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AEC RESEARCH AND DEVELOPMENT REPORT

2981

AN INVESTIGATION OF THE SOLID PARTICULATE COLLECTION EFFICIENCY
OF THE TRAVERSE-TYPE STACK PROBE

R. B. Schappel

UNION CARBIDE NUCLEAR COMPANY
DIVISION OF UNION CARBIDE CORPORATION

Operating

- OAK RIDGE GASEOUS DIFFUSION PLANT • OAK RIDGE Y-12 PLANT
- OAK RIDGE NATIONAL LABORATORY • PADUCAH GASEOUS DIFFUSION PLANT

for the Atomic Energy Commission

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Health and Safety
TID-4500 (16th Edition)

UNION CARBIDE NUCLEAR COMPANY
Division of Union Carbide Corporation

Y-12 PLANT

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With the U. S. Atomic Energy Commission

AN INVESTIGATION OF THE SOLID PARTICULATE COLLECTION EFFICIENCY
OF THE TRAVERSE-TYPE STACK PROBE

R. B. Schappel

Oak Ridge, Tennessee

October 21, 1961

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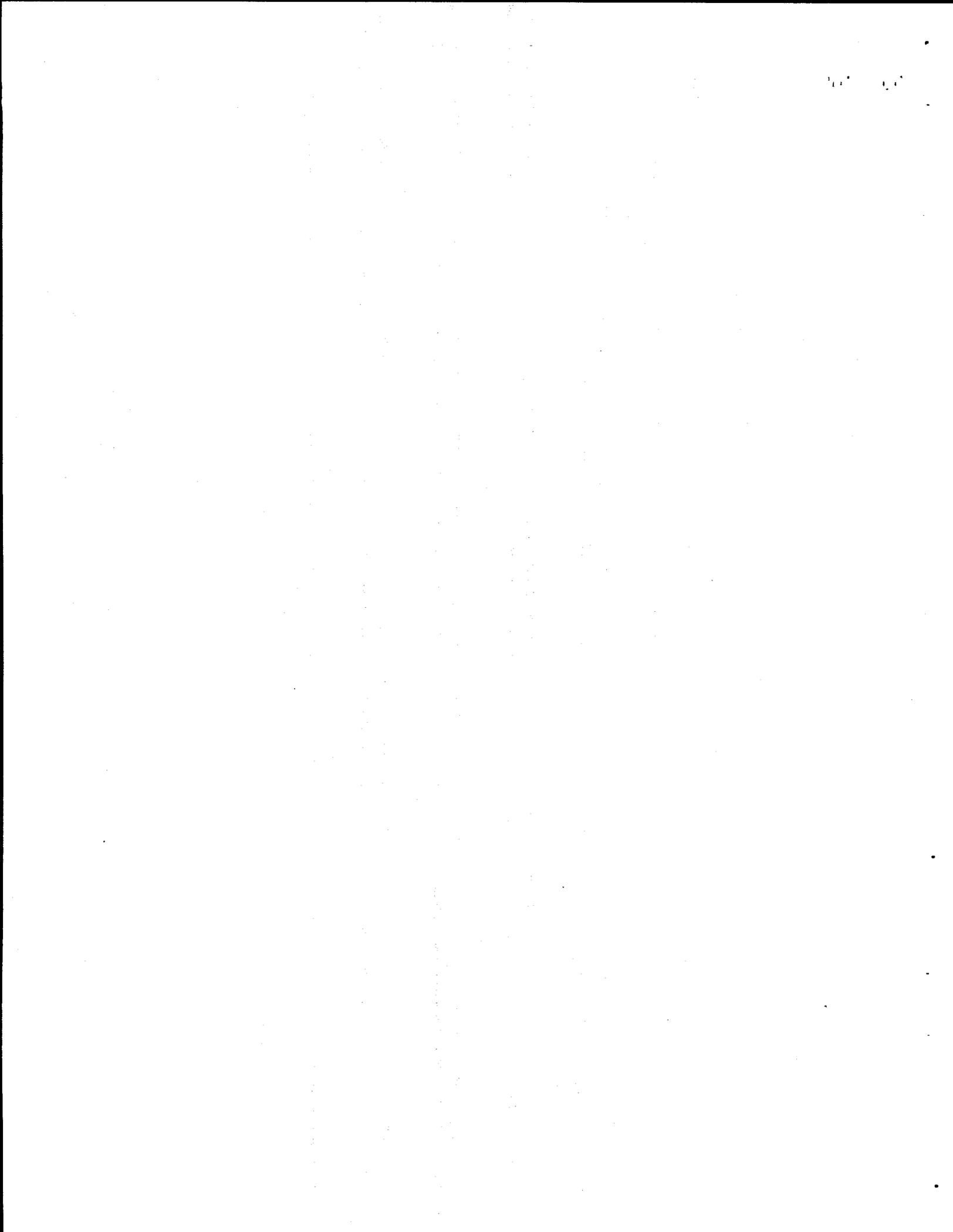
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ABSTRACT

The collection efficiency of the traverse-type probe for sampling dry uranium particulate matter in flowing vapor has been evaluated in a series of stack spiking tests. The information is required for application in the continuous sampling of plant vapor exhaust streams.

The traverse-type probe was found to be capable of representative sampling of stack particulates, but only one-fourth of the sample entering the probe reached the collection point (filter paper) located on the outside of the stack. The remaining three-fourths deposited on the interior walls of the probe.



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SUMMARY

In order to evaluate the traverse-type probe operation, a series of spiking tests were run which involved the introduction of solids (dusts), of which approximately 74% consisted of near normal assay uranium, into an air stream at the bottom of a stack and a sampling of the exhaust leaving the top of the stack to the atmosphere. The particulate concentration of the outgoing sample was converted to total spike passing up the stack by the use of Equation 1 (Page 9). Efforts were made to employ conditions generally representative of Y-12 stack operations and solid particulate sampling. Special tests were run to affirm the computed amount of material passing by the probe.

The results of the investigation can be summarized as follows:

1. The spike tests affirmed that the traverse-type probe mounted in a vertical stack could take representative sample of particulate concentrations when the particulates are distributed over the cross section of the rising exhaust stream. However, only one-fourth of the amount entering the probe reached the filter paper which is customarily analyzed for loss measurements. The remaining three-fourths stayed within the probe (Tables III and IV - Pages 34 and 37).
2. Tests performed on two plant-operated stacks confirmed the fact that in ordinary practice (over one and two-month operating periods) the traverse-type probe does not deliver the full sample to the filter paper outside the stack (Table VI - Page 38).
3. It has been computed that the greatest single mechanism to which retention inside the probe can be attributed is the passage through the 90-degree bends required for sample withdrawal from the stack interior.
4. Probes having filter paper collection heads inside the stack (called inside-stack probes) took representative samples suitable for direct-loss computation because all the catch reached the filter paper (Table V, Pages 38 and 39); however, a more elaborate sampling arrangement was required than that necessary for the "outside" traverse-type probe.

INTRODUCTION

Enriched uranium in solid particulate matter emitted to the atmosphere from process vent stacks is sampled continuously on a routine basis at Y-12 for material auditing purposes.

Much of the sampling is accomplished through the use of a traverse-type probe inserted through the wall of an exhaust stack. A sample of the exhaust is pulled out of the stack stream through the probe and through a sampling filter paper by vacuum. The rate of sample flow is hand regulated. Solid particulates are collected on and in the filter paper, and the exhaust gas passes all the way through the sampling equipment until it is discharged to the atmosphere downstream of the vacuum producer. The filter paper is analyzed periodically.

After the amount of uranium collected by the filter paper has been determined in the laboratory, the total stack loss for any test period is computed by the equation:

$$L = L_s \frac{G}{G_s} \quad (1)$$

where:

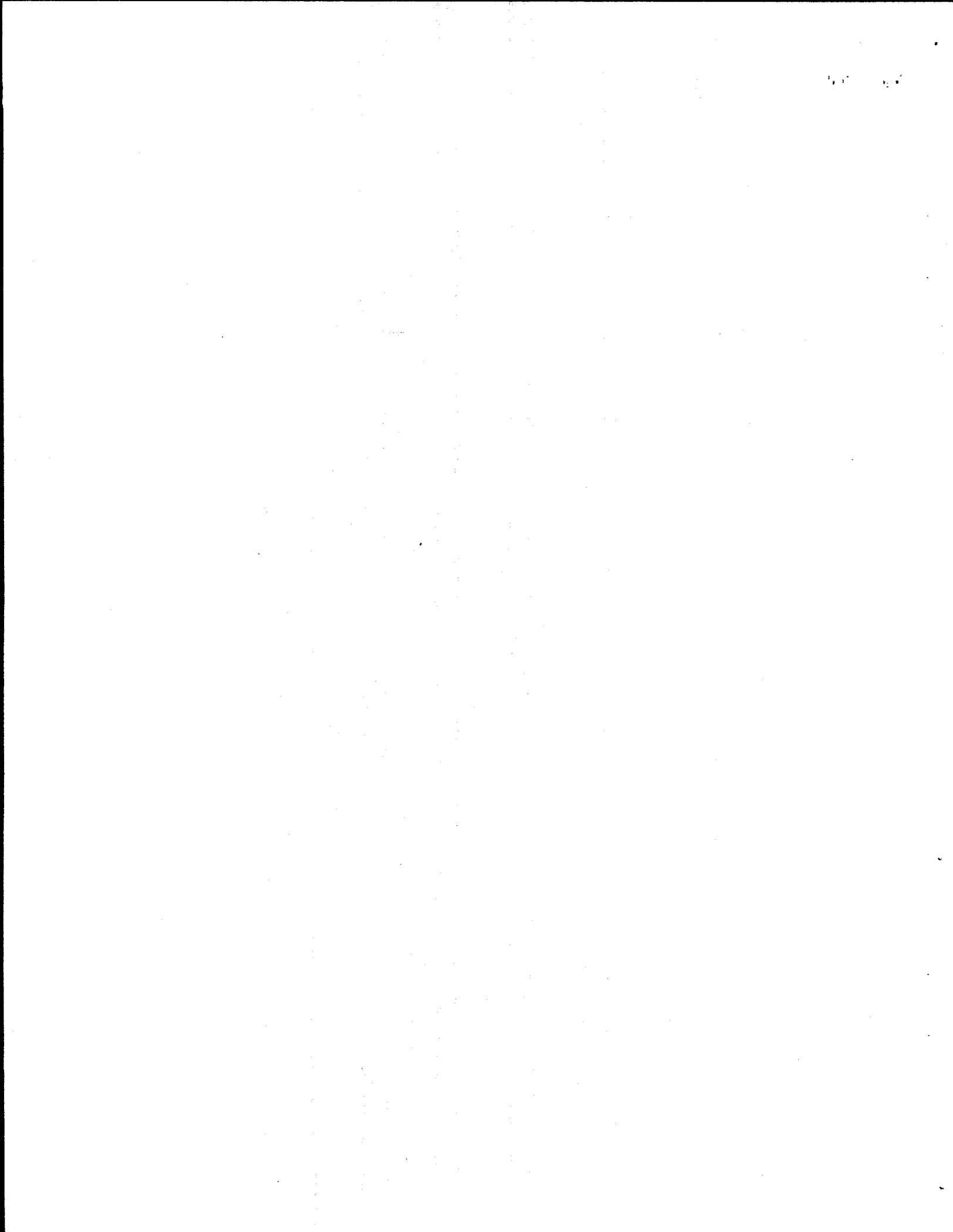
L is the uranium loss from the stack for the sampling period,

L_s is the sample uranium loss for the sampling period,

G is the stack flow, and

G_s is the sample flow at stack conditions.

The traverse-type probe itself consists of a tube (serving as a manifold) mounted completely across the diameter of a stack with openings pointing upstream on a line parallel to the axis of the tube manifold. The openings are spaced and sized to collect local samples of the exhaust from several portions of a stack cross section.



HISTORICAL BACKGROUND

INTRODUCTION

Collection of a stack sample, the particulate concentration of which would be representative of the fluid being exhausted, is complicated by an uneven distribution of velocity, of particulate concentration, and of particle sizing usually experienced at any cross section. The inherent difficulties are compounded when the sampling is to progress on a continuous basis.

Although authoritative studies are readily available on the proper techniques and equipment to be employed to take a single sample, technical information and accounts of industrial experiences in the operation of continuous stack sampling devices are meager.

SAMPLING METHODS FOR A SINGLE TEST

Most testing reported in the literature falls in the one-time-test category, and various types of collection apparatus have been designed for temporary usage so that they can be easily moved about. A probe with a single opening is commonly used which, while inserted through the wall of a stack, can be adjusted to any position in a cross section to obtain a suspensoid sample. Sampling over the stack cross section is recognized as a desirable expedient in overcoming difficulties arising from an uneven distribution of particles. (1 - 4) Thus, separate stack samples are normally taken at several chosen positions; local concentrations are then computed, and a mean concentration for the stack is obtained by averaging the local data. Particles have been collected by the use of porous collection filters, by electrostatic precipitators, or by impingers. High particulate loadings in the gas have been usually encountered in these cases, and consequently, sufficient amounts of particulate matter have been collected by the sampler within a short period of time. This situation permits accurate determinations of the stack emission by use of the weight collected.

Another method frequently employed to obtain the mean concentration involves the shifting of the probe from position to position on the cross section of the stack while drawing the vapor through the sampler. The same flow rate and amount of time are used at each point. In any case, all these methods suffer in that samples cannot be taken simultaneously; for, while the total fluid flow rate and the overall particulate loading may remain relatively constant, the properties at the individual cross sectional sampling positions can change markedly before the sampling process is completed.

SAMPLING METHODS FOR CONTINUOUS TESTING

Continuous testing of the particulate emission from plant stacks appears to be a fairly recent approach. This has probably come with increased industrial activity in the fields of hazardous or valuable materials and the subsequent interest in air pollution or plant losses. Primarily, the difficulties encountered in obtaining a continuous representative sample of a plant exhaust, stem from the fact that there are no known reliable methods and no standardized equipment available for use. Emissions fall into two fairly distinct categories: (1) high suspenoid loadings found in the exhausts from such installations as power plants and steel mills, and (2) low loadings in the exhausts from operations involving radioactive or other valuable materials.

Logically, collecting one sample from one point inside a stack is a simpler and more expedient method for sampling than the collection from multiple points in a cross section, as long as the sample obtained is representative. Some success in obtaining such a sample from a single point has been reported through the use of flow-mixing devices introduced into the stack upstream from the sampler.^(5, 6) These devices are intended to disrupt thoroughly the uneven velocity and dust-loading patterns of a typical stack flow by creating considerable turbulence. More uniform sampling characteristics are then claimed for some spot downstream where a single representative sample may be drawn off into a collecting filter. Further work in this field is needed to confirm the results claimed.

A recently reported device of potential use for obtaining a continuous representative sample from the cross sections of circular stacks consists of a rotating manifold tube, the length of which is approximately equal to the diameter of the stack.⁽⁷⁾ Multiple-sampling nozzles are spaced along the length of the tube to provide full coverage of the stack diameter. Local samples are drawn into the manifold and from there into a filter outside the stack. The principles commonly applied to traverses for velocity determinations are used for the location of the nozzles at the centers of equal areas of the cross section. Rotation of the unit is carried out at a low, fixed speed about the axis of the manifold. The net result is essentially a sampling along an infinite number of stack diameters. Although preliminary tests indicate successful application of the device, installation and maintenance costs for a sampler of this design are probably too high to permit its use in most industrial applications.

Generally speaking, the stationary probe which is equipped to draw simultaneously, multiple local samples,⁽⁷⁾ appears to be the simplest and most practical device for obtaining a continuous representative sample. A probe similar to the manifold tube described in the preceding paragraph, but without the rotating feature, known as the "traverse-type probe" has been in use at Y-12 for some time.

Other probes employing the same sampling principle can be designed. One such device would be to provide an array of sampling nozzles, each with an integral filter, located

inside a stack at the centers of several equal portions of the cross sectional area. While this configuration would seem to offer the most efficient sampling setup, servicing costs and time would be excessive if many stacks were to be tested on a routine basis.



GENERAL THEORETICAL CONSIDERATIONS

INTRODUCTION

The characteristics of dust flow in a gas stream differ from those of the gas itself. Even with a uniform vapor flow pattern in a stack, a similar uniform pattern for the particulate concentration or flow does not necessarily follow. The heaviest dust concentrations may be found in those areas having the lowest vapor velocity.

TYPE OF STACK

Testing for suspensoids is preferably carried out in vertical stacks where the exhaust flows upward. With this arrangement there is more opportunity for uniformity by an internal re-adjustment of particles and vapors. When a sampling station in a horizontal run is chosen, possible stratification of particulates may occur. Moreover, the probe may be located so close to an accumulation of dust lying on the bottom that local turbulence can cause enough agitation of the layer to allow some of the accumulation to enter the sample. On the other hand, when a sampler is inserted in a vertical stack in which the exhaust flows downward, another difficulty exists in that an abnormal particulate flow will result because of the influence of gravity on the suspensoids. Thus, particle flow will not correlate with vapor flow to give a true particulate flow.

LOCATION OF PROBE

Industrial installations, as a rule, do not contain ideally accessible locations for sampling stations, but efforts are frequently made to spot the equipment five to ten stack diameters downstream from a bend or other flow-agitating device. The probe is inserted into the stack with the sample openings facing into the stream.

VELOCITY OF FLUID FLOW

Major importance is attached to the velocity at which the stack fluid is picked up by the sampler. (8, 9) Sampling must be kept "isokinetic" in order to attain representivity; i.e., the sampling velocity must be maintained at the same rate as that of the ambient fluid. Any departure from an isokinetic condition can result in inertial segregation of the suspensoid at the sampler opening and, consequently, in poor samples. If the velocity of the sample stream is low with respect to the stack stream, a portion of the stack fluid which would have entered the sampler is diverted around it, carrying with it the finer particles. Meanwhile, the coarse particles will be carried into the sample opening because of their inertia, and the sample taken will have a larger amount of material than is representative

of the stack fluid. Conversely, if the velocity of the sample stream is higher than the stack stream, a portion of the stack fluid which would have bypassed the sampler opening will now enter it, carrying with it an excess amount of fines. The coarse particles in the fluid which would under isokinetic conditions be most likely to bypass the sampler, will continue to do so because of their relatively unchanged inertia. Thus, the sample will contain an excess of fine over coarse material and will, because of this, be biased low.

A listing of some of the results of tests by other investigators on the departure from isokinetic sampling conditions when Equation 1 is used for loading computations is shown in Table I.

Table I
SAMPLING DEPARTURES FROM ISOKINETIC CONDITIONS

Nature of Particle	Particle Size (μ)	Stack Velocity (ft/sec)	Ratio:	Sampling Velocity Stack Velocity	Ratio:	Observed Sample Weight True Sample Weight
$\rho = 1 \text{ g/cc}$ in air at 20°C, 1 atm pressure ⁽¹⁾	1	1800		1/2		1.013
				1 1/2		0.996
$\rho = 1 \text{ g/cc}$ in air at 20°C, 1 atm pressure ⁽¹⁾	10	1800		1/2		1.54
				1 1/2		0.82
$\rho = 1 \text{ g/cc}$ in air at 20°C, 1 atm pressure ⁽¹⁾	100	1800		1/2		1.99
				1 1/2		0.67
SiC ⁽²⁾	5 - 25	2000		1/2		1.55
				2/3		1.33
				1 1/2		0.85
				2		0.71
SiC ⁽²⁾	5 - 25	3000		1/2		1.79
				2/3		1.37
				1 1/2		0.77
				2		0.59
SiC ⁽²⁾	80 - 100	2000		1/2		1.96
				2/3		1.59
				1 1/2		0.65
				2		0.48
SiC ⁽²⁾	80 - 100	3000		1/2		1.89
				2/3		1.47
				1 1/2		0.61
				2		0.49

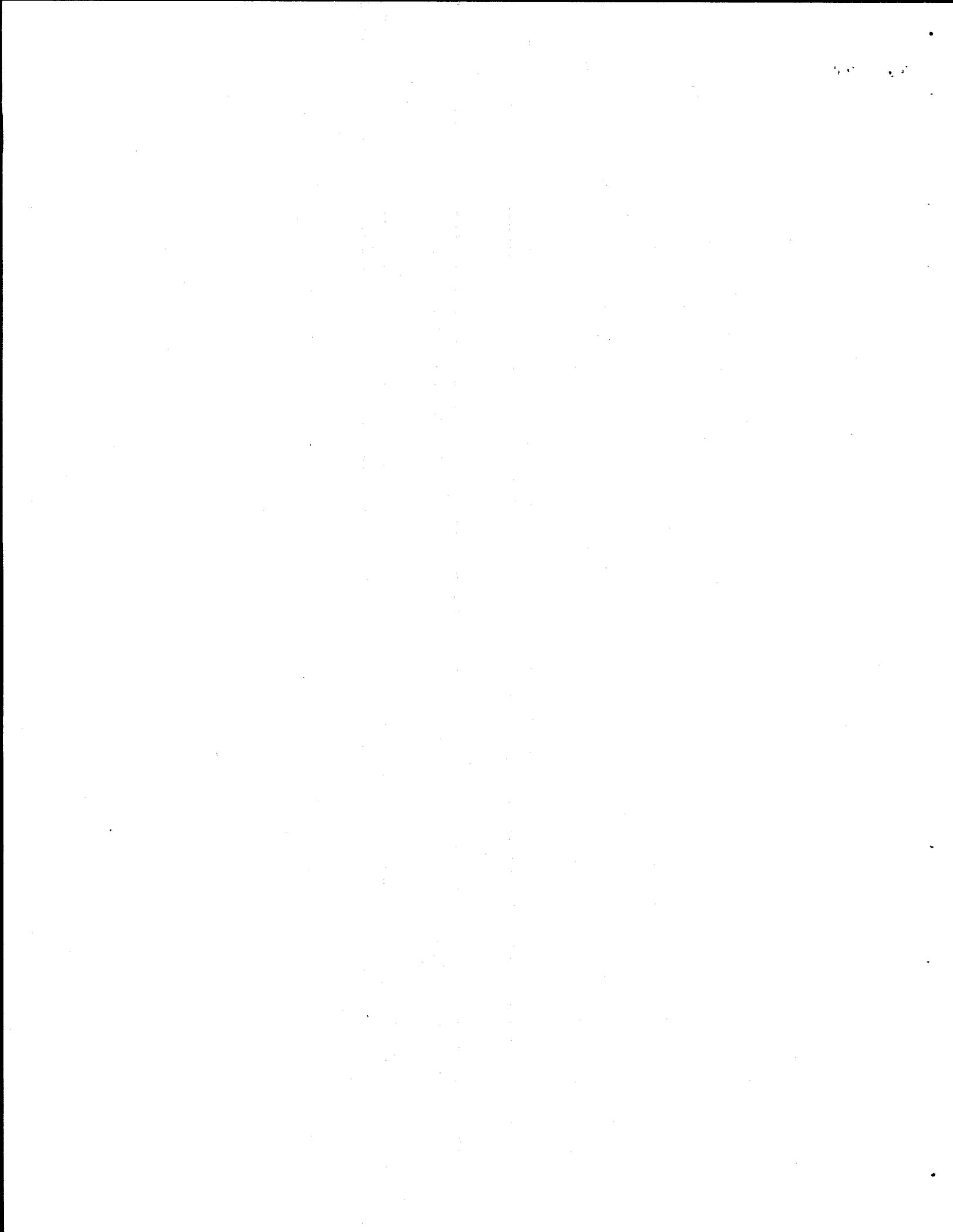
⁽¹⁾Data from Reference (6), Page 45.

⁽²⁾Data from Reference (10), Page 45.

The sampling error becomes smaller as the suspensoid size decreases and becomes negligible at about one micron. Another way of stating it is that sampling velocities which are too low result in greater sampling errors than velocities which are too high.

SIZE OF APERTURE

When coarse particulates ($> 400 \mu$) are sampled, the size of the aperture becomes important⁽¹⁰⁾ because of the blocking effect by the probe wall. As a result, sample openings less than 3/8 inch in diameter are not recommended.^(2, 6) For fine particulate matter ($> 25 \mu$), openings as small as 1/8 inch have no effect on the representativeness of a sample.⁽¹⁰⁾ Sampling nozzles with at least a few inches projection before any bend are frequently used to maintain minimum turbulence at the actual intake point.



MATHEMATICAL THEORY

INTRODUCTION

For use in the existing large-diameter stacks, the Y-12 traverse-type sampler has been designed with long tube lengths and sharp 90-degree bends through which the several local samples enter the manifold tube and proceed to the filter. In spite of the fact that a representative sample may have been taken, the amount of material collected in the filter located on the outside of the stack can be low because of particle retention in the probe.

Particles will reach the wall of a sampling tube through the following mechanisms:

1. Filtering action will change in direction (because of centrifugal action on the particles as the flow passes through a bend).
2. Gravitational settling.
3. Brownian motion.
4. Eddy diffusion by turbulence.
5. Thermal gradient
6. Electrical attraction.

Direct computation of particle retention is not possible since it is not assured that all the particles reaching a wall will be retained there. Logically, the properties of the sample tube material, the angle of impact, and the adhesive quality (tack) of the particles may have an influence on adherence, but these effects are unknown and uninvestigated.

DETAILS OF MECHANISMS AFFECTING PARTICLE RETENTION

Influence of Direction Change

A particle suspended in a vapor undergoing laminar flow through a 90-degree tubing bend will first strike the wall in accordance with the equation:⁽¹¹⁾

$$\ln \left\{ \left(\frac{\epsilon_0 + \sqrt{\epsilon_0^2 - d_0 \left(a - \frac{d_0}{4} \right)}}{\epsilon_0 - \sqrt{\epsilon_0^2 - d_0 \left(a - \frac{d_0}{4} \right)}} \right) \left(\frac{\epsilon_0 - \delta_0}{\epsilon_0 + \delta_0} \right) \right\} = K_3 \epsilon_0 d_0^2 \quad (2)$$

where:

$$\epsilon_0 \quad \text{is equal to } \sqrt{a^2 - \gamma^2}, \quad (2a)$$

$$K_3 \quad \text{is equal to } \frac{\rho G_s}{9 \mu a^4}, \quad (2b)$$

a is the tube radius in centimeters,

d_0 is the diameter of the particle in centimeters,

G_s is the vapor flow in cm^3/sec ,

δ_0 and γ are the coordinates of the center of the particle in centimeters (as projected on the center plane of the tube bend); the former perpendicular to the center line of the tube and the latter parallel to it,

ρ is the particle density in grams/cm, and

μ is the vapor viscosity in gram/cm-sec.

Extended development of this equation can be made to estimate percentage impingement for a specified particle size.

Influence of Gravity

As particulates heavier than the fluid transporting them move through a horizontal tube they exhibit a downward settling characteristic because of gravity. This action can result in an appreciable deposition of material. Particle deposition during laminar flow in a horizontal sampling line can be described by the equation: (12)

$$L_{100} = \frac{16 G_s}{3\pi u_T a} \quad (3)$$

where:

L_{100} is the tube distance for total particle deposition in centimeters, and

u_T is the terminal settling velocity for the particle expressed in cm/min.

If there is a uniform particulate concentration in the vapor, the fraction of particles which deposit in tubing of a given length is expressed as:

$$F_G = 1 - \frac{2}{\pi} (\lambda \beta + \sin^{-1} \beta - 2\lambda^3 \beta) \quad (4)$$

where:

F_G is the fraction of particles which deposit,

$$\lambda \text{ is equal to } \frac{(3 Lu_T)^{1/3}}{(8 Va)}, \quad (4a)$$

$$\beta \text{ is equal to } \sqrt{1 - \lambda^2}, \quad (4b)$$

L is the tubing length in centimeters, and

V is the average fluid velocity in cm/sec.

Influence of Brownian Motion

When the size of the particulates is very small, Brownian movement is superimposed upon gravitational settling. Deposition is therefore accelerated because of the effective impact of gas molecules on very small dust particles. Brownian motion is noticeable on particles of about three-micron size; for particles under 0.1μ , the random movement of particles because of this mechanism is greater than any movement due to gravitational settling.⁽¹³⁾ Consequently, horizontal-system sampling at low flow rates can be extremely unreliable for small particles. The following simplified equation can be used to compute particle loss because of Brownian movement:⁽¹²⁾

$$F_B = 5.2 \frac{(\pi DL)}{(2G_s)} \quad (5)$$

where:

- F_B expresses the fraction of inlet particles deposited,
 L is the tube length in centimeters,
 D is the particle diffusion coefficient in cm^2/sec , and

$$\text{is equivalent to } \frac{2.4 \times 10^{-11}}{d_o} \left(1 + \frac{1.8 \times 10^{-5}}{d_o} \right). \quad (6)$$

Eddy Diffusion by Turbulence

When vapor flow through a horizontal system is changed from a laminar region to a turbulent one, the suspensoids are subject to turbulence along with the flow. Under these conditions they are driven in radial directions by local eddy currents over the full length of the tube. The amount of material striking the wall becomes greater with increasing particle size and velocity, both of which affect momentum. Postma and Schwendiman⁽¹²⁾ were able to correlate eddy diffusion deposition data by use of a plot of dimensionless parameters composed of the physical properties of the fluid and particles. From this plot, a deposition velocity "K", in cm/sec , is obtained which can be used to estimate the deposition fraction by this mechanism. The equations used are:

$$F_T = 1 - C, \text{ and} \quad (7)$$

$$\ln \frac{1}{C} = \frac{2KL}{V_a} \quad (8)$$

where:

- F_T is the fraction of the particles of the given size which are deposited because of turbulence.

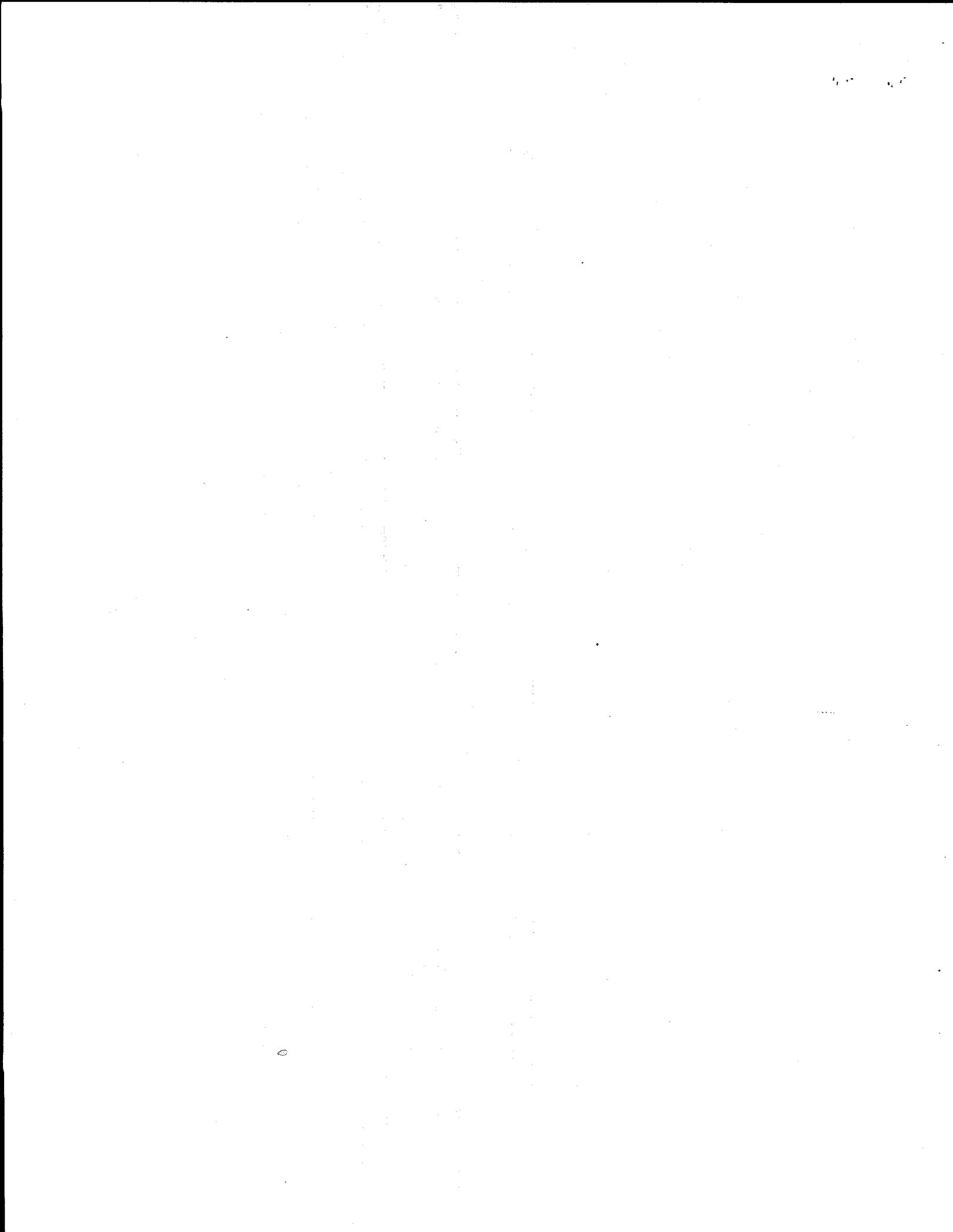
Effect of the Thermal Gradient

If, as a hot fluid with suspensoids passes through a sample line, there is a loss of heat at the tubing wall and a thermal gradient is established in the fluid, unequal molecular impingement can cause the particles to leave the hotter fluid in the center of the tube and

pass toward the cooler walls. However, the loss in sample lines because of this mechanism is considered small in most cases.(12)

Effect of Electrical Attraction

An electrical charge can be built up within the fluid flowing in a sample tube due to air friction if the tube is made of a dielectric material. In this event, particulate material of opposite charge will be repulsed to the wall.(12) Use of grounded metal sample tubing will prevent action of this nature.



EXPERIMENTAL WORK

INTRODUCTION

There are a number of stacks in Y-12 which are monitored for dry particulate emission. The use of typical operating conditions seemed appropriate for this project in order to reduce the number of tests for probe sampling efficiency. Since in actual plant practice, the physical properties of stack emissions, the actual stack vapor velocities, and the sampling equipment were about the same, it was felt that a simple set of tests could be representative of the entire group.

CHOICE OF THE SPIKE

Dry particles emitted from stacks are a mixture of uranium metal, uranium oxides, dirt, rust, and other contaminants, the individual densities of which vary considerably. In all probability, since fine material is involved in these stack streams, the oxides are the most prevalent compounds of uranium in the exhaust by the time the top of the stack is reached. The densities of UO_2 , UO_3 , and U_3O_8 are 10.2, 7.3, and 7.3 grams/cc, respectively; hence, it was assumed that a representative density would fall in the range of 7 to 8 grams/cc.

Samples of the emission from two stacks were found to contain particles in the size range of 0.0125 to 4 microns. The data details are given in Table II. An electron microscope photograph of the material collected from one of the stacks is shown in Figure 1.

The tack of the particle emission encountered was not measured for these tests. Admittedly, this particular property might be influential in the retention of particles on the interior walls of the probe tubing after an impact.

The process ventilation system for a Y-12 near-normal-assay uranium operation involves over 750 feet of horizontal transport of exhaust vapors before a filter is reached, and the dust loading on the filtering system is heavy. During this passage through the long, horizontal ducts, a natural separation of heavy particulates from fines occurs so that the material collected at the filters is fine enough to be representative of the exhausted suspensions.

A large batch of this filter material was collected to serve as a spike. The particle sizing was found by electron microscope to vary between 0.05 and 5.5 μ , with the larger particles the more predominant and chiefly in aggregate form. The true density was measured by the

Table II
PARTICLE SIZES OF DRY STACK PARTICULATES

STACK 1		
Particle Size (microns)	Before Buffing Operation	After Buffing Operation
	November 1959 (%)	November 1959 (%)
< 0.125	33	15
< 0.25	51	39
< 0.50	77	67
< 1.0	88	91
< 2.0	97	98
< 4.0	98	100

STACK 2		
Sample Period	Minimum Size (microns)	Maximum Size (microns)
1	0.0125	1.3
2	0.0125	0.65

helium displacement method and found to be 6.7 grams/cc. For the first seven spike tests, a sufficient amount of material was taken from the batch each time for the individual run. Bits of paper were removed by hand picking, and a portion of the sample was sent to the laboratory for exact uranium content analysis.

For Run 9 and all subsequent runs, the remaining "dust" batch was screened and mixed. A set of samples, intended to serve all the runs subsequent to Run 8 were analyzed for exact uranium content, density, and particle size range. The real density was again found to be 6.7 grams/cc, while the size was found to vary from 0.1 to 2.5 microns. This time the aggregates present were broken up for measurement, an operation considered proper since a breakup because of attrition can be expected during passage of the spike through the injection equipment. A graph of the particle size analysis is shown in Figure 2.

CHOICE OF THE TEST STACK

The spike tests were carried out in an operating ventilation stack which handled process and room vapors. A detail drawing of the stack is presented in Figure 3. Favorable factors involved in the choice of this stack were:

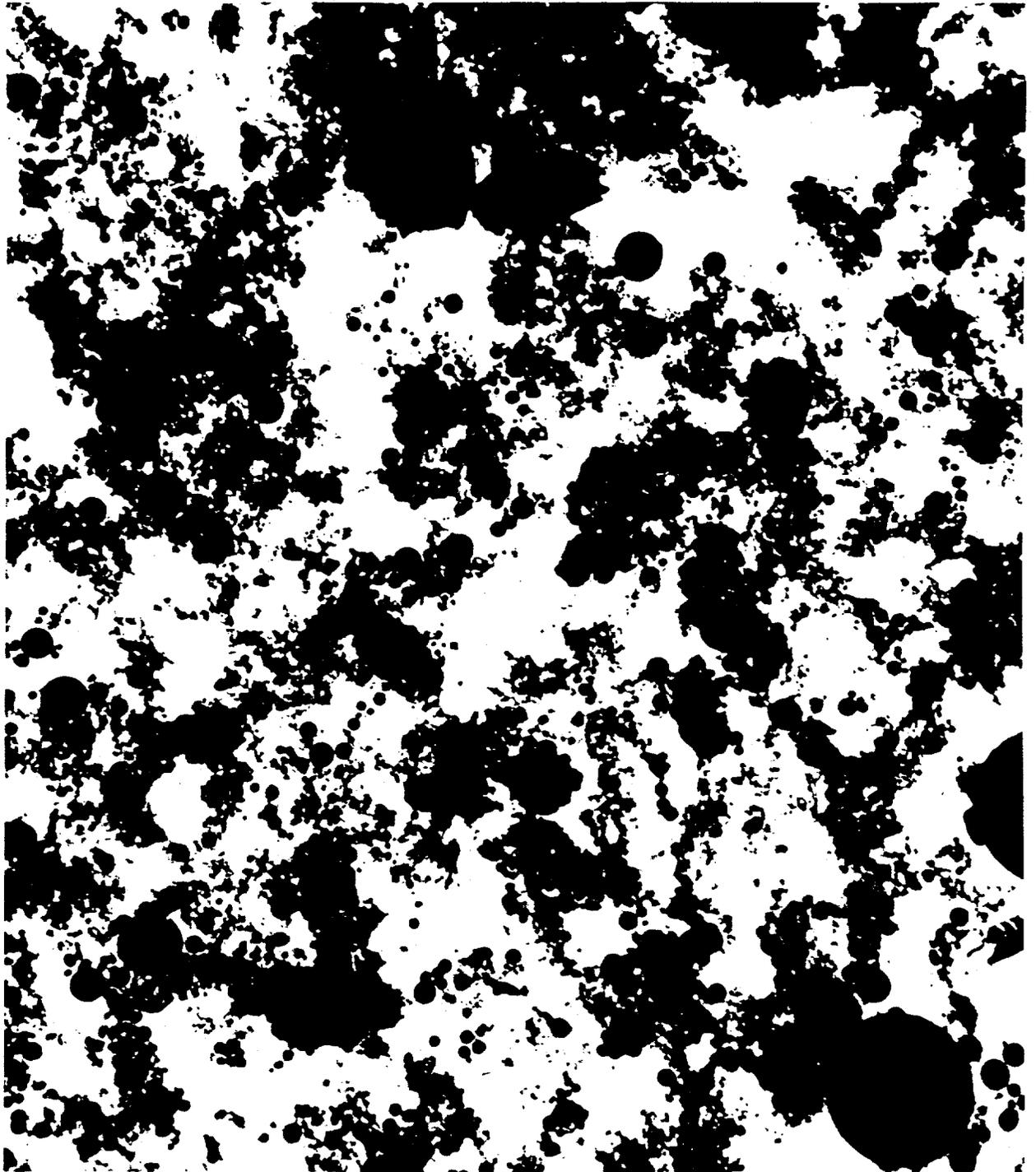


Figure 1. PARTICULATE MATTER FROM STACK 2. (20,000X)

1. The interior walls were dry and not coated so that chance adherence of impacting spike material could be kept to a minimum.
2. The introduced spike would be directed to about the center of the stack and reasonably well dispersed by the flows of other vapor streams entering in the vicinity rather than allowed to strike against a stack wall before dispersion.
3. The uranium loss as industrial particulate matter from this stack was always very low in comparison to the amounts of material to be injected and, consequently, would not bias the test results.

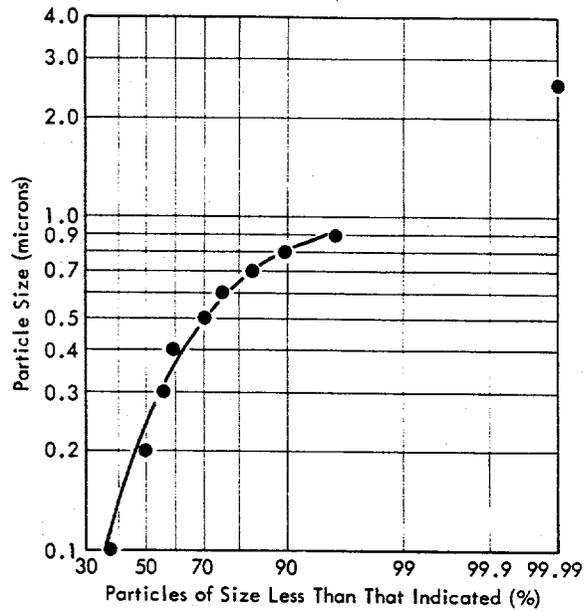


Figure 2. PARTICLE SIZE DISTRIBUTION FOR THE STACK SPIKE USED IN TESTS 9 THROUGH 16.

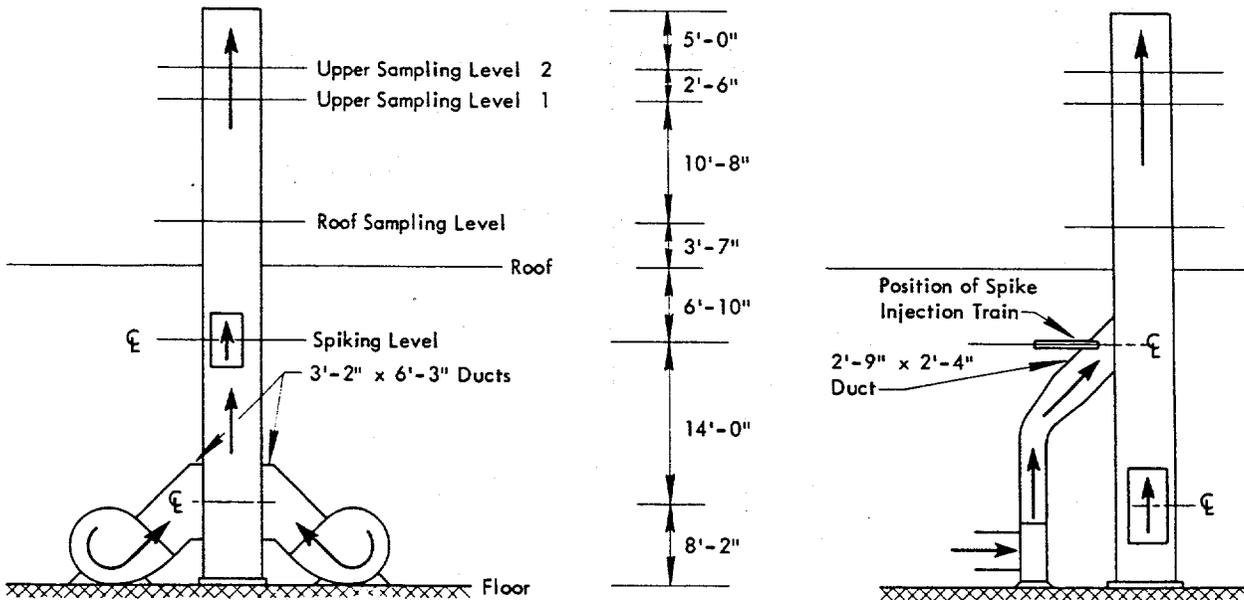


Figure 3. DETAIL DRAWING OF THE STACK USED FOR THE SPIKE TESTS.

SPIKING EQUIPMENT

A Pyrex air ejector was used to introduce the spike into the stack. The complete setup, as shown in detail in Figure 4, was mounted on an inlet side duct and was so positioned that it would direct the stream into the center of the opening in the stack wall from a release point just a few inches upstream. It was observed at the end of each test that a little material was retained inside the ejector discharge nozzle, but the amount was too small to necessitate the application of a correction to the total amount of spike.

PROBE DETAILS AND USAGE

Detailed drawings of the probes used during these tests are given in Figures 5 and 6. The three traverse-type probes with their filters outside the stack were used for performance tests, and the two "inside-stack" probes (filter paper collection heads inside the stack) were used to serve as backup data for the amount of spike injected and the consequent total passage of particulates out the stack. For the first and second Runs, Traverse Probe 1 with ten holes was used; for Runs 3 through 5, Traverse Probe 2 with five holes was used, and for all subsequent Runs, Traverse Probe 3 with five teeth was used. All probes were designed for isokinetic sampling at as near viscous flow as possible by judicious choice of the number of sampling nozzles and nozzle diameter sizes. The reduction in the number of sampling holes between Traverse Probes 1 and 2 was made in order to increase the hole size while retaining the desired conditions.

Traverse Probe 3 was made by placing three-inch-long teeth over the sampling holes of Probe 2. This was done in order that sampling could be achieved without the turbulent effects created by the surface of the manifold tube itself in the path of the stack flow.

For all traverse-type probes, the sample was drawn out of the stack, passed through the filter paper, through a flowmeter (with a vacuum gage for use in correcting the flow to stack conditions) to the vacuum pump, and then discharged to the atmosphere. One of two types of filter paper was used in each run: either H & V 70 (9 mm paper) fixed in a holder mounted on the end of the manifold tube, or Type HA Millipore paper (0.45 μ pore-size) in a millipore holder attached to the manifold by a short piece of rubber hose bent at a right angle. Retaining efficiencies of both papers are above 97% for the face velocities employed during these tests.^(15, 16) Probes were placed in the stack in locations which varied during the runs from a north-south (N-S) position and an east-west (E-W) position at the first upper sampling level, to a N-S position at the roof sampling level.

For each run with the inside-stack probes, both were required, each one mounted at essentially the same level at right angles to the other so that five sampling ports were in operation, designed to draw off five samples from the centers of five equal areas. The second upper sampling level was used for the probes for all these runs.

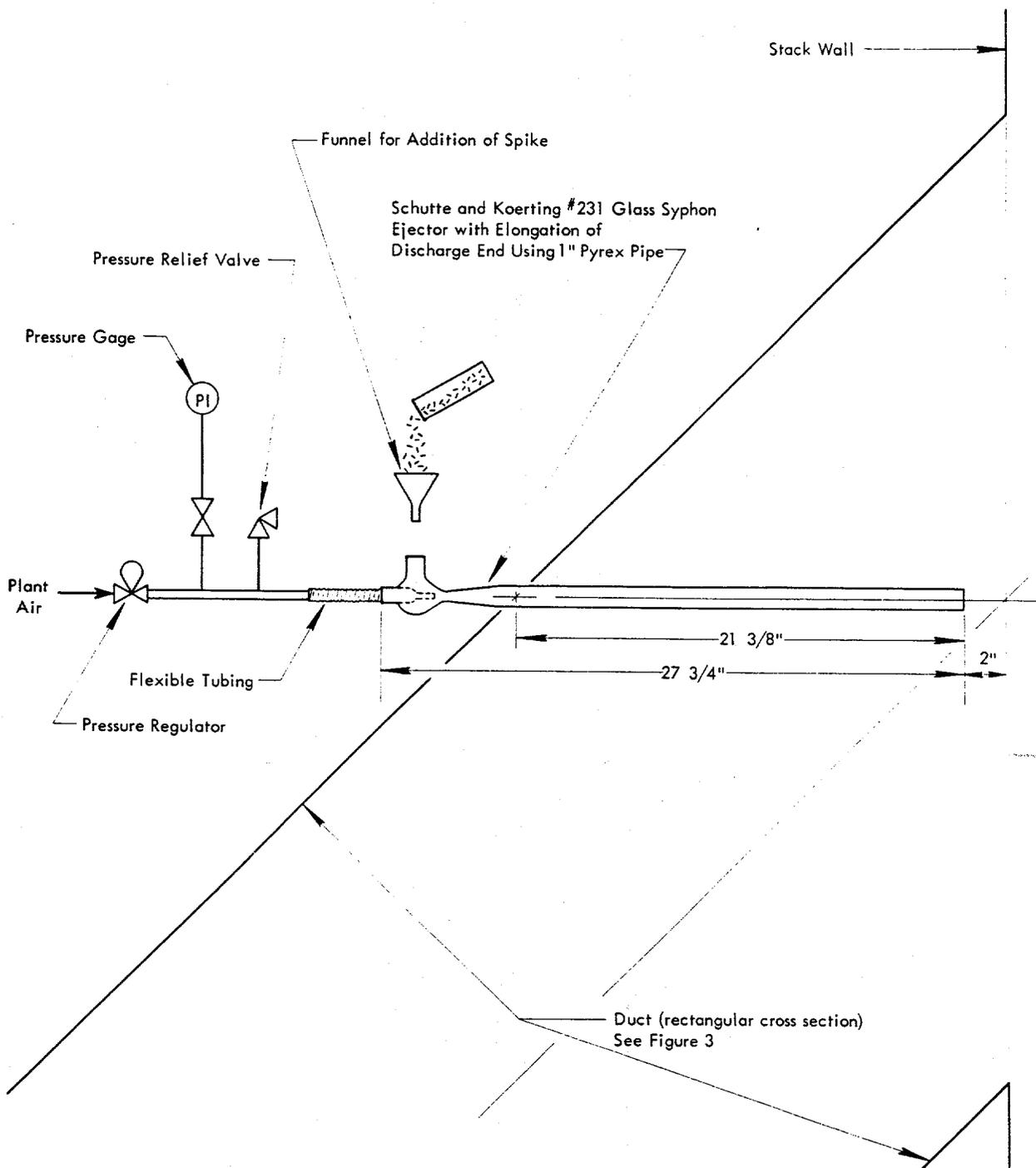
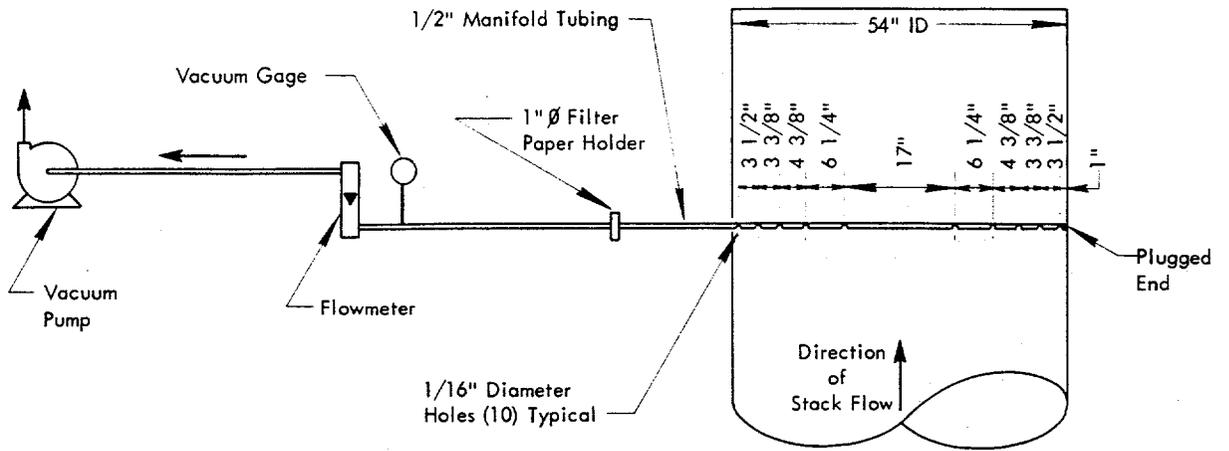
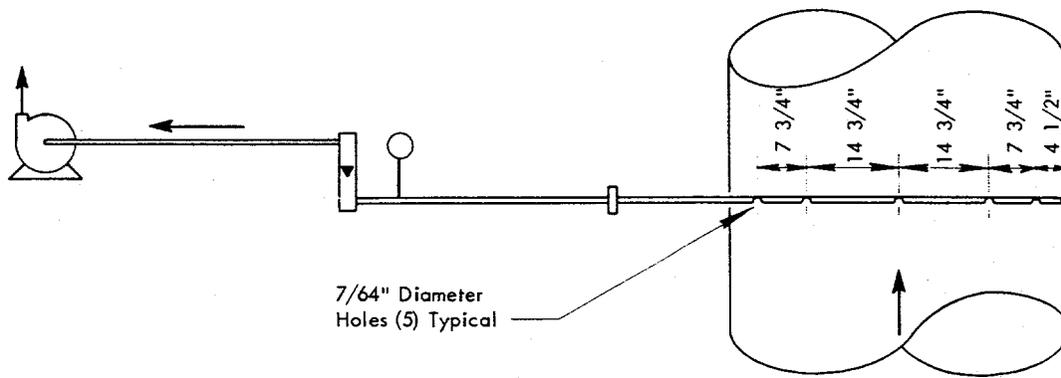


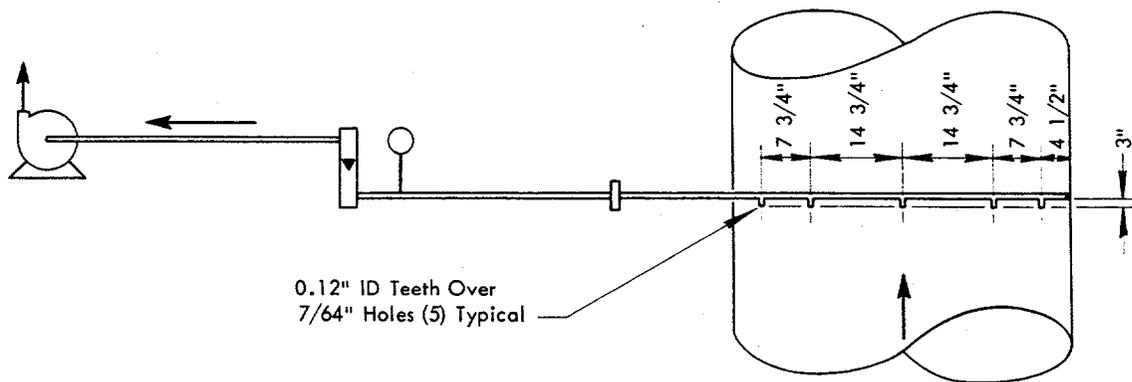
Figure 4. AIR EJECTOR TRAIN FOR STACK SPIKING.



(a) TRAVERSE-TYPE PROBE 1 (with 10 holes)



(b) TRAVERSE-TYPE PROBE 2 (with 5 holes)



(c) TRAVERSE-TYPE PROBE 3 (with 5 teeth)

Figure 5. TRAVERSE-TYPE STACK PROBES USED IN TESTS.

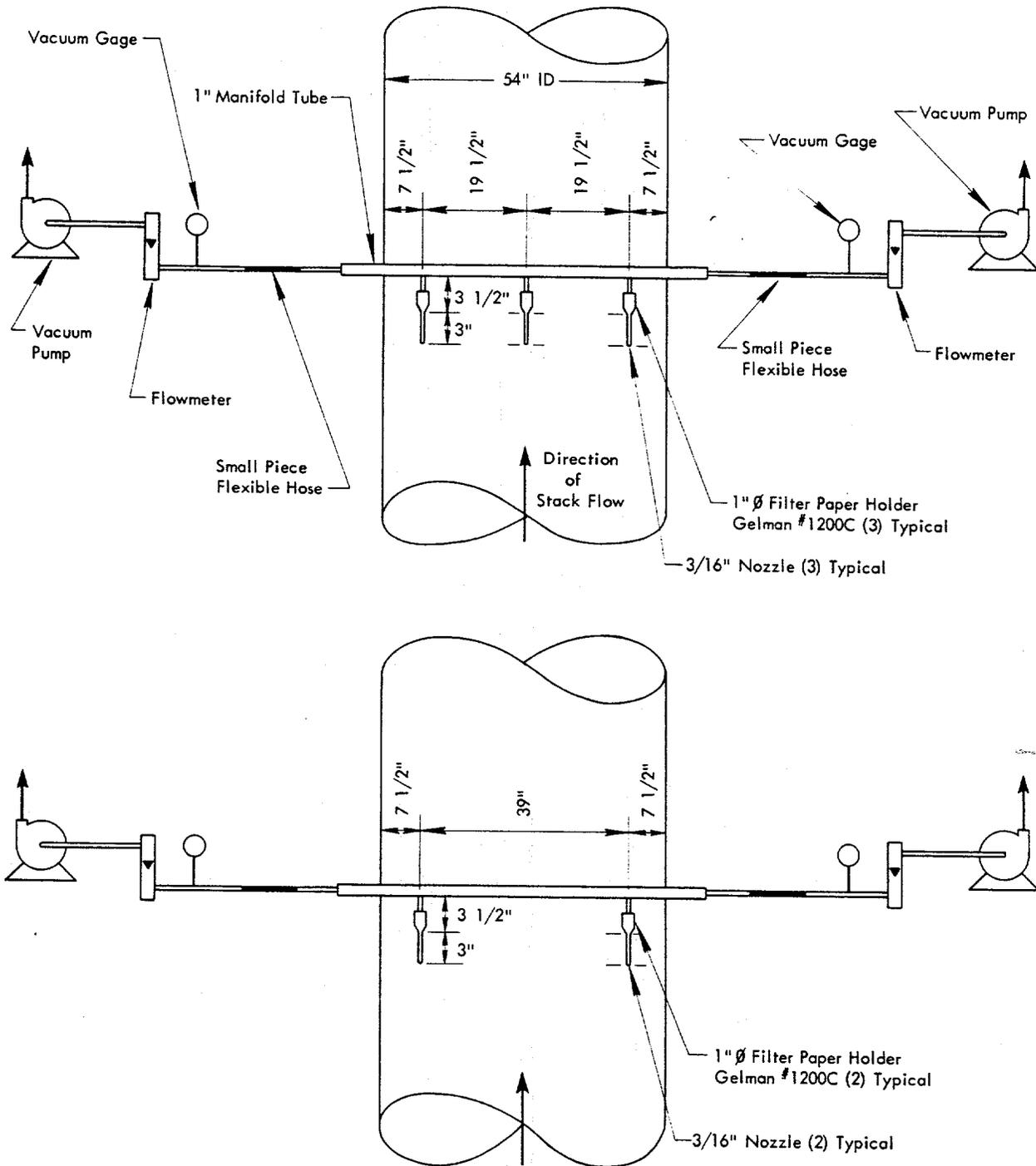


Figure 6. INSIDE-STACK PROBES USED IN TESTS.

Two vacuum pumps were used with each probe in order to be able to draw out the stack aliquots through the large, 3/16-inch sample nozzles under conditions as isokinetic as possible. Millipore, Type HA, paper mounted in Size 1200C Gelman filter holders was used for each nozzle.

Cleaned, traverse-type probes were used in all runs except Numbers 1, 2, and 7. Washing and leaching in 5% nitric acid with occasional agitation for a minimum of 12 hours was employed as the cleaning process. For the first two runs, the probe used had been in service for routine monitoring of the test stack and was borrowed for too short a time for cleaning. Run 7 was combined with Run 6 for material balance data; hence, there was no probe cleaning after Run 6.

TESTING DETAILS AND SAMPLE PREPARATION

The detailed conditions under which tests were run are itemized in Table III. To start a run, the total stack flow was determined and the sampling train was activated. The starting sample flow rate and vacuum were noted. The spike ejector train was turned on using air as motive power, and the spike was added manually over a 7 to 22-minute time period. The amount of spike added varied from run to run from 9.4 to 57.6 grams. The air pressure for each run was varied by choice but retained within the internal 25 to 40 psia. At the completion of a run, about 150 grams of uranium-free quartzite sand were injected for equipment cleanout purposes. The final sample flow rate and the vacuum were again noted: the spike ejector train was cut off, and the probes were removed intact and brought with minimum jarring to the laboratory for sample preparation.

Samples prepared as a result of the tests fell into three categories:

1. That collected by the filter paper.
2. The smear sample: the deposit on the filter paper holder manually rubbed off by using H & V filter papers.
3. The particulate retained inside the probe.

The filter paper, once removed from the holder, was leached in boiling 30 wt % nitric acid until the paper was thoroughly digested. Filtering followed to remove the undissolved shreds of paper. These shreds were then repeatedly washed with nitric acid and water to ensure complete uranium removal. The washings were returned to the mother liquor, and the combined solution was sent to the laboratory for uranium analysis. A similar treatment was given to the smear sample.

Table III
COLLECTION OF PARTICULATE MATTER
(*Traverse-Type Probe*)

Test Number	Probe Number	Filter Paper Type	Probe Direction	Probe Level	Total Spike (grams)	Injection Time (min)	Amount of U in Spike (%)	Air Pressure on Ejector (psig)
1	1	Millipore	E-W	Upper Level 1	30.5	10	74.02	29
2	1	Millipore	E-W	Upper Level 1	34.8	13	74.02	40
3	2	Millipore	N-S	Upper Level 1	33.6	11	73.12	30
4	2	Millipore	N-S	Upper Level 1	35.7	13	73.12	40
5	2	Millipore	N-S	Upper Level 1	57.6	22	74.42	25
6	3	Millipore	N-S	Upper Level 1	27.3	8	74.42	30
6	3	Millipore	N-S	Roof Level	27.3	8	74.42	30
7	3	H & V 70	N-S	Upper Level 1	27.7	9	74.42	30
7	3	H & V 70	N-S	Roof Level	27.7	9	74.42	30
9	3	Millipore	N-S	Roof Level	29.9		74.84	30
10	3	Millipore	N-S	Upper Level 1	31.8	7	74.84	25
10	3	Millipore	N-S	Roof Level	31.8	7	74.84	25
11	3	H & V 70	N-S	Upper Level 1	25.1	11	74.84	25
11	3	H & V 70	N-S	Roof Level	25.1	11	74.84	25
12	3	Millipore	N-S	Upper Level 1	11.6	9	74.84	25
12	3	Millipore	N-S	Roof Level	11.6	9	74.84	25
13	3	Millipore	N-S	Upper Level 1	23.0	8	74.84	25
13	3	Millipore	N-S	Roof Level	23.0	8	74.84	25
14	3	H & V 70	N-S	Upper Level 1	25.7	10	74.84	25
14	3	H & V 70	N-S	Roof Level	25.7	10	74.84	25
15	3	H & V 70	N-S	Upper Level 1	22.8	8	74.84	25
15	3	H & V 70	N-S	Roof Level	22.8	8	74.84	25
16	3	H & V 70	N-S	Upper Level 1	9.4	8	74.84	25
16	3	H & V 70	N-S	Roof Level	9.4	8	74.84	25
Tests 1-5	1, 2	Both Papers		Upper Level 1	192.2			
Total	All	Millipore		Both Levels	409.5			
Total	All	H & V 70		Both Levels	221.4			
Total	All	Both Papers		Upper Level 1	396.6			
Total	All	Both Papers		Roof Level	234.3			
GRAND TOTAL					630.9			

(1) By theoretical sample collection is meant the amount to be expected (based on the amount spiked and the ratio of sample flow to stack flow) if the sampling is unequivocally representative. Equation 1 is used for the computations.

Table III
 COLLECTION OF PARTICULATE MATTER
 (Traverse-Type Probe)

Test Number	Stack Flow (cfm)	Sample Flow at Stack Conditions (cfm)	Theoretical Sample Collection ⁽¹⁾ ($\mu\text{g U}$)	Sample Collected on Filter Paper ($\mu\text{g U}$)	Percent of Theoretical Collection for Filter Paper (%)	Sample Collected on Smears ($\mu\text{g U}$)	Percent of Theoretical Collection for Filter Paper and Smears (%)
1	52,000	0.810	352	64	18	42	30
2	52,000	0.759	376	79	21	13	28
3	52,000	0.772	365	74	20	46	33
4	52,000	0.774	388	72	19	14	23
5	52,000	0.788	650	80	12	42	19
6	52,000	0.790	309	114	37	14	42
6	52,000	0.780	300	87	29	25	37
7	52,000	0.962	381	144	38	49	51
7	52,000	0.954	370	122	33	30	41
9	52,000	0.761	327	100	31	25	38
10	59,000	0.786	317	94	30	11	33
10	59,000	0.822	332	53	16	13	20
11	59,000	0.967	306	90	29	17	35
11	59,000	0.940	298	68	23	19	29
12	61,500	0.769	108	29	27	12	38
12	61,500	0.780	110	34	31	15	45
13	56,529	0.765	233	38	16	8	20
13	56,529	0.780	237	56	24	17	27
14	61,000	0.945	299	99	33	20	40
14	61,000	0.930	293	56	19	22	27
15	61,000	0.944	265	95	36	18	43
15	61,000	0.934	262	50	19	15	25
16	61,000	0.934	108	39	36	10	45
16	61,000	0.933	108	17	16	8	23
			2131	369	17	157	25
			4404	974	22	297	29
			2690	780	29	208	37
			4457	1111	25	316	32
			2637	643	24	189	32
			7094	1,754	25	505	32

As the initial step in the procurement of the sample of particulate matter remaining in the probe interior, the outside had to be cleaned until it was free of uranium. This was accomplished by two or three brisk manual applications of dilute nitric acid followed by tap water and distilled water washings. When the exterior cleaning was finished, the probe was submerged with occasional agitation for a minimum of 12 hours in a narrow-diameter bottle containing about 3 1/2 gallons of 5% nitric acid. Upon removal from the solution, the tube was washed with distilled water, and the washings were added to the 3 1/2 gallons. The solution was then boiled down to about 1/2 liter to bring up the concentration for laboratory analysis.

Computations for total stack emission were made using Equation 1. The flows before and after the test were individually corrected to atmospheric pressure and then averaged to get the sample flow for the run.

For the inside-stack probe runs, no recovery from the interior of the manifolds was necessary since suspensoids were collected on the filter paper in the separate sampling nozzles. Otherwise, testing, sample preparation, and loss computation procedures were the same as for the traverse-type probes. Traverse-probe Runs 14, 15, and 16 were made simultaneously with the 25.7, 22.8, and 9.4-gram spikes, respectively, for the inside-stack tests.

Some extra data were obtained by the use of teathed probes similar to Traverse-type Probe 3 in plant Stacks 1 and 2. The probes had been designed for isokinetic conditions for the stacks involved and were employed for routine sampling (two per day for a five-day week) over periods lasting one and two months. The routine daily samples were analyzed using the common alpha count technique (with a one day wait before measurement to allow Rn-220 and Rn-222 alpha emitting degradation products to decay); but, at the end of a sampling period, the probe was removed and thoroughly cleaned. Recovery and evaluation of the material retained on the inside was executed in the same manner as described previously. The results obtained from these daily samples were totaled for a sampling period. While no overall material balances for material into and out of the stack could be made, a relation between the material caught on the paper and that retained in the probe was provided.

RESULTS

Data obtained during the spike tests on the traverse-type probes for sample collection on the filter paper and smears are shown in Table III. The recoveries from the interior of the probes are listed in Table IV together with material balance closures computed through use of the actual total collection data and the theoretically expected amount. The latter figures would be realized if the sampling were unequivocally representative of the stack flow and is obtained by the use of Equation 1 since the stack loss (as spike) is known.

Table IV
MATERIAL BALANCES
(Traverse-Type Probe Tests)

Test Number	Probe Level	Theoretical Sample Collection ⁽¹⁾ ($\mu\text{g U}$)	Actual Collection			Total ($\mu\text{g U}$)	Material Balance Closure for Collection ⁽²⁾ (%)
			On Filter Paper ($\mu\text{g U}$)	On Smear ($\mu\text{g U}$)	From Inside the Probe ($\mu\text{g U}$)		
6 & 7	Upper Level 1	690	258	63	761	1082	+ 57
6 & 7	Roof Level	670	209	55	358	622	- 7
10	Upper Level 1	317	94	11	171	286	- 10
10	Roof Level	332	53	13	282	348	+ 5
11	Upper Level 1	306	90	17	211	318	+ 4
11	Roof Level	298	68	19	242	329	+ 10
12	Upper Level 1	108	29	12	247	288	+ 167
12	Roof Level	110	34	15	120	169	+ 54
13	Upper Level 1	233	38	8	113	159	- 32
13	Roof Level	237	56	17	194	257	+ 11
14	Upper Level 1	299	99	20	314	433	+ 45
14	Roof Level	293	56	22	290	368	+ 26
15	Upper Level 1	265	95	18	406	519	+ 96
15	Roof Level	262	50	15	236	301	+ 15
16	Upper Level 1	108	39	10	103	152	+ 41
16	Roof Level	108	17	8	99	124	+ 15
TOTAL		4636				5755	+ 24

⁽¹⁾ By theoretical sample collection is meant the amount to be expected (based on the amount spiked and the ratio of sample flow to stack flow) if the sampling is unequivocally representative. Equation 1 is used for computations.

⁽²⁾ $\frac{\text{Actual Collection} - \text{Theoretical Collection}}{\text{Theoretical Collection}} \times 100$

Table V lists the results of sampling during the spike tests with inside-stack probes.

Table V
COLLECTION OF PARTICULATE MATTER
(Inside-Stack Probe)

Test Number	Probe Level	Total Spike (grams)	Total Sampling at Flow Stack Conditions (cfm)	Total Theoretical Sample Collection ⁽¹⁾ ($\mu\text{g U}$)	Actual Collection					Total ($\mu\text{g U}$)
					NW Nozzle ($\mu\text{g U}$)	Center Nozzle ($\mu\text{g U}$)	SE Nozzle ($\mu\text{g U}$)	SW Nozzle ($\mu\text{g U}$)	NE Nozzle ($\mu\text{g U}$)	
14	Upper Level 2	25.7	4.073	1280	465	229	114	92	299	1199
15	Upper Level 2	22.8	4.180	1170	399	285	90	84	324	1182
16	Upper Level 2	9.4	4.225	465	196	110	36	43	110	495

(1) By theoretical sample collection is meant the amount to be expected (based on the amount spiked and the ratio of sample flow to stack flow) if the sampling is unequivocally representative. Equation 1 is used for the computations.

(2)
$$\frac{\text{Actual Collection} - \text{Theoretical Collection}}{\text{Theoretical Collection}} \times 100$$

Data for the amount of holdup retained inside the tubing of the traverse-type probe versus the totaled amount routinely collected on the filter papers over long sampling periods on two actual plant-operated stacks are shown in Table VI. As can be seen, the percentage of the spike collected on the filter paper varied from 12 to 38% but averaged 25% for all tests. For the runs employing the probe with holes, the amount collected was less than the

Table VI
SAMPLE COLLECTION BY TRAVERSE-TYPE PROBE FROM PLANT-OPERATED STACKS

Stack Description	Actual Collection			Total ($\mu\text{g U}$)	Percent of Total Collection from Filter Paper (%)
	From Filter Paper ($\mu\text{g U}$)	From Smears ($\mu\text{g U}$)	From Inside Probe ($\mu\text{g U}$)		
Stack 1					
30-day Test	215	73	179	467	46
57-day Test	425	137	2103	2665	16
Stack 2					
44-day Test	780	38	765	1583	49
41-day Test	1235	131	2015	3381	36
63-day Test	3012	75	2779	5866	51
TOTALS (Both Probes)	5667	454	7841	13962	41 (average)

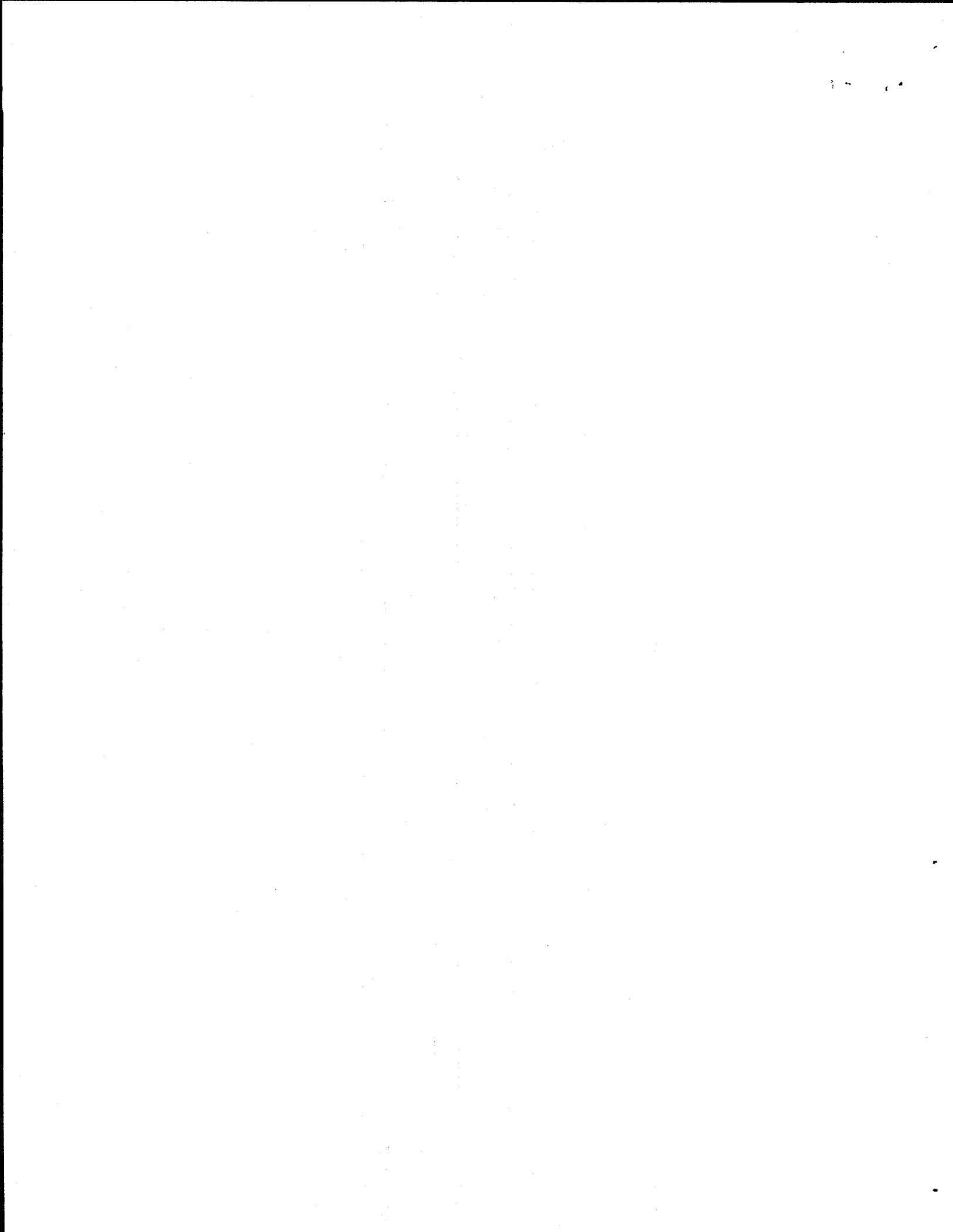
Table V
 COLLECTION OF PARTICULATE MATTER
 (Inside-Stack Probe)

Test Number	Percent of Actual Collection					Material Balance Closure for Collection ⁽²⁾ (%)
	NW Nozzle (%)	Center Nozzle (%)	SE Nozzle (%)	SW Nozzle (%)	NE Nozzle (%)	
14	38.8	19.2	9.5	7.7	24.8	-6.3
15	33.8	24.1	7.6	7.1	27.4	+1.0
16	39.5	22.3	7.3	8.6	22.3	+6.5

overall average. When the millipore filter paper runs were distinguished from the H & V 70 filter paper runs, the average collections were 22 and 29%, respectively. The amounts collected for all the runs at Upper Level 1 averaged essentially the same (24 to 25%) as those for the runs at roof level. The average collection for all runs increased to 32% when both the smear and filter paper were considered.

Actual total collections, including recoveries from inside the probe, averaged, overall, 24% more than theoretical for the traverse-type probe. On the other hand, total collection for inside-stack probes did not differ by more than 6.5% from theoretical.

In the long-period tests on effluent from two different plant stacks, the total material routinely collected on the daily filter paper samples varied from 16 to 51%, but averaged 41% of the total amount obtained from filter papers, smears, and cleaning of the probe interior.



CONCLUSIONS AND RECOMMENDATIONS

As the result of these tests, it is concluded that the traverse-type probe in a vertical stack can take a representative sample from vapor flowing upward containing particulate matter distributed over the cross section. However, not all particulate matter in the aliquot taken reaches the collection filter outside the stack. In these tests about three-fourths of the particulate matter lodged inside the probe.

Under Computation II, Appendix, the detailed computations illustrate the isokinetic sampling feature for the test runs while yet maintaining the flow of the aliquot in or close to the viscous state. It is not usually possible to attain both criteria but rather approach them in plant equipment.

The particle size chosen for the test is representative of the particulate matter normally evolved from plant stacks; but, in the event of plant equipment failure, the evolution of larger particles than these can be expected. In such a case, that portion collected in the filter could be much less than one-fourth of the amount passing up the stack since the large particles could remain in the tube.

It is important to know, in the choice of a representative particle size, whether or not the plant suspensoids are in agglomerate form as they pass up a stack. This information is lacking at this time. For these tests it was assumed that little agglomeration occurred in plant exhaust streams because of particle collisions while in the vapor. Thus, any loosely joined agglomerates would be broken up when caught in the vapor. For this reason it was not considered improper to break down agglomerates prior to size measurement if it could be easily done in the laboratory. On the other hand, well-bonded agglomerate material, which defied easy size reduction, was sized in that condition.

Most of the traverse-type probe runs were made along the N-S (north-south) direction because of general convenience. There was some thought that a bias might be introduced in the data as a result of this single orientation in spite of the use of the two sampling levels. However, in the past, some routine samples taken concurrently along both orientations in the test stack (using Probes 1 and 2) gave, over the long run, the same average results for uranium content of the filter papers. Identical sampling trains and procedures were employed, and only Upper Level 1 was involved. The data taken are given in Table VII.

Variations in the amount of spike, amount of air pressure, length of spiking time, probe location and elevation, type of filter paper, and probe design were made during the test to uncover any major influences on the part of any one of them, but none were in evidence.

Table VII
COMPARISON OF SAMPLING WITH TRAVERSE-TYPE PROBES IN DIFFERENT DIRECTIONS

Sample Number	Traverse Probe 1 In E-W Probe Direction (μg U Collected)	Traverse Probe 2 In N-S Probe Direction (μg U Collected)
1	0.7	0.6
2	1.3	2.0
3	1.8	1.4
4	1.2	0.5
5	4.6	2.1
6	4.3	3.6
7	2.4	2.1
8	2.6	3.2
9	2.0	1.6
10	1.8	1.6
11	2.2	1.9
12	5.8	5.7
13	2.8	1.5
14	1.4	0.8
15	1.6	2.2
16	1.9	1.3
17	4.7	3.8
18	1.0	1.0
19	3.7	1.9
20	1.2	1.7
21	1.3	0.9
22	2.0	1.9
23	1.3	1.4
24	0.6	1.1
25	2.0	4.0
TOTAL	56.2	49.8
AVERAGE READING	2.2	2.0

Stack losses in all probability do not occur continuously over long periods of time at low rates. Rather, it is felt that they occur sporadically over short time periods, and their magnitude is such that the loss rate will vary from very low to very high. In the light of these possibilities, the use of these rates at which the test spikes were injected appears fully justified.

A particle size distribution analysis was made during one spike test to determine if there was any variation in the particle size as the sample was passing up the stack. In Figure 7 the particle-size analyses for both the injected spike and samples are shown. The material

in the sample is somewhat smaller, suggesting a breakup of particles in the stack stream and/or a loss of the larger particles inside the probe. There was no further investigation on this point.

Computations III through VI, Appendix, were made to demonstrate the magnitude of the possible mechanisms for particle retention within the probe. The numbers are not rigorous in that too many major assumptions were made, by necessity, in the derivation and application of equations, but for each computation the most plausible loss-producing conditions were chosen. The loss incurred in rounding the 90-degree bends in the sampling probe is calculated to be the greatest of the individual processes studied. The mechanisms in the order of decreasing importance in particle retention in the traverse-type probe appear as a result of these computations to be:

1. Filtering action with change in direction.
2. Eddy diffusion by turbulence.
3. Gravitational settling.
4. Brownian movement.

The thermal gradient and electrical attraction mechanisms were not studied. However, losses attributable to them are probably negligible.

Results of the inside-stack tests confirm the fact that the total amount of spike added at the foot of the stack did ascend the stack, passed by the traverse-type probes, and was, therefore, available for sample collection. In addition, the inside-stack-type probes would be suitable for stack sampling if they could be serviced easily.

The magnitude of the recovery from inside the traverse-type probes during the plant stack tests enhances the results of the spike tests. These tests were run on two stacks in which

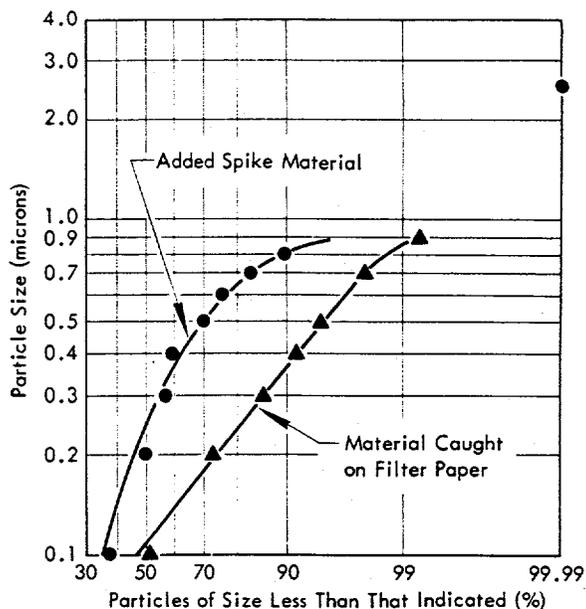


Figure 7. PARTICLE SIZE DISTRIBUTION FOR THE SPIKE INJECTED vs THE STACK SAMPLE COLLECTED.

the tack property of the particulates is at variance. For Stack 2, the suspensoids were wet and sticky, while the Stack 1 suspensoids exhausted were usually very dry. If it could be assumed that the total amount collected in the paper, smears, and probe cleanings was equal to the true representative sample, then the percentage recovery on the filter paper during these last tests would be somewhat greater than the average percentage recovery during the spike tests. However, the bulk of the data available supports the 25% recovery figures as a reasonable overall value.

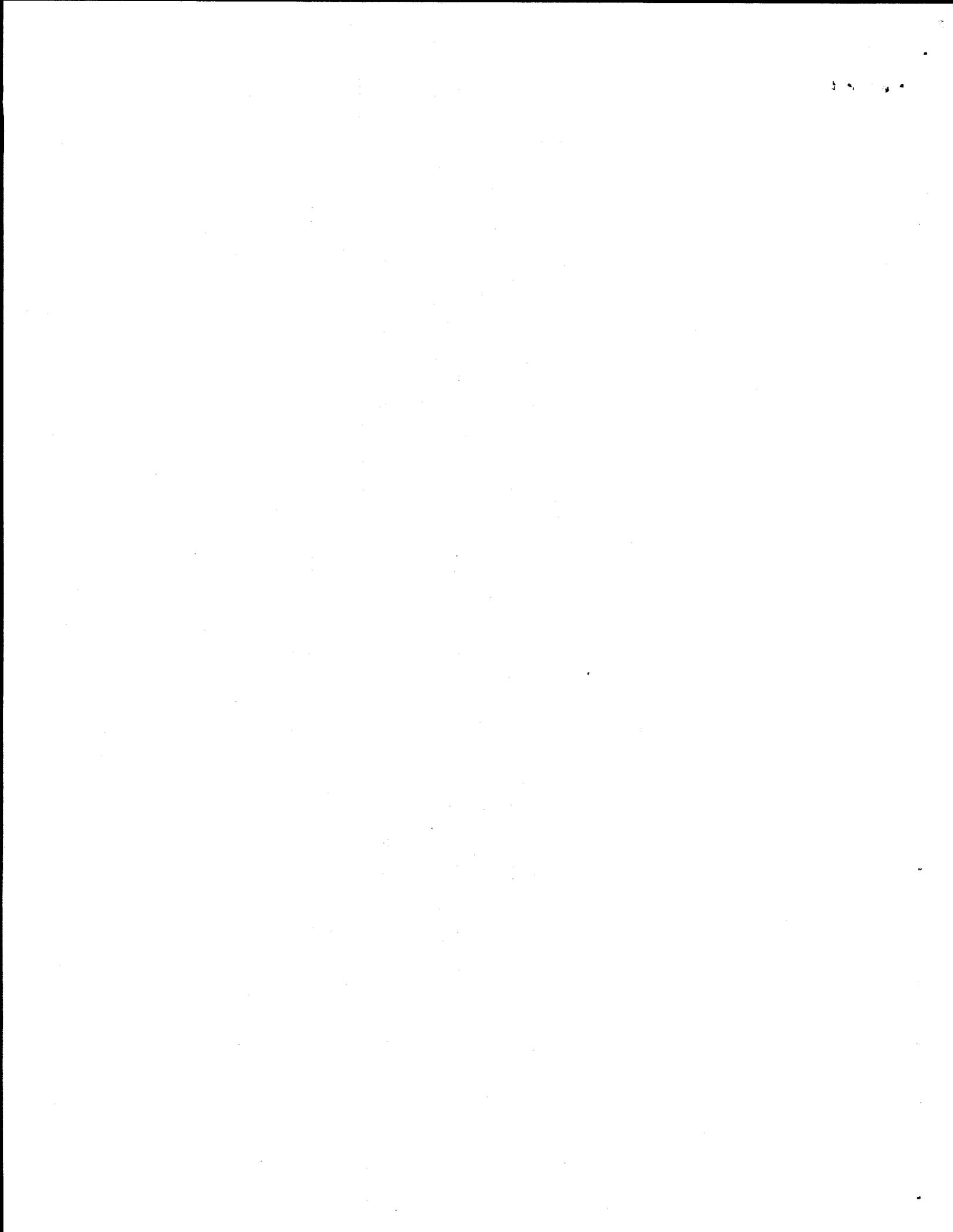
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APPENDIX

COMPUTATIONS

I. VELOCITY OF STACK FLOW:

Stack Diameter	54" ID
Stack Cross-sectional Area	$\left(\frac{54}{12}\right)^2 (0.785) = 15.9 \text{ sq ft}$
Stack Velocities:	At 52,000 cfm = 3260 fpm
	At 56,529 cfm = 3544 fpm
	At 61,500 cfm = 3856 fpm

II. SAMPLE FLOW CONDITIONS WITHIN PROBES AND FILTER HEADS (All Sample Flows at Atmospheric Pressure)

A. Traverse Probe 1 (10 holes at 1/16" dia; 0.8 cfm total)

Velocity at Sample Points:

$$\frac{0.8}{10} \frac{1}{(0.785) \left(\frac{1}{16 \times 12}\right)^2} = 3750 \text{ fpm}$$

Maximum Velocity in Manifold (1/2" OD x 0.035" Wall):

$$\frac{0.8}{(0.785) \left(\frac{0.43}{12}\right)^2} = 797 \text{ fpm}$$

Manifold Flow Condition: (Air at 75° F; $\rho = 0.075 \text{ lbs/ft}^3$;
 $\mu = 1.235 \times 10^{-5} \text{ lbs/ft-sec}$):

Max Reynolds Number =

$$\frac{\left(\frac{0.43}{12}\right) (797) (0.075)}{\left(1.235 \times 10^{-5}\right) (60)} = 2880$$

Barely Turbulent Flow

Flow Through Filter Paper (1" dia):

$$\frac{(0.8) (2.54)}{(0.785) \left(\frac{1}{144}\right) (60)} = 62 \text{ cm/sec}$$

Corresponds to 99.6% Collection Efficiency for 1μ Particles in H & V 70 paper, 9 mils thick. See References (15) and (16).

B. Traverse Probe 2 (5 holes at 7/64" dia; 0.8 cfm total)

Velocity at Sample Points:

$$\frac{\frac{0.8}{5}}{(0.785) \left(\frac{0.11}{12}\right)^2} = 2430 \text{ fpm}$$

Maximum Velocity in Manifold (1/2" OD x 0.035" Wall): 797 fpm

Manifold Flow Condition:

Max Reynolds Number = 2880

Barely Turbulent Flow

Flow Through Filter Paper (1" dia): 62 cm/sec

C. Traverse Probe 3 (5 teeth 0.12" dia; 0.8 cfm total)

Velocity at Sample Points:

$$\frac{\frac{0.8}{5}}{\left(0.785\right) \left(\frac{0.12}{12}\right)^2} = 2040 \text{ fpm}$$

Flow Condition In Any Tooth:

Reynolds Number =

$$\frac{\left(\frac{0.12}{12}\right) (2040) (0.075)}{\left(1.235 \times 10^{-5}\right) (60)} = 2075$$

Barely Turbulent Flow

D. Inside-Stack Probe (2 nozzles at 3/16" dia; 1.7 cfm total)

Velocity at Sample Points:

$$\frac{\frac{1.7}{2}}{\left(0.785\right) \left(\frac{3}{16 \times 12}\right)^2} = 4440 \text{ fpm}$$

Nozzle Flow Condition:

Reynolds Number =

$$\frac{\left(\frac{3}{16 \times 12}\right) (4440) (0.075)}{\left(1.235 \times 10^{-5}\right) (60)} = 7000$$

Turbulent Flow

E. Inside-Stack Probe (3 nozzles at 3/16" dia; 2.3 cfm total)

Velocity at Sample Points:

$$\frac{\frac{2.3}{3}}{(0.785) \left(\frac{3}{16 \times 12} \right)^2} = 4250 \text{ fpm}$$

Nozzle Flow Condition:

Reynolds Number =

$$\frac{\left(\frac{3}{16 \times 12} \right) (4250) (0.075)}{(1.235 \times 10^{-5}) (60)} = 6700$$

Turbulent Flow

III. LOSSES WITHIN THE PROBE: BROWNIAN MOTION

Conditions: Particle Dia = $0.0125 \mu = 0.0125 \times 10^{-4} \text{ cm}$
 Sample Flow = 1 cfm
 Probe Length (manifold) = 70"

$$D = \frac{2.4 \times 10^{-11}}{d_o} \left(1 + \frac{1.8 \times 10^{-5}}{d_o} \right) \quad (6)(a)$$

$$= \frac{2.4 \times 10^{-11}}{0.0125 \times 10^{-4}} \left(1 + \frac{1.8 \times 10^{-5}}{0.0125 \times 10^{-4}} \right) = 2.96 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$F_B = 5.2 \left(\frac{\pi DL}{2G_s} \right) \quad (5)$$

$$L = 70 \times 2.54 = 178 \text{ cm}$$

$$G_s = 1 \text{ cfm} = 472 \text{ cm}^3/\text{sec}$$

(a) Refers to equation number in the main body of the report (Page 22).

$$= 5.2 \left(\frac{\pi \times 2.96 \times 10^{-4} \times 178}{2 \times 472} \right)^{2/3} = 0.0164$$

i.e., 1.6% of all particles (0.0125 μ) reach the wall.

IV. LOSSES WITHIN THE PROBE: GRAVITATIONAL SETTLING

Conditions: Particle Dia	= 4 μ = 4 $\times 10^{-4}$ cm
Particle Density	= 5 gms/cm ³ (spherical)
Probe Length (manifold)	= 70" = 178 cm
Diameter of Probe (manifold)	= 0.43" = 1.09 cm
Sample Flow	= 1 cfm

$$u_T = 2.5 \times 10^{-2} \text{ ft/sec} = 6.36 \times 10^{-2} \text{ cm/sec}$$

Ref.: See Reference (13).

$$V = \frac{(1728)(2.54)}{(60)(0.785)(0.43)^2} = 507 \text{ cm/sec}$$

$$\lambda = \left(\frac{3L u_T}{8 V a} \right)^{1/3} = \left(\frac{3 \times 178 \times 6.36 \times 10^{-2}}{8 \times 507 \times \frac{1.09}{2}} \right)^{1/3} = 0.249 \quad (4a)$$

$$\beta = \sqrt{1 - \lambda^2} = \sqrt{1 - (0.249)^2} = 0.9685 \quad (4b)$$

$$\begin{aligned} F_G &= 1 - \frac{2}{\pi} (\lambda\beta + \sin^{-1} \beta - 2\lambda^3\beta) \quad (4) \\ &= 1 - \frac{2}{\pi} (0.249 \times 0.9685 + \sin^{-1} 0.9685 - 2[0.249]^3 \times 0.9685) \\ &= 0.034 \end{aligned}$$

i.e., 3.4% of all particles (4 μ) reach the wall.

V. LOSSES WITHIN THE PROBE: EDDY DIFFUSION BY TURBULENCE

Conditions: Probe Length (manifold), Diameter of Probe (manifold), Particle Diameter, Particle Density, and Average Fluid Velocity - Same as under Computation IV.

$$\mu \text{ (air)} = 1.235 \times 10^{-5} \text{ lbs/ft-sec} = 0.0001835 \frac{\text{gms}}{\text{cm-sec}}$$

$$\rho_g \text{ (air)} = 0.075 \text{ lbs/ft}^3 = 0.0012 \text{ gm/cm}^3$$

$$f = \text{Fanning Friction Factor for Re. No. At 2800} = 0.012$$

Ref.: Perry, J. H., Chemical Engineer's Handbook, 3rd edition, p 382, McGraw-Hill Book Co, New York, (1950).

Using the method of Postma and Schwendiman, Reference (12)

$$\begin{aligned} & \left[2a \right]^{0.84} \left[\frac{\rho \rho_g d_o^2 f V^2}{\mu^2 \left(1 + \frac{13.5 \rho d_o^2}{\mu} \right)} \right] = \\ & \left[1.09 \right]^{0.84} \left[\frac{(5) (0.0012) (4 \times 10^{-4})^2 (0.012) (507)^2}{(0.0001835)^2 \left(1 + \frac{13.5 \times 5 \times 16 \times 10^{-8}}{0.0001835} \right)} \right] \\ & = 83 \end{aligned}$$

From the Plot of Dimensionless Parameters:

$$\frac{K}{V} \times 10^6 = 75$$

$$K = \frac{75}{10^6} \times 507 = 0.038 \text{ cm/sec.}$$

$$\ln \frac{1}{c} = \frac{2KL}{\sqrt{a}} \quad (8)$$

$$\log \frac{1}{c} = \frac{2 KL}{2.303 \sqrt{a}} = \frac{(2) (0.038) (178)}{(2.303) (507) (0.545)} = 0.0212$$

$$C = 0.95$$

$$F_T = 1 - C \quad (7)$$

$$= 1 - 0.95 = 0.05$$

i.e., 5% of all particles (4 μ)
reach the wall.

VI. LOSSES WITHIN THE PROBE: FILTERING ACTION WITH 90-DEGREE CHANGE OF DIRECTION IN PASSAGE OF SAMPLE FROM HOLES OR TEETH INTO MANIFOLD

Conditions: 1/4" x 0.065" tube bending 90°; ID = 0.25 - 0.13 = 0.12"
Internal Radius = 0.06" = 0.152 cm
Sample Flow in 1/4" tube = 1/5 cfm = 94.5 cm³/sec
Vapor Viscosity = 1.835 x 10⁻⁴ gm/cm-sec
Particle Density = 5 gms/cc
Particle Size = 3 μ = 3 x 10⁻⁴ cm
(3 μ makes a simpler calculation than 4 μ)
Particles Enter the Bend Axially

Using the method of Forstat and Boyd - Reference (11)

$$K_3 = \frac{\rho G_s}{9\mu a^4} = \frac{(5) (94.5)}{(9) (1.835 \times 10^{-4}) (0.152)^4} = 5.375 \times 10^{-8} \quad (2b)$$

$$\ln \left\{ \frac{\left[(a^2 - \gamma^2)^{1/2} + \sqrt{(a^2 - \gamma^2) - d_o \left(a - \frac{d_o}{4} \right)} \right] \left[\frac{\sqrt{a^2 - \gamma^2} - \delta_o}{\sqrt{a^2 - \gamma^2} + \delta_o} \right]}{\left[(a^2 - \gamma^2)^{1/2} - \sqrt{(a^2 - \gamma^2) - d_o \left(a - \frac{d_o}{4} \right)} \right] \left[\frac{\sqrt{a^2 - \gamma^2} + \delta_o}{\sqrt{a^2 - \gamma^2} - \delta_o} \right]} \right\} = K_3 d_o^2 \sqrt{a^2 - \gamma^2} \quad (2)$$

where γ and δ_o are the coordinates locating the particles.

Substituting values:

$$\ln \left\{ \frac{\left[0.0231 - \gamma^2\right]^{1/2} + \sqrt{\left[0.0231 - \gamma^2\right] - 0.0003 \left[0.152 - \frac{0.0003}{4}\right]}}{\left[0.0231 - \gamma^2\right]^{1/2} - \sqrt{\left[0.0231 - \gamma^2\right] - 0.0003 \left[0.152 - \frac{0.0003}{4}\right]}} \right\}$$

$$\left\{ \frac{\left[0.0231 - \gamma^2\right]^{1/2} - \delta_0}{\left[0.0231 - \gamma^2\right]^{1/2} - \delta_0} \right\} = (5.375 \times 10^8) (3 \times 10^{-4})^2 (0.0231 - \gamma^2)^{1/2}$$

Substituting values for γ in this equation, δ_0 can be computed and a location contour can be established for those 3μ particles in the tube cross section just before entering the bend which will strike the wall before passing out of the bend. That contour is shown in Figure A-1 together with annular elements for graphical integration.

Cross Sectional Area of Tube: $(0.785) (0.304)^2 = 0.0726 \text{ in}^2$

Cross Sectional Area A_{i1} of Central Circle, -0.05 to 0.05 :

$$(0.785) (0.1)^2 = 0.00785 \text{ in}^2$$

Cross Sectional Area A_{i2} of Next Annulus: 0.02355 in^2

Cross Sectional Area A_{i3} of Outer Annulus: 0.0412 in^2

Area Above Contour:

$$a_{i1} \text{ in Cross Sectional Area } A_{i1} = 0.00392 \text{ in}^2$$

$$a_{i2} \text{ in Cross Sectional Area } A_{i2} = 0.00982 \text{ in}^2$$

$$a_{i3} \text{ in Cross Sectional Area } A_{i3} = 0.01266 \text{ in}^2$$

Volume Flow in Cross Sectional Area:

$$G_{s_{i1}} \text{ in Cross Sectional Area } A_{i1} = 94.5 \left(\frac{0.00785}{0.0726} \right) = 10.22 \text{ cm}^3/\text{sec}$$

$$G_{s_{i2}} \text{ in Cross Sectional Area } A_{i2} = 30.7 \text{ cm}^3/\text{sec}$$

$$G_{s_{i3}} \text{ in Cross Sectional Area } A_{i3} = 53.6 \text{ cm}^3/\text{sec}$$

ϕ is the fraction of the 3μ particles in the fluid which enter above the contour and hence impinge in bend, is solved as follows:

$$\phi = \frac{\sum_i \frac{G_{s_i}}{A_i} a_i}{G_s}$$

Substituting:

$$\phi = \frac{10.22 \left(\frac{0.00392}{0.00785} \right) + 30.7 \left(\frac{0.00982}{0.02355} \right) + 53.6 \left(\frac{0.01266}{0.0412} \right)}{94.5}$$

$$= 0.365$$

i.e., 36 1/2% of all particles (3μ) impinge on the wall.

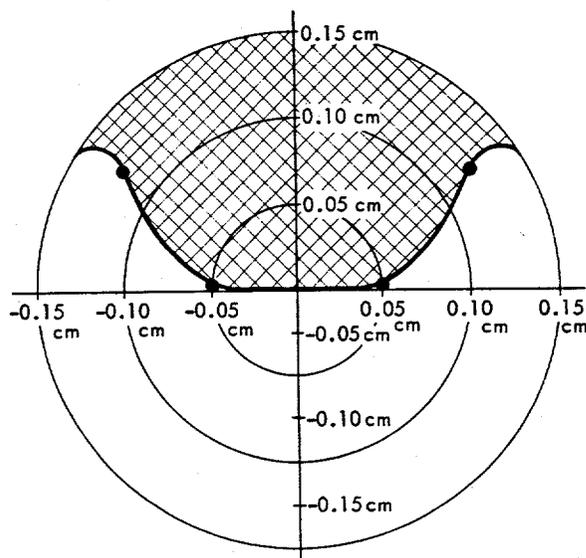


Figure A-1. CONTOUR OF THREE-MICRON PARTICLE IMPINGEMENT.