Radioactive Materials in Biosolids: National Survey, Dose Modeling, and Publicly Owned Treatment Works (POTW) Guidance

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ABSTRACT

The Nuclear Regulatory Commission (NRC) announced the availability of three new documents concerning radioactive materials in sewage sludge and ash from publicly owned treatment works (POTW). One of the documents is a report presenting the results of a volunteer survey of sewage sludge and ash samples provided by 313 POTWs. The second document is a dose modeling document, using multiple exposure pathway modeling focused on a series of generic scenarios, to track possible exposure of POTW workers and members of the general public to radioactivity from the sewage sludge or ash. The third document is a guidance report providing recommendations on the management of radioactivity in sewage sludge and ash for POTW owners and operators. This paper explains how radioactive materials enter POTWs, provides criteria for evaluating levels of radioactive material in sludge and ash, and gives a summary of the results of the survey and dose modeling efforts.

In the United States there are no identified situations in which radioactive materials in sewage sludge are a threat to the health and safety of POTW workers or the general public. However, there have been a small number of facilities where elevated levels of man-made radioactive materials were detected. The United States General Accounting Office (1994) described nine cases where elevated levels were found in sewage sludge or ash or the wastewater collection system, which have resulted in considerable cleanup expense to the POTW authority or specific industrial dischargers of wastewater to the POTW. Also, several states have identified situations where radium from drinking water residuals has been reconcentrated in sewage sludge. Based on this past experience, there have been concerns that radioactive materials could concentrate in sewage sludge and ash and pose a threat to the health and safety of POTW workers or the general public.

As a result of interest from the U.S. Congress, the Interagency Steering Committee on Radiation Standards (ISCORS) conducted a survey of radioactive material in sewage sludge and ash. The committee also performed dose modeling of the survey results to address radiation concerns and to estimate typical levels of radioactive materials in POTWs around the country. The committee then provided recommendations on the management of radioactivity in sewage sludge and ash for POTW owners and operators, including guidance on evaluating whether the presence of radioactive materials in sewage sludge or ash could pose a threat to the safety of their workers or the general public.

The NRC and the USEPA formed ISCORS in 1995 to assist in resolving and coordinating regulatory issues associated with radiation standards. In addition to the NRC and USEPA, ISCORS membership includes senior managers from the Department of Defense, the Department of Energy, the Department of Labor's Occupational Safety and Health Administration, the Department of Transportation, and the Department of Health and Human Services. Representatives of the Office of Management and Budget, Office of Science and Technology Policy, and the states are observers at meetings.

The Interagency Steering Committee on Radiation Standards formed a Sewage Sludge Subcommittee to conduct the ISCORS sewage sludge and ash survey and to develop the POTW guidance document. Most of the information previously available on reconcentration of radionuclides in sludge and ash was from unusual circumstances that triggered discovery of incidents in the course of other POTW operations. The Sewage Sludge Subcommittee evaluated the occurrence of radioactive materials in sewage sludge and ash, including the sampling and analysis of sewage sludge and ash from POTWs across the country, and conducted modeling to evaluate the dose associated with radioactive material found in sewage sludge and ash. These activities were conducted to evaluate the need for future regulatory actions by individual agencies. Recommendations based on the Sewage Sludge Subcommittee's analyses provide prudent steps that may be taken to determine if there is concern associ-

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Published in J. Environ. Qual. 34:64–74 (2005).

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Abbreviations: DOE, Department of Energy; ISCORS, Interagency Steering Committee on Radiation Standards; NORM, naturally occurring radioactive material; NRC, Nuclear Regulatory Commission; POTW, publicly owned treatment works; RESRAD, RESidual RADiation, family of computer code for evaluating radioactivity contamination; TENORM, technologically enhanced naturally occurring radioactive material.

ated with the radiation levels present in POTW sludge or ash.

WHY IS THERE RADIOACTIVE MATERIAL IN SEWAGE AND SEWAGE SLUDGE?

Radioactive materials are an ever-present component of the natural environment and are also produced through some human activities. Generally, the presence of radioactive materials is a concern only when concentrations become sufficiently elevated above background levels (Table 1) to potentially pose a health risk, or in cases where the ability of a POTW to use or dispose of the sewage sludge or ash is limited.

Publicly owned treatment works can receive naturally occurring radioactive material (NORM) or man-made radionuclides from many sources (Table 2). Ground and surface water, as well as food and plants, can contain elevated levels of NORM radionuclides. Some public drinking water supplies depend on ground water sources that have radium levels that exceed the drinking water standard for radioactive material. Radon is also released to the atmosphere from soil and water and can enter any building, including POTW facilities, through ground contact openings in a concrete slab or foundation wall. The levels of radon vary considerably across the country, including within individual states (Fig. 1). Levels of NORM can be enhanced by human activity and by technologies associated with extraction processes, thus producing technologically enhanced naturally occurring radioactive materials (TENORM). The TENORM can be introduced to the sewage system from potential industrial discharges (e.g., water treatment plants, mining and petroleum industries, fertilizers, electronics, ceramics, foundries, and pulp and paper mills). Sources of man-made radionuclides can enter sewers via surface water runoff containing fallout, human wastes from individuals undergoing medical diagnosis or therapy involving radionuclides, licensed discharges of limited quantities of radioactive materials from Department of Energy (DOE) facilities, NRC licensees, and Agreement State licensees (e.g., nuclear laundries, laboratories, medical facilities; Table 3), and anthropogenic materials exempt from licensing. The NRC estimates that of the more than 22 000 regulated users of Atomic Energy Act radioactive materials, about 9000 users have the potential to release radioactive materials to sanitary sewer systems.

Table 1. Average annual exposure to radiation.†

Radiation source	Average exposure	Typical range of variability
	μSv yr^{-1}‡	
	Natural sources	
Terrestrial	300	100–800
Radon	2000	300–8 200
Cosmic	300	300–800
Internal	400	200–1 000
	Man-made sources	
Medical	500	
Consumer products	100	
Other (nuclear fuel cycle and occupational)	10	
	Total	
	3600	900–10 800

† Sources: National Council on Radiation Protection and Measurements (1987a) for average exposure values, Huffert et al. (1994) and Fisher (personal communication, 2003) for ranges of variability.
‡ 1 microsievert (1 μSv) = 0.1 milliroentgens (0.1 mrem).

There are no specific federal regulations that limit the levels of radioactive material in sewage sludge and ash, although both the NRC and the DOE have requirements that control discharges to municipal sanitary sewer systems (Nuclear Regulatory Commission, 1991; United States Department of Energy, 1990). In a manner similar to trace heavy metals, some radionuclides (e.g., ^{131}I, ^{40}K, ^{226}Ra, ^{228}Ra, ^{89}Sr, ^{201}Tl) may concentrate in the sewage sludge produced by POTWs as a by-product of wastewater treatment. The solids-associated radionuclides can be even further concentrated in the ash produced by sewage sludge incineration.

Interagency Steering Committee on Radiation Standards Survey

A USEPA literature review and follow-up telephone survey identified nine references containing data on radioactivity concentrations in sewage sludge (USEPA, 1986). These references included the results of one-time surveys and ongoing monitoring programs by local authorities and state agencies, results for individual facilities and facilities from as many as 10 cities, and reports of incidents of sewage sludge contamination reported by the NRC. The data obtained varied widely with respect to the purpose of data collection, type of material sampled, number of samples, and radionuclides analyzed. The available data identified four radionuclides as most frequently found in sewage sludge: ^{131}I, ^{226}Ra, ^{241}Am,

Table 2. Sources and potential pathways for radioactive materials to reach publicly owned treatment works (POTWs).†

Discharges to POTWs	Treatment process	Infiltration and inflow
• Drinking water and drinking water residuals that contain naturally occurring radioactive material (NORM) • Sewage with radioactive materials from food and medical procedures • Wastewater from Nuclear Regulatory Commission (NRC) or Agreement State licensees handling radioactive materials in unsealed form • Wastewater from industries handling or processing materials containing NORM • Exempt or unlicensed radioactive materials	• Process chemicals with radioactive materials (e.g., lime, fly ash, waste pickle liquor, or wood ash) • Wood chips, saw dust or other bulking agents used in composting sewage sludge • Any process that agitates or aerates water liberates radon gas	• Infiltrating ground water containing NORM, including radon gas • Surface waters runoff containing NORM or fallout, via combined sewers

† Source: Interagency Steering Committee on Radiation Standards (2003c).

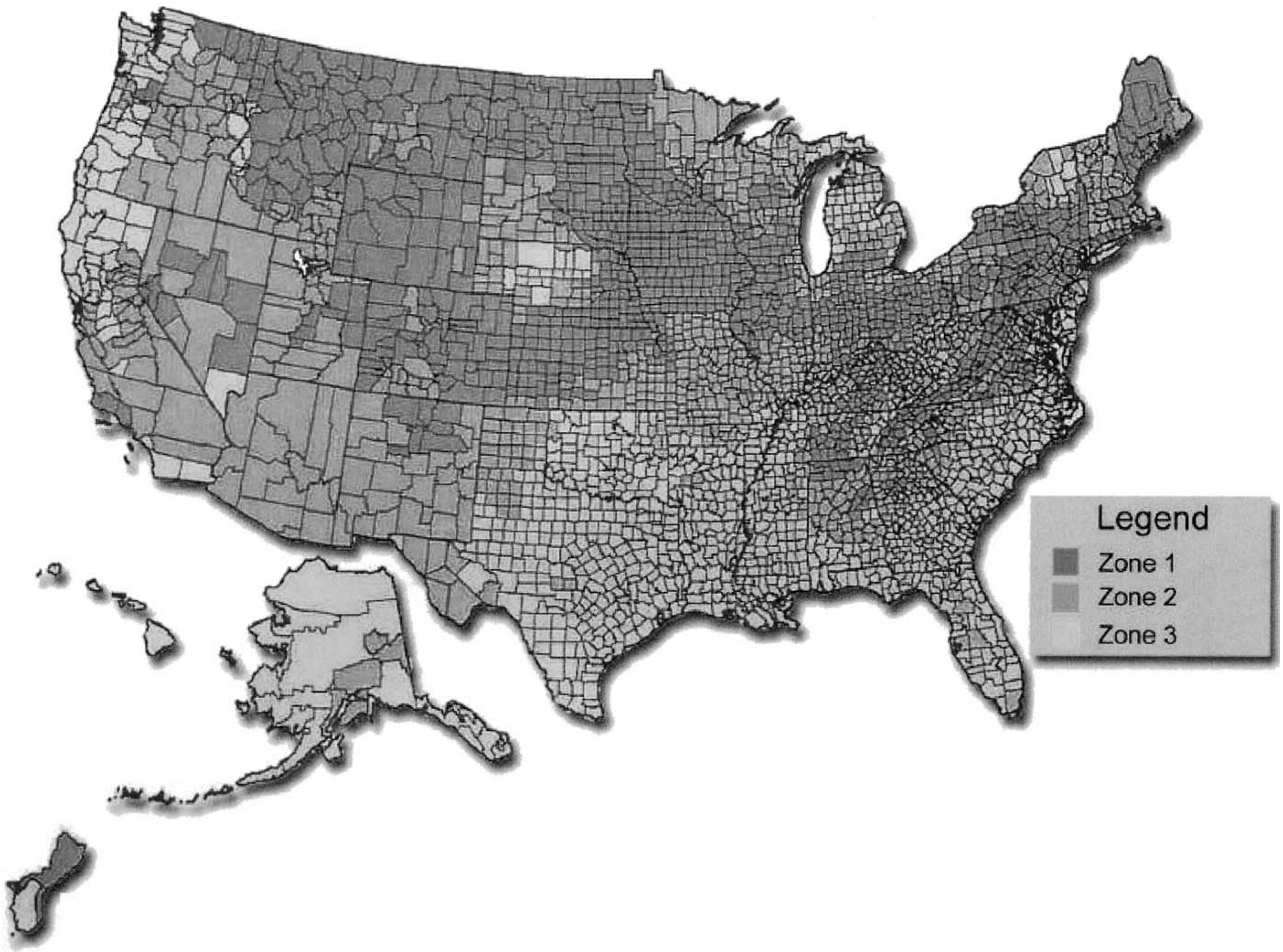

Fig. 1. Map of radon zones. See USEPA (2004) and USGS (2004) for color versions.

and ^{137}Cs. The Association of Metropolitan Sewerage Agencies (AMSA) recently conducted a survey of 55 POTWs that produced similar results to those generated by the ISCORS survey (National Biosolids Partnership, 1999).

The ISCORS survey used NRC and USEPA laboratory capacity for processing environmental samples to collect information on radioactivity in sewage sludge and ash from POTWs. The objectives of the survey were to (i) obtain national estimates of high-probability occurrences of elevated levels of radioactive materials in sewage sludge and ash at POTWs, (ii) estimate how much radioactive contamination comes from NRC and Agreement State licensees and how much from natu-

Table 3. Types of Nuclear Regulatory Commission (NRC) and Agreement State licensees and typical radionuclides.†

Academic (broad scope)	Medical (broad scope, nuclear pharmacies)	Manufacturing and distribution (broad scope, nuclear laundries, decontamination services)	Research and development (broad scope)	Others (e.g., ore processing mills, uranium enrichment plants)
Carbon-14	Carbon-14	Americium-241	Carbon-14	Plutonium-238, 239, 240
Cobalt-60	Chromium-51	Antimony-125	Cesium-134	Radium-226
Cesium-137	Cobalt-57	Cobalt-60	Hydrogen-3	Thorium-228, 232
Hydrogen-3	Gallium-67	Cesium-134, 137	Iodine-125, 131	Uranium-233, 234, 235, 238
Iodine-125, 131	Indium-111	Hydrogen-3	Phosphorus-32	
Iron-59	Iodine-125, 131	Iodine-125, 131	Sulfur-35	
Manganese-54	Iron-59	Manganese-54		
Phosphorus-32	Phosphorus-32, 33	Niobium-95		
Phosphorus-33	Strontium-89, 90	Phosphorus-32		
Sulfur-35	Sulfur-35	Plutonium-238, 239, 240		
	Technetium-99m	Polonium-210		
	Thallium-201	Strontium-89, 90		
		Sulfur-35		
		Uranium-233, 234, 235, 238		
		Zirconium-95		

† Source: Interagency Steering Committee on Radiation Standards (2003c).

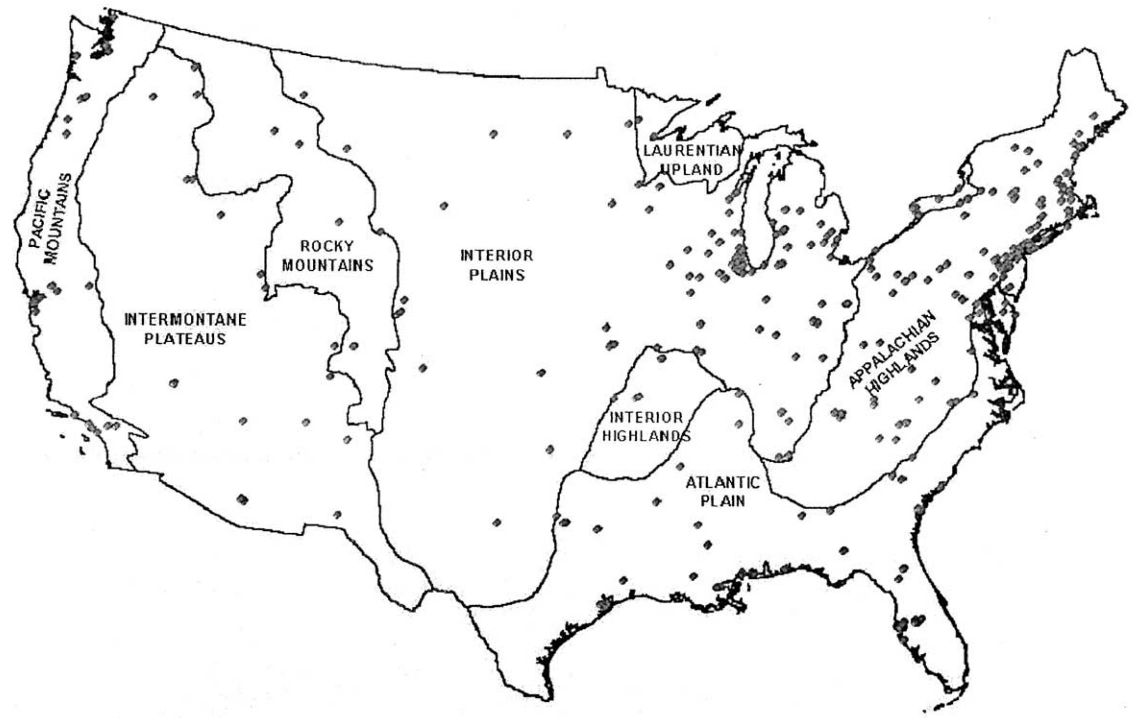

Fig. 2. Location of publicly owned treatment works (POTW) in the Interagency Steering Committee on Radiation Standards (ISCORS) survey (Interagency Steering Committee on Radiation Standards, 2003a).

rally occurring radioactivity, and (iii) support rulemaking decisions by the NRC and USEPA. The voluntary survey had two components: a questionnaire and a program for sampling and analyzing sewage sludge and incinerator ash. Questionnaires were sent to 631 POTWs, requesting information regarding wastewater sources, wastewater and sludge treatment processes, and sewage sludge disposal practices. Using the information from the 420 completed and returned questionnaires, the ISCORS subcommittee selected 313 POTWs (Fig. 2) distributed around the country to provide samples. The selection emphasized POTWs with the greatest potential to receive waste from licensees and in areas with higher levels of NORM. Consequently, the survey results should be considered conservative, and may not necessarily represent typical levels occurring in POTWs across the country. Altogether, 311 sewage sludge samples and 35 ash samples were analyzed. Approximately half of the samples were analyzed by the U.S. Department of Energy's Oak Ridge Institute for Science and Education in Oak Ridge, Tennessee, under contract to NRC. The remaining samples were analyzed by the USEPA's National Air and Radiation Environmental Laboratory. Both labs followed strict quality assurance–quality control procedures and rigorous analytical methods, described in detail elsewhere (Interagency Steering Committee on Radiation Standards, 2003a).

The ISCORS survey resulted in 45 radionuclides being detected in both sewage sludge (Table 4) and ash (Table 5). Six radionuclides were detected only once, including ^{141}Ce, ^{134}Cs, ^{154}Eu, ^{59}Fe, ^{138}La, and ^{153}Sm), whereas eight radionuclides (^{7}Be, ^{214}Bi, ^{131}I, ^{40}K, ^{212}Pb, ^{214}Pb, ^{226}Ra, and ^{228}Ra) were detected in more than 200 samples. The highest concentrations were observed for ^{131}I, ^{89}Sr, and ^{201}Tl (all medical isotopes with short half-lives). Many samples contained radium and uranium. Samples from areas using ground water as a source of drinking water had elevated ^{228}Ra, ^{228}Th, ^{214}Bi, ^{214}Pb, and ^{226}Ra concentrations. Samples from areas using surface water as a source of drinking water had elevated ^{137}Cs, ^{7}Be, and ^{232}Th concentrations. Publicly owned treatment works with combined sewers had greater levels of radioactive material than POTWs with separate sewers. The survey results represent a single sampling event at each of the 313 POTWs, and therefore do not account for seasonal or episodic fluctuations in radionuclide levels.

The analyses revealed that the samples primarily contained NORM and TENORM radionuclides such as radium (Tables 4 and 5). With the exception of NORM and TENORM, most other radionuclides were at, or near, the limit of detection, and generally comparable with levels found in soils and fertilizers (Table 6). The specific results of the analyses and data obtained by the questionnaire are discussed in detail in the survey report (Interagency Steering Committee on Radiation Standards, 2003a).

Interagency Steering Committee on Radiation Standards Dose Modeling

Based on what is known about the potential for reconcentrating radioactive material at POTWs, the three primary pathways for POTW workers and members of the public to be exposed to radiation from POTW operations include inhalation, ingestion, and direct exposure. Human exposure to radiation sources (Table 1) is de-

Table 4. Concentrations of radionuclides in sewage sludge.†

Radionuclide	Minimum	Median	95th Percentile	Maximum	Number of detects, analyses
	pCi g^{-1} dry wt.‡				
Alpha	ND§	7	34	137	309, 311
Beta	1.7	13	34	93	311, 311
Am-241	ND	ND	ND	2.5	10, 311
Be-7	ND	1.2	9	22	263, 311
Bi-212	ND	ND	1.3	13	101, 311
Bi-214	ND	0.3	2.3	16	238, 311
C-14¶	ND	ND	1	3	62, 158
Ce-141	ND	ND	ND	0.016	1, 311
Co-57	ND	ND	ND	0.26	6, 311
Co-60	ND	ND	ND	5.1	13, 311
Cr-51	ND	ND	ND	3.5	6, 311
Cs-134	ND	ND	ND	0.04	1, 311
Cs-137	ND	ND	0.11	3.6	133, 311
Eu-154	ND	ND	ND	21	1, 311
Fe-59	ND	ND	ND	0.4	1, 311
H-3¶	ND	0.3	5	8	111, 158
I-125	ND	ND	ND	40	11, 311
I-131	ND	1.8	51	840	246, 311
In-111	ND	ND	0.04	3.6	19, 311
K-40	ND	4	12	26	308, 311
La-138	ND	ND	ND	0.07	1, 311
Pa-234m	ND	ND	7	27	80, 311
Pb-210	ND	ND	4	13	135, 311
Pb-212	ND	0.44	1.9	15	303, 311
Pb-214	ND	0.31	2.6	17	253, 311
Pu-238	ND	0.01	0.07	0.19	75, 92
Pu-239	ND	0.003	0.04	0.12	68, 92
Ra-223	ND	ND	ND	0.09	2, 311
Ra-224	ND	ND	0.9	12	47, 311
Ra-226	ND	2	13	47	289, 311
Ra-228	ND	0.82	5.1	38	271, 311
Rn-219	ND	ND	ND	ND	0, 311
Sm-153	ND	ND	ND	27	1, 311
Sr-89	ND	0.35	20	70	68, 98
Sr-90	ND	0.1	1	9.4	64, 98
Th-227	ND	ND	0.1	0.5	49, 207
Th-228	0.07	0.605	4.1	9	92, 92
Th-230	0.09	0.34	1	1.7	92, 92
Th-232	0.02	0.2	0.6	1.6	92, 92
Th-234	ND	0.6	6.7	23	191, 311
Tl-201	ND	ND	46	241	151, 311
Tl-202	ND	ND	0.53	1.16	73, 311
Tl-208	ND	0.07	0.96	4.8	180, 311
U-234	0.18	1.95	17	44	92, 92
U-235	ND	ND	0.45	3.1	112, 311
U-238	0.18	1.4	12	26	92, 92
Zn-65	ND	ND	ND	0.06	1, 311

† Source: Interagency Steering Committee on Radiation Standards (2003a).
‡ 1 pCi = 0.037 Bq.
§ ND, not detected or negative concentrations.
¶ Indicates that concentrations for this radionuclide are expressed in pCi g^{-1} wet wt.

rived primarily from background natural radiation; however, a person's occupation, geographic location, time spent outdoors, need for diagnostic medical treatments and testing, time spent traveling in airplanes, and other activities can greatly affect the relative contribution of natural, man-made, and global fallout sources. On the average, 80% of human exposure to radiation comes from natural sources: radon gas, radionuclides in the human body, cosmic radiation, and that present in rocks and soil. The remaining 20% comes from man-made radiation sources, primarily X-rays for medical procedures. Radiation sources at POTWs are generally insignificant compared with background radiation under most conditions. However, under conditions at POTWs where elevated levels of radionuclides have been detected, there is the possibility that doses to POTW workers and to the general public could be of concern.

The ISCORS survey results provide an estimate of the range of concentrations of radionuclides that may be present in sewage sludge (Table 4) and ash (Table 5). The ISCORS dose assessment effort provided a means for estimating potential doses associated with these levels of radionuclides under various sludge management scenarios. Guided in part by examples from previous assessments by the DOE, USEPA, and NRC, the ISCORS subcommittee developed scenarios that were simple and generic (i.e., not based on the unique characteristics of any particular site or sites), but broad and general enough to account for the most common sewage sludge and ash management practices. The scenarios were intended to represent a variety of different uses or disposal options, and situations where radiation exposure is most likely. For each scenario, all the standard environmental transport (resuspension of dust, leaching into ground water) and exposure (external exposure, inhalation, and ingestion) pathways were considered. The scenarios were designed to form the basis for performing a realistic but conservative assessment of the doses associated with typical sewage sludge management practices that could result in human exposures to radioactive materials.

Table 5. Concentrations of radionuclides in sewage sludge ash.†

Radionuclide	Minimum	Median	95th Percentile	Maximum	Number of detects, analyses
	pCi g^{-1} dry wt.‡				
Alpha	5	27	93	178	35, 35
Beta	15	43	95	140	35, 35
Am-241	ND§	ND	ND	0.21	2, 35
Be-7	ND	4.3	15.4	30	34, 35
Bi-212	ND	1.2	3.5	15.7	25, 35
Bi-214	ND	2.4	14	16	34, 35
C-14¶	ND	ND	1	1	5, 18
Ce-141	ND	ND	ND	ND	0, 35
Co-57	ND	ND	ND	0.17	1, 35
Co-60	ND	ND	ND	3.46	2, 35
Cr-51	ND	ND	0.3	35	5, 35
Cs-134	ND	ND	ND	ND	0, 35
Cs-137	ND	0.07	0.23	0.37	34, 35
Eu-154	ND	ND	ND	ND	0, 35
Fe-59	ND	ND	ND	ND	0, 35
H-3¶	ND	ND	4	8	7, 18
I-125	ND	ND	0.4	1	4, 35
I-131	ND	0.22	20	81	23, 35
In-111	ND	ND	ND	ND	0, 35
K-40	7.4	14.2	20.9	22.4	35, 35
La-138	ND	ND	ND	ND	0, 35
Pa-234m	ND	3	11	77	30, 35
Pb-210	ND	ND	8.5	12.3	16, 35
Pb-212	0.36	1.5	3.3	15	35, 35
Pb-214	0.61	2.9	14.8	16.4	35, 35
Pu-238	ND	0.015	0.1	0.1	20, 28
Pu-239	ND	0.01	0.06	0.17	21, 28
Ra-223	ND	ND	0.2	0.8	4, 35
Ra-224	ND	ND	2	4.9	15, 35
Ra-226	ND	3	18	22	33, 35
Ra-228	0.65	2.5	17	30	35, 35
Rn-219	ND	ND	0.2	0.4	3, 35
Sm-153	ND	ND	ND	ND	0, 35
Sr-89	ND	1	60	300	20, 30
Sr-90	ND	0.2	1	6	24, 30
Th-227	ND	ND	0.3	1.1	14, 33
Th-228	ND	1.6	6.7	14	27, 28
Th-230	ND	0.75	2.3	2.6	27, 28
Th-232	ND	0.505	1	1.7	27, 28
Th-234	ND	3.6	11	80	31, 35
Tl-201	ND	0.62	73	105	19, 35
Tl-202	ND	ND	0.99	1.53	7, 35
Tl-208	ND	0.66	2.3	13.5	32, 35
U-234	1.2	5.55	49	91	28, 28
U-235	ND	0.15	0.7	3.4	30, 35
U-238	0.8	3.3	35	74	28, 28
Zn-65	ND	ND	ND	0.06	1, 35

† Source: Interagency Steering Committee on Radiation Standards (2003a).
‡ 1 pCi = 0.037 Bq.
§ ND, not detected or negative concentrations.
¶ Indicates that concentrations for this radionuclide are expressed in pCi g^{-1} wet wt.

The seven scenarios represent four categories of sewage sludge and ash management and processing practices (Tables 7 and 8). Scenarios 1 through 3 consider different situations involving land application of biosolids. For the first two, people are exposed while living or camping on a land application site. In the third, the residents of the nearby town are exposed to radionuclides that are transferred away from the land application site by wind, runoff, ground water flow, or other pathways. The dose assessment for this off-site population is more complex than for the on-site exposure scenarios, and requires more sophisticated modeling. Scenarios 4 and 5 treat two other off-site exposure scenarios involving sewage sludge or ash disposal via landfilling and incineration. The last two scenarios (6 and 7) consider possible exposures of land application workers and of POTW workers.

Each scenario was translated from a qualitative narrative and list of potential transport and exposure pathways into a specific set of parameters for use in widely accepted multipathway environmental transport models. The RESRAD family of codes (including RESRAD Version 6.0, RESRAD-BUILD Version 3.0, and RESRAD-OFFSITE Version 1.0) were used to generate a radionuclide-specific sludge concentration-to-dose conversion factor for each scenario. The RESRAD multimedia computer codes were developed by Argonne National Laboratory under sponsorship of DOE and NRC for use in evaluating radioactively contaminated sites and buildings, respectively. The codes have been widely used in the United States and abroad to (i) develop residual radioactive material guidelines, (ii) calculate radiation dose and excess lifetime cancer risk to a chronically exposed individual at a site with residual contamination, and (iii) evaluate the potential radiological dose to an individual who works or lives in a building contaminated with radioactive material (Yu, 1994, 1999).

The modeling used a manageable number of parameters (about 140 for RESRAD, 300 for RESRAD-OFFSITE, and 40 for RESRAD-BUILD) to account for the major

Table 6. Survey concentration ranges and typical U.S. background concentrations of radionuclides in soil, fertilizer, and common building materials.†

Radionuclide	Soil	Phosphate fertilizer‡	Building materials	Sewage sludge concentration	Ash concentration
	pCi g^{-1} dry wt.§				
Bi-212	0.1–3.5	0.1–4.6	0.1–3.7	0–13	0–16
Bi-214	0.1–3.8	4.0–140	2.5–5.0	0–16	0–16
Cs-137	0.1–0.2	NDA¶	NDA	0–3.6	0–0.37
K-40#	2.7–19	32–160	0.8–30	0–26	7.4–22
Pa-234m#	0.1–3.8	4.0–140	0.2–5.0	0–27	0–77
Pb-212#	0.1–3.5	0.1–4.6	0.1–3.7	0–15	0.36–15
Pb-214#	0.1–3.8	4.0–140	0.2–5.0	0–17	0.61–16
Ra-223#	<0.1–0.2	0.2–6.6	0.1–0.2	0–0.09	0.1–0.8
Ra-224#	0.1–3.5	0.1–4.6	0.1–3.7	0–12	0–4.9
Ra-226#	0.1–3.8	0.1–24	0.1–3.5	0–47	0–22
Ra-228#	0.1–3.5	0.1–4.6	0.1–3.7	0–38	0.65–30
Th-227#	<0.1–0.2	0.2–6.6	0.1–0.2	0–0.5	0–1.1
Th-228#	0.1–3.5	0.1–4.6	0.1–3.7	0.07–9	0–14
Th-230#	0.1–3.8	4.0–140	0.2–5.0	0.09–1.7	0–2.6
Th-232#	0.1–3.5	0.1–4.6	0.1–3.7	0.02–1.6	0–1.7
Th-234#	0.1–3.8	4.0–140	0.2–5.0	0–23	0–80
Tl-208#	0.1–3.5	0.1–4.6	0.1–3.7	0–4.8	0–14
U-234#	0.1–3.8	4.0–140	0.2–5.0	0.18–44	1.2–91
U-235#	<0.1–0.2	0.2–6.6	0.1–0.2	0–3.1	0–3.4
U-238#	0.1–3.8	4.0–140	0.2–5.0	0.18–26	0.8–74

† Sources: Interagency Steering Committee on Radiation Standards (2003c), Tykva and Sabol (1995), National Council on Radiation Protection and Measurements (1987b, 1976), Eisenbud and Gesell (1997), Cohen (1997).
‡ Concentrations of radionuclides in phosphate fertilizers (not typical blended fertilizers) except for the concentration of K-40 in phosphate fertilizers; the concentrations of typical blended commercial fertilizers would be 10 to 50% of these values.
§ 1 pCi = 0.037 Bq.
¶ NDA, no data available.
# Naturally occurring radionuclide.

transport and exposure pathways of interest, and allowed sensitivity and Monte Carlo probabilistic uncertainty analyses to be conducted. For many parameters, values and distributions were selected that were specific to each scenario. For others, generic (non-scenario-specific) values and distributions were used, particularly for plant and animal transfer factors, food ingestion, soil characteristics, and hydrogeological parameters. Details are provided in Interagency Steering Committee on Radiation Standards (2003b).

The dose-to-source ratio (DSR), measured as μSv yr^{-1} per Bq kg^{-1} (mrem yr^{-1} per pCi g^{-1}), for each scenario and radionuclide was defined as the peak total effective dose equivalent (TEDE) or “dose” to an exposed individual. The TEDE is currently the basis of standards and regulations for radiation exposure in the United States. In some cases, additional information on indoor radon and nonradon components of the radiation dose was also calculated. The radionuclides considered were based primarily on the ISCORS survey.

The DSR values ranged widely within each scenario,

Table 7. Scenarios and pathways.†

Pathway		S1	S2	S3	S4	S5	S6	S7
		Scenario‡						
External radiation		X	X	X	X	X	X	X
Inhalation	dust	X	X	X	X	X	X	X
	indoor radon	X						X
	outdoor radon	X	X	X	X	X	X	
Ingestion	ground water	X	X		X			
	plants	X		X	X	X		
	meat and milk	X	X	X	X	X		
	fish	X	X	X	X			
	soil	X	X	X	X	X		

† Source: Interagency Steering Committee on Radiation Standards (2003b).
‡ S1, on-site resident; S2, recreational user; S3, nearby town; S4, landfill neighbor; S5, incinerator neighbor; S6, agricultural application worker; S7, publicly owned treatment works (POTW) workers.

for the various radionuclides, and there were significant differences among the scenarios. Variability in concentrations of radioactivity in sewage sludge and ash was a major factor (up to 100× difference) between 5th percentile and 95th percentile calculated doses. However, the exposure scenarios' uncertainty and variability contributed the most to the overall uncertainty and variability in calculated doses (>1000× differences among doses from different scenarios). These differences, however, are meaningful only when considered in context with the survey results or measurements associated with an individual site. The DSRs computed with the survey measurements (Table 9) clearly show that while some scenario–radionuclides combinations give rise to very low doses, a few combinations are more problematic. In particular, the calculated 95th percentile sample dose for the on-site resident with 50 to 100 yr of prior biosolids application exceeded 1000 μSv yr^{-1} (100 mrem yr^{-1}) while the upper range value for the POTW workers involved with sewage sludge loading was 700 μSv yr^{-1} (70 mrem yr^{-1}). On the other hand, doses to the POTW incinerator neighbor (after 50 yr of incineration) and the biosolids land application worker (after 50 yr of field application) were <100 μSv yr^{-1} (<10 mrem yr^{-1}). Doses to recreational users, residents of a nearby town, and neighbors of a landfill were all of little consequence. While the relatively high doses computed for the on-site resident and POTW worker are notable, several factors account for their elevated values, which suggest that typical exposures would probably not approach such levels. First, the exposure scenarios were conservative (assuming 50 to 100 yr of application for the on-site resident scenario and low air exchange rates for the POTW worker scenario). Second, the high doses are generally attributable to radon exposure via the indoor

Table 8. Scenarios and models used in the dose modeling assessment.†

Scenario	Exposed individual‡	Multiple applications	Model code
	Land application		
1. On-site residents	on-site	X	RESRAD§ Version 6
2. Recreational users, reclamation	on-site		RESRAD Version 6
3. Residents of nearby town	off-site	X	RESRAD-OFFSITE/CAP-88
	Landfill disposal		
4. Landfill neighbors, subscenarios for municipal solid waste (MSW) and impoundment	off-site		RESRAD-OFFSITE/CAP-88
	Incineration		
5. Publicly owned treatment works (POTW) incinerator neighbors	off-site	X	RESRAD-OFFSITE/CAP-88
	Occupational exposure		
6. Agricultural sludge application worker	on-site	X	RESRAD Version 6
7. Indoor POTW worker, subscenarios for different POTW operations	on-site		RESRAD-BUILD Version 3

‡ Source: Interagency Steering Committee on Radiation Standards (2003b).
‡ "Site" refers to the area where sludge is originally applied or, for Scenario 7, produced.
§ Family of computer code for evaluating radioactivity contamination.

air pathway. Exposure associated with both of these scenarios can be decreased radically through the use of readily available radon testing and mitigation practices.

The overall results of the survey and dose modeling effort suggest that:

- elevated levels of radionuclides were found in some sewage sludge and ash samples, but do not indicate a widespread problem;
- estimated doses to potentially exposed individuals are generally well below levels requiring radiation protection actions (described later in this paper); and
- under specific circumstances, doses above protective standards (described later in this paper) could occur, primarily due to indoor radon derived as a decay product from naturally occurring radionuclides, such as ^{226}Ra and ^{228}Th.

If agricultural land application is performed for a long time into the future, the potential exists for future radiation exposure primarily due to radon, as illustrated in the 50- to 100-yr subscenarios. Within the POTW, there is a potential for significant exposure (predominately due to radon) only when workers are in the same room with large quantities of sewage sludge or ash (e.g., for storage or loading). In such situations, the degree

Table 9. Calculated total peak dose from survey samples: summary results with and without indoor radon contribution.†

Scenario	Subscenario	TEDE‡ 95% sample With Rn	TEDE‡ 95% sample Without Rn	Dominant radionuclide(s) (pathways)
		mrem yr^{-1}§		
S1, on-site resident	1 yr of application	3	1	Ra-226 (indoor radon)
	5	14	4.9	Ra-226 (indoor radon)
	20	55	16	Ra-226 (indoor radon)
	50	130	37	Ra-226 (indoor radon)
	100	260	69	Ra-226 (indoor radon)
S2, recreational	NA¶	0.22	–	Ra-226 (external)
S3, nearby town	1 yr of application	3.2×10^{-3}	–	Ra-226 (outdoor)
	5	0.014	–	Ra-226 (outdoor)
	20	0.045	–	Ra-226 (outdoor)
	50	0.094	–	Ra-226 (outdoor)
	100	0.17	–	Ra-226 (outdoor)
S4, landfill	MSW††, sewage sludge	0.027	0.01	Ra-226 (indoor radon)
	MSW, ash	0.041	0.014	Ra-226 (indoor radon)
	impoundment	1.2	0.36	Ra-226 (indoor radon)
S5, incinerator	NA	7.7	–	multiple (multiple)
S6, sludge application worker	1 yr of application	0.15	–	Ra-226 (external)
	5	0.77	–	Ra-226 (external)
	20	3	–	Ra-226 (external)
	50	7.4	–	Ra-226 (external)
	100	15	–	Ra-226 (external)
S7, workers at publicly owned treatment works (POTW)	sampling	4.9×10^{-7}	–	Ra-226 (external)
	transport (mrem h^{-1})	1.9×10^{-4}	5.6×10^{-5}	Th-228 (indoor radon, external)
	loading	17–70‡‡	13	Ra-226, Th-228 (indoor radon)

† Source: Interagency Steering Committee on Radiation Standards (2003b).
‡ Total effective dose equivalent. All values rounded to two significant figures. Dose-to-source ratios (DSRs) of 95% are used in all total peak dose calculations.
§ 1 mrem yr^{-1} = 10 μSv yr^{-1}.
¶ NA, not applicable.
# No value denotes that indoor radon was not separately calculated.
†† MSW, municipal solid waste.
‡‡ Range represents results from nine combinations of air exchange and room height.

of exposure likely depends highly on room size and ventilation. However, even in these cases, current radon testing and management programs should detect and mitigate potentially elevated exposure situations.

Interagency Steering Committee on Radiation Standards Radiation Management Recommendations for Publicly Owned Treatment Works

The Interagency Steering Committee on Radiation Standards developed a guidance document (Interagency Steering Committee on Radiation Standards, 2003c) for use by POTW owners and operators. The document was developed with three major purposes: (i) to alert POTW operators, and state and federal regulators to the possibility of radioactive materials concentrating in sewage sludge and ash; (ii) to inform POTW operators how to determine if there are elevated levels of radioactivity in the sewage sludge, including a flowchart summarizing ISCORS recommendations (Fig. 3); and (iii) to assist POTW operators in identifying actions to reduce potential radiation exposure from sewage sludge and ash. The

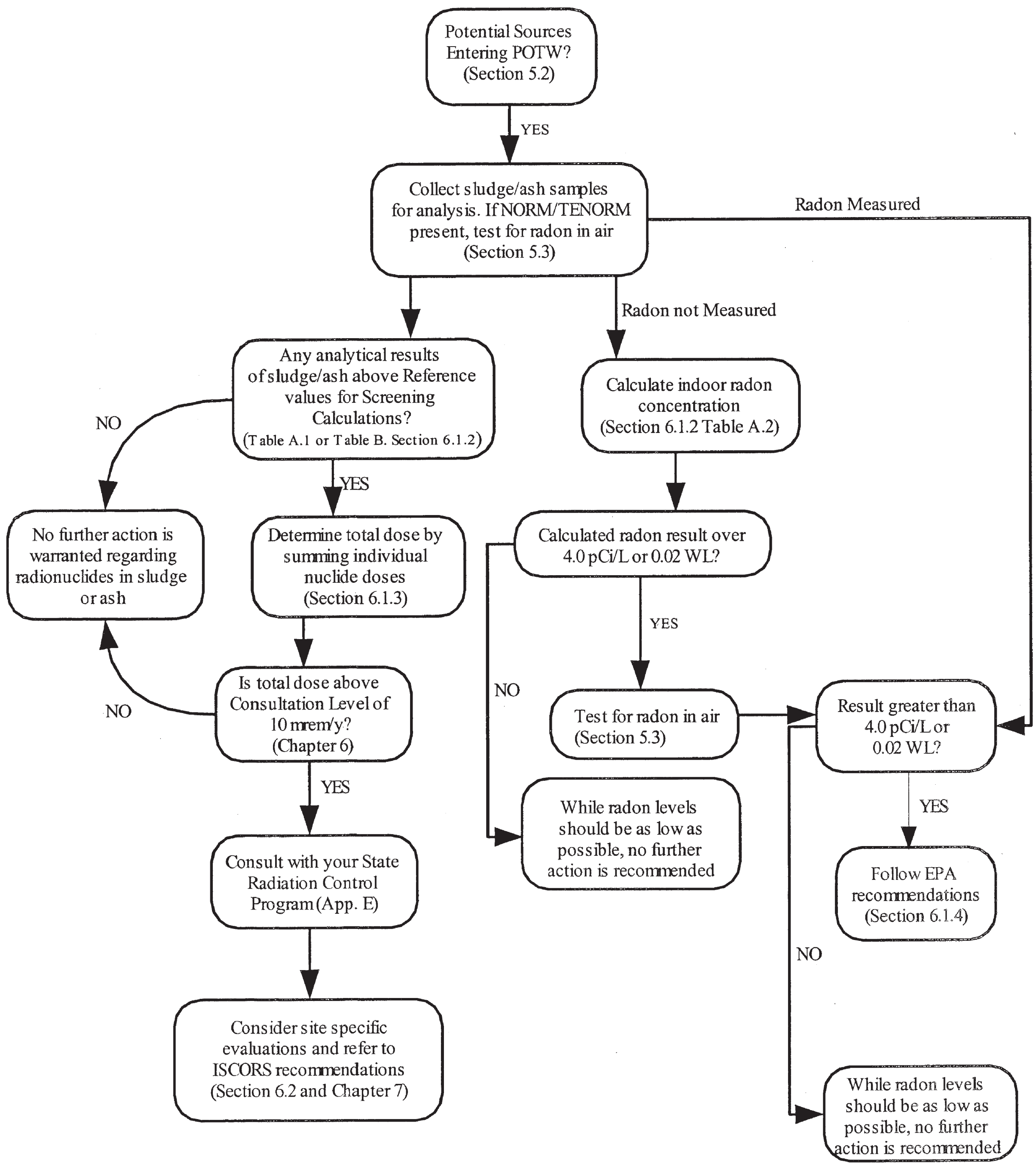

Fig. 3. Flowchart for Interagency Steering Committee on Radiation Standards (ISCORS) recommendations on radioactive materials in sewage sludge and ash (Interagency Steering Committee on Radiation Standards, 2003c).

document also includes background information about radiation and radioactive materials and how they can enter POTWs, an overview of existing regulatory agency responsibilities regarding radiation protection, and a summary of the information produced by the survey and dose modeling efforts.

The document recommends actions that may be taken by a POTW operator when elevated levels of radionuclides are detected. The document advises that, in general, no further action is needed when estimated doses are below 100 μSv yr^{-1} (10 mrem yr^{-1}) (not including estimated or measured radon levels), using the screening calculation procedures provided in the document. When doses are estimated to be ≥100 μSv yr^{-1} (10 mrem yr^{-1}), POTW operators are advised to consult with their state regulatory agency to determine if additional analyses should be conducted or if any response actions need to be considered. The 100 μSv yr^{-1} (10 mrem yr^{-1}) criterion is not a limit, does not include radon, and is not intended to suggest that higher dose levels are unacceptable. Rather, it is a guide for determining when advice from radiological specialists should be considered. Note that the International Commission on Radiological Protection (ICRP) recommended that the acceptable upper limit for public exposure from all controllable sources of radiation should be 1000 μSv yr^{-1} (100 mrem yr^{-1}). Most federal and state regulatory agencies set constraints on individual sources of exposure to the general public that are a fraction of 1000 μSv yr^{-1} (100 mrem yr^{-1}), and limit occupational exposures to ≤50 mSv yr^{-1} (5 rem yr^{-1}). The ISCORS guidance document also recommends radon testing if calculation results exceed the USEPA indoor radon action level of 150 Bq m^{-3} (4.0 pCi L^{-1} or 0.02 WL), and that POTWs take appropriate action to mitigate when test results for indoor radon exceed the same 150 Bq m^{-3} (4.0 pCi L^{-1} or 0.02 WL) action level. A WL is a measure of radon in air; 1 working level (WL) is equal to the total energy emitted by alpha particles from short lived radon decay products in equilibrium with radon gas in air at a concentration of 3.7 kBq m^{-3} (100 pCi L^{-1}). Publicly owned treatment works are advised to contact the state radiation control agency, the NRC, the USEPA, or a radiation protection professional, such as a health physicist, for assistance when designing radiation sampling or monitoring programs, site-specific surveys, or changes in management practices to reduce radiation exposures.

The radiation management document (Interagency Steering Committee on Radiation Standards, 2003c) provides recommendations for POTW operators to determine sources of radioactivity at POTWs, describes sampling and analysis procedures, and suggests alternative courses of action if circumstances (e.g., location in a high NORM area) or actual measurements suggest that a problem exists. Some of these actions include:

- Consulting directly with likely industrial dischargers that may routinely discharge radioactive material to the sewer system to explore the possibility of voluntary reductions in such discharges.
- Encouraging dischargers to use spill prevention measures to reduce the potential for accidental releases.
- Imposing appropriate additional local controls on the dischargers, such as local discharge limits and regular reporting of discharges.
- Requiring notification of planned or accidental discharges, or requesting notification from the source facilities when future releases occur.
- Working with state regulators on enforcement actions against dischargers who violate license conditions and contribute to the elevated levels, and providing information to state regulators on any interferences with operating practices created by discharges.
- Correcting infiltration and inflow problems that transport NORM into the POTW.

CONCLUSIONS

Since it was formed in 1995, the ISCORS Sewage Sludge Subcommittee has addressed concerns associated with radioactive materials present in sewage sludge and ash generated by POTWs. The subcommittee efforts resulted in the recent issuance of a sewage sludge and ash survey report, a dose modeling document, and a POTW guidance document. All three documents along with the laboratory data generated by the sewage sludge survey sample analyses can be accessed via the ISCORS website (Interagency Steering Committee on Radiation Standards, 2003a, 2003b, 2003c). The overall conclusions of the ISCORS subcommittee efforts are:

- The levels of radioactive materials found in sewage sludge and ash samples from most POTWs are generally low and the associated radiation exposure to workers and the general public is very low, and not likely to be of concern.
- The estimated radiation doses to potentially exposed individuals are generally well below levels requiring radiation protection actions. For unique POTW worker and on-site resident scenarios, doses exceeding protective standards could occur, primarily due to indoor radon generated as a decay product from NORM (e.g., ^{226}Ra and ^{228}Th). Such exposures can be significantly reduced through the use of readily available radon testing and mitigation technologies.
- Where the estimated annual dose from all radionuclides exceeds 100 mrem yr^{-1}, ISCORS recommends that the POTW operator consult with the state radiation protection regulatory agency. The 10 mrem yr^{-1} criterion is not a limit, does not include radon, and is not intended to suggest that higher dose levels are unacceptable.

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