Paper

RADIOLOGICAL EFFLUENTS RELEASED BY U.S. COMMERCIAL NUCLEAR POWER PLANTS FROM 1995–2005

Jason T. Harris* and David W. Miller†

Abstract—**Commercial nuclear power plants release gaseous and liquid radiological effluents into the environment as by-products of electrical generation. In the U.S. these releases are monitored by the Nuclear Regulatory Commission (U.S. NRC) and Environmental Protection Agency (U.S. EPA). Traditionally these releases have always been well below the regulatory limits. However, the tracking and analysis of nuclear power radiological effluents was stopped in 1994 by several government agencies. The purpose of this study was to compile the entire U.S. industry effluent data, identify trends, and calculate average population dose commitments since that time. Data were taken from radioactive material release reports submitted by each nuclear power plant. Industry trends were identified using the Mann-Kendall non-parametric test. Total collective effective and population doses were estimated using UNSCEAR and U.S. NRC methodologies. Overall, industry releases have been level over the study time period. Public doses continue to be well below 1% of the regulatory limits.**
Health Phys. 95(6):734–743; 2008

Key words: effluents; exposure, population; nuclear power plant; radioactivity, environmental

INTRODUCTION

The generation of electricity from nuclear power is becoming increasingly important due to the growing concerns of global climate change. Nuclear energy is recognized as a leading energy source that produces minimal pollution that contributes to this phenomenon in the environment. Currently in the U.S., there are 104 operating commercial nuclear power reactors. Of these reactors, 69 are pressurized water reactors (PWRs) and 35 are boiling water reactors (BWRs), located on 65 sites around the country (U.S. NRC 2006a). These power plants contribute about 20% of the electricity production today (U.S. DOE 2007). The location of all commercial nuclear power reactors in the U.S. is shown in Fig. 1.

All commercial nuclear power plants release small amounts of radiation into the environment under normal operating conditions as by-products of electrical energy generation (Eisenbud and Gesell 1997; Glasstone and Jordan 1980). In particular, many of the radioactive isotopes that are released are in the form of gaseous or liquid effluents. U.S. nuclear power plants are required to monitor the release of these effluents and make certain that they fall below government regulatory limits set by the U.S. Nuclear Regulatory Commission (U.S. NRC) and Environmental Protection Agency (U.S. EPA) (Andersen 1995). The NRC and EPA have established radiation protection limits to protect the public against potential health risks from exposure to radiological effluents released from nuclear power plants (U.S. NRC 2006b; U.S. EPA 1977). The release of these effluents is governed by 10 CFR Parts 20 and 50 and by limits established in the Technical Specifications for each facility (U.S. NRC 1996). The 10 CFR 50 Appendix I design objectives were established to keep radiation doses from effluents as low as reasonably achievable (ALARA). For liquid effluents, the ALARA annual offsite dose objective is 0.03 mSv (3 mrem) to the whole body and 0.1 mSv (10 mrem) to any organ of a maximally exposed individual who lives near the plant boundary. The gaseous effluent dose objectives are defined for noble gas and iodine and particulate material releases. The noble gas values are 0.1 mSv (10 mrem) for gamma and 0.2 mSv (20 mrem) for beta at the plant boundary and 0.05 mSv (5 mrem) to the whole body at the nearest residence. Iodine and particulate material are limited to 0.15 mSv (15 mrem) to an organ from inhalation or ingestion (U.S. NRC 1971, 1975, 1977). The radiation dose limits defined by 10 CFR 20 are 0.75 mSv (75 mrem) to the thyroid and 0.25 mSv (25 mrem) to the whole body and any other organ. In addition, an annual dose limit of 1 mSv (100 mrem) to individual members of the public has been set (U.S. NRC 1991). Although these radiological effluent releases have been well below these regulatory

* School of Health Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907; † Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign, 104 South Wright Street, Urbana, IL 61801.

For correspondence contact: J. Harris, Department of Physics, Idaho State University, Box 8106, Pocatello, ID 83209, or email at jastharris@aol.com.

(*Manuscript accepted* 13 *May* 2008)
0017-9078/08/0

Fig. 1. Map of U.S. commercial nuclear power reactor sites (U.S. NRC 2006c).

limits, control of releases is important due to public concerns and for minimizing health impact.

In the past, compilation of industry effluent data was performed for all U.S. nuclear power plants by several government agencies and organizations for government, industry, and public inspection (CEPN 2001; EPRI 2003; U.S. NRC 1994, 1995). The data were also made available to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for inclusion in their publication, *Sources and Effects of Ionizing Radiation*, published every five years or so (2000). However, since 1994 the collection and compilation of the effluent data has ceased due to budget constraints. Compilation and analysis of this data is necessary for trending effluent releases, calculating doses to the public, for industry benchmarking, and comparing reporting standards among U.S. and international nuclear power plants. As commercial nuclear power electrical generation steadily increases in the U.S. and the rest of the world, it has become even more important to evaluate the release of radioactive materials into the environment. An easy way to track industry wide effluent releases is by performing trend analyses. Accumulated data may also be used for analyzing reactor power up-rate consequences, protecting the nuclear power industry against litigation, and for assisting in new power plant siting.

Most importantly, collecting and maintaining an effluent database is necessary in maintaining a favorable public perception in regards to the low environmental and biological impact of nuclear power. This is especially important now as several recent, inadvertent releases of radioactive materials from nuclear power plants have occurred. Since 1996, 15 plants have experienced inadvertent releases of radioactive liquids in the U.S. (U.S. NRC 2006d). The most notable event occurred at the Braidwood Nuclear Power Plant in 2005. A leak in a blowdown line resulted in tritium (^{3}H) entering the groundwater system, which was detected in wells in a nearby community. Similarly, a leak from the spent fuel pool was detected at the Indian Point Nuclear Power Plant in 2005. In addition to the detection of tritium, the radionuclides ^{60}Co, ^{63}Ni, ^{90}Sr, and ^{137}Cs have been detected onsite. Because of these circumstances, the authors have compiled and analyzed the effluent data for all U.S. commercial nuclear power plants since 1995. Doses delivered to the public were also calculated using UNSCEAR and NRC dose methodologies.

This paper presents the effluent activities released by commercial U.S. nuclear power plants from 1995–2005. Industry trends and radiological impact from these releases to the environment from the entire U.S. fleet were evaluated with model calculations. In addition, public doses to maximally exposed individuals were calculated and compared for the period of 1998–2006.

METHODS

Effluent radioactivity was obtained from data reported by the nuclear power plants in their annual radioactive material release reports. The effluent data were compiled for all operating PWR and BWR plants from 1995–2005. The completeness of the data was 98%. In keeping with U.S. nuclear power effluent report formatting, data were compiled and analyzed using the same categories as those listed in NRC Regulatory Guide 1.21 (U.S. NRC 1974). The four gaseous effluent categories used were fission and activation gases (F/A), total iodine (^{131}I), particulate matter or particulates, and tritium. The three liquid effluent categories used were fission and activation products, dissolved and entrained gases, and tritium. Because the radioactivity levels of the fission and activation products and dissolved and entrained gases are several orders of magnitude smaller than tritium, those two categories were added together and listed as "other radionuclides." This category replicates the reporting done by UNSCEAR. Gross alpha radioactivity was not included in this study.

Trend analyses were performed for the data over the time period using the Mann-Kendall non-parametric test. This procedure was used since missing values were allowed and the data need not conform to any particular distribution (Gilbert 1994). Inspection of trends over the time period identifies the overall direction of industry effluent releases and can roughly be used to predict future releases.

For this study, two dose assessment methodologies were used. First, collective effective doses (CED) were

calculated for the U.S. population using the UNSCEAR methodology. For these dose calculations, the effluent data were normalized. This was achieved by taking the amount of radionuclides released per unit of electrical energy generated each year. This method is the most common way to normalize effluent data. The electrical energy generated per year was obtained by multiplying the net electrical energy generated by the capacity factor. The capacity factor is defined as the gross electricity generated divided by the product of the licensed capacity and reference time. The capacity factor and energy generation data were obtained from several sources (Blake 2005; U.S. NRC 2005, 2006a). Normalizing data in this manner takes into account the operational performance of the nuclear power plant. However, it also assumes that effluent release amounts are a direct consequence of operation time. The authors caution against making simplistic comparisons of radioactive releases with the electrical energy generated because of the many factors that affect the amount of radioactive materials released, including the condition of the fuel, primary system integrity, design of effluent and radioactive waste treatment systems, maintenance activities, operations, and equipment performance (U.S NRC 1994).

Second, to give the most conservative estimate of dose received by members of the public, calculations were performed for the theoretically maximally exposed individuals from each plant, regardless of the critical group. Calculations were performed using the methods described in NRC Regulatory Guide 1.109 (U.S. NRC 1977). Plant-surrounding population information, meteorology, and effluent release activity were taken from the annual radioactive material release reports. Other site-specific parameters were taken from the licensee's Off-site Dose Calculation Manuals (ODCMs). Calculated site dose values from every plant were summed for each year and compared. The mean and total whole body doses from liquid and gaseous effluents and total cumulative doses are presented here.

RESULTS AND DISCUSSION

Radiological effluent releases

The annual variations of total nuclear power plant radioactivity released in gaseous effluents in PWRs and BWRs are shown in Figs. 2 and 3, respectively. As expected, the activity from PWR releases is higher than that from BWRs due to the greater number of plants. Regardless of this fact, the average tritium release from PWRs is also higher due to chemistry practices that create more tritium in the plant. Nearly every category from both reactor types is fairly level in terms of activity released for the entire time period. The evaluation of the

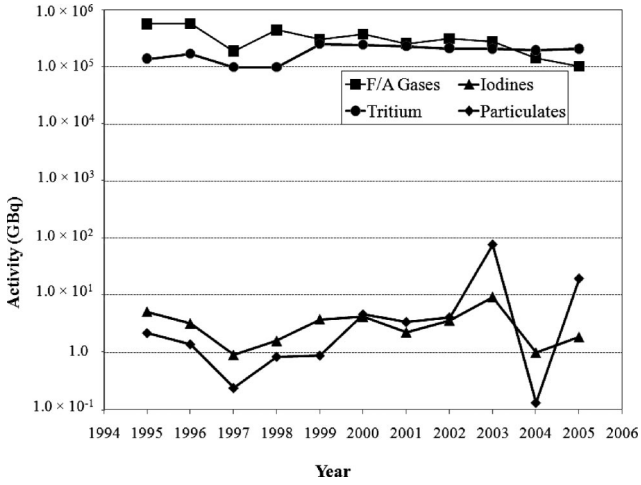

Fig. 2. Variation of total radionuclide activity released in gaseous effluents from PWR plants.

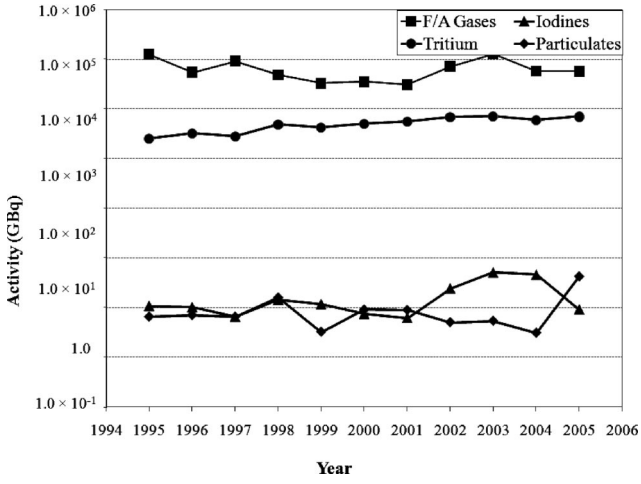

Fig. 3. Variation of total radionuclide activity released in gaseous effluents from BWR plants.

data over the time period partly eliminates variations in annual values. The advantage of using 11 years of data is that operation anomalies, such as long shutdown times for maintenance, are averaged out. The one notable exception appears in the PWR particulate category. In 2003, one plant, Braidwood Nuclear Power Station, experienced an annual release over five orders of magnitude above the mean. This single event was significant enough to skew the entire industry release activity, especially since the annual radioactivity released in particulate matter is so low compared to tritium or fission and activation gases. The following year saw a significant drop in the entire industry radioactivity followed by another sharp increase. This increase in 2005 was due to higher activity releases by several plants.

The annual variation of total nuclear power plant radioactivity released in liquid effluents in PWRs and

BWRs are shown together in Fig. 4. As expected, and for reasons similar to that of the gaseous releases, PWR liquid radioactivity in releases is higher than in BWRs. Liquid releases have stayed very constant over the 11-y period. The most notable exception is the pronounced decline in BWR non-tritium (other radionuclides) radioactivity from 2003–2005.

Radiological effluent trends

U.S. industry effluent trends were evaluated using the Mann-Kendall non-parametric test. The Mann-Kendall test was performed as follows: For any given release category, x, its feature vector consists of the release summation from all plants appearing in a given year i. These release activities are ordered from the first year, 1995, to the final year, 2005, that data were gathered. The x value for each year is compared to all other years greater than that year, and Kendall's statistic S is calculated as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k), \quad (1)$$

where

$$sgn(x_j - x_k) = \begin{cases} 1, & \text{if } x_j - x_k > 0 \\ 0, & \text{if } x_j - x_k = 0 \\ -1, & \text{if } x_j - x_k < 0 \end{cases}.$$

Generally, if a dataset displays a consistently increasing or decreasing trend, S will be positive or negative, respectively, with a larger magnitude indicating the trend is more consistent in its direction. By using the *sgn* function, the algorithm used was able to detect trends featuring either large or small increase steps from year to year equally. The S statistic is then compared to the corresponding P-value (Hollander and Wolfe 1973).

Under the null hypothesis, H_0, that there is no trend displayed by the time series, the distribution of S is then expected to have a zero-mean and variance. The Mann-Kendall test was performed on BWR plant releases, PWR plant releases, and all plant releases (BWR and PWR combined) at a significance level of 0.05.

The results of the trend test are shown in Table 1. Over the past 11 years, it can be seen that for most effluent categories, the releases are level, meaning there is no increasing or decreasing trend. For these categories, improvements in radioactive waste treatment and reactor operations are offset by increased power production, increased capacity factors, and power up-rates. Looking at PWRs only, gaseous fission and activation products have decreased while liquid tritium has increased. Reduction in the fission and activation products over the years is probably a direct result of longer holdup times for radioactive decay, and is consistent with older studies (Harris 2002; NCRP 1987a). In addition lower fission and activation product activities may be due to improved fuel performance from better manufacturing methods. Also, longer operation times in recent years provide stability to the reactor, leading to less fuel shock and defects. The increasing trend for liquid tritium activity is due to an increase in liquid discharges by these plants. Formerly zero-discharge plants have begun to release liquids again to avoid buildup of their tritium inventory. Coupled with this practice, over the last five to ten years many plants have reduced recycling of boron for reactor control. This procedure contributes to increased tritium production.

For BWRs, liquid non-tritium releases have decreased while gaseous tritium has increased. Reduction in the fission and activation products and dissolved and entrained gases in liquid effluents is due to increased fuel performance found in the PWRs. Improvements to radioactive waste treatment systems also reduce the radioactivity released in liquid effluents (NCRP 1987a). The increase in gaseous tritium is a relatively new phenomenon and is probably related more to the increased power production and capacity factors over the last several years than anything else.

Looking at the entire industry (PWRs and BWRs combined), all effluent releases except gaseous fission and activation products and liquid tritium are level. The reasons for these trends are identical to what was discussed previously. Because PWRs make up 66% of the U.S. industry, their releases have a greater impact on the overall release trends, as is evident with the increasing liquid tritium.

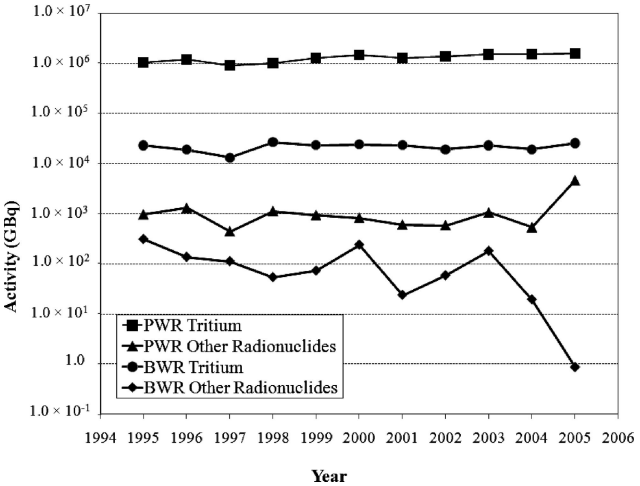

Fig. 4. Variation of total radionuclide activity released in liquid effluents from PWR and BWR plants.

Table 1. Mann-Kendall trend results for U.S. commercial nuclear power plant radiological effluent releases from 1995–2005.

Release category	*S* statistic	*P*-value	Trend[a]
PWR Gaseous—F/A gases	−33	0.005	Decreasing
PWR Gaseous—Iodines	−2	0.47	None
PWR Gaseous—Tritium	8	0.298	None
PWR Gaseous—Particulates	16	0.125	None
PWR Liquids—Tritium	40	0.00004	Increasing
PWR Liquids—Other radionuclides	−8	0.298	None
BWR Gaseous—F/A gases	−4	0.411	None
BWR Gaseous—Iodines	12	0.202	None
BWR Gaseous—Tritium	44	0.000003	Increasing
BWR Gaseous—Particulates	−6	0.357	None
BWR Liquids—Tritium	6	0.357	None
BWR Liquids—Other radionuclides	−28	0.016	Decreasing
Total Gaseous—F/A gases	−26	0.025	Decreasing
Total Gaseous—Iodines	8	0.298	None
Total Gaseous—Tritium	8	0.298	None
Total Gaseous—Particulates	8	0.298	None
Total Liquids—Tritium	40	0.00004	Increasing
Total Liquids—Other radionuclides	−6	0.357	None

[a] Significance level, $\alpha = 0.05$.

Radiological impact of effluent releases—collective effective doses

Tracking effluent release quantities is important in determining radioactivity levels in the environment. However, dose determination of the effluents must be performed to estimate the human effects of these radiation sources. The collective effective dose from radiological effluent releases was obtained using an average collective dose calculation method used by UNSCEAR. UNSCEAR (2000) calculates population dose by first calculating the CED per unit release of radionuclides released from reactors and then normalizes the value with the electrical energy generated. The CED is divided according to type of release (airborne or liquid), radionuclide category (noble gases, tritium, ^{14}C, iodine, and particulate matter), and pathway (immersion, ingestion, inhalation, and external irradiation). The normalized collective effective dose model is given by:

$$D_{CE} = \sum_i \frac{A_i}{E} D_i, \qquad (2)$$

where

A_i = activity of release category i (GBq);
D_{CE} = total CED (person-Sv GW^{-1} y^{-1});
D_i = collective dose for release category i (person-Sv PBq^{-1}); and
E = energy produced by the nuclear reactor (GW y^{-1}).

The dose assessment procedures for this model are applied to a model site with representative environmental conditions. The average population density used is 20 km^{-2} within 2,000 km of the site. Within 50 km of the site, the population density is taken to be 400 km^{-2}. These parameters were obtained from previous UNSCEAR assessments and take into account the transport and dilution of released radionuclides from nuclear installations. The parameters used are assumed to not underestimate dose. Using this model site, the collective effective dose per unit release is obtained for the different release categories. Due to its lack of specificity, this model should be used for general comparisons only.

The collective effective doses resulting from radioactivity released in gaseous effluents from PWRs and BWRs are shown in Figs. 5 and 6, respectively. Liquid effluent collective effluent doses for both reactor types are shown together in Fig. 7. It is not surprising that the CEDs follow similar trends as the raw release activities (Figs. 2–5) since both are determined using the same

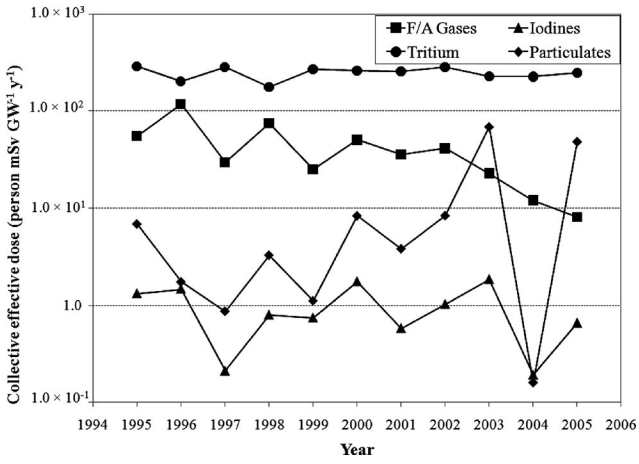

Fig. 5. Gaseous effluent release collective effective doses for PWR plants.

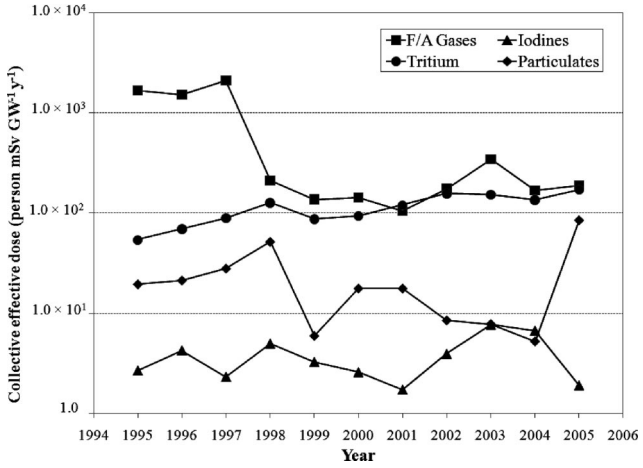

Fig. 6. Gaseous effluent release collective effective doses for BWR plants.

data. Calculated values are similar to that reported by UNSCEAR (2000).

For gaseous releases, the highest collective doses are from the fission and activation gases and tritium. This is partially due to the fact that these are released in the highest quantities. Both of these categories, however, have the lowest collective doses per unit release. Gaseous particulates and iodines, which have higher collective doses per unit release, contribute to a smaller total collective effective population dose. The exception is for 2003 and 2005 particulate matter, discussed earlier. The magnitude of differences is not as great, though, as with the total radioactivity released. For liquid effluents, doses from PWR tritium and particulates are similar. Tritium is released in much larger quantities, but particulates have a much higher collective dose per unit release (330 person-Sv PBq^{-1} or 33 person-krem PBq^{-1} vs. 0.65 person-Sv PBq^{-1} or 65 person-rem PBq^{-1}). In BWRs the particulate doses are higher than the tritium doses, except for the last two years of the study.

The collective effective doses estimated from commercial nuclear power plant radiological effluent releases are very low especially when compared to other man-made sources of radiation (U.S. NRC 2006b). The doses only represent up to a few percent of the regulatory limits. For example, in the year 2000 the highest collective dose calculated was attributed to the fission and activation gases discharged by Cooper Nuclear Station. The collective effective dose was 44.5 person-mSv GW^{-1} y^{-1} (4.45 person-rem GW^{-1} y^{-1}). Using the electrical energy generated that year, the total collective effective dose was 24.03 person-mSv (2.4 person-rem). This represents the dose given to the entire population within the vicinity of the power plant. Using the UNSCEAR number of 20,000 people per 50 km^2 around the site gives a dose commitment of 0.0012 mSv (0.12 mrem). This value is 0.12% of the annual limit set forth in 10 CFR 20 (1 mSv or 0.1 rem).

Effective doses were also computed for the entire U.S. population to give average annual doses. This was done by taking the CEDs calculated for each release category, gaseous and liquid, and dividing them by the U.S. population for each year (U.S. Census Bureau 1999, 2006, 2007). The effective doses were than summed to give a total dose for each person. The results of these effective doses are given in Table 2. For the 11-y period, total effective doses ranged from 5.42×10^{-8} mSv (5.42×10^{-6} mrem) to 1.68×10^{-7} mSv (1.68×10^{-5} mrem). It is evident that the doses calculated in this way are smaller compared to other radiation sources (U.S. NRC 2006b). The doses to an average person would be expected to be even lower since many do not live near a nuclear power plant. This is just one of several ways to calculate a very general effective dose for the population.

Radiological impact of effluent releases—doses to maximally exposed members of the public

Commercial nuclear power plants use the guidelines set forth in NRC Regulatory Guide 1.109 to calculate annual doses to the public from routine releases of radiological effluents using different exposure pathways. This guide bases its calculations on the geographical, meteorological, and population characteristics of the specific nuclear power plant site. In addition to using NRC Regulatory Guide 1.109, plants develop site-specific methods for calculating public doses (U.S. NRC 1977). These methodologies are defined in their ODCMs. The generalized equation for calculating the annual radiation dose to an individual via liquid effluent pathways is given by

$$R_{aipj} = C_{ip} U_{ap} D_{aipj}, \quad (3)$$

where

C_{ip} = concentration of radionuclide i in the media of pathway p (Bq L^{-1}, Bq kg^{-1}, or Bq m^{-3});
D_{aipj} = dose factor, specific to age group a, radionuclide i, pathway p, and organ j (mSv Bq^{-1});
R_{aipj} = annual dose to organ j or an individual of age group a, from nuclide i via pathway p (mSv y^{-1}); and
U_{ap} = exposure time or intake rate (usage) associated with pathway p for age group a (h y^{-1}, L y^{-1} or kg y^{-1}).

The total liquid effluent dose is taken by summing the potable water, aquatic food, shoreline deposit, and irrigated

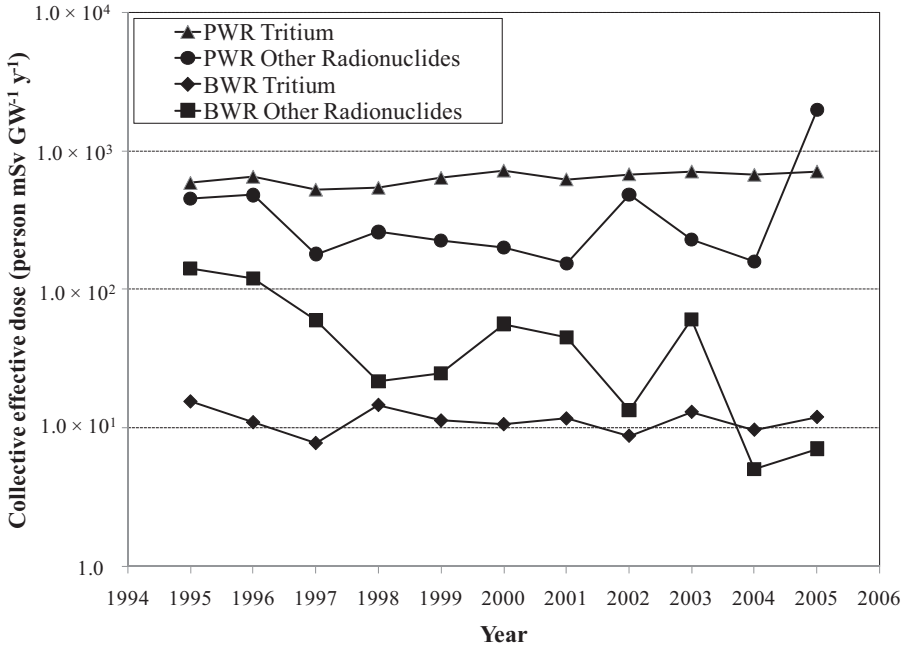

Fig. 7. Liquid effluent release collective effective doses for PWR and BWR plants.

Table 2. Average effective doses received by members of the public in the U.S. from commercial nuclear power plant radiological effluent releases.

			Annual effective dose (mSv GW^{-1} $person^{-1}$)						
			Gaseous releases				Liquid releases		
Year	Electrical energy produced (GW)[a]	U.S. population ($\times 10^4$)[b]	F/A gases	Total iodine	Tritium	Particulates	Tritium	Other radionuclides	Total
1995	77.1	266,557	8.36×10^{-8}	1.95×10^{-10}	1.68×10^{-8}	1.28×10^{-9}	2.93×10^{-8}	2.90×10^{-8}	1.60×10^{-7}
1996	77.3	269,667	7.79×10^{-8}	2.75×10^{-10}	1.31×10^{-8}	1.10×10^{-9}	3.18×10^{-8}	2.89×10^{-8}	1.53×10^{-7}
1997	71.9	272,912	1.08×10^{-7}	1.29×10^{-10}	1.90×10^{-8}	1.47×10^{-9}	2.71×10^{-8}	1.22×10^{-8}	1.68×10^{-7}
1998	74.9	276,115	1.38×10^{-8}	2.80×10^{-10}	1.46×10^{-8}	2.66×10^{-9}	2.68×10^{-8}	1.37×10^{-8}	7.19×10^{-8}
1999	82.3	279,295	7.00×10^{-9}	1.75×10^{-10}	1.57×10^{-8}	3.06×10^{-10}	2.83×10^{-8}	1.10×10^{-8}	6.24×10^{-8}
2000	85.2	282,402	7.98×10^{-9}	1.80×10^{-10}	1.48×10^{-8}	1.08×10^{-9}	3.05×10^{-8}	1.07×10^{-8}	6.53×10^{-8}
2001	87.8	285,329	5.58×10^{-9}	9.21×10^{-11}	1.50×10^{-8}	8.57×10^{-10}	2.54×10^{-8}	7.97×10^{-9}	5.49×10^{-8}
2002	88.6	288,173	8.42×10^{-9}	1.95×10^{-10}	1.73×10^{-8}	6.62×10^{-10}	2.70×10^{-8}	1.96×10^{-8}	7.32×10^{-8}
2003	87.0	291,028	1.44×10^{-8}	3.79×10^{-10}	1.51×10^{-8}	3.04×10^{-9}	2.87×10^{-8}	1.15×10^{-8}	7.30×10^{-8}
2004	88.1	293,907	6.94×10^{-9}	2.67×10^{-10}	1.39×10^{-8}	2.07×10^{-10}	2.64×10^{-8}	6.38×10^{-9}	5.42×10^{-8}
2005	88.6	298,025	7.43×10^{-9}	9.70×10^{-11}	1.58×10^{-8}	5.07×10^{-9}	2.75×10^{-8}	7.55×10^{-8}	1.31×10^{-7}

[a] U.S. NRC (2006a).
[b] U.S. Census Bureau (2006).

food pathway doses. These pathways are considered significant as they yield an additional dose increment equal to or greater than 10% of the total from all pathways.

The combined equation for calculating the annual radiation dose to an individual via airborne effluent pathways is given by

$$D(r, \theta) = D_T + D_{\infty T} + D_G + D_A + D_D. \quad (4)$$

where

$D(r, \theta)$ = total annual dose to an individual from airborne releases at location (r, θ) (mSv y^{-1});

D_T = annual total body dose from noble gas releases from free-standing stacks more than 80 m high (mSv y^{-1});

$D_{\infty T}$ = annual total body dose from all other noble gas releases (mSv y^{-1});

D_G = annual organ dose from external irradiation from radionuclides deposited onto the ground surface (mSv y^{-1});

D_A = annual organ dose from inhalation of radionuclides in air (mSv y^{-1}); and

D_D = annual organ dose from ingestion of atmospherically released radionuclides in food (mSv y^{-1}).

Every dose equation, except D_T, factored into eqn (4) assumes immersion in a semi-infinite cloud. The overall annual dose is then obtained by summing the total liquid and airborne pathway doses, eqns (3) and (4), respectively.

Using the site-specific information from every plant, the dose commitments to theoretically maximally exposed individuals were estimated. Dose calculations were performed using the NRCDose (Bland and Malafeew 2006) computer code. NRCDose includes the suite of the NRC's computer codes (LADTAP II, GASPAR II, and XOQDOQ) used for evaluating routine radioactive effluents from nuclear power plants. The doses from every plant were summed to give a total yearly dose contribution from the entire nuclear power industry. Liquid and gaseous effluents doses were then summed to give an entire whole body dose.

In addition, the annual cumulative dose to the maximally exposed individual was estimated by summing the total body air dose, the skin air dose, the critical organ dose from iodines and particulates, the total body dose from liquid effluents, and the critical organ dose from liquid effluents. The doses from every plant were summed to give a total yearly dose contribution from the entire nuclear power industry. Finally, a U.S. population average dose was estimated by dividing the total dose by the population number for each year. The Radiological Environmental Monitoring Program (REMP) onsite direct radiation thermoluminescent dosimetry (TLD) data from operating reactors or independent spent fuel storage installations (ISFSIs) were not included. Calculations were performed for the time period of 1998–2006. Previous years were not included in this study due to insufficient data.

The results of these calculations are given in Table 3. The summed totals of the liquid and gaseous effluent total body doses ranged from 4.94×10^{-2} mSv (4.94 mrem) to 1.10×10^{-1} mSv (11.0 mrem). For the 11-y time period, the values varied only slightly, no more than one order of magnitude. The cumulative doses were in greater agreement, ranging from 2.12×10^{-1} mSv (21.2 mrem) to 3.44×10^{-1} mSv (34.4 mrem). These numbers validate how stable the radiological effluent releases have been in the U.S. over the last several years.

The individual population cumulative doses were determined using population data. Here, the doses are even smaller than what was calculated using the UNSCEAR methodology. All of the calculated doses are well below both the U.S. regulatory limits and the average dose of 3 mSv received by individuals from background radiation (U.S. NRC 1975, 1991, 2006b). Doses were calculated this way so that comparisons can be made with other radiation sources. Calculating doses by this method is not as accurate as using site-specific population data. However, it does allow for general comparisons with other man-made sources of radiation. Often, the exposure from man-made sources is compared to that of background radiation to give a person's annual dose (NCRP 1987b). Also, doses to maximally exposed individuals are reported to the NRC, not population doses.

CONCLUSION

The release of radiological effluents from U.S. nuclear power plants over the last 11 y has been carefully reviewed. Trends were identified to show long-term U.S.

Table 3. Yearly total body dose and cumulative dose commitments received by maximally exposed individual members of the public in the U.S. from commercial nuclear power plant radiological effluent releases.

	Total body dose (mSv)					Cumulative dose (mSv)		
	Liquid		Gaseous					
Year	Mean ± S.D. ($\times 10^{-4}$)	Total	Mean ± S.D. ($\times 10^{-4}$)	Total	Total effluent	Mean ± S.D. ($\times 10^{-4}$)	Total	Individual population[a]
1998	6.24 ± 13.3	2.81×10^{-2}	11.0 ± 22.4	3.96×10^{-2}	6.77×10^{-2}	40.8 ± 60.3	2.65×10^{-1}	9.60×10^{-10}
1999	7.37 ± 16.2	4.05×10^{-2}	7.61 ± 18.1	3.50×10^{-2}	7.55×10^{-2}	43.6 ± 78.0	2.83×10^{-1}	1.01×10^{-9}
2000	7.42 ± 20.5	3.56×10^{-2}	10.4 ± 23.4	4.57×10^{-2}	8.13×10^{-2}	38.1 ± 61.6	2.48×10^{-1}	8.78×10^{-10}
2001	6.68 ± 17.6	3.41×10^{-2}	5.71 ± 16.3	2.46×10^{-2}	5.87×10^{-2}	46.5 ± 93.6	3.02×10^{-1}	1.06×10^{-9}
2002	4.42 ± 7.87	2.26×10^{-2}	18.9 ± 44.4	8.72×10^{-2}	1.10×10^{-1}	52.9 ± 94.3	3.44×10^{-1}	1.19×10^{-9}
2003	3.97 ± 6.55	2.10×10^{-2}	6.93 ± 20.9	2.84×10^{-2}	4.94×10^{-2}	41.9 ± 68.2	2.72×10^{-1}	9.35×10^{-10}
2004	10.1 ± 40.8	4.74×10^{-2}	4.82 ± 14.3	1.78×10^{-2}	6.52×10^{-2}	47.0 ± 129	3.05×10^{-1}	1.04×10^{-9}
2005	4.37 ± 7.95	2.27×10^{-2}	18.5 ± 58.6	7.97×10^{-2}	1.02×10^{-1}	32.7 ± 55.8	2.12×10^{-1}	7.11×10^{-10}
2006[b]	5.55 ± 7.80	2.33×10^{-2}	13.1 ± 26.9	4.72×10^{-2}	7.05×10^{-2}	46.8 ± 91.8	3.04×10^{-1}	1.01×10^{-9}

[a] Obtained by dividing the total cumulative dose by the annual U.S. population (see Fig. 2 for population numbers).
[b] 2006 U.S. population = 300,889 ($\times 10^4$) (U.S. Census Bureau 2007).

nuclear industry effluent release patterns. For most effluent categories the releases have been very stable. Using a standard model, the average effluent collective effective doses were calculated. Total body and cumulative doses for maximally exposed individuals were estimated using NRC methodologies. These two components of the study showed how low normal operation effluent doses are, compared to regulatory limits.

Normalization by electrical energy generated was used in calculating the collective effective doses. However, as with unnormalized data, atypical releases may dominate the total industry release values. In this case, the normalized releases reflect only the prevailing operating experience, and cannot be taken as representative of the releases from a particular reactor type (UNSCEAR 2000).

This research provided important insight into commercial nuclear power plant discharges. However, radioactive releases are dictated not only by electrical generation, but also by the design of radioactive waste treatment systems, the age of the plant, and the method of release. A total inventory of radioactive materials released needs to be accounted for to understand what factors contribute to effluent releases.

Effluent release data collection and trending will continue to be important for the future of the commercial nuclear power industry. As plants continue to conduct reactor power up-rates, effluent releases will need to be observed to determine effects from these design enhancements. Effluent trending may also reveal insight into the effect of increased reactor lifetime operation on radioactivity releases. Currently, many plants have been approved for, or are applying for, operating license extensions. Tracking data for siting of new nuclear power plants may also be used to determine environmental radionuclide buildup and long-term nuclear power health effects. Finally, calculating public doses from radiological effluent releases is important in maintaining favorable public opinion about nuclear power. The more accurate, scientifically based information that citizens can be provided with, the more likely they are to make informed, non-emotional judgments about nuclear power.

Acknowledgments—The authors are grateful to the many nuclear power plant and U.S. NRC staff that helped with data collection. This work was partially performed under appointment to the Office of Civilian Radioactive Waste Management (OCRWM) Fellowship program administered by the Oak Ridge Institute for Science and Education under a contract between the U.S. Department of Energy and Oak Ridge Associated Universities. Additional support was provided through a North American Technical Center (NATC) Public Radiation Safety Research Program and Electric Power Research Institute (EPRI) grant.

REFERENCES

Andersen RL. Criteria for radiological releases. In: Maletskos CJ, ed. Radiation protection at nuclear reactors. Health Physics Society 1995 Summer School. Madison, WI: Medical Physics Publishing; 1995: 21–44.

Blake EM. U.S. power reactor performance 2002–2004. La Grange Park, IL: American Nuclear Society; 2005.

Bland JS, Malafeew V. NRCDose for Windows, user's guide. Annapolis, MD: Chesapeake Nuclear Services; 2006.

Centre D'etude sur L'evaluation de la Protection dans le Domaine Nucleaire (CEPN). Liquid and gaseous activity released from pressurized water reactors: international data (1975–2000). Fontenay-aux-Roses, France: Information System on Occupational Exposure (ISOE) European Technical Centre; NTE/01/29-C413; 2001.

Eisenbud M, Gesell T. Environmental radioactivity. San Diego: Academic Press; 1997.

Electric Power Research Institute. Strategies for managing liquid effluents—options, actions, and results. Palo Alto, CA: EPRI; 1008015; 2003.

Gilbert RO. Statistical methods for environmental pollution monitoring. New York: Van Nostrand Reinhold; 1994.

Glasstone S, Jordan WH. Nuclear power and its environmental effects. La Grange Park. IL: American Nuclear Society; 1980.

Harris JT. Comparative study of commercial nuclear power plant radiological effluents. Urbana, IL: University of Illinois, Department of Nuclear, Plasma, and Radiological Engineering; 2002. Thesis.

Hollander M, Wolfe DA. Nonparametric statistical methods. New York: Wiley; 1973.

National Council on Radiation Protection and Measurements. Public radiation exposure from nuclear power generation in the United States. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report No. 92; 1987a.

National Council on Radiation Protection and Measurements. Ionizing radiation exposure of the population of the United States. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report No. 93; 1987b.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. New York: United Nations; 2000.

U.S. Census Bureau. State and metropolitan area data book, 1997–1998. Washington, DC: U.S. Government Printing Office; 1999.

U.S. Census Bureau. Statistical abstract of the United States: 2006. Washington, DC: U.S. Government Printing Office; 2006.

U.S. Census Bureau. Annual population estimates 2000 to 2006 [online]. Washington, DC: U.S. Government Printing Office; 2007. Available at: http://www.census.gov/popest/states/NST-ann-est.html. Accessed 2 July 2007.

U.S. Department of Energy, Energy Information Administration. U.S. nuclear generation of electricity [online]. Washington, DC: U.S. Government Printing Office; 2007. Available at: http://www.eia.doe. gov/cneaf/nuclear/page/nuc_generation/gensum.html. Accessed 10 November 2007.

U.S. Environmental Protection Agency. Environmental radiation protection standards for nuclear power operations. Washington, DC: U.S. Government Printing Office; 40 CFR 190, 42 FR 2860; 1977.

U.S. Nuclear Regulatory Commission. General design criteria for nuclear power reactors. Washington, DC: U.S. Government Printing Office; 10 CFR 50, Appendix A, 36 FR 3256; 1971.

U.S. Nuclear Regulatory Commission. Measuring, evaluating, and reporting radioactivity in solid wastes and releases of radioactive materials in liquid and gaseous effluents from light-water-cooled nuclear power plants. Washington, DC: U.S. Government Printing Office; Regulatory Guide 1.21, rev. 1; 1974.

U.S. Nuclear Regulatory Commission. Numerical guides for design objectives and limiting conditions for operation to meet the criterion "as low as is reasonably achievable" for radioactive material in light-water-cooled nuclear power plant effluents.. Washington, DC: U.S. Government Printing Office; 10 CFR 50, Appendix I, 40 FR 19442, 5 May 1975 [as amended at 40 FR 40818, 4 September 1975; 40 FR 58847, 19 December 1975; 41 FR 16447, 19 April 1976; 42 FR 20139, 18 April 1977; 51 FR 40311, 6 November 1986; 61 FR 39303, 29 July 1996]; 1975.

U.S. Nuclear Regulatory Commission. Calculation of annual doses to man from routine releases of reactor effluents for the purpose of evaluating compliance with 10 CFR Part 50, Appendix I. Washington, DC: U.S. Government Printing Office; Regulatory Guide 1.109; 1977.

U.S. Nuclear Regulatory Commission. Standards for protection against radiation. Washington, DC: U.S. Government Printing Office; 10 CFR 20, 56 FR 23361; 1991.

U.S. Nuclear Regulatory Commission. Radioactive materials released from nuclear power plants. Washington, DC: U.S. Government Printing Office; NUREG/CR-2907; 1994.

U.S. Nuclear Regulatory Commission. Dose commitments due to radioactive releases from nuclear power plant sites in 1991. Washington, DC: U.S. Government Printing Office; NUREG/CR-2850; 1995.

U.S. Nuclear Regulatory Commission. Technical specifications on effluents from nuclear power reactors. Washington, DC: U.S. Government Printing Office; 10 CFR 50.36a, 61 FR 39299; 1996.

U.S. Nuclear Regulatory Commission. Information digest 2005–2006 edition. Washington, DC: U.S. Government Printing Office; NUREG-1350, Vol. 17; 2005.

U.S. Nuclear Regulatory Commission. Information digest 2006–2007 edition. Washington, DC: U.S. Government Printing Office; NUREG-1350, Vol. 18; 2006a.

U.S. Nuclear Regulatory Commission. Fact sheet on tritium, radiation protection limits, and drinking water standards [online]. Washington, DC: U.S. Government Printing Office; 2006b. Available at: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/tritium-radiation-fs.html. Accessed 2 July 2006.

U.S. Nuclear Regulatory Commission. Map of power reactor sites [online]. Washington, DC: U.S. Government Printing Office; 2006c. Available at: http://www.nrc.gov/reactors/operating/map-power-reactors.html. Accessed 15 August 2006.

U.S. Nuclear Regulatory Commission. Liquid radioactive release lessons learned task force final report. Washington, DC: U.S. Government Printing Office; 2006d.

■ ■