Progress in Nuclear Energy 51 (2009) 290–296

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Comparative population dose risks from nuclear fuel cycle closure and renewal of the commercial nuclear energy alternative in the U.S.

Charles W. Pennington*

110 Old Chartwell Drive, Alpharetta, GA 30022, USA

Keywords:
Nuclear renaissance
Population dose risks
Nuclear energy radiation exposure
United States population dose risks
Comparative radiation dose risks
Public attitudes on nuclear energy

A B S T R A C T

The debate over a large expansion of commercial nuclear energy for electricity production in the U.S., termed a "nuclear renaissance," has most recently focused on the issues of spent nuclear fuel transportation and the closing of the once-through nuclear fuel cycle through the licensing, construction, and operation of the national spent nuclear fuel repository at Yucca Mountain, Nevada. While such a commercial nuclear energy expansion is postulated to have environmental, climate, resource utilization, and economic benefits, the fundamental issue for typical U.S. citizens about nuclear energy concerns the potential for exposure to ionizing radiation. Two generations of U.S. citizens have experienced public and media "education" that has heightened their primal fears of ionizing radiation from commercial nuclear energy. In such an environment, comparing the risks of radiation doses from commercial nuclear energy fuel cycle closure and further nuclear energy expansion with ionizing radiation population doses experienced year after year, decade after decade from non-nuclear (conventional) industries seems worthwhile for use in achieving stakeholder education and concurrence. The U.S. National Academy of Sciences (NAS) has recently performed its own landmark risk assessment of spent fuel transport in the U.S., demonstrating the guiding principles and methods for use in comparative risk assessments involving radiation dose considerations. Using the NAS assessment approach, this paper broadens its application to the full consideration of the risk of nuclear fuel cycle closure and renewal of the commercial nuclear energy alternative in the U.S., to evaluate the ionizing radiation dose risks of such expansion compared to those routinely accepted for non-nuclear industries by policy makers and the public. The 50-year collective dose risk from the total commercial nuclear fuel cycle, even if the U.S. triples its installed nuclear capacity, transports spent fuel to Yucca Mountain, and operates the Yucca Mountain repository as planned, is shown to be in the range of 3.1-million person-cSv; for five selected non-nuclear industries, the corresponding 50-year collective dose risk exceeds 1 billion person-cSv, a more than 300 times greater risk. A key step towards renewing the commercial nuclear energy alternative, then, is to use this knowledge for education of various stakeholder parties.

1. Introduction

The prospect of a "nuclear renaissance" that greatly expands the use of commercial nuclear energy to produce electricity in the U.S. is a significant topic in the consideration of energy alternatives for the country over the next 50 years. Opposition to expanding the use of nuclear energy in the U.S. has focused on portraying nuclear spent fuel transportation and the operation of the prospective Yucca Mountain nuclear spent fuel repository as fraught with radiological risk to U.S. populations. Such opposition recognizes that spent fuel transportation and fuel cycle closure are vital to any expansion in commercial nuclear energy usage. Indeed, the transport of spent fuel to Yucca Mountain is a vital step in closing the "once-through" nuclear fuel cycle, in which nuclear fuel is used only once in reactors, then sent to a disposal facility, or repository. Such a process is not as fuel efficient as recycling of spent fuel, but it is the approach selected for closing the nuclear fuel cycle in the U.S. This approach has been agreed upon for many years by U.S. utilities, the U.S. Department of Energy (DOE), the U.S. National Academy of Sciences (NAS), and the Legislative and Executive branches of the U.S. government, and the process of developing a repository has now been underway for about 30 years. The Yucca Mountain repository represents the consensus approach for closing the nuclear fuel cycle in the U.S. Alternatives to Yucca Mountain may be acceptable for accomplishing fuel cycle closure in the U.S., including centralized interim long-term storage of spent nuclear fuel, but the key is that any alternative must incorporate legislative and industry support with federal take-title provisions, prompt licensing, a solid

* Tel.: +1 678 328 1229; fax: +1 678 328 1429/770 752 9941.
E-mail address: cwpenn@comcast.net

0149-1970/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pnucene.2008.09.002

plan for ultimate disposal, and implementation in the same time frame as Yucca Mountain to be considered suitable for, and supportive of, renewing the nuclear alternative for electricity generation.

For years, nuclear energy has been declaimed by opponents for generating wastes that have no disposal solution, another way of saying that the nuclear fuel cycle is not closed. Therefore, closure of the once-through nuclear fuel cycle is perhaps the most important step towards a nuclear renaissance and reinvigorating the use of commercial nuclear energy to generate electricity in the U.S. Over the next 30 years or so, the U.S. will need to build dozens of commercial nuclear electricity generating facilities to replace aging coal-and-gas-burning units, as well as older nuclear plants, to meet energy growth needs in environmentally responsible ways. Over the last 30 years, however, through the imposition of large risk premiums on potential borrowings for nuclear power plant construction, financial markets have shown hesitancy in supporting investment in a nuclear energy fuel cycle that is not closed (Tolley and Jones (2004)), as have public interest organizations that participate in rate hearings and new plant decision processes for generating utilities. As a result, the management, legal, and financial leadership at commercial U.S. electricity generating utilities views progress to closure of the nuclear fuel cycle as a most important step in minimizing corporate investment risk for purchasing new nuclear generation plants, as highlighted in Rowe (2008). This is also supported by Hagen et al. (2001) and in Meier et al. (2005), who show many years of U.S. utility management purchases of gas-fired generation capacity, rather than coal or nuclear capacity, because of its low investment and other risks. Thus, remaining on a path for near-term U.S. nuclear fuel cycle closure is important to renewed and extensive deployment of nuclear generating facilities in this country.

Now, nuclear critics are calling for the U.S. to abandon Yucca Mountain as a nuclear spent fuel repository, without a suitable, timely alternative. This would be a significant setback for the future of commercial nuclear energy in the U.S., and future additions of nuclear generating facilities would likely be limited to just a handful or so of plants, rather than the dozens necessary. The safety of spent fuel transportation is but one issue these critics raise, but spent fuel transport is the most important, the very supply line for fuel cycle closure. In military parlance, interdicting enemy supply lines is a vital step in stopping advance.

Therefore, if a renewal of commercial nuclear energy usage in the U.S. is of value, it is important to show that spent fuel transportation and fuel cycle closure, as well as any resulting expansion of nuclear energy usage, present almost negligible risks for the prospective benefits, when contrasted with the risks people ordinarily accept as part of their every day lives. For purposes of simplifying the assessment of these potential risks, the analysis herein assumes that Yucca Mountain remains as the consensus path for fuel cycle closure in the U.S.

2. Background on benefits of expanded nuclear energy usage

Spent fuel transportation is vital to the operation of the Yucca Mountain repository or to any suitable alternative for fuel cycle closure. Without spent fuel transportation, the closed-fuel-cycle cannot function. If fuel cycle closure cannot be accomplished, then future expansion of nuclear electricity generating plants will likely be very, very limited, and the U.S. will have to forego an environmentally responsible path towards meeting a large future growth in electricity demand. A currently used alternative to closing the fuel cycle is the dry storage of spent nuclear fuel at the reactors generating the spent fuel in facilities that are termed Independent Spent Fuel Storage Installations (ISFSI) by the regulations that govern such storage. An expansion of this approach would be to use dry storage of spent fuel in an ISFSI located at a centralized interim long-term storage site away from reactors, which would require spent fuel transport. Opponents of closing the fuel cycle favor the former at-reactor storage because it avoids the transport of spent fuel and leaves the question of closing the fuel cycle without an answer, as summarized in the Introduction, above. Therefore, spent fuel transportation is an integral component of a closed-fuel-cycle solution, which is necessary for renewing the commercial nuclear energy alternative and greatly expanding its use in the U.S.

A significant recommendation for spent fuel transport is that it is one of the safest technological undertakings in human history. A recent study reported in NAS (2006) confirms that there are no known instances of radiation exposures of workers or the public exceeding regulatory limits or of any releases of radioactivity from these transports that exceeded such limits during the 60 years of spent fuel transport of tens of thousands of spent fuel casks in Western Europe, Japan, or the U.S.

The benefits that safe transport of spent fuel, the concomitant closure of the once-through nuclear fuel cycle, and the expansion of nuclear energy usage will afford U.S. citizens are briefly stated below, with detailed assessments of the valuation of those benefits left to individual observers. However, what is clear is that these benefits show an extraordinary potential for both gain by American citizens and for improvement of the global human condition, in general.

- When compared to the combustion of fossil fuels to produce electricity, expanded nuclear generation will avoid the air pollution from millions of tons of sulfurous and nitrous compounds each year from these fossil fuels, offering much cleaner air. The U.S. Environmental Protection Agency (EPA) has produced periodic reports on the National Emissions Inventory (NEI) of criteria air pollutants since 1990, among these being sulfur and nitrogen oxides (SOX and NOX). USEPA (2006) summarizes the latest final report on the U.S. NEI. In USEIA (2007a), the U.S. DOE's Energy Information Agency (EIA) has used EPA's NEI information with the electrical generation statistics that EIA gathers to summarize emissions data from electric generating units. USEIA (2007a) also shows that coal and petroleum (the fossil fuels that produce SOX and NOX) generated 50.6% of U.S. electricity in 2006 and nuclear energy generated 19.4%. The total emissions of SOX and NOX from coal and petroleum used to generate electricity in 2006 were about 14.7 million short tons. From this data, it is clear that current nuclear generation at 19.4% of the total generation avoids about 5 million short tons of SOX and NOX emissions each year if nuclear generation were replaced by coal- or oil-fired generation. Similarly, if nuclear generation can increase as a fraction of total electrical generation, SOX and NOX emissions increases may be reduced or avoided altogether as electrical generation increases in the future.
- The life-cycle greenhouse gas emissions (mostly carbon dioxide (CO_2)) from nuclear-generated electricity are very small when compared to those from fossil fuel baseload alternatives (much less than 10% of fossil-fueled plant emissions) and occur mostly from fuel cycle front-end and back-end activities. A full survey of numerous recent studies demonstrating this fact is contained in Sovacool (2008). USEIA (2007a) shows that, if coal-generated electricity could have been reduced by half during 2006 using an alternative source that does not generate significant CO_2, such as nuclear-generated electricity, about 40% (or more than 900 million short tons) of the CO_2 produced by electricity generation could have been avoided. Going forward with a renewed nuclear alternative could produce similar or greater emission savings, as discussed in Hagen et al. (2001) and in Meier et al. (2005).

- With successful closure of the once-through nuclear fuel cycle, a broad expansion in the use of nuclear energy could allow utilities to reduce reliance on natural gas-fired electric plants. Hagen et al. (2001) discusses utility plans at the time to supply 90% of new electric generation by 2020 from natural gas-fired plants. Increasing nuclear generation can reduce greenhouse gas emissions from such a reliance on natural gas and cut demand for natural gas, making it possible for lower costs for home-owners that use natural gas from the decrease in demand. Meier et al. (2005) shows how a reduction in the use of natural gas may be accomplished by increasing the use of nuclear energy or other renewable resources while fully accounting for the life-cycle emissions impact.
- A broad expansion in nuclear electricity generation can make the development and use of electric vehicles viable and attractive. This could greatly reduce dependence on foreign oil, driving down global oil demand and prices, and increasing the availability of oil for the developing economies of the third world, all while greatly reducing emissions from the transportation sector. USEPA (2006) shows a potential for about a 35% reduction in total NOX emissions from the transportation sector resulting from the use of electric vehicles, while USEIA (2007b) shows a potential for about a 15% reduction in total CO_2 emissions. Such ethical treatment of third world economies and the reduction in transportation emissions can reduce environmental impacts and costs over the longer term.
- Expanded utilization of nuclear electricity and replacement of much of our petroleum-based transportation could enable us to also reduce the Persian Gulf supply source in the longer term, markedly improving our posture for national security and energy stability.
- Expansion of nuclear generation can serve as the platform for producing hydrogen or other portable fuels, a prospect that some postulate will be most attractive for the transportation systems of a more distant future, as discussed in USDOE (2004) and Eerkens (2006). Nuclear energy can produce the hydrogen or other portable fuels with minimal air pollution or CO_2 emissions, as discussed above. Fossil-fueled production plants cannot, and their emissions would sharply reduce the benefits of a new portable-fuel-based transportation system.

The benefits of spent fuel transport and fuel cycle closure, which can allow more environmentally appropriate energy production for the U.S., may be extremely large, as quantified in the previous discussions of nuclear energy's potential impact on pollutant emissions. These benefits, however, must be compared with the risks that may be inherent in the actions required to achieve them. Such risks are the primary subject of this paper and are addressed in the following sections.

3. Methods for risk assessment

The NAS has performed a landmark study of the safety of the transport of spent nuclear fuel and high-level waste in the U.S., which is reported in NAS (2006). For spent fuel transport and related nuclear energy considerations, the NAS report asserts that risk is composed of two major components: health and safety risks principally arising from exposures to radiation (the technology risk), and social risks. In general, social risk arises from both social processes and human perceptions, and is associated with direct social/economic impacts and with perception-based impacts. The NAS further says that social risks are very difficult to quantify and must ultimately be determined by public policy makers and their decisions. The NAS focused, therefore, on radiological health and safety considerations of technology risk, and established its guiding principles for the assessment of comparative risk involving radiological exposures such as could occur with spent fuel transport or other aspects of the nuclear fuel cycle. Its guiding principles are stated as follows:

- ○ compare risks associated with like physical causes, such as radiological exposures; and
- ○ compare risks associated with similar outcomes, such as potential health consequences from exposure to radiation.

Health and safety risk from the NAS study is the product of the probability of an event times the consequences of that event. In the situation of radiological exposures, the NAS asserts that the appropriate consequence consideration is the exposed population's collective radiation dose resulting from the scenario under investigation. As stated in the NAS report, "The mean collective dose risk is most useful as a comparative tool."

The following sections employ the NAS study approach with the same guiding principles and methods and apply them to a broader examination of risk. However, this examination greatly extends the NAS study coverage by considering the complete nuclear fuel cycle risk that would result if closure of the U.S. once-through fuel cycle were achieved and a resulting large expansion of commercial nuclear energy usage were accomplished in the U.S. The NAS report, in its presentation of information and assessment results, uses the approach of brief discussions of the nature of the evaluation followed by tabular presentations of specific assumptions, scenarios, outcomes (collective doses), and comments. This paper utilizes the same approach to presentation of information and assessment results as the NAS report, first for a revision of the risks of spent fuel transportation, then for the complete nuclear fuel cycle technology risks, assuming a large expansion of commercial nuclear energy for the production of electricity. A follow-on discussion is also provided on social risk and the role that technology risk assessment plays in considering the growing importance of social risks in a period of rapidly expanding nuclear generation.

3.1. Revisiting the risks of spent fuel transportation

For transport of spent fuel, collective dose is composed of two risk categories: risk from normal (incident-free) transport and transport accident risks. The NAS has made abundant use of the DOE's Final Environmental Impact Statement (FEIS), USDOE (2002), for the Yucca Mountain repository for the analyses and results detailed in its study. The assessment herein refines the NAS report's conclusions about spent fuel transportation risk with a focus on actual transport planning and expands the NAS study, using the same methods, with data from a more recent DOE environmental impact statement for Yucca Mountain, the Supplemental Environmental Impact Statement (SEIS), USDOE (2008). This paper offers a more up-to-date analysis of spent fuel transport risks than the NAS study could provide because more recent data is available from USDOE (2008). The use of USDOE (2008) makes for especially robust analyses. Because USDOE (2008) is such a key element of the contentious licensing process surrounding Yucca Mountain, it is one of the most thoroughly reviewed and "refereed" studies involving nuclear fuel cycle dose risks from spent fuel transportation and disposal that has been produced in the U.S. Indeed, the contents of USDOE (2008), as well as the contents of USDOE (2002), show how the DOE has reviewed and included or rebutted a number of significant comments from both advocates and critics to arrive at a well-supported presentation of conservative dose risks.

Table 1 presents the data and references for the radiological risk from normal (incident-free) transport of spent fuel by rail, the selected DOE transport method. (Note that the consideration of population doses from additional storage or required truck

Table 1
Radiological impacts and risks from normal (incident-free) rail transport of spent fuel to Yucca Mountain.

Scenario definitions	Rail transport collective dose	Comments and references
Operational period (years)	50	
Worker collective dose (person-cSv)	5600	Dose for 50 years, or about 24 per year; assumes maximum dose rates from cask, which do not occur in practice. USDOE (2008), Table 6-4.
Dose to maximally exposed worker (cSv)	25	Limit is 0.5 per year for 50 years to the same person (highly conservative). USDOE (2008), Table 6-5.
Maximum public collective dose (person-cSv)	1200	Total collective dose over 50 years, or about 24 per year. USDOE (2008), Table 6-4.
Dose to maximally exposed member of the public (cSv)	0.21	Assumes same person refueling 600 trucks over 50 years, or about 0.00042 per year. USDOE (2008), Table 6-5.
Total 50-year Risk (person-cSv)	6800	Sum of collective doses

shipments that may be considered is addressed by rounding up the total nuclear fuel cycle risk from Table 3.) The data from the DOE SEIS is most conservative and includes such assumptions as: every cask emits its maximum regulatory dose rate (shippers attempt to use about 80% of the regulatory limit to assure dose rate measurements at the destination by different people using different instruments at different cask positions do not exceed limits and violate regulations); the same person services casks for 50 years; and collective doses that include populations up to one-half mile away from the casks (dose rates at such distances are very small and, when applied to large urban populations, should not be used for projecting health effects, according to the recommendations of the International Commission on Radiation Protection in ICRP (2007)). The probability of all these scenarios is assumed to be 1.0, which is also very conservative.

The total collective dose is 6800 person-cSv over 50 years, or about 136 person-cSv per year. This is the Yucca Mountain incident-free spent fuel transport risk.

Table 2 presents the data and references for the radiological risk from spent fuel transportation accidents or sabotage that might result over 50 years of such transportation. Once again, this data from the DOE SEIS is very conservative and includes such additional assumptions as: bounding analysis results are used, whether for rail or truck transport; population densities for urban areas are used, rather than those for rural areas (which increases risk by 2–3 orders of magnitude); and periods of maximum population exposure are unrealistically long (e.g., no interdiction or cleanup for one year after the accident or sabotage event). Table 2 shows that the total risk of transportation accidents and sabotage events over 50 years is about 10 person-cSv.

3.2. Total fuel cycle risk from expanded use of commercial nuclear energy

As calculated with the conservative assumptions in Tables 1 and 2, the total risk for spent fuel transport to Yucca Mountain over 50 years is 6810 person-cSv. But with this transport risk, the population risk from the expanded use of nuclear energy in the U.S. that is made possible by spent fuel transport to a repository and closure of the fuel cycle must also be considered. For this evaluation, NAS (2006) provides key guidance. Utilizing the NAS (2006) study methods, Table 3 presents the data and references for the total commercial nuclear energy population risk over 50 years, assuming the U.S. triples its installed nuclear capacity, that spent fuel transport to Yucca Mountain occurs by rail, and that the Yucca Mountain repository starts up and operates as planned.

Table 3 provides a total 50-year risk of about 3.1-million person-cSv resulting from this tripling of U.S. nuclear generation over that 50 years. Note that the 3.1-million person-cSv has been rounded upward and that the rounding is also sufficient (highly conservative, based upon DOE (2008)) to cover uncertainties in time periods for spent fuel shipments by truck to a repository or long-term storage facility that may differ from current DOE planning. The 3.1-million person-cSv implies a total annual U.S. population dose of about 62,000 person-cSv (or about 0.0002 c-Sv per year for each person in the U.S.), and includes population dose from both normal nuclear fuel cycle operations (probability of 1.0) and the risk of nuclear plant accidents or terrorist events over the full 50 years.

Knowing the expected 50-year risk from the expanded use of commercial nuclear energy is all well and good. However, any statement of risk is worthless, even potentially harmful, if there is

Table 2
Radiological impacts and risks from accidents or sabotage associated with rail transport of spent fuel to Yucca Mountain.

Scenario definitions	Rail transport: event description or outcome	Comments and references
Operational period (years)	50	
Design basis accidents		
Conventional accident collective dose (person-cSv)	4.2	Sum of accident probabilities times doses over 50 years; probability of 4.2 is 1.0. USDOE (2008), Table 6-6.
Most severe beyond-design-basis accident		
Accident scenario	Long duration, high temperature fire engulfing cask that results in closure seal failure	USDOE (2008), G.7 and Table G-19.
Worst case collective dose (person-cSv)	16,000	USDOE (2008), Table 6-7.
Annual probability of accident (per year)	5.0×10^{-6}	USDOE (2008), Table G-19.
50-year beyond-design-basis accident risk (person-cSv)	4	Probability × dose × years
Sabotage event		
Event scenario	High energy density device penetrates cask	USDOE (2008) 6.3.4
Worst case collective dose (person-cSv)	47,000	Conservatively assumes urban area attack on *truck* cask; *rail* cask would be much lower. USDOE (2008), Table 6-8.
Annual probability of event (per year)	1.0×10^{-6}	Conservatively use 10 times maximum reasonably foreseeable accident cutoff probability. USDOE (2008) 6.3.3.2.
50-year sabotage event risk (person-cSv)	2	Probability × dose × years
Total 50-year accident and sabotage risk (person-cSv)	10	Design basis + beyond-design-basis + sabotage

Table 3
Radiological risk over fifty years from expanded use of commercial nuclear energy, including spent fuel transport and repository operation.

Event/scenario definitions	Value or description	Comments and references
Evaluation period (years)	50	
Average installed nuclear capacity (gigawatts electric or GWe)	200	Assumes 300 GWe installed after 50 years; average over 50 years is 200 GWe. Deutch et al. (2003)
Population collective dose from normal nuclear fuel cycle operations (person-cSv)	1,900,000	The 50-year collective dose. Pennington (2007)
Nuclear energy worker collective dose (person-cSv)	1,100,000	The 50-year collective dose. Pennington (2007)
Population and worker collective dose from spent fuel transport (person-cSv)	6810	Total from Tables 1 and 2
Population and worker collective dose from Yucca Mountain startup and operation (person-cSv)	13,000	Includes assumptions of handling accidents and releases to the environment. Pennington (2007)
Nuclear plant accident scenario	Chernobyl-type radionuclide release with 10% reactor containment failure	As discussed in Pennington (2007)
Assumed annual probability of nuclear plant accident (per plant per year)	5.0×10^{-6}	Marburger (2008) cites probability range of 1.0×10^{-6} to1.0×10^{-7}; use 5 times highest probability value
Population and worker collective dose per accident (person-cSv)	1,100,000	UNSCEAR (2000d) reported 50 year collective doses from Chernobyl; Pennington (2007)
Annual population and worker accident risk from 200 GWe installed nuclear capacity (person-cSv)	1100	Number of plants × annual probability per plant × collective dose per event
Population and worker 50-year accident risk (person-cSv)	55,000	Number of years × annual risk
Total 50-year risk from expanded use of commercial nuclear energy (person-cSv)	3,100,000	Sum of all collective dose risks over 50 years.

no relative context or comparison to similar risks. For social decision making, comparative technology risk is a most important consideration, especially if the comparison is to something (or things) whose risk is already approved and accepted by society and its policy makers. Such comparative risk information is available and has been developed and presented in earlier publications by Pennington (2006, 2007). This information is summarized below.

4. Comparative risks from non-nuclear industries

Numerous non-nuclear industries expose workers and the public to ionizing radiation greater than a natural background level. Such industries include agriculture, aviation, building design/construction, potable water supply, construction material supply, oil and gas production, coal mining, cigarette supply, natural gas usage, geothermal energy production, coal combustion, metal mining, and many others. These industries do not use or produce man-made radionuclides, but typically reconfigure, redistribute or disperse naturally occurring radioactive material (NORM), composed primarily of potassium (^{40}K) and isotopes from the uranium, thorium, and actinide primordial series found within the makeup of the earth's crust, the leftover "nuclear waste" from the formation of the universe. As shown in Pennington (2006, 2007), NORM is often more hazardous than man-made radionuclides, and we receive radiation from NORM continually, both internally and externally, throughout our lives. Technologically enhanced natural radiation (TENR) results from NORM or from people being in closer or less-shielded proximity to natural radiation due to human activity that has occurred for decades or eons. TENR may be reduced by controlling (e.g., regulating) such human activities.

Examples of human-caused radiation from non-nuclear industries are summarized in the following paragraphs about five such industries. These five industries have been selected because almost every person in the U.S. interacts daily with, and is affected by, at least several of them. The radiological impact of these industries has been previously analyzed and detailed, with supporting references, in Pennington (2006), and a direct comparative assessment of population doses from these industries with those from commercial nuclear energy has been presented in Pennington (2007).

Aviation (flying) causes a reduction in the natural shielding against galactic cosmic radiation provided by the atmosphere's gases and particulate matter, meaning that there is more cosmic radiation available to interact with human bodies. People that fly in commercial, private, corporate, or military aircraft experience an increase in their exposure to ionizing radiation from outer space. Bailey (2000), UNSCEAR (2000a,c), discuss earlier work and dose assessments resulting from this industry.

The industry that designs and constructs buildings for human occupancy is also responsible for the air quality within. Radon, or ^{222}Rn, and its four daughter products contained in soil become "trapped" in buildings after leaking into occupied spaces, becoming major contributors to human ionizing radiation exposure. Currently, indoor radon levels can be more than 50–100 times the natural outdoor levels, significantly increasing the ionizing radiation dose of U.S. populations. Mauro and Briggs (2005) present an assessment of, and dose results for, this industry that are consistent with those shown herein from Pennington (2007), which were fully developed in Pennington (2006).

The potable water supply industry delivers water to homes and businesses for drinking and cooking. Water originates from terrestrial sources and many radionuclides become dissolved or suspended in the water delivered to homes or businesses. When consumed, the ingested radionuclides deliver TENR to the occupants, thereby increasing radiation doses to people. NAS (1998) presents a detailed study of the distribution of radon in water supplied by this industry, and Pennington (2006) uses that study to assess the population dose impact of the broader range of nuclides found in the supply of potable water by this industry.

Construction materials, including stone, concrete, brick, tile, cinder block, or asphalt, are often filled with increased NORM concentrations as the result of human activities and can produce increased radiation exposure to people who live or work in or around buildings, roads, sidewalks, or other structures. Construction materials also result in elevated TENR exposure to people who work in relative proximity to shopping or business districts with an abundance of masonry buildings, paved streets, sidewalks, plazas, and parking lots. NCRP (1987) performed early modeling and dose calculations for this industry, and Pennington (2006) expanded the use of additional modeling from the literature for assessments that include external populations, as well as people occupying structures using such construction materials.

Outdoor agriculture increases the ionizing radiation exposure of both workers and people that live close to farms. Soil contains an abundance of NORM. Left untended, soil is compacted by settling and moisture, and can be covered with dense natural foliage, providing shielding of the radiation emitted by the soil's NORM. Farming keeps large sections of acreage bare of cover for part of the year and encourages low density growth of limited vegetation for the other part. Clearing, plowing, tending, weeding, watering, and harvesting result in exposure to TENR: by removing the shielding of the natural foliage otherwise covering the fields; by loosening and aerating the soil, which reduces its self shielding and increases the surface area of, and diffusion paths from, the soil for radon and thoron (^{220}Rn) radioactive gases; and by providing a large source of both radioactive wind-borne dust and radon and thoron gases. Storage, handling and application of fertilizers, which have even higher concentrations of some NORM radionuclides than soil, also contribute to TENR exposure. Finally, people associated with farming spend many hours in close proximity to these sources, increasing their exposure to both TENR and cosmic radiation. Detailed modeling from a number of references for this industry, together with dose results, were developed and reported in Pennington (2006).

Population and worker annual collective doses from the 5 non-nuclear industry examples above have been developed in earlier publications, Pennington (2006, 2007), and Table 4 provides a summary of each industry's annual collective exposure of U.S. populations in excess of the unavoidable and essentially irreducible natural background radiation in the U.S. These collective doses are also consistent with those reported in Mauro and Briggs (2005), and in UNSCEAR (2000a,b,c), but those in Pennington (2006, 2007) take more account of actual populations exposed, actual source terms from studies by organizations such as NAS and USEPA, and modeling of lognormal distributions of exposures. Note that the probability for each industry's collective dose risk is 1.0, since it is all actually occurring every year, decade after decade. Finally, the 50-year collective dose risk does not assume any increase in the U.S. population over the next 50 years, a very conservative approach that implies the total collective dose risk from these 5 industries alone is likely to be higher than is shown in Table 4.

While the results from Table 4 are likely very conservative, a comparison with the projected doses from the total U.S. commercial nuclear fuel cycle shows that these 5 industries alone present more than a 300 times greater 50-year collective dose risk than does the total U.S. commercial nuclear fuel cycle. The U.S. commercial nuclear fuel cycle assessment is based on the assumptions that the U.S. triples its installed nuclear capacity, that spent fuel transport to Yucca Mountain occurs, and that the Yucca Mountain repository starts up and operates as planned, all with the further assumption that nuclear accidents have some reasonable probability of occurring. Yet, even with such a large population dose risk from these 5 non-nuclear industries (especially in comparison to a renewed U.S. commercial nuclear fuel cycle), no federal or state authority has proposed regulating the radiological aspects of any of these non-nuclear industries, let alone shutting them down because of some radiological threat to the public or workers.

As an added comparison of interest, the collective dose risk presented by the Building Design/Construction industry in just one small state (Nevada, population of about 2.2 million people) can be determined using that state's own published study of radon concentrations in houses throughout the state, Rigby et al. (1994), and a similar study reported in USEPA (1993). Using that data and the methods from Pennington (2006), the annual and 50-year collective dose risk from the Building Design/Construction industry in Nevada is presented in Table 5, again assuming no growth in state population over the next 50 years. The collective dose shown in Table 5 is in very close agreement with that from Mauro and Briggs (2005) for Nevada.

Table 5 shows that one non-nuclear industry in the state of Nevada presents more than a 45% higher 50-year collective dose risk than an expanded commercial nuclear fuel cycle in the U.S. over the same period. The state of Nevada has never proposed regulating the radiological aspects of the Building Design/ Construction industry in the state, let alone shutting it down due to a radiological threat.

5. Social risk considerations

The NAS provided a substantial discussion of social risk in NAS (2006). As stated, social risk arises from both social processes and human perceptions, and is generally associated with direct social/ economic impacts and with perception-based impacts. Social risk resulting from social processes, such as the taking of property or the over-burdening of community resources and infrastructure, cannot be addressed by comparative technology risk assessment and is not considered herein.

Social risk resulting from human perceptions may be defined as the potential effect on local communities and populations that could result from a generally held perception. Social risk arising from human perceptions, therefore, is a display or manifestation of the collective fears of the concerned society, perhaps taking the form of a social condition or response to a popularly held perception. Responses that are typically of concern would be stimulated by a heightened population anxiety level and could result in lower property values, reduced economic activities, and generalized or specific community actions directed at the perceived cause of the anxiety. Addressing communities' concerns that are driven by perceptions of nuclear technology risk is one of the significant uses of the information herein.

NAS (2006) asserts that social risk decisions are the purview of policy makers. In comparison to non-nuclear industries, spent fuel transport, fuel cycle closure, and a significant commercial nuclear energy expansion should be judged as very desirable from a technology risk perspective, since benefits are likely large, comparative risk is small, and the risk comparison to industries already approved and accepted by policy makers shows much greater radiological risks from industries already found acceptable. However, after two generations of active and organized nuclear opposition, some policy makers have learned to fear a perceived radiological threat from commercial nuclear energy, and they remain less than enthused about renewing the commercial nuclear energy alternative. Since policy makers also tend to serve as amplifiers or dampeners of the collective community perception of prospective events, policy makers must become a key element of the public education process.

When social decision makers' actions are internally inconsistent, the public is poorly served and great opportunities can be lost.

Table 4
Radiological risk over fifty years from five non-nuclear industries.

Industry	Annual collective dose risk to population and workers (person-cSv)	50-year collective dose risk to population and workers (person-cSv)
Aviation	>460,000	>23,000,000
Building design/construction	>14,900,000	>745,000,000
Potable water supply	>1,500,000	>75,000,000
Agriculture	>1,300,000	>65,000,000
Construction materials	>2,000,000	>100,000,000
Total collective dose risk	>20,000,000	>1,000,000,000

Table 5
Radiological risk over fifty years from the building design/construction industry in Nevada.

Nevada industry	Annual collective dose risk to population and workers (person-cSv)	50-year collective dose risk to population and workers (person-cSv)
Building design/construction	>90,000	>4,500,000

The challenge posed by this situation, then, is how to provide objectivity to policy makers. This challenge may be resolved only through broadly based public education programs that focus on both benefits and risks. As discussed herein, the public is both well-served and safe with the prospects of spent fuel transportation, fuel cycle closure, and a substantial expansion in the U.S. of commercial nuclear energy. Policy makers must be brought into the spent fuel transport and fuel cycle closure education process early. This may help dampen anxieties within the local communities in order to restore a balanced view of spent fuel transport, fuel cycle closure, and the expanded use of commercial nuclear energy in society.

6. Conclusions

Spent fuel transportation and the closure of the nuclear fuel cycle are vital to assuring that the expanded use of commercial nuclear energy in the U.S. results in more than just a handful of new plants. Major advances in environmentally appropriate electricity production from commercial nuclear energy in the U.S., enhanced national energy security, ethical U.S. energy policies for developing nations, and contributions to an improved national economy suggest a renewal of the commercial nuclear energy option in the U.S. is appropriate. The benefits of such a renewal are potentially large, and the risks are demonstrably very small. Indeed, the risk of spent fuel transport and commercial nuclear energy expansion hinges on hypothetical conditions and resultant population doses that are of extremely low probability, but non-nuclear industries have caused very large actual population doses for decades and will continue to do so for many more decades with a probability of 1.0. One central conclusion is that population collective dose risks of just a few non-nuclear industries are hundreds of times greater than those of a fully robust commercial nuclear energy expansion over the next 50 years, and these non-nuclear industry risks are commonly accepted by society every day. Society's policy makers have judged each of these non-nuclear industries as having a very small technology risk. Indeed, the radiological risk from each is judged so small that essentially no regulation of their radiological characteristics exists today.

This paper has demonstrated that the public is well-served from a safety perspective with the prospects of spent fuel transportation, fuel cycle closure, and a substantial expansion in the U.S. of commercial nuclear energy. The challenge, then, is to assure that policy makers and the public have this knowledge to act and react in their own best rational self-interest during considerations affecting the renewal of the commercial nuclear energy alternative in the U.S.

References

Bailey, S., January 2000. Air crew radiation exposure – an overview. Nuclear News, American Nuclear Society, 32–40.

Deutch, J., Moniz, E.J., Ansolabehere, S., Driscoll, M., Gray, P.E., Holdren, J.P., Joskow, P.L., Lester, R.K., Todreas, N.E., 2003. The Future of Nuclear Power – an Interdisciplinary Study. Massachusetts Institute of Technology (MIT), Cambridge, MA.

Eerkens, J.W., 2006. The Nuclear Imperative: a Critical Look at the Approaching Energy Crisis. Springer, Dordrecht, NY, ISBN 978-1-4020-4930-9.

Hagen, R.E., Moens, J.R., Nikodem, Z.D., 2001. Impact of U.S. Nuclear Generation on Greenhouse Gas Emissions. U.S. Energy Information Administration, Presentation of Study Prepared for the International Atomic Energy Agency (IAEA), November, 2001, Vienna, Austria.

International Commission on Radiological Protection (ICRP), 2007. Publication 104: Scope of Radiological Protection Control Measures. Annals of the ICRP 37 No. 5. Elsevier Science, Stockholm, Sweden.

Marburger, J.H., 2008. Director, Office of Science and Technology Policy, Executive Office of the President, January 22, 2008, Decision Memorandum: Decision on Delegation of Section 127(f) of the Public Health Security and Bioterrorism Preparedness and Response Act of 2002, Washington, DC.

Mauro, J., Briggs, N.M., 2005. Assessment of Variations in Radiation Exposure in the United States. S. Cohen and Associates, prepared under contact number EP-D-05–002 for the U.S. Environmental Protection Agency (USEPA), July 15, 2005, Washington, DC.

Meier, P.J., Wilson, P.P.H., Kulcinski, G.L., Denholm, P.L., 2005. US electric industry response to carbon constraint: a life-cycle assessment of supply alternatives. Energy Policy 33 (9), 1099–1118.

National Academy of Sciences (NAS), National Research Council, 2006. Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States. National Academies Press, Washington, DC.

National Academy of Sciences (NAS), National Research Council, Committee on Risk Assessment of Exposure to Radon in Drinking Water, 1998. Risk Assessment of Radon in Drinking Water. National Academies Press, Washington, DC.

National Council on Radiation Protection and Measurements (NCRP), 1987. Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources. Report No 95. NCRP, Bethesda, MD.

Pennington, C.W., 2006. Assessing unregulated ionizing radiation exposures of U.S. populations from conventional industries. Science of the Total Environment 367, 139–155.

Pennington, C.W., 2007. Exposing America: comparative assessments of ionizing radiation doses to U.S. populations from nuclear and non-nuclear industries. Progress in Nuclear Energy 49 (6), 473–485.

Rigby, J.G., Price, J.G., Christensen, L.G., La Pointe, D.D., Ramelli, A.R., Desilets, M.O., Hess, R.H., Marshall, S.R., 1994. Nevada Bureau of Mines and Geology Bulletin 108, Radon in Nevada. University of Nevada, Reno. Mackay School of Mines.

Rowe, J.W., February 12, 2008. Chairman, President, and CEO of Exelon Corporation and Chairman of the Nuclear Energy Institute (NEI), 2008. Speech Prepared for, and Delivered at, the Brookings Institution, and Published by the NEI.

Sovacool, B.K., 2008. Valuing the greenhouse gas emissions from nuclear power: a critical survey. Energy Policy 36 (8), 2940–2953.

Tolley, G.S., Jones, D.W., 2004. The Economic Future of Nuclear Power. Department of Economics, Graduate School of Business, and Harris School of Public Policy, The University of Chicago, Chicago, IL.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000a. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, Annex B: Exposures from Natural Radiation Sources. United Nations Publications, Vienna, Austria.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000b. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, Annex C: Exposures to the Public from Man-made Sources of Radiation. United Nations Publications, Vienna, Austria.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000c. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, Annex E: Occupational Radiation Exposures. United Nations Publications, Vienna, Austria.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000d. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, Annex J: Exposures and Effects of the Chernobyl Accident. United Nations Publications, Vienna, Austria.

U.S. Department of Energy (USDOE), 2002. Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada. U.S. Government Printing Office, Washington DC. DOE/EIS-0250.

U.S. Department of Energy (USDOE), Office of Science, 2004. Basic Research Needs of the Hydrogen Economy. Washington DC. Available from:. http://www.sc.doe.gov/bes/hydrogen.pdf.

U.S. Department of Energy (USDOE), 2008. Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada. U.S. Government Printing Office, Washington DC (DOE/EIS-0250F-S1) (Final Repository SEIS).

U.S. Energy Information Agency (USEIA), 2007a. Electric Power Annual 2006. Washington, DC. Available from: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html.

U.S. Energy Information Agency (USEIA), 2007b. Emissions of Greenhouse Gases Report 2006. U.S. Government Printing Office, Washington DC. Available from: http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html#transportation DOE/EIA- 573.

U.S. Environmental Protection Agency (USEPA), 2006. 2002 National Emissions Inventory. Washington, DC. Available from: http://www.epa.gov/ttn/chief/net/2002neibooklet.pdf.

U.S. Environmental Protection Agency (USEPA), 1993. EPA's Map of Radon Zones NEVADA. Washington DC: 402-R-93–048.