Paper

COMPARISON OF DOSES AND RISKS OBTAINED FROM DOSE RECONSTRUCTIONS FOR HISTORICAL OPERATIONS OF FEDERAL FACILITIES THAT SUPPORTED THE DEVELOPMENT, PRODUCTION, OR TESTING OF NUCLEAR WEAPONS

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Abstract—**Five dose reconstruction projects focusing on historical public exposures from U.S. government nuclear facilities have been completed in the last 12 y (Fernald, Hanford, Nevada Test Site, Oak Ridge, Rocky Flats). Using information available in published reports, doses and excess health risks of the most serious contaminants in each study are compared for representative maximally and typically exposed individuals. For both the representative maximally exposed individual and the representative typically exposed individual, the highest excess risks of cancer incidence were from ^{131}I released from Hanford, Nevada Test Site, and Oak Ridge and ^{222}Rn released from Fernald (with central estimates for maximally exposed individuals approaching or exceeding 10^{-2}); the lowest risks for both maximally and typically exposed individuals were from $^{239/240}$Pu and carbon tetrachloride released from Rocky Flats. Excess health risks to the representative maximally exposed individual were at or below 10^{-4} for releases from Rocky Flats. For representative typically exposed individuals, the excess risks from releases of mixed radionuclides in the Clinch River (Oak Ridge), PCBs in East Fork Poplar Creek (Oak Ridge), and both plutonium and carbon tetrachloride released from Rocky Flats were mostly below 10^{-5}.**
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Key words: health effects; dose assessment; risk analysis; public information

INTRODUCTION

One of the lingering legacies of World War II and the Cold War is the burden of past exposures of members of the public to a variety of contaminants released by U.S. government nuclear facilities and to widespread radioactive fallout produced by atmospheric nuclear weapons testing. Dose reconstructions have been carried out for several situations to evaluate the historical exposures to contaminants from nuclear weapons facilities or testing, to determine health risk to the public, and to provide information for potential and future epidemiological studies or public health responses. A comparison among reconstructions of doses from different sites and contaminants can be useful to examine similarities and differences in dose and risk and to provide a basis for consideration of health monitoring and compensation issues.

In the last 12 years, four major, federally funded dose reconstruction studies, focused on historical public exposures, have been completed: the Fernald Dosimetry Reconstruction Project (Fernald) (Devine et al. 1999; Killough et al. 1998; Till et al. 2000); the Hanford Environmental Dose Reconstruction Project (HEDR) (Farris et al. 1994a, 1994b, 1996; HEDR 1994; Hoffman et al. 1998; Shipler et al. 1996); the Oak Ridge Dose Reconstruction Project (ORDR) (Apostoaei et al. 1999a, 1999b; Avantaggio et al. 1999; ORHASP 1999); and Historical Public Exposure Studies on Rocky Flats (RFP) (Brorby et al. 1994; Grogan et al. 1999; McGavran and Rood 1999; Rood and Grogan 1999; Rood et al. 2001). In 1983, Congress mandated that the National Cancer Institute (NCI) undertake a dose reconstruction of nationwide exposures to ^{131}I in fallout from the Nevada Test Site (NTS) (IOM/NRC 1999; NCI 1997). Two more public dose reconstruction projects at the Idaho National Engineering and Environmental Laboratory and at the Savannah River Site have not progressed far enough to be included in this review.

All completed dose reconstructions[†] provide dose or health risk estimates for representative individuals. This

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[†] The completion date given for each dose reconstruction reflects the date for the completion of the great majority of the analysis at each site. However, at some sites, a limited amount of follow-up activity is still continuing.

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paper compares the estimates of doses and risks for representative individuals who were maximally[‡] or typically exposed to different contaminants that were released from these U.S. government nuclear facilities.

DESCRIPTIONS OF PUBLIC DOSE RECONSTRUCTION PROJECTS

Four sites for which public dose reconstructions have been completed (Fernald, Hanford, Oak Ridge, and Rocky Flats) were initially constructed as part of the Manhattan Project, the U.S. government's effort during World War II to develop and produce nuclear weapons. Subsequently, all of these sites played an ongoing role as part of the U.S. nuclear weapons production complex during the Cold War. Within the continental United States, the Nevada Test Site was the primary testing ground for atmospheric nuclear detonations. Brief descriptions of the individual dose reconstructions and the representative maximally exposed and typically exposed individuals for each site are presented below.

Fernald Dosimetry Reconstruction Project

The Feed Materials Production Center (FMPC) is a 1,000-acre site about 25 km NW of Cincinnati, Ohio. The FMPC processed uranium concentrates and uranium compounds recycled from other stages of nuclear weapons production as well as some uranium ore and thorium. Particulate matter released from the FMPC from 1951 to 1988 was mostly uranium; in addition, two large silos containing radium-bearing residues were emission sources of radon and its decay products. The largest releases of uranium occurred in the 1950's and 1960's, while releases of radon gas from the storage silos continued into the 1970's. By far the largest releases were atmospheric, with much smaller amounts released to surface water (Killough et al. 1998).

The purpose of the Fernald Dosimetry Reconstruction Project (1990–1998) was to evaluate the doses and health impacts on the public from radionuclides released from FMPC to the environment from 1951 to 1988. The Centers for Disease Control and Prevention (CDC) was the overseeing government agency for the project. Exposure scenarios were developed for 9 hypothetical residents of the FMPC area to account for the effect of location, age, sex, diet, and lifestyle on possible exposure. Inhalation was the most important exposure pathway, and radon decay products contributed most of the dose (85–95%; Killough et al. 1998). For comparisons in this analysis, Scenario 1 (realistic maximum inhalation exposure) and Scenario 4 (realistic average inhalation exposure) were chosen.

The representative maximally exposed individual (Scenario 1) is described as a female, born in 1946, who lived her entire life at the same location (family farm) 1.7 km NE of the FMPC site center and who was exposed to FMPC releases for all 38 y. Fifty percent of vegetables, beef, fish, and poultry and 100% of eggs and milk ingested were assumed to come from local sources, and no contaminated water was used for drinking or irrigation (Killough et al. 1998).

The representative typically exposed individual (Scenario 4) is described as a female, born in July 1960, who lived in Ross (4 km ENE of the FMPC site center) through high school and left the area in 1978, after being exposed to FMPC releases for 18 y. While in the FMPC area, she was assumed to ingest 10% of her vegetables, eggs, and milk from local sources (Killough et al. 1998).

Hanford Environmental Dose Reconstruction Project

Construction at Hanford, near Richland, Washington, began in 1943. Eventually, nine nuclear production reactors were built on the banks of the Columbia River. Fuel fabrication facilities at Hanford prepared the uranium fuel for the reactors; the fuel was irradiated in the reactors, and chemical separation plants separated the plutonium from uranium and from fission products created during the irradiation of uranium fuel. By 1971, all eight reactors using the once-through cooling system that discharged water directly into the Columbia River were shut down. The N reactor, which did not discharge directly into the river, was operated until 1987 (HEDR 1994).

The purpose of the Hanford Environmental Dose Reconstruction Project (1987–1994) was to estimate the radiation dose that individuals could have received as a result of radionuclides released since 1944 from the Hanford Site. HEDR was initiated in 1987 following a 1986 recommendation by the Hanford Health Effects Review Panel, previously formed to consider the potential health implications of past releases of radioactive materials from the Hanford Site. In 1992, a memorandum of understanding between the Secretaries of the U.S. Department of Energy (U.S. DOE) and the U.S. Department of Health and Human Services (U.S. DHHS) transferred responsibility for managing the dose reconstruction and exposure assessment studies to the U.S. DHHS (Shipler et al. 1996). The project resolved itself into two major components: atmospheric releases of ^{131}I and releases of mixed radionuclides to the Columbia River.

[‡] The term "representative maximally exposed," as used in this paper, is not intended to imply that there is no chance that a real individual might have had a higher exposure, but the chance that this exposure would have been exceeded would have been small.

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HEDR: ^{131}I atmospheric releases. One major objective of the HEDR Project was to estimate doses to the thyroid of individuals who were exposed to airborne releases of ^{131}I, released primarily from separation plants until the mid-1950's. The most significant exposure parameters in dose estimates were the origin (backyard cow or commercial) and the quantity of milk ingested by the individuals.

For the purposes of this analysis, the representative maximally exposed individual is described as a female child at Ringold in NW Franklin County, Washington, who consumed foods grown in the backyard garden or farm (milk, vegetables, fruit, grain, eggs, poultry and beef) and whose milk source was a cow fed on fresh pasture (backyard cow) (Farris et al. 1994a; 1996; HEDR 1994).

The representative typically exposed individual is described as a female child in Eastern Washington living between 9 miles and 234 miles (14.5 and 377 km) from the Hanford Reservation who consumed regionally mixed commercial milk and other food from commercial sources (Farris et al. 1994a; 1996; HEDR 1994).

HEDR: Releases of mixed radionuclides to the Columbia River. A second major objective of the HEDR Project was to estimate doses to representative individuals who were exposed to mixed radionuclides released into the Columbia River, with exposures occurring primarily before 1971. The most significant exposure pathway in those dose estimates was ingestion of resident fish (and some waterfowl).

The representative maximally exposed individual is described as an adult who was assumed to have been a significant user of the Columbia River, spending time in or on the river and ingesting maximum or near maximum amounts of fish and waterfowl [20–40 kg y^{-1} of fish (approximately 14–27 oz or 385–770 g wk^{-1});[§] 20 kg y^{-1} of waterfowl] (Hoffman et al. 1998).

The representative typically exposed individual (described for this paper from HEDR information) is an adult who was assumed to be typical of an average individual residing near the Columbia River at Walla Walla, Washington, and who ate some resident fish [a low consumer of resident fish: 1.4–5.6 kg y^{-1} (approximately 1–4 oz or 27–107 g wk^{-1})] (Hoffman et al. 1998).

Nevada Test Site dose reconstruction

The Nevada Test Site Dose Reconstruction (1983–1997) resulted from a congressional mandate. Public Law 97-414 directed the Secretary of Health and Human Services to "(1) conduct scientific research and prepare analyses necessary to develop valid and credible assessments of the risks of thyroid cancer that are associated with thyroid doses of Iodine 131; (2) conduct scientific research and prepare analyses necessary to develop valid and credible methods to estimate the thyroid doses of Iodine 131 that are received by individuals from nuclear bomb fallout; and (3) to develop valid and credible assessments of the exposure to Iodine 131 that the American people received from the Nevada Atmospheric Nuclear bomb tests" (NCI 1997). The National Cancer Institute (NCI) was asked to respond to this mandate and to prepare a report that provided estimates of human exposure to and thyroid radiation doses from ^{131}I resulting from individual nuclear tests conducted at the NTS from 1951 to 1970. One hundred nineteen nuclear tests, almost all atmospheric, were carried out between 1951 and 1958. From 1961 to 1992, 809 tests, almost entirely underground, were carried out. NCI evaluated 90 atmospheric tests of the approximately 100 that resulted in off-site detection of radioactive materials. These 90 tests released about 150 million curies of ^{131}I (mainly in 1952, 1953, 1955, and 1957), almost 99% of the total ^{131}I released into the atmosphere by NTS testing (NCI 1997).

The representative maximally exposed individual for the purposes of this paper is described as a female, born in 1952, who lived in Meagher County, Montana, and who drank milk from a backyard cow (IOM/NRC 1999).

The representative typically exposed individual for the purposes of this paper is described as a female, born in 1952, who lived in Milwaukee, Wisconsin, and who drank milk from a regionally mixed commercial source (IOM/NRC 1999).

Oak Ridge dose reconstruction

The Oak Ridge Reservation (ORR) near Knoxville, Tennessee, was established in 1942. Four separate facilities were built at the time: the Y-12 plant and the K-25 Site, both created to separate the ^{235}U isotope from the more plentiful ^{238}U; the X-10 site (now the Oak Ridge National Laboratory), created to demonstrate capabilities for producing and separating ^{239}Pu for weapons; and the S-50 site, which operated for less than 1 y. Hazardous pollutants have been released from each site in varying quantities over the years with the largest releases occurring from the mid-1940's to the early 1970's (ORHASP 1999).

In 1991, U.S. DOE and the State of Tennessee, through the Tennessee Department of Environment

[§] For clarity and comparison, the fish consumption for maximum and typical receptors for the Columbia River (Hanford) and for the Clinch River (Oak Ridge) was recalculated from kilograms eaten per year to grams (or ounces) eaten per week.

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and Conservation, entered into the two-phase "Tennessee Oversight Agreement," with the purpose of determining whether environmental pollutants released from the ORR created public health problems (ORHASP 1999). Phase I, completed in late 1993, focused primarily on assessing the feasibility of doing a historical dose reconstruction and on identifying the contaminants most likely to have had off-site health consequences. Phase II, begun in mid-1994 and completed in 1999, involved full dose reconstruction analyses for several situations, plus additional screening analyses for several substances that had not been fully reviewed in Phase I. For the purposes of this paper, three types of contaminant releases are used for comparisons: atmospheric releases of ^{131}I (Task 1); release of PCBs into Bear Creek and East Fork Poplar Creek (Task 3); and releases of mixed radionuclides, most importantly ^{137}Cs, into the Clinch River (Task 4).

ORDR: ^{131}I atmospheric releases (task 1). The Oak Ridge National Laboratory (ORNL) released radioactive iodine to the air from 1944 through 1956 as it processed spent nuclear reactor fuels, recovering radioactive lanthanum (RaLa) that was used to support weapons development at Los Alamos, for atmospheric radiation tracking, and for radiation warfare experiments. Task 1 investigated the possible risks of thyroid cancer from releases of ^{131}I between 1944 and 1956 for representative individuals at 41 locations within 38 km of ORNL (Apostoaei et al. 1999a). By far the most significant exposure pathway was ingestion of milk from one of three main sources: goat's milk, backyard cow's milk, or regionally mixed commercial milk.

The representative maximally exposed individual is described as a female, born in 1952, who lived at Gallaher Bend, Tennessee (6.3 km from ORNL), and who consumed milk from a backyard cow and who ate locally produced beef, vegetables, eggs, and cheese (Apostoaei et al. 1999a).

The representative typically exposed individual is described as a female, born in 1952, who lived in Norwood, Tennessee (within 38 km of ORNL), and who consumed regionally mixed commercial milk as well as other commercial food products (Apostoaei et al. 1999a).

ORDR: Release of PCBs to Bear Creek and to East Fork Poplar Creek (task 3). The objective of Task 3 was to investigate all potential current and historical exposures to polychlorinated biphenyls (PCBs) associated with activities at the Oak Ridge Reservation. Although PCBs were released from K-25 and ORNL (going from ORR into the Clinch River and upper Watts Bar Reservoir), the most likely routes of exposure to off-site populations were from the transport of PCBs used at Y-12 to the sediments, surface water, and biota of Bear Creek and East Fork Poplar Creek (EFPC). EFPC was the more likely exposure route for off-site individuals because it flowed through non-restricted and residential portions of Oak Ridge, while most of Bear Creek had very limited public access. Only risk estimates, no dose estimates, are provided in the report (Avantaggio et al. 1999).

The representative maximally exposed individual is described as an adult from a local farm family, consuming fish from EFPC with up to 70 y of exposure (Avantaggio et al. 1999).

The representative typically exposed individual is described as an adult commercial angler, fishing in Watts Bar Reservoir with up to 50 y of exposure (Avantaggio et al. 1999).

ORDR: Release of mixed radionuclides (primarily ^{137}Cs) to the Clinch River (task 4). The purposes of Task 4 of the ORDR were to estimate the historical releases of radionuclides from the X-10 facility via White Oak Creek to the Clinch River to evaluate the potential pathways by which members of the public could have been exposed to radioactive effluents in the Clinch River between 1944 and 1991, and to calculate radiation doses and risks to reference individuals who were potentially exposed to radioactivity released to the Clinch River from ORNL (Apostoaei et al. 1999b).

The maximally exposed reference individual is described as an adult male who consumed 7.1 to 33 kg y^{-1} fish (approximately 4.9–22 oz or 137–635 g wk^{-1}) from Clinch River Mile 20.5 (junction with White Oak Creek) and who had 57 y of exposure (Apostoaei et al. 1999b).

The typically exposed reference individual is described as an adult male who consumed 0.39 to 4.3 kg y^{-1} fish (approximately 0.3–3 oz or 7.5–83 g wk^{-1}) from Clinch River Mile 0 (at Kingston, Tennessee) and who had 57 y of exposure (Apostoaei et al. 1999b).

Historical public exposure studies on Rocky Flats

The primary mission of the Rocky Flats Plant (RFP), Colorado, was to produce components for nuclear weapons from materials including plutonium, uranium, beryllium, and stainless steel. Plutonium reprocessing, waste management, production activities such as metal fabrication and assembly, and chemical recovery and purification of transuranic radionuclides were also part of the RFP mission. Construction of the RFP began in 1952 and the first nuclear weapons components produced at the plant were shipped off-site in 1953; nuclear operations were conducted until 1989.

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The purpose of the Historical Public Exposure Studies on Rocky Flats (1989-present) was to evaluate the doses and potential health impacts to nearby members of the public living off-site. Through a 1989 Agreement in Principle, U.S. DOE provided the State of Colorado with funding for health-related studies that were directed by the Colorado Department of Public Health and Environment. Two phases were carried out. Phase I was an extensive investigation of past operations and releases from the RFP to identify primary materials of concern, to determine release points, events, quantities released, and transport pathways, and to make preliminary estimates of off-site dose and risks. Phase II was an in-depth investigation of the potential doses and risks to the public from key historical releases from RFP. Two airborne contaminants from RFP are considered here: plutonium and carbon tetrachloride. Risk estimates, but no doses, are given in the reports (Grogan et al. 1999; McGavran and Rood 1999; Rood et al. 2001; Rood and Grogan 1999).

Representative maximally and typically exposed individuals were adult residents who were assumed to live in the same location for the entire period that the RFP operated (1953–1989) and who were considered as typical of those reported for the nation's population (Brorby et al. 1994).

RFP: Plutonium inhalation. The representative maximally exposed individual is described as an adult laborer, exposed from 1953–1989, and living and working at Indiana Avenue and 64th Street in Arvada, Colorado (7.5 km S of the RFP) (Rood and Grogan 1999).

The representative typically exposed individual is described as an adult laborer, exposed from 1953–1989, and living and working in Broomfield, Colorado (6.5 km NE) (Rood and Grogan 1999).

RFP: Carbon tetrachloride inhalation. The representative maximally exposed individual is described as a male rancher, exposed from 1953–1989, living and working outside the east cattle fence along Indiana Avenue, north of Arvada, Colorado (within 7.5 km S) (McGavran and Rood 1999; Rood et al. 2001).

The representative typically exposed individual is described as a female office worker, exposed from 1975–1989, living in Broomfield (6.5 km NE) and working in Denver (22 km SE) (McGavran and Rood 1999; Rood et al. 2001).

METHODS

The release sources, contaminants, receptors, dose and risk estimates, and health endpoints from all five dose reconstructions are summarized in Table 1. Review of the validity of the assumptions, calculations, and methodologies used in the individual dose reconstruction reports has not been attempted. Information about doses, risks, and representative maximally and typically exposed individuals is not necessarily consistent among the five studies, and potential differences in methodologies could have affected risk estimates. Two "representative typically exposed individuals" (Hanford: ^{131}I and Hanford: Columbia River) were developed from information found in reports when such information could not be directly obtained from published tables and result summaries.

Dose estimates are provided in the cited reports for all exposures with the exception of PCBs from Oak Ridge and plutonium and carbon tetrachloride from Rocky Flats. Risk estimates are provided in the reports for all situations except for ^{131}I released from Hanford and ^{131}I released from the NTS. Because comparisons can be made more easily between health risks than between doses of different contaminants and different affected organs or tissues, health risk estimates (excess absolute lifetime risk of cancer incidence) were used to develop comparisons.

Specific modifications to the results obtained from the dose reconstruction reports have been made to allow comparisons among the studies. These modifications are as follows.

1. Results are reported in Table 1 in terms of a cancer incidence endpoint, not cancer mortality. In the Fernald Dose Reconstruction, risk was reported in terms of lung cancer mortality. For consistency, the dose and risk figures from Fernald have been converted to lung cancer incidence, based on information on the lethality fraction for lung cancer (Puskin and Nelson 1995);
2. Two radionuclides target specific organs: ^{131}I exposure (Hanford, NTS, Oak Ridge) is assessed in terms of thyroid cancer incidence, and radon exposure (Fernald) is assessed in terms of lung cancer incidence. Cancer incidence in response to all other radionuclide and chemical exposures is reported in this paper in terms of total cancer incidence, except where noted in Table 1;
3. Uncertainty estimates are not always consistent. Some of the doses and risks are reported with a 90% confidence interval (CI) and some with a 95% CI. This is noted in Table 1;

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Table 1. Summary of selected estimates of dose and risk to maximally and typically exposed receptors for completed U.S. dose reconstruction studies.

Release site (contaminant) and receptor	Years exposed	Reported dose[a] (95% CI unless noted)	Lifetime risk of cancer incidence[b] (95% CI unless noted)	Health endpoint	References
Fernald (^{222}Rn)					
Maximum	1951–1988	0.98 to 14 (3.6) Sv[c]	1.0×10^{-3} to 8.7×10^{-2}[c,d] (9.2×10^{-3})	Lung cancer incidence	Killough et al. 1998
Female, b. 1/1946, 1.1 m NE of Fernald.					
Typical	1960–1978	0.40 to 7.2 (1.5) Sv[c]	5.8×10^{-4} to 2.8×10^{-2}[c,d] (3.7×10^{-3})	Lung cancer incidence	Killough et al. 1998
Female, b. 7/1960, 2.5 m NE of Fernald.					
Hanford Site (^{131}I)					
Maximum	1944–1951	0.54 to 8.7 (2.4) Gy[c]	6.6×10^{-3} to 5.4×10^{-1}[c,e] (6.5×10^{-2})	Thyroid cancer incidence	HEDR 1994
Female child at Ringold, WA; milk from backyard cow.					
Typical	1944–1951	0.032 to 0.32 Gy[c,e,f]	8.7×10^{-4} to 8.7×10^{-3}[f]	Thyroid cancer incidence	Farris et al. 1996
Female child in Eastern Washington (see text for definition) milk (and other foods) from commercial sources.					
Hanford Site (mixed radionuclides)					
Maximum	1950–1971	Representative organ doses:[c] Breast: 3.9 to 30 (11) mSv Colon: 36 to 250 (76) mSv Red Bone Marrow: 21 to 180 (56) mSv	8.04×10^{-4} to 4.6×10^{-3}[c,g] (1.8×10^{-3})	Cancer incidence	Hoffman et al. 1998
Adult female at the Columbia River near Richland, WA; 40 kg y^{-1} resident fish and 20 kg y^{-1} waterfowl.					
Typical (low ingestion)	1955–1970	1.2 to 3.5 (1.9) mSv[c,g]	6×10^{-5} to 3.9×10^{-4}[c,e,g] (1.5×10^{-4})	Cancer incidence	Hoffman 1999
Adult at the Columbia River near The Dalles, WA; 1.4–5.6 kg y^{-1} resident fish.					
Nevada Test Site (^{131}I)					
Maximum	1952–1971	0.04 to 9.6 Gy	3.5×10^{-4} to 5.4×10^{-1} [e] (1.5×10^{-2})	Thyroid cancer incidence	IOM/NCR 1999; NCI 1997
Child, b. 1952, in Meagher Co, MT; milk from backyard cow.					
Typical	1952–1971	0.02 to 0.33 Gy	2.2×10^{-4} to 3.4×10^{-2}[e] (2.6×10^{-3})	Thyroid cancer incidence	IOM/NCR 1999; NCI 1997
Child b. 1952, Milwaukee, WI; milk from commercial source.					
Oak Ridge Reservation (^{131}I)					
Maximum	1952–1956	0.06 to 2.5 (0.39) Gy	7.1×10^{-4} to 1.7×10^{-1} (1.1×10^{-2})	Thyroid cancer incidence	Apostoaei et al. 1999a
Female child b. 1952 in Gallaher Bend, TN; milk from backyard cow.					
Typical	1952–1956	0.002 to 0.10 (0.01) Gy	2.6×10^{-5} to 6.1×10^{-3} (4.1×10^{-4})	Thyroid cancer incidence	Apostoaei et al. 1999a
Female child b. 1952 Norwood, TN; regionally mixed commercial milk.					
Oak Ridge Reservation (mixed radionuclides)					
Maximum	1944–1991	Representative organ dose:[h] 0.53 to 52 (5.7) mSv	3.6×10^{-5} to 3.5×10^{-3} (2.8×10^{-4})	Cancer incidence	Apostoaei et al. 1999b
Adult males in E. TN; 7.1 to 33 kg y^{-1} fish from Clinch River Mile 20.5.					
Typical	1944–1991	Representative organ dose:[b] 0.0069 to 0.45 (0.062) mSv	4.3×10^{-7} to 2.4×10^{-5} (3.6×10^{-4})	Cancer incidence	Apostoaei et al. 1999b
Adult males in E. TN; 0.39–4.3 kg y^{-1} fish from Clinch River Mile 0.					
Oak Ridge Reservation (PCBs)					
Maximum	Up to 70 y	—	3×10^{-6} to 2×10^{-3}[c] (1×10^{-4})	Cancer incidence	Avantaggio et al. 1999
Adult from farm family that fished in East Fork Poplar Creek, East Tennessee.					
Typical	Up to 50 y	—	4×10^{-7} to 4×10^{-5}[c] (4×10^{-6})	Cancer incidence	Avantaggio et al. 1999
Adult, commercial angler fishing in Watts Bar Reservoir, East Tennessee.					
Rocky Flats ($^{239/240}$Pu)					
Maximum	1953–1989	—	2.6×10^{-8} to 1.5×10^{-4}[c] (2.6×10^{-6})	Cancer Incidence	Rood and Grogan 1999
Adult laborer; Indiana Street and 64th, Arvada, Colorado.					
Typical	1953–1989	—	2.1×10^{-8} to 2×10^{-5}[c] (4.6×10^{-7})	Cancer incidence	Rood and Grogan 1999
Adult laborer; Bloomfield, Colorado.					
Rocky Flats (carbon tetrachloride)					
Maximum	1953–1989	—	1.3×10^{-6} to 2.1×10^{-5}[c] (5.2×10^{-6})	Cancer incidence	Rood et al. 2001
Rancher scenario, N of Arvada, Colorado.					
Typical	1975–1989	—	4.5×10^{-8} to 5.9×10^{-7}[c] (1.6×10^{-7})	Cancer incidence	Rood et al. 2001
Office worker scenario, Denver, Colorado.					

[a] Range corresponds to 90 or 95% CI; number in parentheses corresponds to the central value.
[b] Note that both ^{131}I and PCBs may induce non-cancer risks that are not included in this summary. Note also that the mortality of lung cancer (^{222}Rn and $^{239/240}$Pu) is very similar to the incidence of lung cancer (see note d below) and that the mortality of lung cancer is much higher than the mortality of thyroid cancer (^{131}I).
[c] 90% CI.
[d] This figure was recalculated to reflect lung cancer incidence (lung cancer mortality/0.95 = lung cancer incidence); BEIR VI risk coefficients were used (NRC 1998).
[e] Calculation was made for this paper from source document information.
[f] The dose represents a range of median doses, so the risk represents the range of median risks.
[g] Calculation is based on data from 5 cancers (colon, leukemia, thyroid, stomach, breast).
[h] Representative organ dose given is for the colon; other organ doses are similar.

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4. At the Hanford site, the representative typical individual exposed to ^{131}I was not defined in the cited reports. However, figure 13 from HEDR (1994) provides the cumulative median ^{131}I dose in rads to a child from commercial milk and food sources during the years 1944 through 1951 by geographical area. An area covering all or most parts of 15 counties in Eastern Washington was selected as comprising typical exposure. The range of median doses among individuals for this area was 3.2 to 32 rads (Farris et al. 1994a). Risk was calculated for a female child;
5. The estimated excess lifetime risks (ELR) of thyroid cancer incidence from exposure to ^{131}I released from Hanford were not given in the cited reports. These risks were calculated from the doses given in HEDR (1994). The risk coefficients used are based on the current excess relative risk (ERR) Sv^{-1} data used in the Interactive Radio-Epidemiological Program (IREP; Land et al. 2000; note that the ERR Sv^{-1} values for thyroid in IREP 4.0 are the same as those in IREP 2.0). The lifetime risk is based on an average lifetime of 70 y, and the background incidence of cancer is that for the U.S. population (Ries et al. 2002); and
6. The cited Hanford reports contain doses for a typical representative individual exposed to mixed radionuclide releases to the Columbia River but who did NOT eat fish. To provide information for comparison (representative typically exposed individual who ate a minimal amount of fish), data based on the HEDR estimates were used. A representative typically exposed individual was defined as someone who lived near The Dalles, Washington, on the Columbia River, between 1955 and 1970, and who consumed a low amount of resident fish (1.4–5.6 kg y^{-1}; Hoffman 1999). Organ specific doses were calculated for this individual. From the organ specific doses, an effective whole body dose was calculated, and then a total cancer incidence risk (all cancer types) was determined, using an age-averaged risk coefficient.

In addition to these modifications, it should be noted that for ^{131}I exposure, although doses from consumption of goat's milk are substantially higher than are those received from cow's milk, only two studies (ORDR and NTS) reported results for individuals ingesting goat's milk. In order to make a consistent comparison across studies and because many more individuals drank cow's milk than goat's milk, ^{131}I exposure through ingestion of milk from a backyard cow was used for the maximum representative individual.

RESULTS

Doses and risks for representative maximally and typically exposed receptors were compared for the major contaminants assessed in five completed dose reconstructions in the U.S. (Table 1; Fig. 1). For maximum receptors at the five sites, Hanford ^{131}I posed the greatest risk, in the range of 10^{-3} to 10^{-1}, followed closely by ^{131}I from NTS and Oak Ridge and ^{222}Rn from Fernald with similar ranges (Fig. 1a). Carbon tetrachloride released from Rocky Flats posed the lowest risk for maximally exposed individuals (range 10^{-6} to 10^{-5}), with plutonium from Rocky Flats second lowest (range 10^{-8} to 10^{-4}).

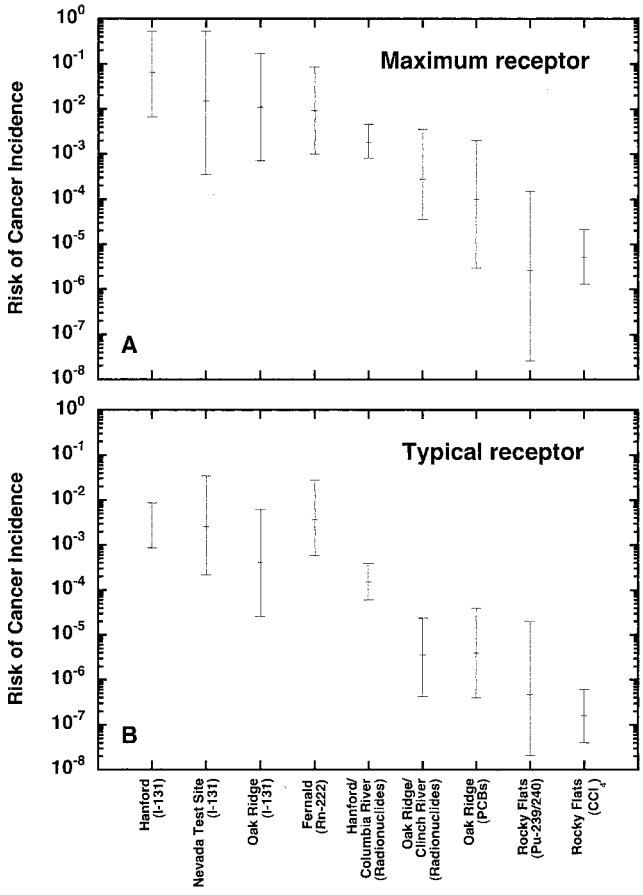

Fig. 1. Excess risk of cancer incidence for representative individuals due to contaminant releases from the indicated sites for (a) a maximally exposed receptor (maximum receptor) and (b) a typically exposed receptor (typical receptor). For ^{131}I and ^{222}Rn, the risk estimates correspond to thyroid cancer and lung cancer, respectively. All other risk estimates correspond to total risk for all cancer types. Details of the risk estimates are provided in the text and in Table 1. The vertical lines represent the 90 or 95% confidence intervals on the risk estimates, as listed in Table 1, except for the typical receptor for Hanford ^{131}I; the central values of the risk estimates are also indicated. For the typical receptor for Hanford ^{131}I, the vertical line indicates the range of median risks for a typically exposed receptor at various locations; the 95% confidence interval would extend further in both directions.

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The highest risk for a typical receptor was from NTS ^{131}I (range of 10^{-4} to 10^{-2}), followed by ^{222}Rn from Fernald, Hanford ^{131}I, and Oak Ridge ^{131}I. The typical cancer risk from exposure to PCBs released from Oak Ridge is slightly higher than that from exposure to radionuclides in the Clinch River; however, for representative maximally exposed receptors, exposure to PCBs posed a lesser risk than did the radionuclides. The lowest risks for representative typically exposed receptors were from exposure to plutonium and carbon tetrachloride released from Rocky Flats (range 10^{-8} to 10^{-5}).

DISCUSSION

Public concern about health risks resulting from exposure to various contaminants released from U.S. government nuclear facilities has prompted the government to support detailed investigations to reconstruct releases, exposures, doses, and estimates of potential health risks. Questions of which contaminants were released, how much was released, how exposures happened, and who was exposed are addressed in these studies to determine the potential for adverse health effects for members of the public who were exposed. Projects that estimate historical doses to the public from contaminants released from these facilities provide an important scientific basis for answering such questions and for confirming or reducing the public's concerns. However, because each study has been performed independently, many aspects, such as the method of reporting results, vary from study to study. This paper brings together each study's definition of representative maximally and typically exposed individuals for the given site or situation, the reported doses to those individuals, and the resulting risk of excess cancer incidence, either as reported or as calculated from reported doses.

The entire range of risks estimated for the various contaminants and sites across the five dose reconstruction projects spans nearly eight orders of magnitude for maximally exposed receptors and almost seven orders of magnitude for typically exposed receptors (Fig. 1). For central estimates of risk to typically exposed receptors, the range still covers at least four orders of magnitude. For some of the dose reconstructions reviewed here, the low end of the range of risks could be even lower if additional contaminant exposure situations with lower risks (whether due to lower toxicity, lower amounts released, or lower likelihood of exposure to have occurred) had been included in the comparison.

Exposure to atmospheric releases of ^{131}I (Hanford, NTS, Oak Ridge) and to atmospheric releases of radon (Fernald) produced the highest risks of cancer incidence for both maximally and typically exposed receptors (Fig. 1; Table 1). These two radionuclides are the only contaminants in the present study that are highly correlated with specific organ exposures and risks, thyroid for ^{131}I and lung for radon. However, it should be noted that lung cancer is much more likely to be fatal than is thyroid cancer. For ^{131}I, the differences in risks between maximally and typically exposed receptors generally exceeded an order of magnitude for any given situation, while for radon the difference was much smaller (Fig. 1; Table 1). This difference probably reflects the much larger differences in milk sources and milk consumption rates among individuals (key parameters for ^{131}I exposure) than in breathing rates (a key parameter for radon exposure), as well as differences in receptor locations.

Exposure to atmospheric releases of contaminants from Rocky Flats produced the lowest risks in this comparison for both maximum and typical receptors; for plutonium, risks were near or below 10^{-4} for both receptors, while risks for carbon tetrachloride exposures were even lower (Fig. 1; Table 1). It is worth noting that, although CCl_4 is implicated in liver cancer in animals, human health effects of long-term exposure to low levels of CCl_4 are unknown. The U.S. Environmental Protection Agency classifies CCl_4 as a probable human carcinogen rather than a known human carcinogen (U.S. EPA 2001).

The waterborne contaminants compared in this paper produced intermediate risks, with median values ranging around 10^{-3} to 10^{-4} for maximum receptors and around 10^{-4} to 10^{-6} for typical receptors (Fig. 1; Table 1). The differences in fish consumption rates along with location of the receptor determine the differences in exposures and risks for the two types of receptors.

The risks from NTS fallout ^{131}I matched or exceeded those from atmospheric releases at Hanford, Oak Ridge, and Fernald, and greatly exceeded those from atmospheric releases at Rocky Flats or waterborne releases from any site (Fig. 1). However, it is extremely important to point out that the domain of impact of NTS fallout ^{131}I included the entire continental U.S., while the impact of releases from each of the other dose reconstruction sites was primarily regional. As a result, the values of dose and risk from NTS fallout listed in Table 1 for a child in Milwaukee drinking commercially produced milk are generally applicable to any child in the Eastern U.S. drinking commercial milk during the time period in question (IOM/NRC 1999).

In addition to comparing estimated risks across sites or studies, comparing the risks from the various facilities or releases with objective criteria for determining their significance also may be useful. For example, the Oak Ridge Dose Reconstruction employed a decision criterion of 10^{-4} risk of cancer incidence as a guide in

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planning next steps in the study and in allocation of resources to those next steps (ORHASP 1999). In general, the authors have advocated that a contaminant or exposure situation for which the upper bound of the risk to a representative maximally exposed individual was clearly below an appropriate decision criterion would not be a candidate for further study unless public concern or new information warranted the additional effort. Those contaminants or exposure situations for which a representative typically exposed receptor had an estimated risk clearly above the criterion are obvious candidates for further attention (Hoffman et al. 1993; Thiessen et al. 1995, 1996; Apostoaei et al. 1999a, 1999b).

The criterion of 10^{-4} (excess lifetime risk of cancer incidence) used at Oak Ridge is typical of criteria used for representative maximally exposed individuals in other decision-making situations where multiple pathways and contaminants are involved as well as being the upper boundary of the target risk range used by EPA in regulatory decisions. If the 10^{-4} criterion is applied to the results of the five studies reviewed here, it is clear that risks for airborne contaminants from Hanford, NTS, Oak Ridge, and Fernald, as well as waterborne contaminants from Hanford (Columbia River) can certainly be considered significant. For Rocky Flats, the upper bound risk for a maximum receptor exposed to plutonium barely exceeds 10^{-4}, indicating that the likely risks for most individuals would have been below 10^{-4}, and in many cases substantially below. Risks for the waterborne contaminants from Oak Ridge similarly reach or exceed 10^{-4} only for maximum receptors.

Approximate costs of the various dose reconstructions range from \$2–3 million for NTS and \$4–4.5 million for Fernald, to \$14 million for Oak Ridge, \$15 million for Rocky Flats, and \$30 million for Hanford (ORHASP 1999; U.S. DHHS et al. 2001).** The cost of each individual study has been influenced by several important factors: (1) the level of concern of the affected public; (2) the level of concern on the part of the funding agency (which may or may not be related to the level of concern of the affected public); (3) the complexity of the situation being studied; (4) the amount of information necessary to evaluate the situation; (5) the difficulty of obtaining and assimilating that information; and (6) the level of detail to which the evaluation is carried. For example, public activism triggering government concern was the driving force behind initiating the dose reconstruction process in general, with Fernald and Rocky Flats. The Oak Ridge study included both airborne and waterborne releases of a variety of chemical and radionuclide contaminants from three major sites, resulting in a rather complex and varied set of analyses, only three of which were included in this review. The NTS study was limited to a single radionuclide from a single geographical point of origin (although in principle, the study could be justifiably expanded to include several other important radionuclides), but with a receptor population comprising the entire country. Most of the effort in the Hanford dose reconstruction went to the iodine issue, with a relatively small portion going to the evaluation of Columbia River releases. The Fernald and Rocky Flats studies both focused on a relatively small geographical area of concern for only a few contaminants, but they vary significantly in the risks posed by the situations and in the resources expended on the studies.

Each dose reconstruction, past and future, has unique characteristics including number of contaminants, geographical area, and affected population size. Lessons learned from completed studies can help focus the goals of future studies. The authors encourage organization of future dose reconstructions to include evaluation of risk using appropriate objective decision criteria at several different stages (e.g., after initial scoping or screening calculations and after each round of more detailed information gathering and calculation), as was done for the Oak Ridge study, which was the last of these five studies to be initiated. This will help to ensure that public resources are spent on situations that truly warrant the effort and that adequate resources will be spent on the most significant situations.

CONCLUSION

Comparison of dose reconstructions provides a valuable perspective on nationwide public health risks from contaminants released from various U.S. government nuclear facilities. The use of risk of adverse health effects as the endpoint of interest allows for comparison among a variety of facilities, contaminants, exposure routes and situations, and site-specific differences in parameters (e.g., typical lifestyles and dietary habits for different geographical regions or different time periods). Use of objective criteria for risk levels of concern can aid in evaluating the significance to public health of a given facility, contaminant, or exposure situation, as well as provide a basis for decisions regarding allocation of limited resources.

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** Personal telephone communications with CDC 2001; Colorado Department of Public Health and Environment 2002; NCI 2002.

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