and including enhanced safety and protection features (e.g., additional redundancy and bunkered safety systems). The reactor designs include the GE advanced BWR (ABWR), the Westinghouse advanced PWR (AP-1000), the GE-Hitachi economic simplified BWR (ESBWR), the AREVA European pressurized reactor (EPR), and the Mitsubishi US-advanced PWR (US-APWR). The units are large—ranging from 1,150 to 1,700 MWe (megawatt-electrical).

New Nuclear Power Plants

From 2007 to the present, 17 COL applications for 26 new reactors have been submitted to the NRC. Thirteen of the new plants would be colocated at existing reactor sites and four would be at new sites. Figure 3 shows the locations and types for all of the new reactors being considered, including some for which applications have not yet been submitted.

Initial construction of new plants is expected to start in 2010, with the first plants expected to start up in 2016-2017. Only a few plants are expected to comprise the first wave of new plants, with more to follow when the new process is proven to be successful, not only from the current batch of applications for the evolutionary BWRs and PWRs, but eventually to include the emerging advanced reactor designs, known as Generation IV.

But that's another story.

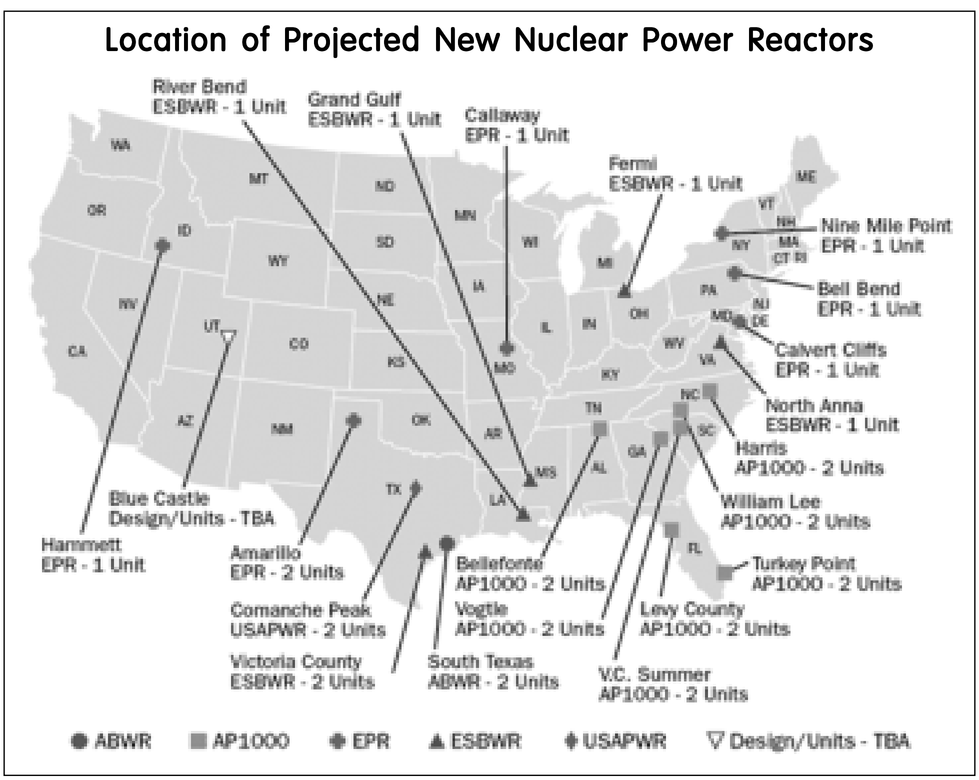

Figure 3

Acknowledgement: The author wishes to acknowledge the wealth of useful information on the Web sites of the NRC (www.nrc.gov) and Nuclear Energy Institute (www.nei.org) that helped shape and inform this article.

The Resurgence of Nuclear Power

Impact on the Health Physics Profession

Ralph Andersen, CHP
Health Physics News *Associate Editor*

This is the sixth in a series of articles in *Health Physics News* that provides an overview of nuclear power so that the effect of a resurgence of this energy source on the profession of health physics can be anticipated. The first five installments (*Health Physics News* July, September, and November 2008 and January and March 2009) presented an overview of nuclear power generation, the uranium recovery industry, the uranium conversion and isotopic enrichment processes, the fuel fabrication process, and the first in the two-part story on the history, status, and outlook for nuclear power in the United States. This second part on the outlook for nuclear power focuses on how radiation safety is fully integrated across all aspects of nuclear power plant design, licensing, construction, startup, operation, refueling and maintenance outages, monitoring, emergency preparedness, and decommissioning and license termination.

Radiation Safety at Nuclear Power Plants

"It Takes a Village …"

So goes the African proverb that provided the title and inspiration for Secretary of State Hillary Clinton's book that reflects the "commonsense conclusion that, like it or not, we live in an interdependent world." In the introduction to her book, Clinton notes that the phrase has caught on in a number of other contexts such as "it takes a village to have a parade," "... to build a zero waste community," and "... to raise a pig."

With due deference to African tribal wisdom and Clinton, it seems fitting to adopt as a theme for this article that it also takes a village to achieve radiation safety at a nuclear power plant.

Clearly, a core group in this endeavor includes the plant radiation protection managers (RPMs), health physicists, radiological engineers, and radiation protection (RP) technicians who are intensely focused on radiation safety. But the "village" also includes civil, mechanical, electrical, chemical, and nuclear engineers; reactor and power plant operators; mechanical, electrical, and instrument and control staff; chemists and chemistry technicians; security officers; welders; pipe fitters; boilermakers; electricians; nondestructive examination and in-service inspection specialists; radiographers; scaffolders; insulators; painters; carpenters; and more.

Beyond the boundaries of the plant site, the corporate/fleet RP staff, along with their counterparts at the Electric Power Research Institute (research and development), Nuclear Energy Institute (policy and planning), Institute of Nuclear Power Operations (performance evaluation and assistance), and American Nuclear Insurers (risk management), form an essential part of the village. Last, but certainly not least, the village includes the headquarters and regional health physics staff of the Nuclear Regulatory Commission (NRC), who independently verify through oversight and inspection that workers, the public, and the environment are being protected.

The village model is especially apt because of the way in which radiation safety has evolved at nuclear power plants over the past 50 years. The dramatic progress in controlling and reducing radiation exposures has been the product of effective sharing of experience and lessons learned throughout the entire village, gained not only from successful innovations, but also from the school of hard knocks. This tribal knowledge is compiled and handed down through successive generations at an individual plant, within a company, and across the industry. It is also carried firsthand by the vitally important skilled craft workers and RP technicians who travel from plant to plant to support refueling outages and plant modification projects.

In summary, it's a big village—one that extends from coast to coast and includes hundreds of thousands of professionals, spanning generations over the past 50 years and another 50 or more into the future. This village collectively contributes to the continuing success in radiation safety at nuclear power plants by each member doing his or her job right every day in a common endeavor to generate electricity safely, reliably, and economically.

The most enduring insight of our nuclear village is that "efficient generation of electricity and effective radiation safety go hand in hand." This critical relationship is well demonstrated in Figure 1.

Preoperational Radiation Safety

In many ways, the radiological destiny of a plant is determined years before the first nuclear fuel bundles arrive at the site, the reactor goes critical, and the plant generates electricity.

During the preoperational phases of design, licensing, and construction, thousands of small and large decisions are made by a myriad of staff at the nuclear steam supply system vendor, the architect-engineering firm, the NRC, the construction company, and the operating utility that will define the sources, modes, and means of control of radiation exposure to workers and the public.

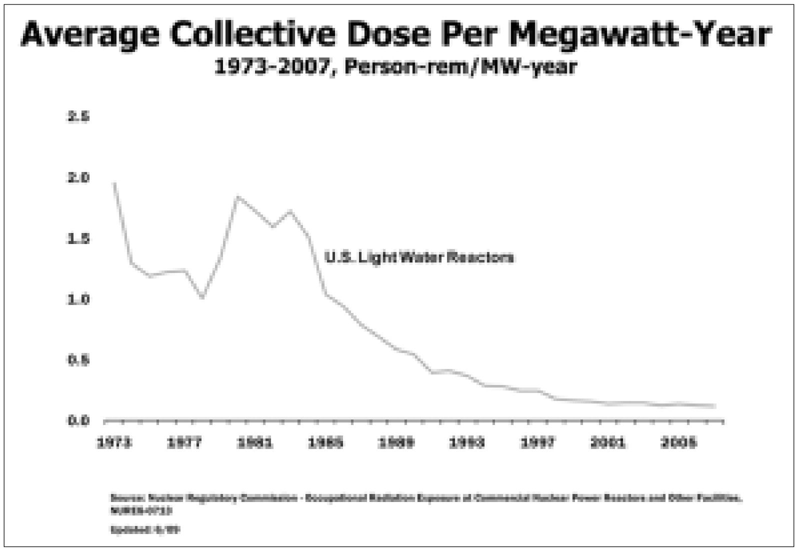

Figure 1

Although many of these decisions are not directly related to radiation protection or health physics, their cumulative impact on the radiation safety challenges and opportunities that will be presented during the lifetime of the plant is profound.

Design

As the saying goes, "an ounce of prevention is worth a pound of cure." This is certainly the case in regard to the effect that the design of a nuclear power plant has on preventing accidents, reducing the potential for unplanned radiological releases, minimizing radiation dose, and facilitating decommissioning.

The underlying philosophy in a nuclear safety design is "defense-in-depth." Overlapping and redundant safety systems and protection capabilities provide assurance that the likelihood of a reactor accident that would result in off-site consequences is vanishingly small. Highly trained and qualified operations and maintenance staff continuously monitor and test those systems and capabilities to verify their availability and effectiveness. Overlying this preventative and protective framework is a comprehensive emergency-response program, in which plant personnel relentlessly drill and practice to be able to respond 24-7 to every conceivable event, including participation in full-scale exercises with off-site medical, fire, police, and other emergency-response organizations, agencies, and officials.

The plant is designed to withstand the effects of natural phenomena, such as earthquakes, hurricanes, tornados, floods, and tsunamis, as well as to provide protection for other events, such as the loss of off-site power (e.g., electrical blackouts), fires, and terrorist attacks. Independent and physically separated protection and control systems assure that the reactor can be safely shut down and cooled. Multiple fission barriers to prevent uncontrolled releases of radioactivity include the fuel cladding, the reactor vessel, the reactor coolant pressure boundary, and a thick, steel and concrete containment designed to be essentially leak tight under all postulated accident conditions.

Nuclear power plants are designed to control and minimize radiological releases to the environment. Extensive waste-processing systems are installed to provide for storage and holdup (for radioactive decay) and filtration of gaseous and liquid effluents such that the radiation dose from releases during routine operations, including anticipated transient conditions, will be ALARA (as low as reasonably achievable). The reactor containment, in conjunction with emergency spray-down and filtration systems, is designed to delay and reduce releases from postulated accidents to allow time for the taking of on-site and off-site protective actions (e.g., sheltering, evacuation, or administration of potassium iodide) and to minimize potential radiation dose.

Plant design plays a key role in maintaining occupational radiation dose ALARA. Radiological engineers and health physicists provide significant input and support, but success in this area hinges largely on assuring that the design and system engineers and specialists are trained and knowledgeable on the design concepts and station features that will ultimately reduce worker exposures. Examples of such concepts and features include providing means for controlling access to expected radiation areas; effective use of permanent shielding (as well as facilitating use of temporary shielding); proper selection of materials in systems and components (e.g., to minimize activation products from erosion, corrosion, and wear); laying out and designing plant systems and components in a way that minimizes the need to access or spend time in radiation areas for operation, maintenance, or testing; providing an extensive and adaptable plant radiation-monitoring system; and designing ventilation systems and contamination-control features to minimize the potential for airborne contaminants and gaseous radiation sources.

The plant design is also required to facilitate eventual decommissioning by minimizing the potential for contamination of the facility and the environment and the generation of radioactive waste. Key design objectives in meeting this requirement include features that (1) prevent and contain leaks or spills, (2) provide for prompt detection of leakage or contamination, and (3) facilitate decontamination and remediation. In addition, the plant is designed to facilitate dismantlement or removal of structures, equipment, or components that will require replacement or removal during facility operation or decommissioning.

Licensing

There are two major elements in licensing a nuclear power plant: a design certification (DC) and a construction and operating license (COL). Some applicants have opted to separately resolve site-related issues through the early site permit (ESP) process, rather than through the COL process. Each part of the process also requires an environmental impact statement (EIS).

The overall objective of the combined process is to conclude with "reasonable assurance" that a nuclear power plant of a specific design at a specific site will be constructed, operated, and decommissioned safely, that the health and safety of workers and the public will be protected, and that there will not be a significant impact on the environment.

In this process, the applicant has the burden of proof to provide all of the necessary information. The NRC staff is responsible for independently reviewing, verifying, and assessing the applicant's information, as well as information provided by others, to decide whether a reasonable assurance conclusion can be reached. At key points in each process, the NRC notifies all stakeholders (including the public) as to how and when they may participate.

A DC is approved by the NRC through a rulemaking, in which a nuclear power plant design is approved independent of a specific operating company or site. The applicant must provide technical information to show that the plant design meets all of the applicable regulatory standards, including the nuclear and radiation safety criteria described in the previous section. In addition, the application must describe in detail how key design features will be verified during construction—known as inspection, test, analysis, and acceptance criteria (ITAAC). Radiation safety ITAAC topics include shielding, ventilation, and radiation-monitoring systems.

A COL is issued by the NRC to authorize a specific licensee to construct and operate a specific-design nuclear power plant at a specific site. In a COL application, the NRC staff reviews the applicant's qualifications, design safety, environmental impacts, operational programs, site safety, and verification of construction with ITAAC. In the area of health physics, the emphasis is on source term and radiological releases during routine operations and postulated accidents, emergency preparedness, and operational programs related to radiation safety. To facilitate licensing, the nuclear industry has developed standard operational programs for radiation protection, ALARA, radiological effluent and environmental monitoring, solid radioactive waste processing, and life-cycle planning for minimization of contamination and radioactive waste generation.

Companies may opt to seek approval for a specific site for a nuclear power plant, independent of a specific design, through an ESP. In reviewing an ESP application, the NRC staff reviews site safety issues, environmental protection issues, and plans for coping with emergencies. To date, three ESPs have been issued and one is under review. Most companies are seeking approval of their respective sites through the COL process.

Applicants for a DC, COL, or ESP are required to submit an environmental report that describes and evaluates potential environmental impacts of site preparation, construction, and plant operation and decommissioning and dismantlement. Health physics aspects include the source term, radioactive waste-processing and radiation-monitoring systems, the radiological impact from routine operation and postulated accidents, and the radiological effluent and environmental monitoring programs, including a preoperational environmental monitoring program. For each regulatory process (DC, COL, and ESP), the NRC issues a corresponding EIS when the agency has determined that there will be no significant impact on the quality of the environment.

The COL review process is estimated to take about four years. With the issuance of a COL, a licensee is authorized to begin construction and eventually operate a specific-design nuclear power plant at a specific site for 40 years—and potentially extend the operating period for an additional 20 years.

Construction

Companies can be authorized to begin some preliminary site-preparation activities prior to receipt of the COL, but the full construction project commences with issuance of the license. Although considered to still be within the preoperational phase, the four-year construction period marks the transition period when staff is being hired, trained, and qualified; operational program procedures are being written and tested; and equipment and instrumentation is being purchased, installed, and made ready for use. This is especially the case for radiation safety.

As part of the construction process itself, the ITAAC must be completed to verify that the plant is being built and will operate as designed—including the radiation safety-related ITAAC for shielding, ventilation, radiation monitoring systems, etc. From day one of being assigned to the new plant organization, RP personnel involve themselves in numerous design and construction details to make sure that future operations and maintenance work can be performed in a manner that is ALARA, that physical control over access to radiation areas can be effectively implemented, and that the layout of radiation-protection facilities will be efficient. Also, the construction project has its own need for radiation safety to address sources that are used during site preparation and construction activities, such as soil density testing and pipe weld radiography.

There are also elements of the operational program that are required to be implemented during construction and prior to startup of the new plant. A preoperational radiological environmental monitoring program must be implemented at least two years prior to plant startup to establish baseline measurements. To address groundwater protection, a site conceptual model for monitoring subsurface groundwater flow must be developed, along with a detailed description of the final postconstruction site configuration, including underground piping and structures.

The operational radiation safety program is implemented in phases during construction, with major milestones at the point of ordering and receiving test and calibration sources under the COL, as well as the initial receipt of nuclear fuel.

Light water reactors use uranium fuel in the form of ceramic-like pellets contained in zircaloy-cladded tubular rods housed in a fuel assembly (see *Health Physics News* January 2009). When new fuel is received at the site, it is inspected, surveyed, and placed into storage until it is loaded into the reactor. New fuel poses a minor source of direct gamma exposure and may have minute amounts of uranium contamination on the outside surface of the fuel rods remaining from the manufacturing process (referred to as "tramp" uranium).

If the new plant is being constructed at a site with an operating nuclear power plant, then dose to the construction workforce from radiological effluents and direct radiation from the neighboring plant needs to be monitored. Also, soil excavation may need to be monitored if there is a potential for residual contamination from operation of the neighboring plant.

When construction is complete and verified and all conditions of the COL have been met, transition from preoperational to operational occurs with the loading of nuclear fuel into the reactor. At that time, the radiation-protection program must be fully implemented, including a complete complement of trained and qualified radiation-protection staff and fully operational radiation-protection facilities, instrumentation, and equipment.

Operational Radiation Safety

Radiation Protection Organization

The overall responsibility for maintaining safe operation of a nuclear power plant, including radiation safety, rests with the plant manager. The plant manager is the one who balances priorities, approves goals and objectives, and allocates resources, and therefore it is the plant manager who assures the essential support of the RPM by the entire plant organization to implement an effective radiation safety program. Typically, a plant manager establishes and chairs a plant ALARA committee, including the RPM and other department managers, to provide effective cooperation and coordination across the site organization to set and meet challenging ALARA goals and objectives. Experience has shown that to be truly successful, the program must be owned by everyone and not just enforced by the RP organization.

Radiation workers get dressed out for work in the plant.

The RPM and the 20 to 40 health physicists, specialists, and technicians who make up a plant's RP organization provide the leadership, technical expertise, and often the conscience to help the plant organization maintain a high level of vigilance in dealing with the daily challenges of working in a radiological environment and respect for the need to comply with all of the RP procedures and good practices that prevent unplanned exposures, contamination, or releases of radioactive material.

The RP organization carries out a number of specialized functions, including personnel dosimetry, bioassay, respiratory protection, instrument calibration and maintenance, and radioactive source control. Control and monitoring of radiological effluents, environmental monitoring, and processing, packaging, and shipping of radioactive waste may be carried by the RP staff or be a shared or supported responsibility of the plant chemistry and operations organizations.

The "face" of the RP organization (if not the heart and soul) as seen by the rest of the plant workforce is the highly trained, qualified, and experienced RP technician who conducts radiological surveys and assessments, participates in work planning, establishes radiation-protection requirements, and provides oversight and monitoring for jobs involving radiation exposure. A unique and vital responsibility that is borne by each RP technician is to stop work or order an area evacuated when, in his or her judgment, the radiological conditions warrant such an action (when such action does not compromise nuclear safety). This calls for a special set of capabilities and qualities that are rare—even within our health physics community that is founded on high standards of professionalism and ethics.

Radiological Monitoring System Control Room at the San Onofre Nuclear Generating Station

Reactor-Related Radiation Sources

When nuclear fuel is loaded into the reactor and undergoes fission, it produces significant quantities of fission products, including noble gases (krypton and xenon), radioiodines, cesium, strontium, tritium, and actinides (uranium, plutonium, neptunium, americium, and curium). Materials in the fuel cladding and assembly itself become neutron-activated, including zirconium, niobium, cobalt, and other metals.

When the fissionable material in nuclear fuel is expended to a level where it is no longer efficient for use, the fuel is removed from the reactor and stored underwater in a spent-fuel pool to allow radioactive decay of shorter-lived fission products and cooling off (thermally). After five or more years, the used fuel may be moved from the spent-fuel pool to dry storage in shielded canisters within an on-site interim spent-fuel storage installation (ISFSI).

During reactor operation, the fission products and actinides are largely contained within the fuel rods, although small amounts may be released into the reactor coolant water through pinhole-size leaks in the cladding material, as well as from the fission of tramp uranium on the external surfaces of the fuel rods. In addition, erosion and corrosion processes introduce small amounts of activated materials into the reactor coolant water from the fuel cladding and assemblies, as well as from other reactor internal components.

Several radionuclides are produced by neutron interactions with the reactor coolant water when it passes through the reactor. Tritium is produced as a result of neutron reactions with boron that is added to the cooling water at pressurized water reactors (PWRs) for reactivity control and lithium added at boiling water reactors (BWRs) for chemistry pH control. ^{14}C is produced by neutron interactions with oxygen and nitrogen in the water.

Neutron reactions with oxygen in the water produce ^{16}N, which emits a high-energy gamma ray (>6 MeV). Despite its very short half-life, ^{16}N that is carried from the reactor into the steam supply system and turbine is the primary source of direct radiation exposure in the environs around a BWR due to skyshine. Therefore, BWR plant turbine buildings are designed with concrete shielding to maintain radiation levels at the site or restricted area boundary within the dose-rate limits set by the NRC.

^{16}N is a primary source of external exposure, along with neutron radiation, within a PWR reactor containment or a BWR dry well when the reactor is in power operation. Although it is not routine, plant personnel do occasionally enter the containment or dry well while the reactor is operating to perform a required surveillance or inspect or repair a component. ^{16}N is also a significant source of radiation exposure in areas of the plant where piping that transports steam to the turbine is located.

A dominant source of radioactivity in a nuclear power plant comes from the neutron activation of metal particles that result from erosion, corrosion, and mechanical wear processes in the piping, pumps, and valves in the various circulating water systems in the plant, when the particles pass through the reactor while it is critical. Primary activation materials include radioisotopes of cobalt, nickel, chromium, manganese, zinc, and iron.

Over time, the activated materials, along with trace amounts of fission products and actinides, are circulated through the plant reactor coolant system and, at BWRs, through the steam supply system, where they plate out on piping surfaces or in pumps, valves, or other components and become a primary source of direct gamma exposure and create a potential source of surface contamination or airborne radioactivity when plant systems and components are opened for inspection, testing, and maintenance during outages.

Reactor Startup

Reactor startup includes loading nuclear fuel in the reactor, reaching initial criticality, and then increasing reactor power through successive stages during which extensive testing is conducted of the reactor system, safety systems, the steam supply and electrical generation system, and auxiliary systems. The start-up testing phase lasts for four to six months, culminating in connecting the plant to the electrical grid and commencing commercial operation.

During the start-up phase, the RP staff is focused on understanding the baseline radiological conditions in the plant and adjusting operational aspects of the RP program to fit the routine work processes of the plant organization. A major effort during this phase includes conducting extensive surveys throughout the plant at each power level to verify shielding effectiveness and put measures in place to monitor and control access to radiation areas.

There are also many opportunities to instill good radiological work practices during operator rounds and surveillances and when systems or components are opened up for inspection, testing, or maintenance. An essential element of planning and executing these work activities is the establishment of shared expectations between the RP staff and plant workers—i.e., team building to achieve a common goal of radiation safety.

Reactor Operation

Reactors are operated for 18- to 24-month periods—limited by the time during which the nuclear fuel can efficiently be used to produce power without the need for rearranging the fuel within the reactor core or replacing used fuel with new fuel. Primary work activities that occur in the plant during reactor operation include operator rounds; routine inspection, testing, and calibration of equipment; and some preventative maintenance on systems and components that can safely be taken out of service. Also, RP technicians perform continuous monitoring and surveys to confirm that radiological conditions haven't changed and radiation areas are properly posted and controlled.

Plant personnel do not routinely access areas with significant levels of radiation or contamination, and consequently, radiation doses during reactor operation are low. The total collective radiation exposure for a plant during the 18- to 24-month operating period is typically less than 10 person-rem (0.1 person-Sv).

Occasionally, a problem may arise with an essential component or safety-related equipment that requires personnel to enter the reactor containment while the reactor is operating or areas of the plant where steam is circulating through the piping and higher radiation levels (e.g., related to neutron radiation or ^{16}N) may be encountered. In such cases, the entry into the area and potential work to be performed is carefully planned and executed to minimize the number of people and time spent in the area. If necessary, the reactor power may be reduced or the plant may be shut down for a brief period to allow for the work to be done with reduced radiation exposure.

A major effort that occurs during power operation is getting ready for the next refueling outage. The relative calm during plant operation allows for all of the necessary resources to be brought to bear on developing an outage plan and schedule, staging and arranging for all the necessary people and materials, and carrying out a detailed review of each job to incorporate lessons learned from previous outages and plan new innovations to make sure that worker exposures will be ALARA.

Refueling and Maintenance Outages

The oft-repeated principle for a successful refueling outage is to "plan the work and work the plan." The substantial investment of time and resources during the 18 to 24 months of operation pays off during careful execution of a precisely planned 4- to 12-week outage (the duration is dependent on the scope of necessary maintenance or special projects, such as modifications to implement an approved power uprate). This is especially true of ALARA planning that is carried out at a task-by-task level.

In advance of the outage, additional RP technicians (typically 40-80) are brought in to supplement the plant RP staff. They are trained and qualified on specific procedures and equipment used in the plant and are integrated into the RP team for the outage. As an added value, these technicians often bring recent experience and lessons learned from other outages that may be incorporated into the current outage plan.

Many of the RP staff are focused on engaging with the incoming workforce of 500-1,000 people to acquire dose records, issue dosimetry, perform whole-body counts, conduct radiation-worker and respiratory-protection training, as well as joining up with the various work teams to finalize ALARA plans and radiation work permits, conduct prejob briefings, and get to know their teammates.

As the shutdown of the reactor approaches, final staging and preparations are completed for installation of temporary shielding and portable ventilation enclosures, decontamination equipment and supplies, supplied-air lines and respirator units, temporary access and work control points, remote communications and monitoring equipment, etc. All members of the RP team review and rereview what they need to do and where and when they need to do it following shutdown.

For a plant outage, the operators and RP technicians are the first in and the last out. As soon as the reactor is safely shut down and secured, the RP technicians enter areas to be accessed during the outage, conduct radiation surveys, set posting and access controls, and trigger plans for temporary shielding, decontamination, enclosures, etc., that need to be in place for the outage work to begin—which is a major campaign that needs to be accomplished in a very short time. For example, many tons of temporary lead shielding are typically installed during an outage.

An outage typically is divided into three parallel efforts: refueling; testing, inspection, and maintenance; and special projects. RP resources are usually aligned to support each of these efforts, assigning staff to the refueling floor, to areas of the plant for coverage of inspection, testing, and maintenance, and as integral members of the teams performing special projects. An RP management team oversees and coordinates RP support between the various activities and interfaces with the outage management team. The outage is conducted around the clock and more often than not is completed within the schedule, budget, and radiation-dose goals set for the outage.

As outage work and refueling comes to completion, the first days' activities are repeated, except in reverse—all the shielding, equipment, and materials must be removed and accounted for, postjob briefings are held to capture lessons learned for the next outage, and the outage workforce is outprocessed (e.g., performing exit whole-body counts and dosimeter processing and completing dose records).

Once the plant is restarted and operating, planning begins for the next refueling outage.

Radiological Effluents and Environmental Monitoring

As a routine part of nuclear power plant operation, gaseous and liquid effluents are released to the environment—at levels that are well below the radiation safety standards set by the NRC and the Environmental Protection Agency. In fact, nuclear power plants are required to maintain effluent releases to the environment at levels that are ALARA, which equates to doses that are estimated to be on the order of 0.01 mSv y^{-1} or less to a hypothetical maximally exposed individual at the site boundary.

Lake-water sampling at the Comanche Peak Nuclear Power Plant

Prior to being released, the effluents are processed through waste treatment systems that provide for holdup and decay of shorter-lived radionuclides and filtering out of most of the radioiodines and particulates in charcoal, ion-exchange resins, and mechanical filter cartridges. The primary radionuclides that are ultimately released from a plant include noble gases and tritium (as HTO vapor) in gaseous effluents and tritium in liquid effluents. Trace quantities of radioiodines and particulate radionuclides may also be present.

Radiological effluents are continuously monitored and are periodically sampled to make sure that radiation monitors are properly calibrated for monitoring the respective mixture of radionuclides in the effluents. Radiation monitors also include set points that actuate an alarm to alert plant operators to take action prior to any release criteria being exceeded.

Each plant maintains an offsite dose calculation manual (ODCM) that contains specific criteria for monitoring and sampling radiological effluents and a detailed methodology for estimating off-site radiation doses. Doses are calculated for each release (or continuous release pathway) and are projected to ensure that all monthly, quarterly, and annual release criteria will be met. Every year, each plant prepares and submits a public annual radioactive effluent release report to the NRC that includes the quantities of principal radionuclides released in gaseous and liquid effluents, calculated radiation doses to the public, and supporting information needed to validate the calculations.

Plants also conduct a separate radiological environmental monitoring program (REMP) that begins prior to operation of the plant and continues throughout its operating lifetime. The objective of the program is to determine if any measurable levels of radiation or radioactive materials in the environment are attributable to operation of the plant and if the levels are consistent with what has been released from the plant. A typical program includes nearly 1,000 sampling results a year of direct radiation, air, surface and underground water, sediments, vegetation, milk, fish, and any other media that is representative of dose pathways for humans.

The REMP also includes an annual land-use census that consists of surveys of areas around the plant to see if there have been any changes to agricultural land use, residences, water use, dairy farms, or other activities that might affect the methodology for calculating doses to the public (i.e., in the ODCM).

Every year, each plant prepares and submits a public annual radiological environmental operating report to the

NRC that includes all of the results of the environmental sampling program and the land-use census.

Emergency Preparedness

Emergency response plans are required by federal law and regulations to be implemented at each nuclear power plant. The plans involve not only the company operating the plant, but also local, state, and federal officials and emergency-response organizations, law enforcement and fire departments, and local hospitals. Emergency-response plans remain in effect during the operating lifetime of the plant and through decommissioning until termination of the license.

Vermont Yankee personnel conduct a medical drill with the local ambulance service.

Nuclear power plant emergency-response plans utilize two emergency planning zones (EPZ) in their development. A 10-mile radius EPZ is used to plan immediate protective actions for the surrounding population, including sheltering, evacuation, and the distribution and administration of potassium iodide. A 50-mile radius is used to plan actions to protect the public from exposure to radioactive material from consumption of food, milk, and water should an event occur.

The plans are tested every two years in a full-scale, integrated exercise that is based upon a confidential scenario that is not known in advance to the participants. Extensive training and numerous drills and tests are conducted between the biennial exercises to assure that everyone is qualified and ready to respond to an event. After each of the drills and exercises, the auditors and participants participate in formal critiques that are used to identify and incorporate improvements and corrective actions.

Members of the RP staff maintain many of the plant's emergency-response capabilities, including plant radiation and effluent monitoring systems, dose-assessment programs, and equipment for protecting plant personnel during emergencies. They also fulfill key functions in the emergency-response organization, such as monitoring radiological conditions in the plant and off-site, projecting doses to the public and recommending protective actions, and providing direct radiation-protection support for a wide range of emergency-response activities.

It has been estimated that during a working career at a plant, a health physicist or technician participates in well over 100 emergency exercises and drills.

Decommissioning and License Termination

In many ways, radiation safety is more challenging during the deconstruction of a nuclear power plant than during its construction and operation.

Systems and components that serve to contain sources of radiation exposure during operation are disassembled, segmented, and packaged for shipment to a disposal site. Structures that provide shielding and physical control of access to radiation areas are dismantled or demolished. Also, many tasks are sufficiently unique as to require detailed planning from the ground up, rather than being routine evolutions for which each repetition provides an opportunity to apply lessons learned and implement increasingly effective radiological controls.

These factors lead to a greater potential for higher levels of radiation, contamination, and airborne radioactivity associated with decommissioning, as well as an increased probability of encountering novel or unexpected situations.

Concrete core sampling at Connecticut Yankee decommissioning

For these reasons, operational RP programs need to be adjusted for decommissioning, especially in regard to detection and monitoring of alpha contamination, internal dose monitoring and assessment, containment and ventilation controls, and training of workers and RP staff.

In addition to the deconstruction aspect, decommissioning presents differences from operation in terms of the much larger scale of shipping radioactive waste and conducting radiation surveys.

The volume of radioactive waste shipped during a decommissioning is orders of magnitude higher than that at an operating plant. The total volume can range up to several million cubic feet of radioactive waste during a five- to seven-year period. Although the vast majority of this waste is very low level, there are challenging shipments such as reactor vessels, steam generators, and segmented reactor vessel internals. Even when this work is not directly managed by the RP department, the

RP staff needs to provide extensive support for the packaging and surveys of these shipments.

Decommissioning also involves several unique radiation survey projects, including a historical site assessment, site characterization, and a final status survey. The historical site assessment includes an exhaustive review of site records and interviews with current and previous site staff to identify potential locations of residual radioactivity and an assessment of how residual radioactivity may have migrated to other locations. It also identifies situations that will require special surveys, such as subsurface radioactivity, sewer and storm drain systems, ventilation ducts, and embedded piping. The results of the historical site assessment serve as input to designing the characterization survey.

The site characterization survey typically follows completion of dismantlement and decontamination activities, in which the majority of radioactive waste has been shipped for disposal. The survey determines the type and extent of residual radioactivity at the site and forms the basis for a license termination plan to remediate the site and conduct a final status survey.

The final status survey demonstrates that any remaining residual radioactivity meets the criteria for terminating the license and releasing the site for unrestricted use (note that nuclear power plants to date have not pursued restricted-use options). The survey is comprehensive and includes total surface activity, removable surface activity, direct exposure rates, and concentrations in soil, water, and other media.

In conjunction with or following license termination, additional actions may be taken to bring the site to a greenfield status by remediating nonradiological contaminants, removing structures and equipment, landscaping, etc.

At present, decommissioned sites still have an ISFSI to provide safe and secure storage of used nuclear fuel until a disposal or other disposition option is made available.

This remaining step in the fuel cycle will be the topic of a future (and final) article in this series.

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The Resurgence of Nuclear Power

Impact on the Health Physics Profession

Ralph Andersen, CHP
Health Physics News *Associate Editor*

This is the seventh and final installment in a series of articles in *Health Physics News* that provides an overview of nuclear power so that the effect of a resurgence of this energy source on the profession of health physics can be anticipated. The previous six articles (*Health Physics News* July, September, and November 2008 and January, March, and September 2009) have presented an overview of the different elements of nuclear power generation, including uranium recovery, uranium conversion and isotopic enrichment, fuel fabrication, and nuclear power plant design, construction, operation, and decommissioning. This final article in the series covers the so-called back end of the fuel cycle—the ultimate disposition path for irradiated nuclear fuel.

As you will read in this article, the path contains a number of options and no small amount of uncertainty about which options may be selected. As with our previous articles in this series, we are fortunate to have an author, Andrew Sowder, PhD, CHP, who is an expert on the subject matter. In light of the fluidity of our own national policy on used nuclear fuel management, *Health Physics News* Editor-in-Chief Gen Roessler and I encouraged Sowder to convey his own well-informed views on how the political and sociological challenges associated with the development of a national used nuclear fuel management policy may play out, in addition to providing us with an in-depth understanding of the underlying science and technology of this issue.

Used Nuclear Fuel Management: The Back End of the Fuel Cycle

Andrew Sowder, PhD, CHP

Introduction

The termination of the Yucca Mountain program moves the construction and operation of a high-level radioactive waste (HLW) repository in the United States into the future once more. This development reinforces a belief among some that there is no answer to the question of what to do with the nation's used fuel from its commercial nuclear power plants. The "no solution to the waste problem" refrain is often cited as a primary argument against continued use and expansion of nuclear as a source of carbon-free electricity. And while recent polling has indicated public support for nuclear energy has returned to levels not seen in decades, the subject of used nuclear fuel continues to figure heavily into the public's view of nuclear.[1]

From a technical perspective, the "no solution" refrain ignores the international scientific consensus developed over the past five decades that deep geologic disposal of used fuel and HLW in a suitable geologic formation can provide adequate protection of the environment and human health over sufficiently long time frames, i.e., thousands to hundreds of thousands of years.[2] To this end, most countries seriously pursuing a nuclear waste management strategy have chosen deep geologic disposal as the approach of choice for managing inventories of used nuclear fuel and/or residual high-level wastes arising from reprocessing. Efforts to site such facilities invariably present social, political, economic, and technical challenges and require slow, deliberate, and difficult decision-making processes. As inventories of used nuclear fuel have accumulated in many countries, dry storage is increasingly seen as a necessary intermediate step in the nuclear fuel cycle (Figure 1). Depending on your point of view, dry storage can be seen as a prudent step that will allow for the United States to make key decisions regarding the ultimate path for used fuel (as a waste or resource) or as an interim measure until a permanent geologic repository is operational.

Through the Nuclear Waste Policy Act (NWPA) of 1982, the U.S. Department of Energy (DOE) selected deep geologic disposal of used nuclear fuel and HLW in a mined repository as the technology of choice. The Act required electric utilities (and their customers) to pay 1/10 of a cent per kW-hr of nuclear power generated into a Nuclear Waste Fund to cover the cost of the repository program. Contributions to the Fund and interest now exceed $33 billion. For its part, the federal

[1] 2009 results of an industry tracking poll of nuclear plant neighbors. Bisconti Research, July 2009, http://www.nei.org/resourcesandstats/documentlibrary/newplants/reports/third-biennial-nuclear-power-plant-neighbor-public-opinion-tracking-survey.

[2] This international technical consensus has its roots in a 1957 report issued by the U.S. National Academy of Sciences titled "The Disposal of Radioactive Waste on Land." National Research Council, Publication 519, National Academies Press, Washington, DC; 1957.

government agreed to begin removing used nuclear fuel from commercial reactor sites beginning in 1998—a contractual timeline explicitly incorporated in a formal arrangement between the government and nuclear utilities known as the Standard Contract for disposal of commercial used fuel. The NWPA also called on DOE to develop plans for transportation and for interim storage of used nuclear fuel if needed, called for siting of a second repository, and set a waste inventory cap of 70,000 metric tons of heavy metal (MTHM) for the first repository until the second was operational (League of Women Voters 1993). In 1983, DOE selected nine candidate sites (comprising five distinct geohydrological environments in six states) with the intent of narrowing the field to five for further characterization and submitting three finalists for Presidential approval for full-scale characterization. The three finalists were sites at Hanford, Washington (basalt), Yucca Mountain, Nevada (tuff), and Deaf Smith County, Texas (bedded salt). Amendment to the law in 1987 narrowed the evaluation of appropriate host sites from three to one: Yucca Mountain, Nevada. Congress and the Bush Administration formally approved Yucca Mountain in 2002 as the first national repository site following DOE confirmation of the site suitability. DOE submitted a license application for construction of the repository to the U.S. Nuclear Regulatory Commission (USNRC) in June 2008. In early 2009, the new Obama Administration indicated that "nuclear waste storage at Yucca Mountain is not an option"[3] and accompanying policy shifts have effectively terminated the Yucca Mountain program, although the licensing process has continued. This major shift in U.S. waste policy has been accompanied by an Executive Branch proposal to establish a blue-ribbon commission that would reevaluate the options for managing the U.S. inventory of commercial used nuclear fuel.

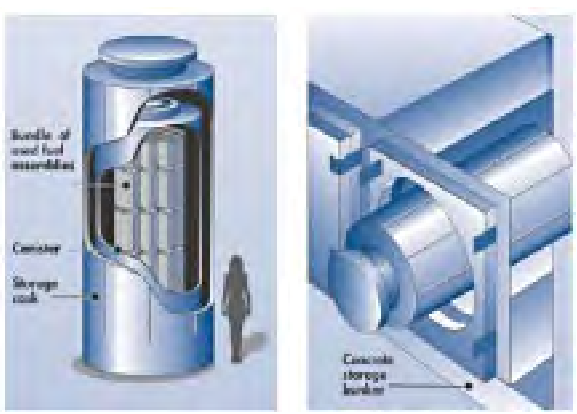

Figure 1. Dry storage of used fuel[4] (Source: USNRC)

Societal Issues

If there is a technical solution, what then is the problem? Simply put, social and political factors heavily impact siting decisions for a facility like a geologic repository. In the United States, two decades of site characterization and associated research have resulted in the description of Yucca Mountain as "the most studied real estate on the planet" (U.S. Senate Committee on Environment and Public Works 2006). Yet, the repository program faces termination before the license application has been fully reviewed largely due to political opposition from the state of Nevada, which has steadily grown in intensity since the narrowing from three candidate sites to one took place with the passage of the 1987 NWPA amendments.

Some of the key social and political obstacles and challenges presented by the siting and design of a geologic repository for disposal of used fuel and HLW are:

- Unprecedented regulatory compliance periods for geologic repositories (10,000 to 1,000,000 years) that far exceed the recorded history of humans on Earth and expectations of institutional control.
- Public distrust of government agencies and programs that have roots in secrecy, such as the nuclear weapons complex.
- Intragenerational, geographical, and procedural equity, i.e., the challenges presented when one geographic region, generation, or social group assumes a burden that it did not benefit from in relation to the costs or other impacts.
- National decisions on the value of used nuclear fuel as a resource versus a waste and reversibility of any siting and design decisions should policy change.
- Responsibility on generator of wastes for dealing with wastes (polluter pays principle) balanced against the ethics of restricting options for future generations, including the option to use the irradiated fuel as an energy resource.

These issues and more must be balanced and accounted for in a transparent selection process that

[3] 26 February 2009 release of administration's draft budget reveals severe cuts to Yucca Mountain program; DOE press secretary announces "nuclear waste storage at Yucca Mountain is not an option." 5 March 2009—Energy Secretary Steven Chu's remarks at Senate hearings confirm the "not an option" position and suggest "blue ribbon commission" formation.

[4] Used nuclear fuel is stored underwater in lined concrete basins to provide cooling and shielding immediately after it is removed from the reactor core. After sufficient time has passed to allow for decay of the shorter-lived radionuclides responsible for much of the initial heat load (on the order of five years for uranium oxide fuel), used fuel can be moved into dry storage with cooling provided by natural convection of ambient air and shielding provided by the engineered container system (typically concrete or steel).

dovetails with the technical elements of the repository program.

There are positive examples for the site-selection process of a geologic repository that have negotiated or appear likely to successfully negotiate the formidable challenges. The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is currently operational, accepting transuranic wastes from U.S. defense programs after being certified by the U.S. Environmental Protection Agency (EPA) under its authority in 40 CFR 194. More recently, voluntary participation of communities in Sweden (motivated in part by economic benefits and government incentives) in a competitive site-selection process resulted in the successful selection of a candidate-used fuel repository site at Forsmark. Approaches that focus on building genuine local and regional support among the public and politicians early in the process may offer the greatest promise for construction and operation of a deep geologic repository for used nuclear fuel or HLW in the early 21st century.

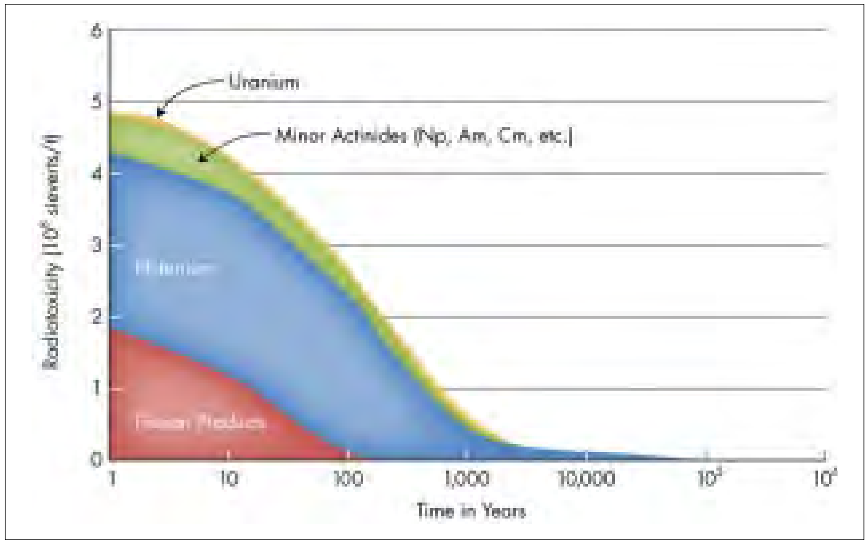

Figure 2. The radiotoxicity of used nuclear fuel decreases with time due to radioactive decay.

There Is a Solution for the Waste Problem

Why is there broad international scientific consensus that the solution for disposal of used nuclear fuel and/or HLW involves deep geological disposal in a suitable geologic formation/environment? Because many formations are known to have been stable for sufficiently long time frames and are likely to remain so. For example, the bedded salt formation in which the WIPP repository resides has been stable since its deposition with the evaporation of an ancient ocean during the Permian Age some 250 million years ago. The fact that the salt deposit exists is evidence that flowing groundwater, which would have dissolved the salt, has not been present over this geologic time frame and will likely not be present for the 250,000 years required for decay of the transuranic wastes (DOE 2003) (Figure 2).

What Is a Suitable Geologic Formation?

There is no simple or single answer to the question of what comprises an appropriate host site for a repository, as many different geological environments could prove suitable, as indicated by the diversity in candidate sites among international programs (Table 1) (IAEA 2003; NAS/NRC 2001). Moreover, the ultimate performance of a repository will be driven by both the intrinsic properties of the geology and environment and by the features of the engineered barrier system, which can augment, supplement, and complement those of the natural system (Figure 3). Therefore, it is important to evaluate a potential host site in light of an appropriately matched

Table 1. Candidate geology, hydrology, and host country for international high-level radioactive waste repository programs[5]

Geology	Hydrology	Countries
Crystalline rock (e.g., granite, gneiss)	Saturated	Sweden, Finland, Japan
Argillaceous rock (e.g., clay)	Saturated	France, Switzerland, Belgium
Salt	Isolated	United States (WIPP), Germany
Volcanic tuff	Unsaturated	United States (Yucca Mountain)

[5] Adapted from Table I, Technical Reports Series no. 413, Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes, International Atomic Energy Agency, Vienna, 2003.

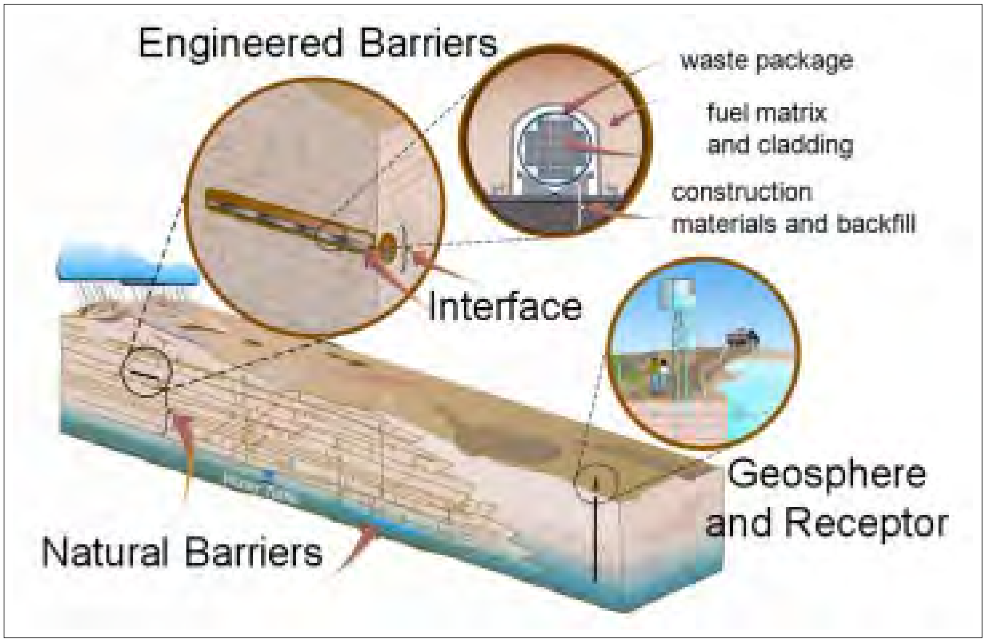

Figure 3. Long-term repository systems will rely on natural and engineered barriers to isolate, contain, and delay the release of radionuclides from used nuclear fuel and high-level waste. Repository system designs are necessarily site-specific, as engineered features need to be tailored to fit the geology, hydrology, seismicity, and other features of the candidate site.

(Adapted from DOE/OCRWM graphic)

repository design and components by focusing on site characteristics, engineering design, and wasteform properties; maintaining "defense in depth"; and keeping a prudent eye on the overall performance of the total system versus individual system components.

Seeking a Suitable or Adequate Site

The appropriate question to ask about a candidate location is whether it is suitable or adequate, not whether it is the best location. Requiring a site to be "the best" implies a level of knowledge that is unattainable without characterizing a large number of locations to a degree that is not feasible, affordable, or wise in terms of resource utilization (NAS/NRC 2001; OTA 1985).

Also, as pointed out in 1990 by the National Academy of Sciences (NAS) Board on Radioactive Management, "Surprises are inevitable in the course of investigating any proposed site, and things are bound to go wrong on a minor scale in the development of a repository" (NAS/NRC 1990). Thus the pursuit of a perfect site inevitably fails as detailed investigations can be expected to reveal some nonideal features or characteristics. The purpose of a repository is to provide adequate protection of human health and the environment by maintaining releases below some defined level, which is greater than zero. Accordingly, the repository concept necessarily allows for some releases to the environment.

All Nuclear Fuel-Cycle Options Will Require Some Form of Permanent Disposal

Another common argument is that fuel-cycle alternatives and advanced reactor technology can obviate the need for a permanent geologic repository. Quite simply, all nuclear fuel cycles and alternatives will require geologic disposal (or other form of permanent disposal) for some form of used fuel or high-level waste at some point in the future. Many recent arguments for pursuing advanced fuel cycles, recycling, and eventual closure of the fuel cycle have been heavily predicated on significant reduction of waste inventories and radiotoxicity. However, dynamic modeling of fuel-cycle strategies generally shows that waste-management benefits are modest and offer only a secondary, not primary, justification for the pursuit of more advanced fuel cycles. For example, Electric Power Research Institute (EPRI) modeling of a fuel cycle optimized for destruction of actinides through the use of fast reactors as burners (as opposed to breeders) indicates that while modest gains are achievable in the first 100 years of operation, truly substantial reductions in actinide inventories can require time frames on the order of 100s to 1,000s of years (Figure 4). This

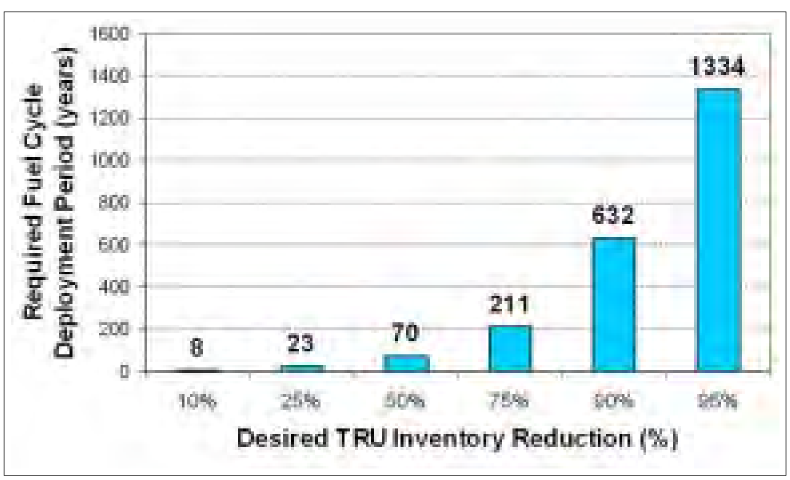

Figure 4. Dynamic modeling of the entire fuel cycle by EPRI indicates that substantial reductions in transuranic (TRU) nuclides require long time frames that can exceed centuries or millennia.

Table 2. Disposition options for high-level radioactive waste[6]

Approach	Description	Advantages and/or Disadvantages
Surface storage	Long-term storage provided by emplacement of waste into a suitable waste package, canister, cask, or vault system under dry conditions Currently practiced in the United States and other countries on a short-term/interim basis	Requires monitoring and maintenance over entire storage period
Geologic disposal (mined repository)	Emplacement of packaged waste into mined repository at large depths in a suitable geological formation and environment (i.e., 100s of meters below surface)	Reference permanent disposal concept
Deep borehole disposal	Emplacement of packaged solid waste in boreholes drilled deep into crust far below groundwater influence	Retrieval of waste may not be feasible (can also be considered a benefit) Most feasible for small volumes (e.g., small inventories or separated minor actinides)
Sub-seabed disposal	Emplacement of packaged solid waste in geologically stable deep-ocean sediments or in sub-seabed rock formations	Retrieval of waste may not be feasible (can also be considered a benefit) Likely to conflict with international policy and law
Deep well injection	Direct injection of liquid wastes into appropriate geological formation Used historically for injection of low-level wastes in the United States and for intermediate-level wastes in former Soviet Union	For liquid wastes only Phased out in favor of other geologic disposal methods
Partitioning and transmutation	Exposure of very long-lived radionuclides, e.g., plutonium and minor actinides, to neutron fluxes resulting in transmutation to shorter-lived radionuclides	Complete destruction of problematic wastes generally judged to be technically and/or practically unfeasible Some form of disposal will be required to isolate residues Long time frames required to achieve significant waste-reduction benefits
Extraterrestrial disposal	Physical removal of waste from the Earth through launch of waste form into space	Excessive risk due to probability of launch failure and number of launches required

challenge is due in part to the fact that new inventories of actinides continue to be generated even as actinides are destroyed and large inventories of actinides are maintained in operating reactors (EPRI 2008).

If Yucca Mountain Is Off the Table, What Is Plan B?

While permanent geologic disposal represents a fundamental component of the nuclear fuel cycle, it is just one element of used fuel and HLW management and is not technically required for the other elements of the back end to function (Table 2). Accordingly, the termination of the current repository program does not mean that utilities are suddenly without options. The back end of the fuel cycle is an integrated system consisting of on-site storage, potential centralized storage, advanced nuclear fuel options, and permanent disposal for final waste forms resulting from commercial nuclear power operation and recycling.

Used Fuel Can Be Safely Kept in Dry Storage for a Long Time

The challenge associated with managing used nuclear fuel is driven primarily by the large quantity of radioactivity contained in a relatively small volume, heat generation from decay of short-lived radionuclides, and the long-lived nature of the actinides and a handful of other nuclides. It is also important to recognize that some of these challenges are inextricably linked to important advantages and benefits of nuclear energy, particularly with respect to waste volumes and emissions.

Used fuel represents an extremely small volume/quantity relative to the energy produced and in comparison to other comparable generation technologies. For example, a model 1,000 MWe pressurized water reactor operating at an 80 percent availability factor requires on the order of 25 metric tons of

[6]Information in Table 2 adapted from NAS/NRC, 2001.

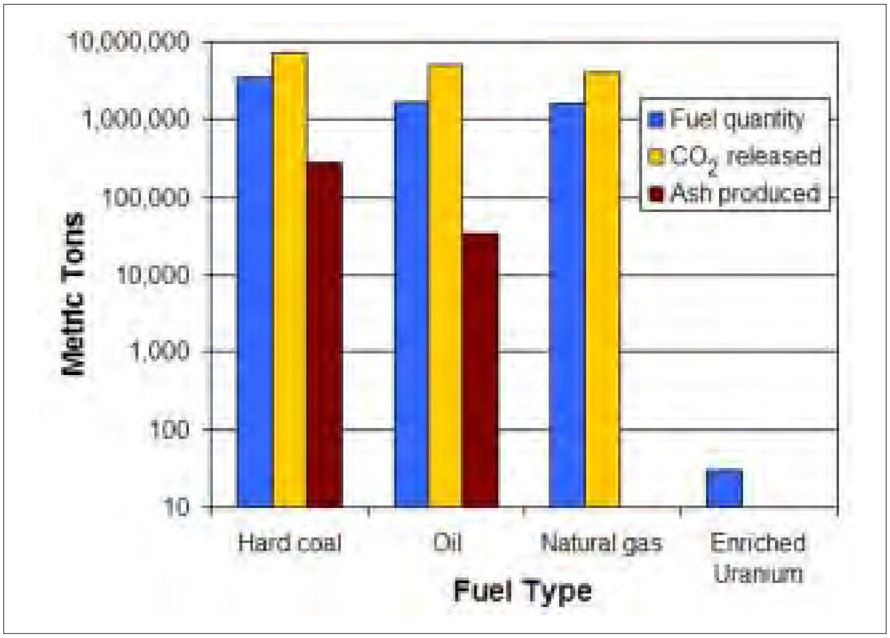

Figure 5. Quantities associated with generation of 7 TWh of electricity (1,000 MWe power plants operating at an 80 percent load factor)[7]

Currently deployed systems can be licensed under the present USNRC regulations up to 60 years, and work is underway to understand longer-term aging issues. Numerous statements from USNRC staff and the commission suggest that U.S. regulators have confidence in dry storage system lifetimes of 100 years or more (Klein 2009).

Metal and concrete structures built by humans are known to persist for millennia, as shown in Table 3. The Eiffel Tower, an iconic Parisian landmark, was constructed of iron using 19th century erection methods and technology. Yet the 120-year-old, 324-meter, 10,000-metric-ton attraction remains standing and in use with the help of a fresh coat of paint every seven years (Visit Guide: The Eiffel Tower Web site). It is worth noting that concrete and metal alloys employed in dry storage systems are designed with degradation/corrosion resistance in mind and that the field of material science has greatly enhanced the durability and corrosion resistance of concrete and metal alloys. With routine inspection and maintenance, robust engineered systems such as dry cask storage systems can be expected to remain operable over periods extending well beyond a century (EPRI 2003; Miller et al. 2006).

If necessary, any limitations on canister/cask system lifetimes and performance can be overcome through periodic repackaging. While feasible, repeated handling of the same fuel is not desirable because it will incur additional occupation exposures and will present substantial logistical challenges in situations where wet storage facilities are no longer available for conducting fuel transfers and inspections.

fresh uranium oxide fuel annually, whereas a comparable coal-fired power plant consumes three million metric tons of coal annually (or roughly 36,500 railcars) (OECD/NEA 2007). Essentially all byproducts of nuclear-generated electricity are contained in the relatively small volume of the original fuel. Figure 5 illustrates the high energy density and small quantities of byproducts for uranium oxide fuel versus fossil sources. Nuclear energy also has the benefit of internalizing many of the costs and impacts of energy production in terms of pollution and waste; for example, consumers of nuclear-generated electricity pay for the waste management of the fuel through the Nuclear Waste Fund fees, whereas the costs of pollution from other comparable baseload sources of electricity mostly remain external to electricity pricing.

In principle, there is no technical limit to dry storage during the period of institutional controls.

Table 3. Examples of archaeological structures and artifacts that indicate persistence of structural materials over millenia

Material	Analog	Estimated Date of Manufacture (years before present)
Cement	Roman structures	> 1,900
Copper	The Kronan cannon	> 400
Iron	Roman nails	> 1,900
	Iron pillar in Dehli, India	> 1,600

[7]Data from Table 1.1, OECD/NEA, 2007. Management of Recyclable Fissile and Fertile Materials. NEA No. 6107.

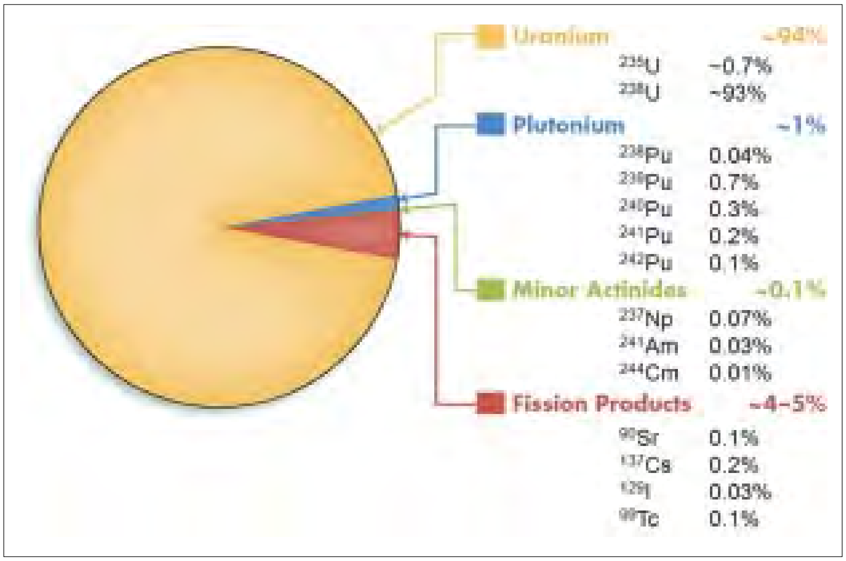

Figure 6. Representative composition of uranium oxide fuel (nominally 3 percent ^{235}U initial enrichment) following irradiation in a light water reactor for electricity generation

Used Fuel: Waste or Resource?

After low-enriched uranium oxide fuel is irradiated in a light water reactor (LWR) to a point where increasing neutron poison concentrations and decreasing fuel reactivity become limiting, the used or "spent" fuel is discharged and replaced by fresh fuel. However, as illustrated in Figure 6, very little of the total uranium resource is consumed in the reactor, and other actinides are produced that have potential value for recovery and use in nuclear fuels. The remaining ^{235}U persists at or near natural enrichment levels, ^{238}U continues to represent the bulk of fuel material (at ~93 percent), and fissile plutonium isotopes (^{239}Pu and ^{241}Pu) comprise almost 1 percent of the used fuel inventory by mass. The 4-5 percent fission product fraction represents the truly unusable portion—requiring disposal regardless of the fuel-cycle option selected. The remaining 95-96 percent of material in the used fuel could potentially be recovered. In short, used fuel can be considered a waste if the existing technology continues to dominate the fuel cycle, i.e., LWRs that can only make secondary and minimal use of the ^{238}U present.

However, used fuel could offer an untapped and very large energy resource if advanced commercial reactor technologies, such as fast reactors, are deployed on a sufficient scale to make full use of ^{238}U as a fertile source of fissile ^{239}Pu.

Ultimately, the necessary fuel-cycle decisions must be made at the national level. Major fuel-cycle facilities are large, complex, high-risk, and expensive projects not well suited for private investment. Fuel-cycle goals, attributes, and waste-disposal requirements ultimately touch on issues and policies that must be addressed at the national level, such as nonproliferation, energy, disposal, economic development, and national security.

With the apparent end to the Yucca Mountain program, the United States has surrendered an international leadership role in the nuclear waste management arena, as other countries with nuclear technology continue down the path blazed in large part by the United States (NWTRB 2009).

In any case, some form of permanent disposal of HLW will be required for all fuel-cycle options. The decision not to proceed with Yucca Mountain, therefore, cannot erase the fact that the United States will need to develop a permanent disposal route for its nuclear fuel cycle, and this route will likely be a deep geologic repository.

Conclusion

From a technical perspective, the question isn't, What *can* we do with the used nuclear fuel from commercial nuclear power generation? Technical answers to this question exist. Rather, the relevant question remains, What *will* we do with used nuclear fuel?

The key to answering this question lies not only in defining what is technically possible, but also in determining which option (or options) can receive sufficient public and political support to maintain viability over the multidecade time frame that any credible solution will take to implement. In a democratic society such as ours, this is primarily a question for elected and duly-appointed decision makers, although hopefully, the final answer will be well informed by science and engineering.

Editors' Note: We would like to express our utmost appreciation to the authors of this series for their patience, hard work, and dedication to high standards of excellence in producing their articles. We sincerely hope that we have achieved our mutual goal of conveying the challenges and opportunities arising in nuclear power health physics to our friends and colleagues across the Health Physics Society.

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