Environmental monitoring of radioactive and non-radioactive constituents in the vicinity of WIPP

By P. Thakur, J. Monk and J. L. Conca^{*,#}

Carlsbad Environmental Monitoring & Research Center, 1400 University Drive, Carlsbad, NM 88220, USA

(Received December 22, 2009; accepted in revised form November 12, 2010)

Environmental monitoring / WIPP / Plutonium / Aerosols / Whole body counting / Transuranic waste

Summary. The Waste Isolation Pilot Plant (WIPP), a US Department of Energy (DOE) facility, is a deep geologic transuranic waste disposal site designed for the safe disposal of transuranic (TRU) wastes generated from the US defense program. Monitoring is a key component of the development and operation of any nuclear repository and is important to the WIPP performance assessment. Initial concerns over the release of radioactive and chemical contaminants from the WIPP led to various monitoring programs, including the independent, academic-based WIPP environmental monitoring (WIPP-EM) program conducted by the New Mexico State University (NMSU) Carlsbad Environmental Monitoring and Research Center (CEMRC) located in Carlsbad, NM. The mission of CEMRC is to develop and implement an independent health and environmental monitoring program in the vicinity of WIPP and make the results easily accessible to the public and all interested parties. Under the WIPP-EM program constituents monitored include: (1) selected radionuclides, elements, and ions of interest in air, soil, vegetation, drinking water, surface water and sediment from within a 100-mile radius of WIPP as well as in the air exiting the WIPP exhaust shaft, and (2) internally deposited radionuclides in the citizenry living within a 100-mile radius of WIPP. This article presents an evaluation of more than tens years of environmental monitoring data that informed the public that there is no evidence of increases in radiological contaminants in the region that could be attributed to releases from the WIPP. Such an extensive monitoring program and constant public engagement is an ideal model for all nuclear waste repositories anywhere in the world.

1. Introduction

Sixty years of nuclear technology and weapons development in the United States were a key component of the United States national security during the cold war. However, treatment of the chemical and radioactive wastes produced over this time, and the potential impacts on the environment, were of secondary concern to the production of nuclear weapons. Much of the resulting wastes from these research, develop-

ment and processing activities were stored in various underground and surface containment facilities. With the end of the Cold War, the focus changed to the treatment of these wastes for permanent disposal and to the remediation of the contaminated land. The United States has opened one nuclear repository, Waste Isolation Pilot Plant (WIPP). The WIPP is the world's only operating deep underground geologic nuclear repository for the disposition of defense generated transuranic radioactive waste.

The WIPP is located in southeastern New Mexico, 26 miles east of Carlsbad (Fig. 1). The WIPP site is an essential effort to clean-up the nation's TRU waste which is currently stored at eleven federal facilities around the country. The history of the WIPP goes back to 1957, when the National Academy of Science recommended bedded salt formations as the optimal geologic formation for underground disposal of radioactive waste. The impetus to go forward with the project came in 1969–1970 when a series of fires at the DOE Rocky-flats facility near Denver, Colorado caused airborne release of plutonium. DOE agreed to stop storing plutonium wastes at Rocky flats and begun shipping TRU wastes to Idaho National Engineering and Environmental Laboratory in southeastern Idaho. Idaho was promised that the wastes would only be stored for ten years in Idaho and the search began for a site where these wastes could be permanently disposed. DOE had previously looked at a site near Lyon, Kansas, in an abandoned salt mine, but strong political opposition by state officials and a combination of numerous borehole and large volumes of water “lost” in fractures in the salt forced them to look elsewhere. They considered several New Mexico sites and eventually settled on the site near Carlsbad. The encouragement of local politicians and businesses, the depressed economic conditions in that part of the state, and a ready labor force already trained in what was needed to construct the repository, were all important factors in bringing WIPP to this area.

Disposal rooms are excavated in the ancient, stable Salado salt formation 2150 feet (almost one-half mile) below the surface. The WIPP repository consists of eight panels, each of which contains seven waste disposal rooms. Each room is approximately 300 feet (91 m) long, 33 feet (10 m) wide and 13 feet (4 m) high. Five panels have already been excavated. The first four have been filled and closed, and disposal is continuing in the fifth panel as the sixth is being excavated. Because of the tendency of salt to creep closed

^{*} Author for correspondence (E-mail: jconca@cemrc.org).

[#] Present address: RJ LeeGroup, Inc., Richland, WA 99352, USA.

Fig. 1. Location of the WIPP site.

and fill excavated voids or fractures, mining of panels and storage rooms is performed on a staggered, as-needed schedule dictated by the rate at which waste is received at WIPP.

Two types of TRU wastes are disposed of in WIPP: (1) mixed transuranic waste (MTRU) and (2) non-mixed waste that contain only radioactive elements, mostly plutonium. The TRU waste is subdivided into contact-handled (CH) and remote-handled (RH) waste on the basis of the dose equivalent rate at the surface of the waste container. If the dose rate is less than 200 mrem/h, the waste is categorized as CH-TRU waste; otherwise, the categorization is RH-TRU waste. The WIPP became operational in 26 March 1999 for the disposal of transuranic waste, and the WIPP first received mixed waste shipments on 9 September 2000. The WIPP mission is to dispose of 176 000 m³ (6.2 million cubic feet) of contact-handled waste and 7080 m³ (250 000 cubic feet) of remote-handled waste, the equivalent to about 800 000 55-gallon drums.

2. WIPP – environmental monitoring program

Environmental monitoring is a key component of the development and operation of a nuclear waste repository and is important to the WIPP performance assessment. WIPP celebrated 10 years of safe disposal of TRU wastes in March of 2009 and completion of TRU waste cleanup at 15 generator sites in 12 states. Many factors contributed to the success of this project, one being the environmental monitoring in the

vicinity of the WIPP. The mission of the WIPP environmental monitoring program at NMSU CEMRC (WIPP-EM) is to develop and implement an independent health and environmental monitoring program in the vicinity of WIPP and make the results easily accessible to the public and all interested parties.

The first radioactive waste shipments were received at the WIPP on 26 March 1999, and this is considered the cut-off date separating the pre-operational phase from the operational phase. The main objectives of the pre-operational program were to collect baseline measurements of radionuclides and inorganic non-radioactive constituents that are known or expected to present in the wastes to be disposed at the WIPP. The baseline data are important prior to operations using actual waste in order to determine whether WIPP operations have affected concentrations of these radionuclides in the environment. Based on an evaluation of various release events, it has been established that the atmospheric pathway is the most credible exposure pathway to the public from the WIPP, because that is the pathway by which radioactive or chemical contaminants released from the site would likely be most rapidly and widely dispersed throughout the environment.

3. WIPP exhaust air monitoring

The CEMRC ambient aerosol monitoring studies focus on both man-made and naturally-occurring radionuclides in

ambient air in and around the WIPP site as well as air entering and exiting the WIPP underground. For monitoring of the WIPP underground air, the samples are collected from a shrouded probe, commonly referred to as a Fixed Air Sampler (FAS) collecting particulate from the effluent air stream using a 47 mm diameter filters (Versapor® membrane filter, PALL Corporation) at a location designated as Station A. It has a transfer line running to each of three sampling legs; thus a total of three concurrent samples can be collected from the FAS, one each for CEMRC, the site contractor (Washington TRU Solutions, WTS) and the New Mexico Environment Department (NMED). Test of the probes confirmed that this configuration allows collection of representative air samples [1]. Sampling operations at Station A provide a way to monitor for releases of radionuclides and other substances in the exhaust air from the WIPP. In addition, if radioactive materials were to be released from the facility, the Station A data also would be invaluable for reconstructing exposure scenarios. The airflow through the FAS is approximately 170 liters per minute (6.0 cubic feet per minute). The samples at Station A are typically collected daily except for weekends (the weekend samples run from Friday to Monday so the coverage is continuous). If waste operations occur on the weekend then samples are also collected on the weekends. However, occasionally more than one sample per day is collected if the flow rate on any of the sampler legs drops below 51 liter per minute (1.8 cubic feet per minute).

Samples for the ambient aerosol/radionuclide studies have been collected using total suspended particle (TSP) high-volume samplers ("hivols", flow rate $\sim 1.13 \text{ m}^3 \text{ min}^{-1}$). The TSP samplers have been collected from three stations: (1) On Site station, which is $\sim 0.1 \text{ km}$ northwest (downwind) of the WIPP exhaust shaft, (2) Near Field station, $\sim 1 \text{ km}$ northwest of the facility; and (3) Cactus Flats station, $\sim 19 \text{ km}$ southeast (upwind) of the WIPP. The sites were selected on the basis of the prevailing wind directions at the WIPP. In establishing these sites, it was recognized that there was no ideal "control" location from which to collect samples, that is, a site far enough from the WIPP to ensure complete isolation from aerosol releases while adequately replicating key ecological features, aerosol composition, soil topology, biota and weather conditions, etc. The cactus flats station was used as a reference location because it represents a reasonable compromise based on these considerations. The Near Field and Cactus Flats stations also supported a second hivol sampler for studies of PM_{10} samplers (particulate matter less than $10 \mu\text{m}$ aerodynamic equivalent diameter), but the PM_{10} sampling was terminated in December 2000. The decision to use TSP samplers rather than PM_{10} samplers was based on the overall objective of the WIPP-EM, which is to evaluate any possible impacts of the WIPP. In particular this decision was made because it could be argued that the PM_{10} samplers would not capture any releases of the largest aerosol particles as effective as the TSP samplers. A fourth set of samples was collected at Hobbs over a period of approximately a year and a half, but the sampling there was discontinued in April 2002 because WIPP is located approximately 61 km (38 miles) from Hobbs and an ambient air baseline has been established for the vicinity of Hobbs during prior years. An

overview of the WIPP-EM monitoring program is illustrated in Table 1.

The air filters from station A are counted for gross alpha/beta activities for 1200 min using a low-background Gas Proportional Counter (Protean MPC 9604); after that weekly and monthly filter samples are composited. The monthly composites are spiked with appropriate tracers and routinely analyzed for ^{238}Pu , $^{239,240}\text{Pu}$, ^{241}Am and $^{235,234,238}\text{U}$ [2]. The high-volume samples are analyzed for selected radionuclides, including ^{238}Pu , $^{239+240}\text{Pu}$ and ^{241}Am as described in CEMRC reports [2]. Samples are counted for 5 d on alpha spectroscopy (Oxford Oasis), in order to reduce the detection limits. Analyses of gamma emitters are performed on the same monthly composites as used for the actinides studies; the gamma analyses are done using a low-background, high-purity Ge co-axial detector with a count time of 48 h.

The gross alpha and beta activities are expressed as *activity concentration* (the activity per unit volume of air sampled, Bq/m^3) and *activity density* (the activity per unit aerosol mass collected, Bq/g). The minimum detectable activity concentrations and densities for the gross alpha emitters are $\approx 1 \times 10^{-7} \text{ Bq/m}^3$ and $\approx 0.7 \text{ Bq/g}$, respectively, while for gross beta emitters the corresponding values are $\approx 2 \times 10^{-7} \text{ Bq/m}^3$ and $\approx 1.7 \text{ Bq/g}$. The gross alpha and beta activities in Station A samples from 1998 to 2009 are shown in Fig. 2. The bulk of the activity in pre-operational samples result from naturally occurring radioactive materials, specif-

Fig. 2. Gross alpha and beta activity concentrations (Bq/m^3) at Station A.

Fig. 3. Annual $^{239+240}\text{Pu}$ and ^{241}Am activity concentrations (n Bq/m³) in the WIPP exhaust air during the period from 1998–2009.

Section 191.03(b) from the WIPP facility [4]. Such small occasional detections are probably due to environmental levels of plutonium and could not be attributed to release from the WIPP. The 2003, 2008 and 2009 hits provide a baseline for future events. The radionuclides being investigated and their minimum detectable activities (MDA) for the environmental medium are summarized in Table 2.

The low-volume samplers ($\sim 10 \text{ L min}^{-1}$) and Graseby-Anderson dichotomous samplers (dichots) are used for collection of aerosols (TSP, PM_{10} and $\text{PM}_{2.5}$) for the studies of non-radioactive, inorganic and trace elements (TE), using ion chromatography (IC) and inductively-coupled Mass spectrometry (ICP-MS), respectively. For these studies, samples are collected at Near Field and Cactus Flats, but again only TSP samples are collected at On Site. After 2002, samplings for the non-radiological aerosols were done using dichots exclusively. In November 2004, the collection of aerosols by dichots was discontinued. Elemental analyses are conducted on weekly composites of the filters. Because of space restriction, elemental and non-radiological data are not discussed in this manuscript. Data for the high volume ambient aerosol samples (hi-vols) are presented in Fig. 4 for 1998 to 2009. During most years studied, the peak $^{239+240}\text{Pu}$ activities generally occur from March to June, which is when strong and gusty winds in the area frequently give rise to blowing dust [5]. Some samples taken at Cactus Flats in 1999 and 2000, and at On Site in 2004 and 2008 exhibited slightly higher $^{239+240}\text{Pu}$ activity concentrations (Fig. 4) than surrounding data points. The points correspond with higher activity densities as well, *i.e.*, greater activity per gram of dust, indicating changes in dust composition and origin [6].

4. Drinking water

The WIPP-EM studies of ground water focus on the major drinking water supplies used by communities in the WIPP region. Water samples are collected from five sources in the vicinity of the WIPP: Carlsbad, Loving, Otis, WIPP-Double Eagle, and Hobbs. Both radiological and inorganic and trace elements analyses of drinking water are done using the standard CEMRC procedures [2]. As shown in Fig. 5,

Fig. 4. $^{239+240}\text{Pu}$ activity in high volume ambient aerosol as activity density and activity concentration around the WIPP site.

Pu has not been measured above MDC (minimum detection concentration) in any drinking water samples since 1998. The federal and state action level for gross alpha emitters is 15 pCi (0.56 Bq/L). This is over 10,000 times the levels measured by CEMRC in any drinking water sample over the last ten years. Naturally occurring actinides ($^{234}, ^{235}, ^{238}\text{U}$) have been detected in all of the samples as in the case of for most waters in New Mexico. These levels and ratios of uranium are typical of natural variations in ground water and agree well with the few directly comparable values reported in the region [7]. The low concentration of ^{235}U in water samples is consistent with the lower concentration of ^{235}U in the natural environment as compared to the concentrations of ^{234}U and ^{238}U . The groundwater monitoring is not done by CEMRC as the two geologic units that are potential groundwater pathway for radioactive releases to the environment *i.e.*, Culebra Dolomite unit in the Rustler formation and Salado Anhydrite within the salt bed are not highly permeable. Both groundwater units were studied in the past and were found to have only minor contributions to releases from the WIPP repository.

5. Surface soil

Soil samples are collected from 16 locations in the vicinity of WIPP. At each location, soil is collected at three randomly

Table 2. The radionuclide concentrations detected in environmental medium and the minimum detection concentration (MDC).

Environ- mental medium	RN	Average MDC	Amount detected	Comments
Air, FAS (Bq/m ³)	²³⁹⁺²⁴⁰ Pu	4.0×10^{-8}	<MDC	Station A
	²³⁸ Pu	3.3×10^{-8}	<MDC	
	²⁴¹ Pu	2.5×10^{-6}	<MDC	
	²⁴¹ Am	2.7×10^{-8}	<MDC	
	²³⁴ U	1.3×10^{-8}	9.5×10^{-7}	Cactus flats Hobbs Near field On site Cactus flats Near field On site Cactus flats Near field On site
	²³⁵ U	3.7×10^{-8}	4.4×10^{-8}	
	²³⁸ U	1.6×10^{-8}	9.1×10^{-7}	
	²³⁹⁺²⁴⁰ Pu	2.6×10^{-9}	1.1×10^{-8} (PM ₁₀)	
			1.8×10^{-8} (TSP)	
			1.2×10^{-8} (TSP)	
			8.1×10^{-9} (PM ₁₀)	
			1.3×10^{-8} (TSP)	
			1.4×10^{-8} (TSP)	
	²³⁸ Pu	3.9×10^{-9}	(PM ₁₀)	
			3.4×10^{-9} (TSP)	
			1.5×10^{-9} (TSP)	
			3.4×10^{-9} (TSP)	
	²⁴¹ Pu	1.2×10^{-6}	NR	Cactus flats Near field On site
	²⁴¹ Am	3.1×10^{-9}	NA (PM ₁₀)	
Soil (Bq/g)			7.0×10^{-9} (TSP)	
			NA (PM ₁₀)	
			4.4×10^{-9}	
			NA (PM ₁₀)	
	²³⁹⁺²⁴⁰ Pu	0.04×10^{-3}	$0.15\text{--}0.40 \times 10^{-3}$	—
	²⁴¹ Am	0.06×10^{-3}	$0.037\text{--}0.11 \times 10^{-3}$	—
	²³² Th	0.34×10^{-3}	$4.70\text{--}15 \times 10^{-3}$	—
	²³⁰ Th	1.37×10^{-3}	$4.50\text{--}16 \times 10^{-3}$	—
	²²⁸ Th	1.20×10^{-3}	$4.20\text{--}17 \times 10^{-3}$	—
	²³⁸ U	3.00×10^{-3}	$5.60\text{--}12 \times 10^{-3}$	—
	²³⁵ U	3.40×10^{-3}	$0.20\text{--}0.65 \times 10^{-3}$	—
	²³⁴ U	3.40×10^{-3}	$5.40\text{--}12 \times 10^{-3}$	—
	¹³⁷ Cs	0.06×10^{-3}	$1.37\text{--}7.48 \times 10^{-3}$	—
	⁴⁰ K	1.00×10^{-3}	$168\text{--}298 \times 10^{-3}$	—
Sediments (Bq/g)	²³⁹⁺²⁴⁰ Pu	0.16×10^{-3}	$0.13\text{--}0.94 \times 10^{-3}$	—
	²³² Th	0.28×10^{-3}	$11\text{--}48 \times 10^{-3}$	—
	²³⁰ Th	0.36×10^{-3}	$12\text{--}48 \times 10^{-3}$	—
	²²⁸ Th	0.55×10^{-3}	$11\text{--}44 \times 10^{-3}$	—
	²³⁸ U	0.19×10^{-3}	$3.0\text{--}40 \times 10^{-3}$	—
	²³⁴ U	0.21×10^{-3}	$3.4\text{--}54 \times 10^{-3}$	—
	¹³⁷ Cs	0.11×10^{-3}	$0.68\text{--}29 \times 10^{-3}$	—
	⁴⁰ K	1.21×10^{-3}	$302\text{--}2130 \times 10^{-3}$	—
	²³⁹⁺²⁴⁰ Pu	0.00012×10^{-3}	$0.0\text{--}0.0015 \times 10^{-3}$	—
	²³² Th	0.010×10^{-3}	$0.0\text{--}0.019 \times 10^{-3}$	—
Surface water (Bq/L)	²³⁰ Th	0.014×10^{-3}	<MDC	—
	²²⁸ Th	0.020×10^{-3}	$0.0\text{--}0.055 \times 10^{-3}$	—
	²³⁸ U	0.70×10^{-3}	$1.90\text{--}64 \times 10^{-3}$	—
	²³⁴ U	0.74×10^{-3}	$3.30\text{--}73 \times 10^{-3}$	—
	¹³⁷ Cs	25.70×10^{-3}	<MDC	—
	⁴⁰ K	280×10^{-3}	$1050\text{--}1160 \times 10^{-3}$	—
	²³⁹⁺²⁴⁰ Pu	5.30×10^{-6}	<MDC	—
	²⁴¹ Am	8.80×10^{-6}	<MDC	—
	²³² Th	7.30×10^{-6}	$0.80\text{--}8.70 \times 10^{-5}$	—
	²³⁰ Th	4.50×10^{-6}	$0.80\text{--}2.70 \times 10^{-5}$	—
Drinking water (Bq/L)	²²⁸ Th	9.70×10^{-6}	$0.75\text{--}2.20 \times 10^{-4}$	—
	²³⁸ U	2.40×10^{-6}	$0.31\text{--}2.30 \times 10^{-3}$	—
	²³⁴ U	2.90×10^{-6}	$0.93\text{--}2.60 \times 10^{-3}$	—
	¹³⁷ Cs	0.37×10^{-6}	<MDC	—
	⁴⁰ K	0.33	<MDC	—

RN = radionuclides; NA = not analyzed; NR = not reported.

selected sites within a 50 m radius of a selected reference point. Individual sampling sites are selected on the basis of relatively flat topography, minimum surface erosion and

minimum surface disturbance by human or livestock activity. Samples for radiological and non-radiological analyses are prepared according to the CEMRC procedures [2]. Ac-

Fig. 5. Average plutonium and uranium concentrations in (Bq/L) measured in drinking water around the WIPP from 1998–2009.

tivity greater than MDC was detected in all samples for ^{234}U , ^{238}U , ^{235}U , $^{239+240}\text{Pu}$, ^{40}K and ^{137}Cs (Table 2). Fallout from above ground nuclear testing is the primary source of ^{137}Cs in the soils [8,9], although a potential source in the near vicinity of the WIPP site is the Gnome test site, about

8.8 km southwest of the WIPP site [10]. This test involved a 3.1 kiloton yield nuclear underground detonation in 1961 from which venting to the atmosphere occurred. $^{239+240}\text{Pu}$ in WIPP soil is all derived from the detonation of nuclear devices and primarily from global fallout from nuclear test. Although contamination of WIPP soil from Gnome test remains a possibility, $^{240}\text{Pu}/^{239}\text{Pu}$ ratios obtained from WIPP soils were consistent with that expected from global fallout whereas soil samples collected near the Gnome site showed isotopic ratios similar to those found at the Nevada Test Site (Table 3). An important finding of radiological studies in soils is that the activities of Pu and Am were correlated with the concentration of Al in aerosols, and that this was driven by the resuspension of dust particles contaminated with radioactive fallout from nuclear weapons tests. Related studies of soils collected on and near the WIPP site have shown that correlations exist among Al and both naturally-occurring and bomb-derived radionuclides including $^{239+240}\text{Pu}$ [5].

6. Surface water and sediments

Surface water and sediments are collected from three regional reservoirs situated on the Pecos river-Brantley Lake, Red Bluff and Lake Carlsbad. Sediments samples are collected at four randomly selected locations within the deep basins of each reservoir. Deep basin are chosen for sampling to minimize the disturbance and particle mixing effects of current and wave action that occur at shallower depths. Also, many of the analytes of interest tend to concentrate in the fine sediments that settle in the deep reservoir basins. The concentrations range of radionuclides in sediments and surface waters measured in 1998 are summarized in Table 2. It is interesting to note that that sediment has higher activity concentration than soil for all radionuclides. The observed difference in concentration is not surprising as reservoir sediments are often a sink or integrator for many contaminants as the soil in the surrounding watershed is leached and eroded. One of the primary factors that may influence contaminant concentrations in both sediment and soil is the particle size distribution. It is well documented

Table 3. Mean concentration (Bq/kg) of radionuclides for each of nine Gnome soils and the soils collected in the vicinity of the WIPP site and the isotopic ratio in soil samples.

Radionuclides	Gnome	Cactus flats	Near field
^{137}Cs	840 ± 247	5.63 ± 0.33	3.46 ± 0.21
^{60}Co	0.658	NA	NA
^{238}Pu	28.8 ± 20	0.023 ± 0.002	0.026 ± 0.009
$^{239+240}\text{Pu}$	149 ± 105	0.204 ± 0.011	0.119 ± 0.007
^{241}Pu	782 ± 430	NA	NA
^{241}Am	36.1 ± 25.2	0.070 ± 0.004	0.047 ± 0.003
^{228}Ac	10.3 ± 0.80	11.3 ± 0.3	8.56 ± 0.19
^{40}K	218 ± 15	224 ± 437	214 ± 5
	Ratio	Ratio	
	Gnome	WIPP site	Nevada Test Site
$^{137}\text{Cs}/^{239+240}\text{Pu}$	3591.26 ± 1635.70	29.33 ± 0.42	–
$^{238}\text{Pu}/^{239+240}\text{Pu}$	0.140 ± 0.025	0.130 ± 0.027	–
$^{240}\text{Pu}/^{239}\text{Pu}$	0.114 ± 0.013	0.175 ± 0.005	0.19
$^{239+240}\text{Pu}/^{241}\text{Am}$	3.95	2.72	3.0*

* Global fallout; NA = not analyzed.

that many contaminants (including radionuclides) are found in higher concentrations in the fine-grained particles [11]. One method that is used to correct the concentrations for differences in the amount of the fine grained slits and clays, is to normalize the concentration data to the amount of Al present in the samples [11].

7. Human population

In addition to the environment, the people working at WIPP, people who live and work close to the facility in Eddy and Lea counties are at risk of potential exposure for any releases of contaminants that could occur at WIPP. The In-

ternal Dosimetry and Whole Body Monitoring of citizens living within a 100-mile radius of WIPP were established as part of the WIPP-EM program to obtain baselines concerning aspects of human health and the citizen concerns which change with time. The program consists of a lung and whole body count of individuals every two years. The internal dosimetry program (ID) conducts analyses and consultations for the study and management of radiation exposure on both citizens with no possibility of occupational dose, and workers at WIPP and other facilities with occupational dose. In the *Lie Down and Be Counted* Program (LDBC), citizens within a 100-mile radius of WIPP, can simply come into CEMRC for a whole body count. Analyses include collection of information on work and residence history, past and

Table 4. “Lie Down and Be Counted” results through 31 December 2009.

Radionuclide	<i>In vivo</i> count type	Baseline counts ^a % of results $\geq L_C$ ^b	Operational counts % of results $\geq L_C$ ^c
²⁴¹ Am	Lung	5.2 (4.0 to 6.4)	4.2 (3.5 to 4.9)
¹⁴⁴ Ce	Lung	4.6 (3.5 to 5.7)	3.9 (3.2 to 4.5)
²⁵² Cf	Lung	4.1 (3.1 to 5.1)	5.5 (4.7 to 6.3)
²⁴⁴ Cm	Lung	5.7 (4.5 to 7.0)	4.7 (4.0 to 5.5)
¹⁵⁵ Eu	Lung	7.1 (5.8 to 8.4)	5.2 (4.4 to 6.0)
²³⁷ Np	Lung	3.6 (2.6 to 4.5)	4.1 (3.4 to 4.8)
²¹⁰ Pb	Lung	4.4 (3.3 to 5.4)	6.5 (5.6 to 7.4)
Plutonium isotope	Lung	5.7 (4.5 to 7.0)	5.8 (5.0 to 6.7)
²³² Th ^d via ²¹² Pb	Lung	34.2 (31.7 to 36.6)	33.4 (31.8 to 35.1)
²³² Th	Lung	4.9 (3.8 to 6.0)	5.2 (4.5 to 6.0)
²³² Th via ²²⁸ Th	Lung	4.1 (3.1 to 5.1)	4.7 (4.0 to 5.5)
²³³ U	Lung	5.7 (4.5 to 7.0)	9.6 (8.5 to 10.6)
²³⁵ U/ ²²⁶ Ra	Lung	10.7 (9.0 to 12.3)	11.2 (10.1 to 12.3)
Natural Uranium via ²³⁴ Th	Lung	5.2 (4.0 to 6.4)	6.1 (5.3 to 6.9)
¹³³ Ba	Whole body	3.6 (2.6 to 4.5)	3.1 (2.5 to 3.7)
¹⁴⁰ Ba	Whole body	5.2 (4.0 to 6.4)	4.1 (3.4 to 4.8)
¹⁴¹ Ce	Whole body	3.6 (2.6 to 4.5)	4.6 (3.9 to 5.3)
⁵⁸ Co	Whole body	4.4 (3.3 to 5.4)	2.9 (2.3 to 3.5)
⁶⁰ Co ^d	Whole body	54.6 (52.0 to 57.2)	26.8 (25.2 to 28.3)
⁵¹ Cr	Whole body	5.7 (4.5 to 7.0)	3.9 (3.2 to 4.5)
¹³⁴ Cs	Whole body	1.6 (1.0 to 2.3)	2.7 (2.2 to 3.3)
¹³⁷ Cs	Whole body	28.4 (26.1 to 30.8)	20.0 (18.6 to 21.5)
¹⁵² Eu	Whole body	7.4 (6.0 to 8.7)	6.1 (5.3 to 6.9)
¹⁵⁴ Eu	Whole body	3.8 (2.8 to 4.8)	2.9 (2.3 to 3.5)
¹⁵⁵ Eu	Whole body	3.8 (2.8 to 4.8)	3.5 (2.8 to 4.1)
⁵⁹ Fe	Whole body	3.8 (2.8 to 4.8)	5.5 (4.7 to 6.3)
¹³¹ I	Whole body	5.2 (4.0 to 6.4)	4.1 (3.4 to 4.8)
¹³³ I	Whole body	3.3 (2.3 to 4.2)	4.0 (3.3 to 4.7)
¹⁹³ Ir	Whole body	4.1 (3.1 to 5.1)	4.0 (3.3 to 4.7)
⁴⁰ K	Whole body	100.0 (100.0 to 100.0)	100.0 (100.0 to 100.0)
⁵⁴ Mn ^d	Whole body	12.3 (10.6 to 14.0)	11.8 (10.7 to 13.0)
¹⁰³ Ru	Whole body	2.2 (1.4 to 3.0)	1.9 (1.4 to 2.3)
¹⁰⁶ Ru	Whole body	4.4 (3.3 to 5.4)	3.9 (3.2 to 4.5)
¹²⁵ Sb	Whole body	5.2 (4.0 to 6.4)	3.9 (3.2 to 4.5)
²³² Th via ²²⁸ Ac	Whole body	34.7 (32.2 to 37.2)	25.3 (23.8 to 26.9)
⁸⁸ Y	Whole body	7.7 (6.3 to 9.0)	6.1 (5.3 to 7.0)
⁹⁵ Zr	Whole body	6.6 (5.3 to 7.9)	3.7 (3.1 to 4.4)

a: N = number of individuals ($N = 366$). Baseline counts include only the initial counts during this baseline period;

b: To determine whether or not activity has been detected in a particular person, the parameter L_C is used; the L_C represents the 95th percentile of a null distribution that results from the differences of repeated, pairwise background measurements; an individual result is assumed to be statistically greater than background if it is greater than L_C (margin of error, data prior to 27 March 1999, $N = 366$);

c: The margin of error represents the 95% confidence interval of the observed percentage; under replication of this experiment, one would expect 95% of the confidence intervals to include the true population if the sample was representative of the true population;

d: These radionuclides are present in the shield background, so they are expected to be detected periodically.

current radiation exposure, bioassays to measure the presence of radionuclides within body tissues (*in vivo*) or body fluids and excretions (*in vitro*), and calculation of dose associated with observed uptakes.

As of December 2009, 883 individuals have participated in the LDBC project. At the time the WIPP opened, 366 of these individuals had been measured, constituting the pre-operational baseline to which subsequent results are compared. Based on the data obtained thus far, there is no evidence of an increase in the frequency of detection of internally deposited radionuclides for citizens living within the vicinity of WIPP since WIPP began receipt of radioactive waste. As discussed in detail in Ref. [12], the criterion, L_C , is used to evaluate whether a result exceeds background, and the use of this criterion will result in a statistically inherent 5% false-positive error rate per pair-wise comparison (5% of all measurements will be determined to be positive when there is no activity present in the person). The LDBC results through 31 December 2009 are summarized in Table 4.

For the baseline measurements, the percentage of results greater than L_C are observed for radionuclides ^{232}Th via the decay of ^{212}Pb , $^{235}\text{U}/^{226}\text{Ra}$, ^{60}Co , ^{137}Cs , ^{40}K , ^{54}Mn , ^{232}Th via the decay of ^{228}Ac (Table 4). Five of these (^{232}Th via ^{212}Pb , ^{60}Co , ^{40}K , ^{54}Mn (^{228}Ac interference) and ^{232}Th (via ^{228}Ac)) are part of the shield-room background and positive detection is expected at low frequency. ^{40}K is a naturally occurring isotope of an essential biological element, so detection in all individuals is expected. ^{137}Cs and $^{235}\text{U}/^{226}\text{Ra}$ are not components of the shielded room background and were observed at frequencies greater than the 95% confidence interval for the false positive error rate.

For the operational monitoring, the percentage of results greater than L_C is consistent with baseline, except for ^{60}Co and ^{232}Th (via ^{228}Ac). For these radionuclides, the percentage of results greater than L_C decreased relative to the baseline. This is likely due to the short half life of ^{60}Co (5.2 years) and the replacement of aluminum (tends to contain Th and U) in some of the detector cryostat components with those manufactured from low radiation background steel.

^{40}K results have been positive for all participants and is range from 792 to 5558 Bq/person with an overall mean of 2494 ± 24 Bq/person. Such results are expected since K is an essential biological element contained primarily in muscle, and a theoretical constant fraction of all naturally occurring K is the radioactive isotope ^{40}K . The mean ^{40}K value (3068 ± 28 Bq/person) for males is significantly greater than that of females (1893 ± 20 Bq/person) because of larger body sizes and greater muscle content of males than females.

Detectable ^{137}Cs is present in $22 \pm 3\%$ of citizens living in the Carlsbad area and is ranged from 4.9 to 132 Bq/person with an overall mean of 10.6 ± 0.6 Bq/person. The mean ^{137}Cs body burden for males is 11.5 ± 0.8 Bq/person, which is significantly greater than that of females, which is 11.7 ± 0.8 Bq/person. The presence of ^{137}Cs is independent of ethnicity, age, and radiation work history, consumption of wild game, nuclear medical treatments and European travel. However, the occurrence of detectable ^{137}Cs is associated with gender where males had higher prevalence of ^{137}Cs relative to females. Furthermore, the presence of ^{137}Cs is associated with smoking. Smokers had a higher prevalence of detectable ^{137}Cs (28.5%) as compared

to non-smokers (23.8%). It is likely that the association with gender is related to the tendency for larger muscle mass in males than in females, as supported by the ^{40}K results. The association of ^{137}Cs with smoking could be related to the presence of fallout ^{137}Cs in tobacco, decreased pulmonary clearing capability in smokers, or other as yet unidentified factors.

The absence of detectable levels of plutonium, suggest that there have been no significant releases from WIPP. As reported in previous CEMRC reports, the percentage of results greater than L_C for $^{235}\text{U}/^{226}\text{Ra}$ (11%) are significantly higher than the distribution-free confidence interval for a 5% random false-positive error rate. These data are not nearly as compelling as those for ^{137}Cs , but the large sample size of the current cohort tends to support the observed pattern. Although ^{235}U and ^{226}Ra cannot be differentiated via gamma spectroscopy, it is likely that the signal is the result of ^{226}Ra because the natural abundance of ^{226}Ra is much greater than that of ^{235}U .

8. Conclusion

The Carlsbad Environmental Monitoring & Research Center (CEMRC), located in Carlsbad, New Mexico, is an independent, academic-based environmental monitoring facility developed to monitor the environment around the WIPP transuranic nuclear waste to below background levels for radionuclides and other contaminants of interest to the regional community. The program was developed in conjunction with the US Department of Energy, contractor, state and local government and regional citizens to monitor the environment and people in a 100-mile radius around WIPP. Over the ten years of environmental monitoring of the area residents and for selected aerosols, soils, drinking water and surface water, there is no evidence of increases in radiological contaminants that could be attributed to releases from WIPP. The success of such a monitoring program is important to boost public confidence, and thereby to enhance public acceptance, in localities where a "not in my-backyard" attitude could hinder the siting of a nuclear waste repository anywhere in the world.

Acknowledgment. This work is funded by US Department of Energy through a grant DE-FG29-91AL7416 from the Carlsbad Field Office.

References

- Chandra, S., Ortiz, C. A., McFarland, A. R.: Effects of Salt Loading and Flow Blockage on the WIPP Shrouded Probe. Report 8248A/01/08/93/SC, Aerosol Technology Laboratory, Texas A&M University Department of Mechanical Engineering, College Station, TX (1993).
- Carlsbad Environmental Monitoring and Research Center: Annual Report, CEMRC 1999 Report (<http://cemrc.org/reports/99rept/1999Report.pdf>), New Mexico State University, Carlsbad, NM (1999).
- Carlsbad Environmental Monitoring and Research Center: Annual Report. <http://cemrc.org/reports/09rept/index.html>, New Mexico State University, Carlsbad, NM, (2009).
- DOE/WIPP: Waste Isolation Pilot Plant Annual Site Environmental Report for 2008, DOE/WIPP-09-2225.
- Arimoto, R., Kirchner, T., Webb, J. L., Conley, M., Stewart, B. D., Schoep, D. A., Walthall, M.: $^{239,240}\text{Pu}$ and inorganic substances in

- aerosols from the vicinity of a waste isolation pilot plant: the importance of resuspension. *Health Phys.* **83**, 456–470 (2002).
6. Arimoto, R., Webb, J. L., Conley, M.: Radioactive contamination of atmospheric dust over southeastern New Mexico, *Atmos. Environ.* **39**, 4745–4754 (2005).
 7. Cothorn, C. R., Lappenbusch, W. L.: Uranium in USA drinking water. *Health Phys.* **43**, 89–172 (1983).
 8. Ritchie, J. C., McHenry, J. R.: Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. *J. Environ. Qual.* **19**, 215–233 (1990).
 9. Beck, H. L., Bunnett, B. G.: Historical overview of atmospheric nuclear weapons testing and estimates of fallout in the continental United States. *Health Phys.* **82**, 591–608 (2002).
 10. Faller, S.: Residual Soil Radioactivity at the Gnome Test Site in Eddy County, New Mexico, Report No. EPA 600/R-94/117, Washington DC, Environmental Protection Agency, July (1994).
 11. Mudroch, A., Azcue, J. M.: *Manual of Aquatic Sediment Sampling* Lewis Publishers, Ann Arbor, Michigan (1995).
 12. Webb, J. L., Kirchner, T. B.: An evaluation of *in vivo* sensitivity via public monitoring. *Radiat. Prot. Dosim.* **89**, 183–191 (2000).