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Transuranic and Tracer Simulant Resuspension

by
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TRANSURANIC AND TRACER
SIMULANT RESUSPENSION

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ABSTRACT

Plutonium resuspension results are summarized for experiments conducted at Rocky Flats, onsite on the Hanford reservation, and for winds blowing from offsite onto the Hanford reservation near the Prosser barricade boundary. In each case, plutonium resuspension was shown by increased airborne plutonium concentrations as a function of either wind speed or as compared to fallout levels. All measured airborne concentrations were below maximum permissible concentrations (MPC).

Both plutonium and cesium concentrations on airborne soil were normalized by the quantity of airborne soil sampled. Airborne radionuclide concentrations in $\mu\text{Ci/g}$ were related to published values for radionuclide concentrations on surface soils. For this ratio of radionuclide concentration per gram on airborne soil divided by that for ground surface soil, there are eight orders of magnitude uncertainty from 10^{-4} to 10^4 . This uncertainty in the equality between plutonium concentrations per gram on airborne and surface soils is caused by only a fraction of the collected airborne soil being transported from offsite rather than all being resuspended from each study site and also the great variabilities in surface contamination.

Horizontal plutonium fluxes on airborne nonrespirable soils at all three sites were bracketed within the same three to four orders of magnitude from 10^{-7} to 10^{-3} $\mu\text{Ci}/(\text{m}^2 \text{ day})$ for plutonium-239 and 10^{-8} to 10^{-5} $\mu\text{Ci}/(\text{m}^2 \text{ day})$ for plutonium-238. These are the entire experimental base for nonrespirable airborne plutonium transport.

Airborne respirable plutonium-239 concentrations increased with wind speed for a south east wind direction coming from offsite near the Hanford reservation Prosser barricade. Airborne plutonium fluxes on nonrespirable particles had isotopic ratios, $^{240}\text{Pu}/^{239+240}\text{Pu}$, similar to weapons grade plutonium rather than fallout plutonium.

Resuspension rates were summarized for controlled inert particle tracer simulant experiments. Wind resuspension rates for tracers increased with wind speed to about the fifth power. This wind speed dependency is comparable to the wind speed dependency measured for offsite plutonium resuspension

near the Prosser barricade. However, plutonium resuspension data near U-Pond showed an air concentration dependency on wind speed to the 1.5 power. There is still uncertainty in the wind speed dependency of airborne concentrations at different sites.

The weathering half-life is the average time required for airborne concentrations from resuspension sites to decrease by one-half when airborne concentrations are averaged over all meteorological conditions. Airborne plutonium and cesium concentrations measured at Hanford as well as tracer resuspension experiments show the weathering half-life is much greater than usually reported in the literature: five months or much longer rather than only 35 to 45 days.

Resuspension rates for local mechanical resuspension of inert tracer particles caused by vehicular and pedestrian traffic are summarized.

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INTRODUCTION

Resuspension occurs when particles on a surface are disturbed and carried up into the air by air currents. Wind-caused resuspension is the process by which wind blows particles from a surface into the air and transports them downwind. For radionuclide contaminated surfaces, wind might cause radionuclide particles to be resuspended and transported to other sites. Resuspension occurs at radionuclide contaminated sites on the Hanford reservation in Washington^(1,2), at Rocky Flats in Colorado⁽³⁻⁸⁾, at the Nevada test site^(9,10), at the Savannah River Laboratory reservation in Tennessee⁽¹¹⁾, and at other sites^(12,13) but with our present knowledge,^(14,15) amounts of wind-caused resuspension and its effects cannot be adequately predicted.

Radioactive particles deposited on natural or man-made surfaces are resuspended by both wind and mechanical activity. Wind resuspension may occur over a wide area as well as a local area. In contrast, mechanical activity resuspension is usually more localized and may present an immediate inhalation problem to the worker in a contaminated zone. In both wide-area and local resuspension of radionuclide particles, particles transported downwind could become a potential radiological concern to man. Sources for resuspended particles include radioactive fallout as well as releases from nuclear facilities. At present, the significance of fallout resuspension is unknown. Data are needed to define the relative inhalation hazard of fallout particle resuspension versus the direct delivery of stratospheric debris.

Radioactive particle resuspension is probably more important at nuclear facilities near which the environment has been contaminated with radioactive particles. These particles can be resuspended by both wind stresses and mechanical disturbances. However, resuspension mechanisms are poorly understood and, consequently, resuspension rates and potential airborne inhalation hazards cannot now be adequately predicted.

The need for such predictions are not new: resuspension has been known for many years to be occurring at nuclear sites. Some of the earliest data were obtained^(9,10) at the Nevada test site. Ground radioactivity contours were determined as a function of time after a test

detonation. These contours show deposited radionuclide particles were resuspended by prevailing winds, and ground surface concentrations decreased with increasing distance from the test center during the initial time period after the test.⁽⁹⁾ Subsequent ground radioactivity contours showed a migration of radionuclides from the test site, indicating that resuspension had occurred. Similarly, aerial surveys at Hanford⁽¹⁶⁾ have shown transport of ^{241}Am by wind resuspension.

Resuspension is of considerable interest at the Rocky Flats nuclear plant in Colorado where ground surfaces were contaminated with plutonium from leaking storage barrels containing plutonium-contaminated cutting oil.⁽³⁻⁸⁾ After leakage was discovered, barrels were removed and corrective actions were taken, but plutonium resuspension from residually contaminated soil surfaces is still occurring.

More recently, resuspension has been reported at study sites on the Hanford reservation.^(1,2) These sites were low-level liquid waste disposal sites.

Although environmental plutonium resuspension is receiving attention, resuspension physics is poorly understood. Resuspension was early characterized by a "resuspension factor". The resuspension factor is defined as the ratio of airborne pollutant concentration (amount/ m^3) at breathing height divided by the ground surface contamination level (amount/ m^2). Thus, the resuspension factor has units of m^{-1} . Reported resuspension factors vary many orders of magnitude with values from 10^{-11} up to 600 m^{-1} .^(12,13,17) Resuspension factor variations have not been adequately explained as a function of experimental conditions.

Resuspension factors from about 10^{-9} to 10^{-5} m^{-1} are often used in hazard evaluations. The resuspension factor is useful since a worker's inhalation hazard is most likely related to the local resuspension caused by his work activities within a contaminated zone; however, resuspension factors are only a very rough estimate of the potential airborne contaminant concentration since resuspension factors cannot be accurately predicted. In addition to local resuspension, airborne contaminated particles can reach

workers from upwind contaminated areas. Hence, both local and upwind resuspension should be considered, but resuspension factors in either case cannot be used in downwind transport models.

The resuspension factor is an index of only the potential inhalation concentration and not the total resuspension release rate from a surface-contaminated area. Resuspension release rates are needed for source terms in calculating total downwind diffusion and transport of resuspended particles. It is only recently that particle resuspension rates have been measured. (17-22)

The objective of this paper is to summarize reported resuspension rates (6,7) and parameters (1,19) determined by Battelle-Northwest between 1971 and early 1977. These include plutonium resuspension measurements at Rocky Flats and at Hanford as well as results from controlled tracer simulant source resuspension experiments.

In these experiments, airborne concentrations were measured as functions of wind speed, airborne particle size, wind direction, and the collected radionuclides or tracer simulants determined per gram of airborne soil or solids. Particulate air samples were collected as a function of wind speed to determine whether airborne radionuclide concentrations increased at higher wind speeds, while concentrations as a function of particle size were measured to determine the distribution of radionuclide particles resuspended as individual particles or attached to host soil and solid particles. In addition, airborne radionuclides were normalized by the total amount of airborne solids to relate concentration per gram of airborne solid to concentration per gram of radionuclide on the ground.

CONCLUSIONS

This review of resuspension data indicate the following problem areas:

- There are more theoretical resuspension models available for prediction than data to validate or to use in those models. Theoretical model development is limited by availability of experimental data.
- The entire data base for relating plutonium contamination of surface soils to plutonium on airborne soil is based on gross surface soil and airborne soil samples. Data have not been collected to determine any relationship between plutonium size distributions and concentrations on airborne soil and plutonium soil size distributions and concentrations on surface soils.
- Resuspended plutonium is transported on both respirable as well as nonrespirable soil particles. Data reported are the entire data base for plutonium transport on airborne nonrespirable soil. Additional data are needed to describe plutonium transport on nonrespirable particles and the subsequent degradation to a respirable resuspension source.
- One possible assumption for describing resuspension concerns the prediction of plutonium concentration per gram of airborne soil versus plutonium concentrations per gram of surface soil. However, ranges of airborne concentrations per gram versus surface soil concentrations per gram indicate a wide discrepancy between airborne versus surface soils. This wide uncertainty shows there seems to be no justification for assuming any equalities between plutonium concentrations on surface soils versus airborne soils.
- The rate of change of average airborne radionuclide concentrations with time has been described by a weathering half-life. However, the weathering half-life is not well known. Data shown for radionuclides as well as inert tracer particles indicate the half-life is from five months or longer, rather than the often quoted 35 to 40 days.

- At Rocky Flats, the $^{238}\text{Pu}/^{239}\text{Pu}$ ratio on airborne nonrespirable soils can be much greater than on surface soils. Thus, there is a preferential resuspension transport of ^{238}Pu versus ^{239}Pu . For migration within surface soils, there are data showing preferential migration with depth as well as of ^{238}Pu compared to ^{239}Pu .

Both ^{238}Pu and ^{239}Pu resuspension occurred onsite at Rocky Flats and the Hanford reservation, but all airborne plutonium concentrations were significantly below maximum permissible concentrations in air. In addition, plutonium was resuspended from offsite near the Hanford reservation. In all cases plutonium was deposited on each stage of particle cascade impactors, showing that most plutonium was resuspended while attached to larger host soil particles.

Plutonium was transported on both respirable and nonrespirable airborne soil particles. In most resuspension research reported by other researchers as well as in air monitoring activities, airborne concentrations of particles have been measured without regard for all particle sizes present. However, only respirable or near-respirable size particles are frequently measured since the usual air sampling techniques tend to keep larger, nonrespirable particles from being collected. Consequently, total airborne plutonium concentrations could be greater than normally reported using most existing sampling equipment systems. However, results from those systems are a conservative estimate (high concentration) of airborne respirable plutonium concentrations. Nevertheless, plutonium transport on nonrespirable particles may be a significant factor in total plutonium transport. Larger than respirable particles are resuspended and may not travel too far downwind before redepositing again. In contrast, respirable particles remain airborne for a much longer distance. Additional research is needed to clarify the relative significance of plutonium transport on respirable as compared to nonrespirable particles.

Plutonium concentrations per gram of both respirable and nonrespirable airborne soils discussed in this report are summarized in Table 1. Agreement is within several orders of magnitude from 2×10^{-8} to 6×10^{-5} $\mu\text{Ci/g}$ for respirable ^{239}Pu and from 1×10^{-7} to 3×10^{-4} $\mu\text{Ci/g}$ for nonrespirable ^{239}Pu .

In all cases, these ratios were calculated based upon total soil samples. In addition, there is no proven method to predict the ratios of concentration per gram of airborne soil to concentration per gram of surface soil. As shown in Tables 4 and 6, this ratio ranges eight orders of magnitude from 10^{-4} to 10^4 . This uncertainty range is almost as large as the uncertainty range of 10^{-11} to 600 m^{-1} for resuspension factors. (12,13,17)

Airborne plutonium transport fluxes on nonrespirable particles are summarized in Table 2. These data and the decrease of flux with distance shown in Figures 8 and 9 are the present knowledge on this subject. There is reasonable agreement within several orders of magnitude for nonrespirable airborne plutonium fluxes. However, the agreement may be caused in part by relatively more soil transport with a lower plutonium-on-soil concentration being comparable to a lower soil transport and concurrent higher plutonium-on-soil concentration. Nevertheless, these ranges of horizontal plutonium fluxes on nonrespirable particles can be used in modeling efforts and hazards analysis until a greater data base is experimentally obtained.

Airborne concentrations of ^{239}Pu , ^{241}Am , ^{238}Pu , ^{137}Cs , and ^{90}Sr increase⁽¹⁾ as a function of wind speed to the 1 to 6 power for on-site resuspension study sites. Airborne plutonium concentrations for off-site resuspension increased as a power function of wind speed. Above a wind speed of about 5 m/sec, plutonium air concentrations increased with wind speed to the 3 to 5 power. Explanation for differences in exponents are needed. Differences might be attributed to source characteristics and extent.

In contrast for controlled source experiments, tracer particle resuspension rates increase with about the 5th power of wind speed. This 5th power is similar to offsite plutonium resuspension.

TABLE 1. Summary of Plutonium Concentrations on Total Airborne Solids

Site	Total Airborne $\mu\text{Ci/g}$ Range			
	^{238}Pu		^{239}Pu	
	Respirable	Nonrespirable	Respirable*	Nonrespirable
Rocky Flats (6,7)	NR	2×10^{-7} to 5.1×10^{-6}	2.1×10^{-6} to 6.2×10^{-5}	1×10^{-6} to 3.1×10^{-4}
Hanford Reservation On-site (1)	1×10^{-9} to 1×10^{-6}	4×10^{-9} to 1×10^{-7}	2×10^{-8} to 6×10^{-5}	1×10^{-7} to 4×10^{-6}
From Off-site Near Prosser Barricade	NR	NR	5×10^{-8} to 1×10^{-6}	1.3×10^{-7} to 2.1×10^{-7}

NR, no radiochemical results.

*"Respirable" as used in this report are those particles which are found on all filter and impactor stages as contrasted to nonrespirable particles collected by gravity in rotating cowls.

TABLE 2. Summary of Plutonium Total Transport Fluxes on Nonrespirable* Particles

Site	Ranges of Total Plutonium Fluxes, $\mu\text{Ci}/(\text{m}^2 \text{ day})$	
	^{238}Pu	^{239}Pu
Rocky Flats (7)	1×10^{-8} to 1×10^{-5}	1×10^{-7} to 6×10^{-4}
Hanford Reservation On-site	2×10^{-8} to 2×10^{-7}	4×10^{-7} to 4×10^{-6}
From Off-site near Prosser Barricade for 190 to 260° Winds	NR**	1.4×10^{-6} to 3.9×10^{-6}

*Nonrespirable as used in this report are those particles collected within the rotating cowl shown in Figure 3.

**NR is no radiochemical results.

Plutonium concentrations on collected airborne soil at Rocky Flats ranged from a maximum of twice the concentration on ground surface soil to as low as 10^{-4} of the concentration on surface soils. The maximum reported⁽⁴⁾ surface soil concentration was 3×10^{-3} $\mu\text{Ci/g}$. Even at this relatively high plutonium surface soil concentration, airborne respirable plutonium concentrations were significantly below maximum permissible airborne concentrations (MPC) on a yearly basis. Similarly at the Hanford resuspension study sites,⁽¹⁾ maximum concentrations per gram of airborne solid for transuranics were for ^{239}Pu , 6×10^{-5} $\mu\text{Ci/g}$; for ^{238}Pu , 1×10^{-6} $\mu\text{Ci/g}$ and for ^{241}Am , 7×10^{-5} $\mu\text{Ci/g}$.

There is much uncertainty in the relationships between radionuclide concentrations per gram of airborne solid and per gram of soil surface solids. For the transuranic data reported, at Rocky Flats the ratio ranges from 10^{-4} to 2 and at Hanford the ratio ranges from 2 to 8×10^3 . Uncertainties are probably complicated by spatial distributions of surface contamination.

Radionuclide particles may be resuspended either as individual particles or, more probably, attached to host soil or solid particles. An average or "normal"-activity radionuclide particle distribution is usually collected on sampling filters. However, at both Rocky Flats and Hanford, one filter sample collected in each case showed significantly greater plutonium concentration than the maximum for all other samples collected during the same time period. These anomalous higher concentrations are attributed to one or more plutonium particles of unusually higher activity than those normally, or most frequently, resuspended.

There is increasing but still conflicting data that ^{238}Pu is more mobile than ^{239}Pu . The isotopic ratio data reported for airborne plutonium transport on nonrespirable particles at Rocky Flats support the greater mobility concept. This conclusion was obtained by comparing airborne $^{238}\text{Pu}/^{239}\text{Pu}$ ratios on nonrespirable soil near the eastern security fence and the eastern cattle fence. At the eastern security fence, airborne $^{238}\text{Pu}/^{239}\text{Pu}$ ratios were similar to ground surface ratios. However, at the eastern cattle fence, the $^{238}\text{Pu}/^{239}\text{Pu}$ ratios were significantly greater than measured on local surface soils (see Figure 11). Consequently, an explanation is needed to explain the increased $^{238}\text{Pu}/^{239}\text{Pu}$ ratio at distances from the

original oil storage area. Possible explanations include preferential biodegradation of ^{238}Pu compared to ^{239}Pu , preferential ejection of ^{238}Pu during decay, as well as differences in the soil chemistry between the eastern security and the eastern cattle fence. These possibilities exist, but are not definitive. Further research is needed to explain the higher relative airborne $^{238}\text{Pu}/^{239}\text{Pu}$ concentrations near the eastern cattle fence.

The weathering half-life is the time required for airborne concentrations at a resuspension site to decrease by one-half. Weathering is probably a function of the source characteristics. However, very little is known about predicting weathering. For fallout, previous literature has indicated this half-life to be between 30 and 45 days. However, results of ^{137}Cs and transuranic air concentration measurements at resuspension study sites at Hanford reported here indicate a resuspension half-life of from 5 months⁽¹⁾ to a year or greater. Knowledge of this ill-defined half-life is important in modeling efforts to describe airborne effects of surface contamination. Changes in surface contamination availability with time must be known if models are to predict airborne concentrations. This range of from 5 months to a year or greater for a weathering half-life is an important new addition to resuspension literature.

Measurements of transuranics resuspension rates have not been directly measured at surface contaminated sites since published characteristics of the contaminated surface sources are not adequate for direct measurement of particle resuspension rates. Consequently, resuspension rates were measured with controlled tracer particle simulants using a uniform surface contamination source. Based upon those measurements, the following conclusions were reached.

Particle resuspension rates are a function of at least wind speed and mechanical disturbances. Mechanical disturbances such as vehicular traffic or a man walking can cause high local resuspension rates. In comparison, average wind resuspension rates from a local area could be less important per unit area than local mechanical disturbance resuspension. However, wind-caused resuspension rates apply to the entire contaminated area. If one compares relative resuspension from wind-caused and mechanical disturbances,

one would need to know the total surface contamination area for wind resuspension versus small localized surface contamination levels for mechanical disturbance resuspension rates. Both mechanisms, however, do resuspend and transport potentially hazardous respirable particles.

Resuspension rates for respirable and nonrespirable particles are needed for inclusion as source terms in atmospheric diffusion and transport equations; however, model predictions are no better than the uncertainty in the source data. In the case of resuspension rates, uncertainties are very large. Much research is yet needed to develop resuspension models to predict particle resuspension rates for any situation.

Wind-caused resuspension rates from a sparsely vegetated area have only been measured with submicrometer tracer particles. The potential effects of different particles diameters and chemical properties on resuspension rates are unknown. It might be hypothesized that similar results would be expected for other submicrometer particles of interest since submicrometer particles are probably attached to host soil particles when particles are resuspended. If the particles of interest were much larger, it is unknown whether the particles would be resuspended attached to host soil particles or resuspended as discrete particles.

The change in airborne concentration of a pollutant as a function of time is often attributed to a weathering half-life, the fixation of the pollutant particle into the ground surface soil. In contrast, weathering half-lives for respirable tracer particles are now estimated here as being on the order of years. Predictions using weathering half-lives of months versus years could have a significant implication in environmental hazards evaluations. At the present time, credit for decreased airborne radioactivity from resuspension could be attributed to a weathering half-life of months. If a weathering half-life of years were applicable for transuranics, the potential downwind inhalation hazard from resuspended particles would be significantly increased. Additional experimental data are needed to determine what weathering half-life or variation of half-life with time should be used in hazards evaluations.

Vegetation on a resuspension surface will decrease resuspension rates. This is rather obvious, but can be definitely concluded from decreased tracer particle resuspension rates for vehicles driven on a cheat grass area compared to an asphalt area. Since vegetation does decrease resuspension, vegetation should be retained on all areas of potential surface contamination and existing surface contaminated areas until constructive cleanup operations can be initiated.

STUDY SITES

The Hanford Reservation and Rocky Flats were ideal sites at which to measure resuspension and determine resuspension physics. At Hanford⁽¹⁾, nuclear reactors and separation plants have been operated for over 30 years. Fuel elements have been processed and high- and low-level liquid wastes from those separation plant process streams have been stored and accumulated. These include low-level wastes discharged to ponds and trenches to be filtered through soil and sediments. As a result, residual radioactive materials in liquid waste are retained on soil particles or trench bottoms. Several areas of low-level waste disposal were resuspension source study sites⁽¹⁾. In contrast at Rocky Flats⁽³⁻⁸⁾, the ground source of plutonium was an area where oil had originally contaminated a relatively small area of soil. This primary contaminated soil was covered with asphalt. Low-level ground contamination⁽⁴⁾ was from plutonium resuspended and deposited prior to asphalt covering of the primary source.

For these plutonium-contaminated sites, plutonium ground source characteristics as to particle diameter, concentration, etc., were not sufficiently defined to determine resuspension rates. Nevertheless, information applicable to resuspension models has been collected from these sites.

Our research goals are to develop general models for predicting particle resuspension rates and potential downwind hazards. Consequently we are also experimentally developing the data base for these models by seeding surfaces at Hanford with inert tracer simulant of known properties and subsequently by mass budgets are determining wind-caused particle resuspension rates under various meteorological and surface conditions.

EXPERIMENTS

The experiments for measuring particle resuspension reported here have been reported in fuller detail in the following references:

- plutonium and americium from resuspension study sites at Hanford⁽¹⁾
(see Figure 1)
- plutonium from contaminated environmental surfaces at Rocky Flats^(6,7)
(see Figure 2)
- controlled inert simulant tracer particles from selected surfaces on the Hanford reservation⁽¹⁷⁻²²⁾

Plutonium resuspension results from off-site Hanford near the Prosser barricade are reported here for the first time. Most wind-caused resuspension research concerns resuspension from vegetated areas. Experiments concerning local resuspension caused by mechanical activity include tracer studies of resuspension rates for a man walking across an asphalt strip and for cars and trucks driven on asphalt or cheat grass.

Two different resuspension rates are used. For wind-caused resuspension, resuspension rates are reported as the fraction of particles resuspended/sec. Thus, the total wind-caused resuspension is a product of the surface contamination level, the duration of resuspension, and the resuspension rate. For local mechanical disturbances by vehicular or pedestrian traffic, resuspension was measured each time a car, 3/4-ton truck, or person passed across the length of a 3-m-wide, tracer-contaminated area. Thus traffic resuspension rates are reported as the fraction of particles resuspended/pass.

PARTICLES

Resuspension was measured for several types of particles. The plutonium particle size distributions on soils at Rocky Flats and Hanford were uncontrolled. A forest spray operation provided an opportunity to measure resuspension of DDT as tracer particles not specifically controlled for size. The controlled, inert tracer particles used were submicrometer CaMoO_4 particles and ZnS particles with an 8- μm mass aerodynamic equivalent diameter.

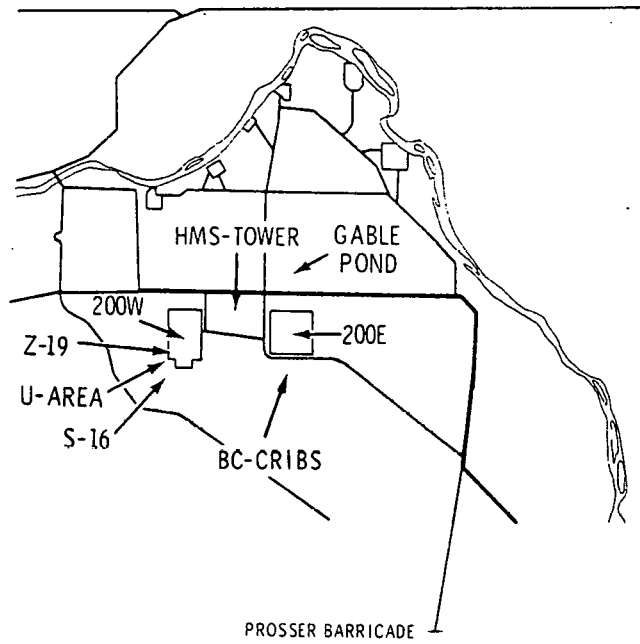


FIGURE 1. Location of Hanford Study Sites (Neg. 772705-5)

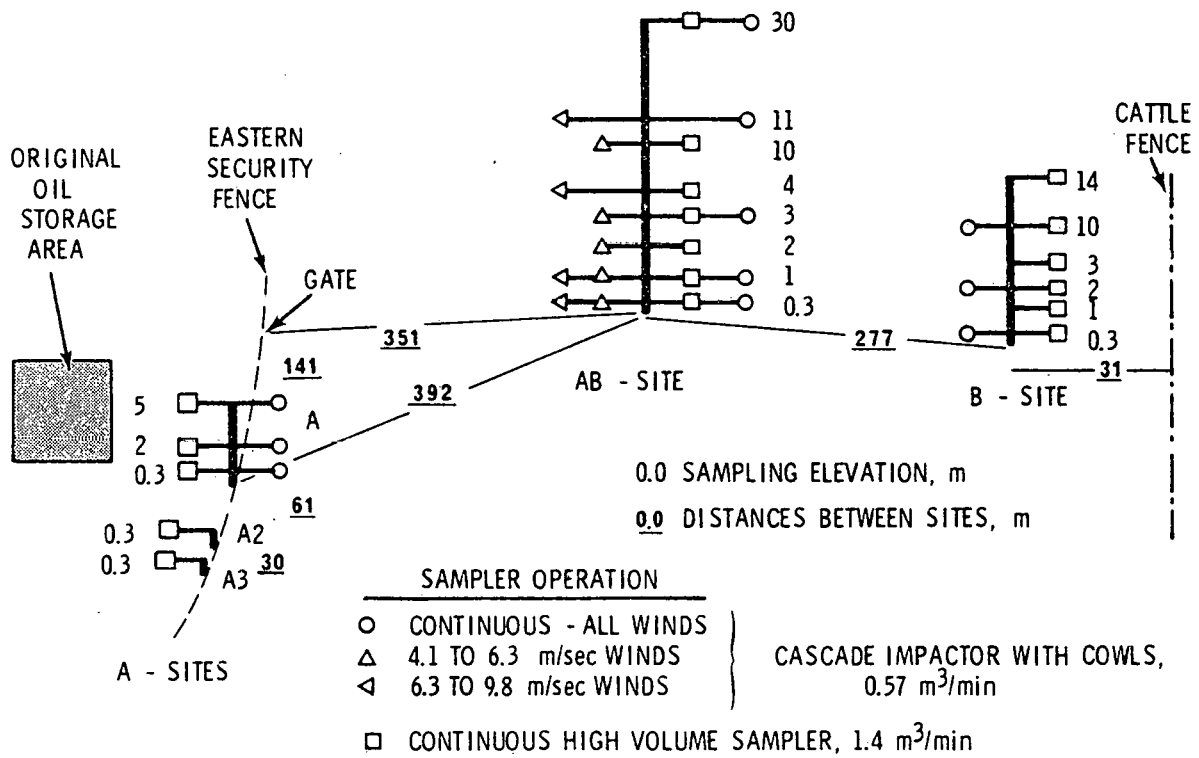


FIGURE 2. Schematic of Rocky Flats Resuspension Tower Locations (Neg. 744429-3)

AIR SAMPLERS

Airborne resuspended particles were either sampled with total air samplers* or sized while airborne with particle cascade impactors.** Particle cascade impactors were used for plutonium and CaMoO_4 particles.

The particle cascade impactor for sampling respirable particles was attached to a rotating cowl, allowing simultaneous sampling of larger non-respirable particles. The cowl-impactor system⁽²³⁾ is shown in Figure 3. Particles entering the 15-cm-dia cylindrical sampler inlet of the cowl either settled on the cowl floor or were drawn up into the impactor. Particles settling on the cowl floor will be called "nonrespirable" in this report. Respirable particles entering the particle cascade impactor were separated into nominal aerodynamic diameter ranges of 7, 3.3, 2.0 and 1.1 μm , which are impactor stage 50% cutoff diameters for unit-density spheres. Smaller particles were collected on an impactor backup filter.

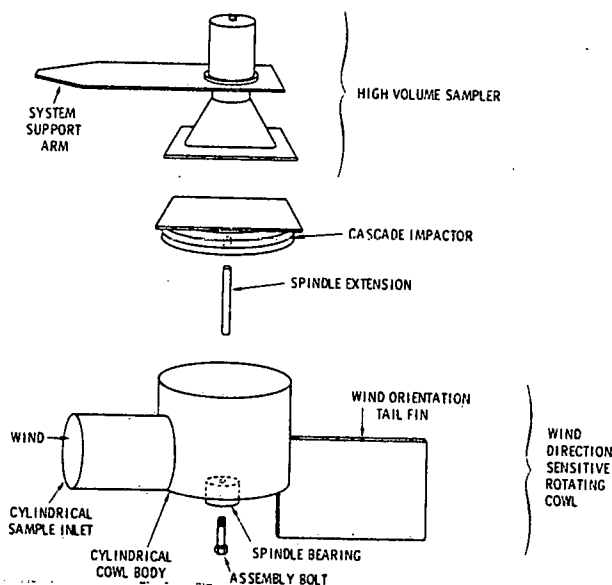


FIGURE 3. Rotating Cowl and Impactor
(Neg. 744581-12)

*General Metal Works, Inc., Model GMWL-2000-hi-vol air sampler with filter holder, 8368 Bridgetown Road, Cleves, Ohio 45002.

**Andersen 2000, Inc., Model 65-100 High-Volume Sampler Head, P.O. Box 20769, AMF, Atlanta, Georgia 30302.

RESULTS AND DISCUSSION

Airborne radionuclide concentrations were determined at transuranic resuspension study sites at Rocky Flats, Colorado^(6,7) and the Hanford reservation in Washington.^(1,2) In addition some cesium resuspension data are reported for Hanford.⁽¹⁾ In contrast to transuranic resuspension, tracer simulants⁽¹⁹⁾ were used to determine particle resuspension rates. Results for each set of experiments will be discussed separately.

RADIONUCLIDE PARTICLE RESUSPENSION "ON-SITE"

Airborne plutonium concentrations at Rocky Flats and Hanford were measured as a function of particle diameter, wind speed, and sampling site. Radionuclide concentrations per gram of airborne solid were determined.

Plutonium Resuspension Research at Rocky Flats

Plutonium resuspension at Rocky Flats was investigated experimentally.^(6,7) In early work, an empirical resuspension model was developed⁽²⁴⁾ based on published weekly plutonium concentrations at Health and Safety Laboratory sampling station S-8 along the site's eastern security fence. The plutonium data were analyzed in terms of the meteorology occurring during sampling times. Collected airborne plutonium was related to hourly average wind speeds and wind directions. Model results showed airborne plutonium concentrations increased as the 2.1 power of wind speed. Subsequently, airborne concentrations were predicted for the succeeding time period. These results showed a wide difference between predictions and experimental results. The interpretation of these differences was that the plutonium resuspension source characteristics had changed.⁽²⁵⁾

Battelle-Northwest experimental measurements of plutonium resuspension at Rocky Flats were made in July 1973.^(6,7) As shown in Figure 2, airborne plutonium concentrations were measured at three sampling sites east of the plant. The first sampling site was along the eastern security fence. This site was called sampling site A. Sampling site B was along the eastern cattle fence, and sampling site AB was between sites A and B. The distance

from site A to site AB was 227 m. Airborne plutonium at these sites was sampled and analyzed as a function of sampling height, particle size, and wind speed. For comparison, a particle cascade impactor sample was simultaneously collected at a background site 13 km west in the mountains.

Fallout levels of ^{239}Pu entering the area were estimated from the cascade impactor operated in the mountains. There was no detectable ^{239}Pu activity on the 7, 3.3, and 1.1- μm impactor stages, and there was no radiochemical result for the 2- μm stage. The only detectable background plutonium activity was on the backup filter which nominally collects submicrometer particles. Airborne ^{239}Pu concentration at the back-ground station was $4 \pm 3.5 \times 10^{-18} \mu\text{Ci}/\text{cm}^3$, which corresponds to $0.7 \pm 0.62 \times 10^{-6} \mu\text{Ci}/\text{g}$ of airborne soil on the backup filter. Error limits are the 2σ radiochemical counting limits.

In onsite research, airborne particles were separated in the sampling process into two main fractions. One sample contained particles collected by gravity settling in the inlet cowl section of the sampler as shown in Figure 3. The second fraction contained those particles passing through the inlet section and collected within the high volume cascade impactor. The smallest particles collected in the inlet cowl section were about 10 μm diam. This fraction was assayed for ^{238}Pu and ^{239}Pu . In some cases, nonrespirable particles were sieved into smaller size fractions and these fractions also assayed for ^{238}Pu and ^{239}Pu . Data for respirable and nonrespirable particles will be discussed separately.

Respirable Plutonium Concentrations at Rocky Flats

Airborne ^{239}Pu concentrations at the three Rocky Flats sampling stations were reported⁽⁶⁾ in $\mu\text{Ci}/\text{cm}^3$ of air and $\mu\text{Ci}/\text{g}$ of airborne soil. The maximum airborne ^{239}Pu concentration was $3.7 \times 10^{-15} \mu\text{Ci}/\text{cm}^3$. The maximum ^{239}Pu concentration on the airborne soil was $5 \times 10^{-5} \mu\text{Ci}/\text{g}$ total airborne soil and $7 \times 10^{-3} \mu\text{Ci}/\text{g}$ for the respirable fraction of airborne soil collected on the 2- μm particle impactor stage. All airborne ^{239}Pu

concentrations were significantly less than maximum permissible concentrations of soluble ^{239}Pu in air for occupational exposure in a 40-hr work week ($2 \times 10^{-12} \mu\text{Ci}/\text{cm}^3$) or nonoccupational exposure in a 168-hr week period ($6 \times 10^{-13} \mu\text{Ci}/\text{cm}^3$). (26)

Airborne plutonium concentrations were a function of both sampling height and particle diameter. Airborne concentrations in $\mu\text{Ci}/\text{cm}^3$ are shown for site AB in Figure 4 for each particle cascade impactor stage. In contrast to simple modeling concepts, airborne concentrations did not always decrease with an increase in height. There were unexpectedly high ^{239}Pu concentrations at this site for several particle diameters and heights.

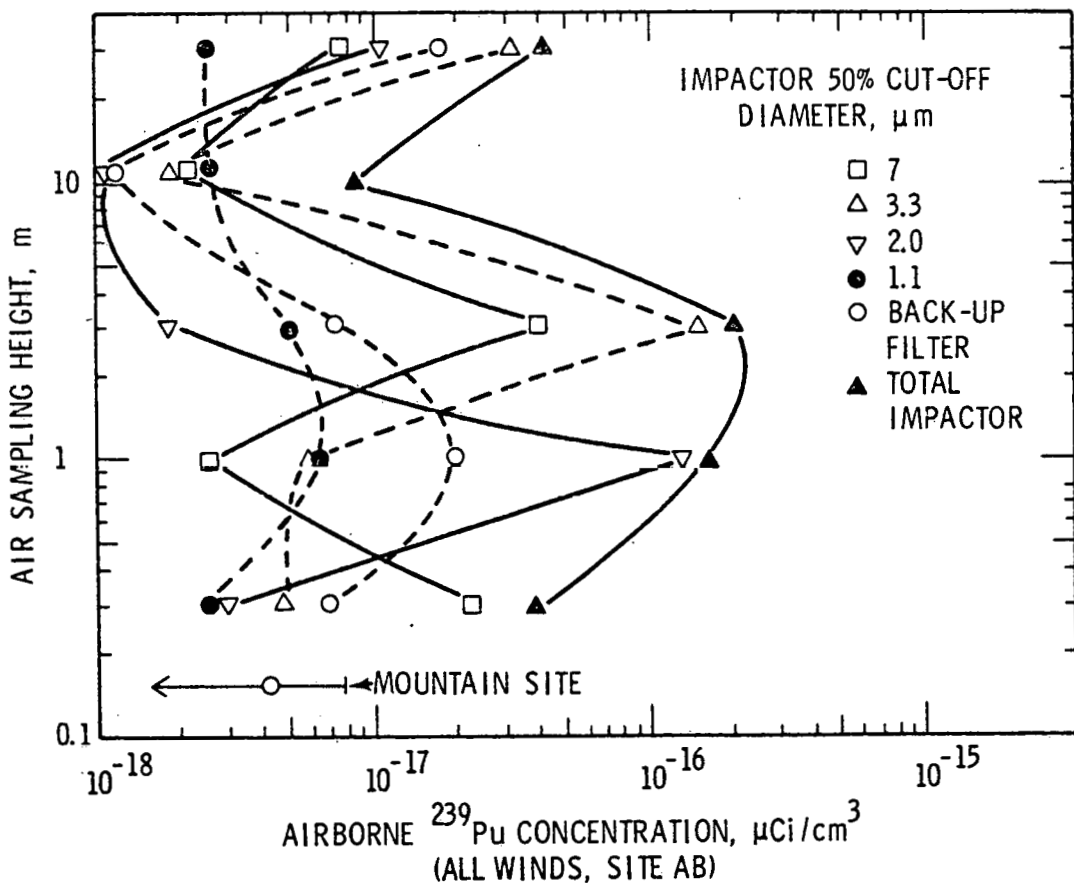


FIGURE 4. Airborne ^{239}Pu Concentration at Site AB at Rocky Flats as a Function of Impactor Collection Site (Neg. 772705-8)

Plutonium was associated with particles collected on each particle cascade impactor stage. Since there was no plutonium in the upper stages of the impactor at the background mountain site, the ^{239}Pu found in upper stages of impactors at Rocky Flats sampling sites indicates some plutonium was resuspended while attached to larger particles. Resuspension of sub-micrometer particles also occurred at Rocky Flats.

The general trend of the complete airborne ^{239}Pu concentration data is a decrease in concentration with increasing distance eastward from site A. (6) As might be expected, this decrease in concentration corresponded to increasing distance from the original oil storage area, which was the principal source of ground contamination. However, significant deviations did occur in concentration profiles of airborne ^{239}Pu with both distance and height. These deviations might be attributed to sampling some more-active-than-normal particles or clusters of particles. These increases in average airborne ^{239}Pu concentrations were present at both sites AB and B.

As indicated in Figure 5 for site AB, some more-active-than-normal particles or clusters of particles ("hot") particles may have been present in the 2.0- μm size range. In this case, the concentration at the 1-m height of site AB is 1 to 2 orders of magnitude greater than at other heights for this site. More important to the "hot" particle concept is the concentration at the 10-m height of B. This concentration of $2.3 \times 10^{-16} \mu\text{Ci}/\text{cm}^3$ was the largest ^{239}Pu concentration for 2- μm particles measured at any Rocky Flats location. This relatively high concentration was unexpected since this sampling location was the most remote from both the ground and the original oil storage area. This suggests other relatively "hot" particles could also be escaping from the plant boundaries; however, due caution is indicated in interpreting this "hot" particle concept. The total of 6 dis/min collected on the 2- μm stage or $2.3 \times 10^{-16} \mu\text{Ci}/\text{cm}^3$ is much less than the maximum permissible air concentration of $2 \times 10^{-12} \mu\text{Ci}/\text{cm}^3$ (occupational). It is conceivable that the majority of this "hot" plutonium was attached to one soil particle.

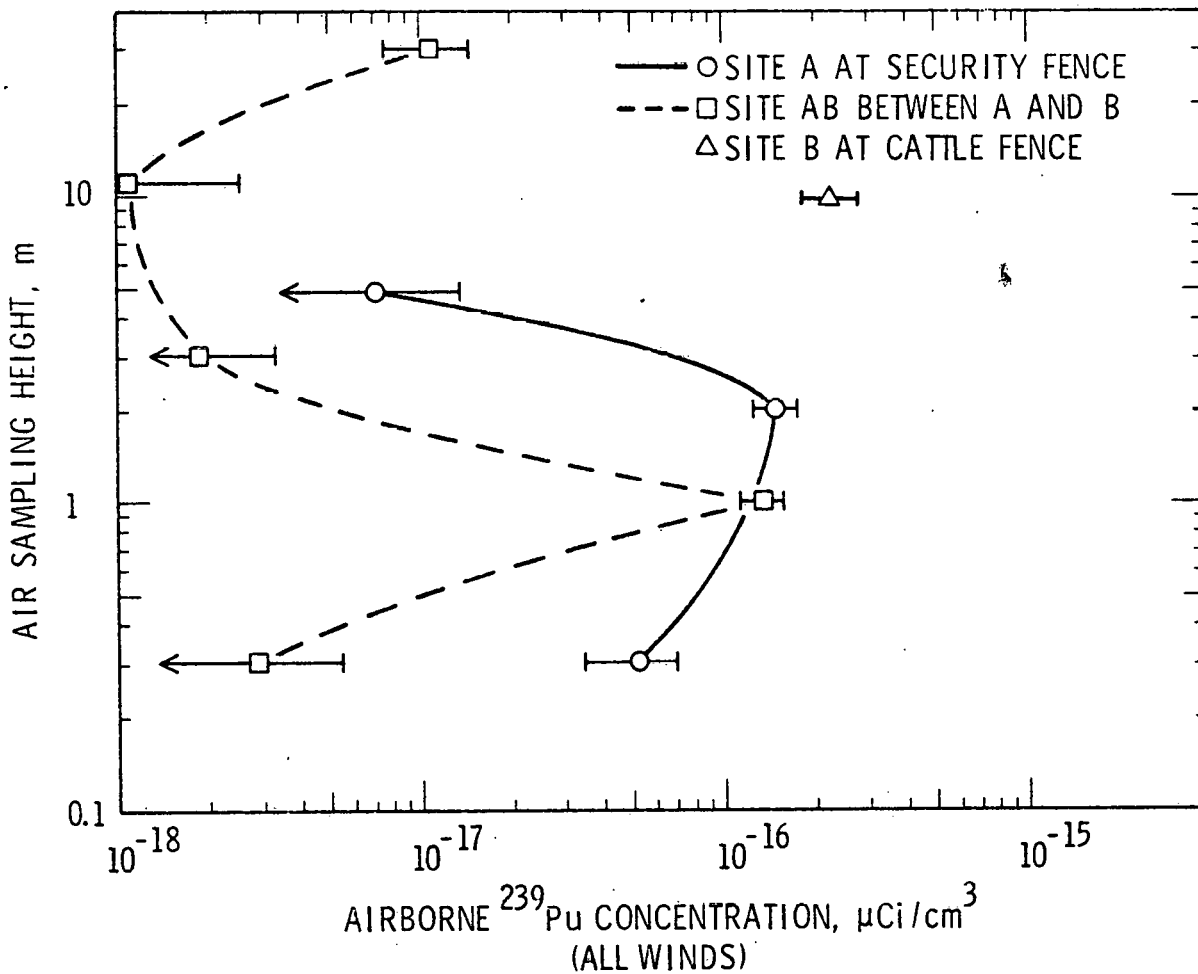


FIGURE 5. Airborne ^{239}Pu Concentrations from Impactor 2.0 μm Stage Collections at Rocky Flats (Neg. 772705-3)

The functional relationship between airborne plutonium resuspension concentrations and wind speed could not be developed as unequivocally as initially anticipated.⁽⁶⁾ This was due in part to the inadvertent loss of about a fifth of the collected filter samples during radiochemical analysis. Unfortunately, most samples from the higher wind speeds were lost. Even with the limited plutonium data collected in this experiment, it was evident

airborne ^{239}Pu concentrations increased with an increase in wind speed. In Figure 6, total airborne concentrations are shown for air sampled at all wind speeds (average wind speed of 0.9 m/sec), at wind speeds from 4.1 to 6.3 m/sec, and at wind speeds from 6.3 to 9.8 m/sec. Airborne ^{239}Pu concentrations at wind speeds from 4.1 to 6.3 m/sec are definitely larger than average airborne concentrations for continuous air sampling. However, the 2σ radiochemical counting statistics error limits are too large to determine the wind speed dependency. Nevertheless, an attempt to approximate airborne ^{239}Pu concentrations and consequently the resuspension rate dependency upon wind speed was made for the 7- μm -diameter particles. This approximation was for the 0.3-m height at sampling site AB. For the three data points taken at the 0.3-m height, ^{239}Pu concentrations increased with the 5.9th power of wind speed.

The July 1973 plutonium resuspension experiment at Rocky Flats showed resuspension of both ^{238}Pu and ^{239}Pu . However, all airborne plutonium concentrations were significantly below maximum permissible concentrations in air. Since ^{239}Pu was collected on each particle cascade impactor stage, the suggestion is that most plutonium was attached to soil particles when the plutonium was resuspended.

Respirable Plutonium Concentrations at Hanford

Extensive data were obtained on airborne radionuclide concentrations around resuspension sites studied.⁽¹⁾ These concentrations were expressed both in $\mu\text{Ci}/\text{cm}^3$ of filtered air and $\mu\text{Ci}/\text{g}$ of airborne solids. This report summarized ranges of data collected, but did not detail data for each experiment.

Airborne plutonium concentrations for both ^{238}Pu and ^{239}Pu measured⁽¹⁾ in resuspension experiments are shown in Figure 7 and are compared with Hanford 300 Area fallout levels⁽²⁷⁾ approximately 30 Km distant. The data represented experiments conducted over various time periods. For each data symbol, the vertical line is plotted at the mid-time of the resuspension experiment while the experiment duration is shown by horizontal lines drawn at both maximum and minimum measured airborne concentrations. Airborne peak plutonium

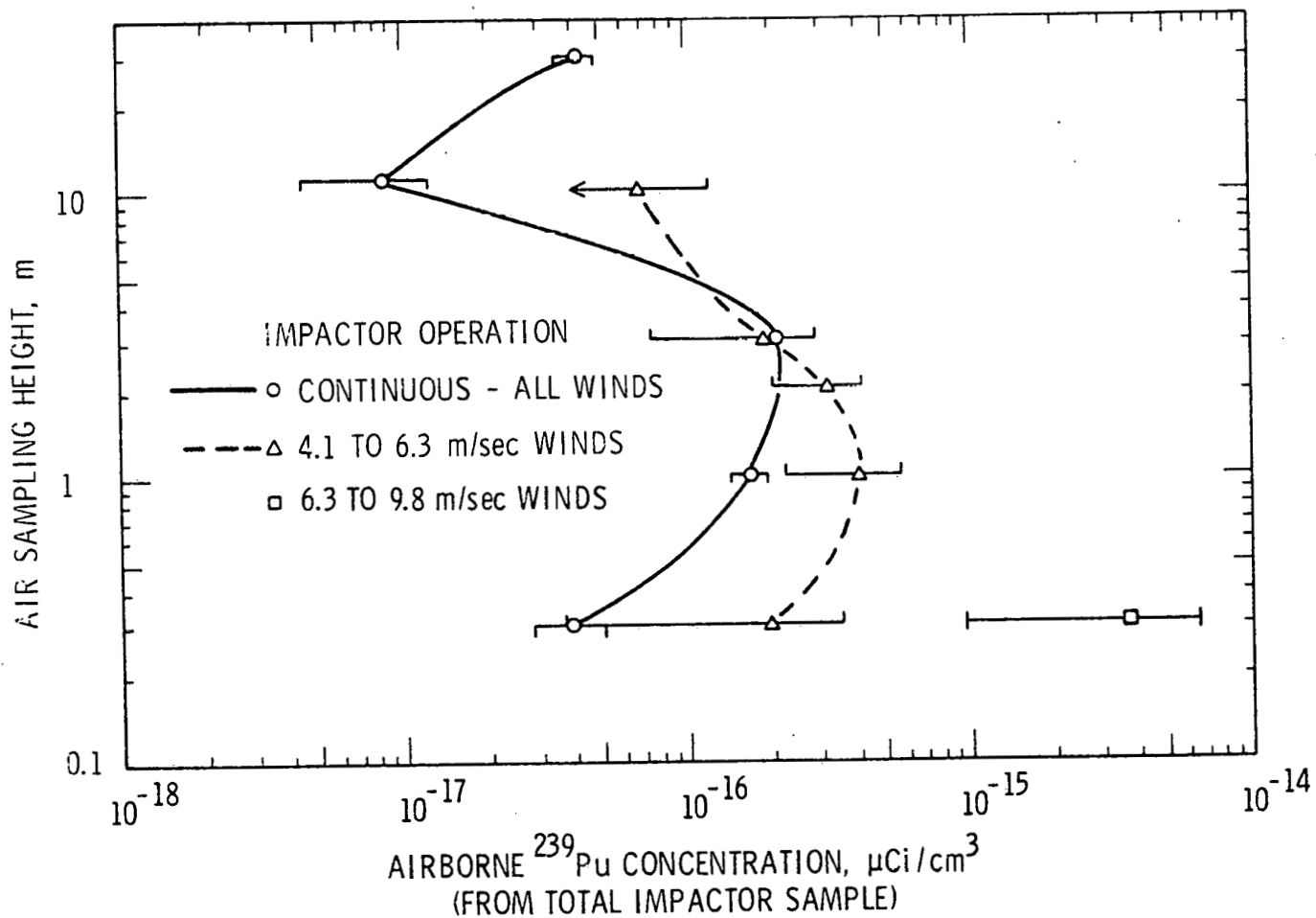


FIGURE 6. Total Airborne ^{239}Pu Concentration at AB Site at Rocky Flats as a Function of Wind Speed (Neg. 772705-2)

concentrations at resuspension study sites were significantly greater than 300 Area fallout levels⁽²⁷⁾, and airborne ^{239}Pu concentrations in general were greater than airborne ^{238}Pu concentrations. However, although resuspension was and is still probably occurring at these sites, measured airborne concentrations were significantly less than maximum permissible concentrations⁽²⁶⁾ (MPC's).

Airborne plutonium concentrations at the U-Pond area tended to remain constant as a function of time. This constancy indicates the weathering (or fixation) half-life for surface contamination available for resuspension is on the order of years. This is much greater than the 35 to 40 days often quoted⁽¹⁰⁾ in resuspension literature. However, the year weathering half-life at U-Pond could be a manifestation of some resuspension surface renewal process since this is an active waste disposal site. The explanations are unclear for differences in weathering half-life.

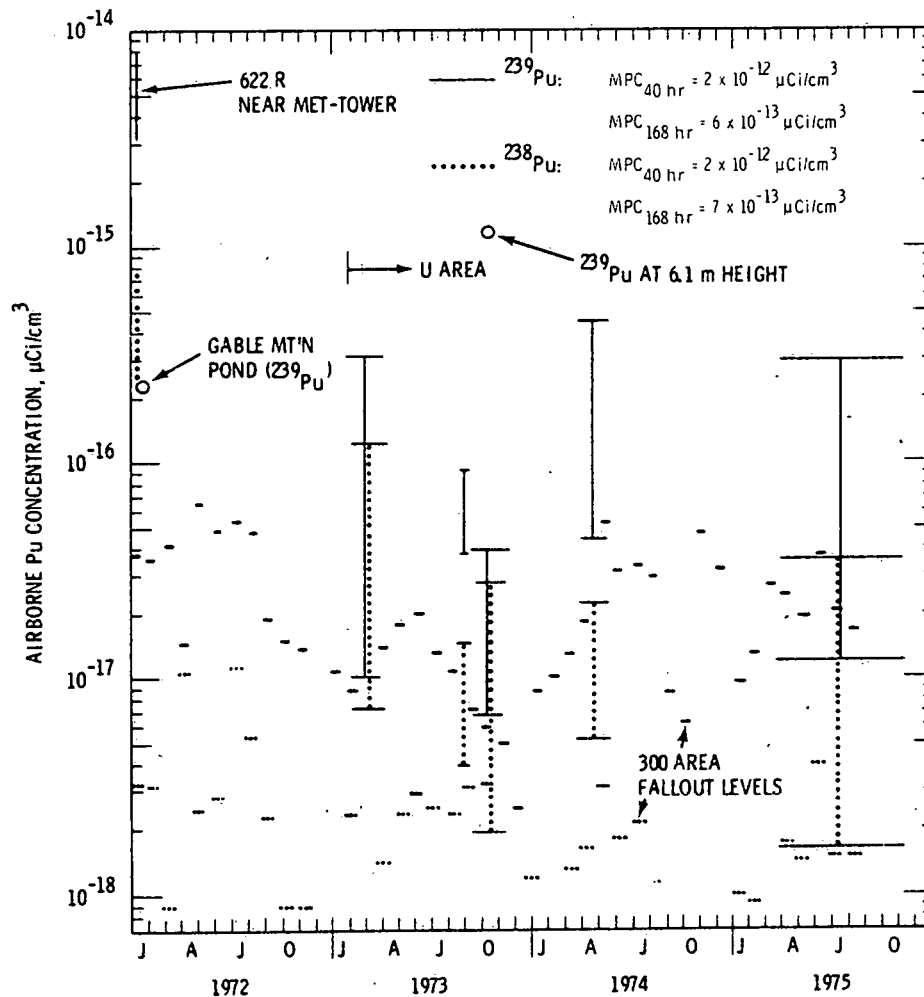


FIGURE 7. Range of Airborne Plutonium Concentrations at Onsite Hanford Resuspension Sites Compared to Fallout Levels (Neg. 768423-4)

The maximum airborne ^{239}Pu concentration measured was $8 \times 10^{-15} \mu\text{Ci}/\text{cm}^3$ near the Hanford Meteorological Station (HMS) Tower on January 11, 1972. All other plutonium concentrations except one were at least one order of magnitude lower. This one exception was measured 6.1 m above ground at U-Pond during October 1973. In comparison with other October data, the concentration for this sample was about one and one half orders of magnitude greater than any other sample. We hypothesized that some more-active-than-normal particles or clusters of particles ("hot") were resuspended and collected on this filter.

AIRBORNE PLUTONIUM NONRESPIRABLE FLUXES AT ROCKY FLATS AND HANFORD

Nonrespirable airborne plutonium fluxes were calculated for both ^{238}Pu and ^{239}Pu . The Rocky Flats data⁽⁷⁾ are shown in Figures 8 and 9.

In Figure 8, the airborne ^{239}Pu nonrespirable horizontal flux in $\mu\text{Ci}/(\text{m}^2 \text{ day})$ is shown as a function of sampling distance and sampling height. As might be expected, the maximum airborne ^{239}Pu flux on nonrespirable particles was at Site A near the original oil storage area. The maximum airborne ^{239}Pu flux was $6 \times 10^{-4} \mu\text{Ci}/(\text{m}^2 \text{ day})$. The airborne flux decreased with both distance and sampling height. At Site A, the ^{239}Pu flux decreased over one order of magnitude as sampling height was increased from 0.3 to 2 m above ground level. Similarly, at Site AB, the airborne ^{239}Pu nonrespirable flux again decreased about one order of magnitude as sampling height was increased from 0.3 to 1 to 2 m above ground level. Airborne ^{239}Pu fluxes on nonrespirable particles decreased almost two orders of magnitude between sampling Sites A and AB. However, between sampling Sites AB and B, airborne ^{239}Pu nonrespirable fluxes did not show a significant variation with distance.

By comparing data for the three different Rocky Flats sites, the conclusion is the airborne nonrespirable ^{239}Pu flux does not decay as a simple exponential function of distance from Site A. In addition, data for sampling heights above 1 m at Sites AB and B show the airborne ^{239}Pu flux did not significantly decrease for heights greater than 1 m up to 10 m. The nonrespirable particle plume height above 10 m is unknown.

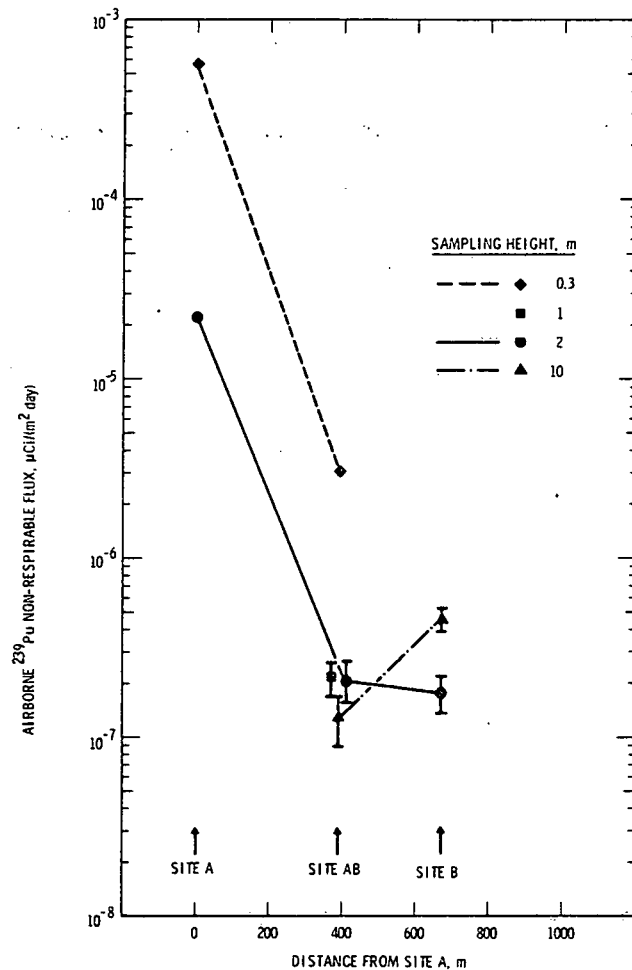


FIGURE 8. Decrease with Distance of Total ^{239}Pu Flux on Nonrespirable Particles at Rocky Flats (Neg. 767208-4)

Similar results are shown in Figure 9 for total ^{238}Pu flux on non-respirable particles at Rocky Flats as a function of a sampling site and sampling height. The maximum airborne ^{238}Pu nonrespirable flux was $1.2 \times 10^{-5} \mu\text{Ci}/(\text{m}^2 \text{ day})$ and was at the 0.3-m sampling height at Site A. Again, at Site A as well as Site AB, airborne ^{238}Pu fluxes decreased rapidly as sampling height increased from 0.3 up to 10 m. However, from Site AB to B, an unexplained observation was made. Airborne ^{238}Pu fluxes

at 2 and 10 m heights of Site B were greater than at Site AB. An explanation for this increase is not apparent, but the increase is supported by comparing plutonium analyses uncertainties. Error bars for Site B show a ^{238}Pu flux range significantly above error bars around Site AB.

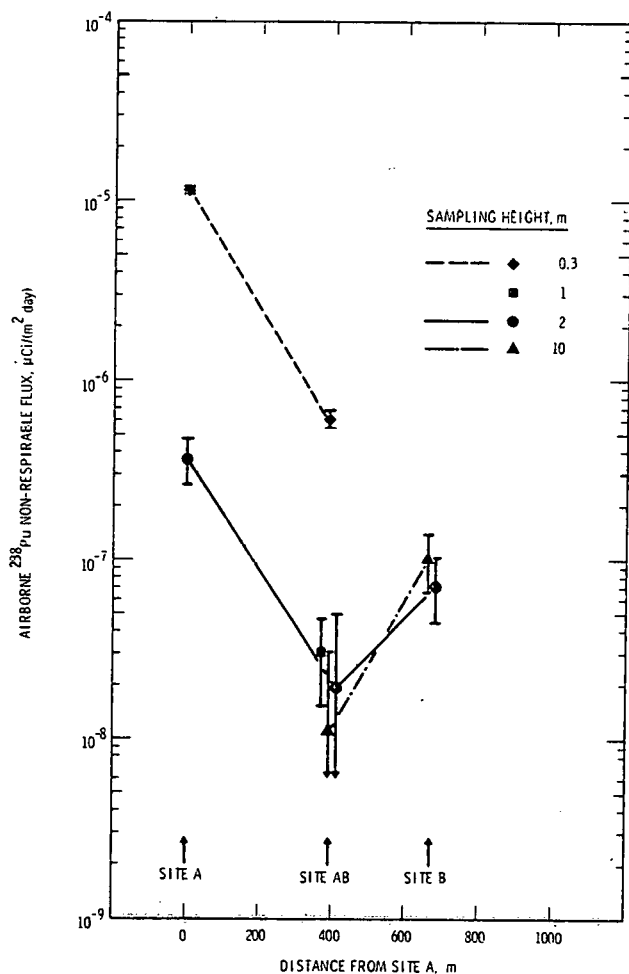


FIGURE 9. Decrease with Distance of Total ^{238}Pu Flux on Nonrespirable Particles at Rocky Flats (Neg. 767208-6)

Airborne nonrespirable fluxes at Rocky Flats were greatest near the original oil storage area (source of contaminated leakage) and near ground level. Fluxes of ^{239}Pu ranged from 10^{-7} up to $10^{-3} \mu\text{Ci}/(\text{m}^2 \text{ day})$. In contrast, fluxes of ^{238}Pu ranged from 10^{-8} to $10^{-5} \mu\text{Ci}/(\text{m}^2 \text{ day})$.

Nonrespirable airborne plutonium fluxes around U-Pond on the Hanford Reservation are shown in Figure 10. The ^{238}Pu flux was less than the ^{239}Pu flux. This decrease is similar to the Rocky Flats data. However, the U-Pond data show the nonrespirable plutonium flux extends at least up to 30 m above ground level. Also, there was a greater airborne plutonium flux east of U-Pond than west of U-Pond. This is to be expected since prevailing winds are from the west.

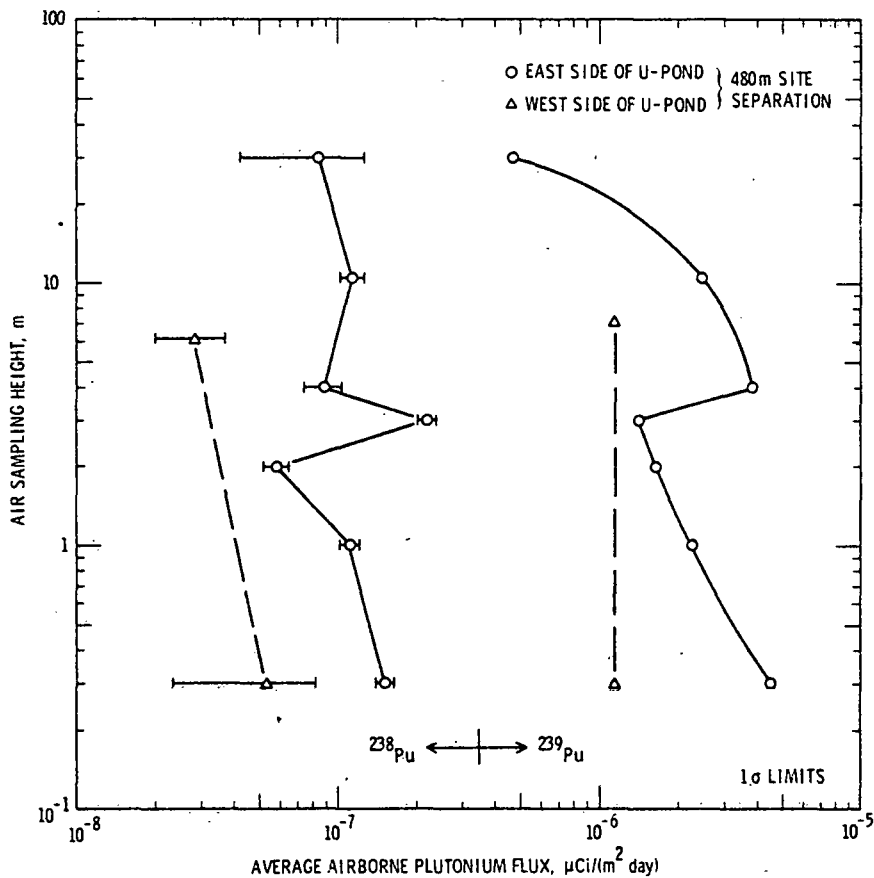


FIGURE 10. Plutonium-239 and ^{238}Pu Airborne Fluxes on Nonrespirable Particles at Hanford U-Pond During February 27 - November 10, 1975 (Particles Collected in Cowls) (Neg. 772994-1)

At U-Pond, the airborne ^{238}Pu flux ranged from 10^{-8} to 10^{-7} $\mu\text{Ci}/(\text{m}^2 \text{ day})$, which is within the midrange of 10^{-8} to about 10^{-5} $\mu\text{Ci}/(\text{m}^2 \text{ day})$ measured at Rocky Flats. Similarly, the ^{239}Pu flux at U-Pond ranged from about 10^{-6} to 10^{-5} $\mu\text{Ci}/(\text{m}^2 \text{ day})$, which is within the 10^{-7} to 10^{-3} $\mu\text{Ci}/(\text{m}^2 \text{ day})$ measured at Rocky Flats. The bracketing of the airborne nonrespirable particle fluxes near U-Pond and at Rocky Flats even within three to four orders of magnitude may be coincidental since surface sources and other factors are peculiar to each site.

These onsite data reported are the first results to quantify the range of nonrespirable airborne plutonium fluxes. Ground contamination on nonrespirable particles at both sites is poorly defined or nonuniform,⁽²⁸⁻³⁴⁾ hence, the data can at present not be analyzed to reflect resuspension rates or resuspension factors for nonrespirable particles.

PLUTONIUM CONCENTRATION PER GRAM OF AIRBORNE SOIL

Airborne plutonium concentrations were normalized to the soil collected with the airborne plutonium. Plutonium concentrations in $\mu\text{Ci}/\text{g}$ were determined as a function of particle diameter as determined with both particle cascade impactors for respirable diameters as well as sieve sizes for nonrespirable particles. Resuspended plutonium is attached to nonrespirable as well as respirable particles. Hence, nonrespirable soil particles may contribute significantly to downwind airborne plutonium concentrations and represent one mechanism for transporting plutonium to surrounding land.

For Rocky Flats, nonrespirable soil collected at 0.3 m above ground level was sieve sized⁽⁷⁾ into twelve different size increments. Each size increment was analyzed for ^{238}Pu and ^{239}Pu . Plutonium concentrations were normalized ($\mu\text{Ci}/\text{g}$) to the grams of soil collected within each size increment. Results are shown in Figure 11 for ^{239}Pu as a function of particle size at Sites A and AB. Plutonium-239 was associated with all particle sizes. The maximum concentration was about 10^{-4} $\mu\text{Ci}/\text{g}$ for particle sizes between 10 and 20 μm . For larger particle diameters up to 230 μm , concentrations tended to

decrease with an increase in particle diameter. Concentrations at Site A were greater than at Site AB. This is expected since Site A was closer to the original oil storage area at which plutonium leakage occurred.

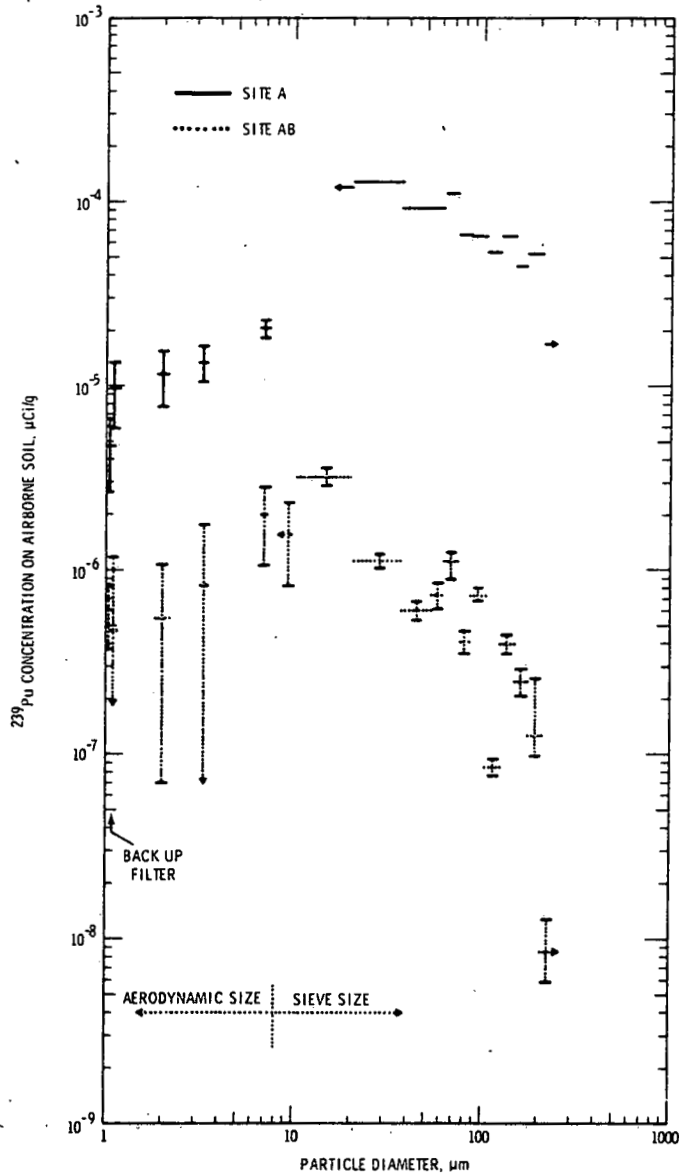


FIGURE 11. Plutonium-239 Concentration on Airborne Soil as a Function of Particle Diameter at Rocky Flats (Neg. 767208-1)

At each site, Pu concentrations in $\mu\text{Ci/g}$ indicate general continuous relationships as a function of particle diameter. For nonrespirable particle diameter ranges determined from sieve sizes, the data could be approximated by a straight line inversely proportional to particle diameter. The relationship is complicated by collection of both contaminated onsite and uncontaminated offsite nonrespirable particles within the cowl.

For respirable particles, the ^{239}Pu $\mu\text{Ci/g}$ was nearly independent of particle diameter. This independency might suggest plutonium attachments are volume phenomena for these respirable particles. In contrast, Pu particle attachment to soil particles is expected to be controlled by available soil particle surface area for nonrespirable particles. Additional data are required to conclude how plutonium particles are attached to airborne particles in both respirable and nonrespirable size ranges.

Plutonium-238 concentrations in $\mu\text{Ci/g}$ on airborne soil are shown in Figure 12. In this case, only nonrespirable particle diameter ranges are shown. There was insufficient ^{238}Pu collected in the particle cascade impactor samples to yield positive results in respirable diameter ranges. Similar to ^{239}Pu , ^{238}Pu nonrespirable concentrations were greater at Site A than at Site B and also showed an inverse relationship with particle diameter. However, there is fine structure showing deviation around any apparent inverse relationship. This fine structure indicates there is yet much to be learned about plutonium resuspension and plutonium attachment to nonrespirable as well as respirable host particles.

Both ^{239}Pu and ^{238}Pu concentrations on airborne soil decreased from Site A to Site AB. Site AB/Site A ratios of $\mu\text{Ci/g}$ are shown in Figure 13. Concentrations per gram decreased by a factor of up to about 10^{-3} in the intervening 392-m distance separating sampling Sites A and AB. Concentration ratios for ^{239}Pu on respirable particles were about 10^{-1} and were independent of particle size. In contrast for nonrespirable particle sizes, ^{239}Pu

ratios between sites decreased nearly linearly as particle diameter increased. Plutonium-239 concentrations on nonrespirable particles decreased at rates greater than the ^{238}Pu decrease. For ^{238}Pu , the $\mu\text{Ci/g}$ ratios for Site AB/Site A were nearly one order of magnitude greater than ^{239}Pu . These larger ratios suggest ^{238}Pu resuspended more readily relative to ^{239}Pu .

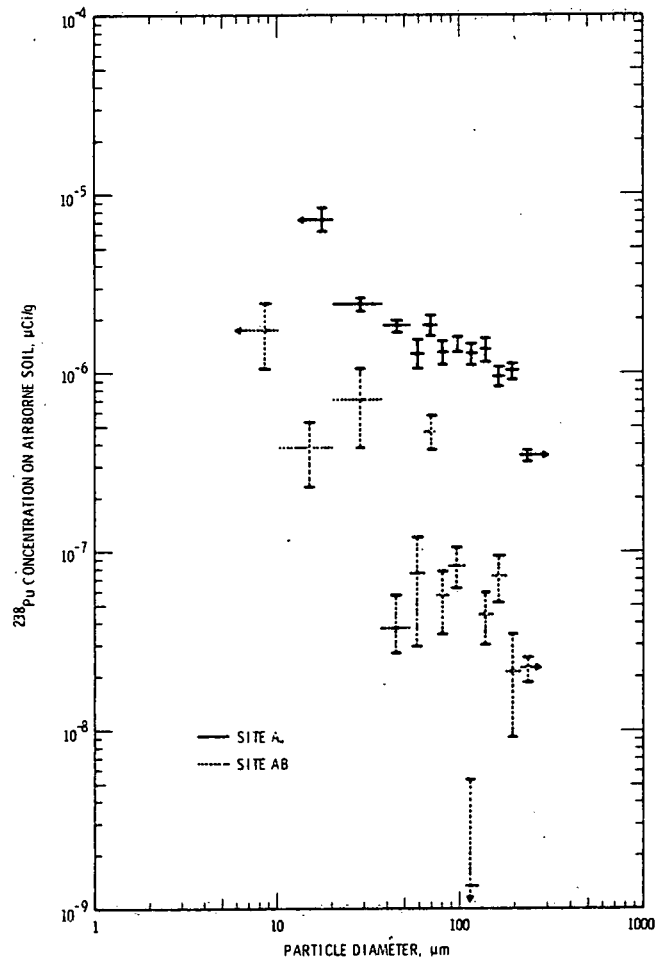


FIGURE 12. Plutonium-238 Concentration on Airborne Soil as a Function of Particle Diameter at Rocky Flats (Neg. 767208-5)

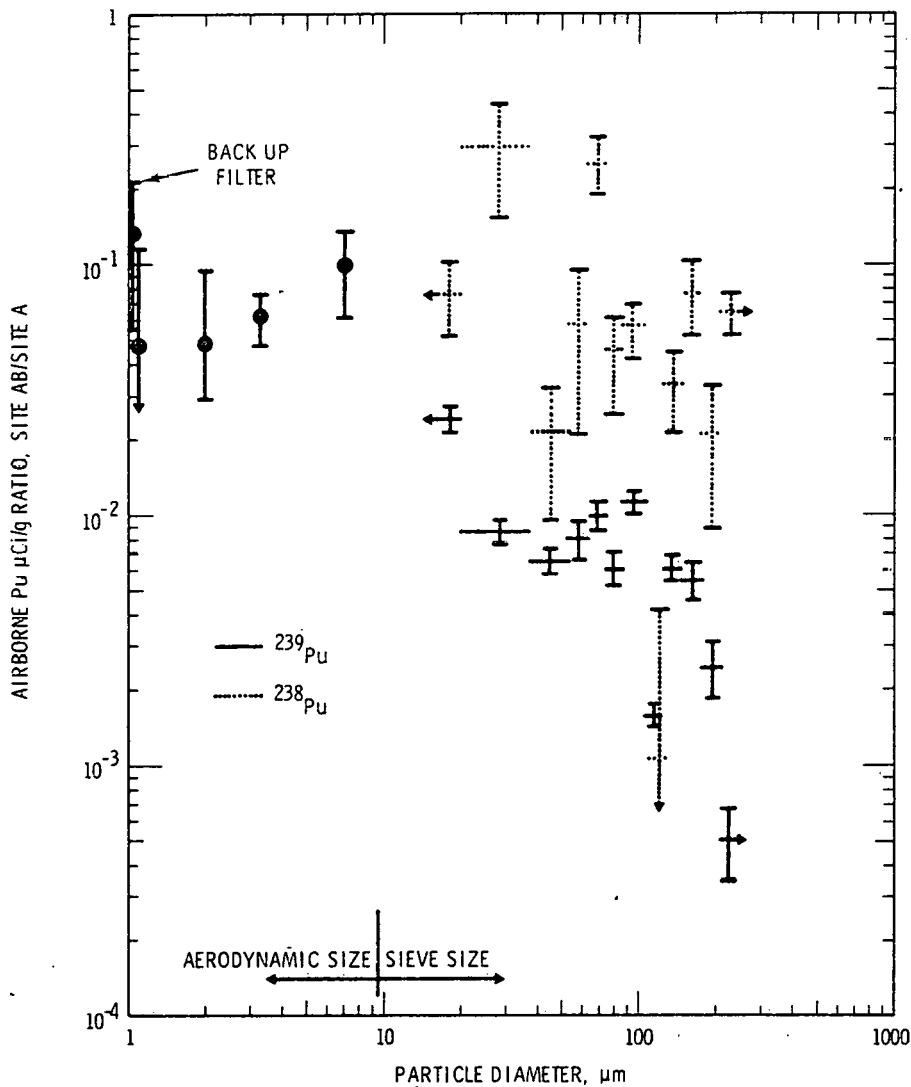


FIGURE 13. Decrease in ²³⁸Pu and ²³⁹Pu Concentrations on Nonrespirable Particles from Site A to Site AB at Rocky Flats (Neg. 767208-7)

For onsite Hanford experiments, airborne ²³⁸Pu and ²³⁹Pu concentrations expressed in μCi/g of airborne solids are shown in Figure 14 for collection on filters. Concentrations of ²³⁹Pu were somewhat greater than those of ²³⁸Pu. Plutonium concentrations on airborne solids ranged from 10⁻⁹ to 10⁻⁵ μCi/g. The only exception was the October 1973 single sample described above, for which the concentration was 6 x 10⁻⁵ μCi/g. Otherwise, plutonium concentrations on airborne solids around U-Pond appeared to be nearly independent of time.

Plutonium concentrations on airborne nonrespirable particles were also determined⁽³⁵⁾ near U-Pond on the Hanford reservation for sampling heights from 0.3 up to 30 m above ground. Airborne solids were sampled continuously for all wind directions at sites both east and west of U-Pond. The distance between sampling sites was 480 m. Samples were analyzed for both ^{239}Pu as well as ^{238}Pu . Calculated results shown in Figure 15 are for $\mu\text{Ci/g}$ of nonrespirable airborne solids collected within cowl. Results show plutonium concentrations on airborne nonrespirable solids were approximately one order of magnitude higher east as compared to west of U-Pond. This increase is caused by prevailing west winds which caused resuspension from this low level liquid waste disposal area. East of U-Pond, plutonium concentrations on airborne nonrespirable solids tended to be uniform with height up to 30 m. The plume height above 30 m is unknown.

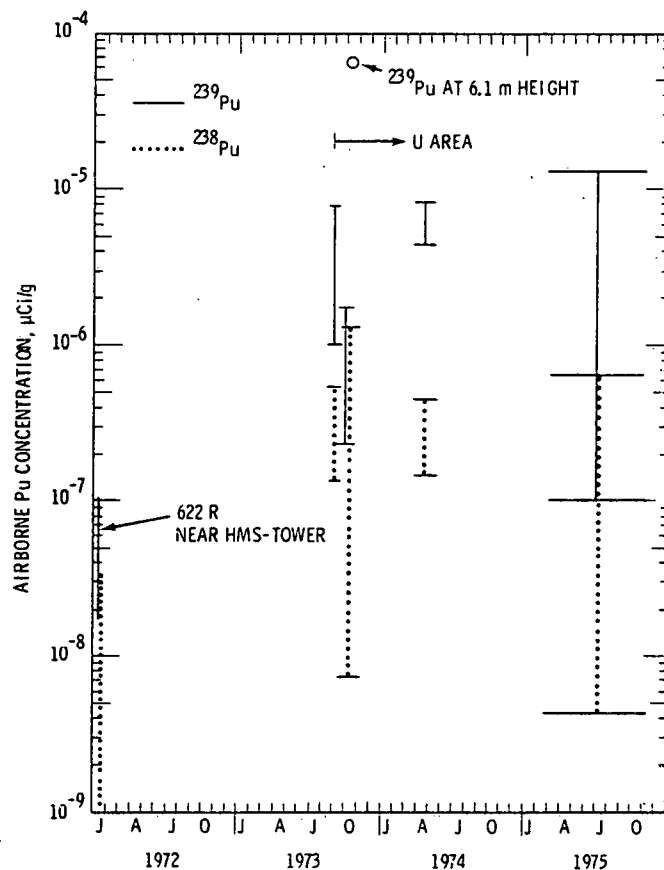


FIGURE 14. Range of Plutonium Concentration on Airborne Solids at Onsite Hanford Resuspension Sites (Neg. 768423-2)

Both ^{238}Pu and ^{239}Pu concentrations on nonrespirable airborne solids near U-Pond were less than concentrations determined at Rocky Flats site A. This comparison can be seen by comparing data in Figures 11 and 12 with data in Figure 15. However, plutonium concentrations on airborne nonrespirable solids at Hanford's U-Pond and Rocky Flats site AB tended to be comparable.

AIRBORNE AND GROUND PLUTONIUM $\mu\text{Ci/g}$ RATIOS

There should be some relationship between Pu concentrations on airborne soil and Pu concentrations on ground surface soil. At Rocky Flats ground surface soils were characterized⁽²⁸⁾ for the same time period these airborne nonrespirable samples were collected. Ground surface sample results are summarized in Table 3 for sampling sites near Sites A, AB, and B in both dpm/g and $\mu\text{Ci/g}$. Similarly, ground surface $^{238}\text{Pu}/^{239}\text{Pu}$ ratios are also shown.

TABLE 3. Selected Surface Soil Sample Results at Rocky Flats*

<u>Locations Near Site</u>	<u>HASL-304⁽²⁸⁾ Map Sites</u>	<u>^{239}Pu $\mu\text{Ci/g}$</u>	<u>^{238}Pu $\mu\text{Ci/g}$</u>	<u>$^{238}\text{Pu}/^{239}\text{Pu}$</u>
A	25	3.10×10^{-3}	5.77×10^{-5}	0.019
	26	6.89×10^{-4}	1.24×10^{-5}	0.018
AB	2	7.70×10^{-5}	1.56×10^{-6}	0.020
	4	3.86×10^{-5}	7.66×10^{-7}	0.020
B	6	2.66×10^{-6}	5.09×10^{-8}	0.019
	7	3.85×10^{-5}	7.12×10^{-7}	0.018

* dpm/g dry soil \pm % Stnd. Dev., samples from 2000 cm^2 , 5 cm deep

Ground and airborne Pu soil sample results are compared in Table 4 for both ^{239}Pu and ^{238}Pu . Comparisons are for plutonium in ground surface samples 5 cm deep versus airborne nonrespirable particle concentrations in particle diameter ranges. Airborne concentrations were taken from data limits in Figures 11 and 12. Maximum ranges of $\mu\text{Ci/g}$ airborne compared to $\mu\text{Ci/g}$ in the ground surface soil are shown in the last two columns. These ratios range from 1×10^{-4} up to 2. Thus in hazard evaluations⁽³⁾ one might consider maximum Pu concentrations on airborne soil to be comparable to Pu concentrations on ground surface soils. This is indicated by the ratio 2. However, in most cases Pu concentrations on airborne soil were significantly less than Pu concentrations on ground surface soils.

TABLE 4. Ratio of Plutonium Concentration Per Gram of Soil: Airborne Soil/Ground Surface Soil at Rocky Flats

Site	Range, $\mu\text{Ci/g}$				Ratio Range, $\frac{\mu\text{Ci/g Airborne}}{\mu\text{Ci/g Surface}}$	
	^{239}Pu		^{238}Pu		^{239}Pu	^{238}Pu
	Airborne*	Surface**	Airborne***	Surface**		
A	1.3×10^{-4} to 4.6×10^{-5}	3.10×10^{-3} to 6.89×10^{-4}	7.2×10^{-6} to 3.4×10^{-7}	5.77×10^{-5} to 1.24×10^{-5}	0.04 to 0.2	0.006 to 0.6
AB	3.2×10^{-6} to 8.5×10^{-9}	7.70×10^{-5} to 3.85×10^{-5}	1.8×10^{-6} to 1.4×10^{-9}	1.57×10^{-6} to 7.66×10^{-7}	0.0001 to 0.08	0.0009 to 2

* From Fig. 11 as a function of particle diameter

** From Table 3 for total ground surface sample 5 cm deep

*** From Fig. 12 as a function of particle diameter

Identification of relationships between sites of radionuclide concentrations on airborne solids and contaminated ground solids would be useful in establishing criteria for releasing contaminated areas for other uses. Concentrations on Hanford ground surfaces obtained from the literature^(29,30,32,34) are shown in Table 5 for ^{239}Pu as well as ^{137}Cs in $\mu\text{Ci/g}$ of solids. The range

for ^{239}Pu was from less than radiochemical detection limits to 6.9×10^{-7} $\mu\text{Ci/g}$ of surface solids. The maximum reported ^{239}Pu concentrations for surface solids were within the 200 areas. The minimum ^{239}Pu concentrations on surface solids reported⁽²⁹⁾ in the literature occurred at 19 to 34 km from Hanford. Surface contamination levels were reported only out to 34 km. The ^{137}Cs concentrations ranged from 3×10^{-8} to 2.5×10^{-2} $\mu\text{Ci/g}$. These contamination levels are used in Table 6.

Table 6 is a summary of Hanford airborne solids concentrations⁽¹⁾ in $\mu\text{Ci/g}$ for ^{239}Pu , ^{241}Pu , and ^{137}Cs . Plutonium and americium concentrations were obtained from Figures 14 and 19. Table 6 also shows ground surface contamination levels for ^{239}Pu and ^{137}Cs , expressed in $\mu\text{Ci/g}$. From these, ratios of $\mu\text{Ci/g}$ of airborne solids were determined. The last column shows maximum ratio ranges. Ratios vary from 10^{-3} to 8×10^3 , indicating that contamination levels on airborne solids can be either much less than or much greater than contamination levels on contaminated surface solids.

TABLE 5. Concentrations of Plutonium and Cesium in Hanford Ground Surface Solid Samples Reported in the Literature

Location	Year	$\mu\text{Ci/g}$		
		^{239}Pu	^{137}Cs	
		Range	Avg	Range
Onsite ⁽³⁰⁾	1973	*LAL to 8×10^{-9}	9.7×10^{-7}	3×10^{-8} to 2.4×10^{-6}
Inside 200 Areas ⁽²⁹⁾	1971	2.6×10^{-8} to 6.9×10^{-7}		NR
BC Area ^(30,32,34)	1974			2.1×10^{-5} to 2.5×10^{-2}
Within Hanford ⁽³⁰⁾ Site Boundary (3 to 26 km)	1971	9.9×10^{-9} to 1.2×10^{-7}		NR
Site Perimeter ⁽³⁰⁾	1973	*LAL to 6×10^{-9}	7×10^{-7}	1.4×10^{-7} to 1.5×10^{-6}
Offsite ⁽²⁹⁾ (19 to 34 km)	1971	3.6×10^{-9} to 7.6×10^{-8}		NR

*LAL, less than analytical limit.

NR, not reported

Caution should be used in interpreting these data. The ground surface contamination data are limited in quantity and were not necessarily obtained in the same areas where resuspension experiments were performed. Airborne particle and ground contamination levels are shown for BC-Crib area in the last two columns of Table 6. In this case, BC-Crib area was sampled ⁽³¹⁾ in ten 1-m² areas. Data from these ten squares indicated surface contamination levels varied by about a factor of 100. Ratio ranges calculated from these data may be more representative than ranges calculated for ²³⁹Pu. The ¹³⁷Cs data for BC-Crib area ranged from 10⁻² to 30. The magnitude of this range is important, since one might as a first approximation assume air contamination levels per gram of solids to be equal to surface contamination levels per gram of solids.

TABLE 6. Ratio of Airborne to Ground Surface Radioactivity Concentrations Per Gram of Solids at Hanford

Material	Concentration, $\mu\text{Ci/g Solids}$				Maximum Ratio Range, $(\mu\text{Ci/g})_{\text{air}} / (\mu\text{Ci/g})_{\text{surface}}$
	Airborne Solids		Ground Surface Contamination		
	Minimum	Maximum	Minimum	Maximum	
²³⁹ Pu	2×10^{-8}	6×10^{-5}	LAL	$8. \times 10^{-9}(30)$	2×10^0 to 8×10^3
²⁴¹ Am	1×10^{-7}	7×10^{-5}	NR	NR	
²³⁸ Pu	1×10^{-9}	1×10^{-6}	NR	NR	
¹³⁷ Cs	2×10^{-5}	1×10^{-2}	NR	NR	
¹³⁷ Cs at BC-Crib Area 10 areas, ⁽³³⁾ 1 m ²	3×10^{-5}	7×10^{-4}			
Maximum reported value ⁽³⁴⁾			2.1×10^{-5}	1.2×10^{-3}	1×10^{-3} to 3×10^1
				2.5×10^{-2}	

LAL - less than analytical limit.

NR - Surface contamination levels not reported for all areas. If available, data for each area reported separately.

* - Ratios from positive reported ground contamination values.

AIRBORNE $^{238}\text{Pu}/^{239}\text{Pu}$ RATIOS

Airborne $^{238}\text{Pu}/^{239}\text{Pu}$ ratios at Rocky Flats consistently changed⁽⁷⁾ from sampling Site A to Site B. Ratios shown in Figure 16 are for total plutonium collected within each cowl at each sampling site and sampling height. At Site A, the $^{238}\text{Pu}/^{239}\text{Pu}$ ratio on airborne nonrespirable soil is comparable to ratios determined from 5-cm-deep surface soil samples. The surface soil range is shown as the crosshatched soil sample range. This range⁽²⁸⁾ represents surface soil samples taken between the eastern security fence and beyond the eastern cattle fence to Indiana Avenue.

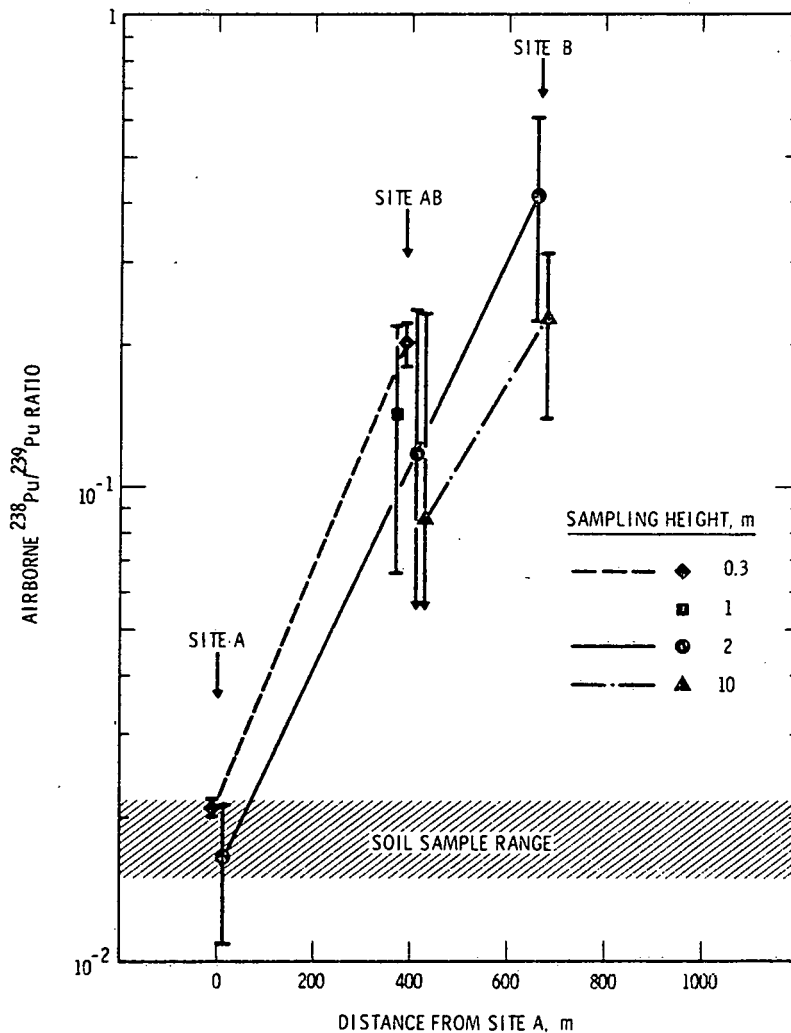


FIGURE 16. Plutonium 238/239 Ratio on Nonrespirable Airborne Particles as a Function of Distance at Rocky Flats (Neg. 767208-5)

At Sites AB and B, airborne $^{239}\text{Pu}/^{238}\text{Pu}$ ratios on nonrespirable particles are over one order of magnitude greater than similar ratios from 5-cm-deep surface soil samples. These ratios do not appear to be significantly affected by sampling height between 0.3 to 10 m above ground level. However, considerations of the data counting statistics error bars at Site A and AB tend to indicate higher $^{238}\text{Pu}/^{239}\text{Pu}$ ratios closer to the ground.

The $^{238}\text{Pu}/^{239}\text{Pu}$ ratio was determined for all nonrespirable particle diameter ranges at Sites A and AB at the 0.3-m sampling height. These results are shown in Figure 17 along with the total ground surface soil sample range. At Site A, the $^{238}\text{Pu}/^{239}\text{Pu}$ ratio is nearly independent of particle diameter for all particle diameters above 20 μm . It is only for particles less than 20 μm that the $^{238}\text{Pu}/^{239}\text{Pu}$ ratio is significantly elevated at Site A. The $^{238}\text{Pu}/^{239}\text{Pu}$ ratios on nonrespirable particles greater than 20 μm at Site A are all comparable to ratios in the 5-cm-deep surface soil samples. This similarity would be expected if there were no preferential ^{238}Pu to ^{239}Pu separation on soil surface. In contrast to Site A, $^{238}\text{Pu}/^{239}\text{Pu}$ ratios for Site AB are much different and are significantly elevated for all particle diameters above the surface soil sample range.

One can only hypothesize as to why there should be a difference in $^{238}\text{Pu}/^{239}\text{Pu}$ ratios at Sites AB and A as compared to soil surface samples. One difference is the surface activity level at Site A is greater than at Site AB. As was shown in Table 3, the ground soil surface activity level at Site A was approximately 10 time greater than at Site AB. If plutonium particles were attacked by microorganisms in the soil, microorganism activity might be decreased by the increased activity level at Site A. If microorganisms preferentially attacked ^{238}Pu at Site AB with a lower Pu contamination, ^{238}Pu on surface soils might become more readily available for resuspension. Other possibilities for increased resuspendability of surface ^{238}Pu at Site AB might be differences in soil chemistry between Sites A and AB or preferential ^{238}Pu ejection⁽¹⁵⁾ from particles during decay. Many possibilities exist, but the reasons for the elevated $^{238}\text{Pu}/^{239}\text{Pu}$ ratios at Site AB are uncertain. Additional research is needed to determine causes of elevated $^{238}\text{Pu}/^{239}\text{Pu}$ ratios at Site AB.

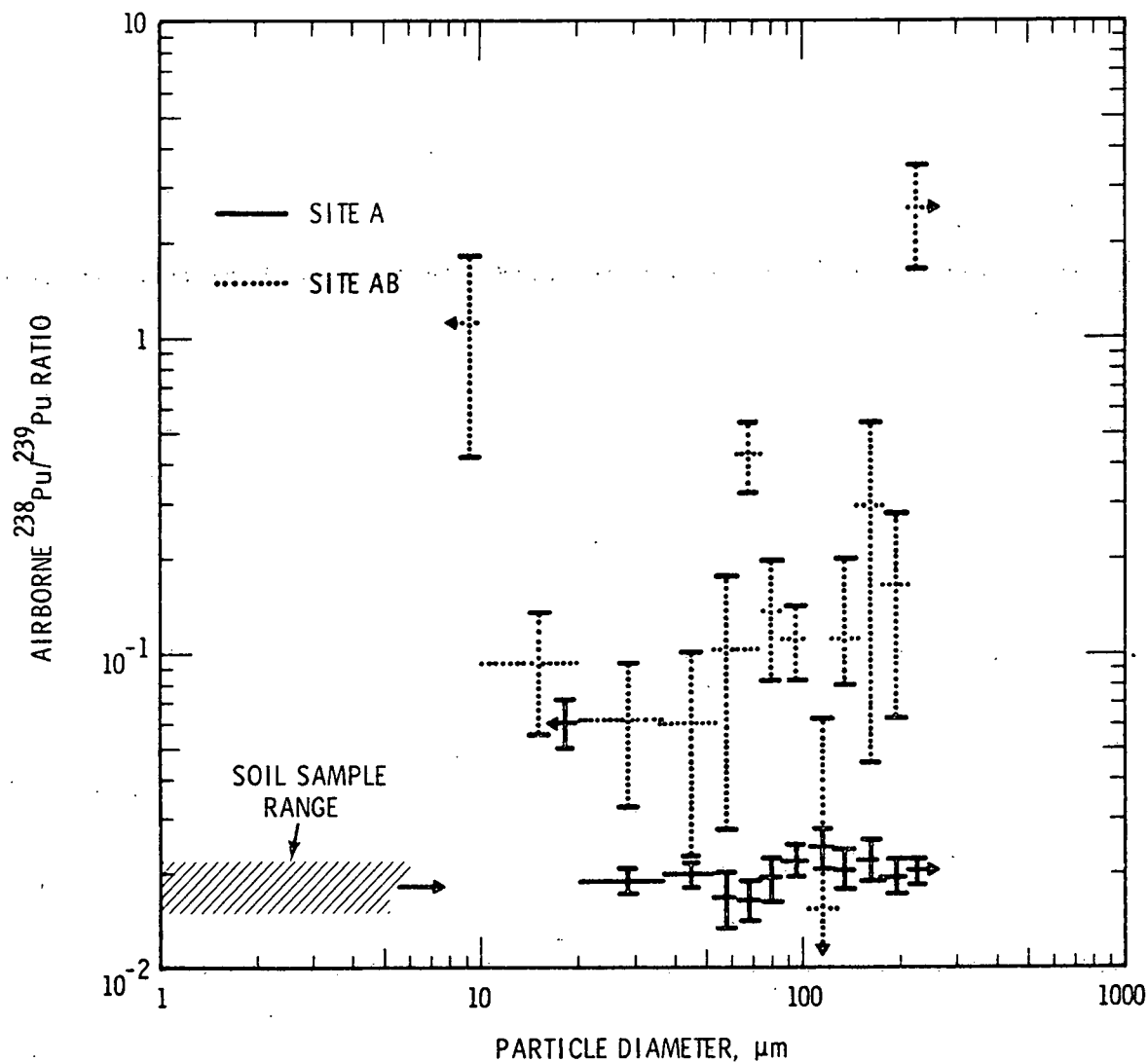


FIGURE 17. Plutonium 238/239 Ratio on Nonrespirable Airborne Soil as a Function of Particle Diameter at Rocky Flats (Neg. 767208-11)

ESTIMATION OF RELATIVE RESPIRABLE AND NONRESPIRABLE PLUTONIUM FLUXES

Direct comparisons between airborne fluxes on respirable and nonrespirable particles were not made since respirable and nonrespirable samples were sampled differently. Respirable particles at Rocky Flats were sampled at a constant flow rate of $0.57 \text{ m}^3/\text{min}$ while nonrespirable particles were collected by inertial collection within cowls. In order to calculate the relative flux on respirable and nonrespirable particles, one needs to know (1) the average

wind speed to determine the average flux on respirable particles, and (2) how particles were collected within the cowl by inertial impaction. In this case inertial impaction means particles would enter the cowl as if cowl sampling were isokinetic. In actuality, there is flow divergence around the cowl inlet. Consequently correction factors are needed for calculating true airborne particle fluxes for nonisokinetic sampling. However, nonisokinetic correction factors are not available. Even with these qualifications, one might still be interested in approximating the relative Pu fluxes for respirable and nonrespirable particles. Consequently, a simple calculation was made using the Rocky Flats data to illustrate the relative orders of magnitude for respirable and nonrespirable Pu fluxes.

The horizontal plutonium flux can be estimated from airborne soil fluxes and plutonium concentrations on airborne soil. Since soil fluxes are reported⁽⁷⁾, plutonium concentrations on airborne soil will be discussed prior to discussing plutonium fluxes. Plutonium concentrations in $\mu\text{Ci/g}$ of airborne respirable and nonrespirable soil are shown in Table 7. This table summarizes both total plutonium concentrations per gram of soil collected within cowls, and also respirable concentrations per gram for cases in which air was sampled continuously with particle cascade impactors. Respirable ^{239}Pu concentrations ranged from 2×10^{-6} to 6.2×10^{-5} $\mu\text{Ci/g}$ airborne soil. Concentrations of ^{238}Pu on respirable soil were less than radiochemical analytical limits. On nonrespirable soil, ^{239}Pu concentrations ranged from 1×10^{-6} up to 3×10^{-4} $\mu\text{Ci/g}$ and ^{238}Pu concentrations ranged from 2×10^{-7} up to 5×10^{-6} $\mu\text{Ci/g}$. In order to estimate the average plutonium concentration on airborne soil, respirable and nonrespirable concentrations were combined in the last two columns. For this calculation, isokinetic sampling was assumed. This assumption will be discussed further in a later section. Total Pu concentrations on airborne soil ranged from 1×10^{-6} up to 1.9×10^{-4} $\mu\text{Ci/g}$ for ^{239}Pu , and from 2×10^{-7} up to 3×10^{-6} $\mu\text{Ci/g}$ for ^{238}Pu .

Average airborne plutonium fluxes entering cowl inlets at Rocky Flats were calculated from airborne soil fluxes and plutonium concentrations on airborne soil. As shown in Table 8, plutonium fluxes on both respirable

and nonrespirable particles were calculated in units of $\mu\text{Ci}/(\text{m}^2 \text{ day})$. The calculation was based on collected plutonium, the sampling time, and the cross sectional area of the cowl inlet. The cowl inlet diameter was 15.2 cm. The maximum ^{239}Pu flux was $1 \times 10^{-5} \mu\text{Ci}/(\text{m}^2 \text{ day})$ and the minimum flux was $3 \times 10^{-9} \mu\text{Ci}/(\text{m}^2 \text{ day})$. Based on these limited data, these calculated fluxes might be used for estimating total plutonium fluxes over larger integrated areas. However, such estimates should be made with caution since the flux variability at other sites and elevations is unknown.

TABLE 7. Plutonium Concentration on Airborne Soil Collected During Continuous Air Sampling at Rocky Flats

Sampling Site	Sampling height, m	$\text{pCi/g} = (10^{-6}) (\mu\text{Ci/g})$				
		"Respirable"*	Nonrespirable		Total Assuming Isokinetic Sampling	
		^{239}Pu	^{239}Pu	^{238}Pu	^{239}Pu	^{238}Pu
A	0.3	62.3	203	4.2	188	3.8
	2	4.6	313	5.1	98.3	1
AB	0.3	5.0	1	0.2	1.6	0.2
	1	*	11.5	1.6		
	2	*	12.4	1.6		
B	2	2.1	10.2	2.4	3.1	0.2
	10	38.2	10.0	4.2	36.4	0.2

* Respirable samples were collected for wind speed increments rather than continuous sampling, ^{238}Pu was LAL (less than radiochemical analytical detection limits).
 1 dpm/g = 0.45 pCi/g

TABLE 8. Average Plutonium Flux Entering Cowl-Impactor System During Continuous Air Sampling at Rocky Flats

Sampling Site	Sampling Height, m	$\mu\text{Ci}/(\text{m}^2 \text{ day})$			
		Respirable		Nonrespirable	
		^{239}Pu	^{238}Pu	^{239}Pu	^{238}Pu
A	0.3	4.06×10^{-7}	LAL	1.02×10^{-5}	2.11×10^{-7}
	2	2.43×10^{-7}	LAL	4.03×10^{-7}	6.68×10^{-9}
AB	0.3	3.22×10^{-8}	LAL	5.66×10^{-5}	1.13×10^{-8}
B	2	1.16×10^{-8}	LAL	8.23×10^{-9}	1.85×10^{-9}
	10	1.93×10^{-7}	LAL	3.18×10^{-9}	1.32×10^{-9}

"Respirable" is all material collected with a particle cascade impactor LAL, less than radiochemical analytical limit

Average plutonium fluxes entering the cowl impactor system are used to estimate the respirable fraction of airborne plutonium. Estimates are given⁽⁷⁾ in Table 9 based on an isokinetic sampling assumption. Respirable fractions ranged from 3 to 98% of total airborne plutonium. However, one should use these numbers with caution. Plutonium collected within particle cascade impactors contained particles of 7, 3.3, 2.0, and 1.1- μm diam (which are impactor stage 50% cutoff diameters for unit density spheres) as well as smaller particles collected on the impactor backup filter. From the inhalation standpoint, particles collected on the 7- μm stage should not be included within the respirable size range. Only the smaller particles are usually considered respirable. However, in the present comparison between cowl-collected nonrespirable particles and impactor-collected respirable particles there is much uncertainty in calculating the relative 7- μm particle concentration as compared to the cowl-collected particle concentration.

TABLE 9. Estimated Respirable Percent of Total Airborne ^{239}Pu Flux at Rocky Flats

Sampling Site	Sampling Height, m	Airborne ^{239}Pu Assumed Isokinetic*	Respirable Percent Assumed Correction**
A	0.3	3.8	9
	2	37.7	60
AB	0.3	36.3	59
B	2	58.5	78
	10	98.4	99

*Isokinetic = $\text{Res}/(\text{Res} + \text{Non})$

** Correction =
$$\frac{(\text{Res}) (U_a/U_s)}{(\text{Res}) (U_a/U_s) + \text{Non}}$$

Where Res = dpm/min collected in impactor

Non = dpm/min collected in cowl

U_s = average flow rate through cowl inlet, 0.36 m/sec

U_a = average windspeed, 0.9 m/sec

The better estimate of the respirable Pu fraction at Rocky Flats is shown in the last column of Table 9. Based on the assumed correction factor, the respirable fraction of airborne plutonium increased from 4 to 98% for an isokinetic sampling assumption up to 9 to 99% of the total airborne plutonium. True respirable fractions should be between these limiting values.

Respirable fractions have been reported⁽⁸⁾ as 25% for plutonium collected within particle cascade impactors at Rocky Flats. Since the present results show that plutonium is also attached to particles in much larger size ranges for cowl-collected samples than for particles collected on the initial stage of an impactor, published respirable fractions are probably indicative of maximum fractions rather than a true respirable fraction.

Even if all Pu collected in the cowl-impactor sampling systems were respirable, airborne Pu concentrations were still below maximum permissible concentrations (MPC). The MPC_{168Hr-air} for ²³⁹Pu is $6 \times 10^{-13} \mu\text{Ci}/\text{cm}^3$. The smallest respirable fraction in Table 9 is 3.8%. This sample at 0.3 m for Site A also represents the largest airborne Pu concentration measured in our experiments. For this sample, the real respirable ²³⁹Pu concentration (<3.3 μm diameter) was $2 \times 10^{-16} \mu\text{Ci}/\text{cm}^3$ while the concentration was $5 \times 10^{-16} \mu\text{Ci}/\text{cm}^3$ if the 7- μm particles of the particle cascade impactor are included. If all airborne Pu is assumed respirable, a maximum calculated ²³⁹Pu concentration is $(5 \times 10^{-16}/0.038) 1.3 \times 10^{-14} \mu\text{Ci}/\text{cm}^3$, which is still significantly less than the MPC of $6 \times 10^{-13} \mu\text{Ci}/\text{cm}^3$.⁽²⁶⁾

AMERICIUM RESUSPENSION AT HANFORD

At Hanford, airborne ²⁴¹Am concentrations measured⁽¹⁾ at U-Pond, Z-19, S-16 and HMS Tower areas ranged from about 10^{-18} to $10^{-15} \mu\text{Ci}/\text{cm}^3$. However, other filter samples indicated total ²⁴¹Am collected was below radiochemical detection limits. In Figure 18 airborne ²⁴¹Am concentrations are compared to 300 Area fallout levels.⁽²⁷⁾ However, the comparisons are incomplete since ²⁴¹Am fallout level data were not reported for all time periods. In addition, many fallout level data were below radiochemical detection limits; these are indicated by short horizontal dotted lines. Obviously, actual fallout levels for these time periods could have been significantly less.

Airborne ²⁴¹Am concentrations at U-Pond were of the same order of magnitude as reported fallout levels. In contrast, airborne concentrations at Z-19 and S-16 were significantly above fallout levels during February to May 1975. Comparisons of upwind and downwind tower air sample results at S-16 showed increased ²⁴¹Am airborne concentrations were from ²⁴¹Am resuspension from the dry S-16 area. (This area has since been covered.) Maximum ²⁴¹Am concentrations measured in November 1975 at the HMS Tower are also comparable to concentrations measured at S-16 and Z-19. However, ²⁴¹Am was above radiochemical detection limits on only two HMS Tower air filters for this time period.

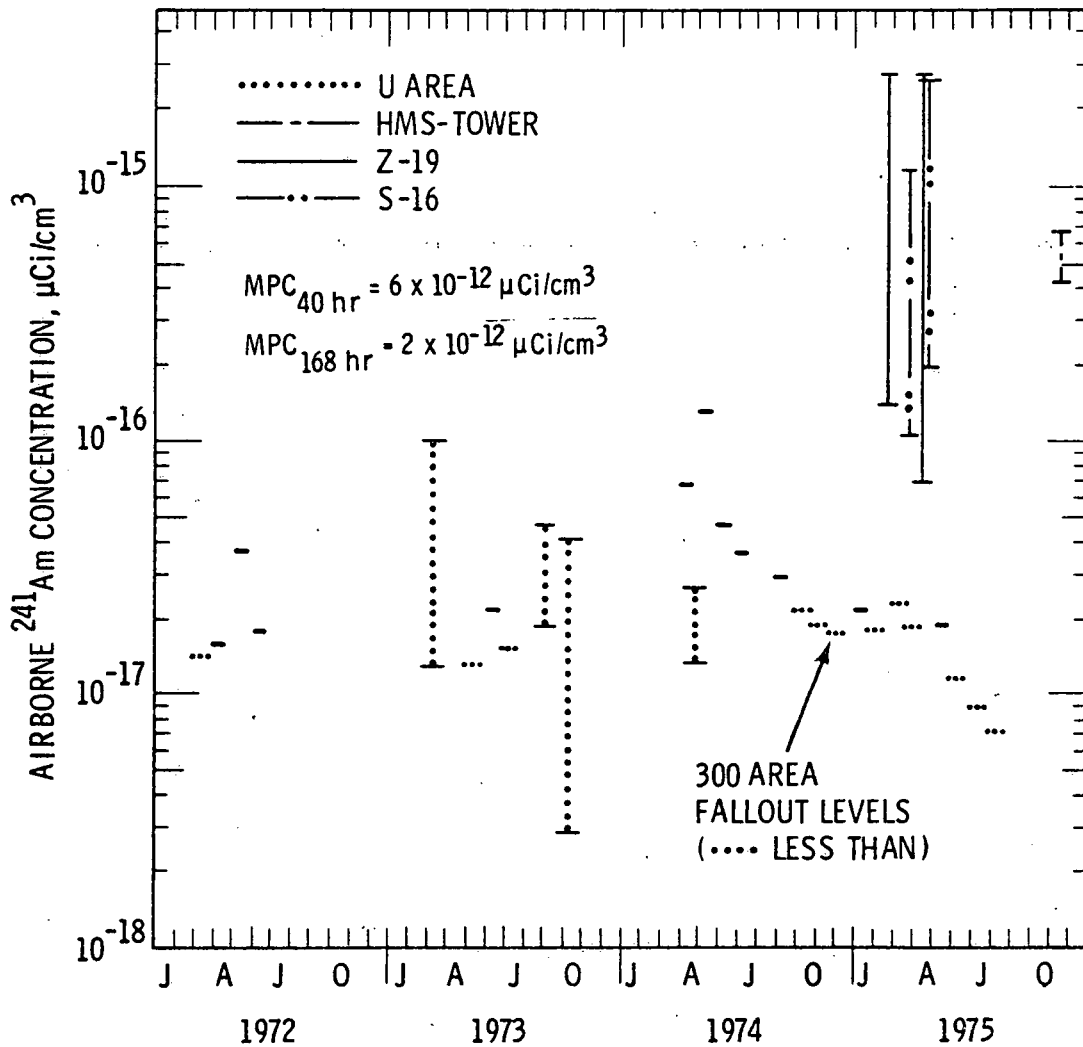


FIGURE 18. Range of Airborne ^{241}Am Concentrations (Above Radiochemical Detection Limits) at Onsite Hanford Resuspension Sites Compared to Fallout Levels (Neg. 768423-3)

Concentrations of ^{241}Am on airborne solids at each resuspension site, shown in Figure 19, ranged from about 10^{-7} to 10^{-4} $\mu\text{Ci}/\text{g}$ of airborne solids. Airborne concentrations were least for U-Pond and greatest for Z-19 and S-16 areas. For the HMS tower data, many air filters collected less than the two positive ^{241}Am results indicates that many air filters had collected

radiochemical detection limits. Nevertheless, maximum ^{241}Am concentrations per gram of airborne solids at the HMS Tower for two samples above radiochemical detection limits were comparable to concentration ranges measured at Z-19 and S-16.

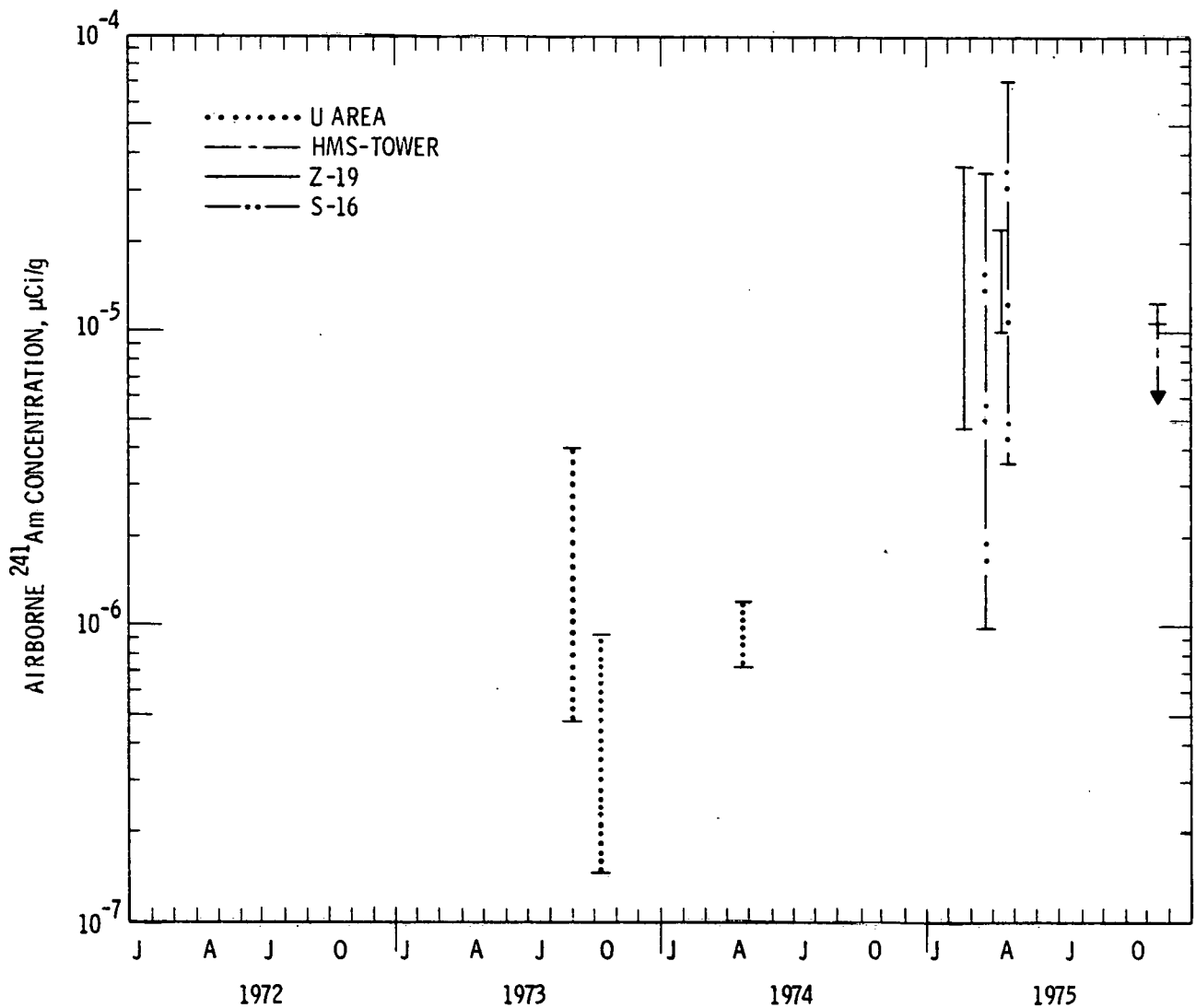


FIGURE 19. Range of ^{241}Am Concentrations on Airborne Solids at Onsite Hanford Resuspension Sites (Neg. 768423-1)

PLUTONIUM RESUSPENSION FROM OFFSITE NEAR HANFORD

Plutonium on offsite locations near nuclear facilities has deposited from fallout as well as from onsite low level releases. Resuspension of this offsite plutonium was studied near the Prosser barricade on the Hanford reservation. The Prosser barricade is located about 19 to 20 Km southeast (130 to 160°) from the fuel processing areas. Airborne solids were collected by sampling with particle cascade impactors and rotating cowl systems. Air sampling was only when wind was blowing from 190-260°. This range of southwest (225°) winds came from offsite towards the Hanford reservation. All southwest winds were continuously sampled with rotating cowl systems for nonrespirable particles while respirable particles were sampled with particle cascade impactors for wind speed increments of 3 to 5, 5 to 7, and 7 to 11 m/sec at a height of 1.5 m.

Airborne plutonium concentrations blowing in from offsite are shown in Figure 20 for the particle cascade impactor data. Both airborne concentrations in $\mu\text{Ci}/\text{cm}^3$ air and $\mu\text{Ci}/\text{g}$ collected solid are given. Airborne plutonium concentrations determined with particle cascade impactors are shown as a function of wind speed increments for plutonium collected on the impactor backup filter, the 1.1 plus 2.0 μm stages, and the 3.3 plus 7 μm stages.

Airborne plutonium concentrations increased with increasing wind speed. Concentrations increased up to about 2 orders of magnitude as wind speed increased from 3 to 5 up to 7 to 11 m/sec. Straight lines are drawn through data in order to direct attention to the wind speed tendency of the data. For the plutonium collected on the cascade impactor backup filter, lines proportional to wind speed to the 1.1 and 4.2 power are shown. For wind speeds below about 5 m/sec, airborne plutonium concentrations tended to increase nearly linearly with wind speed. However, above 5 m/sec, plutonium concentrations increased with wind speed to the 4.2 power. At the present time, it is unknown whether these indicated relationships would suggest a threshold windspeed of 5 m/sec for resuspension or whether a smooth curve should be drawn through all data points.

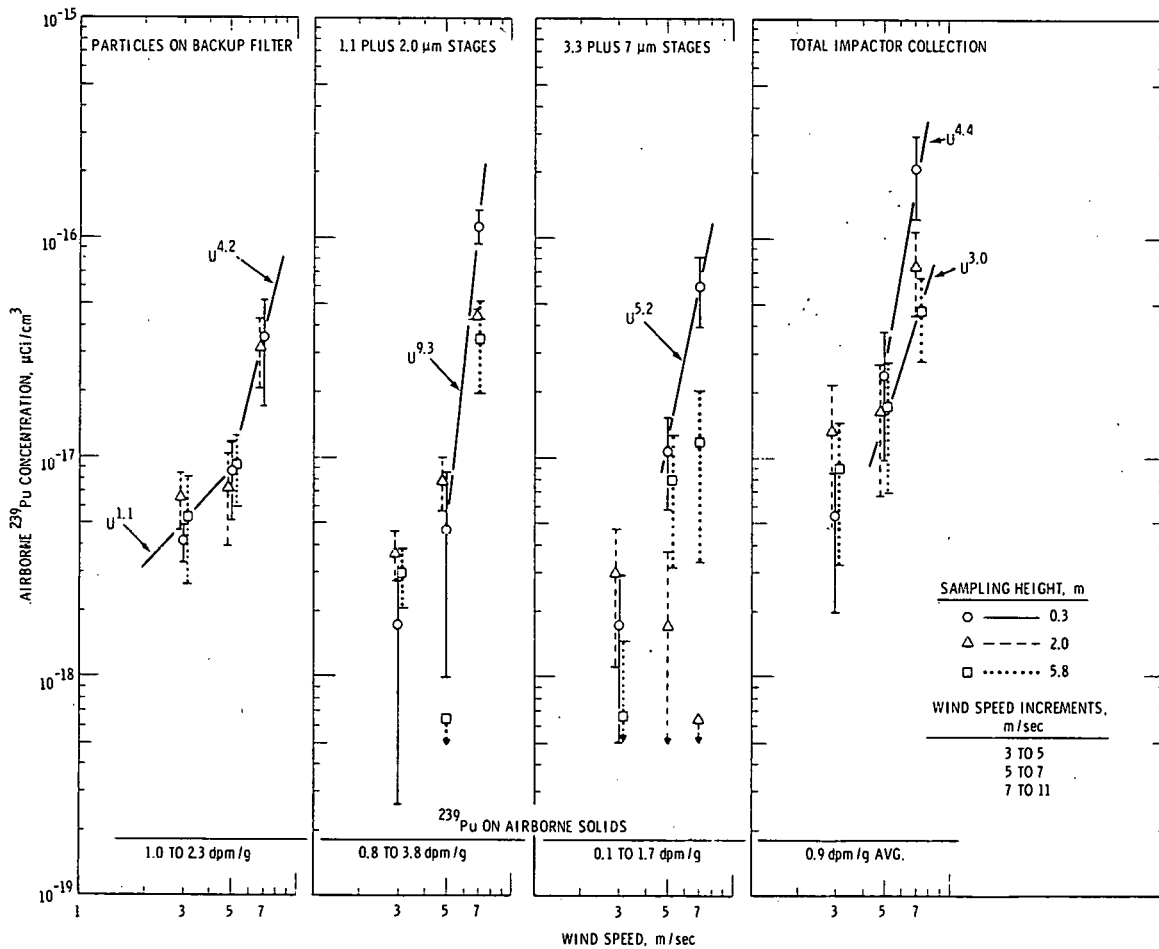


FIGURE 20. Airborne ^{239}Pu Concentrations Near Prosser Barricade at Hanford from April 12 to June 29, 1976 When Sampling Only 190 to 269° Winds (Neg. 77614-1)

In other portions of this figure, selected straight lines suggesting wind speed dependencies are shown only for wind speeds above 5 m/sec. For the 1.1 plus 2.0 μm impactor stages, airborne concentrations increased with wind speed to the 9.3 power. For the 3.3 plus 7 μm impactor stages, airborne concentrations increased with wind speed to the 5.2 power. For total plutonium collection within particle cascade impactors, a range of wind speed dependency is shown on the right side of the figure. For a sampling height of 0.3 m, air concentrations increased with wind speed to the 4.4 power. However, at a sampling height of 1.8 m, airborne concentrations increased with wind speed to the 3.0 power.

These data in Figure 20 are the first to show plutonium is resuspended from offsite locations. In addition, airborne plutonium concentrations show a very high wind speed dependency for this offsite plutonium resuspension. As will be discussed later, tracer wind resuspension rates suggest a wind speed dependency to the 4.8 power. This is similar to the wind speed dependency shown by this offsite plutonium resuspension data. However, there are other plutonium resuspension data which show a different wind speed dependency. West of U-Pond on the Hanford reservation, airborne plutonium concentrations increased⁽¹⁾ with wind speed to only the 1.5 power. Reasons for these differences in the wind speed dependency of onsite versus offsite plutonium resuspension are unknown. Possibly a threshold wind velocity above which resuspension increases rapidly with wind speed was not exceeded at U-Pond.

Nonrespirable airborne plutonium blowing from offsite onto the Hanford reservation was also measured. In this case, sampling direction was controlled by placing stops which allowed the rotating cowl (Figure 3) inlet to rotate only with the range of 190° to 260°. Plutonium analysis was for the total nonrespirable solids collection in cowls at each height, rather than as a function of particle size as was done for Rocky Flats (See Figures 11 and 13.)

Plutonium-239 concentrations in mCi/g and fluxes in mCi/(m²day) for nonrespirable particles blowing from offsite near the Hanford Prosser barricade are shown in Table 10. Plutonium concentrations on nonrespirable airborne solids ranged from 1.3×10^{-7} up to 2.1×10^{-7} μ Ci/g. These concentrations are similar to those shown in Figure 15 for airborne nonrespirable particles collected west of U-Pond.

Airborne nonrespirable ²³⁹Pu fluxes also were calculated for these Prosser barricade samples. Horizontal flux calculations were made for both the total time wind was between 3 and 11 m/sec and 190° to 260° and for the total time cowl air samplers were in the field. Fluxes are shown in the last two columns of Table 10. When the shorter time period (3 to 11 m/sec winds) is used for calculating the horizontal plutonium flux, fluxes range from

TABLE 10. Plutonium Transport on Nonrespirable Particles from Offsite Near the Prosser Barricade on the Hanford Reservation

Sampling Height, m	^{239}Pu on Airborne Solids		Airborne ^{239}Pu Nonrespirable Flux, $\mu\text{Ci}/(\text{m}^2 \text{ day})$ for Times Of	
	dpm/g	$\mu\text{Ci/g}$	Only for 190 to 260 Winds, 3 to 11 m/sec	Total Field Time
0.3	0.29	1.3×10^{-7}	3.9×10^{-6}	8.0×10^{-7}
2	0.46	2.1×10^{-7}	4.0×10^{-6}	8.3×10^{-7}
5.8	0.32	1.5×10^{-7}	1.4×10^{-6}	2.8×10^{-7}

3.9×10^{-6} to $1.4 \times 10^{-6} \mu\text{Ci}/(\text{m}^2 \text{ day})$. This Prosser barricade flux range is within the range measured near Site A at Rocky Flats which was shown in Figure 8. However, if the total time cowl air samplers were in the field is used for calculation, Prosser barricade airborne nonrespirable offsite plutonium fluxes were lower and comparable to those measured at Rocky Flats Sites AB and B (See Figure 8).

These cross comparison data show there is a comparable plutonium flux on nonrespirable particles offsite at Hanford, onsite at Hanford U-Pond, as well as onsite at Rocky Flats for the time periods investigated. Comparable fluxes may be caused by more soil being transported from offsite at the Prosser barricade site. As shown by the range of ^{239}Pu concentrations on airborne soil from 1.3×10^{-7} up to $2.1 \times 10^{-7} \mu\text{Ci/g}$, this range is greater than fallout levels in soil surface samples. As shown in Table 3, reported ^{239}Pu concentrations in surface samples 19 to 34 Km from Hanford had a range from 3.6×10^{-9} to $7.6 \times 10^{-8} \mu\text{Ci/g}$. These last values are similar to a fallout level of $3.8 \times 10^{-8} \mu\text{Ci/g}$ measured⁽³⁶⁾ at North Eastham, MA.

Most plutonium collected appears not to have originated from fallout. Rather, most plutonium collected on these airborne nonrespirable particles near the Prosser barricade resembles weapons grade plutonium.^(37,38) Plutonium isotopic ratios ($^{240}\text{Pu}/^{239+240}\text{Pu}$) in atom percent for these non-respirable samples were 6.10 ± 0.02 at 0.3 m height, 6.31 ± 0.02 at 2 m height, and 6.28 ± 0.03 at 5.8 m height. In comparison, the isotopic ratio determined from a sample of forest fire smoke plume near Mt. St. Helens, WA, was 13.82 ± 0.05 . Isotopic ratios for respirable particles sampled near the Prosser barricade were not determined. Although plutonium was blowing from offsite near the Prosser barricade, airborne respirable plutonium concentrations were below maximum permissible concentrations as was shown by Figure 20.

RELATIVE AMOUNTS OF RADIONUCLIDE "CLUSTERS" ON PARTICLES RESUSPENDED

Data from these studies indicate that occasionally some more-radioactive-than-normal particles or clusters of radioactive particles were resuspended and collected on sampling filters. In the October 1973 plutonium data for Hanford shown in Figures 7 and 14, one filter at 6.1-m height collected 6.5×10^{-5} $\mu\text{Ci/g}$ airborne solid (1.2×10^{-15} $\mu\text{Ci/cm}^3$ of filtered air). The plutonium measurement was 36 times greater than the maximum value of 1.8×10^{-6} $\mu\text{Ci/g}$ airborne solid (4.0×10^{-17} $\mu\text{Ci/cm}^3$ of filtered air) collected on other filters simultaneously sampling at heights of 6.1 and 0.3 m. We hypothesize that this relatively high plutonium collection on this filter was due to collection of one or more larger (more radioactive than normal usually resuspended and sampled) particles or clusters of particles.

The size of the larger particle(s) cannot be measured since the filter samples were dissolved for plutonium analysis. Nevertheless, the relative size can be estimated from the ratio of radioactivities collected for "normal" and "larger" particle sizes. Assuming that a particle's radioactivity is proportional to its volume, then the filter with a plutonium activity 36 times greater the next highest measured activity may have collected "larger" particles of plutonium activity 36 times the activity of "normal" particles. This would correspond to a diameter for the larger, less frequently resuspended particle(s) which may be three times the diameter of normally resuspended plutonium particles. Only since extensive air

samples have been collected has the resuspension of these unusually active particles been suggested. However, the frequency of their resuspension appears to be very low.

The presence of a more-radioactive-than-normal resuspended particle is also indicated by the ^{241}Am data shown in Figures 18 and 19. The two positive ^{241}Am air samples for the HMS Tower may indicate that larger-than-normal ^{241}Am particles or clusters of particles were collected on these filters.

As discussed earlier for resuspended particles at Rocky Flats, a more-radioactive-than-average particle (or cluster of particles) was collected on the 2- μm stage of a particle cascade impactor.

RESUSPENSION FACTORS AT HANFORD

Resuspension factors have been used to describe resuspension air concentrations. The resuspension factor (expressed in a unit of m^{-1}) is defined as the airborne concentration of contaminant per cubic meter divided by the surface contamination level per square meter immediately below the point where the airborne concentration was measured. Often air concentrations for determining resuspension factors have been measured from about 1 to 1-1/2 m above ground. However, airborne concentrations are a function of the upwind contamination level, not a contamination level immediately below the air concentration measurement site. It is the transport from upwind contamination sites to the concentration measurement site that determines the airborne concentration.

Although the validity of resuspension factors is questionable, they were for a long time the only method for estimating air concentrations. Consequently resuspension factors were estimated from data obtained at Hanford.⁽¹⁾ Resuspension factors and the basis for their calculation are shown in Table 11 for both ^{239}Pu and ^{137}Cs ; literature values are used as an indication of ground surface contamination levels in $\mu\text{Ci}/\text{m}^2$, while airborne concentrations⁽¹⁾ were shown in Figure 9. Resuspension factors calculated from air concentrations and ground surface contamination levels are shown in the last column. Resuspension factors for ^{239}Pu range from 6×10^{-10} to $2 \times 10^{-5} \text{m}^{-1}$. Resuspension factors for ^{137}Cs range from 4×10^{-11} to $7 \times 10^{-8} \text{m}^{-1}$. These ranges from 10^{-11} to 10^{-5}m^{-1} are within ranges reported in the literature.^(12,17)

TABLE 11. Resuspension Factors at Hanford

Material	Area	x, Air Concentration $\mu\text{Ci}/\text{cm}^3$		G, Surface Contamination $\mu\text{Ci}/\text{m}^2$		Resuspension Factor* Range, m^{-1}
		Minimum	Maximum	Minimum	Maximum	
^{239}Pu	"Inside chemical separation areas"(29)	7×10^{-18}	8×10^{-15}	4.9×10^{-4}	1.2×10^{-2}	6×10^{-10} to 2×10^{-5}
^{137}Cs	BC(16,33)	2×10^{-15}	2×10^{-14}	0.29	55.4	4×10^{-11} to 7×10^{-8}

*Resuspension factor = $(10^6)(x)/G$

PREDICTED AIRBORNE RADIONUCLIDE CONCENTRATIONS FROM RESUSPENSION FACTORS

Airborne concentrations can be predicted from resuspension factors and surface contamination levels if both values are known. Equivalencies of airborne concentrations and ground surface concentrations are presented in Figure 21. The reader can estimate two of the parameters and use this figure to predict the third parameter. However, as indicated in the last section, the range of experimental resuspension factors is very large. Consequently, realistically predicting the relationship between surface and airborne concentration is fraught with uncertainties.

PREDICTED AIRBORNE RADIONUCLIDE CONCENTRATIONS FROM AIRBORNE SOLIDS AT HANFORD

Airborne concentrations can either be determined experimentally or calculated on the basis of simplifying assumptions. For example, one assumption is that radionuclide concentrations on airborne solids are equal to radionuclide concentrations per gram of ground surface contaminated solids. As was shown in Table 6 for very limited data, this assumption is usually not valid since the ratio of radionuclide concentration per gram of airborne solids to the radionuclide concentration per gram of surface solids ranged from 10^{-3} to $x \times 10^3$. Nevertheless, two equality assumptions are used in this section to predict airborne radionuclide concentrations.

Airborne plutonium concentrations can be predicted by assuming both parameters of airborne soil concentration as well as plutonium concentration per gram on that airborne soil. In this case, the equivalency between these two parameters and airborne plutonium concentrations are shown in Figure 22. As a point of reference, airborne concentrations at Hanford are⁽¹⁹⁾ about $80 \mu\text{g}/\text{m}^3$ for wind speeds of 5 m/sec. Hence, in using Figure 22, a plutonium concentration on airborne soil of approximately $10^{-2} \mu\text{Ci}/\text{g}$ would be required (assuming a surface contamination depth of one cm and a soil density of $2 \text{ g}/\text{cm}^3$) at an airborne soil concentration of $80 \mu\text{g}/\text{m}^3$ to exceed or approach maximum permissible airborne ^{239}Pu concentrations.

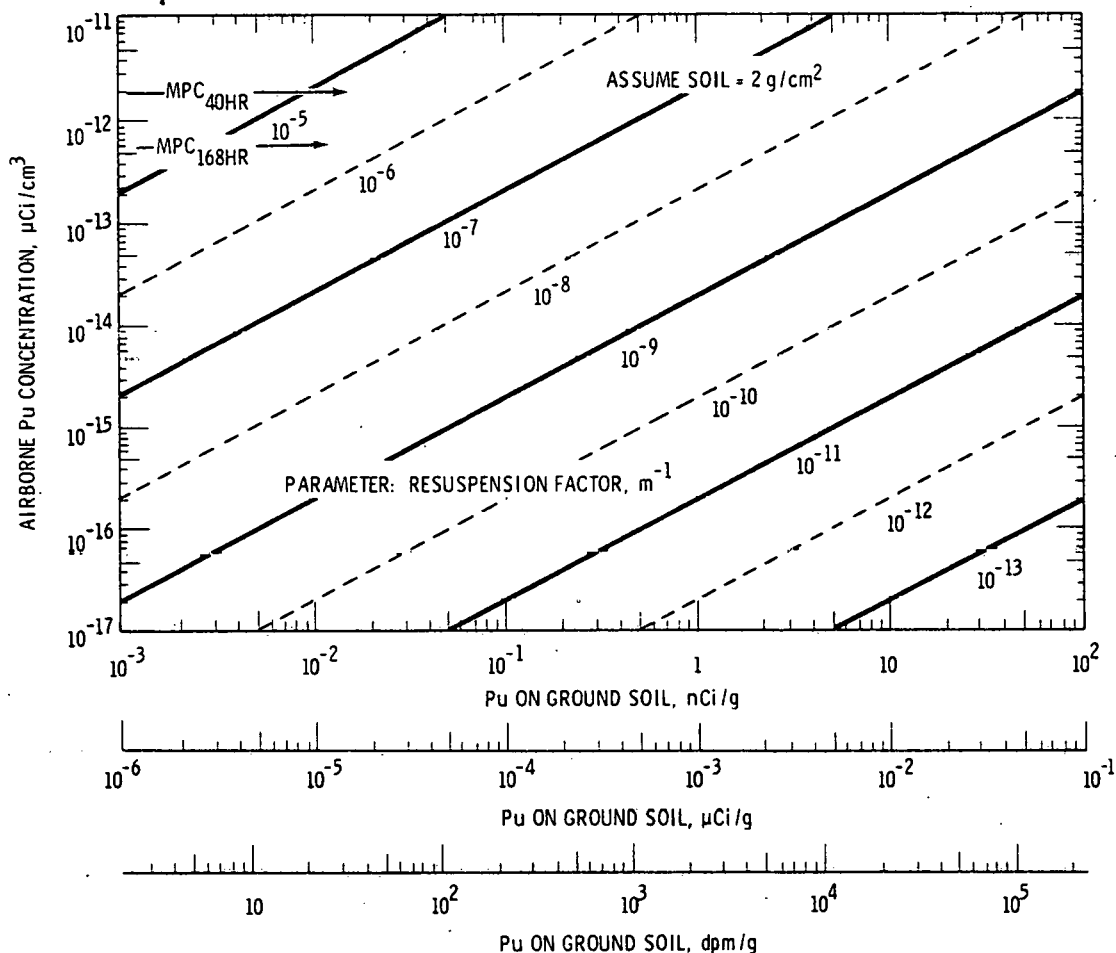


FIGURE 21. Equivalency of Airborne Pu Concentrations and Ground Surface Concentrations Based Upon the Resuspension Factor Concept (Neg. 772994-2)

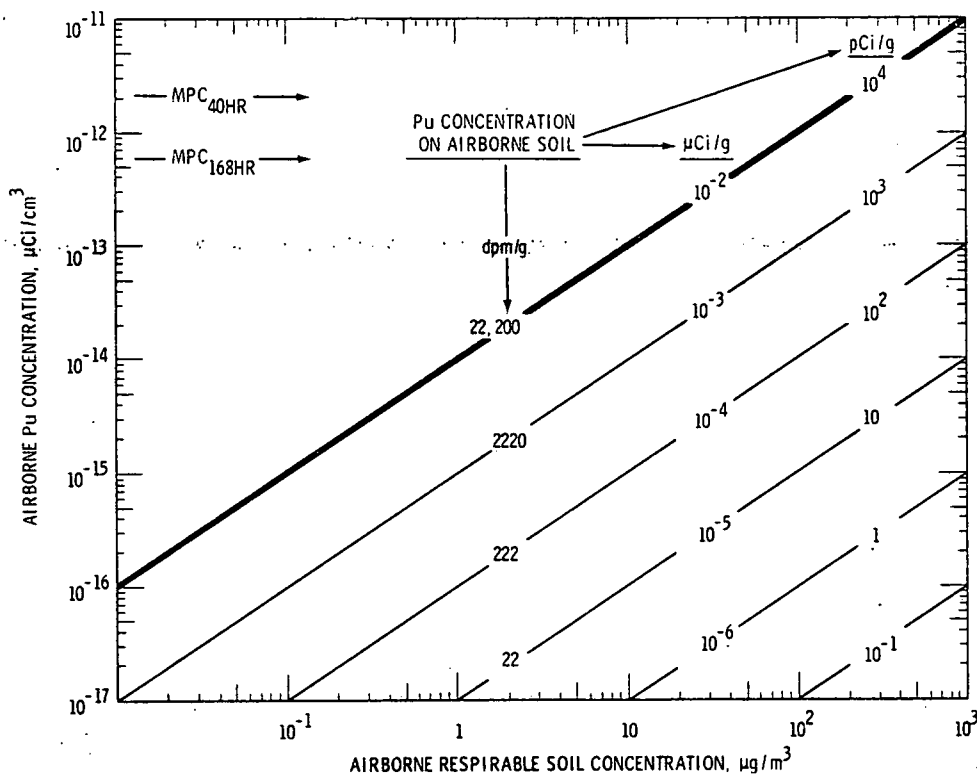


FIGURE 22. Equivalencies Between Pu on Airborne Soil and Airborne Pu Concentrations (Neg. 772705-4)

As was shown in Tables 4 and 5, there is no experimental basis for adequately predicting plutonium concentration on total airborne soil since airborne soil usually consists of both uncontaminated soil blowing in from offsite as well as, the resuspended contaminated soil. At our present state of knowledge, there are only limited data for ratios of plutonium on total airborne soil compared to total surface soil. Moreover, there is no experimental resuspension data to relate plutonium concentrations on respirable surface soils versus plutonium concentrations on respirable airborne soils.

Airborne solids concentration levels were estimated from data (1,39) shown in Figure 23. Airborne particle volume distributions were determined on the Hanford Reservation using both an optical particle counter and a cowl-impactor system. (23) The range obtained with the optical particle counter is shown as a cross-hatched area. The cowl impactor data have an upper limit,

increasing with wind speed and decreasing height, (the April 1972 data) and a lower limit for other test periods indicated by the lines described by $3.46D^{0.12}$ and $1160D^{-1.48}$ where D is the particle diameter. To determine maximum airborne mass loadings, the upper or maximum limits of the curves for any particle diameter were integrated as a function of particle diameter. The lower limits were also integrated as a function of particle diameter. These integrations predicted the solids mass loading per unit volume of air (shown in Table 12) as a function of four different particle diameter ranges: 0.16 to 1 μm , 1 to 10 μm , 10 to 100 μm , and 100 to 230 μm .

Particles less than 10 μm diameter are frequently considered respirable (i.e., small enough to be inhaled into the lungs), even though 3.5 μm appears to be more exact. In the following discussion, particles with diameters less than 10 μm are considered respirable and those larger than 10 μm are nonrespirable.

Mass loadings in these respirable and nonrespirable ranges are shown as upper limits of 0.7 mg/m^3 for respirable particles and 231.8 mg/m^3 for non-respirable particles. The lower limits are 7.7 $\mu\text{g}/\text{m}^3$ for respirable particles and 20 $\mu\text{g}/\text{m}^3$ for nonrespirable particles. These mass loadings were multiplied by maximum surface contamination levels for ^{239}Pu and ^{137}Cs shown in Table 5. This approach yielded a predicted maximum airborne ^{239}Pu concentration for respirable particles of $4.92 \times 10^{-10} \mu\text{Ci}/\text{cm}^3$ and a predicted lower limit of $5.33 \times 10^{-12} \mu\text{Ci}/\text{cm}^3$.

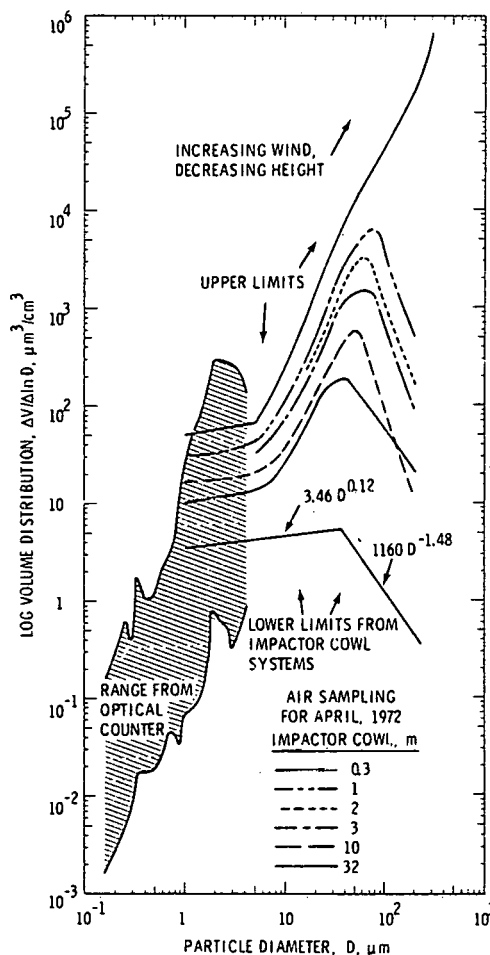


FIGURE 23. Airborne Particle Volume Distributions at Hanford (Neg. 765836-1)

TABLE 12. Calculated Airborne Concentrations From Airborne Solid Concentrations and Surface Contamination

Airborne Particles	Particle Diameter Range, μm					
	0.16 to 1	1 to 10	Respirable 0.16 to 10	10 to 100	100 to 230	Non-respirable 10 to 230
Total Volume, $\mu\text{m}^3/\text{cm}^3$						
Upper Limit	4.58	3.5×10^2	354.6	2.22×10^4	9.37×10^4	1.16×10^5
Lower Limit	0.036	3.83	3.87	9.39	0.609	10.0
Solids Mass Loading						
Upper Limit, mg/m^3	0.00916	0.704	0.713	44.4	187.4	231.8
Lower Limit, $\mu\text{g}/\text{m}^3$	0.072	7.66	7.73	18.78	1.218	20.0
Calculated * Extreme Maximum Airborne Concentration From Limits of Airborne Solids Concentrations, $\mu\text{Ci}/\text{cm}^3$						
^{239}Pu , Upper Limit			4.92×10^{-10}			1.60×10^{-7}
Lower Limit			5.33×10^{-12}			1.38×10^{-11}
^{137}Cs , Upper Limit			1.78×10^{-5}			5.79×10^{-3}
Lower Limit			1.93×10^{-7}			5.00×10^{-7}

* Concentration on airborne solids assumed equal to maximum reported in Table 5 for concentration on ground solids:

$$^{239}\text{Pu} = 6.9 \times 10^{-7} \mu\text{Ci}/\text{g}$$

$$^{137}\text{Cs} = 2.5 \times 10^{-2} \mu\text{Ci}/\text{g}$$

where

$$^{239}\text{Pu} : \begin{aligned} \text{MPC}_{40\text{hr}} &= 2 \times 10^{-12} \mu\text{Ci}/\text{cm}^3 \\ \text{MPC}_{168\text{hr}} &= 6 \times 10^{-13} \mu\text{Ci}/\text{cm}^3 \end{aligned}$$

$$^{137}\text{Cs} : \begin{aligned} \text{MPC}_{40\text{hr}} &= 6 \times 10^{-8} \mu\text{Ci}/\text{cm}^3 \\ \text{MPC}_{168\text{hr}} &= 2 \times 10^{-8} \mu\text{Ci}/\text{cm}^3 \end{aligned}$$

Upper and lower limits of ^{137}Cs concentrations on respirable and non-respirable particles were calculated similarly. However, a comparison of airborne ^{137}Cs and ^{239}Pu concentrations predicted by this method and measured airborne concentrations shows the shortcomings of this calculational approach. This method predicts air concentrations could exceed MPC values. In contrast, average measured⁽¹⁾ concentrations were less than 4×10^{-3} of $\text{MPC}_{40\text{-hr}}$.

This airborne particle mass loading approach to calculated airborne radionuclide concentrations does not distinguish the sources of airborne material. For simple wind resuspension, airborne solids included contaminated solids (lower or higher radionuclide concentrations per gram of solid) blown in from the surrounding area as well as solids resuspended from the prime resuspension study site. In contrast, airborne solids above a mechanically disturbed area are resuspended from the study site. In this case, possibly such an equality assumption of radionuclide concentration per gram of solids would be appropriate for mechanical disturbances⁽¹¹⁾ of contaminated soil area.

TRACER PARTICLE RESUSPENSION

In order to determine particle resuspension rates, tracer particles placed on selected surfaces were used to measure⁽¹⁹⁾ resuspension rates caused by both mechanical and wind resuspension. Mechanical resuspension was measured for vehicular traffic on asphalt and cheat grass areas and pedestrian traffic on an asphalt area. Wind resuspension was measured as a function of wind speed and also as a function of respirable and nonrespirable particle diameters.

Mechanical Resuspension Rates

Mechanical resuspension includes both vehicular resuspension and pedestrian resuspension.

Vehicular Resuspension

A 3/4-ton truck and a car were driven over ZnS tracer particles (8 μ m mass median diameter) placed upon one lane of asphalt road. Resuspended tracer was measured to determine resuspension rates.⁽²²⁾ Results are shown in Figure 24 for particle resuspension rates at vehicle speeds of 5, 15, 30, and 50 mph. The resuspension rate is the fraction of particles resuspended from the tracer lane each time the vehicle was driven down the road (fraction resuspended/pass). When a car was driven through the tracer lane at

speeds up to 30 mph, resuspension rates increased with the square of car speed from about 10^{-4} to 10^{-2} fraction resuspended/pass. This means that these resuspension rates were proportional to car-generated turbulence. When the car was driven on the lane adjacent to the tracer lane, resuspension rates were lower for each vehicle speed but increased with vehicle speed from about 10^{-5} to 10^{-3} fraction resuspended/pass.

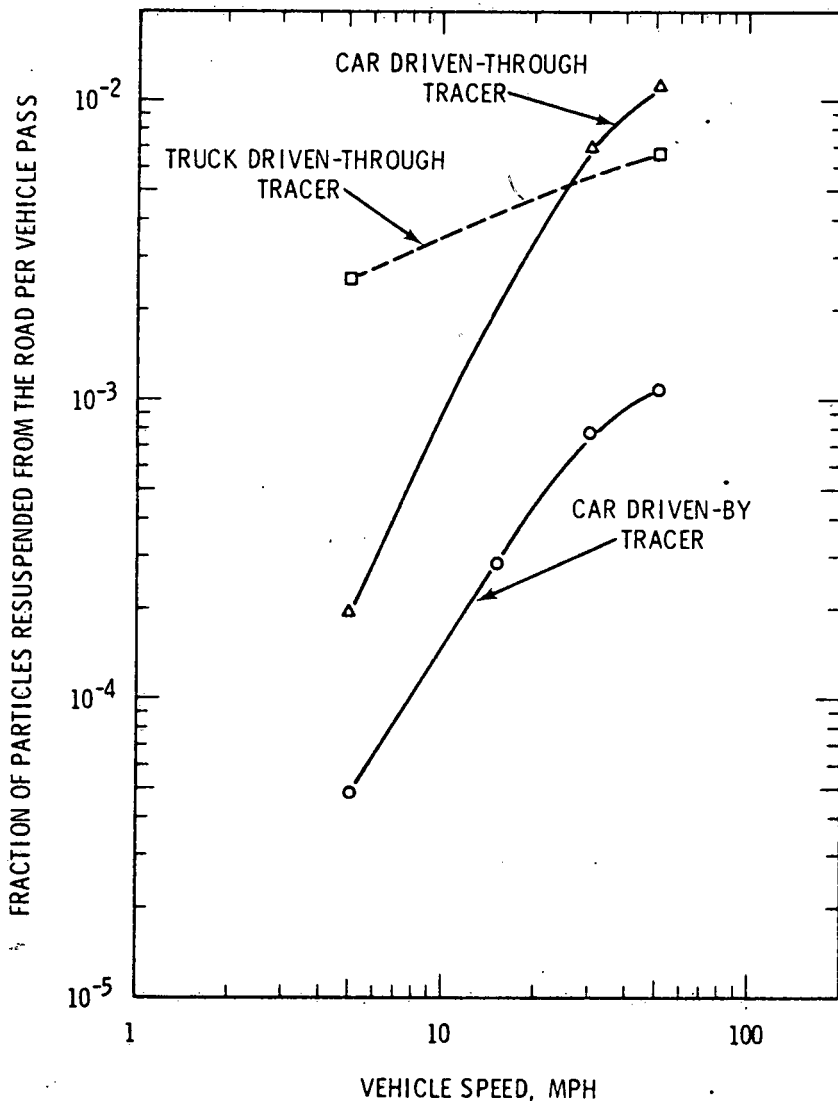


FIGURE 24. Rates of Tracer Particle Resuspension Caused by Vehicle Passage Over an Asphalt Road (Neg. 715289-3)

Resuspension was also measured when a 3/4-ton truck was driven on the tracer lane. Resuspension rates for truck passage increased from about 10^{-3} to 10^{-2} fraction resuspended/pass. Since resuspension rates were higher, truck-generated surface stress turbulence appears to have been much greater than for car-generated turbulence. For vehicle speeds above 20 mph, resuspension rates for car and truck passage are comparable. This similarity might be caused by tire surface stress rather than air turbulence.

Resuspension rates were also a function of the time tracer particles were on the asphalt road. As shown in Figure 25, particle resuspension rates decreased as a function of time. For these data, the tracer had been on the road for four days. Vehicle-generated resuspension rates increased from about 10^{-5} to about 10^{-3} fraction resuspended/pass as vehicle speed increased from 5 to 50 mph. For both vehicles, resuspension was greater when the vehicle was driven through the tracer lane than when driven on the lane adjacent to the tracer lane.

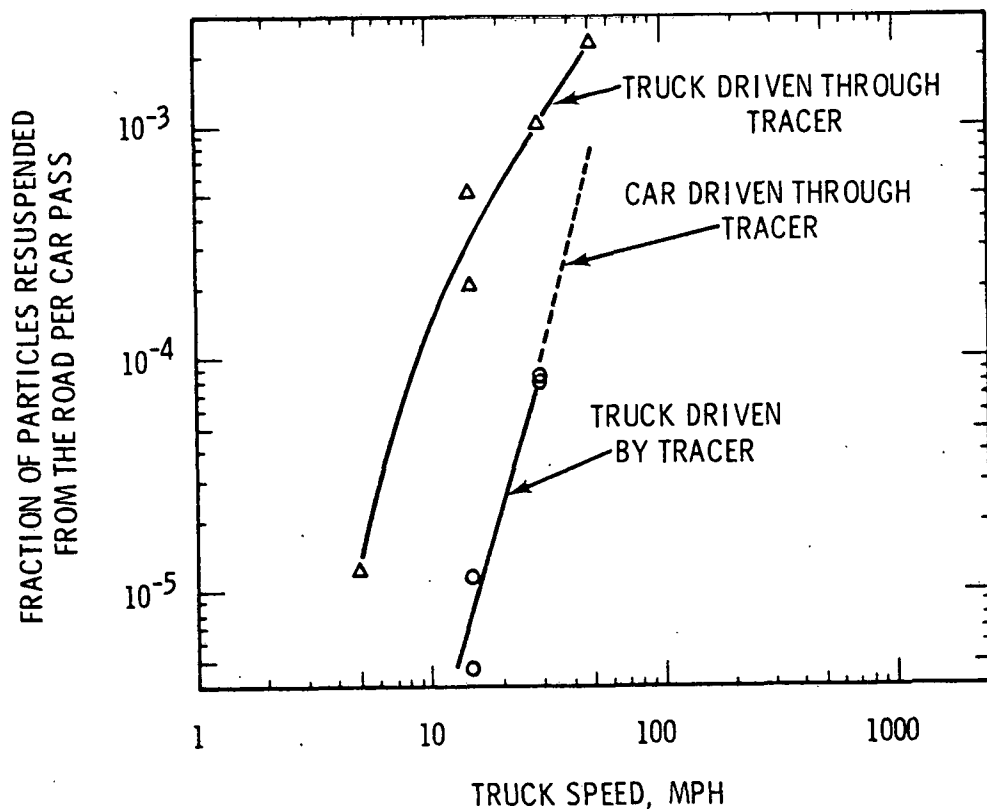


FIGURE 25. Rates of Tracer Particle Resuspension Caused by Vehicle Passage Over an Asphalt Road Four Days After Particle Deposition (Neg. 715289-1)

Resuspension caused by truck passage through a cheat grass area was also measured.^(19,21) Results are shown in Figure 26 along with resuspension rates from the asphalt road. Truck-caused resuspension from the cheat grass area was always less than from the asphalt road. This decrease is attributed to the protective action of cheat grass in hindering truck-generated turbulence in reaching the ground and resuspending tracer.

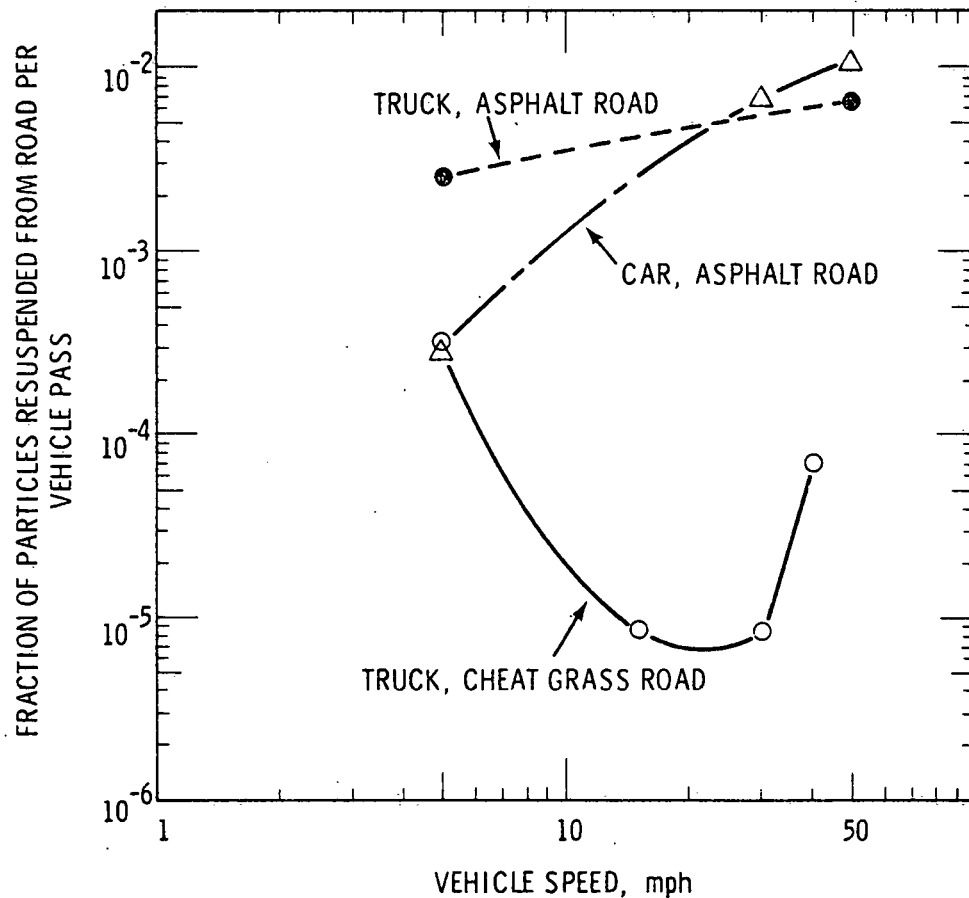


FIGURE 26. Rate of Tracer Particle Resuspension Caused by Vehicle Passage Over Asphalt and Cheat Grass Roads (Neg. 760188-4)

Resuspension from the cheat grass area decreased for truck speeds from 5 to 30 mph. This decrease is attributed to the sequence of experimental truck speeds. The initial truck speed was 5 mph. Apparently, the relatively larger resuspension rate at 5 mph was caused by the most readily resuspended

particles being removed from the cheat grass. In succeeding experiments at increasing truck speeds up to 15 mph, and possibly 30 mph, all readily resuspended tracer was removed from the cheat grass foliage. When truck speed was subsequently increased from 30 to 40 mph, resuspension per pass also increased. Apparently, increased air turbulence at the base of the cheat grass increased resuspension rates.

Pedestrian Resuspension

Resuspension caused by a man walking along the ZnS tracer lane of the asphalt road was also measured.^(19,48) The man walked across the tracer area in a leisurely fashion; the stride and pacer per second were not measured. For tracer on a 3-m-wide road lane, the reported resuspension rate was the fraction of particles resuspended each time the person walked down the length of the tracer lane. With wind speeds of 3 to 4 m/s, pedestrian caused resuspension rates were from 1×10^{-5} to 7×10^{-4} fraction resuspended/pass along the tracer lane. This pedestrian-generated resuspension was greater than wind resuspension during the experiment.

Wind-Caused Resuspension

Experimental values of wind-caused resuspension rates of tracer particles from environmental surfaces have not been experimentally determined from mass balance techniques other than for the present data.^(17-20, 40-42) Some data were initially obtained using 8- μ m mass median diameter (MMD) ZnS particles and average wind speeds from 1 to 5 m/sec. More extensive data as a function of wind speed were obtained using submicrometer CaMoO_4 particles. Average resuspension rates for ZnS particles were measured for resuspension from an asphalt surface⁽⁴⁰⁾ and a cheat grass surface.⁽²¹⁾ For average wind speeds of 1 to 4 m/sec, wind resuspension rates from an asphalt surface ranged from 5×10^{-9} to 6×10^{-8} fraction resuspended/sec. For average wind speeds of 1 to 5 m/sec, wind resuspension rates from a cheat grass surface ranged from 5×10^{-9} to 6×10^{-8} fraction resuspended/sec.

Wind-caused resuspension was measured for submicrometer CaMoO_4 particles deposited in a lightly vegetated area on the Hanford reservation. Tracer particles were deposited in a circular area of 23-m radius around a centrally located air sampling tower. Resuspended particles were measured at the tower as a function of wind speed increments for respirable particle

diameters and for nonrespirable particles at all wind speeds. Respirable particles were collected within particle cascade impactors (Figure 3) while nonrespirable particles were collected by impaction and gravity settling within cowls.

Wind-caused resuspension rates are shown in Figure 27 as a function of wind speed. Resuspension rates ranged from about 10^{-11} to 10^{-7} fraction resuspended/sec. Different functional dependencies of resuspension rates on wind speed can be obtained from these data, depending upon which set of wind speed increments are used. During the January to February period, air sampling was for large wind speed increments, while in subsequent experiments wind speed increments were smaller. The straight lines shown in Figure 27 were drawn through all data points. In these cases, resuspension rates increased with the 1.0 to 4.8 power of wind speed. However, when only data points for smaller wind speed increments are used, wind-caused resuspension rates increased with wind speed to the 4.8 power for 7, 3.3, 2.0, and 1.1- μm diameter particles as well as for the smaller particles collected on the cascade impactor back-up filter.

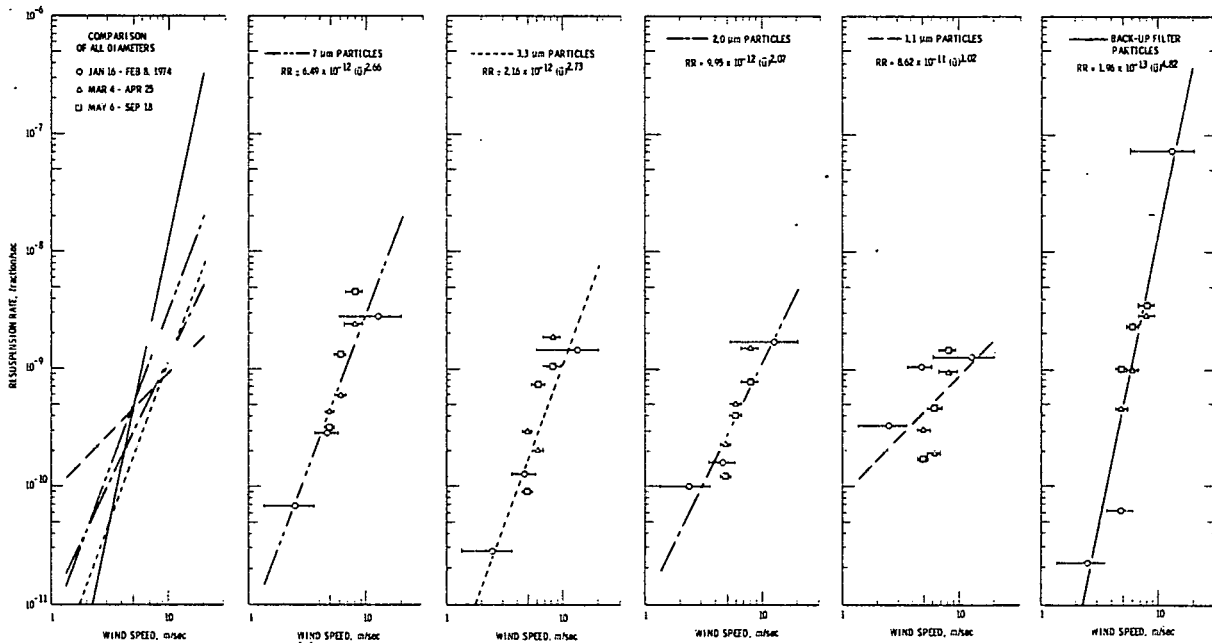


FIGURE 27. Tracer Resuspension Rates as a Function of Particle Diameter and Wind Speed Increments (Neg. 762426-9)

For comparable wind speed increments, tracer resuspension rates were nearly independent of time tracer was on the ground surface. However, it is often assumed in theoretical modeling that particles become less available for resuspension with time. The assumption in these models is that pollutant particles become fixed or attached to soil particles and subsequently "migrate" into the ground surface. This process is called weathering.

The independence of wind-caused resuspension rates with time is a significantly different observation than some others have made. Radioactive resuspension literature indicates that airborne radioactivity concentrations decrease with a weathering half-life of 35 days.^(9,10) In contrast, if there is a weathering half-life for the controlled tracer experiments described above, the weathering half-life must be on the order of years. Some differences in reported weathering might be explained by how air samples were collected. In work reported by others, air concentrations were measured continuously. In contrast, in our tracer experiments air concentrations and hence resuspension rates were measured as a function of wind speed. Even these differences in determining weathering half-lives illustrate how poorly weathering is understood.

Average wind-caused tracer resuspension rates are reported for both respirable and nonrespirable particles in Figure 28. In these cases, respirable refers to all particles collected within cascade impactors while nonrespirable refers to particles collected within cowls. Nonrespirable particle resuspension rates were nearly independent of time and were of the order of 10^{-11} fraction resuspended/sec.

Resuspension rates for respirable particles ranged from about 10^{-11} to 10^{-7} fraction resuspended/sec. These resuspension rates did not decrease with time. For the first two sampling periods, resuspension was measured for all wind speeds. In succeeding experiments, resuspension rates were measured only for wind speeds above 1 and above 4 m/sec. The upper or solid line portion of the respirable particle curve corresponds to resuspension rates calculated for the wind sampling periods. These periods correspond to wind speeds above 1 and above 4 m/sec. The lower limit of

the respirable particle curve corresponds to resuspension rates calculated by assuming resuspension time corresponds to the total time that cascade impactors were in the field (i.e., time included for winds less than 1 and less than 4 m/sec).

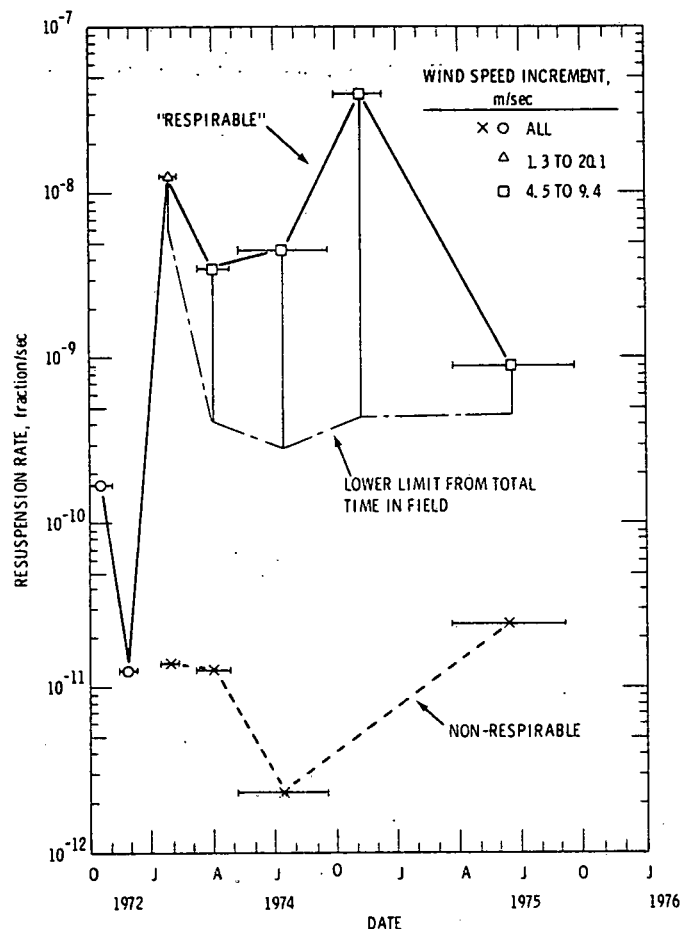


FIGURE 28. "Average" Wind Caused Tracer Resuspension Rates (Lightly Vegetated Desert on Hanford Reservation) (Neg. 762426-16)

INITIAL GENERALIZED WIND RESUSPENSION RATE CORRELATION

Guidelines for estimating resuspension rates are needed based upon existing experimental resuspension rate data. An initial correlation^(19,20) was developed from data reported for uranine particles resuspended from a smooth surface, ZnS from an asphalt surface⁽⁴⁰⁾, submicrometer molybdenum tracer from a vegetated desert soil⁽¹⁷⁾, and for DDT from a forest.^(41,42)

Each of these surfaces has a much different estimated aerodynamic surface roughness height, z_0 , ranging from 4×10^{-3} cm for the smooth surface to 1 m for a forest. Roughness height is calculated from the log-linear velocity profile and is the height at which the extrapolated velocity profile reaches zero velocity.

Ranges of measured average resuspension rates were correlated^(19,20) as a function of measured or estimated surface roughness heights in Figure 29. Resuspension rates range seven orders of magnitude from 10^{-10} to 10^{-3} fraction resuspended/sec. The practical significance of these numbers can be made apparent by noting that a year is 3.2×10^7 sec.

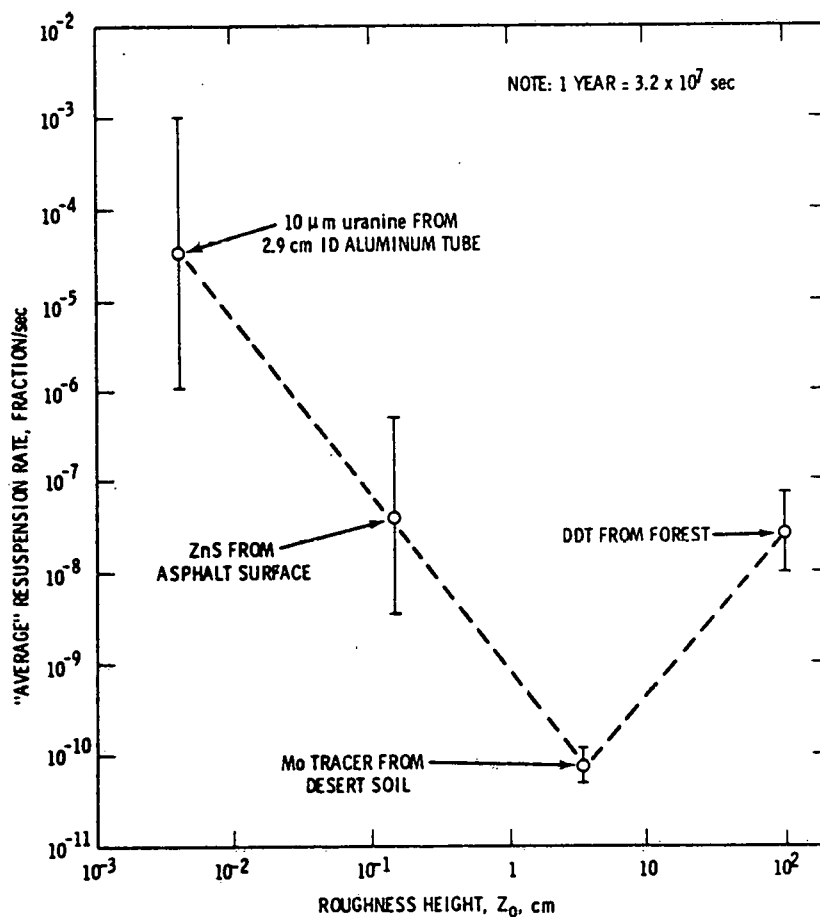


FIGURE 29. Initial Correlation of Wind Caused Tracer Resuspension Rates (Neg. 747270-8)

This initial resuspension rate correlation shows resuspension rates decrease as surface roughness increases, at least for the three smaller roughness heights. However, measured resuspension rates for DDT sprayed on a forest are two orders of magnitude greater than rates for the desert soil. This is an unexpected and unexplained increase in resuspension rates. A possible explanation of the increase might be increased resuspension caused by tree movement in the wind. Also, various other gross differences in controlling variables and experimental factors may have influenced results. Since the data are so extremely limited, this apparent correlation should be used with extreme caution until correlations are developed based upon several physical parameters instead of only z_0 . Nevertheless, this correlation does give some justification for estimating resuspension rates until better correlations are developed.

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