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Risks to the public from historical releases of radionuclides and chemicals at the Rocky Flats Environmental Technology Site

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This paper summarizes the methods and results of estimating risks of cancer incidence resulting from plutonium, carbon tetrachloride, and beryllium releases from operations at the Rocky Flats Environmental Technology Site, near Denver, Colorado, from 1953 through 1989. The key findings show that people who lived near the facility were exposed to plutonium mainly through inhalation during routine operations, from a major fire in 1957, and from plutonium resuspended from contaminated soil from an outdoor drum storage area, called the 903 Area. Results were presented for five exposure scenarios that were location-independent. Individuals described by the laborer scenario received the highest risk of all scenarios considered. Upper bound (95th percentile) incremental lifetime cancer incidence risks for the laborer scenario were in about the 10^{-4} range (1 chance in 10,000) for developing cancer from Rocky Flats plutonium releases during a lifetime. At the 5th percentile level, the maximum cancer risk was about 10^{-7} (1 chance in 10 million) for developing cancer during a lifetime. Estimated cancer risks at the 95th percentile level are within the range of for acceptable risks established by the US Environmental Protection Agency of 10^{-6} to 10^{-4}. Carbon tetrachloride was found to be the chemical that presented the highest risk to the public. The 5th and 95th percentile risk values for exposure to carbon tetrachloride were 9.2×10^{-7} and 2.5×10^{-5}, respectively.
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Introduction

The Rocky Flats Environmental Technology Site (RFETS) is a US Department of Energy (DOE) facility and is currently operated by Kaiser-Hill. For most of its history, the site was called the Rocky Flats Plant (RFP) and was operated by Dow Chemical as a nuclear weapons production, research, and development facility. The RFETS is located on 2650 ha of Federal property about 8–10 km from the cities of Arvada, Westminster, and Broomfield, and about 26 km northwest of downtown Denver, CO. The site is now closed down and is being cleaned up.

The Rocky Flats Historical Public Exposures Studies were undertaken to help the Colorado Department of Public Health and Environment (CDPHE) evaluate potential health impacts to the public resulting from contaminant releases from the site to the environment during its years of operation. This health study, funded by the DOE, focused on members of the public living offsite. In 1991, the Governor of Colorado appointed a Health Advisory Panel (HAP) to act as an advisory and oversight panel. The HAP provided direction to the technical work and enhanced public accountability and credibility.

Phase I of the study was carried out by ChemRisk[1] (a division of McLaren/Hart Environmental Engineering),

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[1] ChemRisk was sold to J.A. Jones Environmental Services in October of 2000.

which conducted an extensive investigation of past operations and releases from the RFP; identified the primary materials of concern; determined release points, events, quantities released, and transport pathways; and made preliminary estimates of offsite risk. The conclusions from Phase I were documented in a series of task reports and publications (ChemRisk, 1992, 1994a,b; Mongan et al., 1996a,b; Ripple et al., 1996a,b).

Phase II of the study was performed by *Risk Assessment Corporation (RAC)*[2] and involved a more detailed investigation of the potential cancer incidence risks to the public from the major historical releases from the RFP. A primary question of interest was whether the risks posed to the public warranted an epidemiological study.

A careful evaluation initially done in Phase I, and confirmed during Phase II, indicated that of the more than 8000 materials used or stored at the RFP during the 40 years of operation, plutonium and carbon tetrachloride were the most important contaminants released into the environment in terms of potential exposure and associated risk to the public. Plutonium was processed at Rocky Flats for nuclear weapons components and the solvent carbon tetrachloride was used to clean plutonium metal parts, processing machinery, and instruments. Beryllium was also targeted for further investigation during Phase II because of its extensive use at the RFP. Inhalation was the most important exposure pathway for these materials. This paper focuses on the extensive process involved in the reconstruction of historical releases from the RFP to the environment and subsequent estimates of risk. Releases from RFP resulted from both routine operations and from discrete events such as fires.

Construction of the RFP began in 1952, and its first nuclear weapons components were shipped offsite in 1953. Operations involving nuclear materials were conducted at the site from 1953 to 1989. The plant's primary mission was to produce components for nuclear weapons from materials including plutonium, uranium, beryllium, and stainless steel. During plant operations, materials were released to air, surface water, and indirectly to groundwater either through routine operations or accidentally. Some contaminants have been detected in groundwater under the site but, to date, the contamination has not traveled offsite. Because the Historical Public Exposures Studies on Rocky Flats addressed past exposures and risks to the public living offsite, the groundwater pathway was not considered. It is recognized that exposure of the public by way of the groundwater pathway might be important in the future.

[2] In 1998, *Radiological Assessments Corporation* changed its name to *Risk Assessment Corporation*. For consistency throughout the project, all reports were published under the name of *Radiological Assessments Corporation*.

Figure 1 shows the general location and key environmental features of the site. Approximately 2.5 million people currently live within an 80-km radius of the site. Before 1990, adjacent land use was a mixture of agriculture, open space, industry, and low-density housing. The population of the area is rapidly growing, especially in the corridor between Boulder and Denver.

Dry, cool winters and warm summers characterize the climate. The site's sloping topography and its proximity to a major mountain range can create dramatic changes in temperature and rapidly changing weather conditions. Of particular importance are the strong westerly downslope winds that often occur in winter and early spring, sometimes exceeding 36 m s^{-1} ($\sim$80 miles h^{-1}). This environmental factor is especially important because it affects resuspension of plutonium-contaminated soil from around the site.

Annual precipitation averages slightly greater than 38 cm (15 in.), with more than 80% of the precipitation occurring between April and September. Surface drainage at the site occurs in a west-to-east pattern along several ephemeral streams. Historically, North Walnut Creek, South Walnut Creek, and Woman Creek drained from the main plant facilities area into the Great Western Reservoir and Standley Lake. Therefore, the transport of materials from the site through surface water pathways was of concern to the public and was evaluated in this study (Meyer and Till, 1999).

Approach to risk assessment

The process of estimating risks to people from radionuclides and chemicals released to the environment can best be described using the illustrative equation below (Till, 1995):

$$\text{Risk} = (S \cdot T \cdot E \cdot R)_{uvcp}$$

where: S=source term (characterization of the quantity and type of material released); T=environmental transport and fate of the material released; E=exposure factors (characteristics of individuals exposed that affect their intakes); R=conversion of intakes to risk; u=uncertainty analysis; v=validation; c=communication of results; p=public participation.

Each of the terms of the equation listed above could be considered a discipline in itself, but the combination of these different areas of expertise provides estimates of risk for an exposed population. This equation also provides a guide for completing the risk assessment process in a credible way and was instrumental for carrying out the Rocky Flats project. The equation translates release estimates (S) into concentrations of radionuclides and chemicals in the environment over time based upon the movement of radionuclides in the environment around the RFP (T). These environmental concentrations form the basis of the risk estimates depending upon exposure conditions

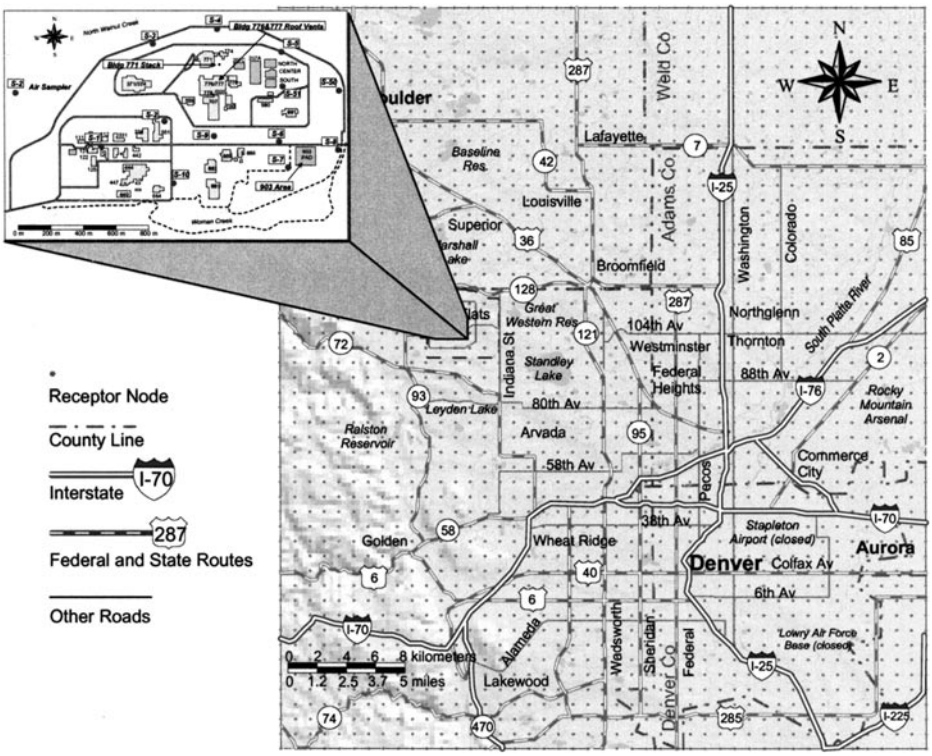

Figure 1. Location and key environmental features of the Rocky Flats Environmental Technology Site.

(E and R). Finally, the estimates of risk consider uncertainties (u), validation (v), communication of the results (c), and public involvement (p) in the process. The discussion that follows addresses each of these areas in relation to the Rocky Flats Historical Public Exposures Studies.

Source Term (S)

The source term characterizes the amount, type, and temporal duration of the materials released to the environment. In Phase II, we analyzed specific sources of plutonium, carbon tetrachloride, and several other materials of concern that have been released from Rocky Flats since site operations began.

Plutonium Plutonium releases to the atmosphere were divided into four types: routine operational releases, releases during major fires in both 1957 and 1969, and releases from the 903 Area, an outdoor storage location for drums of waste oil. Releases from the 903 Area were further divided into discrete event releases and continuous releases. Each is described below.

Routine Operations Initially, Building 771, which became operational in 1953, housed essentially all of the plutonium operations. These included plutonium recovery and purification and plutonium component manufacturing. In 1958, many of the plutonium fabrication operations were moved from Building 771 to Building 776/777 when that building came online. The recovery operations stayed in Building 771 (Ripple et al., 1996a). Construction of Building 707, which was used for plutonium fabrication, was completed in 1972. Plutonium was released *via* the ventilation exhaust from these plant buildings as a result of normal routine operations at the RFP. Even though the ventilation exhaust systems included high-efficiency particulate (HEPA) filters designed to remove the bulk of the plutonium, measurements showed that some plutonium was continuously released to the environment.

The amount of plutonium released from routine operations (including many minor fires and other off-normal conditions that did not warrant separate analysis during this project) was considerably less than from nonroutine events (accidents that were considered separately and are addressed later in this paper). Voillequé (1999a) evaluated the effects of nonrepresentative sampling of the plutonium concentration in the large exhaust ducts and of the self-absorption correction factor on the site-reported release estimates. By combining these results with the bias and uncertainty estimates for the routine effluent monitoring data reported earlier in the study (Ripple et al., 1996a), Voillequé (1999a) generated revised estimates of plutonium releases to the environment for routine operations. The Phase II release estimates are higher and reflect a broader

range of uncertainty than those developed in Phase I. The greatest uncertainties are for the years before 1964 and reflect the correction for nonrepresentative sampling. The estimates of releases during four decades, which reflect the distributions of the annual estimates, are shown in Table 1 (Voillequé, 1999a). The estimated median release for the entire period (1953–1989), 4.4 GBq, is about three times greater than previous estimates.

Effluent was passed through HEPA filters before discharge to the atmosphere. The particle size most likely to penetrate air filtration systems is ~0.3 μm. However, when filter leakage occurred, larger particles that were more typical of the workplace aerosols would have been released. For this reason, routine operational releases were assumed to be characterized by a plutonium aerosol with an activity median aerodynamic diameter (AMAD) of ~1 μm and a GSD of 2.5 (Voillequé, 1999a).

1957 Fire A major fire occurred in Building 771 on September 11, 1957, which resulted in a significant release of plutonium to the atmosphere. A detailed analysis of the fire chronology established the probable sequence of events during the fire, described the progression of the fire through the filter systems, and provided input for the possible range of oxidation conditions to which plutonium metal was exposed during the fire (Voillequé, 1999b). The timing of the release of plutonium from the fire was modeled beginning at 10:00 p.m. on the evening of September 11, 1957, and ending at 2:00 a.m. the following morning (September 12, 1957). The first 45 min of the fire were modeled in 1-min intervals to account for the rapidly changing conditions, and releases during this time were summed to give 15-min totals. The remainder of the fire was modeled in 15-min intervals, corresponding to the resolution of the available meteorological data.

The fire began in a glove box at about 10 p.m., as a result of spontaneous ignition of metallic plutonium casting residues. Subsequently, the Plexiglas glove boxes caught fire and burned, as did the rubber gloves attached to the glove boxes. At 10:39 p.m., there was an explosion in the ventilation system. The exhaust filter plenum consisted of a long concrete block-walled room into which the individual exhaust systems discharged. Exhaust air was passed through a structural steel framework that contained 620 flammable 61-cm square Chemical Warfare Service (CWS) filters. Four exhaust fans were connected to the filtered side of the plenum and discharged into a common exhaust duct leading to a concrete tunnel and the 44-m-high stack for Building 771. Burning of some plenum filters was estimated to occur as early as 10:25 p.m., permitting the direct release of plutonium up the building stack. The firemen ultimately used water to extinguish the primary fire at 10:38 p.m.; however, the fire had already spread to the exhaust filter plenum system.

RAC's analysis showed that the largest releases of plutonium occurred between 10:15 and 10:45 p.m. because of the rapid burn-through of the booster system filters[3] and the main plenum filters before water was applied to the plenum filter fire (Voillequé, 1999b). The exhaust fans were placed on high speed at 10:25 p.m. and then stopped working at 10:40 p.m. when fire burned through the power cable. After 10:45 p.m., the main fire was out and releases were much lower. At 2:00 a.m., the fire was declared extinguished. By this time, water had been applied to the plenum fire for almost 3 h. The sum of all plutonium releases after 2:00 a.m. was a small fraction of the total estimated release.

A number of factors and their uncertainties were taken into account in our analysis of the fire. The different sources of plutonium that could have contributed to atmospheric releases during the fire were identified. These included the plutonium present in the fire area; plutonium that had accumulated on the booster system filters, main plenum filters, glove box exhaust filters, and room air prefilters before the fire; and plutonium deposited in ductwork that may have been suspended during the fire. Estimates of the collection efficiencies of the various filtration systems were made and supported by historic measurements of activity in plant exhaust systems.

The median estimate of the total quantity of plutonium released was 290 g (780 GBq). The 5th and 95th percentiles of the distribution were 160 g (410 GBq) and 510 g (1300 GBq), respectively. The release estimates were sensitive to the amount of vigorous oxidation of plutonium assumed, and there is considerable uncertainty that sufficiently high temperatures were achieved for this to occur. If vigorous oxidation did not occur in the manner assumed, the release estimate would be biased high.

The size of plutonium particles released during the fire is not known. It was assumed that all the particles released were respirable and could have ranged from submicron up to 10-μm AMAD. For this reason, particle size was treated as a distribution and handled stochastically in the transport calculations.

Table 1. Estimates of Rocky Flats routine plutonium releases.

Period	Median estimate (GBq)[a]	5th–95th percentile values (GBq)[a]
1953–1959	2.2	1.0–6.3
1960–1969	2.1	1.7–3.2
1970–1979	0.16	0.13–0.21
1980–1989	0.0028	0.024–0.33
1953–1989	4.4	3.2–8.9

[a]To convert to grams, divide by 2.7 GBq g^{-1} (e.g., 4.4 GBq=1.7 g).

[3] The name given to the glove box exhaust filters. This system employed eight CWS filters in two stages to remove plutonium from the glove box exhausts and was located before the main filter plenum.

1969 Fire A major fire also occurred on May 11, 1969. It began in a glove box in the North Foundry glove box line in Buildings 776/777. The fire started at about 2:00 p.m. when a pressed plutonium metal briquette, stored in an open can in the glove box, spontaneously ignited. At 2:27 p.m., the alarm was received at the fire station. Two minutes later, when the captain and three firemen arrived at the west end of the building, there were flames about 45–50 cm above the glove box line. At this time, the firemen reported two loud noises and observed fireballs, presumably because of the rapidly burning gases. Based on his personal experience from the 1957 fire, the captain soon directed that water be used to fight the fire. The fire spread along the North Foundry glove box line, but it was prevented from moving into the north machining glove boxes by a barrier. The fire then spread along the north–south conveyer glove box line. The fire was observed in that area at 2:50 p.m., at which time a loud noise was heard and firemen felt vibrations on the second floor of the building. Considerable damage was done to the building and its equipment. Between 3:20 and 4:10 p.m., smoke was observed issuing from the roof and exhaust vents. The roof was sprayed with water and watched until after 5:00 p.m. The fire was considered contained by 6:40 p.m., and extinguished by 8:00 p.m., at which time a fire watch was established. Several small fires recurred within the building during the night and the following morning (Voillequé, 1999c).

During the early stages of the fire, Booster System No. 2 in Building 776/777, which serviced the North Foundry line, became clogged. Air from this portion of the building was then processed through Booster System No. 1. Releases from the booster systems were monitored until 4:00 p.m., at which time the stack samplers were disabled by power failure. It was reported that the first two of the four HEPA filter banks in Booster System No. 1 were breached and that the gaskets in the third and fourth filter banks had also failed. The main exhaust system samplers, which operated between May 9 and 15, indicated that approximately 2.8 mg (0.0074 GBq) of plutonium was released *via* that exhaust. Measurements made following the fire of surface contamination on the roof indicated that most of the releases were through Booster System No. 1 exhaust duct. These measurements were central to estimating the magnitude of releases during the fire, which was modeled from 2:00 to 8:00 p.m., May 11, 1969. The total release, which was primarily from Booster System No. 1, was estimated to be in the range of 140–900 mg (0.37–2.2 GBq) of plutonium.

As with the 1957 fire, there were no measurements of the particle size of the plutonium released during the fire. Because the HEPA filters in the main filter plenum and booster systems were largely intact after the fire, it was assumed that most of the particles released were relatively small and, therefore, respirable. Significant deposition of larger particles on the roof and nearby ground surfaces was likely because the main discharge from the building was through a duct that turned downward toward the roof of the building.

903 Area The 903 Area is located in the eastern part of the main production area of the RFP (Figure 1) and, during the late 1950s and 1960s, served as a waste storage area for barrels containing plutonium-contaminated cutting oil and degreasing agents, primarily carbon tetrachloride. More than 4500 barrels were reported to have been stored at the 903 Area (Meyer et al., 1996).

Site personnel reported barrel corrosion and subsequent leakage onto the soil as early as 1962. By 1964, this had become a major issue, and fences were constructed to limit the spread of contamination by intruding wildlife. In 1967, efforts were made to remove the barrels from the 903 Area, repackage the contents, and ship the waste offsite. Barrel removal was completed in June 1968. However, by late 1968, there was evidence that wind action had transported plutonium-contaminated soil beyond the 903 Area. In 1969, the area was paved with asphalt to prevent further transport of plutonium-contaminated soil away from the area. The first coat of asphalt was placed over the contaminated area in July 1969, although paving was not completed until November of that year. High-wind events during January 1969 had already spread the contamination further, as did the surface grading and leveling operations that took place in March and April 1969 in preparation for paving. Various estimates of the mass of plutonium released to the soil from the leaking barrels ranged from 85 g (230 GBq) to 800 g (2200 GBq) (Meyer et al., 1996).

To estimate releases from the 903 Area for our risk calculations, atmospheric releases from the 903 Area were calculated for a 6-year period, 1964 through 1969, and were divided into two types: discrete event releases and continuous releases. Discrete event releases occurred during short-term high-wind events in 1968 and 1969 and were modeled as individual days. In contrast, continuous releases occurred during typical meteorological conditions from 1964 to 1969 and were calculated annually (Weber et al., 1999).

Air monitoring data from a sampler located east of the 903 Area in the path of soil particles suspended by wind storms were used to identify discrete event releases. The wind usually blows from west to east during such storms. A total of 24 discrete release event days were identified. Meteorological data for these 24 days were obtained from a portable meteorological station located about 10 km north of RFP. Further investigation determined that 6 of 24 days accounted for about 90% of the total releases (Weber et al., 1999). These 6 days were modeled as discrete events, and the remaining 18 days were included with the continuous plutonium releases.

Table 2. The 903 Area discrete release estimates for plutonium attached to < 30 μm AED soil particles (Weber et al., 1999).

Release date	Distribution of estimated release quantity (GBq)		
	5th percentile	50th percentile	95th percentile
December 5, 1968	0.36	1.9	9.3
January 6, 1969	1.3	6.7	32
January 7, 1969	6.7	33	160
January 30, 1969	3.6	20	89
March 19, 1969	0.44	2.0	10
April 7, 1969	2.8	14	70
Total[a]	44	104	520

[a]The distribution of total releases was determined by sampling from the distribution of each individual release event and summing. It is not the sum of the given percentile value.

The uncertainty estimates for the amount of plutonium released into the atmosphere from the 903 Area during the 6-year period for discrete and continuous releases are summarized in Tables 2 and 3. The median estimate for the total activity of plutonium released on particles <30 μm of aerodynamic equivalent diameter (AED) was 110 GBq (43 g), and the 5th and 95th percentiles of the distribution were 52 GBq (19 g) and 560 GBq (210 g), respectively.

Summary of Plutonium Releases Distributions of the total estimated plutonium release quantities to air for the four categories of release events evaluated in Phase II are shown in Table 4. The 1957 fire and 903 Area releases dominate the total estimated quantity of plutonium released from the site.

Carbon Tetrachloride Large quantities of carbon tetrachloride (CCl_4), a highly volatile solvent, were used at Rocky Flats to clean and degrease product components and equipment. During the years of highest use (1958–1970), it was estimated that between 36,000 and 180,000 kg (40 and 200 tons) of carbon tetrachloride was used annually at the Rocky Flats (Figure 2). Most of the carbon tetrachloride was assumed to evaporate during cleaning and degreasing operations and escape to the atmosphere through roof vents on Buildings 776/777 and Building 707 where operations of this type were performed (Rood et al., 2001a). Because the information base for release estimates was quite variable, release estimates were made for three time periods and are summarized in Table 5. The estimates were based on inventory amounts, plutonium production, and solvent degreaser use during the different time periods (ChemRisk, 1994a). In total, 1–4.5 million kg of carbon tetrachloride was estimated to have been released from 1953 to 1989 (McGavran et al., 1999). Uncertainty in the annual release of carbon tetrachloride was described by a uniform distribution between the lower- and upper-bound estimate.

Table 3. The 903 Area continuous release estimates (1964–1969) for plutonium attached to < 30 μm AED soil particles.

Year	Distribution of estimated release quantity (GBq)		
	5th percentile	50th percentile	95th percentile
1964	0.03	0.24	1.4
1965	0.035	0.48	3.7
1966	0.048	0.52	3.7
1967	0.11	0.96	5.9
1968	1.4	7.0	37
1969	0.81	4.1	20

Table 4. Plutonium release estimate distributions by event.

Release event	Distribution of estimated release quantity (GBq)		
	5th percentile	50th percentile	95th percentile
Routine operations 1953–1989	3.2	4.4	8.9
1957 Fire	410	780	1300
1969 Fire	0.05	1.4	2.3
903 Area	52	110	560

Beryllium Beryllium is a nonradioactive metal used in the production of nuclear weapons components. Beryllium manufacturing operations in Building 444 (Figure 1) included casting (foundry), cutting, heat treating, rolling, and machining. Details about these beryllium component operations and ventilation systems used to control beryllium emissions at the RFP have been described at length (ChemRisk, 1992; McGavran et al., 1999). At Rocky Flats, beryllium dust was produced during its machining and was released through vents and stacks at the plant. With the possible exception of effluent from one building in the early

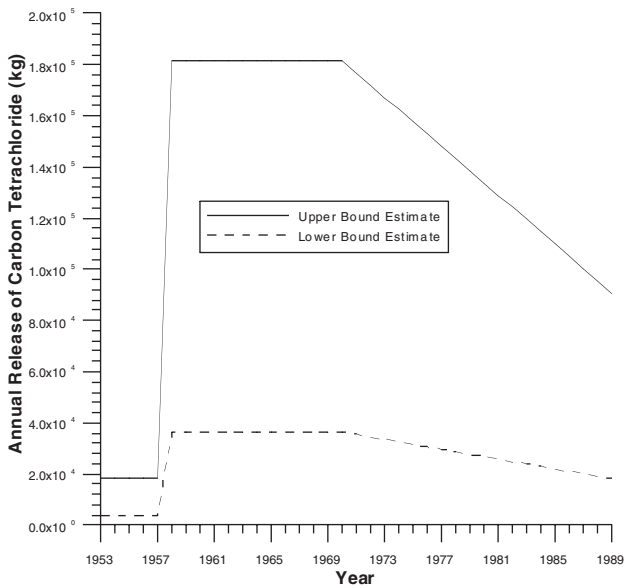

Figure 2. Carbon tetrachloride release estimates for each year of the assessment period (1953–1989).

Table 5. Carbon tetrachloride source term estimates.

Time period	Estimated release (kg year^{-1})[a]
1953–1957	4000–20,000
1958–1970	40,000–200,000
1971–1989	40,000–200,000 in 1970, decreasing linearly to 20,000–100,000 by 1989

[a]Lower- and upper-bound estimates.

1960s, all air discharged from RFP beryllium-processing facilities was filtered (ChemRisk, 1994a). Between 1958 and 1989, beryllium was released to the air during routine operations and three accidental fires (1962, 1964, and 1978) at the RFP.

Beryllium was monitored in the plant air exhaust effluent from at least 1963. The sampling practices, sampling system design, sample line losses, calculations of flow rates, and exhaust volume and uncertainties determined previously for radioactive particles were applied to the beryllium sampling data (ChemRisk, 1994a). Figure 3 summarizes the estimates for beryllium releases to air and shows that release estimates were less than 15 g year^{-1} through the mid-1960s and then increased dramatically to over 30 g year^{-1} for 1965–1968. Releases were generally less than 10 g year^{-1} after 1971. The median estimate for the total release from 1958 to 1989 was 324 g. Beryllium was also released during three fires that occurred in 1962, 1964, and 1978. Those releases were monitored by the stack sampling equipment and, therefore, were included in the annual release estimates.

Environmental Transport (T)

Elements of the environmental transport and exposure history are critical to understanding the dose and risk calculations that emerge from this modeling effort. Some of these elements are the types of events for which dose and risk were calculated, the model domain or geographical area of concern, the atmospheric transport calculations, the historical exposure scenarios, and the types of uncertainty associated with the calculations.

For the most part, the releases that emerged as important for exposure and risk calculations in this study were those that occurred over relatively short periods of time (less than a day or so), referred to as discrete releases. For this study, there were three primary discrete releases of plutonium at the RFP: the 1957 fire in Building 771, the 1969 fire in Buildings 776/777, and releases from the 903 Area largely during high-wind events that occurred on 6 days in 1968 and 1969.

Continuous releases occurred over the operational history of the facility. In particular, routine operational releases of plutonium from the Building 771 stack and from roof vents on Buildings 776/777 were important contributors to routine plutonium releases. The suspension of plutonium-contaminated soil from the 903 Area during typical meteorological conditions from 1964 to 1969 was also treated as a continuous release. Releases of nonradiological contaminants (particularly carbon tetrachloride and beryllium) were more or less continuous.

For discrete events, exposure was dependent on spatial location and timing. If an individual was not in the path of the contaminant plume at the time of the event, that individual was not exposed to the release. In contrast, for continuous events, exposure occurred throughout the model domain, and the magnitude of exposure was mainly a function of direction and distance from the plant.

Model Domain and Computational Grid A domain was developed within which contaminant concentrations, receptor exposures, and cancer risks were calculated. The model domain encompassed a 2200-km^2 area that extended 28 km south, 12 km west, 22 km north, and 32 km east from the center of the RFP (Figure 1). Most of the Denver metropolitan area and the city of Boulder are included in the domain. The domain was limited in its western extent because few individuals lived there and most of the contaminants traveled east and southeast of the plant. The number of computational grid nodes was 2295 with a grid node spacing of 1000 m.

Atmospheric Dispersion and Transport Atmospheric transport modeling was performed using the RATCHET model (Ramsdell et al., 1994). The RATCHET model was selected based on the results of a model comparison study involving five models, and results of a site-specific tracer study conducted in 1991 (Rood et al., 1999). While no model consistently outperformed the others, estimated concentrations from RATCHET exhibited better correlation

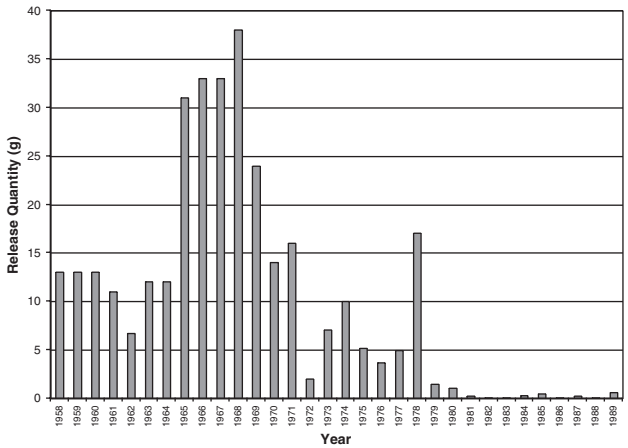

Figure 3. Annual release estimates for beryllium as estimated by ChemRisk (1994a).

to observed values overall. In addition, RATCHET incorporates spatially varying meteorological and environmental parameters and modules that perform random sampling of the meteorological parameters, which permitted a Monte Carlo analysis of uncertainty.

Atmospheric transport simulations were performed differently for discrete and continuous events. For discrete events (Rood and Grogan, 1999a,b,c), meteorological data for the specific days of the event were obtained. RATCHET was run using the Monte Carlo sampling features that sample from distributions of the basic transport parameters for each Monte Carlo trial.

Continuous events were modeled somewhat differently because meteorological data from the RFP for most of the assessment period were not available. Therefore, compilations of more recent meteorological data served as a surrogate for approximating past conditions. A 5-year meteorological data set from 1989 to 1993 was used to estimate annual average plutonium concentrations from routine operational releases and continuous 903 Area suspension releases (Rood and Grogan, 1999a; Rood et al., 1999). This technique was also used to estimate annual average concentrations of beryllium and carbon tetrachloride (McGavran et al., 1999; Rood et al., 2001b).

Air concentrations from discrete and continuous releases were integrated over the relevant years of RFP operations at each computational node in the model domain. Next, the time-integrated concentration values were combined with scenario exposure information and risk coefficients to yield the incremental lifetime cancer incidence risk to hypothetical individuals in the model domain.

Environmental Transport: Plutonium For routine releases of plutonium, estimated annual concentrations of plutonium in air east of RFP along Indiana Street (the location of highest concentration outside the buffer zone) are shown in Figure 4. These values can be compared to weapons' testing fallout concentrations of ^{239,240}Pu in air of 4.8 μBq m^{-3} in 1957 and 1.8 μBq m^{-3} in 1978 (Rope et al., 1999). The geometric standard deviation (GSD) of the estimated concentration of plutonium in air was typically around 2–2.4. A comprehensive analysis of the atmospheric dispersion and transport calculations for the routine releases is given in Rood (1999), together with the exposure and risk calculations.

Plutonium released during the 1957 fire was modeled as puffs that entered the atmosphere every 15 min from 10:00 p.m. of September 11 until 2:00 a.m. of September 12, 1957 (Rood and Grogan, 1999b). The transport calculations were continued until 7:00 a.m. of September 12, 1957 to allow all the released plutonium to disperse throughout the model domain. The computer code simulations performed using RATCHET covered a 9-h period. Because the effluent release temperature was estimated to be near 400°C, there was significant plume rise, and maximum

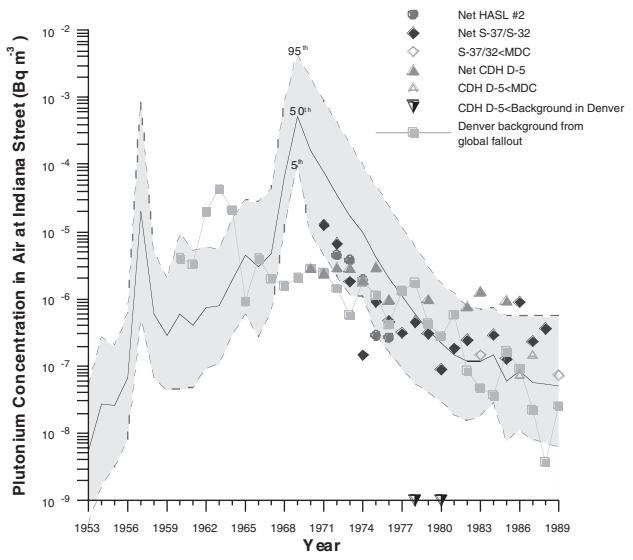

Figure 4. Comparison of estimated annual average plutonium concentrations in ambient air with measurements east of the RFP on Indiana Street outside the current buffer zone. Lines labeled 5th, 50th, and 95th represent the 5th, 50th, and 95th percentiles of the distribution of estimated concentrations. Weapons testing fallout measured in Denver represents estimated ^{239,240}Pu concentrations in air from nuclear weapons tests as reported in Rope et al. (1999). Measured concentrations at each of the samplers are corrected for this background contribution. The inverted triangles on the x-axis represent concentrations measured at the D-5 sampler (operated by the Colorado Department of Health) that were less than background ^{239,240}Pu concentrations measured in Denver.

plutonium concentrations in ground-level air were estimated some distance southeast of RFP, not adjacent to it. The concentration in air at ground level (typically 1 m in height) represents the air concentration to which people would have been exposed.

At the time the fire started, the plume was transported in a westerly direction for a few kilometers. Around 10:45 p.m., the wind direction at the RFP shifted so that it blew out of the northwest and continued to blow from that direction until about 4:00 a.m. of September 12. These winds transported the bulk of the airborne plutonium to Arvada and toward the Denver metropolitan area. Near southern Arvada, the air mass converged with air flowing from the southwest in the Platte River Valley, which resulted in a northeasterly plume trajectory. Figure 5 shows the median (50th percentile) estimated time-integrated plutonium concentrations in air near ground level.

The plutonium released during the 1969 fire was also modeled as puffs that entered the atmosphere every 15 min after 2:00 p.m. until 8:00 p.m. of May 11, 1969 (Rood and Grogan, 1999c). The transport calculations were continued until 5:00 a.m. the following morning to allow all the released plutonium to disperse throughout the model domain. The RATCHET simulations covered a 15-h period.

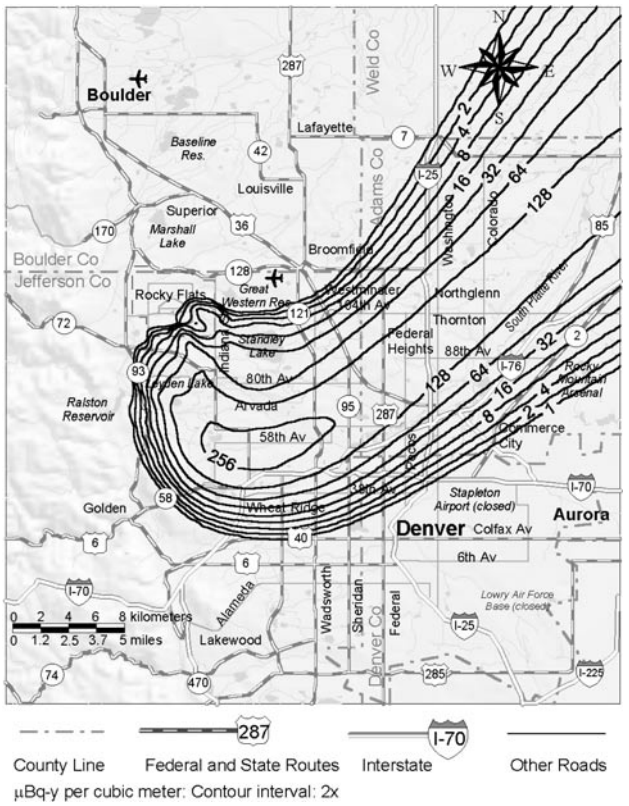

Figure 5. Estimated time-integrated plutonium concentration in air 1 m above ground during the 1957 fire. The median (50th percentile) of the distribution of estimated air concentrations is shown.

The plume of contamination was initially transported west of the RFP by the prevailing easterly winds that occur during upslope conditions. This continued until about 10:00 p.m., when there was a change to downslope conditions and a reversal of the plume trajectory to the east. The largest releases are estimated to have occurred from about 3:00 to 6:00 p.m. The highest 15-h plutonium concentrations in air (0.25 mBq m^{-3} at the 95th percentile) were estimated at the west entrance of the RFP.

The six discrete release events from the 903 Area resulted in relatively narrow plumes of airborne contamination that extended in an easterly direction but with a more pronounced northeast–southwest elongation (Rood and Grogan, 1999a). These high-wind events were responsible for suspension of relatively large amounts of plutonium-contaminated soil.

In contrast to discrete events, the continuous releases from the 903 Area resulted in an east–southeast trending ellipsoidal plume that reflects the predominant wind direction that is from the west–northwest. Higher concentration isopleths near the source move mostly easterly; however, farther away from the source, they shift to the northeast. The northeast trend is believed to be due to the influence of the Platte River Valley and the diurnal pattern of upslope–downslope conditions that characterize the general air movement on the Colorado Front Range. The estimated time-integrated concentration of plutonium attached to respirable soil particles in air (<15 μm AED) for all 903 Area releases (discrete and continuous) is shown in Figure 6.

For the 903 Area releases, three different particle size fractions were considered for the risk calculations: <3 μm AED, 3–10 μm AED, and 10–15 μm AED. Particles >15 μm AED were not considered "respirable" because most do not penetrate beyond the bronchial region of the respiratory tract, and they are eliminated from the body either by direct expulsion (e.g., nose blowing) or *via* transfer to the gastrointestinal tract.

Carbon Tetrachloride Transport For carbon tetrachloride releases, inhalation is the primary pathway of interest for releases from Rocky Flats. Carbon tetrachloride does not bioconcentrate, and it is estimated (ChemRisk, 1994b) that the dose from direct inhalation is at least 1800 times higher than that from indirect exposure pathways that involve transfer from air through plants and animals before transfer to humans. No monitoring for carbon tetrachloride released to surface water or soil was conducted. Carbon tetrachloride

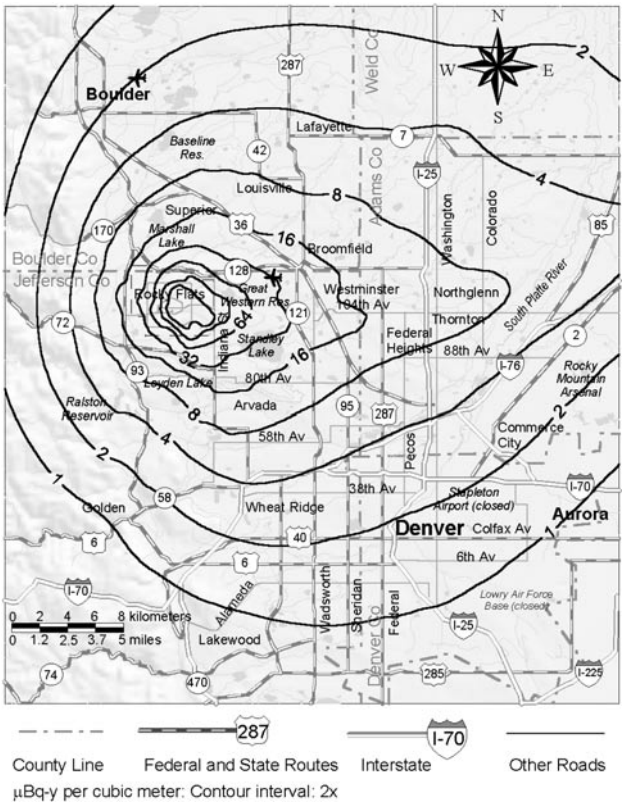

Figure 6. Estimated time-integrated concentration of plutonium attached to respirable particles (< 15 μm AED) for 903 Area releases (1964–1969). The median (50th percentile) of the distribution of estimated air concentrations is shown.

rapidly volatilizes from soil and surface water and would have likely evaporated from creeks and reservoirs within days of its release. Therefore, concentrations in these media were expected to be inconsequential compared to concentrations in the ambient air.

Historical environmental monitoring data for carbon tetrachloride were very limited. For 1988, the maximum estimated air concentration for carbon tetrachloride along Indiana Street was 0.19 μg m^{-3}. Concentrations for 1988 ranged from 0.095 μg m^{-3} (5th percentile) to 3.2 μg m^{-3} (95th percentile). This can be compared to typical background concentrations in rural areas of 1 μg m^{-3}. Air concentrations for earlier years (1957–1969) would most likely have been higher (see Figure 2).

Beryllium Transport Beryllium moved offsite in the air and in creeks that flowed to reservoirs used as drinking water sources. Starting in 1980, beryllium was monitored in liquid effluents but routine surface water monitoring showed less than the analytical detection limit of 0.05 mg of beryllium per liter of water. Historically, inhalation of beryllium has been a much greater human health concern than ingestion because less than 1% of ingested beryllium is absorbed through the gastrointestinal tract (EPA, 1991) and beryllium is not known to bioaccumulate. Releases of beryllium to surface water were not evaluated because of a lack of effluent and environmental monitoring data to quantify the releases, insufficient evidence of accumulation in soils and sediments, and low solubility and gastrointestinal absorption. Therefore, inhalation was the exposure pathway of greatest concern for beryllium releases from the RFP and beryllium releases to air were evaluated. The median estimated concentrations for beryllium at the location of highest concentration outside the buffer zone (east of the plant along Indiana Street) ranged from 1.3×10^{-6} ng m^{-3} in 1986 to 7.3×10^{-4} ng m^{-3} in 1968, the year of highest release. These concentrations can be compared with an annual average natural background range of 0.03–0.3 ng m^{-3} (median of 1×10^{-1} ng m^{-3}) (Rope et al., 1999).

Exposure Factors (E)

A key component of the Rocky Flats dose reconstruction work was estimating the health impacts to hypothetical, but representative, individuals in the model domain. The cancer risk to a person from exposure to the contaminants released depended upon a number of factors, such as where the person lived and worked, when and how long that person lived near the site, the age and gender of the person, and lifestyle. To consider the many factors that influence exposure, we developed exposure scenarios of hypothetical residents for whom representative risk estimates could be made, incorporating typical lifestyles, ages, genders, and times in the area. The scenarios provide a range of potential profiles, and included a laborer, an office worker, a homemaker, an infant–child, and a student. The infant–child scenario represented a single individual who matured during the exposure period. Table 6 lists key features of the exposure scenarios used in the analysis.

The five exposure scenarios were organized according to occupational and nonoccupational activities. Occupational activities included work, school, and extracurricular activities away from the home. Nonoccupational activities included time spent at home doing chores, sleeping, and leisure activities. In these calculations, the person was assumed to perform occupational and nonoccupational activities at the same location. The age of the individual during which exposure occurred was also considered when calculating risk. In addition, the scenarios were location-independent, which allowed the spatial dependency of risk for each scenario within the model domain to be observed.

Risk Factors (R)

Combining the exposure scenarios with the time-integrated air concentration at the location of interest allowed the total contaminant intake *via* inhalation to be estimated. Plutonium dose and risk coefficients were developed specifically for this project (Grogan et al., 2001); the risk factors were used in calculations discussed here. Published US Environmental Protection Agency (EPA) risk factors (also called slope factors) for chemicals were used to convert contaminant intake to estimates of incremental lifetime cancer incidence risk.

Plutonium The principal plutonium isotopes of concern at the RFP are ^{239}Pu and ^{240}Pu. Lung, liver, bone, and bone marrow were shown to be the principal organs of concern (Grogan et al., 2001) and the dose per unit activity inhaled varied for these four tissues. Furthermore, the dose per unit activity also varied depending on the particle size

Table 6. Exposure scenario descriptions.

Exposure scenario	Gender	Year of birth	Year beginning exposure	Year ending exposure	Days per year exposed
Laborer	Male	1934	1953	1989	365
Homemaker	Female	1934	1953	1989	350
Office worker	Female	1940	1965	1989	350
Infant–child	Female	1953	1953	1960	350
Student	Male	1957	1964	1974	350

distribution of the inhaled plutonium aerosol. Three different particle size distributions (1, 5, and 10 μm AMAD and GSD of 2.5) were assumed to characterize plutonium releases from the RFP. Lifetime cancer incidence risk coefficients with uncertainties for plutonium inhalation were developed for lung, liver, bone, and bone marrow (leukemia) as part of the project (Grogan et al., 2001) using four independent sources of information.

(1) Epidemiological studies of workers exposed to plutonium in Russia.
(2) The dose–response relationship observed in the Japanese atomic bomb survivors exposed primarily to gamma (low-linear energy transfer) radiation combined with a relative biological effectiveness factor to account for the difference in biological effectiveness of alpha radiation compared to gamma radiation.
(3) Human dose–response relationships determined for populations exposed to other alpha-emitting radionuclides (mainly radon, thorium, and radium).
(4) The results of controlled experiments with animals exposed to plutonium and other alpha-emitting radionuclides, and extrapolated to humans.

The independent cancer risk coefficient distributions were combined to develop an overall cancer incidence risk coefficient distribution that accounted for both the uncertainties associated with the estimate and an assigned intrinsic merit of the approach. These analyses are described in detail in Grogan et al. (2001).

Carbon Tetrachloride Although acute and chronic inhalation exposure to carbon tetrachloride may cause toxic injury to the liver, kidney, and nervous system, liver cancer is the health effect expected to occur at lower exposure concentrations. The EPA (1998a) classifies carbon tetrachloride as a probable human carcinogen because it has been shown to cause liver cancer in several animal species; however, studies of workers exposed to high levels of carbon tetrachloride are inconclusive.

Liver cancer risk from carbon tetrachloride inhalation was calculated using cancer risk factors established by the EPA (Rood et al., 2001a). The EPA cancer risk factor represents the 95% upper confidence limit of the probability of a carcinogenic response per daily unit intake of a chemical over 70 years. Uncertainty in the risk factor was also accounted for in the analysis.

Beryllium Beryllium is classified as a B1 probable human carcinogen (EPA, 1998b) because even though numerous studies have shown that beryllium compounds are carcinogenic in experimental animals by several routes of exposure (including inhalation), there has been debate as to whether beryllium causes cancer in humans. A number of epidemiological studies have reported an increased risk of lung cancer in beryllium workers, but deficiencies in the studies have not allowed an unequivocal conclusion to be reached.

Cancer risk factors established by the EPA were used for calculating lung cancer risk from beryllium inhalation. Uncertainty in the cancer risk factor values was accounted for based on the relative risk estimates from an occupational epidemiological study used by the EPA to determine the risk factors (McGavran et al., 1999). Beryllium can also cause a serious progressive granulomatous disease called chronic beryllium disease. Although the lung is primarily involved, it is a systemic disease and granulomatous inflammation may involve other organs. No clear dose–response relationship or duration of exposure–response relationship has been established for chronic beryllium disease, which is interpreted as involving a delayed hypersensitivity that may be induced by very low exposures. The estimated beryllium air concentrations were compared to the EPA's established reference concentration (RfC) for beryllium of 2.0×10^{-2} μg m^{-3} (EPA, 1998b). The EPA defines the RfC as an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime. The RfC was established based on evidence of sensitization to beryllium that can be detected by measuring *in vitro* proliferative responses of lymphocytes to beryllium.

Uncertainty (u)

Finally, the estimates of cancer risk considered uncertainties to provide a level of confidence in the results. The uncertainty analysis for this project included evaluating both parameter and model uncertainties. Parameter uncertainties were evaluated using Monte Carlo simulation combined with simple random sampling to generate an empirical approximation of the probability distribution of the model output. Model uncertainty was determined through model validation, comparing estimated concentrations in environmental media (air, soil, vegetation, and lake sediment) to independent measurements of relevant environmental concentrations.

Parameter uncertainty in the air dispersion process was addressed differently for the discrete and continuous events. For the discrete events, uncertainty was represented by providing probability distributions of the basic transport parameters (wind speed, wind direction, mixing height, precipitation, and Monin–Obukhov scaling length). For the continuous events, uncertainty was represented using several multiplicative correction factors that accounted for uncertainty in the dispersion process, meteorology, deposition, and plume depletion. Source term and risk coefficient uncertainties were also included in both discrete and continuous release simulations.

Uncertainty in the plutonium risk coefficients, expressed as risk per unit activity intake for a given particle size distribution, accounted for dosimetric uncertainties as well as the uncertainties associated with the approaches used to derive risk per unit dose. Some of the uncertainties in the beryllium and carbon tetrachloride risk factors were addressed by using a distribution of risk factors in the risk analyses. For example, for carbon tetrachloride, we accounted for variation among cancer studies in rodents, metabolic conversions from animals to humans, body weight, and breathing rate variation. Other sources of uncertainty, like uncertainty associated with assuming low-dose linearity, extrapolating from high-dose animal studies to low-dose human exposures, and variability in cancer response among animals and humans, could not be quantified and were not considered.

In summary, the components of parameter uncertainty that appear in the cancer risk estimates express uncertainty in the source terms, environmental transport, and risk coefficients. Such components of uncertainty are real in the sense they can be derived from measured quantities or inferred from historical records.

Validation (v)

Validation compares the estimated results to measurement data that were collected over the years. In this study, models were used extensively to estimate the risks to people from releases of plutonium, carbon tetrachloride, and beryllium to the atmosphere from the RFP. The choice of models was based on the available data, the required resolution of the calculations, and uncertainty considerations. Throughout this project, every effort was made to validate the models to establish confidence in the estimated magnitudes and impacts of the contaminant releases (Rood et al., 2001b). Peer review of the models and assumptions by established experts in the fields of application were used to address many of these aspects.

An important early step in the project was to compile potentially useful data for model validation (Rope et al., 1999). At the end of the study, these data were compared with estimates of concentrations in environmental media for validation purposes. Although it is rarely possible in risk assessment to completely validate the models and assumptions, it is always essential to use whatever data are available for validation to help provide confidence in the results. An important aspect of the validation process used in this study is that the environmental data sets applied in model validation exercises were independent of the data sets used to develop and calibrate the model.

The validation effort focused on plutonium because quality environmental measurement data were lacking for carbon tetrachloride and beryllium. Nevertheless, the validation results for plutonium transport in the environment provided some confidence that the transport of other contaminants was estimated reasonably well because the same models were used to estimate the atmospheric release and transport of carbon tetrachloride and beryllium as for routine releases of plutonium. While a wealth of historic environmental data were compiled for the project, the model used for the analysis provided estimates of plutonium concentrations in ambient air and soil. In general, model comparisons were limited to measurements in soil, ambient air, lake sediment, and vegetation.

The comparison between model predictions and measurements for plutonium in air provides a good example of this validation process (Rood et al., 2001b). Comparisons with annual average ambient air measurements were performed for post-1970 data only because of the lack of quality data before 1970. Comparisons of air data tested the resuspension portion of the model because releases after 1970 were dominated by resuspension of contaminated soil east of the 903 Area rather than routine releases or discrete events. Estimated concentrations onsite and at the RFP boundary were generally within the range of measured values, except for a few years. The model underestimated concentrations at community locations in the late 1970s and early 1980s. However, many of these measurements were below the monitoring agency's minimum detectable concentrations (MDCs) and some reported concentrations were less than atmospheric weapons testing fallout concentrations in Denver.

Four monitoring stations were selected for evaluating the annual average plutonium concentrations in air, and they include measurements made by the RFP contractor, Health and Safety Laboratory,[4] and CDPHE. The four locations were: (1) the original RFP boundary (about 2300 m west of Indiana Street), where it intersected the east access road; (2) Indiana Street, where it intersected the east access road (three air monitoring stations); (3) the city of Broomfield; and (4) Leyden (Rope et al., 1999). Annual contributions from fallout sources were estimated from the US Public Health Service/Environmental Protection Agency monitoring of air in Denver and were subtracted from the annual average measured concentrations to yield net annual average plutonium concentrations in air resulting from RFP releases. The net plutonium concentrations were compared to model estimated concentrations from the RFP releases (Figure 7).

Estimated concentrations during the 1970s are dominated by resuspension sources, with some perturbations during routine releases from buildings and stacks. The peaks observed in the estimated concentrations in 1974 and 1984 (most pronounced at the Leyden location) reflect routine

[4] Later known as the Environmental Measurements Laboratory (EML). This laboratory, located in New York City and operated by the DOE and its predecessors, is known for long-term global monitoring of radionuclides in the environment.

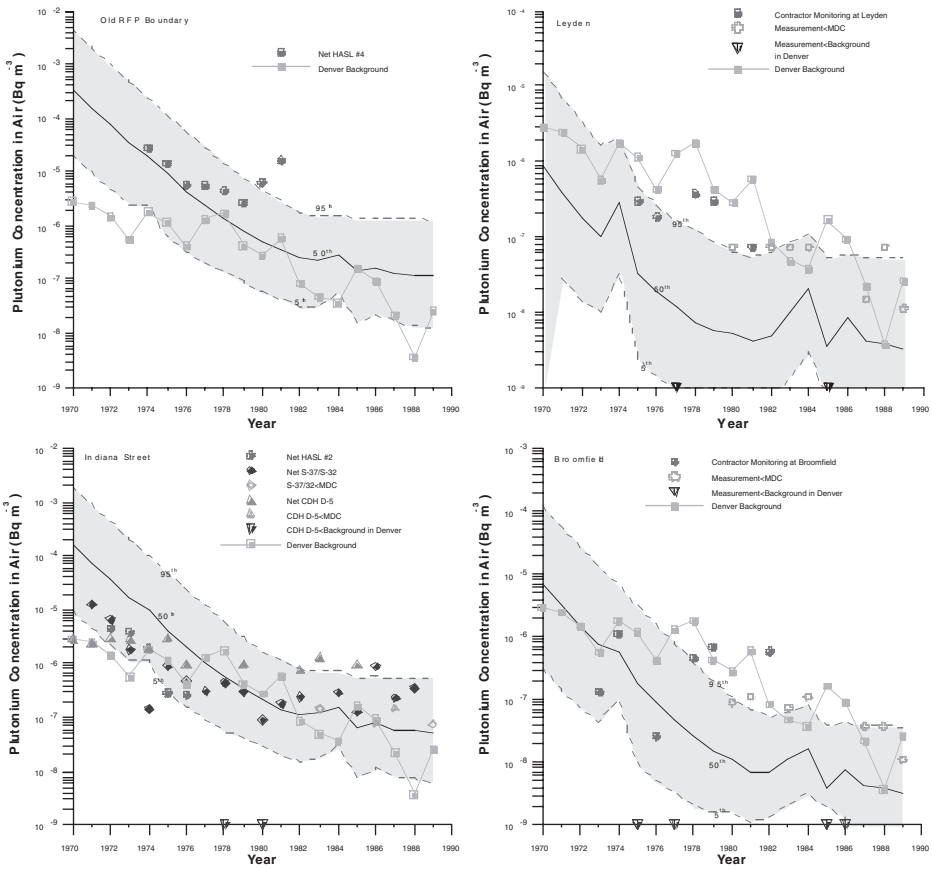

Figure 7. Comparison of estimated annual average plutonium concentrations in ambient air with measurements at four locations in the model domain. Lines labeled 5th, 50th, and 95th represent the 5th, 50th, and 95th percentiles of the distribution of estimated concentrations. Weapons testing fallout measured in Denver represents estimated ^{239,240}Pu concentrations in air from nuclear weapons tests as reported in Rope et al. (1999). Measured concentrations at each of the four locations are corrected for this background contribution. The inverted triangles on the *x*-axis represent concentrations that were less than the background ^{239,240}Pu concentrations measured in Denver.

releases from the Building 771 stack and Buildings 776/777 roof vents. The decrease in the estimated concentrations of plutonium in air from 1970 to 1980 is in response to the decrease in resuspension over time and, to a lesser extent, the weathering of plutonium from the 0- to 3-cm soil layer. The 903 Area was paved in 1969, which reduced the amount of plutonium available for resuspension.

In general, the range of model estimates between the 5th and 95th percentiles of uncertainty encompasses the measured values until about 1976. After 1976, the model tends to underestimate air concentrations at all locations except Indiana Street. There is a noticeable increase in the measured concentrations during the years 1976 to ~1982 at all stations except Indiana Street. The reason for this increase was not determined. During that same time frame, several of the annual average concentrations at Leyden and Broomfield were either less than Denver fallout or less than the monitoring agency's MDC. These measurements should be interpreted with caution because of the large uncertainty associated with them. After 1983, all annual average concentrations at the Leyden and Broomfield stations were less than the RFP contractor's MDC.

It is interesting to note that the measured concentrations at the original RFP boundary (about 2300 m west of Indiana Street) between the years 1974 and 1979 (HASL 4) decrease with about the same slope as the estimated values (Figure 7, upper left plot). This observation provides some validation of the time-dependent soil resuspension model used in this study. In 1980–1981, measured concentrations at HASL 4 increased substantially probably because of resuspension resulting from vehicular traffic.

Communication of Results and Public Involvement (c and p)

One goal of risk communication is to document the results of a scientific study in a straightforward and technically accurate way so that people can understand them. To do this effectively, the public must be involved throughout the process for credibility and to consider their concerns and ideas (Till and Meyer, 2001). Throughout the course of the

project, extensive involvement and dialogue were maintained with the members of the public and other stakeholders. It was recognized early on that public concerns are very important for both the credibility of the research and for identifying issues perceived to be critical. As a result, a number of changes were made in the direction of the research to help respond to questions raised.

Early in Phase II, a meeting was held with members of the public to identify and discuss their concerns about the project. Transcripts of the meeting were used to understand existing criticisms about the work. These issues were catalogued as part of the permanent project record so each item could be addressed as well as possible. As Phase II continued, the list of citizens' concerns was updated based on letters, written reports, electronic mailings, and questions at public meetings, and responses for them were developed (Meyer et al., 1999). It was not possible to respond to every issue, but from 210 questions and issues that were raised, responses were developed for more than 200. The few that remain unresolved are issues that lie beyond the scope of the study, or for which there was inadequate historical information with which to work.

Meetings of the HAP were open to the public and evening public meetings were also held to report progress. During Phase II, public meetings were held on a wide variety of topics ranging from atmospheric transport to developing source terms for releases to the environment. These meetings and one-on-one conversations with interested members of the public were a primary means of communicating the technical work as it progressed and the findings. In addition to direct communication with people, newsletters, fact sheets, and layman summaries of technical reports were employed.

Results

In this section, we present cancer risk estimates for inhalation of plutonium, carbon tetrachloride, and beryllium released from the RFP from 1953 to 1989. Risks are presented for the individual described by the laborer scenario because, in all cases, this scenario exhibited the highest risk. The laborer was exposed longer and had a higher breathing rate than any of the other exposure scenarios (see Table 6). Results are presented in terms of an uncertainty distribution represented by the 5th, 50th, and 95th percentiles. Uncertainty distributions were developed from 500 model realizations. While adding more realizations would result in greater confidence in the output distribution, the real question is what confidence do we have in any given percentile of the overall distribution. Confidence intervals were defined for percentiles on the tails of the output distribution using a distribution-free approach developed in Hahn and Meeker (1991). Using the ordered statistics, an interval is defined where the true value lies at a specified level of confidence. In this way, the confidence for any given percentile within the distribution could be defined. The tails of the distribution are of most interest because values at the top and bottom of the distribution change most with the number of model realizations; central values are more stable. The ordered statistics for the 5th and 95th percentiles for 500 model realizations are 25 and 475, respectively. That is, if the output values for 500 realizations are sorted in ascending order, the 5th percentile represents the 25th highest value and the 95th percentile represents the 475th highest value. The 95% confidence interval around the 5th percentile in terms of the ordered statistics is 15 and 35. The 95% confidence interval around the 95th percentile in terms of the ordered statistics is 465 and 485. The range of *values* represented by these ordered statistics will vary depending on the distribution. Model estimated risks and air concentrations reported in this paper are expressed in terms of the 95% confidence interval around the 5th and 95th percentile values. That is, the 95th percentile (with 95% confidence) is given by the ordered statistic 485 and the 5th percentile (with 95% confidence) is given by the ordered statistic 15.

Risks from Plutonium

The spatial distribution of the lifetime cancer incidence risk for the sum of the four main cancer sites (lung, liver, bone surface, bone marrow) for plutonium inhalation for the laborer scenario is shown in Figure 8. These sites account for ~97% of the total risk from plutonium inhalation (Grogan et al., 2001). The individual organ risks were highest for the lung, followed by the liver, bone surface, and bone marrow. The two risk isopleth maps in Figure 8 show the spatial distribution of the 5th and 95th percentile values of the output distributions. The area of highest risk at the 95th percentile level extended south of the RFP to the intersection of Colorado 58 and Interstate 70. Highest estimated incremental lifetime cancer incidence risks at the 95th percentile level were in the 10^{-4} range (1 chance in 10,000) of developing cancer from Rocky Flats plutonium releases during a lifetime. At the 5th percentile level, the highest cancer risk was in the 10^{-7} range (1 chance in 10 million) of developing cancer during a lifetime.

To demonstrate the importance of location and time of exposure, plutonium cancer risk estimates were examined by decade of exposure since plant operations began in 1953 at selected locations in the model domain for the laborer scenario (Figure 9). The relative importance of each decade of exposure depended on the location within the model domain and the percentile level chosen. The highest risks at the 95th percentile were estimated from exposure during the years 1953–1959, provided the laborer was located in the path of the plume from the 1957 fire. The selected locations

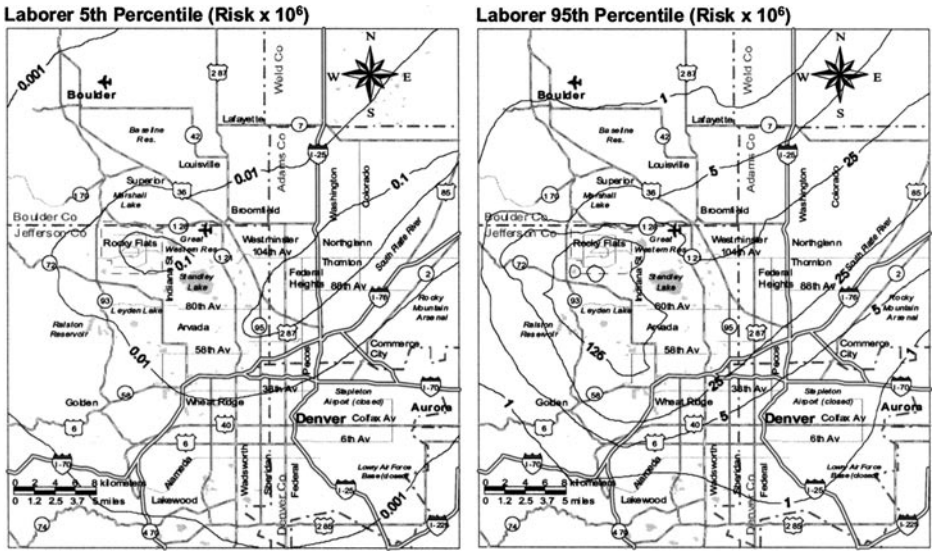

Figure 8. Lifetime cancer incidence risk from plutonium inhalation for the laborer scenario; 5th percentile (left plot) and 95th percentile (right plot). Risk values have been multiplied by 10^6 so a value of 1.0 in the plot represents a risk of 1×10^{-6} or 1 chance in 1 million of developing cancer.

outside the plume from the 1957 fire were Denver, Boulder, Broomfield, Superior, and RFP east entrance. Highest cancer risk estimates at these and other locations outside the path of the plume from the 1957 fire were estimated from exposure during the 1960s primarily from 903 Area releases. In most cases, the 50th and 5th percentile levels followed this trend. One exception was the Coal Creek location (Figure 9), which lies to the east of the RFP. The highest estimated risk at the 50th percentile level was from exposures in the 1960s; at the 95th percentile level, the highest risk was estimated from exposures in the 1950s. There is a large uncertainty in the estimated risk from exposure during the 1950s for the laborer located at Coal Creek. This uncertainty reflects the uncertainty in the 1957 fire plume path. While there is a low probability that the plume traveled in that direction, the resulting risks are relatively high.

Estimated cancer risks at the 95th percentile level are within the point of departure for acceptable risks established by the EPA of 10^{-6} to 10^{-4}. However, a single grid node near the southwest corner of the RFP boundary had a 95th percentile cancer risk value of 1.1×10^{-3}. The spatial extent of this excursion above the EPA's acceptable risk range was limited to an area no greater than 1 km^2 that historically was uninhabited.

Risks from Carbon Tetrachloride

The spatial distribution of lifetime cancer incidence risk for carbon tetrachloride inhalation (Figure 10) is somewhat different from that of plutonium. The difference is attributed to the nature of carbon tetrachloride releases, which were assumed to vary only by annual release quantities in any particular year. There were also no known catastrophic releases of carbon tetrachloride during RFP operations. Consequently, dispersion patterns reflect annual average characteristics of the release quantities and meteorological conditions. For a laborer living near the RFP east entrance along Indiana Street, the 5th and 95th percentile risk values were 9.2×10^{-7} and 2.5×10^{-5}, respectively. These risks were comparable to the risks from inhalation of Rocky Flats plutonium at the same location.

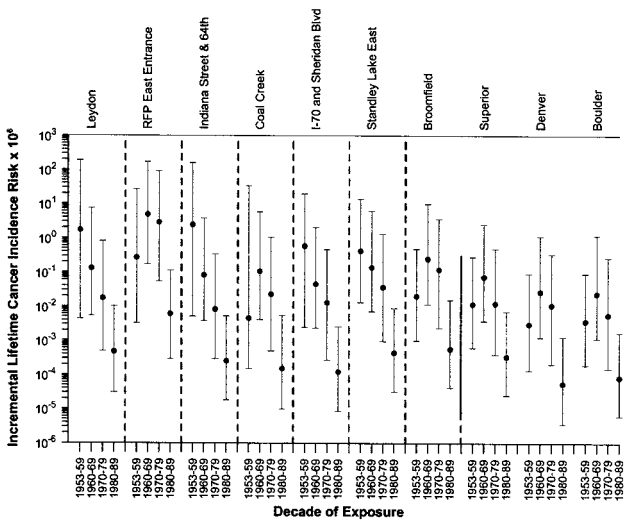

Figure 9. Lifetime cancer incidence risk from plutonium inhalation for the laborer scenario at selected locations in the model domain. Dots represent the 50th percentile value; horizontal bars represent the 5th and 95th percentile ranges. Cancer risks have been sorted by decade of exposure.

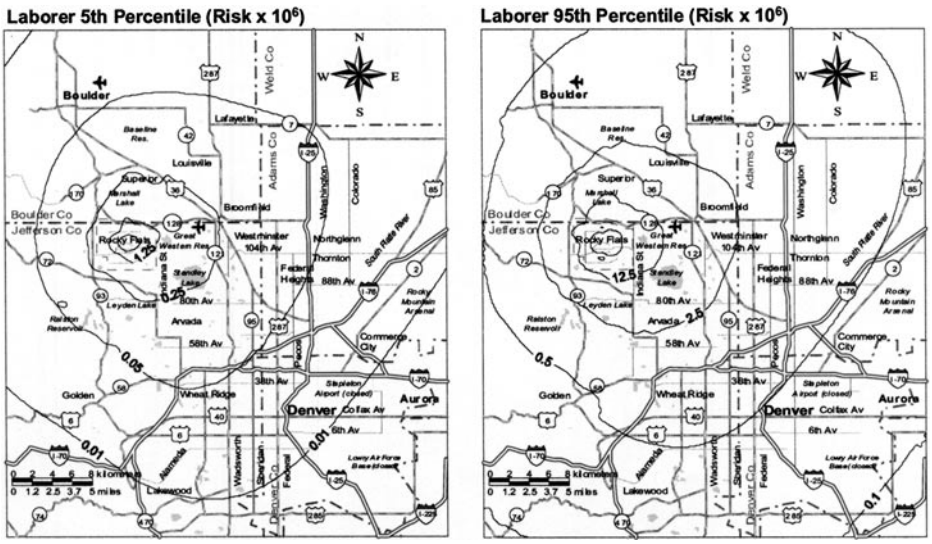

Figure 10. Lifetime cancer incidence risk from carbon tetrachloride inhalation for the laborer scenario; 5th percentile (left plot) and 95th percentile (right plot). Risk values have been multiplied by 10^6 so a value of 1.0 in the plot represents a risk of 1×10^{-6} or 1 chance in 1 million of developing cancer.

Risks from Beryllium

The spatial distribution of lifetime cancer incidence risk for beryllium is similar to that of carbon tetrachloride. That is, dispersion patterns reflect annual average characteristics of the source term and the prevailing meteorological conditions. For a laborer living near the RFP east entrance along Indiana Street, the 5th and 95th percentile risk values were 7.5×10^{-11} and 1.8×10^{-9}, respectively. These risks were substantially lower than those calculated for plutonium and carbon tetrachloride.

Although beryllium exposures for workers at the RFP have been of great concern and the attention to workers caused public concern about health effects from beryllium exposure offsite, the results of this assessment estimated that the lung cancer risk from offsite exposure to Rocky Flats beryllium was negligible. However, great uncertainty is associated with estimating the risk for chronic beryllium disease in the offsite public. The maximum estimated annual average beryllium concentration in air in the entire model domain was calculated within the RFP industrial boundaries and ranged from 2.5×10^{-6} to 6.8×10^{-5} μg m^{-3} (5th and 95th percentiles, respectively). These concentrations are over 300 times lower than the EPA's RfC of 2.0×10^{-2} μg m^{-3}. The maximum annual average air concentration estimated along Indiana Street ranged from 9.4×10^{-7} to 1.4×10^{-5} μg m^{-3} (5th and 95th percentiles, respectively), concentrations over 1400 times lower than the RfC. A hazard index calculated using these values would be well below 1 and, therefore, any cases of chronic beryllium disease are unlikely. However, because of the complexity and apparent immunological nature of chronic beryllium disease, one cannot conclude that no cases of chronic beryllium disease occurred from offsite exposure.

Conclusions

This study is a comprehensive and detailed analysis of the exposure circumstances surrounding the RFP since it began operating as a facility in 1952. The results of the Rocky Flats Historical Public Exposures Studies show that the primary risks posed to the public from operations at the RFP were from plutonium and carbon tetrachloride. The most important pathway of exposure was inhalation of these materials. Other pathways, such as ingestion of food and water that contained plutonium or carbon tetrachloride and external exposure, were much less important. The major event contributing risk from plutonium exposure was the 1957 fire. This important finding differs from previous analyses of risk to the public near the site, in which it was determined that exposures and risks from plutonium released to the atmosphere from the 903 Area were the largest contributors to health risk to the public. Based on the estimated exposures and risks reported in these findings, further epidemiological studies of the exposed population do not appear to be justifiable or warranted.

There are several important contributions to science and public policy from the Rocky Flats Historical Public Exposures Studies that are noteworthy. First, and most importantly, these results help people who lived near the RFP understand what they may have been exposed to and the associated risks. It is important that this knowledge be accessible to everyone who lived near Rocky Flats. It is also

important to thoroughly document past events since the site is no longer operating and parts of it will eventually be released for public use after cleanup and remediation have been carried out. The study provided a number of new contributions to the development of technical methods that will be of value in future risk assessments. Examples of these contributions include: (a) reconstruction of the releases of plutonium to the atmosphere (source terms) from the 1957 fire; (b) evaluation of particle resuspension during high-wind events that occasionally occur in the Rocky Flats area; (c) comparison of five air dispersion models to select the model most appropriate for the data available and the geographic location; and (d) estimation of uncertainties in converting dose to risk following inhalation of plutonium.

The study analyzed the resuspension of particles during high-wind events to determine if these events could have contributed significantly to the risk to the public from soil contaminated with plutonium on site. This was a key question that had been raised by the public early in the study. The present analysis indicated that risk from the high-wind events was actually lower than previously calculated when the release was evaluated as a steady-state process over a 5-year period. The reason for this finding was that although significant numbers of large particles were resuspended during high-wind events, atmospheric dilution at downwind locations is much greater than during normal environmental conditions. Furthermore, the large particles are less likely to be inhaled and, if inhaled, are not readily transported to organs of the body most likely at risk.

In conclusion, the Rocky Flats Historical Public Exposures Studies yielded many lessons that must be remembered. Many of the techniques that were applied during this dose reconstruction project can be adapted not only to retrospective but also to prospective risk assessment. Many of these methods can be applied to cleanup and decision making currently ongoing at the site and at other DOE facilities. Most importantly, the public now has a comprehensive analysis upon which to rely, in order to understand what happened at Rocky Flats in the past and to know what their own risk might have been from releases of materials to the environment during past operations at Rocky Flats.

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