SOME EXPERIMENTAL MEASUREMENTS
OF AIRBORNE URANIUM
(REPRESENTING PLUTONIUM)
IN TRANSPORTATION ACCIDENTS

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AUGUST, 1973

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SOME EXPERIMENTAL MEASUREMENTS OF AIRBORNE URANIUM (REPRESENTING PLUTONIUM) IN TRANSPORTATION ACCIDENTS

ABSTRACT

Experiments were performed to measure the fractional release of uranium compounds when these materials are involved in gasoline fires. Uranium was used as a reasonable stand-in for plutonium. In the experiments reported uranium dioxide particles or uranium nitrate in solution was deposited on various materials ranging from a smooth metal surface to soil. Gasoline was added to these materials, then ignited. Airborne particles were collected at points downstream in the duct in which the combustion tray was located. Various air flow and burning conditions were used. In the burning experiments in which a uranyl nitrate solution was deposited on a stainless steel plate, 11% was made airborne with an air flow of 23 mph. This release was the largest for the burning experiments; however, as much as 24% of uranium dioxide powder was aerodynamically entrained from dry, sandy soil by air at a velocity of 20 mph. No single variable of the conditions imposed in 40 experiments could be identified as having an over-riding influence on the releases of uranium within the range of variables included in these experiments. A gasoline fire in which 500 gallons was dumped and burned, affirmed that the smaller scaled experiments were reasonably representative of actual fires.

INTRODUCTION

Because of the low maximum permissible concentration of plutonium in air, great care is exercised in every operation involving this material. Extreme precautions are taken to protect workers and people in the vicinity of plutonium facilities, yet experience has shown there can be low probability incidents which may give rise to airborne release of plutonium and its compounds. In order to assess the seriousness of inadvertent incidents in which control may be momentarily lost during some planned operation, those responsible for safety of the operation must have reasonable estimates of the amount and nature of the plutonium which could be made airborne under these circumstances. Only meager information has been available to assess the fractional release of plutonium in various accident situations. Battelle-Northwest has performed studies in the past to furnish data for estimating the potential airborne hazard

from plutonium in specific situations which are of concern in fuel reprocessing, plutonium recovery, and related operations. Situations with significant potential for the airborne release of plutonium have been identified.^[1,2] In these earlier experiments relatively small specimens of plutonium and its compounds were subjected to heat stress and airflow regimes and the fraction of plutonium airborne measured. The results were regarded as indicative rather than definitive because of the many variables which could operate to change the release fraction. These experiments did reveal the potential for airborne release under several circumstances. The desirability of carrying out similar experiments on a more realistic scale was early acknowledged; however, the difficulties, expense and risks posed in using plutonium in large-scale experiments required that a simulant be used. A study of several possible materials for a suitable stand-in for plutonium showed that uranium could be used for this role.^[5] In the work to be described, uranium was used in experiments on a scale such that reasonable simulation of gasoline fires engulfing uranium oxides and nitrate spilled on various surfaces could be achieved. A tacit assumption was made that plutonium compounds would behave similarly.

Hypothetical, serious situations occurring during the transport of plutonium within the Hanford site boundaries were used as reference cases for the experimental program. Following is a brief description of the most serious potential transporting accident considered and some observations on the availability of data to permit consequences to be assessed.

A vehicle carrying up to 28 kg of plutonium as a nitrate solution, or 80 kg of plutonium as a dry dioxide powder collides with a gasoline truck. The contents of both vehicles spill onto the ground and intermix. The gasoline ignites and burns.

In the situation described various factors may influence the fraction of plutonium that might be made airborne.

- The physical characteristics of the surface involved -- porous or impervious, plastic or rigid, rough or smooth -- and interaction between the surface and the materials spilled.
- Windspeed and direction.
- Physical and chemical nature of the plutonium compound.
- Sequence of events during accident -- local conditions and mechanisms

operative at time and site of release.

- Presence of other materials -- i.e., if vegetation is present, the active material could be distributed in the vegetation already in the air stream.
- Rate of burning may produce thermal plumes and cause near-ground turbulence.

Some data were available which could be used to evaluate the airborne release of plutonium in such an accident. Data available were the following:

Nitrate Solutions

Some data existed on fractional airborne release from nitrate solutions during slow drying from a hard impervious surface^[3]; from the solid residues after evaporation at high temperatures^[3]; from the dried residues on sand^[4]; and during the burning of flammables impregnated with a nitrate solution.^[4] The fraction airborne during the evaporation (less than 130°C) of nitrate solution from a hard impervious surface (stainless steel) in air with a velocity of up to 100 cm/sec was low -- maximum value detected under experimental conditions imposed was 0.003 wt. percent. Even less of the dried residue was made airborne under these conditions -- maximum quantity measured was 3×10^{-6} wt. percent. The quantity of plutonium airborne during the heating of a nitrate solution to near dryness indicated dependency on heat input with a maximum value under experimental conditions imposed of 0.18 wt. percent. An additional quantity, as much as 1.7 wt. percent was deposited as "fallout" close to the vessel, presumably from droplets too large to be carried away. As much as 0.018 wt. percent of partially air dried plutonium nitrate held in sand was made airborne when heated to high temperatures (probably in excess of 900°C) in an upsweep of air at a nominal velocity of 100 cm/sec. When incorporated with flammable materials producing a fine ash, as much as 8 wt. percent of a uranium nitrate solution could be made airborne in air at a velocity of 100 cm/sec.

Dry Dioxide Powder

Experimental data were available on the fraction airborne during the heating of dry dioxide powder on an impervious surface and during the burning of flammables in which dry dioxide had been incorporated. Limited data on entrainment from various surfaces by air in the absence of heat were available. Only

a moderate amount (maximum value of 0.025 wt. percent) of a dry dioxide powder ranging from 15 to 150 microns aerodynamic equivalent (AED) was made airborne from a hard, impervious surface (stainless steel) during heating. A considerably greater quantity was airborne (up to 50 wt. percent) during the burning of flammable materials incorporating dry uranium dioxide powder in air with a velocity of 100 cm/sec. A considerable amount of active material can be entrained by impinging high velocity air from the proper angle upon the surface.^[3]

Transporting radioactive materials intuitively appears to be an operation possessing a great potential for release. The carrier in motion possesses great energy and is capable of inflicting great damage upon impact, and shipping containers, though having high integrity, can be caused to fail under extreme stresses.

With the advent of wide-scale nuclear power reactors and the attendant need for transportation, reprocessing, and other handling of very large quantities of plutonium, it is important that the consequences of failure in these operations be known.

OBJECTIVE

The objective of this study was to provide data on fractional airborne release and aerosol properties to permit more realistic evaluation of the potential airborne hazard from plutonium in accidents during the transport of plutonium.

SUMMARY

The amount of aerodynamic equivalent size distribution of particles that may become airborne under conditions found in some shipping accidents were studied in a special wind tunnel at the 242-B facility. Airborne release from uranium dioxide powder or nitrate liquid, representing plutonium, dispersed on four types of surfaces were evaluated in forty combinations of conditions believed to be representative of circumstances which could prevail in a transportation accident. A wind speed of 2.5 mph and a higher wind speed of 20-23 mph were used, both with and without gasoline fire (see Appendix A). Procedures and equipment used are described. A large scale gasoline fire test in which 500 gallons of gasoline was rapidly released to the soil and ignited

affirmed that the conditions observed in the engineering scale experiments were a reasonable simulation of the postulated transportation-type accidents. The results of the fractional release indicate:

- No single parameter of those evaluated -- physical form of the active material, type of surface, wind speed nor the presence of a gasoline fire -- exerts a controlling influence on the fractional airborne release under all circumstances.
- For the combination of variables used in these experiments, the greatest fractional release occurred from aerodynamic entrainment of uranium dioxide powder deposited on sandy soil from which 24 percent was airborne in air at 20 mph. For gasoline fires the largest fraction airborne, 11 percent, was from uranyl nitrate solution on a smooth metal plate, when air was passed through the duct at 23 mph.

EXPERIMENTAL

ENGINEERING SCALE EXPERIMENTS

Accidents are unique occurrences, and the actual sequence of events can have many variations. Performing a parametric study of all factors would encompass a very large number of experiments. In order to embrace the broadest coverage of situations within a tenable number of experiments, we performed experiments representing forty combinations of parameters (uranium form, wind speed, surfaces and the presence or absence of a gasoline fire) that could attend a serious shipping accident with container breaching. The combinations of parameters involved two physically different forms of the active material deposited on four commonly available surfaces. The amount and size distribution of the particles airborne at two wind speeds with and without a petroleum fire were measured. The individual experiments are tabulated in Table I.

Description of Experimental Apparatus and Procedures

All experiments were performed in the furnace section of the inlet duct to the Radioactive Aerosol Release Tank (R.A.R.T.) in the 242-B Building facility^[5] (see Figure 1). Uranium was used as a simulant for plutonium in these engineering scale experiments.^[5]

The furnace section is located on a concrete pad on the west side of the

TABLE I

EXPERIMENTAL PROGRAM -- AIRBORNE RELEASE UNDER SELECTED CONDITIONS POSTULATED
FOR SHIPPING ACCIDENTS

SA-1	Aerodynamic re-entrainment of uranium dioxide powder from bare ground at a wind speed of 23 mph.	SA-18b	Fractional release of uranium immediately <u>following</u> a petroleum fire into air passing over the surface at a speed of 23 mph from uranium nitrate solution deposited on a stainless steel surface.
SA-2	Aerodynamic re-entrainment of uranium dioxide powder from bare ground at a wind speed of 4 mph.	SA-19a	Fractional release of uranium <u>during</u> a petroleum fire into air passing over the surface at a speed of less than 4 mph from a uranium nitrate solution deposited on a stainless steel surface.
SA-3	Fractional release of uranium dioxide powder from bare ground during and immediately following a petroleum fire into air passing over the surface at a speed of less than 4 mph.	SA-19b	Fractional release of uranium immediately <u>following</u> a petroleum fire into air passing over the surface at a speed of less than 4 mph from a uranium nitrate solution deposited on a stainless steel surface.
SA-4a	Fractional release of uranium from a uranium nitrate solution poured on the bare ground into air with a velocity of less than 4 mph.	SA-20a	Fractional release of uranium <u>during</u> a petroleum fire into air passing over the surface at a speed of less than 4 mph from a uranium nitrate solution deposited on a road-like** surface.
SA-4b	Fractional release of uranium from solid residue from air-dried uranium nitrate solution poured on the bare ground into air with a velocity of less than 4 mph.	SA-20b	Fractional release of uranium immediately <u>following</u> a petroleum fire into air passing over the surface with a speed of less than 4 mph from a uranium nitrate solution deposited on road-like** surfaces.
SA-5	Fractional release of uranium from solid residue from air-dried uranium nitrate solution poured on the bare ground during and immediately following a petroleum fire into air with a nominal speed of less than 4 mph.	SA-21a	Fractional release of uranium dioxide powder deposited on a road-like** surface during a petroleum fire into air passing over the surface at a speed of less than 4 mph.
SA-6a	Fractional release of uranium from a uranium nitrate solution poured on the bare ground into air with a speed of 23 mph.	SA-21b	Fractional release of uranium dioxide powder deposited on a road-like** surface immediately following a petroleum fire into air passing over the surface at a speed of less than 4 mph.
SA-6b	Fractional release of uranium from solid residue of air-dried uranium nitrate solution poured on the bare ground into air with a speed of 23 mph.	SA-22a	Aerodynamic re-entrainment of uranium dioxide powder sprinkled over smooth, sandy soil by air passing across the surface at a nominal speed of 2.5 mph.
SA-7	Fractional release of uranium from solid residue of air-dried uranium nitrate solution poured on the bare ground during and immediately following a petroleum fire into air with a nominal speed of 23 mph.	SA-22b	Fractional airborne release from uranium dioxide powder on smooth, sandy soil involved in a gasoline fire by air at a nominal speed of 2.5 mph.
SA-8a	Rerun of experiment SA-4a.	SA-22c	Aerodynamic re-entrainment of uranium from the solid residues of uranium dioxide powder on smooth, sandy soil involved in a gasoline fire by air passing across the surface at a nominal velocity of 2.5 mph.
SA-8b	Rerun of experiment SA-4b.	SA-23a	Aerodynamic re-entrainment of uranium dioxide powder sprinkled over smooth, sandy soil by air passing across the surface at a nominal velocity of 20 mph.
SA-9	Rerun of experiment SA-5.	SA-23b	Fractional airborne release from uranium dioxide powder sprinkled over smooth, sandy soil by air passing across the surface at a nominal velocity of 20 mph.
SA-10	Fractional release of uranium during and immediately following a petroleum fire into air passing over the surface at a nominal speed of less than 4 mph from a uranium nitrate solution poured on bare ground.	SA-23c	Aerodynamic re-entrainment of uranium from the solid residues of uranium dioxide powder on smooth, sandy soil involved in a gasoline fire by air at a nominal velocity of 20 mph.
SA-11	Aerodynamic re-entrainment of uranium dioxide powder sprinkled over vegetation*-covered ground by air at a speed of less than 4 mph.	SA-25a	Aerodynamic re-entrainment of uranium dioxide powder sprinkled on stainless steel by air passing across the surface at a nominal velocity of 20 mph.
SA-12	Fractional release of uranium powder sprinkled on vegetation*-covered soil during and immediately following a petroleum fire into air with a speed of less than 4 mph.	SA-25b	Fractional airborne release from uranium dioxide powder sprinkled on stainless steel involved in a gasoline fire by air passing across the surface at a nominal velocity of 20 mph.
SA-13	Aerodynamic re-entrainment of uranium dioxide powder sprinkled over vegetation*-covered ground by air at a speed of 23 mph.	SA-25c	Aerodynamic re-entrainment of uranium from the solid residues from uranium dioxide powder on a stainless steel surface involved in a gasoline fire by air passing across the surface at a nominal speed of 20 mph.
SA-14	Fractional release of uranium dioxide powder sprinkled on vegetation*-covered soil during and immediately following a petroleum fire into air with a speed of 23 mph.	SA-26a	Fractional airborne release of uranium from a uranium nitrate solution poured on sandy soil involved in a gasoline fire by air passing across the surface at a nominal velocity of 20 mph.
SA-15	Fractional release of uranium during and immediately following a petroleum fire from a uranium nitrate solution sprinkled on vegetation*-covered ground into air with a speed of 23 mph.	SA-26b	Aerodynamic re-entrainment of uranium from the solid residues after a gasoline fire involving uranium nitrate on sandy soil by air passing across the surface at a nominal velocity of 20 mph.
SA-16	Fractional release of uranium during and immediately following a petroleum fire from a uranium nitrate solution sprinkled on vegetation*-covered ground into air with a speed of less than 4 mph.		
SA-17a	Fractional release of uranium dioxide powder from a stainless steel surface into air with a speed of less than 4 mph <u>during</u> a petroleum fire.		
SA-17b	Fractional release of uranium dioxide powder from a stainless steel surface into air with a speed of less than 4 mph immediately <u>following</u> a petroleum fire.		
SA-18a	Fractional release of uranium <u>during</u> a petroleum fire into air passing over the surface at a speed of 23 mph from uranium nitrate solution deposited on a stainless steel surface.		

* Surface completely covered by green tumble weed plants 3 to 10 inches long pressed into the ground.

** Heated and pressed asphalt/gravel mixture used as a roadway at the Hanford site.

FIGURE 1. RADIOACTIVE AEROSOL RELEASE FACILITY, 242-B BUILDING

242-B Building and is a part of the inlet duct to the R.A.R.T. (see Figure 2). Fresh air is drawn through a bank of four 24-inch by 24-inch by 12-inch deep HEPA filters by a centrifugal blower at the downstream end, with a rated flow of 4000 cfm at 6-inch W.G. static pressure. A flash arrestor separates the filters from the 3-foot long furnace section which is lined with a refractory material. Three half-couplings ($3/4$, 2 and $1/4$ inch) welded over holes drilled in the north wall of the furnace section provided access to the interior. A 24-inch diameter by 6-inch flanged duct enters the furnace section from the bottom and supports a 23-inch diameter by 6-inch deep burner tray (see Figure 3). Air passing through the inlet duct can be sampled via 4 sets of 4-inch blind flanges located on the top and south side of each duct section. A 2-inch half-coupling welded to the bottom of the last duct section can also be used. Air flow in the wind tunnel was controlled by adjusting the damper upstream of the exhaust filters. Nominal velocities at various damper settings determined before and during the experimental program are shown in Appendix A.

All four types of surfaces used in these experiments were held in the 23-inch diameter by 6-inch deep flanged burner tray shown in Figure 3. For experiments involving a smooth surface of sandy soil bare of vegetation, the flanged burner tray was filled with soil collected from the immediate locale. The surface was scraped level with the rim of the tray using a straight edge. For vegetation-covered soil, small tumbleweeds growing near the building were uprooted and pressed into the soil until the entire surface was covered with vegetation. The stainless steel surface was a 15-inch diameter by 2-inch deep pan embedded in the upstream side of the flanged burner tray. The rim of the pan was made flush with the rim of the tray by a bed of sandy soil and the space around the pan was filled with additional soil. The asphalt was held in a 15-inch diameter by 4-inch deep steel pan with a 4-inch wide lip which rested on the rim of the flanged burner tray. Heated asphalt was tamped into the pan to provide a 2-inch deep bed.

A measured amount of depleted uranium dioxide powder or uranyl nitrate solution was dispersed over the surface. The uranium dioxide powder is a ball-milled material whose size distribution using various modes of dispersion is shown in Figure 4. The powder was sprinkled onto the various surfaces by hand and the uniformity of dispersion estimated visually. The amount of uranium dioxide dispersed was determined by weight difference of the dispenser before

FIGURE 2. INLET DUCT TO RADIOACTIVE AEROSOL RELEASE TANK - WIND TUNNEL
(PNL NEG. 710964-6)

APPROX SCALE: 1/4" = 1"

FIGURE 3. FLANGED BURNER TRAY, ELEVATION

FIGURE 4. URANIUM DIOXIDE POWDER SIZE DISTRIBUTION BY WHITBY CENTRIFUGE

and after distributing the powder.

A concentrated (0.51 g uranium per milliliter) uranyl nitrate solution in nitric acid was dispensed by a graduated cylinder. Three dilute nitric acid rinses of the cylinder were added to the liquid poured onto the various surfaces. The tray with contents was inserted into the furnace section and bolted in place. Air sampling equipment was inserted and placed into operation.

Particles in the air stream were sampled and collected by two filters and an 8-stage Andersen cascade impactor (see Figure 1). Sample filter holders were inserted into the air stream through the two 4-inch openings in the last duct section upstream of the R.A.R.T. and the impactor sample via a 1/2-inch stainless steel tube inserted through the 2-inch half-coupling in the bottom of the duct. One of the filter samplers was fixed in the approximate center of the duct while the other was moved down through the duct during sampling. In later runs where separate samples were taken during and immediately following a petroleum fire, the movable filter was held at the top of the duct during the fire (the duration of the fire in many experiments was too short for any manipulation) and moved through the duct after the fire. Flow through all samplers was measured and appropriate corrections were applied to the volumes of samples collected as required. Nominal sampling rate was 1 cfm on all three samplers in all runs.

In experiments involving a gasoline fire, a gallon of gasoline was poured onto the surface via a 1/2-inch stainless steel tube with a 90° bend entering the top of the furnace section. A spray nozzle was placed over the end of the tube to lessen the force of the liquid striking the surface and provide greater dispersal of the gasoline. A gasoline-soaked rag was inserted into the furnace section via the 2-inch half-coupling and ignited with a match. If the gasoline was uniformly distributed throughout the soil, the gasoline concentration would be 0.70 gallons per cu. ft. of soil. At this level the soil was saturated with shallow standing pools on the surface and exhibited burning characteristics similar to those found in large scale fires (see later section, "Large Scale Outdoor Gasoline Fires"). A gallon of gasoline produced a pool approximately 1.3 inches deep over the stainless steel and asphalt (road-like) surfaces.

As soon as combustion was established, air flow was initiated. In most cases, the gasoline ignited violently and, in a few cases, extinguished the

flames. For soil surfaces, bare or with a cover of vegetation, burning was vigorous for 5 to 10 minutes. The vigorous burning was followed by a period of stable, low flames covering the entire burner surface. Various areas then stopped burning and flames became widely separated. Eventually, all flames were extinguished. All the gasoline in the soil was not consumed; a strong odor of gasoline was detected even after the burner tray had cooled and was removed (approximately 16 hours). The soil surface was dry in most cases, but the soil greater than an inch under the surface was moist. The burning of gasoline on the stainless steel and asphalt surface exhibited the characteristics of a standing pool fire. Ignition was vigorous and the subsequent rate somewhat dependent on air velocity over the surface. The fire on asphalt (road-like) surfaces appeared to burn somewhat longer (see Table II, "Shipping Accident Experiments -- Operating Conditions") and with more smoke indicating some involvement of the asphalt. Air temperatures were monitored via thermocouples inserted through the duct wall and soil, the soil temperature 1/2- and 1-inch under the surface was monitored by dial thermometers inserted through the bottom of the burner tray and the duct wall temperature monitored by surface thermometers attached to the side of the middle of the three downstream sections.

Samples were collected immediately upon completion of a run and the remainder of the equipment allowed to stand overnight before clean-up. The filter holders and cascade impactor were removed and taken to the analytical hood for processing. Sample dissolution was initiated if time allowed. The flanged burner tray was removed and covered with a large plastic bag until the soil could be packaged for disposal. In the experiments involving a stainless steel surface (SA-17, SA-18, and SA-19), attempts were made to recover uranium residues in the 15-inch diameter tray.

The pertinent operational parameters for the 40 shipping accident experiments are tabulated in Table II, and are detailed in Appendix B, "Experimental Observations During Individual Shipping Accident Experiments."

Sample Preparation and Analysis

Particles of uranium compounds collected on the glass fiber filters and glass impactor collection plates were dissolved by mixed acid leach. The filters or plates were placed in pre-marked beakers and covered with a 9N HNO₃-0.1 N HF solution. The solution was warmed for approximately an hour. Impactor plates were then removed but the 2-inch diameter glass fiber filters

TABLE II

SHIPPING ACCIDENT EXPERIMENTS -- OPERATING CONDITIONS

Sample Designation	Uranium Form Used	Grams Used	Wind Speed (mph)	Temp. (°C)	Burning Time (min.)	Total Sampling Time (hr.)
<u>Sandy Soil, No Vegetation</u>						
SA-1	UO ₂ Powder	51.5	23	--	--	5
SA-2	UO ₂ Powder	74.9	<4	--	--	6
SA-3	UO ₂ Powder			750	40	6
SA-4a	UNH Solution	36.2	<4	--	--	6
SA-4b	Air Dried UNH			--	--	23.75
SA-5	Air Dried UNH			1000	Unknown	5.5
SA-6a	UNH Solution	51.0	23	--	--	27.75
SA-6b	Air Dried UNH			--	--	23.5
SA-7	Air Dried UNH			750	Unknown	6
SA-8a	UNH Solution	51.5	<4	--	--	23.75
SA-8b	Air Dried UNH			650	58	24
SA-9	Air Dried UNH			--	--	5
SA-10	UNH Solution	47.8	<4	250	25	5.5
SA-22a	UO ₂ Powder	50.0	2.5	--	--	24
SA-22b	UO ₂ Powder			*	60	1
SA-22c	UO ₂ Powder			--	--	24
SA-23a	UO ₂ Powder	50.0	20	--	--	24
SA-23b	UO ₂ Powder	37.8		*	18	0.3
SA-23c	UO ₂ Powder			--	--	24
SA-26a	UNH Solution	51.0	20	*	8	0.13
SA-26b	UNH Residue					
<u>Sandy Soil, Vegetation Cover</u>						
SA-11	UO ₂ Powder	78.3	<4	--		23.5
SA-12	UO ₂ Powder			550	50	6
SA-13	UO ₂ Powder	69.5	23	--	--	24
SA-14	UO ₂ Powder			600	7	6
SA-15	UNH Solution	51.1	23	300	40	6
SA-16	UNH Solution	51.1	<4	550	125	6
<u>Stainless Steel</u>						
SA-17a	UO ₂ Powder	19.5	<4	1000	9	0.15
SA-17b	UO ₂ Powder			--	--	4.77
SA-18a	UNH Solution	25.5	23	*	9	0.17
SA-18b	UNH Residue			--	--	5
SA-19a	UNH Solution	25.5	<4	*	13	0.22
SA-19b	UNH Residue			--	--	6
SA-25a	UO ₂ Powder	50.0	20	--	--	24
SA-25b	UO ₂ Powder	47		*	8	0.13
SA-25c	UO ₂ Powder	46		--	--	24
<u>Road-Like Surface</u>						
SA-20a	UNH Solution	25.5	<4	*	26	0.28
SA-20b	UNH Residue			--	--	5
SA-21a	UO ₂ Powder	58.1	<4	*	22	0.37
SA-21b	UO ₂ Powder			--	--	6

* Not Measured

UNH - Uranyl Nitrate Hexahydrate

were in almost all cases dissolved. The heat was increased and the solutions concentrated to near dryness. After cooling, the solution was filtered and the volume made up to a known quantity. The solutions were placed in 15 ml, screw cap vials and submitted to the Technical Analysis Section for measurement.

The quantity of uranium in the liquid was measured by fluorimetry. A 100 microliter aliquot of solution or a dilution was dried in a platinum dish and fluxed with NaF. The uranium fluorescence under ultraviolet light was measured. Replicate aliquots were run on each sample as well as "spikes" to measure the amount of fluorescence quenched by extraneous materials in the liquid. Appropriate corrections for quench were applied as required. The minimum detectable concentration under these conditions is 10^{-9} gram uranium per milliliter. Due to the quenching problem encountered with these samples, the precision at a 95 percent confidence level is ± 35 percent.

LARGE SCALE OUTDOOR GASOLINE FIRE

To investigate the realism of the conditions obtained during the engineering scale experiments, we conducted a large-scale gasoline fire test. Very little recorded data has been published on the temperatures, surface area encompassed and duration of such fires. Information is available on the general characteristics of petroleum fires,^[6,7,8] extinguishment^[9], and the consequences of fires.^[10,13] Combustible liquids burn by the formation of a combustible vaporous mixture near the surface.^[14] The rate of burning is largely determined by the rates of mass and heat transfer between phases.^[15] Plant fire protection personnel estimated the area encompassed under various conditions as:

- On an impervious surface, in the range of 3 to 5 sq. ft. per gallon of gasoline if the gasoline is immediately ignited. Maximum temperatures are in the range of 1700 to 2500°F.
- On porous surfaces, the gasoline will not spread as widely and encompass an area in the range of 2 to 4 sq. ft. per gallon, depending on the porosity of the soil. Temperatures will be lower in the range of 400 to 700°F.

Large gasoline carriers can hold up to 12,000 gallons of gasoline and would burn in an estimated 2 to 3 hours if unrestrained. Blacktop will burn if sat-

urated with gasoline.^[16]

A vehicular accident involving a large quantity of gasoline occurred locally on September 8, 1970.^[17] A gasoline truck and trailer carrying some 8000 gallons was struck by another vehicle. The trailer containing approximately 2000 gallons of gasoline was hurled over the truck. Although the side of the trailer was ruptured, the vehicle came to rest on the undamaged side and retained most of its contents. The truck slid on its side, rupturing that side. The contents of the truck spilled onto the road and were ignited by sparks. The fire burned some 2 to 2-1/2 hours intermittently over a 5 hour period -- fire control measures would extinguish the flames which would be reignited by "hot spots". The fire covered an estimated 10,000 sq. ft. of surface.

To ascertain if the conditions observed during the engineering scale experiments provide a reasonable simulation of a large scale outdoor fire, 500 gallons of gasoline were quickly released, dispersed and ignited on an instrumented test site. The quantity of gasoline chosen is one-third the maximum volume (1500 gallons) trucked within the Hanford site boundaries. The area involved was determined by actual measurement of the area after combustion. Both air and surface temperatures were measured. Wind speed and direction were monitored. An attempt was made to evaluate the fractional airborne release from uranium dioxide powder and nitrate solutions by determining the amount lost from exposed prepared surfaces held in canisters buried in the ground.

Description of Site and Apparatus

The study was conducted in a natural depression some 15 to 20 feet deep located on arc 12 of the "unstable grid" system east of the 200-W Exclusion area (see Figure 5). The site is some 1/2 to 1 mile northeast of the 622-R Building. The depression extends some 200 feet in a southwest to northeast direction. A 30 ft. by 30 ft. test plot was located in the southwestern end of the depression with the test equipment for the quick release and dispersal of gasoline (described below) located in the center of the southwest edge of the test section. A 30 ft. wide fire break was bladed around the test site and filled with foam prior to the test. The Fire Protection unit provided coverage during the initial portions of the test. Relationship of the 500-gallon tank, spillway and location of temperature sensors and canisters is shown in Figure 6.

FIGURE 5. LARGE SCALE OUTDOOR GASOLINE FIRE SITE (PNL NEG. 713037-1)

FIGURE 6. LARGE SCALE GASOLINE FIRE-ARRANGEMENT OF CANISTERS, TEMPERATURE SENSORS AND IGNITERS

Air and surface temperatures were measured by a cluster of thermocouples and thermistors held by a support rod in 6 locations on the test site (see Figures 6 and 7). Each cluster contained 3 stainless steel clad, iron-constantan thermocouples and 2 thermistors fixed to a 1/2-inch diameter iron support rod. The support rod was buried in the ground so that the thermocouples extended 6, 4, and 2 inches above the surface and the thermistors were positioned 1/2 and 1 inch under the surface. The arrangement is pictured in Figure 8, "Temperature Sensor Cluster". A third thermistor was located at the thermocouple-lead wire junction approximately 12 inches beneath the surface for temperature compensation. The lead wire was buried some 12 inches under the surface of the test site and connected to a magnetic tape data collection unit located on the rim of the depression some 100 feet southwest of the test site. Wind speed and direction by a cup anemometer and vane were monitored and recorded at this location.

Six pairs of 3-inch, open, soil-filled canisters -- one with uranium dioxide powder and nitrate solution on the surface -- were positioned on the test site at each temperature sensor cluster location (see Figures 6 and 7). The canister arrangement is diagrammed in Figure 9, "Large Scale, Outdoor Gasoline Fire -- Uranium Canister". Prior to the test, each canister was filled with soil from the test site within an inch of the top. The desired quantity of uranium dioxide powder or nitrate solution was dispersed over the surface, and a plastic bag taped over the opening. The canisters were inserted 11 inches into the ground so the level of the soil in the canister was level with the test site surface. The rim was allowed to project above the surface to provide some protection from the deluge that would sweep the surface on release of the gasoline. Immediately before the test, the soil in each canister was saturated with gasoline. The plastic bags were left loosely in place to afford a little additional protection to the surfaces in the canisters.

The equipment used for the fast release and dispersal of 500 gallons of gasoline during this study is diagrammed in Figures 10 and 11, and consisted of:

- A 4 ft. by 4 ft. by 5 ft. box of unpainted 1/4 inch thick steel with a hinged lid. The volume of the box was approximately 80 cu. ft. (600 gallons).

FIGURE 7. LARGE SCALE OUTDOOR GASOLINE FIRE, TEMPERATURE
SENSORS AND URANIUM CANISTERS (PNL NEG. 713037-5)

FIGURE 8. LARGE SCALE OUTDOOR GASOLINE FIRE, TEMPERATURE SENSOR CLUSTER

FIGURE 9. LARGE SCALE OUTDOOR GASOLINE FIRE, URANIUM CANISTER

FIGURE 10. LARGE SCALE OUTDOOR GASOLINE FIRE, GASOLINE CONTAINER

FIGURE 11. GASOLINE CONTAINER AND TEST SITE (PNL NEG. 713037-12)

- A frame of 4 in. by 8 in. "I" beam which supported the box some 4-1/2 feet above the ground. The base of the support was a 6 ft. by 12 ft. rectangle.
- A spillway channeling the gasoline to the edge of the test site. The spillway was 5 ft. wide and about 16" deep.

The box was held in the "I" beam support structure by a 1-3/4 inch diameter axle welded into each end. The axles were held in a bearing welded onto the "I" beam support. Spacers on the axles centered the container. An inherently unstable configuration was produced by welding the axles off-center (approximately 6 inches below and 3 inches behind center). The box was held in an upright position by a 1-3/4 inch rod welded to the back of the box and held at each end by "dogs" of 3/8 inch steel. Positive locks were also provided to prevent inadvertent release of the contents. Gasoline was pumped into the container via a 3-inch nipple welded into the hinged lid used to provide some containment of the vapor yet allowing a rapid release of the contents. The gasoline was released by removing the positive locks and disengaging the "dogs" from a distance by ropes attached to the 4 ft. arms on the "dogs". A mechanical stop -- a strip of 2-inch angle iron welded to the "I" beam support -- limited the rotation of the box and assured the release of all the gasoline. The hinged lid was prevented from entering the spillway by a 2-inch angle iron welded on its edge. The gasoline was remotely ignited by smoke bombs held off the ground and fired by a solenoid-activated pin (see Figure 12).

An attempt to disperse the gasoline over the test site by placing large rocks directly in its path were only partially successful. A considerable number of loose rocks and a fair amount of soil were displaced during the initial wave of gasoline. A 12 ft. length of 4-inch by 8-inch "I" beam was positioned at the opposite edge of the test site to limit the flow of gasoline.

FIGURE 12. LARGE SCALE OUTDOOR GASOLINE FIRE, IGNITER
WITHOUT SMOKE BOMB ATTACHED (PNL NEG. 713037-2)

RESULTS

ENGINEERING-SCALE EXPERIMENTS

The percentage of uranium airborne based on the quantity of uranium found in each sampler, the fraction of the total airstream sampled and the amount of uranium used as a source is tabulated in Table III, "Uranium Results -- Engineering Scale Experiments". In experiments conducted in the first phase of the study (experiments SA-1 to SA-21), airborne concentrations were calculated from the quantity of uranium collected on the "fixed" and "movable" filter as well as the summation of all uranium collected in stages and filter of the Andersen cascade impactor. The individual samples show considerable variation (in a few cases two orders of magnitude) and may indicate a serious channeling of airflow (see Appendix C). No sampling position exhibited a consistently higher value than any other. Since there is no overriding reason for the choice of one value over another, the percent uranium airborne for a given experiment is simply an arithmetic average of all three samples taken. Only the "fixed" filter values were used in the second phase (experiments SA-22 to SA-26).

The aerodynamic size fractions with which the airborne uranium was associated was determined by measuring the uranium collected on 3.25 inch diameter glass plates and final 2-inch diameter glass fiber filters in an 8-stage Andersen cascade impactor (see Appendix D). The fraction of the total uranium collected in the impactor was determined for each stage and final filter. The cumulative fraction in successive stages was plotted against the nominal stage cut off diameters on log-probability paper to produce the size distributions of the uranium airborne during each experiment. Figure 13 shows some examples of the distributions found, "The Activity Median Diameter"*(AMD) was picked off these curves as was the percent of uranium associated with particles less than 10 microns Aerodynamic Equivalent Diameter (AED). Particles enter and are deposited in the lungs with varying efficiencies dependent upon particle size. Above a certain size, particles are trapped in the nose and throat and are ingested. Below a certain size, particles behave as a gas and flow with the tidal volume. Considering all particles less than 10 microns AED as respirable would give a "conservative estimate" of the inhalation hazard.

* Activity Median Diameter -- 50 percent of the uranium airborne is associated with particles that have aerodynamic equivalent diameters less than the stated diameter.

TABLE III

URANIUM RESULTS -- ENGINEERING SCALE EXPERIMENTS

Uranium Form Used	Wind Speed	AERODYNAMIC ENTRAINMENT					PETROLEUM FIRE				
		Expt. No.	Wt. Percent Source Airborne (hours sampled)			Less Than ¹ 10 microns	Expt. No.	Wt. Percent Source Airborne (hours sampled)			Less Than ¹ 10 microns
<i>Smooth Sandy Soil</i>											
UO ₂	low ²	2	0.43	6	hrs.	56	3+	0.63	6	hrs.	5
		22a	0.042	24	hrs.	54	22b	0.048	1	hr.	72
		22c*	0.0092	24	hrs.	54					
	moderate ³	1	2.3	24	hrs.	75					
		23a	24.4	24	hrs.	40	23b	0.34	0.3	hrs.	62
		23c*	1.0	24	hrs.	68					
Air Dried ⁴ UNH	low ²	4b	0.0069	24	hrs.	74	5+	0.0074	5.5	hrs.	64
		8b	0.0054	24	hrs.	77	9+	0.004	5	hrs.	18
	moderate ³	6b	0.93	24	hrs.	22	7+	0.12	7	hrs.	32
		26b*	1.1	24	hrs.	64					
UNH ⁵	low ²	4a	0.049	6	hrs.	76	10+	0.0017	5.5	hrs.	75
		8a	0.012	24	hrs.	84					
	moderate ³	6a	0.039	28	hrs.	68	26a	0.54	0.13	hrs.	40
<i>Vegetation</i>											
UO ₂	low ²	11	0.046	24	hrs.	82	12+	0.014	6	hrs.	91
	moderate ³	13	1.0	24	hrs.	40	14+	3.1	6	hrs.	19
UNH ⁵	low ²	--	--	--	--	--	16+	0.096	6	hrs.	78
	moderate ³	--	--	--	--	--	15+	0.2	6	hrs.	86
<i>Stainless Steel</i>											
UO ₂	low ²	17b*	0.09	4.8	hrs.	83	17a	0.12	0.12	hrs.	66
	moderate ³	25a	7.6	24	hrs.	14	25b	1.3	0.13	hrs.	7
		25c*	0.7	24	hrs.	42					
UNH ⁵	low ²	19b*	0.023	6	hrs.	76	19a	1.1	0.22	hrs.	40
	moderate ³	18b*	2.6	5	hrs.	30	18a	11.4	0.17	hrs.	34
<i>Road-like Surface</i>											
UO ₂	low ²	21b*	0.14	6	hrs.	62	21a	0.041	0.37	hrs.	70
UNH ⁵	moderate ³	20b*	0.063	5	hrs.	58	20a	0.24	0.28	hrs.	68

¹ Percent airborne less than 10 microns aerodynamic equivalent diameter.² Approximately 2.5 mph.³ In range of 20 to 23.5 mph.⁴ Dried in flowing air at stated velocity for a minimum of 24 hours.⁵ Uranyl Nitrate Hexahydrate.

* Residue after gasoline fire.

+ During and immediately following a gasoline fire.

FIGURE 13. ACTIVITY DISTRIBUTION INTO VARIOUS AERODYNAMIC SIZE FRACTIONS DURING SELECTED EXPERIMENTS

Aerodynamic Entrainment of Uranium from Various Surfaces

The quantities of uranium particles in the respirable range that were aerodynamically entrained in the airstream under the stated conditions are tabulated in Table IV. The data indicate:

- a. Entrainment of uranium under all combinations used in this study are low in low wind speeds (maximum of 0.23 percent in 5 hours from uranium dioxide on sandy soil).
- b. Entrainment of uranium dioxide powder from all surfaces by wind speeds around 20 mph are considerably higher (0.4 to 24.4 percent in 24 hours).
- c. Entrainment of uranium from the nitrate solution on soil is low.
- d. The entrainment from the dried solid residue of uranium nitrate solutions is higher than from the solution itself. The residues from solutions involved in a gasoline fire at higher wind speeds appear to be higher.

Since the collection period for these samples range from 5 to 24 hours, some information on the rate of entrainment was obtained in the second phase of the experimental program. The data from these experiments is shown in Figures 14 through 17, where the percent of total uranium collected under the stated conditions are plotted against time. At a wind speed of 2.5 mph, the entrainment of uranium dioxide powder, fresh or involved in a gasoline fire, from sandy soil appears to be essentially complete in approximately 16 hours. The initial rise is fairly rapid -- around 50 percent of the total entrained is entrained in the first two hours. At a wind speed of 20 mph, entrainment from freshly deposited uranium dioxide powder on sandy soil is approximately 99 percent complete within the first hour. If the powder is involved in a gasoline fire, the uranium is entrained more slowly and may not be complete in 24 hours. The entrainment of uranium dioxide powder, fresh or involved in a gasoline fire, from a stainless steel surface by air at 20 mph also appears to be incomplete in 24 hours. Again the entrainment of the powder involved in a fire is slower. The entrainment of uranium from the solid residue of a nitrate solution on smooth, sandy soil devoid of vegetation appears to be far from complete and could continue for an appreciable period of time.

If the data presented in Table IV is viewed in the light of this information, the aerodynamic entrainment of materials involved in gasoline fires increases in importance. At a wind speed of 20 to 23 mph, the entrainment from residues of uranium dioxide from stainless steel could rise to the levels found

TABLE IV

AERODYNAMIC ENTRAINMENT OF URANIUM PARTICLES IN THE RESPIRABLE
SIZE RANGE FROM VARIOUS SURFACES

Surface	Percent Airborne			
	Uranium Dioxide Powder		Uranium Nitrate Solution	
	2.5 mph	20-23 mph	2.5 mph	20-23 mph
Smooth, Sandy Soil	0.24 (6)	1.7 (24)	0.0051 ⁺ (24)	0.20 ⁺ (24)
	0.023 (24)	9.8 (24)	0.0042 ⁺ (24)	0.70 ⁺ (24)
	0.005 (24)*	0.68 (24)	0.037 (6)	0.027 (28)
			0.010 (24)	
Vegetation Cover	0.0038 (24)	0.4 (24)	--	--
Stainless Steel	0.075 (4.8)*	1.1 (24) 0.29* (24)	0.017* (6)	0.78 (5)
Asphalt Road-like Surface	0.087* (6)	--	0.033* (6)	

+ Solid Residues from air dried UNH solutions.

* Solid residues remaining after a gasoline fire.

FIGURE 14. AERODYNAMIC ENTRAINMENT OF URANIUM DIOXIDE POWDER FROM SMOOTH, SANDY SOIL AT AN AIR VELOCITY OF 2.5 MPH

FIGURE 15. AERODYNAMIC ENTRAINMENT OF URANIUM DIOXIDE POWDER FROM SMOOTH, SANDY SOIL AT AN AIR VELOCITY OF 20 MPH

FIGURE 16. AERODYNAMIC ENTRAINMENT OF URANIUM DIOXIDE POWDER FROM A STAINLESS STEEL SURFACE AT AN AIR VELOCITY OF 20 MPH

FIGURE 17. AERODYNAMIC ENTRAINMENT OF SOLID RESIDUES FROM URANIUM NITRATE AFTER A GASOLINE FIRE ON SMOOTH, SANDY SOIL AT AN AIR VELOCITY OF 20 MPH

for freshly deposited powder. Entrainment from uranium nitrate residue could also rise to or exceed this level.

Fractional Release of Uranium During a Petroleum Fire

The fraction of uranium which was present in the source that becomes airborne during a gasoline fire, or attached to particles in the respirable size range, are listed in Table V. No single surface or uranium form appears to have an overriding effect on the fractional values. It appears that a combination of circumstances determines the fractional airborne release under these circumstances. Some of these values are for fractional airborne releases during and immediately following a gasoline fire (marked with an asterisk). The data from experiments where separate values were measured indicated that the quantity airborne during the fire in these experiments is significantly greater than the quantity entrained after the fire.

A few general observations can be made:

- Under comparable conditions, increasing the velocity of air passing over the surface increases the amount of material airborne under the stated conditions. As indicated by the aerodynamic entrainment experiments discussed in the previous section, the rate at which the material is airborne increases (see Figure 9 through 12).
- Evaporation of liquids which results in the formation of a film on surfaces appears to provide a potential for greater release. The highest fractional release measured was from uranium nitrate solution on a stainless steel surface at an air speed of 23 mph -- 4.3 percent. The same combination of conditions gave the third highest fractional release at an air speed of approximately 2.5 mph. Uranium nitrate solutions on vegetation-covered soil and asphalt gravel mixtures also had fractional releases in the upper half of the table. The fractional release value for uranium nitrate solutions on vegetation -- 0.17 and 0.075 percent -- represent some 0.39 and 0.19 milliliters of the 0.51 grams uranium per milliliter solution used as the source and could easily be visualized as liquid clinging to the vegetation.
- Fractional releases of both liquid and powder are higher from hard, impervious surfaces.

TABLE V

FRACTIONAL RELEASE OF URANIUM INVOLVED IN A GASOLINE FIRE
(Weight percent of source airborne as particles in respirable range.)

<u>Experiment</u>	<u>Source</u>	<u>Air Velocity (mph)</u>	<u>Surface Area sq. ft.</u>	<u>Grams Of U in Source</u>	<u>Grams Uranium/ sq. ft.</u>	<u>Percent Release</u>
SA-18a	UNH Solution, Stainless Steel	23	1.23	25.5	20.7	4.3
SA-14	UO ₂ Powder, Vegetation Cover	23	2.89	69.5	24	0.59*
SA-19a	UNH Solution, Stainless Steel	<4	1.23	25.5	20.7	0.44
SA-23b	UO ₂ Powder, Sandy Soil	20	2.89	50	17.3	0.3
SA-15	UNH Solution, Vegetation Cover	23	2.89	51.1	17.7	0.17*
SA-20a	UNH Solution, Road-like Surface	<4	1.23	25.5	20.7	0.16
SA-25a	UO ₂ Powder, Stainless steel	20	1.23	50	40.6	0.12
SA-17a	UO ₂ Powder, Stainless Steel	<4	1.23	51.1	15.8	0.079
SA-16	UNH Solution, Vegetation	<4	2.89	51.1	17.7	0.075*
SA-7	Residue Air Dried UNH, Sandy Soil	23	2.89	51	17.6	0.038*
SA-3	UO ₂ Powder, Sandy Soil	<4	2.89	74.9	25.9	0.030*
SA-21a	UO ₂ Powder, Road-like Surface	<4	1.23	58.1	47.2	0.029
SA-26a	UNH Solution, Sandy Soil	20	2.89	51	17.6	0.029
SA-22b	UO ₂ Powder, Sandy Soil	2.5	2.89	50	17.3	0.017
SA-12	UO ₂ Powder, Vegetation	<4	2.89	78.3	27.1	0.013*
SA-9	Residue Air Dried UNH, Sandy Soil	<4	2.89	51.5	17.8	0.0072*
SA-5	Residue Air Dried UNH, Sandy Soil	<4	2.89	51	17.6	0.0045*
SA-10	UNH Solution, Sandy Soil	<4	2.89	47.8	16.5	0.0013*

* During and immediately following a gasoline fire.

- The smallest fractional releases found in these experiments are under those conditions which allow the uranium to penetrate into and becomes a part of the surface.

LARGE-SCALE OUTDOOR GASOLINE FIRE

The large scale, outdoor gasoline fire demonstrated that the conditions produced in the engineering scale experiments approach those produced in a large gasoline fire and are thus a reasonable simulation of such occurrences.

- The burning characteristics of the large scale gasoline fire progressed through three stages:
 - a. An intense violent stage lasting approximately 15 minutes. Temperatures exceeded 1000°C with flames 15 to 20 feet high (see Figure 18).
 - b. A period of about 30 minutes of uniform stable burning with temperatures in the range of 500 to 700°C. Flame heights varied from approximately 6 to 12 inches near the end of the period.
 - c. A period of increasing flame breakup and separation lasting some 45 minutes. Temperatures decreased to approximately 300°C.

The sequence, duration and characteristics of the fire are within the range found in the wind tunnel experiments in the 242-B Building facility. Flame height and ground turbulence may be less accurately scaled.

- The fire covered an area of about 1000 sq. ft. (see Figure 19). The gasoline was thus at a concentration of about 0.5 gallon of gasoline per sq. ft. of surface similar to that used in the engineering scale experiments. Since the gasoline could only penetrate to a maximum depth of 6 inches in the engineering scale experiments while the soil was moist to a depth of 12 inches following the large scale gasoline fire, as much gasoline was probably available in the wind tunnel experiments per unit area as occurred in the large scale test.
- The uranium recovered from the soil-filled canisters following the fire did not vary significantly from unexposed, soil-filled canisters of the same material. All six pairs of canisters were collected and examined following the fire. Three of the twelve canisters distributed over the test site were still intact:
 - a. Both canisters (#3 containing uranium dioxide powder and #4 contain-

FIGURE 18. LARGE SCALE OUTDOOR GASOLINE FIRE, INITIAL STAGES OF BURNING (PNL NEG. 713037-27)

FIGURE 19. AREA COVERED BY LARGE SCALE OUTDOOR GASOLINE FIRE

ing uranium nitrate solution) at position #2 were buried under several inches of loose rocks and soil. The plastic bag over both canisters was retrieved intact.

- b. Canister #12 at grid position #6 containing uranium nitrate solution was not in the burn area (See Figure 19) and, although the tip of the plastic bag was melted, most of the bag was found on the canister. At no point in the test was this canister observed burning.

All the material in the upper portion of each canister was placed in a pre-marked beaker and repeatedly leached using warm 9 N HNO₃-0.1 N HF. Quantity of material processed varied from 250 to 650 grams. Due to the large amounts of salts generated, reliable answers could not be obtained using controlled potential coulometry. Uranium measurements were obtained via fluorimetry by making large dilutions to reduce the effects of extraneous cations. The average recoveries for the exposed uranium dioxide powder and nitrate solution canisters did not vary significantly from the control and unexposed canisters of the same material. Because of the wide statistical variation in analyses, it is estimated that the minimum fraction which could have been measured and shown to be significantly different from the uninvolved canisters would be about 50%. In light of the anticipated release of a fraction of one percent, from the R.A.R.T. experiments, no conclusions regarding release fraction in the large scale fire experiment can be made.

CONCLUSIONS

The engineering scale experiments conducted in the wind tunnel in the 242-B Building facility reasonably simulated the conditions imposed by a large scale gasoline fire on a porous surface. The sequence, burning characteristics, temperatures and duration of a fire involving 500 gallons of gasoline were within the range of those observed during the engineering scale experiments.

No single parameter of those evaluated in this study -- physical form of the active material, surface, wind speed or the presence or absence of a fire -- exerts a controlling influence on the fractional airborne release under all circumstances. The combination of all these parameters produces a situation

favorable or unfavorable to release. Thus, a liquid which penetrates, incorporates and binds together a porous surface produces a situation unfavorable to airborne release. The same liquid on a hard, impervious surface may produce a thin film which produces a fine particle when heated. The presence of vegetation cover reduces the airborne release of powder, but may increase the quantity of material airborne from a liquid -- by drying of the thin film of liquid clinging to the vegetation and the subsequent release of the particle formed in the air stream. Higher air speeds and fires generally increased fractional airborne release.

The greatest release combination of those evaluated was uranium nitrate liquid on a hard impervious surface in a gasoline fire. During the fire, 4.5 percent of the uranium in the source was airborne in the aerodynamic equivalent size fraction less than 10 microns (nominal respirable range) under a wind at a velocity of 23 mph. At a wind speed of less than 4 mph, 0.44 percent was airborne. Even after the fire, the fractional airborne release remains high.

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APPENDIX AAIR VELOCITIES VS. DAMPER SETTINGS -- INLET DUCT R.A.R.T. 242-B BUILDING

AIR VELOCITIES VS. DAMPER SETTINGS -- INLET DUCT R.A.R.T. 242-B BUILDING

All engineering scale experiments in this study were performed in the furnace section of the inlet duct of the Radioactive Aerosol Release Tank located in the 242-B Building facility. Since the velocity of the air passing over the contaminated surfaces is one of the variable parameters of the study, air velocities in the furnace section vs. damper settings were measured on three occasions -- before the initial experiments and before and after replacement of the exhaust HEPA filters.

The inlet duct is a 24-inch by 24-inch duct, 22 feet long, made of 1/8 inch steel and is shown in Figure 1. The inlet is sealed by four 24-inch by 24-inch by 12-inch deep HEPA filters (see Figure A1). An 18-inch long flash arrestor separates the filters from the furnace section. Air is drawn into the system by a large blower located downstream of the RART.

The furnace section is a 3-foot long section of the duct lined on the top and sides with castable refractory material and is shown in Figure A2. Three half couplings (3/4", 2", and 1/4", Sch. 40 pipe) provide access into the section. A 24-inch diameter by 6-inch deep flange at the bottom holds the 23-inch diameter Flanged Burner Tray shown in Figure A-2. The internal dimensions of the furnace section are 19-1/2 inch by 18 inch.

Prior to the beginning of the study, velocities were measured by a vane anemometer placed in the duct at its entry into the R.A.R.T., and a pitot tube inserted through the side of the duct. The results are tabulated in Table A-I. The damper position indicator was mounted such that the indicated settings are 90° out of phase with the damper position. Useful accurate readings could not be obtained using the vane anemometer or pitot tube at the damper setting corresponding to minimum flow. Velocities greater than 250 ft. per minute should be measurable with the vane anemometer used. Under the atmospheric conditions prevailing, significant differential pressure readings should be obtained at air velocities in excess of 450 ft. per minute.

An air velocity of 215 ft. per minute in the inlet duct corresponds to a nominal velocity of 4 mph in the furnace section and was arbitrarily assigned to the lowest airflow used. The velocity profiles in the duct and furnace section at higher air flow was also measured and, although a considerable variation in velocity was found across the duct, the centerline velocity was found to be a reasonable average value through the duct.

FIGURE A-1. FILTER BOX, FLASH ARRESTOR AND FURNACE SECTION OF INLET DUCT TO THE RADIOACTIVE AEROSOL RELEASE TANK (SECTION)

FIGURE A-2. VERTICAL SECTION THROUGH FURNACE

TABLE A-IAIR VELOCITY IN INLET DUCT VS. INDICATED DAMPER SETTING

<u>Indicated Damper Setting</u>	<u>Vane Anemometer</u>		<u>Differential Pressure</u>	
	<u>Sec.</u> <u>1000 ft.</u>	<u>Ft.</u> <u>Min.</u>	<u>Inches W.G.</u>	<u>Ft.</u> <u>Min.</u>
Open	*	<250	< 0.01	<450
1/4	92.5	648	.038	770
	92.3	650	.04	790
1/2	59	1017		
	60	1000	.059	960
	59.5	1008		
3/4	55.2	1087		
	55.2	1087	.059	960
Closed	56	1071	.075	1085
	56.6	1060	.081	1130

Relative Humidity: 37%

Barometric Pressure: 30.002 in.

Temperature: 61°F

 *Would not turn vane.

In order to measure air velocities at minimum flow in the system, a vane anemometer with a pressure drop in hundredths of an inch water gauge was obtained.[†] The anemometer was calibrated with a Roots meter.* The configuration used in calibration is shown in Figure A3, and the results are shown in Table A-II. A value of 0.097 cu. ft. per count was determined as compared with the factory calibration of 0.093 std. cu. ft. per count. The response of the anemometer checked at various flow rates between 20 and 50 cfm did not indicate any change in calibration related to flow rate.

The pressure drop through the exhaust HEPA increased towards the end of the initial portion of the experimental study. The decision was made to replace the exhaust HEPA filters after the experimental work was completed and the duct could be thoroughly cleaned. The filters were replaced between experiments SA-21 and SA-22.

FIGURE A3

CALIBRATION SETUP FOR PR-3 FLOWMETER

[†] SCI-MED model PR-3, SCI-MED, 13010 County Road 6, Minneapolis, Mn. 55441

* Roots Connerville positive displacement flowmeter 7M 125, Connerville, Indiana.

TABLE A-II

CALIBRATION OF SCI-MED MODEL PR-3 FLOWMETER

Flow Rate cfm	Time Min.	Roots Meter Reading-Ft ³	Count Flow Sensor	Count Ft ³	Ft ³ Count
<u>4/13/72 -- Flow Sensor No. 109</u>					
42	1	42	513	12.2	0.0819
42	10	420	5356	12.7	0.0787
43.2	20	863	8554	9.9	0.101
42	30	1260	13080	10.4	0.0961
42	60	2522	26166	10.4	0.0961
50.8	60	3046	31724	10.4	0.0961
<u>4/14/72 -- Using Cyclonaire 1 pump</u>					
34.7	30	1040	10859	10.4	0.0961
50.3	30	1510	15848	10.5	0.0952
21.8	60	1312	13546	10.3	0.0971
33.5	60	2010	20784	10.3	0.0971
50.5	10	505	5314	10.5	0.0952
22	10	220	2262	10.3	0.0971
21.8	60	1310	13486	10.3	0.0971
21.2	60	1309	13565	10.3	0.0971
<u>4/19/72 -- Flow Sensor No. 109</u>					
23	3	69	698	10.1	0.0990
23	10	230	2383	10.3	0.0971
51.2	10	512	5372	10.5	0.0952
22.9	10	229	2362	10.3	0.0971
22.8	30	685	6950	10.3	0.0971
<u>4/24/72 -- Flow Sensor No. 109</u>					
51.2	10	512	5168	10.1	0.0990
50.8	10	508	4991	9.8	0.102
21.9	10	219	2162	9.9	0.101

Average: 0.097 cu.ft./count

The air velocities in the furnace section at various damper settings were measured before and after the filter change (see Figure A-5).

A schematic drawing of the sensor placement is shown in Figure A-4, and the results are given in Table A-III. Very little change in air velocity was detected before and after filter replacement at minimum flow. The measured values were 2.46 and 2.65 mph respectively. A value of 2.5 mph was assigned for the air velocity at minimum flow for all subsequent experiments. The air velocity increased at maximum flow from 15.8 to 19.6 mph after replacement. A nominal velocity of 20 mph was assigned for maximum flow experiments.

Dimension Duct: 24" 24" (4 ft²)
 Dimension Furnace Section: 19.5" × 18", 351 in.² (2.44 ft²)
 Cross Section Flow Sensor: Diameter 4.81 in.
 Area 18.18 in.², 0.126 ft²

FIGURE A-4
SENSOR PLACEMENT

TABLE A-IIICALIBRATION OF AIR FLOW IN 242-B WIND TUNNEL

<u>Damper Setting</u>	<u>Counts</u>	<u>Time Min.</u>	<u>Counts/ Min.</u>	<u>cfm Sensor</u>	<u>cfm Duct</u>	<u>Air Velocity fpm</u>
Closed	2817	10	281.7	27.32	529	216.9
1/8 Open	8499	10	848.9	82.44	1596	654.3
1/4 Open	11963	10	1196.3	116.04	2247	921
3/8 Open	15296	10	1529.6	148.36	2874	1178
1/2 Open	16969	10	1696.9	164.60	3186	1306
3/4 Open	17844	10	1784.4	173.09	3352	1374
Open	18049	10	1804.9	175.08	3990	1389
Open	18039	10	1803.9	174.98	3388	1388

$$\text{fpm} \times \frac{\text{mi}}{5280 \text{ ft.}} \times \frac{60 \text{ min.}}{\text{hr.}} = 0.01136 \text{ mi per hr.}$$

After HEPA filters at blower changed. Δp before change > 6 in W.G.
 Δp after change 1.6 in W.G.

Open	22049	10	2204.9	213.8	4140	1697
1/2 Open	19526	10	1952.6	189.4	3668	1503
1/4 Open	12626	10	1262.6	122.5	2372	972
1/8 Open	8510	10	851.0	82.5	1598	655
Closed	3035	10	303.5	29.4	569	233
Open	22470	10	2247.0	218.0	4222	1730
Open	22501	10	2250.1	218.2	4225	1732

$$\frac{2.44 \text{ ft}^2}{0.126 \text{ ft}^2} = 19.365$$

$$\text{Flow increase, low flow} \quad \frac{3035}{2817} = 107.7\%$$

$$\text{Flow increase, high flow} \quad \frac{22340}{18044} = 123.8\%$$

FIGURE A-5. AIR VELOCITY IN 242-B BUILDING WIND TUNNEL VS DAMPER SETTINGS

APPENDIX BEXPERIMENTAL OBSERVATIONS DURING INDIVIDUAL SHIPPING ACCIDENT EXPERIMENTS

EXPERIMENTAL OBSERVATIONS DURING INDIVIDUAL SHIPPING ACCIDENT EXPERIMENTS

SA-1 -- 58 grams of UO_2 powder were sprinkled over the 2.9 sq. ft. of soil in the flanged burner tray. Nominal air velocity in the furnace section was 23 mph. The air stream was sampled during a period of five hours with the filter collector and the cascade impactor.

SA-2 -- 85 grams of UO_2 powder were dispersed on the soil and air at a nominal velocity of less than 4 mph (see Appendix A) drawn over the surface for 6 hrs.

SA-3 -- The flanged burner tray was left in place upon completion of experiments SA-2, and one gallon of gasoline poured onto the surface. After the gasoline was ignited, air at a nominal velocity of less than 4 mph was drawn over the surface. The maximum recorded temperature in the duct was approximately 750°C with little increase of temperature of the soil or R.A.R.T. surface. Flames were visible in the furnace for around 40 minutes. Air flow and sampling were continued for a total time of 6 hours.

SA-4 -- 71 cc of a 0.51 g U/cc UNH solution and 3-6N HNO_3 rinses were poured onto the soil held in the flanged burner tray. Air at a speed of less than 4 mph was drawn over the surface and sampled for 6 hours (part "a" of experiment). Airflow was stopped and all samplers replaced. After an additional 16 hours drying, airflow and sampling were resumed for 23-3/4 hours (part "b" of experiment).

SA-5 -- The flanged burner tray was left in place upon completion of experiment SA-4 and one gallon of gasoline was poured onto the surface. The gasoline extinguished itself with the violence of its ignition. After reignition, the exterior paint on the flash arrestor and inlet filter holder was smoking. Maximum temperatures of 950°C and 900°C were noted for the downstream and upstream thermocouple projecting 2 inches above the soil. Flames were visible for less than 10 minutes. A maximum air temperature exceeding 1000°C was observed. All HEPA filters over the inlet were checked and replaced although none appeared damaged sufficiently to impair performance. Air flow and sampling were continued for a total of 5-1/2 hours.

SA-6 -- 100 cc of a 0.51 g U/cc UNH solution and acid rinses of the graduated cylinder were poured over the soil held in the flanged burner tray. Air at a nominal speed of 23 mph was drawn across the surface and sampled for a total

of 27-3/4 hours (part "a" of the experiment). Airflow was stopped and all samplers replaced. Airflow and sampling were resumed for an additional 23-1/2 hours (part "b" of experiment).

SA-7 -- The flanged burner tray was left in place upon completion of experiment SA-6 and one gallon of gasoline was poured onto the surface. A considerable quantity of gasoline leaked out of the flanged opening (1/4 to 1/2 gallon). Gasoline ignited and air at a nominal speed of 23 mph was drawn across the surface. Flames were visible for less than 10 minutes and a maximum temperature was not recorded. Total airflow and sampling period was 6 hours.

SA-8 -- Rerun of conditions used in experiment SA-4. Sampling period part "a" was 23-3/4 hours and 24 hours for part "b".

SA-9 -- The flanged burner tray was left in place upon completion of experiment SA-8 and one gallon of gasoline poured onto the surface. After the gasoline was ignited, airflow at a nominal speed of less than 4 mph was drawn over the surface and sampling was initiated. Flames were visible in the furnace for some 58 minutes with a maximum recorded temperature of 650°C. Total air flow and sampling time was 5 hours.

SA-10 -- 93 cc of a 0.51 g U/cc UNH solution was poured onto the soil held in the flanged burner tray. One gallon of gasoline was poured onto the surface and ignited. Air at a nominal speed of less than 4 mph was drawn over the burning surface and sampling was initiated. Gasoline did not appear to burn as vigorously as in previous experiments. Flames were visible in the furnace for approximately 25 minutes with a maximum recorded temperature of 200°C. Total air flow and sampling period was 5-1/2 hours.

The next group of experiments involved the fractional airborne release from ground having a vegetation cover. The flanged burner tray was filled with soil collected from around the 242-B Building. Young, green tumble weed plants common in the area were up-rooted and transplanted in the soil held in the flanged burner tray.

SA-11 -- 89 grams of UO₂ powder were sprinkled over the vegetation-covered surface of the flanged burner tray which was then inserted in the furnace. Air at a nominal speed of less than 4 mph was drawn across the surface for 23-1/2 hours and sampled.

SA-12 -- The flanged burner tray was left in place at the completion of experiment SA-11 and a gallon of gasoline poured onto the surface. The gasoline was ignited and airflow plus sampling resumed. Flames were visible in the furnace for 50 minutes with a maximum recorded temperature of 550°C. Total airflow and sampling period was 6 hours.

SA-13 -- 79 grams of UO₂ powder were dispersed over the 2.9 sq. ft. of vegetation-covered surface of the flanged burner tray. The tray was inserted into the furnace and air at a nominal velocity of 23 mph was drawn over the surface for 24 hours. Total sampling period was also 24 hours.

SA-14 -- After the completion of experiment SA-13, the samplers were replaced but the flanged burner tray was left in place. A gallon of gasoline was poured onto the surface and ignited. Airflow and sampling were resumed. Flames were visible in the furnace for only 7 minutes with a maximum recorded temperature of 600°C. Total airflow and sampling period was 6 hours.

SA-15 -- 100 cc of a 0.51 g U/cc UNH solution was poured onto the vegetation-covered soil surface held in the flanged burner tray and the tray inserted into the furnace. A gallon of gasoline was added. A force sufficient to extinguish the flames was generated during the ignition. The material was re-ignited but the vegetation did not burn well -- only the downstream 1/3 of the vegetation burned. Attempts to spread the flames were unsuccessful. Air at a nominal velocity of 23 mph was drawn across the surface. Visible burning continued for 40 minutes. The total period of airflow and sampling was 6 hours.

SA-16 -- 100 cc of a 0.51 g U/cc UNH solution was poured onto the 2.9 sq. ft. vegetation-covered surface held in the flanged burner tray and the tray inserted into the furnace section. A gallon of gasoline was poured onto the surface and ignited. Flames were visible over the entire surface. Air at a nominal velocity of less than 4 mph was drawn across the surface and sampled. Observable burning persisted for 125 minutes. Airflow and sampling were continued for a period of 6 hours.

The next group of engineering scale experiments involved the fractional release of uranium from a stainless steel surface during a petroleum fire. The flanged burner tray was partially filled with soil collected from around the 242-B Building. A stainless steel pan 15 inches ID by 2 inches deep was embedded in the upstream end of the flanged burner tray and additional soil added to make the rim of the pan flush with upper edge of the rim of the flanged burner tray.

SA-17 -- 22 grams of uranium dioxide powder were placed in the stainless steel pan held in the flanged burner tray and inserted in the furnace section. A gallon of gasoline was poured into the dish and ignited. Air at a nominal velocity of less than 4 mph was drawn over the surface and sampled. Flow rates on both filter samples could not be maintained and decreased to 0.25 and 0.75 cfm respectively for the fixed and movable filters. The RART surface temperature increased during the experiment reaching approximately 70°C after 7 minutes of burning. The water spray was turned on to cool the air. After 9 minutes, no flames were visible and the airflow and sampling halted (part "a" of the experiment). The samplers were replaced. Airflow and sampling were resumed for an additional 4.77 hours to measure the aerodynamic entrainment of uranium from the fire residue (part "b" of the experiment).

SA-18 -- 50 cc of a 0.51 g U/cc UNH solution were poured onto the stainless steel pan held in the flanged burner tray and inserted in the furnace. A gallon of gasoline was poured into the dish and ignited. Air at a nominal speed of 23 mph was drawn over the surface and sampled. Flow through the filter samples decreased during the course of the experiment to 0.67 and 0.9 cfm for the fixed and movable samplers respectively. Airflow and sampling were halted in 9 minutes when burning ceased (part "a" of experiment). After the samplers were replaced, airflow and sampling were resumed for an additional 5 hours (part "b" of experiment).

SA-19 -- 50 cc of a 0.51 g U/cc UNH solution was poured into the stainless steel dish in the flanged burner tray and inserted in the furnace. A gallon of gasoline was poured into the dish and ignited. Air at a nominal speed of less than 4 mph was drawn across the surface. Flowrates through the filter samples decreased to 0.67 and 0.3 cfm through the fixed and movable samplers respectively. The water spray within the R.A.R.T. was initiated after 6 minutes of burning to cool the air. The fire went out after 13 minutes, and airflow and sampling were halted. After the samplers were replaced, airflow and sampling were continued for an additional 6 hours.

The last two experiments in the series involved the fractional release of uranium from a "road-like" (gravel/asphalt mixture) surface. The gravel/asphalt mixture was poured into a 15-inch diameter by 4-inch deep steel pan and heated. The material was tamped to produce a smooth bed approximately 1 inch deep in the bottom of the pan. The 4 inch lip of the pan rested upon the rim of the

flanged burner tray creating a continuous smooth surface with the bottom of the furnace section.

SA-20 -- 50 cc of a 0.51 g U/cc UNH solution was poured onto the road-like surface and inserted into the furnace. A gallon of gasoline was poured onto the surface and ignited. Air at a nominal speed of less than 4 mph was drawn over the surface and sampled. A large amount of soot was generated during the burning and filter sample flowrates dropped to 0.4 and less than 0.3 cfm for the fixed and movable samplers respectively. Sampling was terminated in approximately 17 minutes due to the lack of flow through the samplers although the gasoline-surface mixture burned for 26 minutes. Cooling water spray was initiated after 5 minutes of burning. Airflow was halted after the fire was extinguished and all samplers were replaced (part "a" of the experiment). Airflow and sampling were then continued for 5 hours to measure aerodynamic entrainment of the uranium from the fire residue (part "b" of the experiment).

SA-21 -- 66 grams of uranium dioxide powder were sprinkled over a road-like surface and placed into the furnace. A gallon of gasoline was poured onto the surface and ignited. Air at a nominal speed of less than 4 mph was drawn over the surface and sampled. Cooling water spray was instituted after 8 minutes of burning. Flow through the fixed and movable filters decreased to 0.42 and 0.45 cfm during the course of the burning. Flames were no longer visible after 22 minutes and airflow and sampling were discontinued (part "a" of the experiment). After the samplers were replaced, airflow and sampling were resumed for an additional 6 hours.

Upon evaluation of the data from the initial series of experiments (SA-1 to SA-21) additional data in certain areas appeared desirable. Eleven additional experiments were performed to measure the aerodynamic resuspension and fractional release during a fire of uranium dioxide powder from bare, sandy soil and stainless steel and uranium nitrate solution from bare, sandy soil at air speeds not covered in previous experiments.

SA-22 -- 56.8 grams of uranium dioxide powder were sprinkled on a smooth surface of sandy soil held in the burner tray. The tray was inserted into the wind tunnel and air at a nominal speed of 2.5 mph was passed over the surface for 24 hours. The airborne concentration was continuously sampled with filters in the airstream and size distribution of the uranium airborne evaluated

from periodic cascade impactor samples (part "a" of experiment). The burner tray bearing the material was left in place and a gallon of gasoline was poured onto the surface. The gasoline ignited vigorously and burned for 60 minutes. Both a filter and cascade impactor sample were taken during the entire period although flow through the filter was reduced to 0.85 cfm during the final 30 minutes. Upon completion of the burning (part "b" of experiment), airflow was stopped and the samplers replaced. Airflow was resumed and resuspension of uranium from the residue from the fire was measured during the subsequent 24 hour period (part "c" of experiment).

SA-23 -- 56.8 grams of uranium dioxide powder were sprinkled on a smooth surface of sandy soil held in the burner tray and experiment SA-22 repeated using an air speed of 20 mph. Under these conditions, the gasoline burned with a visible flame for 18 minutes. Some sandy soil was found on the initial sieve of the cascade impactor after this portion of the experiment.

SA-25 -- 56.8 grams of uranium dioxide powder were sprinkled into a 15-inch diameter stainless steel pan embedded in sandy soil held in the flanged burner tray. Aerodynamic resuspension by air at a nominal velocity of 20 mph was measured by continuously sampling of the air over a 24-hour period. Periodic cascade impactor samples were taken to evaluate the size distribution of the uranium airborne (part "a" of experiment). A gallon of gasoline was then poured onto the surface and ignited. The gasoline burned with a visible flame for 18 minutes and the fractional release and size distribution of the uranium airborne evaluated from filter and cascade impactor samples taken during this period (part "b" of experiment). After the samplers were replaced, aerodynamic resuspension of uranium from the solid residue remaining after the fire was determined by collection of airborne particles during a 24 hour period. Examination of the stainless steel pan after the experiment indicated the uranium dioxide powder was washed towards the edges of the pan during the introduction of the gasoline.

SA-26 -- 100 ml of the 0.51 g uranium per ml solution of uranium dioxide in dilute nitric acid plus 3 dilute nitric acid rinses of the graduated cylinder were poured on a smooth surface of sandy soil held in the flanged burner tray. The tray was inserted into the wind tunnel and a gallon of gasoline was poured onto the surface. The gasoline ignited vigorously and, under these conditions, burned for 8 minutes. Both filter and cascade impactor sample were taken of

the air drawn over the surface at a speed of 20 mph during this period (part "a" of experiment). Aerodynamic resuspension of uranium from the solid residue at 20 mph evaluated by sampling over the next 24 hours (part "b" of the experiment).

APPENDIX CEVALUATION OF SAMPLING SYSTEM -- INLET DUCT R.A.R.T. 242-B BUILDING

EVALUATION OF SAMPLING SYSTEM -- INLET DUCT R.A.R.T. 242-B BUILDING

Samples to evaluate the concentration and size distribution of particles airborne during the shipping accident experiments were collected by two filters and a cascade impactor sampler located at the downstream end of the inlet duct of the R.A.R.T. Figure C-1 is a representation of a view of this arrangement looking downstream towards the R.A.R.T. A 1/2-inch Swagelok male connector enlarged to allow passage of a 1/2 ODT was attached to the 3-inch flanged opening located on the top of the duct. An open face 2-inch filter holder was attached to a 1/2-inch diameter stainless steel tube with a 90° bend which passed through the Swagelok fitting. A vertical traverse of the duct could be made with the filter holder by loosening the Swagelok fitting and manipulating the tube. The depth of penetration of the centerline of the filter could be determined by marking on the tube. A second open face 2-inch filter holder was inserted via the 3-inch flanged opening located on the side of the duct. The position of this holder was fixed at the centerline of the duct. Samples for the cascade impactor were drawn through a stainless steel 1/2-inch tube with a 90° bend and inserted into the bottom of the duct through a 2-inch diameter pipe half-coupling. The opening of the tube was approximately 2 inches from the floor of the duct.

A series of tests was performed to ascertain if a representative sample of the concentration of airborne particles could be obtained by such an arrangement. Rhodamine particles were generated into the airstream by nebulizing a dilute aqueous solution (0.01 g rhodamine per ml) from various positions in the furnace section of the inlet duct to the R.A.R.T. while drawing air through the duct at velocities of 2.5 and 20 mph. The locations used for generation are designated in Figure C-2. In all cases the rhodamine particles were generated with the nozzle of the nebulizer pointing downstream on approximately the centerline of the duct.

Samples were taken to measure both the quantity of rhodamine airborne at the end of the duct and deposited on the ducts. Airborne concentrations were evaluated by samples collected on both the fixed and vertical traversing filters. Cascade impactor samples were taken to measure the size distribution of the particles airborne. Particles falling to the floor of the duct were collected on an 18-inch wide sheet of aluminum foil which extended from the

FIGURE C-1. WIND TUNNEL SAMPLING SYSTEM

FIGURE C-2. RHODAMINE GENERATION POINTS

furnace section to the downstream end of the duct. 12-inch by 12-inch sheets of aluminum foil were taped in 5 places at mid-height on each wall to measure the quantity deposited on the wall.

The quantity of rhodamine in various samples was determined by measuring the fluorescence from the aqueous sample in a calibrated fluorimeter. The simplest and most efficient means of removing the rhodamine from the various sample matrices -- plastic nebulizer parts, glass fiber filters, glass impactor collection plates, aluminum foil and impactor parts -- was to soak the item in distilled water with periodic agitation. Quantitative recovery of standard quantities of rhodamine dried on the material were obtained using this procedure for all matrices tested.

A total of seven tests was performed. The operating conditions used and results are tabulated in Table C-I. Rhodamine particles were generated for periods ranging from 30 to 80 minutes and were generally limited by the capacity of the nebulizer. The quantity generated was assumed to be the difference between the amount placed in the nebulizer (concentration times volume of liquid) and the amount found in the nebulizer at the end of the test. Some difficulties were encountered in the initial experiments (1 and 2) with recovering the rhodamine from the nebulizer and the quantity listed as generated is probably in error.

The quantity airborne as measured by the "fixed" and "movable" (vertical traverse) filter samples are generally in good agreement. The exceptions are run #6 when the "movable" filter was not traversed and run #5. In all but one instance, the quantity airborne calculated by summation of the rhodamine collected on the impactor stages is higher than measured on the filters indicating some channeling of the particles. The effect is not as pronounced when particles are generated in the center of the furnace section (point B) or elevated from the floor of the duct (point C). In the shipping accident experiments, the particles are released from the furnace section (not in the duct) and must be slightly elevated to become airborne.

The amounts of rhodamine found on the floor and walls was insignificant. Considerably greater amounts were found on the floors as anticipated. But a significant portion of the material found on the floor was found in the first few feet and may have resulted from direct impingement of liquid droplets. Thus, the sampling arrangement was found adequate to obtain fairly represen-

TABLE C-I

EVALUATION OF INLET DUCT SAMPLING SYSTEM -- OPERATING PARAMETERS AND RESULTS

	1	2	3	4	5	6	7
Generation Point	A	A	B	B	A	A	C
Air Speed, mph	20	20	20	2.5	2.5	2.5	2.5
Length of Time Generated, Min.	30	80	60	70	66	61	69
g rhd Used	1.0	0.5	0.5	0.5	0.5	0.5	0.5
g rhd in Neb. at End of Test	0.69	0.41	0.108	0.166	0.22	0.15	0.18
g rhd Generated*	0.31	0.09	0.392	0.334	0.28	0.35	0.32
Percent rhd Recovered [†]	38	259	125	68.4	76.1	72.0	123
Median Mass Diameter of Particle Airborne, microns	0.72	0.19	1.4	2.4	2.4	2.4	2.2
g rhd Airborne, Fixed Filter	0.093	0.168	0.363	0.205	0.154	0.20	0.34
g rhd Airborne, Movable Filter	0.91	0.173	0.462	0.205	0.094	0.039**	0.43
g rhd Airborne, Impactor [°]	0.15	0.34	0.619	0.266	0.377	0.47	0.41
r rhd Airborne, South Wall	1.5×10^{-5}	2.4×10^{-6}	9.6×10^{-5}	9.6×10^{-6}	1.3×10^{-5}	5.2×10^{-5}	5.2×10^{-5}
g rhd Airborne, North Wall	3.8×10^{-5}	2.3×10^{-6}	1.9×10^{-4}	2.3×10^{-5}	2.4×10^{-5}	2.0×10^{-5}	2.2×10^{-5}
g rhd Airborne, Floor	6.6×10^{-3}	6.4×10^{-3}	9.4×10^{-3}	3.4×10^{-3}	5.2×10^{-3}	1.4×10^{-3}	1.1×10^{-3}

* Difference between amount rhodamine used and found in nebulizer following experiments.

** No traverse, filter held at topmost position during entire experiment.

+ Based on arithmetic average of quantity measured on filter and cascade impactor samples.

° Amount collected on eight stages and back-up filter.

tative samples of the airborne concentration. In most cases, the "fixed" filter result can be used as an overall average since it agrees with the "movable" filter in most cases. The size distributions determined by the cascade impactor samples are probably accurate. After the initial runs, the Median Mass Diameter of the particles airborne remains relatively stable even in experiments where the airborne concentrations calculated from cascade impactor results is significantly higher. Thus the high concentrations are attributed to a "channeling" effect, not settling of particles.

APPENDIX DLOSSES OF MATERIAL IN ANDERSEN CASCADE IMPACTOR

LOSSES OF MATERIAL IN ANDERSEN CASCADE IMPACTOR

The Andersen eight-stage, cascade impactor* is commonly used to evaluate the size distribution of airborne particles and was used in the shipping accident study. O'Donnel, et al,^[1] reported considerable losses of material on the initial perforated plate but states losses do not affect size distribution of particles below 9 microns (stage 3 and less). Since determining the wall losses in the impactor required relatively little additional effort during the evaluation of the sampling system, losses of rhodamine to the impactor walls and sieves were measured during the seven tests described in Appendix C.

Table D-I lists the weight of rhodamine recovered from various components of the cascade impactor sampling arrangement. The total weight of rhodamine collected ranged from 4.5×10^{-5} (in test #1) to 9.5×10^{-4} g (in test #6). The percentage of the total loss for each component is listed in Table D-II. The total loss and distribution appears to be related to the size distribution of the particles sampled.

The smallest loss (9.2 percent) is found in Test #2 which has the smallest MMD by far of all tests. The distribution also varies radically from those found in other tests -- approximately 1/2 the loss was found in the exit tube from the impactor in this run while relatively little was recovered from the inlet probe or first sieve. Losses in the other six tests ranged from 12.2 to 16.6 percent. In the four tests in which larger particles were found (test #4 to #6), approximately 1/2 the loss was to the first sieve with a significant amount found in the entry probe. In Tests #1 and #3 where smaller particles were found, a broader distribution of losses was found.

If the loss is related to distribution, as seems reasonable, the size distribution would not be disturbed if the loss in each component is proportionate to the amount of material in that fraction. Table D-III lists the ratios of weights found on the sieves and collection plates beneath the sieves. On this basis, the first stage collector only contains 15 to 50% of the material which should be on the plate. The second stage is better containing from 23 to 62%. The percentage collected reaches a maximum in the sixth stage where collection is better than 99% in most cases. Collection in the eighth stage again decreases to 69 to 91%. Thus, the distribution determined appears to be heavily

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TABLE D-I

GRAMS OF RHODAMINE MEASURED IN VARIOUS COMPONENTS OTHER THAN STAGE COLLECTORS
OF CASCADE IMPACTORS

	10 ⁻⁸ g Rhodamine						
	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Test No. 5	Test No. 6	Test No. 7
Total collected in experiment	4508	8113	14950	53678	77930	94599	37604
In entry tube	48	36	220	1160	1650	2820	900
In entry cone	0.9	0.6	0.9	4	9	9	5
On sieve 0	310	29	660	3550	6480	5600	3075
On sieve 1	58	48	300	600	860	795	475
On sieve 2	37	50	110	460	670	675	375
On sieve 3	39	45	79	290	525	450	224
On sieve 4	20	58	65	155	295	206	163
On sieve 5	18	30	75	92	208	230	120
On sieve 6	22	31	102	108	178	168	139
On sieve 7	54	110	245	182	345	250	310
In exit tube	145	310	260	450	630	382	291
Total on Components	751	747	2117	7051	11850	11585	6077
Percent of Total Rhodamine measured not on stage collectors	16.6	9.2	14.2	13.1	13.1	12.2	16.2
Median Mass Diameter of Particles Airborne, microns Aerodynamic Equiv- alent Diameter	0.72	0.19	1.4	2.4	2.4	2.4	2.2

TABLE D-IIDISTRIBUTION OF RHODAMINE BETWEEN VARIOUS COMPONENTS (OTHER THAN
STAGE COLLECTORS) OF CASCADE IMPACTOR

	<u>Test No. 1</u>	<u>Test No. 2</u>	<u>Test No. 3</u>	<u>Test No. 4</u>	<u>Test No. 5</u>	<u>Test No. 6</u>	<u>Test No. 7</u>
Median Mass Diameter Of Particles, Microns AED	0.72	0.19	1.4	2.4	2.4	2.4	2.2
Percent of Rhodamine Measured on Components*	26.6	9.20	14.2	13.1	15.2	12.2	16.2
Percent of Rhodamine* On Individual Components							
Entry Tube	6.32	4.81	10.39	16.45	13.92	24.34	14.80
Entry Cone	0.12	0.08	0.04	0.05	0.07	0.07	0.08
Sieve 0	41.29	3.88	31.17	50.34	54.68	48.33	50.60
Sieve 1	7.69	6.36	14.16	8.50	7.26	6.86	7.81
Sieve 2	4.92	6.69	5.19	6.52	5.65	5.82	6.10
Sieve 3	5.19	6.02	3.73	4.11	4.43	3.88	3.68
Sieve 4	2.59	7.76	3.06	2.19	2.49	1.77	2.68
Sieve 5	2.39	4.01	3.54	1.31	1.76	1.98	1.97
Sieve 6	3.00	14.14	4.84	1.52	1.50	1.45	2.28
Sieve 7	7.19	14.72	11.57	2.58	2.91	2.16	5.10
Exit Tube	19.31	41.49	12.27	6.38	5.31	2.39	4.78

* Other than stage collectors.

TABLE D-III

PERCENT OF RHODAMINE ON STAGE COLLECTORS FOUND ON
PERFORATED PLATE PRECEEDING COLLECTORS

	Percent Rhodamine*						
	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Test No. 5	Test No. 6	Test No. 7
Sieve 0	536	341	220	104	252	112	146
Sieve 1	243	328	152	60	100	66.8	66.7
Sieve 2	26.0	27.8	19.0	7.7	13.0	7.6	10.3
Sieve 3	8.7	14.1	5.8	5.1	4.5	4.9	4.1
Sieve 4	4.1	10.7	3.0	1.7	1.8	1.0	1.9
Sieve 5	2.6	2.5	2.1	.8	1.2	1.0	1.2
Sieve 6	7.3	3.3	9.3	3.6	3.6	2.7	4.8
Sieve 7	45.5	23.9	57.0	10.2	15.1	7.4	24.3
Bottom & Outlet	9.7	9.2	7.6	8.2	12.6	5.7	5.1

*
$$\frac{\text{grams rhodamine on perforated plate (sieve)}}{\text{grams rhodamine on stage collector}} \times 100$$

weighted towards the middle fractions (0.3 to 2 microns) and probably overestimates the fraction of material in the respirable size range.

REFERENCE

- [1] H. O'Donnell, T.L. Montgomery, and M. Corn. "Routine Assessment of the Particle Size Weight Distribution of Urban Aerosols," Atmospheric Environment, 4, pp. 1-7 (1970).

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