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**Characteristics of the Aerosol Produced
from Burning Sodium and Plutonium**



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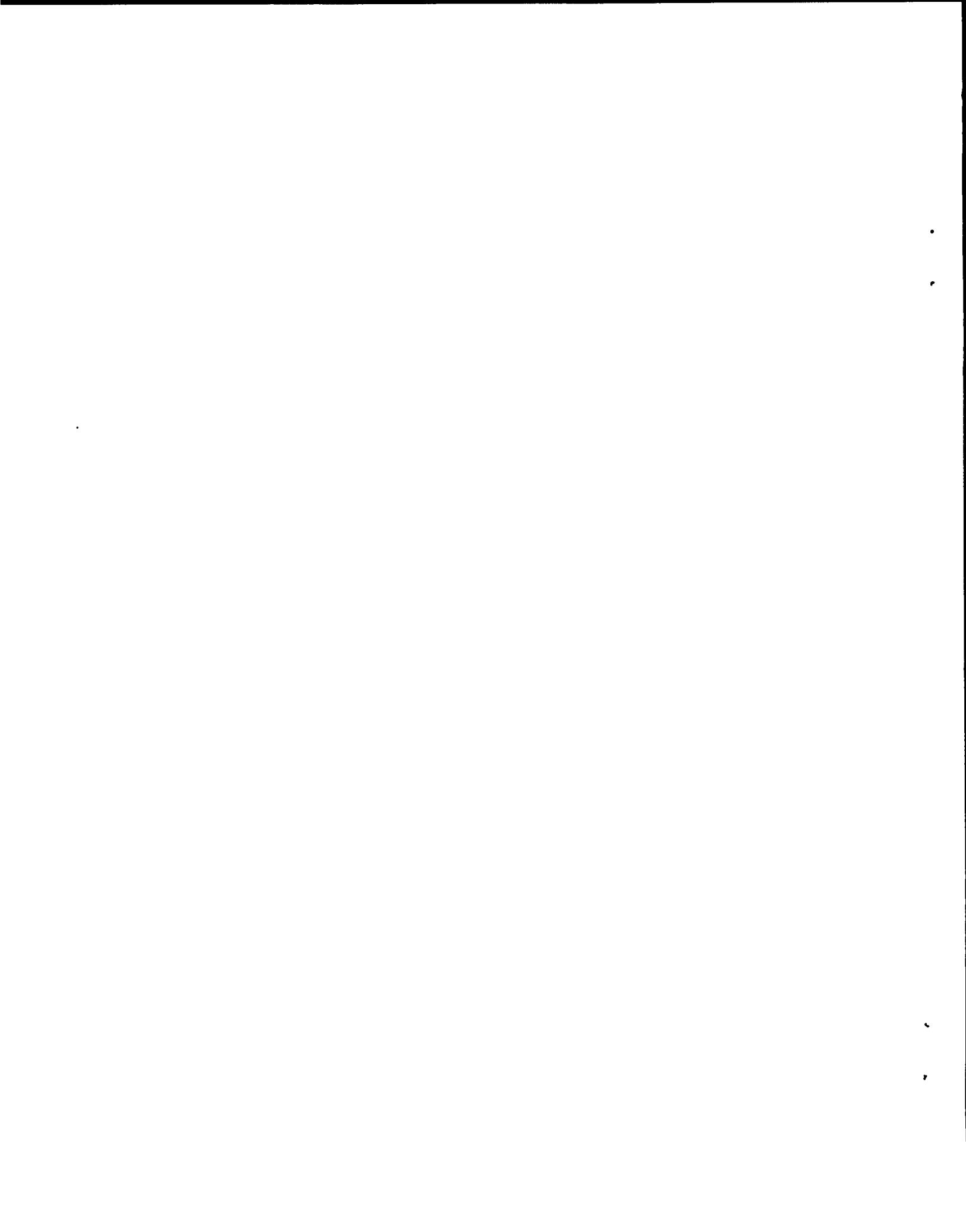
Characteristics of the Aerosol Produced
from Burning Sodium and Plutonium

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ABSTRACT

Safety analysis of sodium-cooled, plutonium-fueled, fast reactor plants must be concerned with the possibility of fires involving these materials. Design of an air cleaning system for such a facility requires basic data defining the aerosol characteristics of sodium and plutonium released during a fire.

Size characteristics of the aerosol produced during sodium and plutonium fires were determined for different atmospheres ranging from 20.8% oxygen, 79.2% nitrogen to 100% nitrogen. Gram quantities of metallic sodium, plutonium-cobalt-cerium alloy, and alpha- and delta-phase plutonium metal were burned separately. The aerosol produced by burning gram quantities of sodium was compared with that produced by a fire involving 600 pounds of sodium. Data were obtained regarding the fraction of plutonium alloy airborne during a plutonium fire. Fires simulating a reactor accident involving both fuel and coolant defined the relative airborne concentrations of plutonium and sodium.

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I. Summary

1. The following aerosol characteristics were determined by burning gram quantities of sodium under various oxygen and humidity conditions.

Count median diameter (C.M.D.) : 0.07 - 0.91 microns (μ)

Geometric standard deviation (σ_g): 1.68 - 3.25

Mass median diameter (M.M.D.) : 0.90 - 14.3 μ

Under small-scale burning conditions sodium aerosol size is not related to oxygen content, but shows some dependence on humidity.

2. Sodium aerosol characteristics, under large-scale (600 pounds) burning conditions at various low oxygen concentrations were:

C.M.D.: 0.20 - 1.09 μ

σ_g : 1.53 - 2.82

M.M.D.: 0.53 - 16.17 μ

Under large-scale burning conditions, sodium aerosol size is not related to oxygen concentration.

3. Sodium aerosols produced from small- and large-scale fires have comparable size characteristics. Aerosol parameters can be determined for any special conditions without building a large burning system.

4. The aerosol collected directly above burning chips of plutonium-cobalt-cerium alloy (57.7% plutonium) showed the following size characteristics.

C.M.D.: 0.04 - 0.09 μ

σ_g : 1.24 - 1.54

M.M.D.: 0.05 - 0.14 μ

5. The aerosol collected directly above burning metallic plutonium turnings (alpha- and delta-phase) showed the following size characteristics.

C.M.D.: 0.02 - 0.06 μ

σ_g : 1.24 - 1.76

M.M.D.: 0.03 - 0.13 μ

6. Oxygen concentration of the burning atmosphere does not affect the particle size of the aerosol produced from burning plutonium metal or alloy.

7. When plutonium-cobalt-cerium alloy is burned, the fraction airborne ranges from 1.8×10^{-7} to 38.8×10^{-7} depending on burn temperature and oxygen concentration.

8. Fires involving plutonium alloy and sodium produce airborne particulates with a plutonium-sodium ratio ranging from 0.34 to less than 0.008%. The high initial ratio is rapidly reduced as the molten sodium blankets the release of plutonium.

II. Introduction

Safety analysis of sodium-cooled, plutonium-fueled, reactor plants must consider the possibility of a fire involving these materials during the maximum credible accident (M.C.A.). To provide design criteria for the plant air cleaning system and to evaluate any potential hazard due to release of radioactive particulates, basic data defining the aerosol characteristics of sodium and plutonium produced during an M.C.A. fire are required.

A test program determined the size characteristics of the aerosol produced during sodium and plutonium fires.

Since a system of this type may be operated at reduced oxygen conditions, aerosol parameters were determined for fires in which the atmosphere consisted of various oxygen-nitrogen mixtures ranging from 20.8% to less than 0.5% oxygen.

Data were also obtained defining the percent of burned plutonium airborne during a fire, and the relative concentrations of airborne sodium and plutonium resulting from a fire involving both reactor fuel and coolant.

III. Small-Scale Sodium Fires

A. Procedures

A glove box was equipped to permit the introduction of various oxygen-nitrogen gas mixtures and to contain the equipment necessary for burning sodium and obtaining aerosol samples for sizing. Oxygen-nitrogen gas mixtures were supplied from Type-H cylinders (water pumped). Each gas was individually metered, mixed, and passed through a column of Drierite to produce a dry gas stream of the desired reduced oxygen concentration. The gas stream was delivered just above the tantalum dish holding the sodium, which is positioned within the copper burning pot during each test run (Fig. 1). Thermocouples placed in holes in the base plate permitted temperature measurement. Burning was limited to gram quantities of freshly cut sodium. Aerosol samples were obtained directly on carbon-coated electron microscope (E.M.) grids, using a battery-operated oscillating thermal precipitator¹ (Fig. 2) located directly above the burning sodium. Oxygen concentration within the dry box was determined using a calibrated oxygen meter.*

*Mine Safety Appliances Company Portable Oxygen Indicator.

To evaluate the effects of humidity, two techniques were employed. When 100% relative humidity was desired, a beaker of water was heated inside the dry box. When intermediate relative humidities (58% and 74%) were desired, the oxygen-nitrogen gas mixture was passed through two large bubblers in series, containing distilled water, before introduction into the dry box.

The possibility of the aerosol sample being modified by exposure to air during transfer from the dry box to the electron microscope was considered. A special transfer box was constructed to permit transfer of the E.M. grid to the electron microscope without any contact with room air. Preliminary tests showed that the sodium aerosol collected on the E.M. grids was not affected by brief contact with room air. Therefore, use of the transfer box was not necessary. All air samples were shadowed with chromium prior to obtaining electron micrographs which were sized on the basis of equivalent area (projected diameter)² using the Zeiss Particle Size Analyzer.* The results were plotted on log-probability paper,³ and the aerosols' count median diameter (C.M.D.) and geometric standard deviation (σ_g) were determined graphically. The aerosol mass median diameter (M.M.D.) was then calculated using the Hatch and Choate⁴ equation, $\text{Log M.M.D.} = \text{Log C.M.D.} + 6.9 \text{ Log}^2 \sigma_g$.

B. Results

Table I details the sodium aerosol produced at various oxygen concentrations and relative humidity conditions. Table II summarizes aerosol characteristics under the four different humidity conditions (dry air, 58% relative humidity,

Carl Zeiss (mfgr.) Particle Size Analyzer, Model TGZ3.

74% relative humidity, and 100% relative humidity). Intermediate relative humidity conditions (58% and 74%) produced an aerosol with the smallest C.M.D. Dry oxygen-nitrogen conditions produced an aerosol with the smallest σ_g , and as a consequence, the smallest aerosol M.M.D. In all runs, C.M.D.'s were below 1μ , and during one run they fell below 0.1μ . A slight error in the relatively high σ_g could result in major variations in the calculated M.M.D. In most instances a plot of the data on log-probability paper indicated a good log-normal size distribution with typical divergence of the data from a perfect log-normal at the extreme data points. The relationship between C.M.D. and oxygen concentration is plotted in Fig. 3 which also distinguishes among the four different humidity conditions. This plot shows no correlation between oxygen content and C.M.D. Figures 4, 5, 6, and 7 show typical electron micrographs of the sodium aerosol under the four different humidity conditions.

Qualitative inspection of the electron micrographs indicated that the concentration of sodium aerosol decreased at lower oxygen concentrations.

IV. Large-Scale Sodium Fires

A. Introduction

Since laboratory tests were limited to burning less than 10 grams of freshly cut sodium and an M.C.A. would involve much larger quantities, it was desirable to evaluate aerosol characteristics when burning relatively large quantities of sodium. Arrangements were made to obtain aerosol samples when 600 pounds of sodium were burned at Atomic International Nuclear Field Laboratory, Canoga Park, California.

B. Test Procedure

Figure 8 is a schematic of the sodium large fires test apparatus at Atomics International.⁵ Approximately 600 pounds of sodium was burned in the 2-foot-diameter burning pot. Liquid oxygen and liquid nitrogen were converted to the gaseous phase, metered, and introduced through a manifold system just above the burning pot. Oxygen analyzers (Beckman Model E-2) were located at the manifold inlet and just before the wet scrubber used to clean the airstream before discharge to the atmosphere (positions 1 and 2). Relative humidity within the burning system was measured by a hygrometer.

The test program was designed to vary (1) oxygen content of the burn atmosphere, (2) sodium temperature, and (3) air velocity through the test system. During the several test runs, nominal oxygen content was varied from 0 to 4%. Air-flow through the system was set at a low rate (10-20 C.F.M.) and a high rate (approximately 200 C.F.M.). Relative humidity within the burning system was less than 25 ppm. All test runs were carried out with sodium temperature ranging between 500 and 540°C.

Sampling ports were located just above the sodium surface (position A), at both 90° bends in the 10-inch-diameter duct leading from the burn chamber to the bubbler and wet scrubber (positions B and C), and just before the bubbler (position D). The several sampling positions would indicate any significant agglomeration effect.

Aerosol samples were obtained for particle size analysis using the oscillating thermal precipitator¹ to collect sodium aerosol directly on carbon-coated E.M. grids. Samples obtained at the Atomics International Nuclear Field Laboratory were scanned with a light microscope and an electron microscope. At Los Alamos, the samples were shadowed with

chromium at 30° before electron micrographs were obtained. These electron micrographs were sized on the basis of equivalent area (projected diameter)² using the Zeiss Particle Size Analyzer. Data were plotted on log-probability paper,³ and C.M.D. and σ_g were determined graphically. Mass median diameter was calculated using the Hatch and Choate equation.⁴

C. Results

Table III details the sodium aerosol characteristics obtained from burning 600 pounds of sodium in various oxygen-nitrogen atmospheres. Table IV details the sodium aerosol characteristics measured under laboratory conditions using dry oxygen and dry nitrogen for comparison with those obtained during the tests at Atomics International. A summary of the laboratory results is also included in Table III.

Table III shows a sodium aerosol C.M.D. between 0.20 and 1.09 μ with no correlation between C.M.D. and oxygen concentration. In comparison, a C.M.D. of 0.50 to 0.78 μ was produced under laboratory burn conditions using dry oxygen and nitrogen. It should be noted when comparing aerosol characteristics from laboratory and large-scale burn conditions, that the smallest aerosol C.M.D. was produced with a nitrogen atmosphere. In laboratory test runs using dry gas mixtures, the oxygen content was at or above 1.6%. If we compare sodium aerosol C.M.D. under the two burn conditions at oxygen concentrations at or above 1%, the C.M.D. range from large-scale burning is 0.46 to 1.09 μ which agrees with laboratory results (0.50 to 0.78 μ).

Calculated M.M.D. ranged from 0.53 to 16.17 μ under large-scale burn conditions. This wide range is due to the relatively large σ_g . The effect of a slight variation in σ_g on the calculated M.M.D. was mentioned previously.

Smallest aerosol C.M.D. and M.M.D. were produced during those test runs with a nitrogen atmosphere. During the test runs at a high flow rate this was especially pronounced, suggesting that system flow rate may be a significant test parameter in setting aerosol characteristics. There was no size difference in the aerosol collected at positions A and D, showing that significant agglomeration did not occur in the system.

During this test program, air samples were also obtained by Atomics International personnel using cascade impactors. Their samples showed the following size parameters.⁶

C.M.D.: 0.14 - 1.2 μ

σ_g : 1.3 - 2.7

M.M.D.: 1.0 - 2.0 μ

These results are comparable to those obtained using electron microscopy at Los Alamos except for a smaller range in M.M.D. values.

The similarity of the sodium aerosol produced from small-scale and large-scale fires suggests that the aerosol produced during any specific conditions can be evaluated without building a complex, large-scale, test facility.

The electron micrographs obtained from these samples are shown in Figs. 9-13. Each is a composite showing the sample obtained at each position during fixed operating conditions.

V. Plutonium Aerosol

A. Background

Several investigators have attempted to determine the aerosol characteristics of airborne plutonium produced from fires. Carter^{7,8} found an aerodynamic M.M.D. of 8.5 to 9.7 μ when sampling with a cascade impactor. He confirmed these values by autoradiography of fallout samples. This is

equivalent to a unit density M.M.D. range of 29 to 33 μ . Using cascade impactors, Stewart⁹ found M.M.D.'s (unit density) ranging from 1 to 16 μ . He suggested a single particle size distribution to define the airborne plutonium aerosol. This aerosol had an M.M.D. of approximately 1.5 μ . Sherwood¹⁰ used autoradiographic techniques on filter paper samples to evaluate the particle size of airborne plutonium in radiochemical laboratories. He found the airborne plutonium generally attached to inactive particles of dust. Using autoradiography, Moss et al.¹¹ found an M.M.D. of 0.14 to 0.65 μ when sampling for plutonium outside the glove boxes in metal fabrication areas. They estimated the size of plutonium aerosols by relating the number of tracks arising from a particle of plutonium to the mass. It was evident from these data that the best way to view and characterize these small plutonium aerosols was by electron microscopy.

The present test was designed to characterize the aerosol present just above a plutonium fire. The air sampler selected collected the aerosol directly on E.M. grids and permitted the use of electron microscopy to evaluate any sub-micron aerosol produced.

B. Procedures

Because of the toxicity of plutonium, all burning apparatus and sampling equipment had to be located in a glove box, and all sampling manipulations carried out through glove ports. Approximately 50 to 100 grams of plutonium or plutonium-cobalt-cerium alloy were burned in a tantalum dish which fitted inside the copper burning pot shown in Fig. 1. For plutonium burning tests, special oxygen-nitrogen gas cylinders were prepared, and each cylinder was analyzed using a gas chromatograph. The oxygen-nitrogen gas mixture was

supplied to the burning pot to evaluate the effects of oxygen concentration on aerosol characteristics. Thermocouple holes in the copper base plate permitted measurement of the burning pot temperature. Relative humidity within the glove box was consistently below 25 ppm.

Since the air sampler could not be used outside the glove box after completion of the experiment because of contamination, a relatively inexpensive sampler was desirable. The all-glass, point-to-plane electrostatic precipitator (E.S.P.) shown in Fig. 14 was used. This sampler permits aerosol collection directly on carbon-coated E.M. grids. The unit is operated at a flow rate of 5 liters per minute and a high voltage potential of 9,000 to 10,000 volts a.c. provided by a conventional neon-lamp transformer. Previous work¹² has shown that this sampler has representative aerosol collection characteristics comparable to those defined by several thermal and electrostatic precipitators. Figure 15 shows the E.S.P. just above the plutonium burning pot inside the glove box. The distance between the burning pot and the E.M. grid was 23 centimeters.

After sampling, the E.M. grid was removed from the glove box and monitored for alpha activity to estimate the quantity of plutonium collected. The grids were then alpha-counted and shadowed with chromium or platinum at 30°. Electron micrographs were obtained from random grid openings.

All electron micrographs (enlarged photographically to 50,000X) were sized on the basis of equivalent area (projected diameter)² using the Zeiss Particle Size Analyzer, and the data obtained were plotted on log-probability paper.³

Count median diameter and geometric standard deviation were determined graphically. Mass median diameter was calculated using the Hatch and Choate⁴ equation which also

assumes a log normal distribution, $\text{Log M.M.D.} = \text{Log C.M.D.} + 6.9 \text{ Log}^2 \sigma_g$.

C. Results

Table V summarizes the aerosol characteristics from burning plutonium-cobalt-cerium alloy (57.7% plutonium) and plutonium metal (alpha- and delta-phase). In all instances the C.M.D. was below 0.1μ and the M.M.D. below 0.15μ . There was no correlation between aerosol size and oxygen concentration. The aerosol C.M.D. produced from burning alpha- and delta-phase plutonium was somewhat smaller than that resulting from burning the alloy.

The small particle size (C.M.D. of 0.02 to 0.09μ) shows that careful attention must be given to the design of air cleaning systems.

Figures 16-19 show the aerosol collected while the plutonium alloy or metal was burned at four different oxygen concentrations. These electron micrographs show the typical aerosol collected and sized. Figure 20 shows the background within the glove box when no burning was taking place. The large particle in this sample is approximately 0.5μ and is similar to the few large particles present in Figs. 16-19.

Since the plutonium aerosol C.M.D. was as small as 0.02μ , it was feared that the platinum or chromium deposited on the E.M. grid during shadowing might present an artifact. Figure 21 shows a grid shadowed on both sides at a magnification of 50,000 times; the shadowing material presents no background problem.

Several of the samples collected during burning of delta-phase plutonium showed small amounts of a relatively large chain-structured aerosol. This aerosol was not present in samples taken when burning plutonium-cobalt-cerium alloy or

alpha-phase plutonium. The possibility that gallium present in delta-phase plutonium produced this chain-structured aerosol was investigated. Figure 22 shows the aerosol produced from burning gallium metal. Figure 23 shows the chain-structured material present when delta-phase plutonium was burned. Because of this similarity, the chain-structured material was omitted when sizing the aerosol collected from burning delta-phase plutonium.

VI. Airborne Plutonium

To fully evaluate the potential hazard from a plutonium fire, it is necessary to estimate what fraction of the material burned would be airborne. Stewart⁹ has found that from 2.1×10^{-2} to 6×10^{-5} of burned plutonium metal or alloy is airborne. His tests were conducted under oxygen concentrations at or above 20.8% with nitrogen constituting the remainder of the burn atmosphere. A limited test program was carried out at Los Alamos to obtain similar information for reduced oxygen conditions.

Plutonium-cobalt-cerium alloy (2.0 grams) was placed in the tantalum boat located in the center of the quartz tube shown in Fig. 24. Oxygen-nitrogen gas mixtures ranging from 0.4 to 2.76% oxygen flowed over the tantalum boat at a velocity of approximately 300 feet per minute. This gas velocity was selected to simulate conditions during a postulated M.C.A. No attempt was made to evaluate the effect of varying gas velocity past the burning plutonium alloy. After a combustion furnace was brought to temperature, the quartz tube was positioned in the furnace and the entire gas mixture passing over the plutonium was sampled with an AA Millipore filter. This closed-system test procedure guaranteed collection of any airborne particulate material. There was no

attempt to compensate for any plate-out on any surface between the tantalum boat and the sampling Millipore filter. The Millipore filters were alpha-counted to determine what fraction of the original 2.0 grams of alloy was airborne.

Table VI and Figure 25 summarize the results obtained. At 500°C the airborne fraction is about 2×10^{-7} and is independent of oxygen concentration. At 700°C the airborne fraction ranges from 4×10^{-7} to 4×10^{-6} with the larger value at the higher oxygen concentration.

VII. Sodium-Plutonium Fires

A fire under M.C.A. conditions probably would involve both plutonium and sodium. To simulate an accident of this type, the rocking furnace shown partially assembled in Fig. 26 was used. Sodium metal and plutonium alloy were inserted into the vertical tube, heated to a molten state, and thoroughly mixed by rocking the Tee-shaped furnace through an angle of 60°. During heating and rocking, a nitrogen atmosphere was maintained within the furnace. After being rocked at 550 to 600°C, the molten mixture was dumped into the burning pot previously described. A 2.67% oxygen, 97.33% nitrogen gas mixture was supplied to the burning pot. Air samples were obtained using Millipore filter field monitors, and the relative concentrations of airborne plutonium and sodium were determined. Figure 27 shows the test apparatus in the glove box.

During the tests, the initial melt consisted of 45 grams of sodium and 20 grams of plutonium-cobalt-cerium alloy (57.7% plutonium). To minimize contamination from plutonium within the glove box, filter samples were removed from their plastic holder after removal from the glove box.

Table VII summarizes the results obtained in two

different test series. The "Reference Time" shows the time interval between dumping of the sodium-plutonium mixture out of the rocking furnace and the start of sampling. In Test Series B, the molten sodium-plutonium mixture was agitated after sample 4 and again after sample 8. The sampling period for each sample was one minute.

Excluding sample A-1, the relative concentration of airborne plutonium to sodium ranges between 0.34% and < 0.008%. In all likelihood, the single high value (sample A-1) was caused by contamination of the Millipore filter during handling in the dry box. These data, with the exception of sample A-1, are plotted in Fig. 28 with sample B-7 (Pu/Na < 0.008%) assumed to be 0.001%. These data indicate that the sodium tends to blanket the release of plutonium after the simulated accident (dumping of the molten mixture from the rocking furnace), and that this trend is reversed when the mixture is agitated. This trend is shown by the three sets of data points in Fig. 28 (A-2 through A-4, B-1 through B-4, and B-5 through B-7). The remaining data points (B-8 through B-11) fall within the range of values similarly outlined but do not show any consistent trend.

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TABLE I
SODIUM AEROSOL SIZE

Test Run No.	Count Median Diam. (C.M.D.) Microns	Geometric Standard Deviation (g)	Mass Median Diam. (a) (M.M.D.) Microns	No. of Particles Sized	Oxygen Content (b) (%)	Temp (°C)	Relative Humidity (%)
Na 8A	0.61 0.75	1.99 1.73	2.56 1.88	455 336	1.7	Not measured	Dry gas
Na 9A	0.73 0.73	1.78 1.78	1.97 1.97	288 306	1.7	Not measured	Dry gas
Na 12B	0.55	2.10	2.92	455	Not measured	400	Dry gas
Na 12C	0.50	2.08	2.50	498	Not measured	400	Dry gas
Na 13	0.52 0.68	1.69 2.06	1.20 3.26	490 301	2.8	670	Dry gas
Na 14	0.68 0.60	1.84 2.15	2.04 3.54	263 233	2.5	400	Dry gas
Na 15A	0.57	1.94	2.17	205	1.6	430	Dry gas
Na 15C	0.73 0.78	1.71 1.68	1.75 1.79	524 476	6.2	450	Dry gas
Na 16A	0.17	2.53	2.30	512	0.7	540-600	58 (c)
Na 16B	0.22	3.25	14.3	344	4.3	550-600	58 (c)
Na 16C	0.28	3.05	11.8	491	2.5	590-600	58 (c)
Na 16D	0.07	2.75	1.54	597	~6.7	540-590	58 (c)
Na 18A	0.91	2.17	5.64	116	2.1	630	100 (d)
Na 18B	0.77	----	----	101	4.9	600	100 (d)
Na 18C	0.43	2.53	5.81	206	2.9	660	100 (d)
Na 19A	0.76	2.11	4.03	134	1.8	390	100 (d)
Na 19B	0.40	2.53	5.40	136	~12.	530	100 (d)
Na 19D	0.60	2.38	6.0	40	4.9	500	100 (d)
Na 20A	0.38	2.21	2.55	483	2.7	490	74 (c)
Na 20B	0.38	2.24	4.75	213	5.7	490	74 (c)
Na 26	0.33	1.78	0.90	305	20.8	460	(e)
Range	0.07- 0.91	1.68- 3.25	0.90- 14.3	--- ---	0.7- 20.8	400- 670	--- ---

- (a) M.M.D. calculated from Hatch and Choate Equation. $\text{Log M.M.D.} = \text{Log C.M.D.} + 6.9 \text{Log}^2 \sigma_g$.
 (b) Oxygen content determined with MSA oxygen meter.
 (c) Humidity condition produced by passing oxygen-nitrogen gas stream through two large bubblers prior to introduction into glove box.
 (d) Humidity condition produced by heating beaker of water within glove box.
 (e) Humidity measurement not obtained during run. Room air, with relative humidity of approximately 20-30%, used during test.

TABLE II
SODIUM AEROSOL SIZE AS FUNCTION OF RELATIVE HUMIDITY

<u>Relative Humidity</u>	<u>C.M.D. (μ)</u>	<u>σ_g</u>	<u>M.M.D. (μ)</u>	<u>No. of Runs</u>
Dry air	0.50 - 0.78	1.68 - 2.15	1.20 - 3.54	8
58%	0.07 - 0.28	2.53 - 3.05	1.54 - 14.3	4
74%	0.38	2.21 - 2.24	2.55 - 4.75	2
100%(a)	0.40 - 0.91	2.11 - 2.53	4.03 - 5.81	5

(a) Run 19D, where less than 100 particles were sized, has been excluded.

Run 26 has been excluded since the humidity measurement was not obtained during the test.

TABLE III
SODIUM AEROSOL CHARACTERISTICS FROM ATOMICS INTERNATIONAL FIRES

Figure	Conditions (a)	Position				
		A	B	C	D	
3	500°C 11.3 C.F.M. nitrogen	0.59 μ	0.41 μ	0.40 μ	No sample	C.M.D.
		1.79	1.79	1.56		σ
		1.65 μ	1.15 μ	0.72 μ		M.M.D.
4	505°C 17.0 C.F.M. nitrogen	0.36 μ	No sample	0.35 μ	0.31 μ	C.M.D.
		2.10		1.93	2.16	σ
		1.91 μ		1.30 μ	1.86 μ	M.M.D.
5	540°C 11.3 C.F.M. 1.16% O ₂ 98.84% N ₂	(b)	(b)	0.46 μ	No sample	C.M.D.
				2.56		σ
				6.67 μ		M.M.D.
6	535°C 19 C.F.M. 1.9% O ₂ 98.1% N ₂	0.92-0.94 ^(c) μ	0.72 μ	0.98 μ	0.92-0.94 ^(c) μ	C.M.D.
		(d)	2.31	2.62	(d)	σ
		(d)	6.34 μ	16.17 μ	(d)	M.M.D.
7	535°C 19 C.F.M. 3.9% O ₂ 96.1% N ₂	0.59 μ	0.64 μ	0.72 μ	1.09 μ	C.M.D.
		2.82	2.17	2.04	2.24	σ
		15.34 μ	3.97 μ	3.31 μ	13.60 μ	M.M.D.
8	535°C 202 C.F.M. 0.18% O ₂ 99.82% N ₂	0.28 μ	(b)	0.28 μ	0.20 μ	C.M.D.
		1.57		2.18	2.38	σ
		0.53 μ		1.76 μ	3.40 μ	M.M.D.
9	505°C 192 C.F.M. nitrogen	0.35 μ	0.21 μ	0.20 μ	No sample	C.M.D.
		1.53	2.08	2.26		σ
		0.61 μ	1.05 μ	1.50 μ		M.M.D.
LASL (e)		0.50-0.78 μ C.M.D.				
Lab		1.68-2.15 μ σ				
Data		1.20-3.54 μ M.M.D.				
		1.6-6.2% oxygen				

- (a) Sodium temperature, system flow rate, test gas.
 (b) Samples could not be sized.
 (c) Samples from positions A & D were not labeled in field. C.M.D.'s given are for each sampling position. It is not possible to distinguish between these two samples.
 (d) Data did not fit log normal distribution, so M.M.D. could not be calculated using the Hatch and Choate Equation.
 (e) Only those Lab runs using "Dry Gas."

TABLE IV
SODIUM AEROSOL CHARACTERISTICS FROM LABORATORY FIRES

<u>Test Run No.</u>	<u>C.M.D. (μ)</u>	<u>σ_g</u>	<u>M.M.D. (μ)</u>	<u>No. of Particles Sized</u>	<u>Oxygen Content (%)</u>	<u>Temperature (°C)</u>
8A	0.61 0.75	1.99 1.73	2.56 1.88	455 336	1.7	Not measured
9A	0.73 0.73	1.78 1.78	1.97 1.97	288 306	1.7	Not measured
12B	0.55	2.10	2.92	455	Not measured	400
12C	0.50	2.08	2.50	498	Not measured	400
13	0.52 0.68	1.69 2.06	1.20 3.26	490 301	2.8	670
14	0.68 0.60	1.84 2.15	2.04 3.54	263 233	2.5	400
15A	0.57	1.94	2.17	205	1.6	430
15C	0.73 0.78	1.71 1.68	1.75 1.79	524 476	6.2	450
Range	0.50-0.78	1.68-2.15	1.20-3.54		1.6-6.2	400-670
A.I. Fires	0.20-1.09	1.53-2.82	0.53-16.17		0.0-3.9	500-535

TABLE V
PLUTONIUM AEROSOL CHARACTERISTICS

<u>Material Burned</u>	<u>Oxygen Content (%)</u>	<u>Temperature (°C)</u>	<u>C.M.D. (μ)</u>	<u>σ_g</u>	<u>M.M.D. (μ)</u>
Pu-Co-Ce	20.8	550-575	0.04	1.24	0.05
Pu-Co-Ce	8.8	500-550	0.08	1.45	0.13
Pu-Co-Ce	1.7	510	0.08	1.54	0.14
Pu-Co-Ce	0.49	505	0.09	1.41	0.13
None	20.8	25	---	---	---

Pu (α phase)	20.8	575	0.02	1.33	0.03
Pu (α phase)	8.8	525	0.05 0.03	1.72 1.49	0.13 0.05
Pu (α phase)	1.7	500	0.06 0.03	1.64 1.76	0.13 0.08
Pu (α phase)	0.49	495	0.06	1.46	0.09
None	20.8	25	~ 0.5-0.6	---	---

Pu (δ phase)	20.8	550	0.04	1.24	0.05
Pu (δ phase)	10.6	525	0.05	1.38	0.06
Pu (δ phase)	2.67	505	0.04	1.55	0.07
Pu (δ phase)	0.55	500	0.03	1.47	0.05

TABLE VI
 FRACTION PLUTONIUM AIRBORNE DURING FIRE

<u>Oxygen Concentration (%)</u>	<u>Temperature (°C)</u>	<u>Fraction Pu Airborne</u>
1.9	700	38.8×10^{-7}
0.4	700	4.2×10^{-7}
2.76	500	1.9×10^{-7}
0.5	500	1.8×10^{-7}

TABLE VII

RELATIVE AIRBORNE CONCENTRATION OF PLUTONIUM AND SODIUM

<u>Test Series</u>	<u>Sample Number</u>	<u>Reference Time (min)</u>	<u>Sodium Collected (mg)</u>	<u>Plutonium Collected (mg)</u>	<u>Pu/Na (%)</u>
A	1	0	0.96	0.194	20.2
	2	1.5	1.08	0.002	0.19
	3	3.0	1.20	0.004	0.34
	4	7.0	9.34	0.007	0.08

B	1	0	1.06	0.0017	0.16
	2	1.5	1.42	0.0008	0.06
	3	3.0	1.49	0.0005	0.03
	4	4.5	3.16	0.0002	0.01
	5	7.0	2.31	0.0014	0.06
	6	8.5	4.79	0.0005	0.01
	7	10.0	0.38	< 0.00003	< 0.008
	8	11.5	1.91	0.0004	0.02
	9	14.0	2.00	0.0001	0.01
	10	15.5	1.46	0.0007	0.05
	11	18.5	1.68	0.0005	0.03

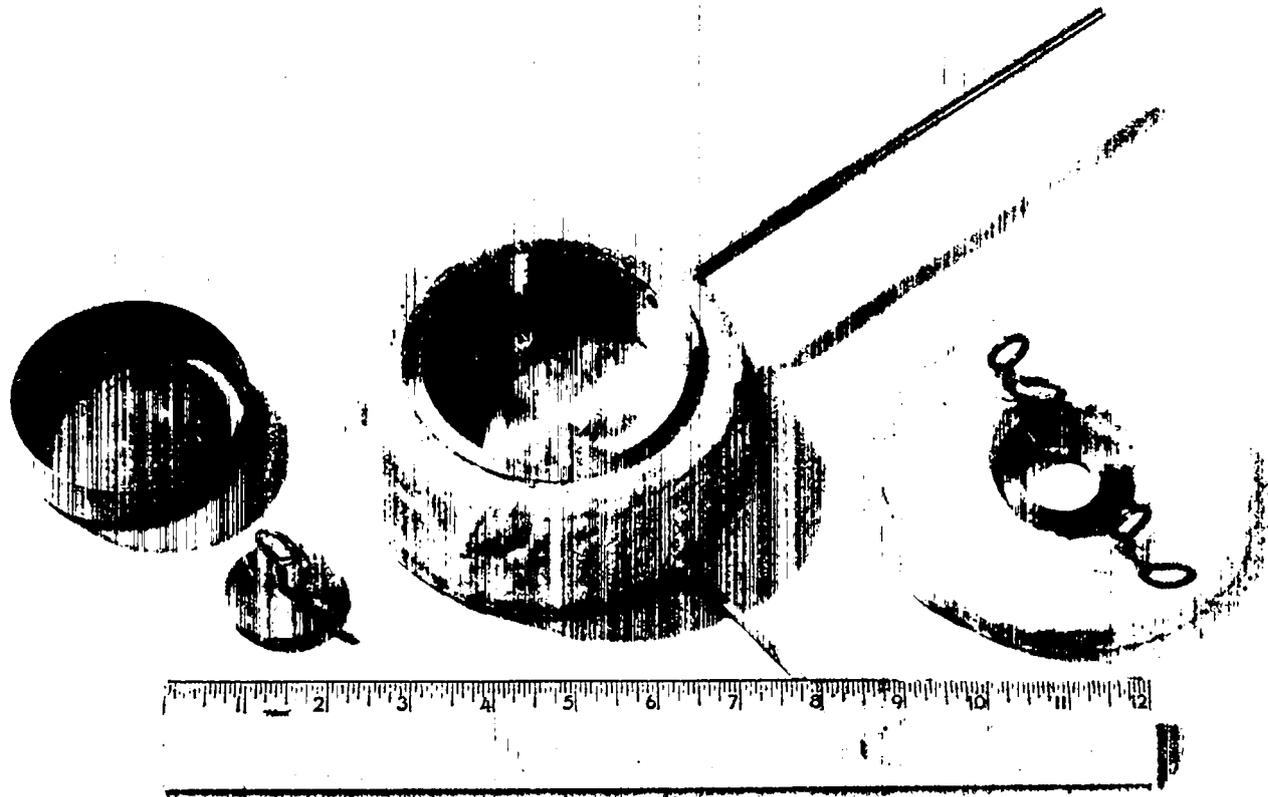


Fig. 1. Copper Burning Pot with Tantalum Dish.

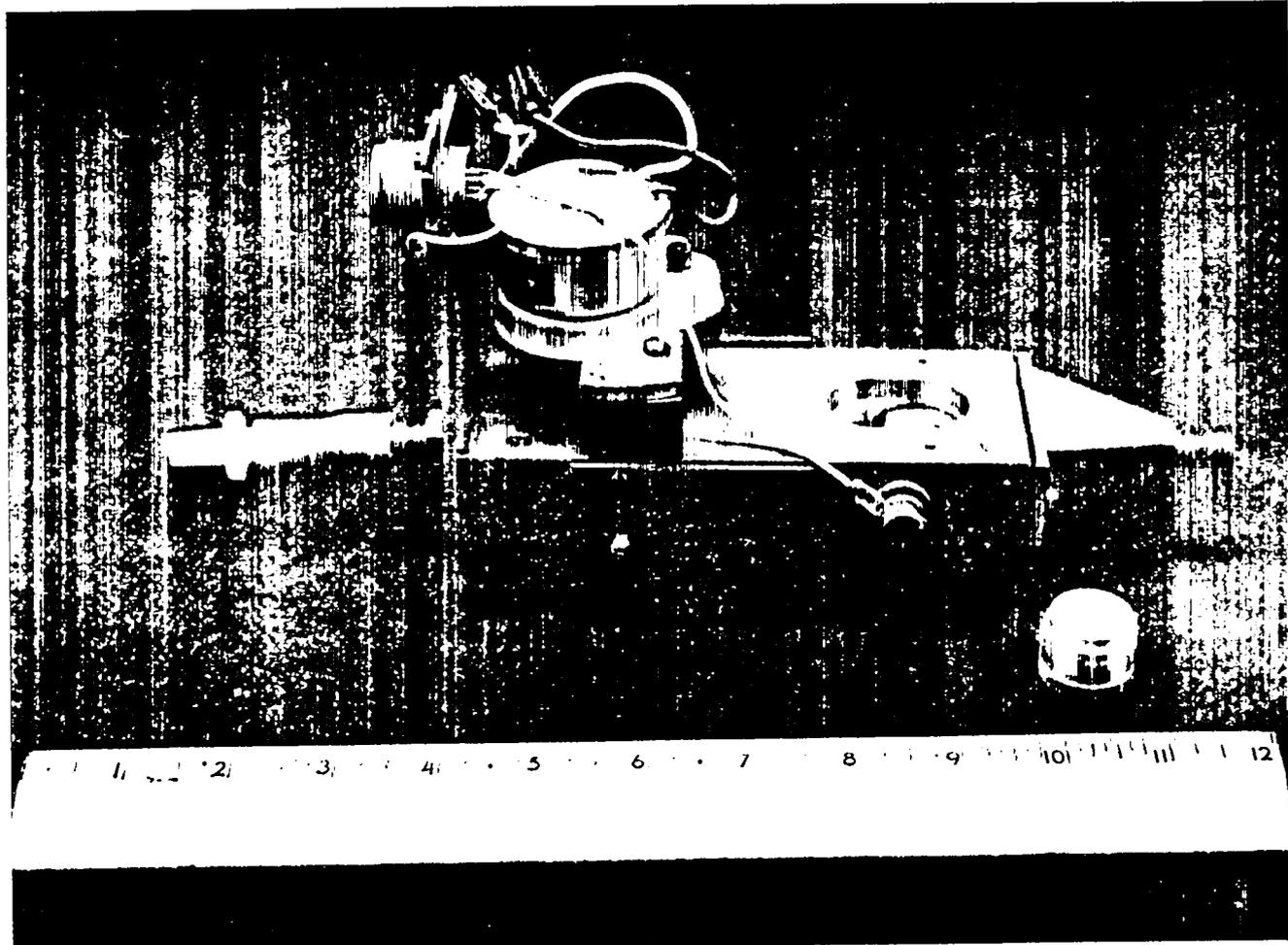


Fig. 2. Battery-Operated Oscillating Thermal Precipitator.

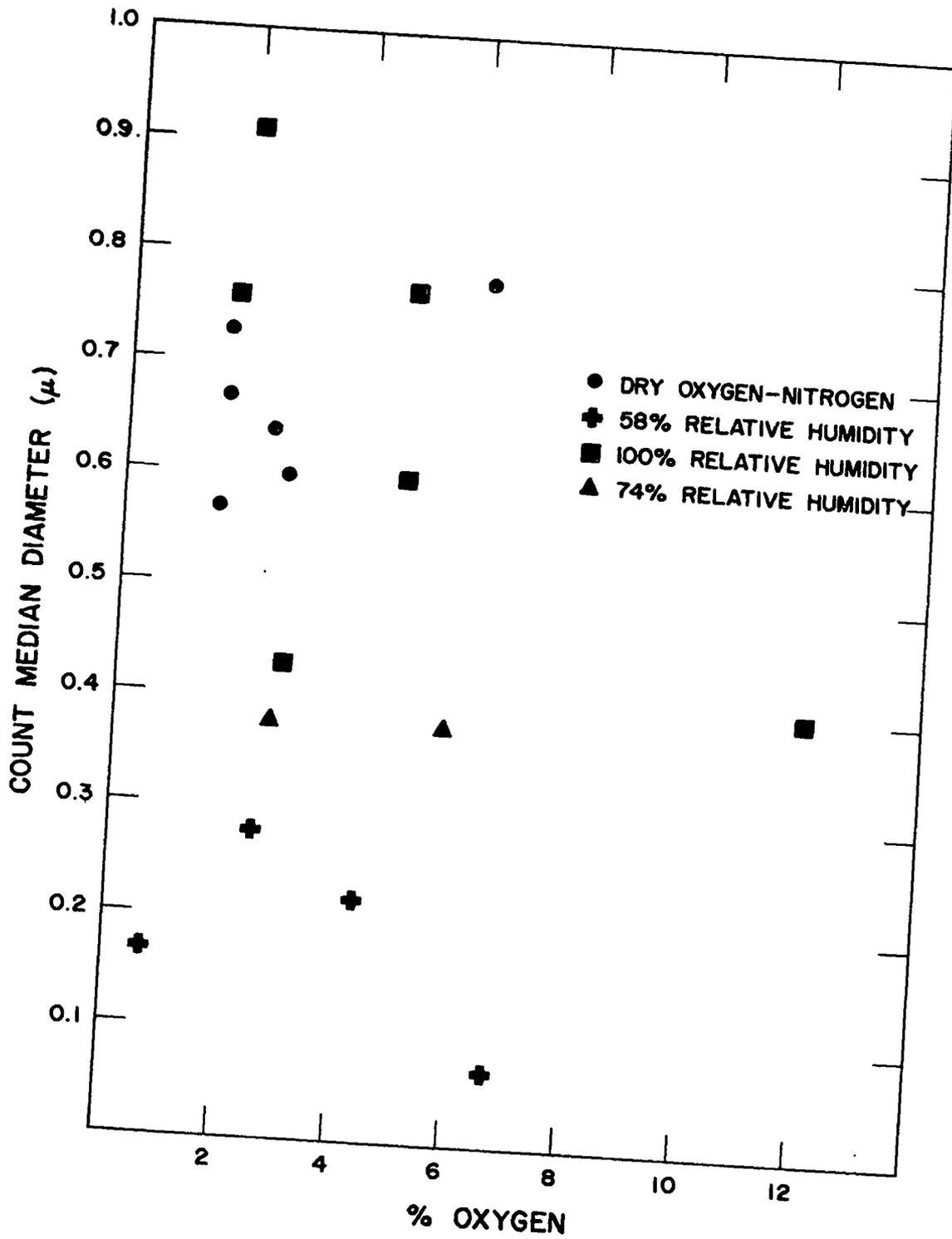


Fig. 3. Variation of Sodium Aerosol C.M.D. vs % Oxygen.

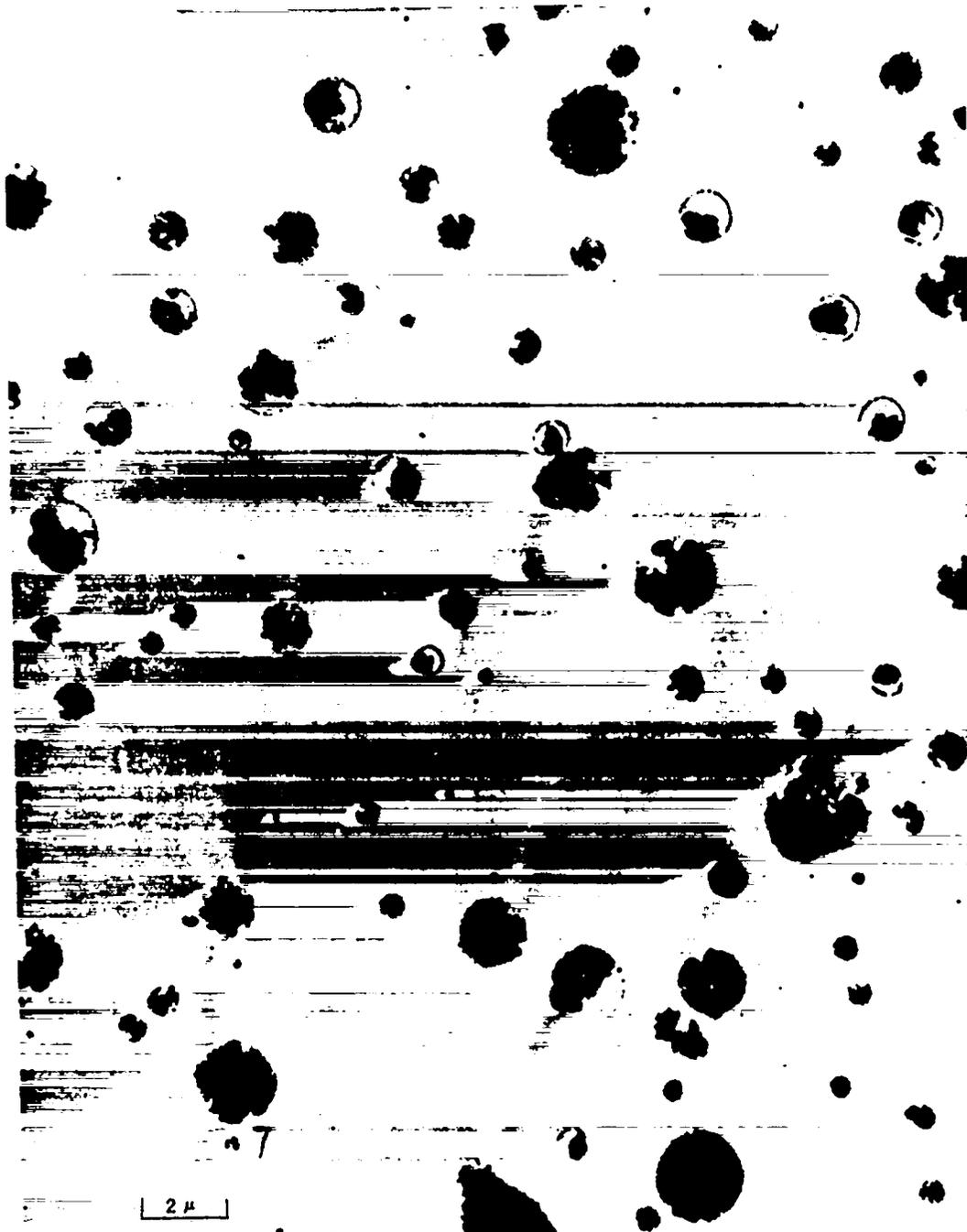


Fig. 4. Typical Aerosol Produced by Burning Sodium in Dry Oxygen-Nitrogen Mixtures. Shadowed with Chromium at 30°.



Fig. 5. Typical Aerosol Produced by Burning Sodium in Oxygen-Nitrogen Mixtures at 58% Relative Humidity. Shadowed with Chromium at 30°.

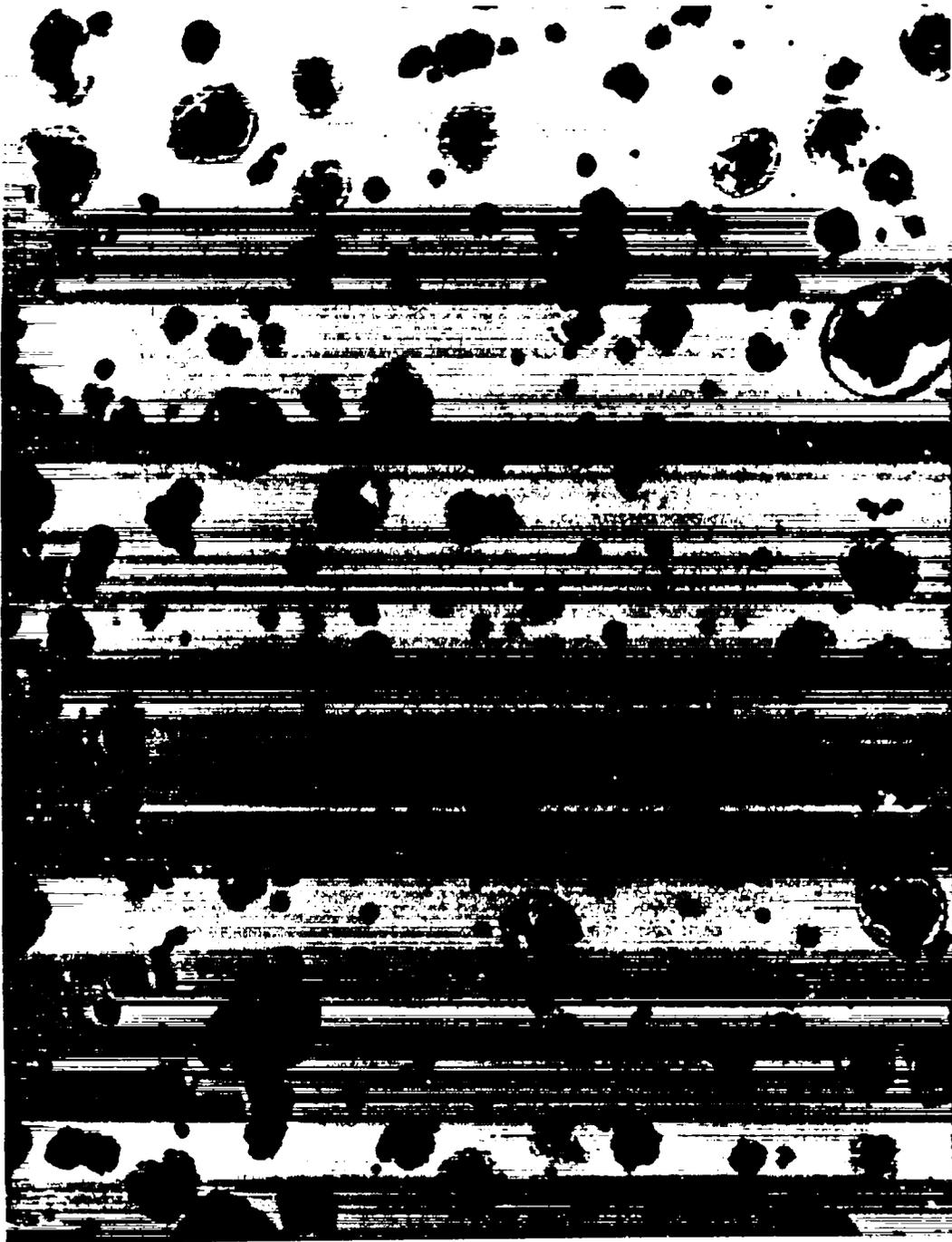


Fig. 6. Typical Aerosol Produced by Burning Sodium in Oxygen-Nitrogen Mixtures at 74% Relative Humidity.



Fig. 7. Typical Aerosol Produced by Burning Sodium in Oxygen-Nitrogen Mixtures at 100% Relative Humidity. Shadowed with Chromium at 30°.

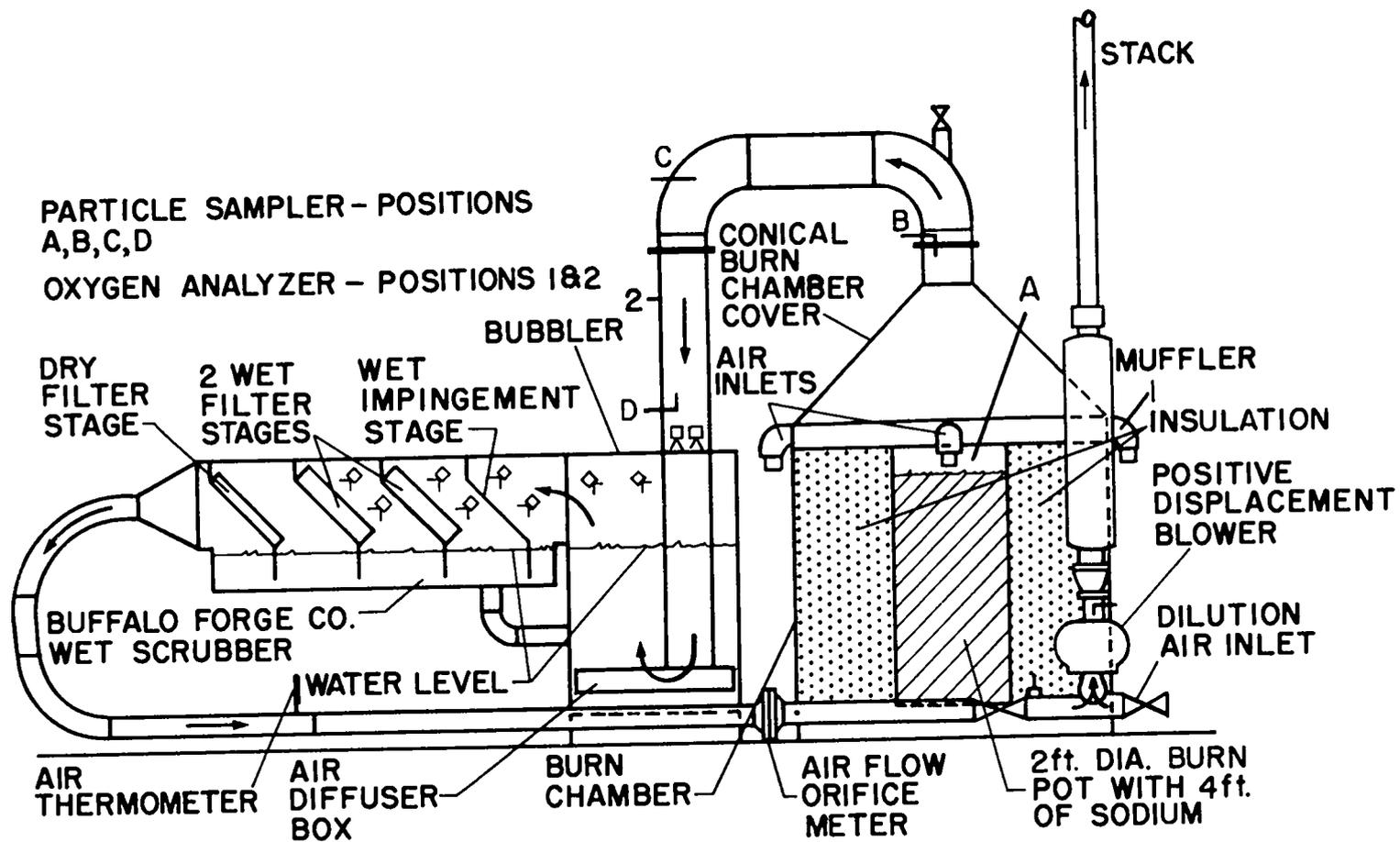


Fig. 8. Atomics International Large Fires Test Apparatus.

POSITION AC.M.D. 0.59μ σ_g 1.79M.M.D. 1.65μ POSITION BC.M.D. 0.41μ σ_g 1.79M.M.D. 1.15μ POSITION CC.M.D. 0.40μ σ_g 1.56M.M.D. 0.72μ

Fig. 9. Typical Aerosol Produced during Sodium Burning Experiment.

Operating Conditions: Sodium Temp., 500°C ; Flow Rate, 11.3 C.F.M.;
Nitrogen Atmosphere.

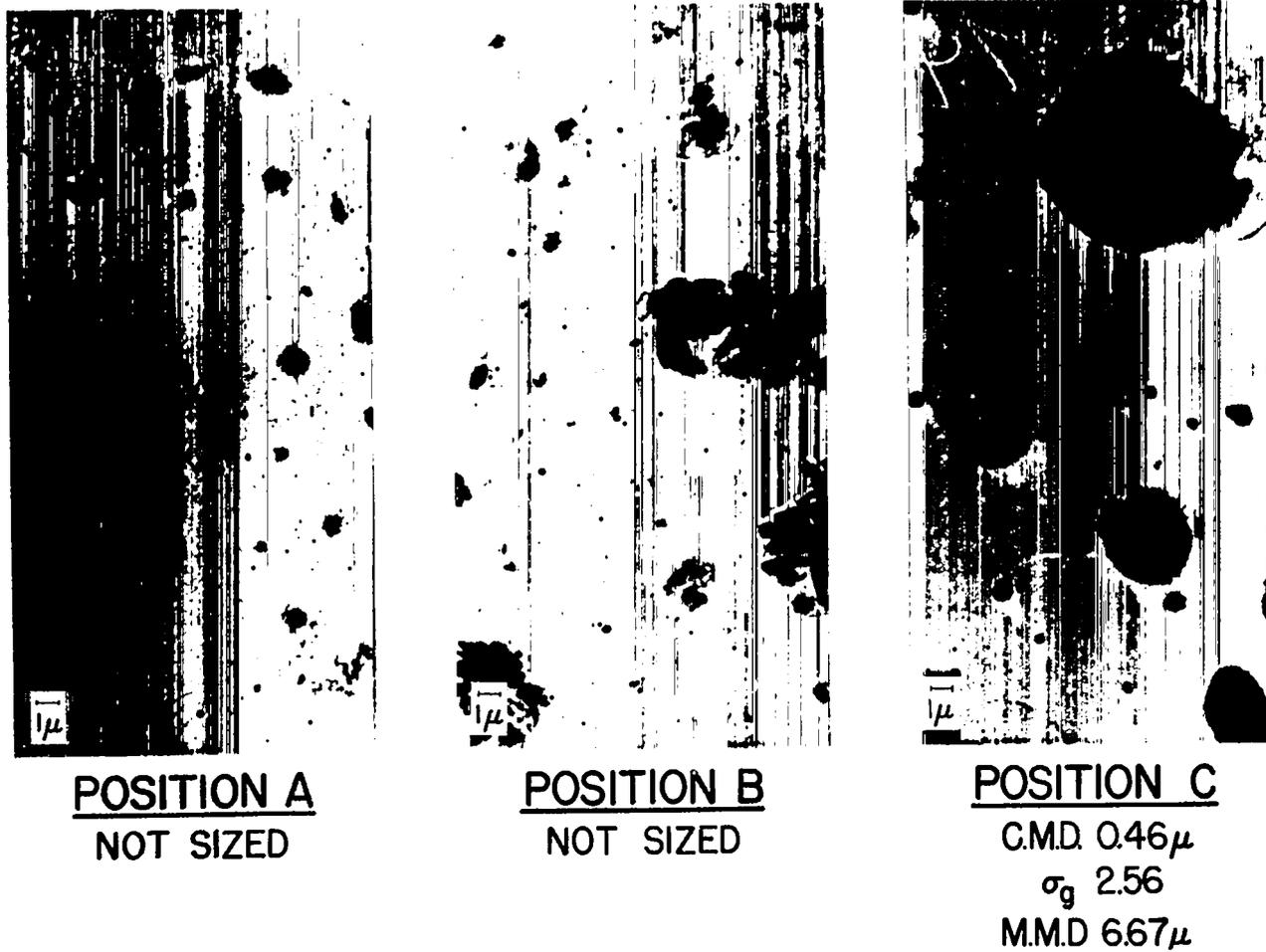


Fig. 10. Typical Aerosol Produced during Sodium Burning Experiment.
Operating Conditions: Sodium Temp., 540°C ; Flow Rate, 11.3 C.F.M.;
1.16% Oxygen Atmosphere.



POSITION B

C.M.D. 0.72μ , σ_g 2.31, M.M.D. 634μ



POSITION C

C.M.D. 0.98μ , σ_g 2.62, M.M.D. 16.17μ

Fig. 11. Typical Aerosol Produced during Sodium Burning Experiment.

Operating Conditions: Sodium Temp., 535°C ; Flow Rate, 19.0 C.F.M.;
1.9% Oxygen Atmosphere.

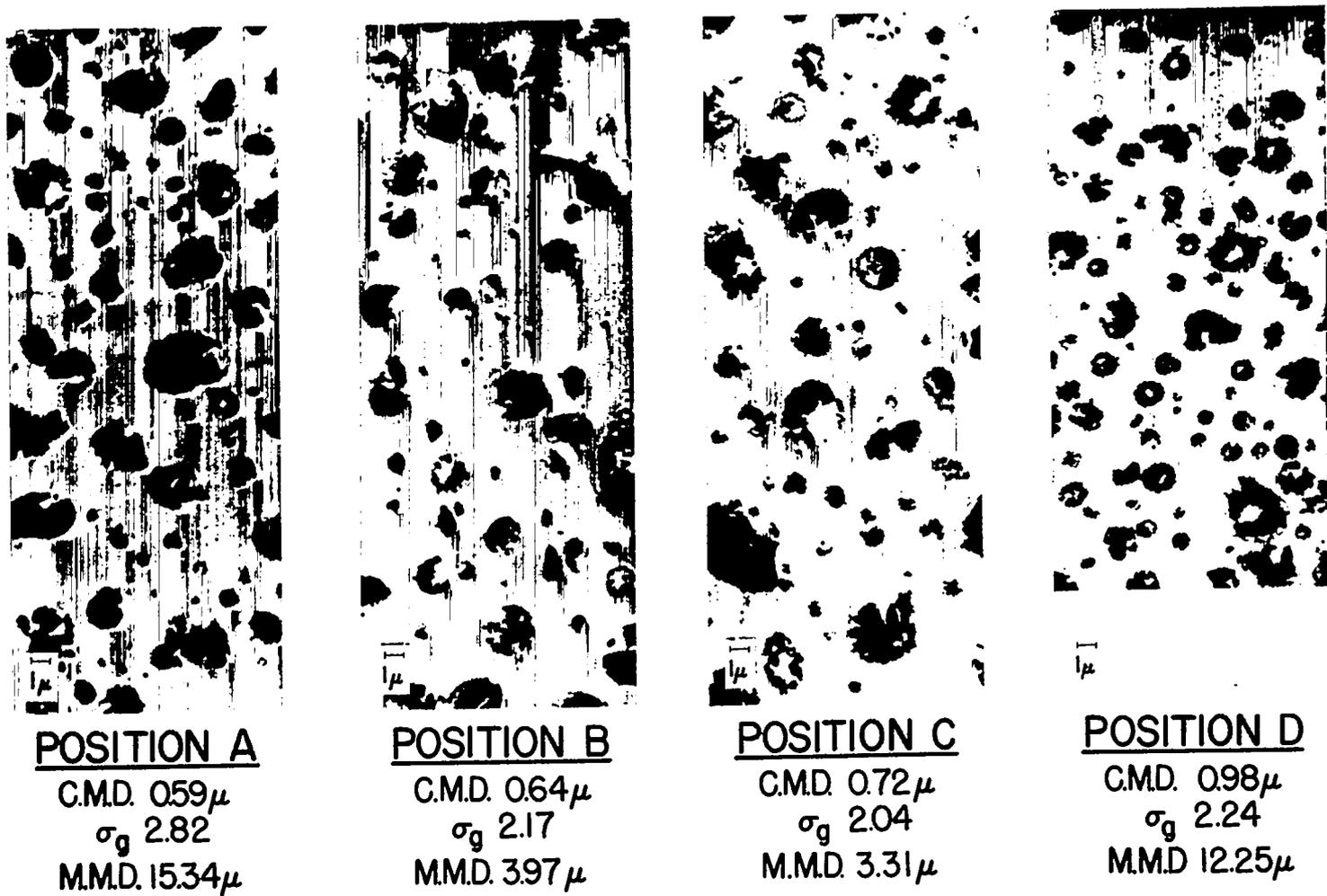


Fig. 12. Typical Aerosol Produced during Sodium Burning Experiment.

Operating Conditions: Sodium Temp., 535°C; Flow Rate, 19.0 C.F.M.;
3.9% Oxygen Atmosphere.

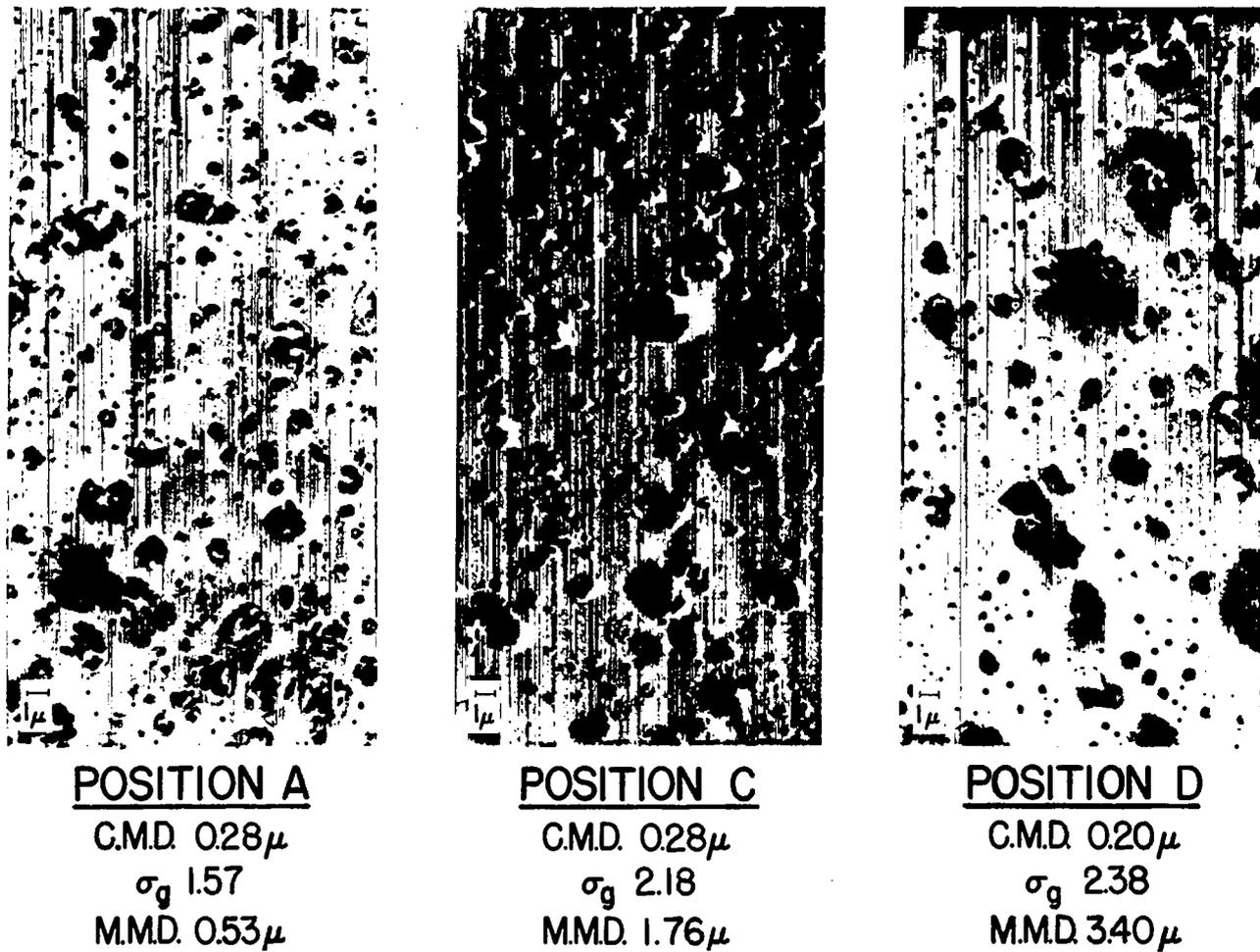


Fig. 13. Typical Aerosol Produced during Sodium Burning Experiment.

Operating Conditions: Sodium Temp., 535°C ; Flow Rate, 202 C.F.M.;
 0.18% Oxygen Atmosphere.

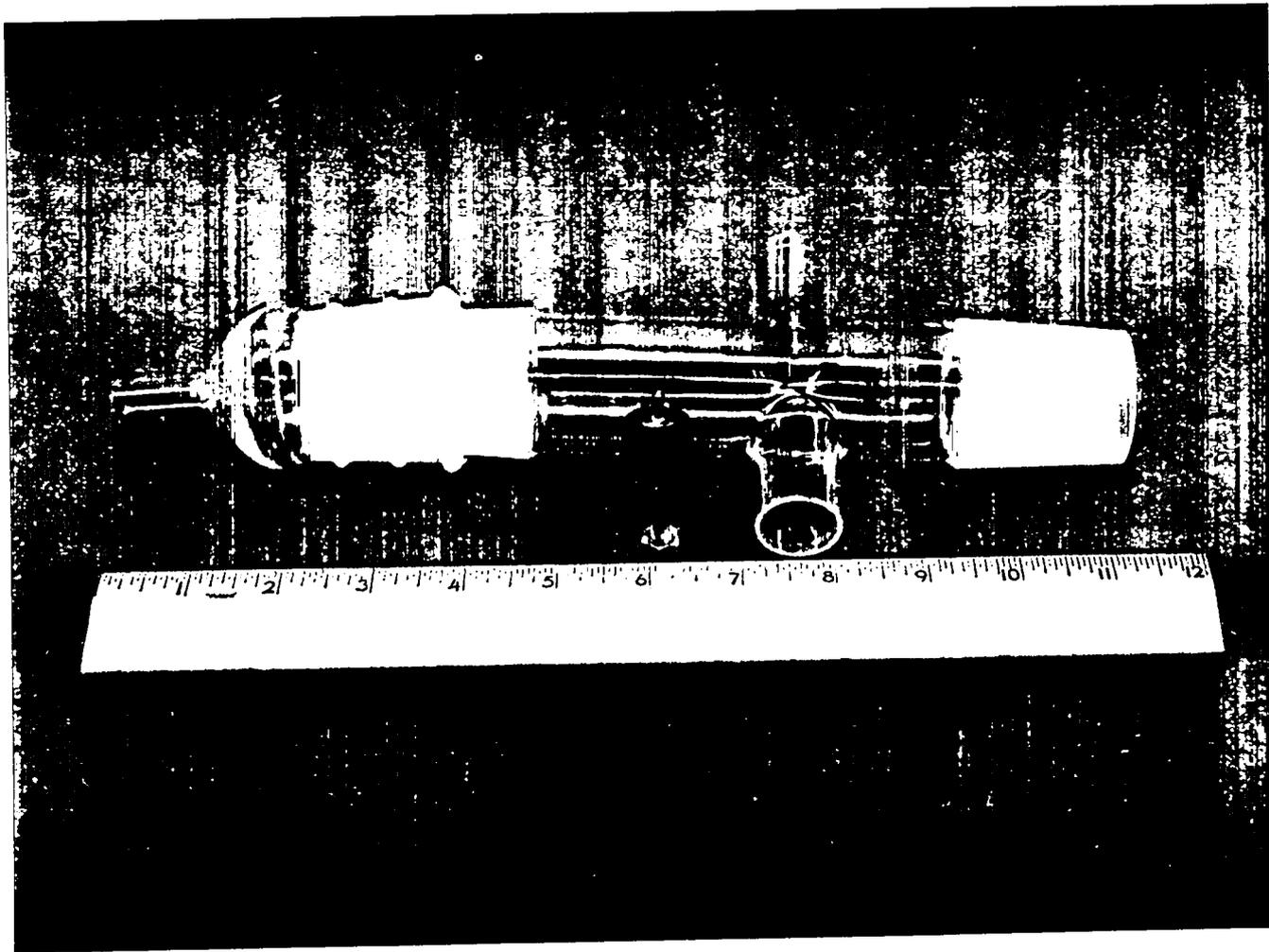


Fig. 14. Point-to-Plane Electrostatic Precipitator.

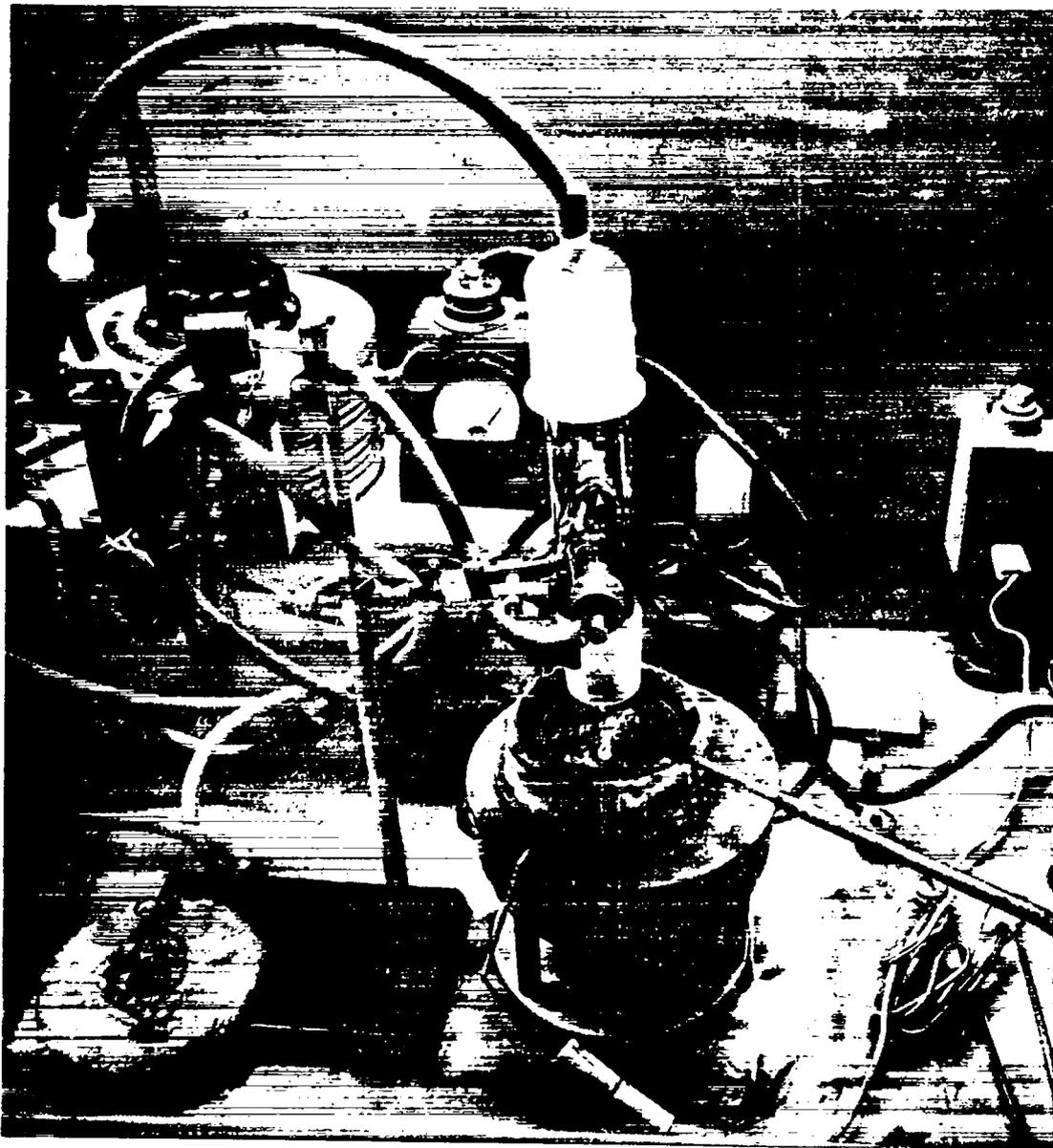


Fig. 15. Plutonium Burning Apparatus and Sampler in Glove Box.

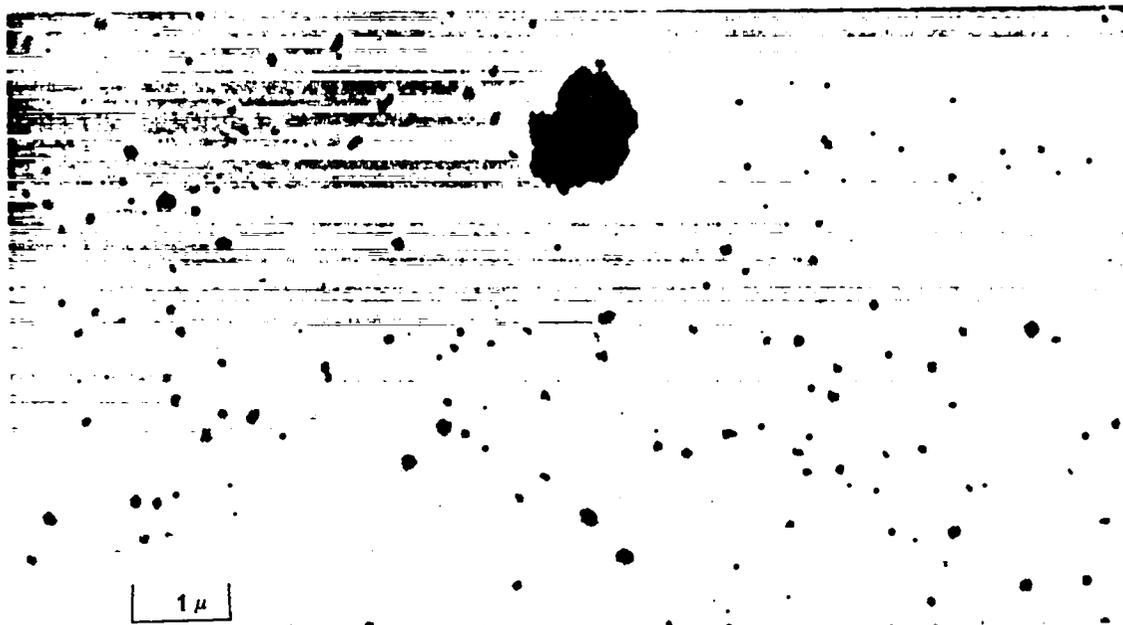


Fig. 16. Aerosol Produced by Burning Pu-Co-Ce (57.7% Pu) in 8.8% Oxygen. Shadowed with Chromium at 30°.

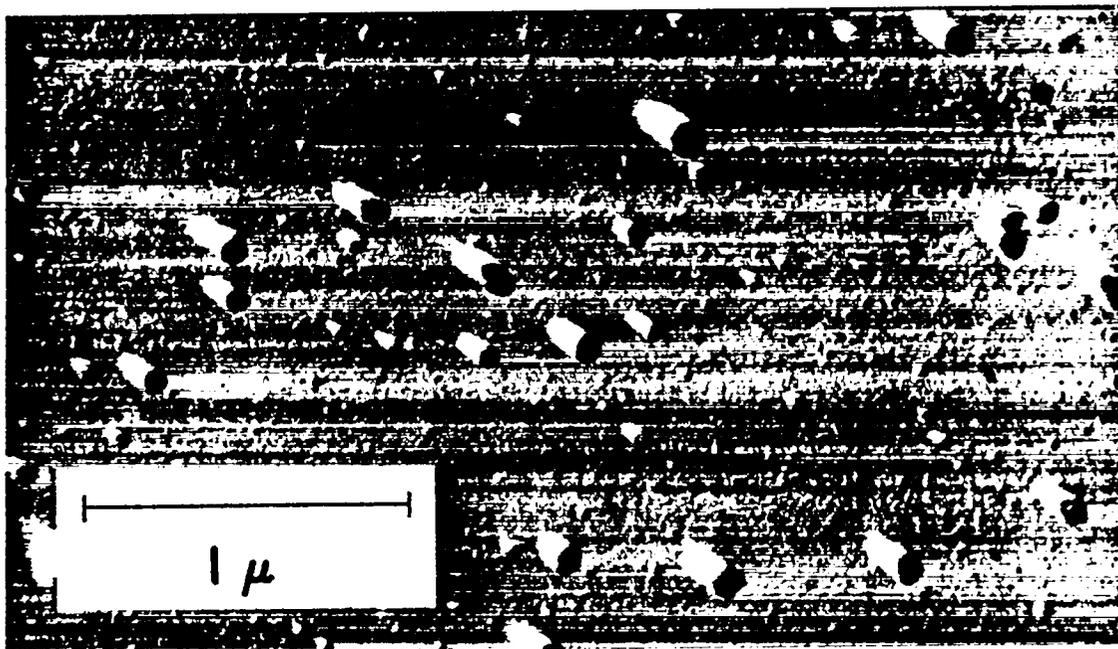


Fig. 17. Aerosol Produced by Burning Plutonium Metal (α phase) in 1.7% Oxygen. Shadowed With Platinum at 30°.



Fig. 18. Aerosol Produced by Burning Plutonium Metal (δ phase) in 0.55% Oxygen. Shadowed with Platinum at 30°.



Fig. 19. Aerosol Produced by Burning Plutonium Metal (δ phase) in Air. Shadowed with Platinum at 30°.

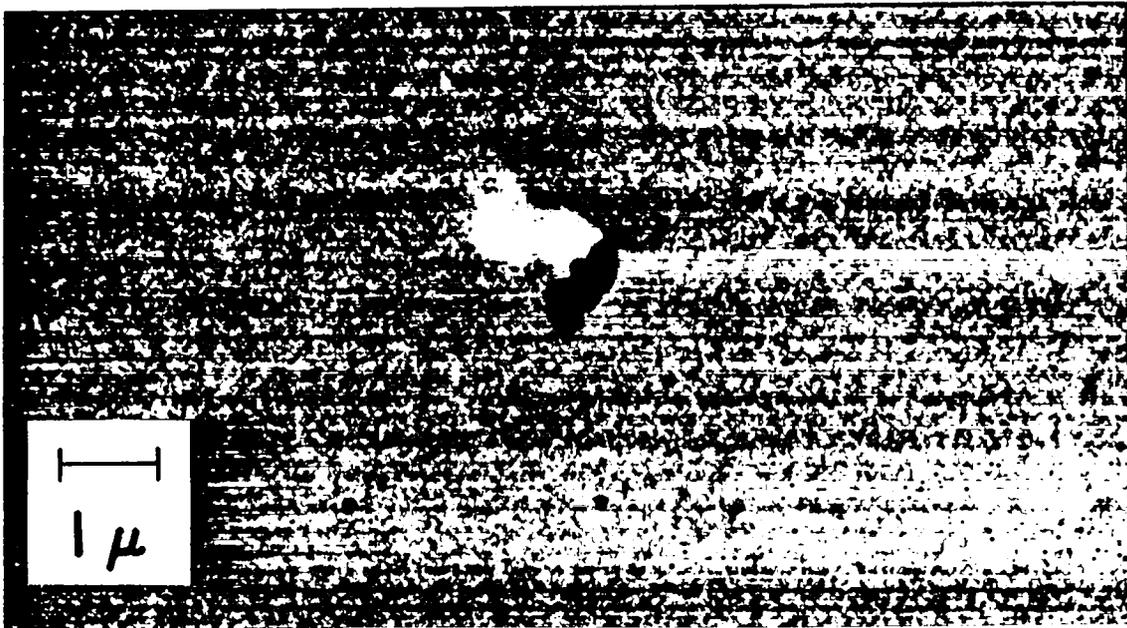


Fig. 20. Control Air Sample (no burning). Shadowed with Chromium at 30°.

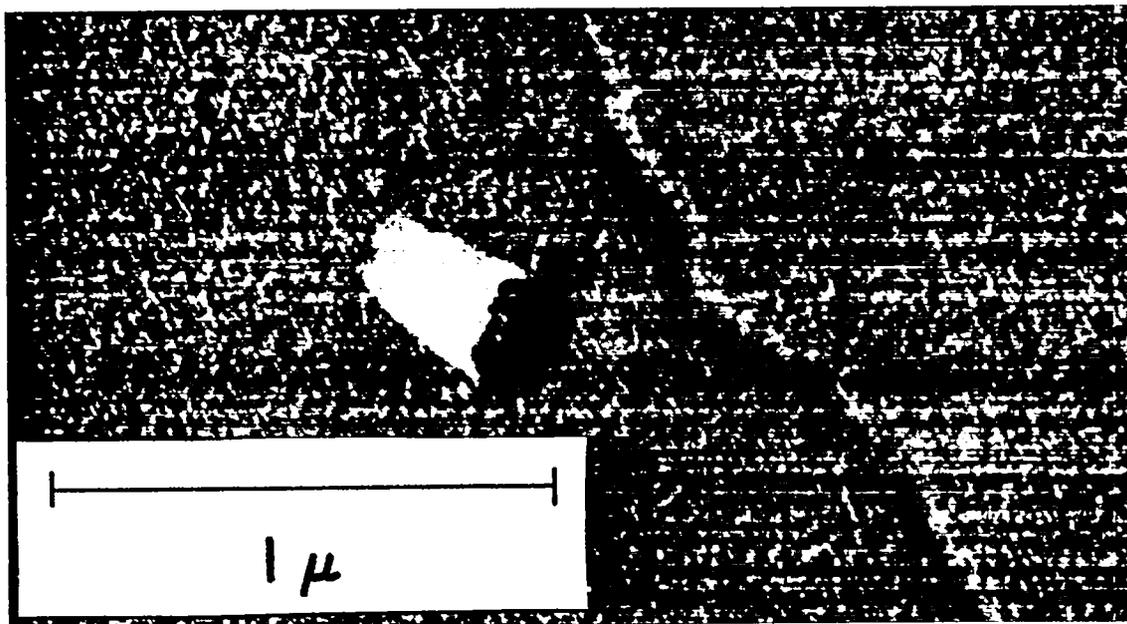


Fig. 21. Electron Microscope Grid Double Shadowed with Platinum.

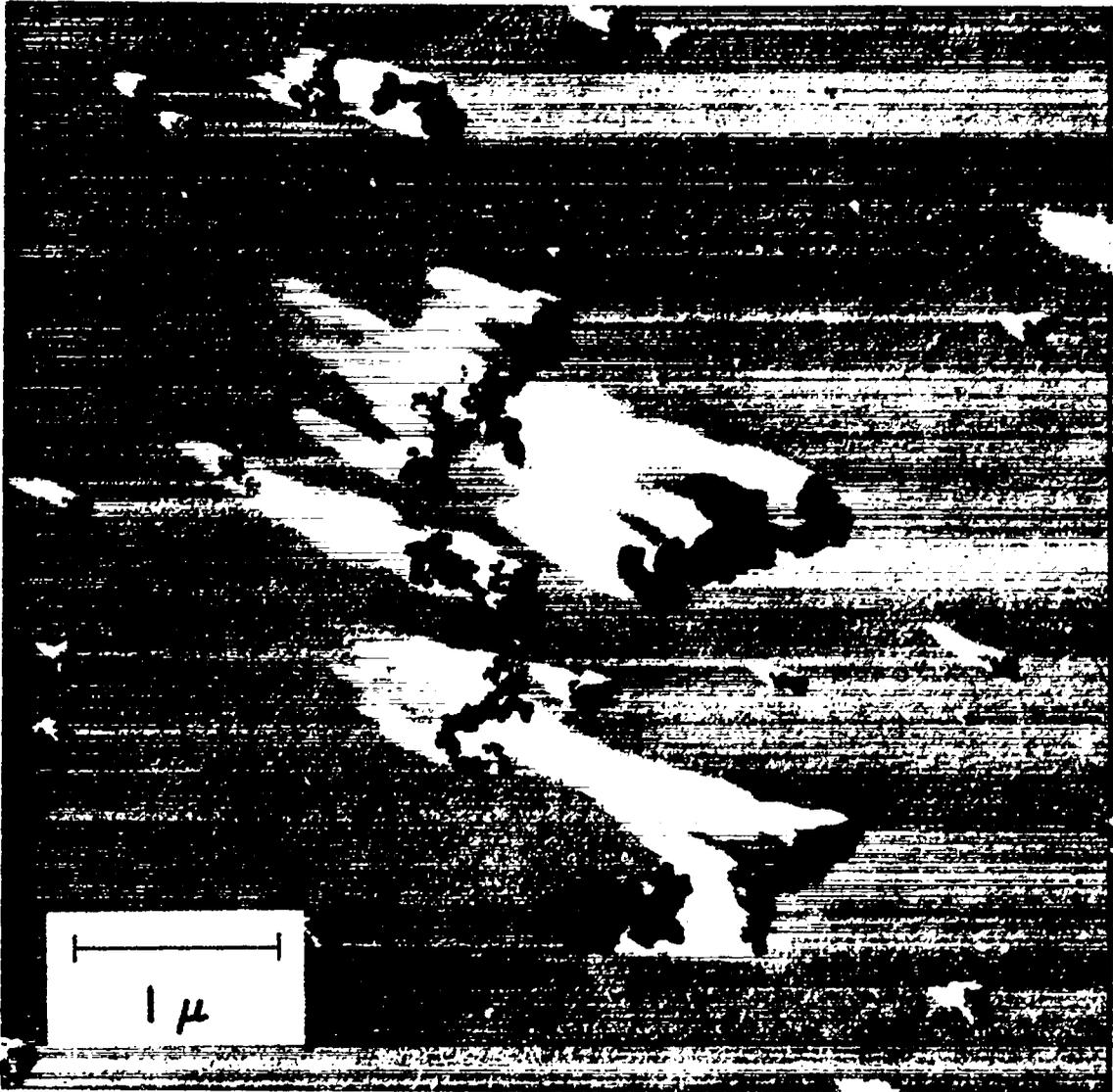


Fig. 22. Aerosol Produced by Burning Gallium Metal.
Shadowed with Platinum at 30° .

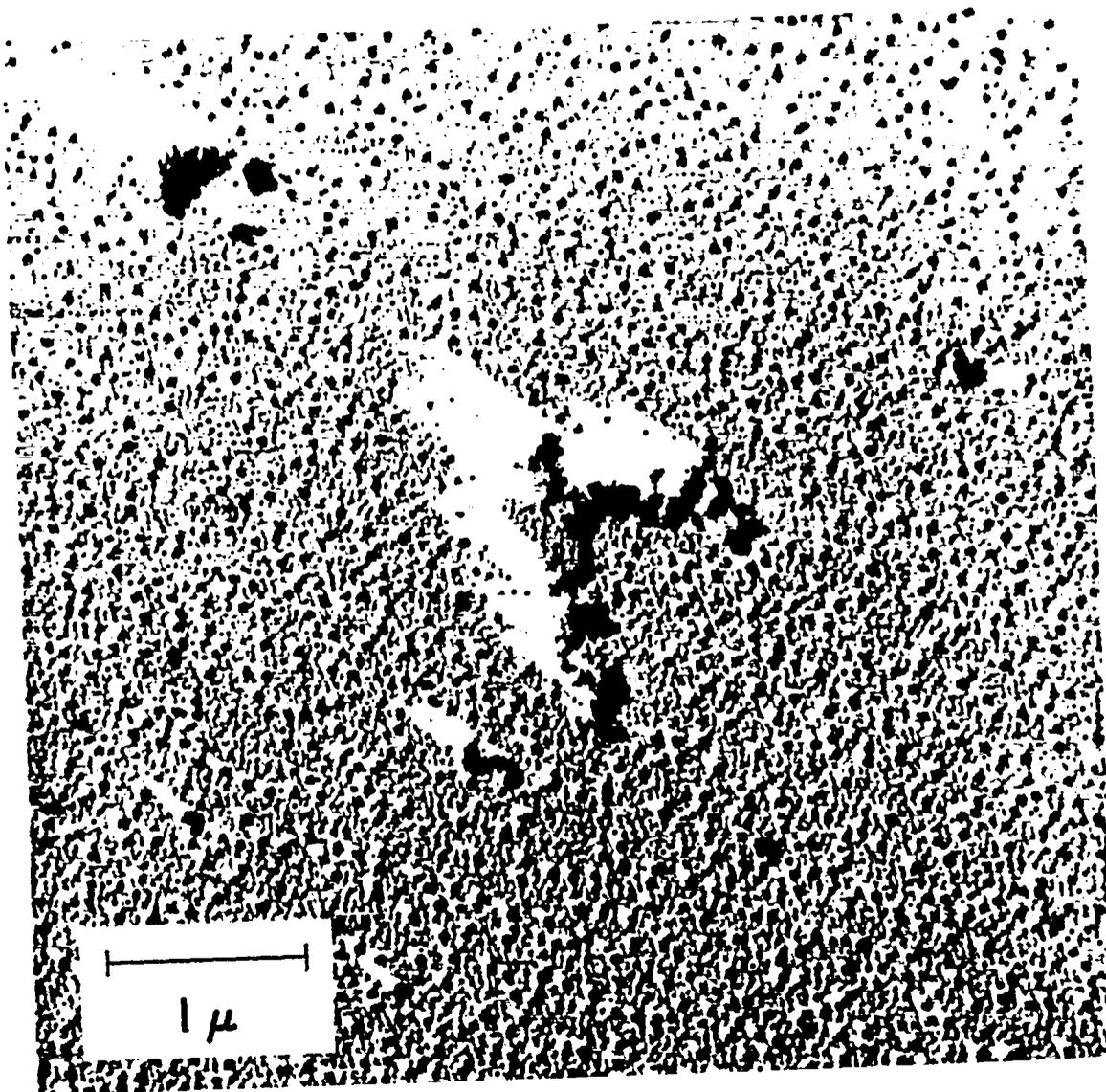


Fig. 23. Aerosol Produced by Burning Delta-Phase Plutonium.
Shadowed with Platinum at 30°.

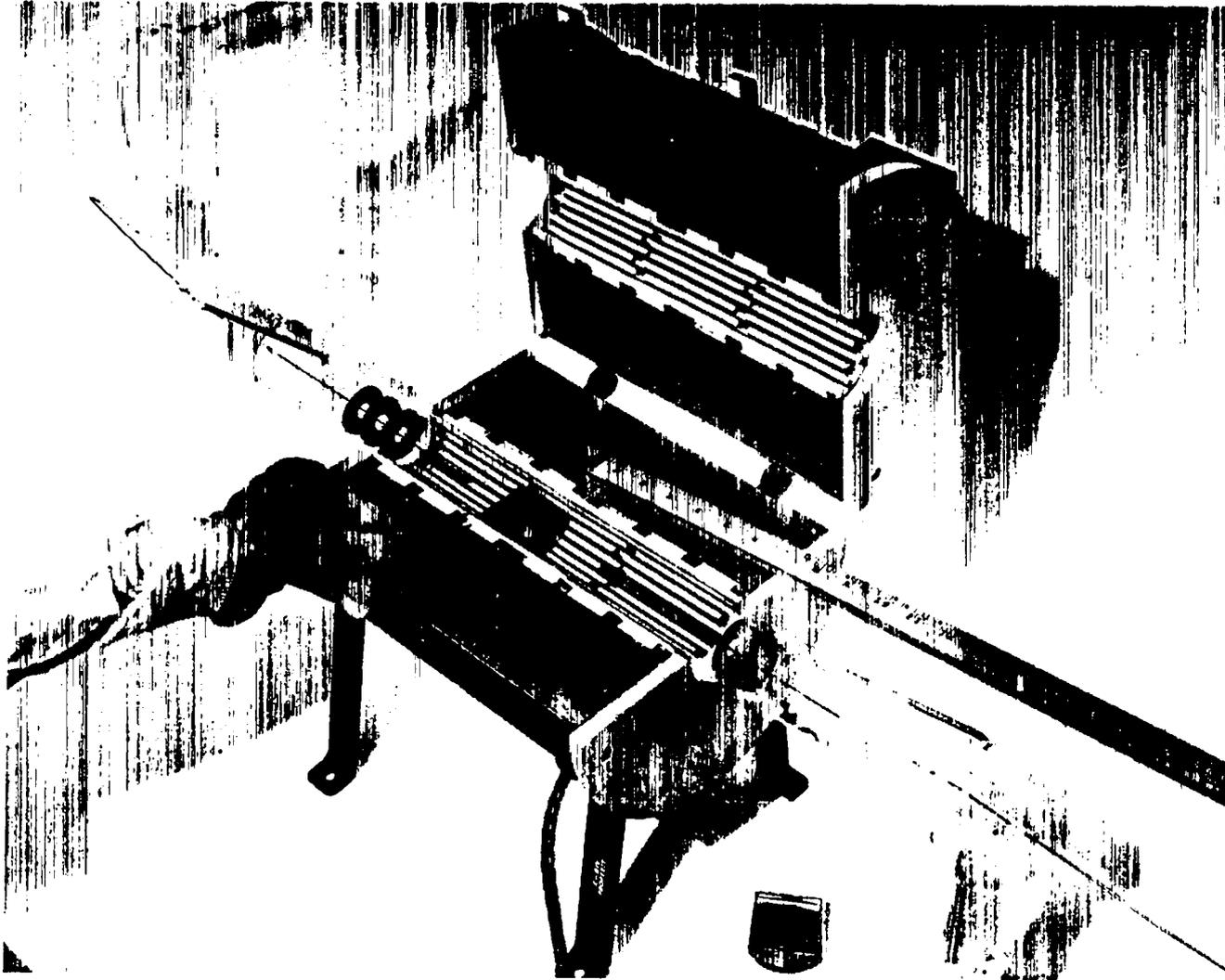


Fig. 24. Quartz Tube Used to Determine Fraction of Plutonium Airborne During Fire.

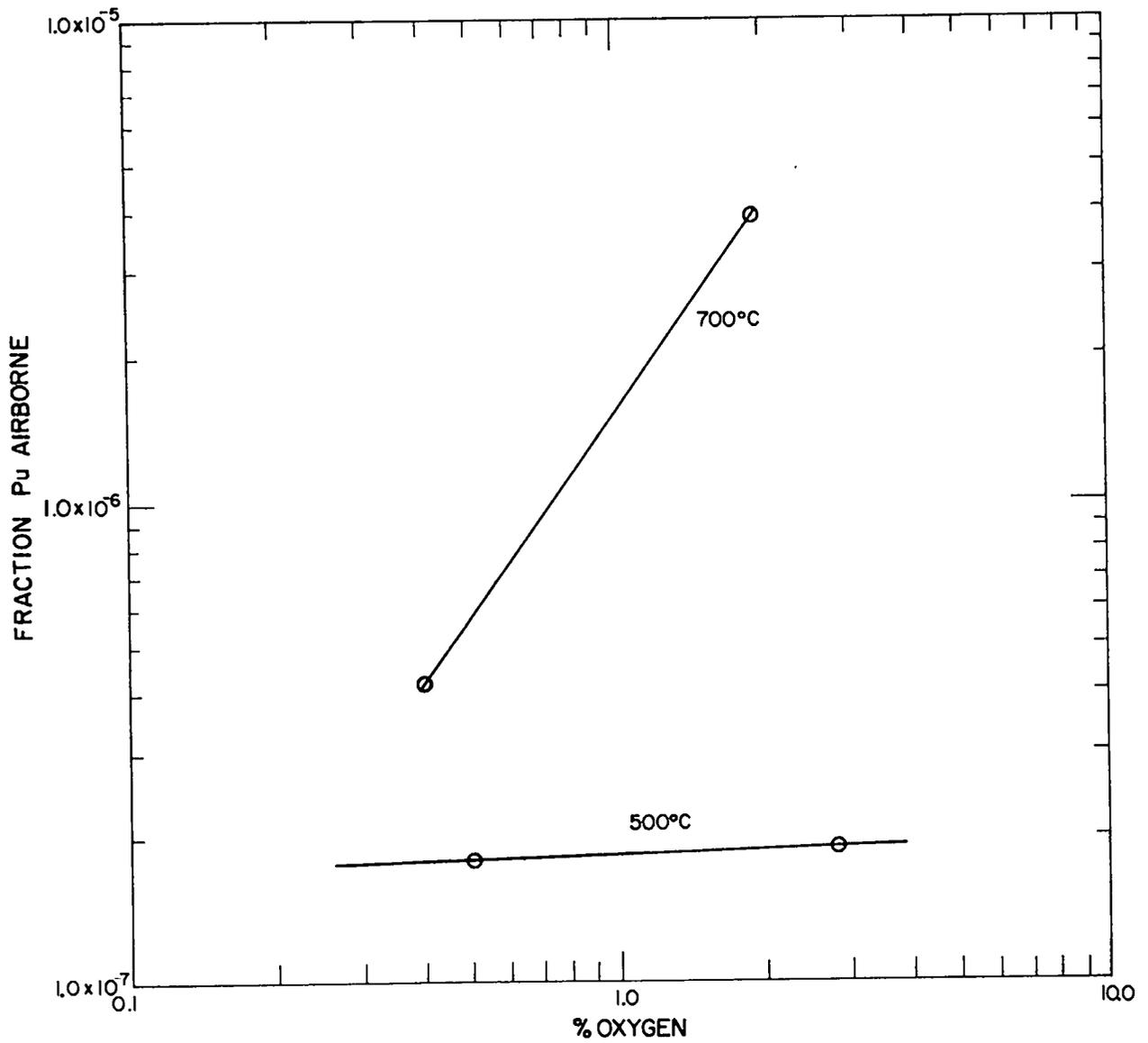


Fig. 25. Fraction of Plutonium Airborne During Fire as Function of Burn Temperature and Oxygen Concentration.

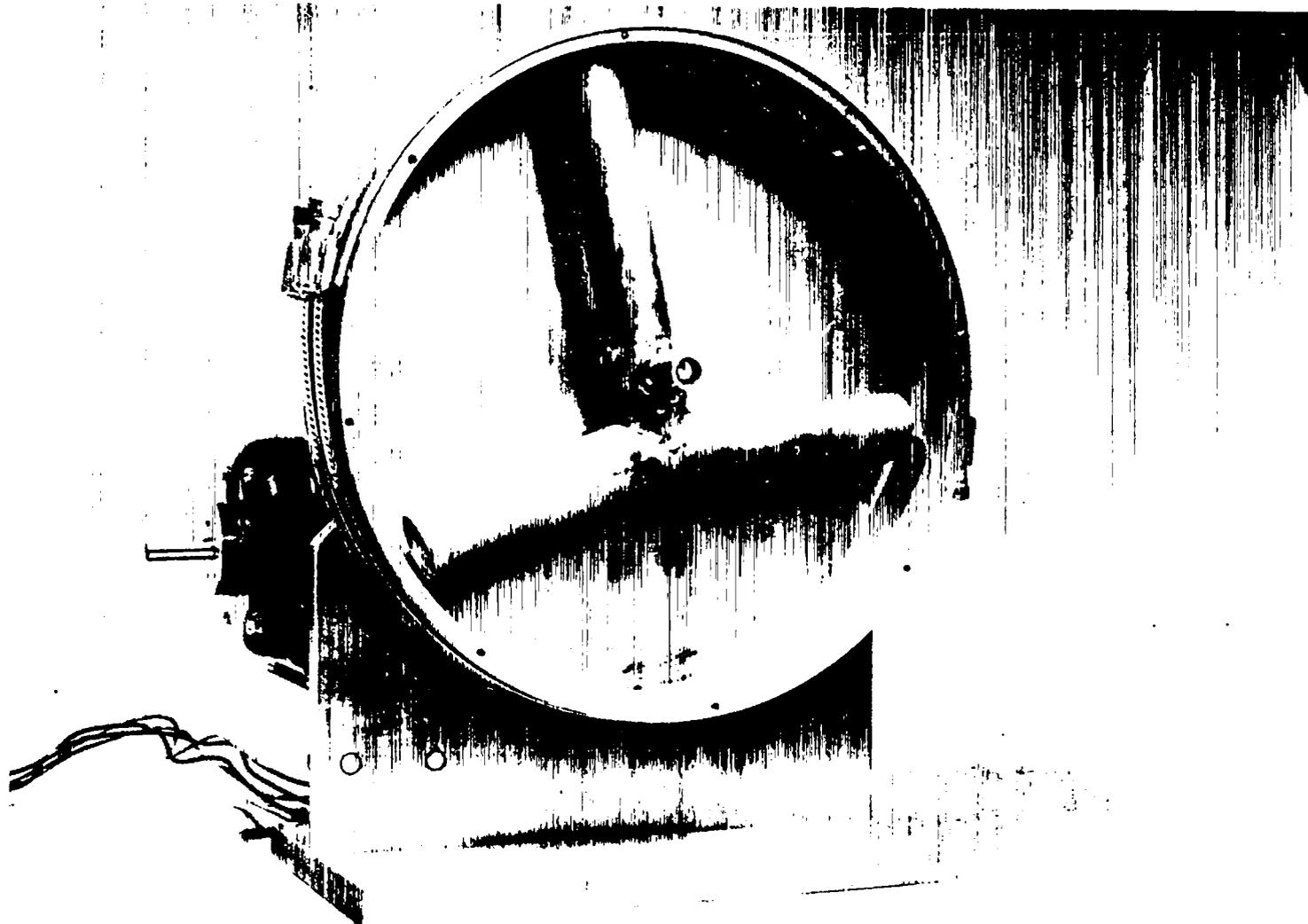


Fig. 26. Rocking Furnace Used for Sodium-Plutonium Fires.

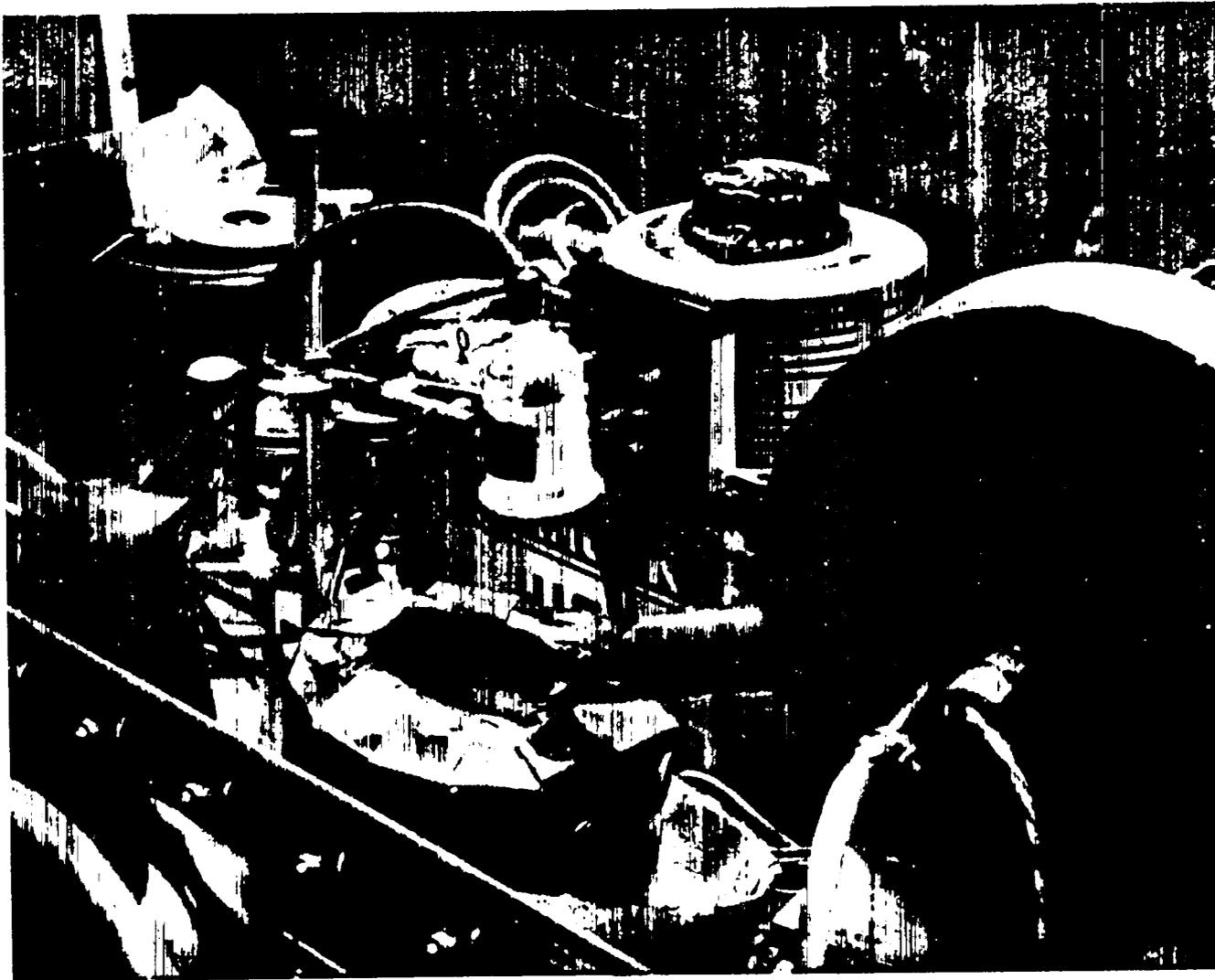


Fig. 27. Test Setup in Glove Box For Sodium-Plutonium Fires.

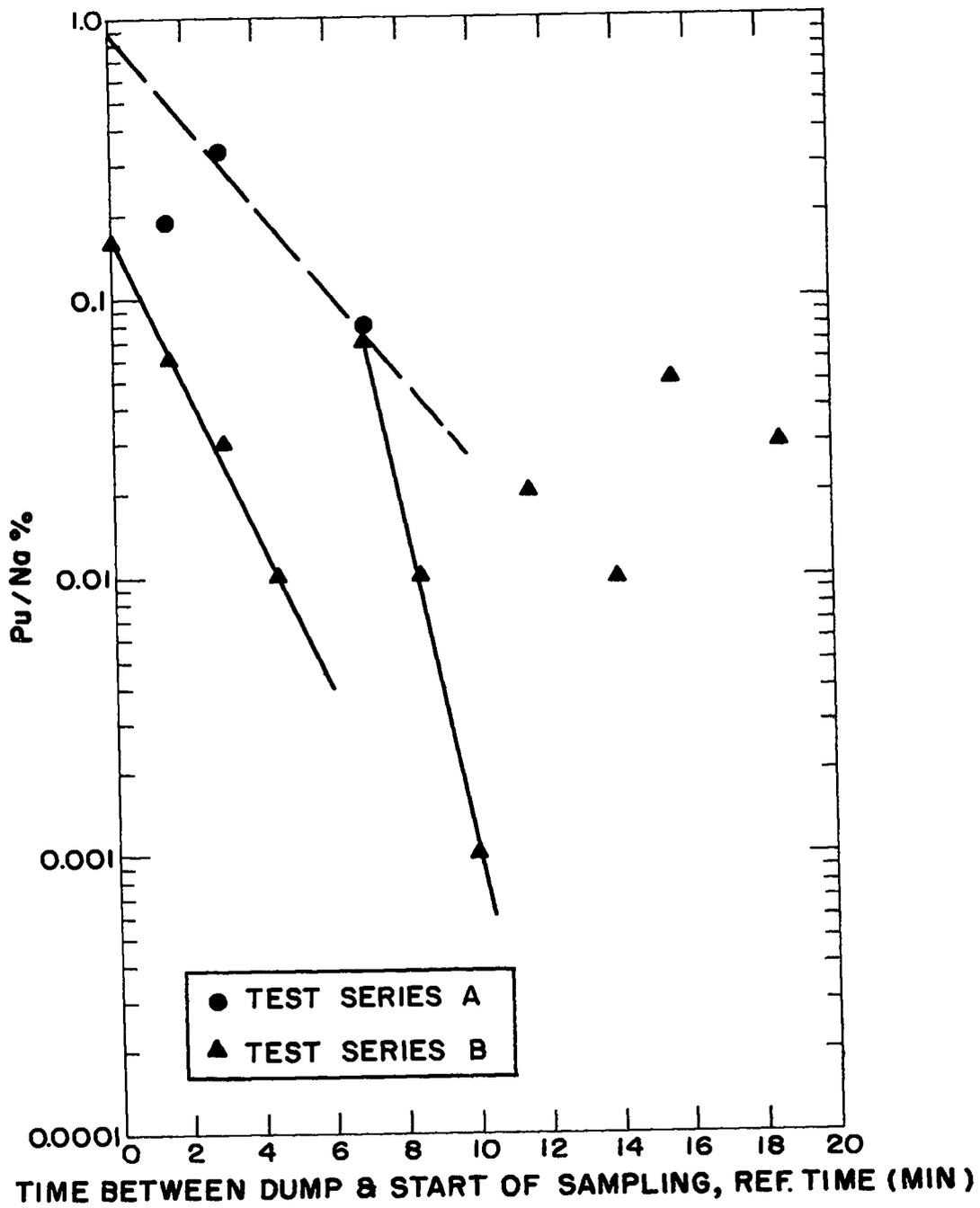


Fig. 28. Relative Airborne Concentration of Sodium and Plutonium as Function of Time After Dumping Melt from Rocking Furnace.