AN INVESTIGATION OF FACTORS IMPORTANT IN THE DESIGN OF A THERMAL PRECIPITATOR FOR USE AT HIGH ALTITUDE

by

THOMAS W. WILSON and CLYDE ORR, JR.

COVERING THE PERIOD
15 MAY 1959 to 15 MAY 1962

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OAK RIDGE, TENNESSEE
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DEFINITION OF SYMBOLS

A   empirical constant appearing in slip-correction equation.

$A_x$   cross-sectional area of aerosol stream in precipitator, normal to direction of flow.

a   particulate radius.

$a_{rd}$   particulate radius evaluated at outer periphery of thermal precipitation deposit.

B   empirical constant appearing in slip-correction equation.

C   empirical constant appearing in slip-correction equation.

$C_1$   proportionality factor in thermal force-temperature gradient relationship.

$D_p$   particulate diameter.

$\frac{dT}{dy}$   temperature gradient in vertical direction.

$F$   force

$\bar{F}$   net force.

$(F_d)_K$   kinetic drag force.

$(F_d)_H$   hydrodynamic drag force.

$F_g$   gravitational force.

$F_t$   thermal force.

$(F_t)_E1$   thermal force defined by Einstein for Kn $\gg 1$.

$(F_t)_E2$   thermal force defined by Einstein for Kn $\ll 1$.

$K$   energy correction factor in parameter of stability in laminar flow.

$Kn$   Knudsen number.

$k$   proportionality constant.

$k_g$   thermal conductivity of aerosol carrier medium (gas).

$(k_g)_{tr}$   translational constituent of thermal conductivity of gas.

$k_p$   thermal conductivity of particulate material.
DEFINITION OF SYMBOLS (Continued)

L  precipitator plate separation, or a characteristic linear dimension of a flow channel.

M  molecular weight of the aerosol carrier medium (gas).

N_{Re}  Reynolds number.

P  pressure of the aerosol carrier medium (gas).

P_{e}  precipitator exit pressure.

P_{o}  precipitator inlet pressure.

Q  volumetric flow rate of the aerosol.

R  universal gas constant.

\bar{R}  total radial distance across precipitator plates \( \bar{R} = r_{e} - r_{o} \).

r  radial coordinate or radial distance.

r_{d}  deposit radius.

r_{e}  precipitator exit radius.

r_{o}  precipitator inlet radius.

S  slip-correction factor.

T  absolute temperature of aerosol carrier medium (gas).

t  time.

\bar{t}_{r}  transit time required for particulate to move from precipitator inlet to cold plate surface.

U  local (or point) fluid velocity.

\bar{U}_{avg}  average fluid velocity \( \bar{U}_{avg} = Q/A_{x} \).

U_{max}  maximum fluid velocity.

V  linear velocity.

V_{g}  gravitational component of particulate velocity.

V_{h}  horizontal component of velocity.

V_{r}  radial component of particulate velocity.
DEFINITION OF SYMBOLS (Concluded)

\( V_t \) thermal component of particulate velocity.

\( (V_t)_{EP} \) thermal velocity defined by Epstein.

\( (V_t)_W \) thermal velocity defined by Waldmann.

\( V_y \) vertical component of particulate velocity.

\( \bar{v} \) mean molecular speed of gas molecules.

\( W \) width of inlet or plate in rectilinear flow precipitator.

\( y \) vertical coordinate or vertical distance measured from midplane of the precipitation region.

\( Z \) mobility of particulate.

\( Z_s \) particulate mobility corrected for slip effect.

\( \alpha \) coefficient of diffuse reflection

\( \mu \) viscosity of aerosol carrier medium (gas).

\( \lambda \) mean free path of aerosol medium (gas).

\( \rho \) density.

\( \rho_p \) particulate density.

\( \sigma \) stability parameter, a modified Reynolds number for a diverging radial flow system.
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I. SUMMARY

An experimental investigation of the particle collecting capability of thermal precipitators has been conducted. The objectives of the study have included the effectiveness of thermal precipitation and its dependence upon operating pressure, particle size, precipitator plate separation distance, and aerosol throughput velocity. Throughout this investigation the actual performance of the experimental precipitator has been of primary concern. Data have been accumulated to provide a practical guide for the design of a thermal precipitator for the high altitude sampling of atmospheric particulate material. Results have been compared with theory and found to be generally consistent.

A radial flow thermal precipitator of conventional design has been used for the experimental precipitation of finely divided airborne particulate materials, including magnesium and aluminum oxides, silver, and platinum, at pressures in the range from 1.0 to 0.01 atmosphere. Observations have been made with plate separations from 0.025 to 0.41 cm and with average aerosol velocities at the precipitator inlet in the range from 0.6 to 90 meters per second.

The experimental results indicate an increase in precipitator effectiveness, in terms of mass throughput capacity, as high as 700 per cent for a decrease in operating pressure from 1.0 to 0.01 atmosphere. Particles have been collected in the diameter range from 2 microns to less than 30 Å at pressures as low as 2 mm Hg (a particulate system characterized by a Knudsen number on the order of $10^{-4}$). The effectiveness of thermal precipitation with relatively low flow rates at atmospheric pressure has been found to be independent of precipitator plate separation in the range from
0.025 to 0.41 cm. The effectiveness of thermal precipitation with relatively high gas velocities at 0.01 atmosphere pressure is apparently independent of precipitator plate separation in the range from 0.5 to 1.5 mm. Furthermore, it appears that the effectiveness under these conditions is independent of the velocity of the aerosol, at least within a range of average precipitation inlet velocities from 5.5 to 36 meters per second.

These experimental observations establish the feasibility of thermal precipitation as a technique for high altitude sampling. It is estimated that a deposition surface area of about 0.3 square meter would be required for a sampling rate of 500 cfm at 0.01 atmosphere (equivalent to an altitude of 100,000 ft) using a thermal precipitator operating at a temperature gradient of 2500°C/cm. A reasonable distance between precipitator plates would be one millimeter, therefore requiring an actual temperature difference of 250°C. This estimate is based on an increase in precipitator effectiveness over atmospheric performance by a factor of about 2.5, with an efficiency of essentially 100 per cent, independent of particle diameter.

Theoretical considerations suggest that thermal precipitation could be employed at altitudes well above 100,000 ft without a decrease in effectiveness. It is recommended that a thermal precipitator be designed specifically for high altitude operation on the basis of the experimental data presented in this report.
II. INTRODUCTION

Airborne particles in a temperature gradient experience a force, due to interaction of the gas molecules with the particles' surface, which tends to move each particle in the direction of decreasing temperature. This force may be utilized in a thermal precipitator to collect air-suspended particulate material. The aerosol is directed between two surfaces of different temperatures. The particles are precipitated upon the cooler surface. Currently accepted theories of thermal force phenomena predict an increased effectiveness for thermal precipitators operating at low air pressures. This investigation originated as an experimental study of the particle collecting capability of thermal precipitation at simulated high-altitude conditions, with the primary objective of determining its pressure dependence in the range from 1.0 to 0.05 atmosphere (equivalent to an altitude range from sea level to 104,000 feet).

Because of favorable results initially obtained, the study was extended to provide experimental data needed for the design of a thermal precipitator for high altitude sampling. Of specific interest were (1) the effectiveness of thermal precipitation in collecting submicron particles and (2) the optimization of the distance of precipitator hot and cold plate separation.

Up to this point in the current investigation, experimental precipitation had been conducted at relatively low aerosol sampling rates. Estimates of precipitator performance at high altitudes, while based on experimental observations, were of proven reliability only for very low aerosol throughput velocities and, with that restriction, dictated a bulky geometry in precipitator design. In order to increase the compactness and to
minimize weight and power requirements of the precipitator, a knowledge of the effectiveness of thermal precipitation at much greater throughput velocities is highly desirable. Extrapolation of experimental observations into a region of higher Reynolds number is risky. If this is to be done, entrance effects must be ignored, simplifying assumptions regarding the linearity of the temperature profile must be made, the error in the approximation of pressure drop is magnified, and there is a possibility of exceeding the stability criteria for laminar fluid flow. Neither theoretical nor experimental observations sufficient for an accurate evaluation of these effects in radial flow thermal precipitation were, heretofore, available. Because of these uncertainties, further experimental studies were undertaken to extend the range of information. Of primary concern in this phase of study has been the actual performance of a thermal precipitator in collecting particulate material from an aerosol flowing at low pressures and relatively high radial velocities through the unit. Entrance effects, nonlinear temperature profiles, laminar stability, etc., are of importance only insofar as they affect precipitator effectiveness and design.
III. THEORETICAL BACKGROUND

A. Effectiveness of Thermal Precipitation

In the analytical sampling of an aerosol, the efficiency of the sampling device is commonly defined as the mass per cent of the total gas-suspended particulate material recovered in the collector. For most devices, the efficiency is dependent upon particle size and generally increases with increasing particle diameter. Since the mass fraction of very fine particles in the typical distribution of atmospheric debris is rather low, the efficiency defined on a mass basis is usually quite high, even when the very fine material is not collected. Thermal precipitation efficiency is essentially independent of particle size, however, in that all particles move to the collecting plate at nearly equal velocities. The recovery of particulate material from an aerosol is essentially complete provided the aerosol flow rate does not exceed the limiting capacity of the thermal precipitator. Hence the term "effectiveness" is used in this report to distinguish performance from efficiency, which is assumed to be always 100 per cent. The effectiveness of thermal precipitation has been measured in terms of the decrease in the deposition area required for a given aerosol sampling rate. This may be interpreted in terms of the increase in the throughput capacity of a given precipitator with a fixed deposition area.

The basic functional mechanism of any precipitator is easily visualized by considering the movement of an aerosol particle within it. As a particle is swept through the precipitator by the flowing gas, it is moved also in the direction of the collecting surface by a precipitating force. The effectiveness of a precipitator is determined primarily by the
particulate velocity. To illustrate the significance of this factor, the particulate velocity may be resolved into two components, viz., (1) the precipitating velocity component directed toward the collecting surface upon which particulate material is deposited and (2) the traversing velocity component in the direction of aerosol flow. The ratio of the precipitating velocity component to the traversing velocity component determines how far the particles will travel through the precipitator before striking the collecting surface. Thus the effectiveness of precipitation can be increased only by increasing this velocity component ratio.

In most standard precipitators the two velocity components are directed at right angles to each other, and in the usual operating position the collecting surface is located in the horizontal plane. The aerosol is directed along the collecting surface and its direction of flow is also horizontal. The traversing particulate velocity is therefore horizontal and may generally be assumed equal in magnitude to the velocity of the aerosol stream. The precipitating force is directed normal to the collecting surface (vertically) and, in the case of thermal precipitation, possesses thermal and gravitational constituents. Generally, for small particles the gravitational component is negligible and the precipitating velocity may be considered equal to the thermal velocity component (i.e., attributable solely to thermal force). Obviously, geometric design and extraneous forces are important influences in the effectiveness of a thermal precipitator, but the basic factor is the magnitude of the thermal velocity relative to that of the traversing velocity. The thermal velocity in turn is dependent on the interrelationship of thermal force and drag force. In the usual analysis these forces are treated independently and
are set equal to each other in order to obtain the terminal thermal velocity.

B. Pressure Dependence of Thermal Velocity

The mechanisms of both thermal and drag forces involve gas-surface interactions and are therefore dependent upon the Knudsen number, Kn, which characterizes the system, i.e., the ratio of the mean free path length of the gas molecules to the particle radius. In analyzing the effect of pressure on thermal velocity it is convenient to define first the Knudsen regime of interest and then to consider the effect of pressure on thermal force and drag force individually. In the region of small Knudsen numbers, Kn << 1, the drag force is independent of pressure. Thus thermal velocity will reflect the pressure dependence of the thermal force, which according to Epstein, is an inverse proportionality in this case (see equations 5.32 and 5.35). On the other hand, when the particulate system is characterized by a large Knudsen number, Kn >> 1, the thermal force is theoretically independent of pressure according to Waldmann. The thermal velocity again may be expected to vary inversely with pressure since the drag force in this region is directly proportional to pressure (see equations 5.34 and 5.36). In the transition region, where Kn ≈ 1, little can be said about the quantitative pressure dependence of thermal force, but the drag force decreases exponentially with decreasing pressure due to slip phenomenon. This effect should be reflected in an increase in thermal velocity more rapid than the inverse pressure dependence associated with the Knudsen number extremes. Furthermore, it has been asserted by Schmitt (who supports his argument with experimental observations) that the thermal force will increase with decreasing pressure, toward a limiting value defined by Waldmann's equation, as the characteristic Knudsen number increases.
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beyond unity. Hence thermal velocity may be expected to be inversely proportional to pressure through the range from one atmosphere down to the limit of applicability of thermal force analyses, except in the transition region where the thermal velocity may be expected to increase very rapidly.

In considering the performance of a thermal precipitator, it is evident that for a fixed volumetric flow rate, the area of deposition can be expected to decrease with decreasing pressure due to the increase in thermal velocity. However, since the volume of the air to be sampled is inversely proportional to pressure, a given mass flow rate can be maintained at a lower pressure only by a corresponding increase in the velocity of the airstream. Hence, in terms of mass throughput capacity the effectiveness of thermal precipitation will increase only where the increase in thermal velocity with decreasing pressure is greater than the increase in the airstream velocity required to maintain a specified mass sampling rate.

A true increase in the effectiveness of thermal precipitation may be anticipated, when the Knudsen number of the particulate system defines the pressure range of interest as a transition region. Theoretical estimates of the increased effectiveness required more specific considerations, e.g., for the pressure range from 1.0 to 0.01 atmosphere the mean free path length increases from about 0.07 to 7.0 microns. Thus gas-surface interactions for a 2 micron diameter particle are characterized by a Knudsen number in the range from 0.07 to 7.0. Over this range the mobility of the particle increases by a factor of approximately 10 (due to slip effect) while the thermal force, according to Epstein, increases by a factor of approximately 100. The sampling velocity over this pressure range due to volumetric expansion of the aerosol must also be increased by a factor of
approximately 100. Hence a tenfold increase in the effectiveness of thermal precipitation may be expected. If the particle diameter is 0.4 micron, the Knudsen number range becomes 0.3 to 33 and the mobility of the particle increases by a factor of about 40. An increase in thermal force may be expected in this Knudsen regime. While the applicability of Epstein's equation is doubtful under these conditions, it again indicates an increase in the magnitude of thermal force by a factor of 100. Hence, the effectiveness of thermal precipitation may be increased correspondingly by as much as a factor of 40. If a much smaller particle is considered, the characteristic Knudsen number becomes very large, even at atmospheric pressure, and the theoretical analysis for the extreme case applies. No true increase in effectiveness of thermal precipitation is to be expected then. However, even in this case, the increase in thermal velocity is sufficient to offset the required increase in aerosol throughput velocity, and the effectiveness of precipitation remains constant. An overall improvement in the performance of a precipitator is predicted for high altitude sampling due to the size distribution of atmospheric debris. Since the pressure dependence of thermal force is not quantitatively predictable for the transition region (as encountered in the preceding illustration) the experimental study seemed advisable.

C. Effect of Particle Size in Thermal Precipitation

The foregoing analysis of precipitator performance suggests that it depends upon particle diameter. Actually, since the terminal thermal velocity is attained as a result of opposing thermal and drag forces and the mechanism of each is dependent upon the Knudsen number, the particle size is significant in defining the transition region. Otherwise, in
either of the regions of extreme Knudsen numbers, thermal force and drag force are dependent upon the diameter of the particle to the same degree, so that the terminal thermal velocity is independent of particle size; that is, for Kn << 1 both forces are directly proportional to the diameter, while for Kn >> 1 both forces are directly proportional to the square of the diameter. Furthermore, the application of the thermal force theories of Epstein \(^8\) and Waldmann \(^18\) for any given pressure results in a thermal velocity for the smaller particles generally greater than that attained by the larger particles. Thus it appears that thermal precipitator performance should be independent of particle diameter except in the transition region, where the effectiveness of thermal precipitation can be estimated by interpolation between the values obtained for the two Knudsen number extremes.

There is some evidence of the effect mentioned above. Schmitt,\(^17\) who conducted an experimental study oriented toward the confirmation of Waldmann's thermal force theory, obtained data for Knudsen numbers in the range from 0.05 to 3.0 which were consistent with these conclusions. It should be pointed out that while his confirmation of theory may be extended to the behavior of particles as small as 0.01 micron at atmospheric pressure, it is based on observations of velocity variation with pressure for a particle radius range from 0.3 to 1.3 microns. Inherent in the analysis is the assumption that the thermal velocity is a function of the Knudsen number, and that the same function value applies whether the experiment is conducted by varying the radius at constant pressure or by varying the pressure for some constant particle size. This assumption is apparently justifiable and there is no reason to expect precipitation of submicron
particles to be less effective than that of micron size particles. This same conclusion is supported by other investigators. Walkenhorst, in an electron microscope evaluation of dust sampling by means of a thermal precipitator, reports its application in collecting an aerosol having a maximum abundance at about 0.045 micron. He concludes, in accordance with the observations of earlier studies, that a thermal precipitator remains fully effective for particles as small as 0.03 micron. It remains to be shown conclusively that such small particles can be quantitatively precipitated at low pressure, and if so, whether there is a lower particle size limit for effective precipitation. These were, in part, the objectives of the second phase of this investigation.

D. Importance of Precipitator Plate Separation

One of the practical aims in the design of a high altitude precipitator should be the achievement of maximum effective throughput with a minimum expenditure of energy. In this respect, the distance between the hot and cold plates of the thermal precipitator is a significant factor. For a given sampling rate the pressure drop across a radial flow precipitator is inversely proportional to the third power of the plate separation. Likewise, the aerosol throughput velocity is inversely proportional to this distance. By a hydrodynamic analysis of laminar radial flow, it can be shown that the deposit radius and therefore the effectiveness of the precipitator, should be independent of the plate separation provided the temperature gradient is constant. (See equation 5.11.) In the interest of minimizing the aerosol throughput velocity and the energy requirement for generating aerosol flow, maximum practicable separation is desirable. Thus it would appear that the most restricting limitations on
the distance between plates would be the practical considerations involved in maintaining the thermal gradient, i.e., maximum hot plate temperature limitations and energy requirements. This analysis is based on the assumptions that entrance effects and turbulence are negligible and that a linear temperature profile is established. When the distance between plates becomes large, these assumptions are questionable. If the thermal field is not adequately established, precipitation would become ineffective. Experimental evidence seems to be the only reliable basis for conclusions regarding the significance of precipitator plate separation. The evaluation of this factor was chosen as a secondary objective for this study.

E. Thermal Precipitation with High Aerosol Throughput Velocity

Entrance effects as mentioned above, may be important in the performance of a thermal precipitator. The entrance length, i.e., the distance from the inlet required for the establishment of temperature and velocity profiles in fluid flow, is generally proportional to the fluid velocity. Hence, any significant entrance effect at a relatively low sampling rate would be magnified when the throughput velocity is materially increased, and the effectiveness of thermal precipitation would be impaired.

An equally prominent factor for consideration is the stability of aerosol flow. Laminar flow within the precipitator has been assumed as a prerequisite in the analysis of precipitator performance. The stability of a flowing system is established by a critical Reynolds number, or its equivalent, that defines the maximum velocity permitting laminar flow, beyond which turbulence is encountered. The Reynolds number, $N_{Re}$, can be written in any of several dimensionless forms, e.g., as

$$N_{Re} = \frac{L V \rho}{\mu}$$  \hspace{1cm} (3.1)
where $L$ is a characteristic linear dimension of the flow channel, $V$ is the linear velocity of the flowing fluid, $\rho$ is the fluid density, and $\mu$ is the absolute viscosity of the fluid.

It has been found that the critical Reynolds number for transition from laminar to turbulent flow in tubes is about 2300, and that, under usual conditions, flow in tubes is turbulent when the Reynolds number exceeds 3000.\(^1\) The transition Reynolds number depends, in addition to other factors, on the variation of pressure and velocity along a surface. In particular, it has been observed that a flow deceleration decreases the critical Reynolds number.\(^5\) Hence, diverging radial flow may be expected to be less stable than rectilinear flow. An expression for this stability criterion has been derived by McGinn\(^14\) in a study of the radial flow of water between fixed parallel plates. He developed a dimensionless parameter, $\sigma$, defined by

$$\sigma = \frac{K \rho Q L}{24 \pi \mu r_o^2} < 1$$

which is a conventional Reynolds number multiplied by the ratio of two characteristic lengths. In the above expression, $K$ is an energy correction factor (the value of which depends on the shape of the velocity profile), $L$ is the distance between plates, $r_o$ is the inlet radius, and $Q$ is the volumetric flow rate. Again, the viscosity and density of the fluid are represented by $\mu$ and $\rho$, respectively. It should be noted that the use of the inequality, equation 3.2 as a stability criterion has been justified only by its successful application to limited experimental data for liquid flow.\(^14\) The applicability of this criterion to gaseous radial flow in a thermal precipitator must be determined experimentally; however its use indicates that the maximum sampling rate is limited.
The entrance effects and flow stability in a radial-flow thermal precipitator cannot be readily evaluated. Any attempt at a theoretical analysis is further complicated by the variable (temperature and pressure dependent) properties of the aerosol. Again, experimental observations seem to be the best basis for evaluation of these effects.
IV. EXPERIMENTAL METHODS AND EQUIPMENT

A. General Approach

Throughout this investigation the evaluation of thermal precipitation was based on analyses of precipitated deposits. The general experimental approach embodied three fundamental procedures: (1) the generation of an aerosol, (2) the collection of particulate material by thermal precipitation and (3) the subsequent analysis of the deposit to determine its area and particle size, and to provide data for the calculation of thermal velocities.

B. Generation of Aerosols

Aerosols for experimental precipitation have been generated by three techniques: (1) burning magnesium ribbon, (2) atomizing a powder, and (3) electrically exploding a conducting element. By burning magnesium ribbon in air or oxygen an aerosol was formed consisting of cubic crystals of magnesium oxide primarily in the size range from 0.1 to 2.0 microns. Powdered materials, chiefly aluminum oxide, were atomized with compressed air using a Holmspray Powder Atomizer No. 520-1. The exploding-wire generator was designed and constructed as a means of producing the very finely divided material needed for the study involving the thermal precipitation of submicron particles.

The exploding-wire particle generator, modeled after a similar device in use at Oak Ridge National Laboratory, produces an aerosol by vaporizing an electro-conducting material and condensing the product. A sudden release of electrical energy provides the heat of vaporization and, also, the explosive force which disperses the particulate material. The essential elements of this aerosol generator are a high voltage power supply, a
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capacitor bank and an explosion chamber. The system is capable of delivering an almost instantaneous discharge of 1600 joules of electrical energy (32 microfarads at 10,000 volts) into the material to be aerosolized.

The dispersion of most metals in air usually yields an aerosol of finely divided metallic oxide. If the noble metals are exploded in air, or if more reactive materials are dispersed in an inert atmosphere, the aerosol product consists of very small metallic particles predominantly spherical in shape. While the aerosol products have not been analyzed here, other investigators have found that most of the exploded filament is recoverable from the aerosol in a particle size range from a few tenths to less than one hundredth of a micron in diameter.

C. Experimental Thermal Precipitation

The experimental variables of importance in this study were the operating pressure of the precipitator, the temperature gradient, the distance of precipitator plate separation, and the aerosol flow rate. The experimental apparatus was designed with these factors in mind; it may be described in terms of its three functional components, viz., the pressure control system, the precipitator system, and the flow control system.

The pressure control system consisted essentially of a gas-tight chamber, a vacuum pump, and a pressure gauge. The chamber housed the thermal precipitator and served as a reservoir for the aerosol.

The precipitator system included the thermal precipitator and its auxiliary equipment for maintaining and measuring the temperatures of its hot and cold plates. The precipitators used in this investigation were the radial flow type consisting essentially of two horizontal circular plates concentrically mounted in such a way that the distance between the
plates could be varied by the insertion of shims (see Figure 1). The
general construction details are shown in Figure 2. The uppermost plate
was electrically heated. The lower plate was water cooled. In operation,
an aerosol was introduced through an inlet in the center of the hot plate;
it flowed radially between the hot and cold plates; the particulate matter
was collected on the cold plates; and the gas was subsequently exhausted
from the system. The deposit was collected on a removable glass disk seated
on the cold plate (see Figure 3). All controlling and measuring devices
were located outside the chamber. The hot plate temperature was controlled
by a powerstat and was continuously monitored with an assembly consisting
of a thermocouple, a self-balancing potentiometer, and an ammeter. The cold
plate temperature was regulated by cooling water.

The system initially used for regulating the aerosol flow, shown sche-
matically in Figure 4, was a positive displacement mechanism specifically
designed to insure constant flow and precise measurement. The mechanism
consisted of two calibrated cylinders, the bases of which were connected
by a flexible hose. The cylinders contained a low vapor pressure fluid
that gravitated from one cylinder into the other if the fluid levels were
unequal. The cylinders were suspended by a motor-driven cable system that
raised one cylinder as it lowered the other, thus maintaining a constant
fluid pressure head. The flow rate was controlled by a valve in the con-
necting hose. The inlet to the flow control system was connected directly
to the precipitator exhaust. The gas displaced by the flowing fluid was
exhausted into the chamber. Thus the flowing fluid regulated the aerosol
flow through the precipitator while maintaining a constant pressure in the
chamber. The flow rate was determined by measuring the flow of fluid between
Figure 1. Radial Flow Thermal Precipitator.
Figure 2. Thermal Precipitator Detail.
Figure 3. Collecting Plate Showing Particle Deposit.
Figure 4. Schematic Diagram of the Original Low Pressure Flow Control System.
the cylinders. Inlet and exhaust lines of the flow control system were equipped with three-way stopcocks so that the direction of fluid flow could be reversed without altering the direction of aerosol flow through the precipitator. This arrangement permitted sampling of any aerosol up to the capacity of the chamber.

In collecting the experimental data, the following procedure was employed. The thermal precipitator was set for the desired temperature gradient and allowed to come to thermal equilibrium. An aerosol was generated (either inside or outside the chamber), reduced to the desired pressure, and passed through the precipitator at a constant flow rate. The particulate material was deposited on the glass collecting-disk and the disk was subsequently removed for analysis.

The use of the flow control system described above imposed two critical limitations on the original experimental apparatus, viz., low aerosol flow rates and a small total sample volume (about 2 cubic feet). The objectives of the final phase of study have demanded a modification of the flow control system to provide for high aerosol velocities within the precipitator. Also, in view of the pressure dependent effectiveness of thermal precipitation it has been expedient (in the interest of minimizing the size of experimental precipitation equipment and permitting the use of existing precipitators) to conduct the investigation at a relatively low pressure. Because of these desired test conditions the entire experimental test system was rebuilt as diagrammed in Figure 5, and as shown in the photograph of Figure 6.

As before, the thermal precipitator was housed within a pressure chamber. Auxiliary heat control and temperature measuring devices (not shown
Figure 5. Schematic Diagram of Experimental System for Thermal Precipitation Studies at High Aerosol Throughput Velocities.
Figure 6. The Experimental System for Studies at High Aerosol Throughput Velocities.
in the diagram but pictured in the center of Figure 6) were externally mounted. The exhaust system was constructed so that the air or aerosol within the chamber might be pumped alternately through the precipitator or through a bypass by a 30 cfm vacuum pump installed downstream from the test chamber. A surge drum was placed between the pressure chamber and the pump to eliminate pulsations. Flow through the precipitator was controlled with throttle valves in the exhaust lines. Either clean air or the test aerosol could be continuously introduced into the pressure chamber through a controlled leak at a sufficient rate to maintain a constant test pressure.

Two changes in the precipitator itself were necessary to accommodate the higher aerosol velocities. First, the inlet diameter was enlarged to reduce the inlet pressure drop and the initial radial velocity. Second, an attachment was provided which permitted the aerosol to exhaust into a manifold through ten equally spaced peripheral ports. The purpose of the manifold was to ensure a uniform flow pattern between the precipitator plates and to reduce the pressure drop downstream from the precipitation zone. By providing these design and modifications, the conductance of the system was determined predominantly by the pressure drop between the plates of the precipitator and in the throttle valves.

The experimental procedure was simplified by use of the newly designed system. It was no longer necessary to change the pressure in the system while introducing the aerosol. The modified system was prepared for a test run by decreasing drum pressure to the operating level and regulating the incoming airstream to the desired rate. With clean air flowing through the precipitator, the hot and cold plates were brought to the proper temperatures, and steady state conditions were established. The test run was initiated by introducing an aerosol into the incoming airstream.
The duration of the run was adjusted to produce the desired deposit density. After a deposit was collected, it was removed from the precipitator and analyzed as described below.

D. Analysis of Precipitated Deposits

The effectiveness of thermal precipitation and the associated thermal forces and velocities were evaluated from the dimensions of the precipitated deposits. The measurement of deposit radii where the deposits were dense and sharply defined was accomplished by direct visual observation. The glass collecting-disk, after having been removed from the precipitator, was placed on a rectilinear grid having one-millimeter divisions. The deposit was oriented with its center at the grid origin, and a series of eight radial measurements of the distance from the center to the periphery of the deposit was made at 45° increments under 30x magnification. The average of these measurements was then recorded as the deposit radius. Radial measurements could then be read directly from the vernier scale of the calibrated traversing mechanism.

In the precipitation of particles large enough to be seen with the optical microscope, the particle size was determined by measurements of the individual unagglomerated particles which were clearly visible in the outer fringe area of the deposit. This evaluation technique was based on the assumption that thermal velocities are relatively independent of particle diameter in this size range and that the particles observed at the outer periphery are those whose travel is indicative of the thermal force.

The evaluation of a deposit of submicron particles presented complications not encountered where the particle size of concern was on the order of one micron. As was mentioned earlier, the thermal velocities of very
small particles are higher than those of large particles. It follows that
the former are deposited at relatively shorter distances. Measurements
of fine particle travel have been obscured by an overlapping deposit of
larger particles and agglomerates when the aerosol was sufficiently con-
centrated to produce a dense deposit, as required for radii measurement.
Conversely, a sparse deposit, while essential for the resolution of indi-
vidual particles within the deposit, complicates the measurement of the
significant deposit radius for particles smaller than a few tenths of a
micron in diameter. For such small particles the electron microscope must
be used in making measurements. Because of the high magnification and the
very small objective area a large number of examinations would have to be
made to establish the average deposit radius. The time and expense of
electron microscopy prohibit its use in an evaluation technique similar
to that found suitable for deposits of larger particles.

Ideal evaluation techniques can be visualized much more easily than
they can be put into practice. The best results in this investigation
have been obtained by precipitating a dense deposit from an aerosol con-
taining particles in the diameter range from a few tenths of a micron
down to a hundred angstrom units. The average deposit radius associated
with the larger particles is obtained by the usual techniques employing
optical microscopy. Regions of the collecting plate surface at regular
radial increments both within the deposit and beyond its periphery are then
examined using the electron microscope to establish the absence or presence
of the very small particles. This technique yields qualitative measure-
ments only.
V. CALCULATIONS

The relative effectiveness of thermal precipitation for various operating conditions can be established by direct comparison of the particulate deposits. However, thermal force phenomena in thermal precipitation are deduced from the path which a particle describes in moving through the precipitation zone. As a particle falls under the influence of both gravitational and thermal forces, it is moved horizontally by the ambient airstream. Hence, the particulate path is a function of both vertical precipitating forces and the radial movement of the air in which the particle is suspended. By joint application of Stoke's law and the principles of laminar fluid flow, the particulate behavior and the motivating forces can be resolved. This treatment is presented in the following derivations and is essentially the same as that presented in the final report on a fundamental study of thermal forces conducted by the authors.

A. Derivation of Equations for Reduction of Thermal Precipitation Data

1. Calculation of Particulate Velocity. Aerosol flow through a thermal precipitator must be laminar for the analysis of results. Assuming a parabolic velocity profile for laminar flow between parallel plates, not significantly altered by the temperature gradient, the relationship between the point velocity, $U$, and the maximum velocity, $U_{\text{max}}$, of the flowing fluid may be expressed in the nomenclature of Figure 7 by

$$U = U_{\text{max}} \left[ 1 - \left( \frac{y}{L^2} \right)^2 \right]$$

(5.1)

For a parabolic velocity profile, the maximum velocity and the average fluid velocity are related through
Figure 7. Coordinate System for Defining Particulate Trajectory.
\[ U_{\text{max}} = \frac{3}{2} \ U_{\text{avg}} \] (5.2)

Direct substitution of \( U_{\text{max}} \) in equation 5.1 yields

\[ U = \frac{3}{2} \ U_{\text{avg}} \left( 1 - \frac{4y^2}{L^2} \right) \] (5.3)

The average fluid velocity is defined as

\[ U_{\text{avg}} = \frac{Q}{A_x} = \frac{Q}{\pi r L} \] (5.4)

where \( Q \) is the volumetric flow rate of the aerosol and \( A_x \) is the cross-sectional area of the aerosol stream normal to the direction of flow. Thus

\[ U = \frac{3Q}{4\pi r L} \left( 1 - \frac{4y^2}{L^2} \right) \] (5.5)

The relationship between the point velocity of the fluid and the horizontal velocity component, \( V_r \), of a particle suspended in the fluid at that point may now be considered. The time required for a one-micron particle of unit density initially at rest to be accelerated to 95 per cent of the flowing fluid velocity is on the order of 10 microseconds.* This time is

\[ \frac{(U - V_r)}{Z} = \frac{\rho_p \pi D_p^3}{6} \frac{dV_r}{dt} \]

Integration of this differential equation yields

\[ t = \frac{\rho_p \pi D_p^3 Z}{6} \ln \left[ 1 - \frac{(V_r/U)} \right] \]

*This calculation was made by equating the particulate drag force to the inertial force:
very small relative to the residence time of the aerosol in the precipitator. It may therefore be assumed that the particulate velocity and the fluid velocity are identical. Thus, the horizontal velocity of the particle may be expressed by

$$\frac{dr}{dt} = \frac{3Q}{4\pi rL} \left( 1 - \frac{y^2}{L^2} \right)$$

(5.6a)

or, rearranging, by

$$r \frac{dr}{dt} = \frac{3Q}{\pi L} \left[ 1 - \left( \frac{y}{L} \right)^2 \right] dt$$

(5.6b)

Integration of equation 5.6b requires knowledge of the vertical coordinate of the particulate position, y, as a function of time. In the absence of precise information regarding $y = y(t)$, the simplest case has been assumed, namely, a constant vertical velocity, $V_y$, defined as follows:

$$V_y = \frac{L}{t_f}$$

(5.7)

where $t_f$ is the total time in transit. It follows then, from Figure 7, that

$$y = \frac{L}{2} - V_y t = \frac{L}{2} - \left( \frac{L}{t_f} \right) t$$

(5.8)

Substituting this expression for $y$ in equation 5.6b, and integrating between limits gives

$$\int_{r_o}^{r_d} r dr = \int_{0}^{t_f} \frac{3Q}{4\pi L} \left[ 1 - \left( \frac{y}{L} \right) \left( \frac{L}{2} - \frac{Lt}{t_f} \right)^2 \right] dt$$

(5.9)

for a particle starting at $r_o$ and moving to $r_d$. Performing the indicated
integration and simplifying gives

\[ t_f = \frac{\pi L}{Q} (r_d^2 - r_o^2) \quad (5.10) \]

in which precipitation time, \( t_f \), is a function of plate spacing, aerosol flow rate, and the precipitation radius. The vertical component of particulate velocity, \( V_y \), may then be expressed in terms of the aerosol flow rate and the deposit radius (both of which are experimentally determined quantities) by substitution of the above result for \( t_f \) in equation 5.7.

\[ V_y = \frac{Q}{\pi (r_d^2 - r_o^2)} \quad (5.11) \]

2. Calculation of Thermal Force and Thermal Velocity. After the vertical component of particulate velocity has been determined, the thermal force and thermal velocity may be evaluated in the following manner.

A particulate moving in a viscous medium under the influence of a constant force attains a constant velocity, \( V \), that is indicative of the force. The relationship may be expressed by

\[ V = FZ \quad (5.12) \]

where \( Z \), the mobility\(^\text{12} \) of the particulate, depends on its size and shape and on the properties of the fluid medium. For a sphere in a homogeneous medium, the definition of mobility is analogous to Stoke's law\(^\text{16} \)

\[ Z = \frac{1}{6 \pi \mu a} \quad (5.13) \]

where \( \mu \) is the viscosity of the fluid and \( a \) is the radius of the particle. As the inhomogeneity, i.e., mean free path length, \( \delta \) of the fluid becomes
comparable in size with the particle, equation 5.13 must be modified by the inclusion of a slip-correction factor, $S$, and the mobility is then defined by

$$z_s = \frac{S}{6\mu a} \quad (5.14)$$

The slip correction, a function of $\frac{a}{a'}$, accounts for the tendency of the particle to slip between the molecules of the fluid medium.\(^3\),\(^4\),\(^15\) By rearranging equation 5.12 and making the appropriate substitutions for $V_Y$ and $Z$ (equations 5.11 and 5.14) the total precipitating force may be computed from experimental quantities.

$$F = \frac{6\mu a q}{(r_d^2 - r_o^2)S} \quad (5.15)$$

It should be noted that in the usual experimental operating position, i.e., hot plate above cold plate, the precipitating force defined above is the resultant of both gravitational and thermal forces. The gravitational force may be easily resolved according to the following equation from a knowledge of the particle radius, $a$, and density, $\rho_p$,

$$F_g = \frac{1}{3} \pi g_c a^3 \rho_p \quad (5.16)$$

where $g_c$ is the gravitational constant.

It is therefore possible to compute the thermal force acting on the particle from experimental data by

$$F_t = \frac{6\mu a q}{(r_d^2 - r_o^2)S} - F_g \quad (5.17)$$
The thermal velocity, $V_t$, can be computed by substituting the thermal force obtained from equation 5.17 for the force in equation 5.12.

$$V_t = F_t Z_b$$ (5.18)

3. Evaluation of Mean Free Path Length and Slip-Correction Factor.

In order to apply the equations developed in the preceding treatment, it is necessary to evaluate the mean free path length of the carrier gas molecules and, in turn, the slip-correction factor. The mean free path length, $\lambda$, from the pressure-independent viscosity concept of kinetic theory, is defined such that the pressure-mean free path product, $\lambda P$, for a given gas is a function of temperature, $T$, only. The proper relationship is given by

$$\lambda = \frac{\mu RT}{0.499 MPV}$$ (5.19)

where $\bar{v}$, the mean molecular speed, is defined as

$$\bar{v} = \sqrt{\frac{8g c RT}{\pi M}}$$ (5.20)

where $R$ is the universal gas constant and $M$ is the molecular weight of the gas.

The slip effect mentioned above was investigated by Knudsen and Weber$^{11}$ who deduced an empirical equation which defines a correction factor of the form

$$S = 1 + \frac{\lambda}{a} \left[ A + Be^{-\frac{a}{\lambda}} \right]$$ (5.21)

The empirical constants, $A$, $B$, and $C$, have been evaluated for several systems. According to Davies, the proper values consistent with the above
4. Derivation of Linear Relationships between Deposit Radius and Independent Variables. It was found in a preliminary investigation of thermal precipitation that rigorous duplication of operating conditions for each experimental observation was time consuming and sometimes impossible with available equipment. While precise measurement is essential for reproducibility, it is not necessary to establish identical aerosol flow rates and temperature gradients for each run. It can be shown from theoretical considerations that relationships suitable for interpolation can be established between those variables and the magnitude of the deposit radius. Rearranging equation 5.15 yields

\[(r_d^2 - r_o^2) = \left(\frac{\phi u_0}{F_0}\right) Q\]  \hspace{1cm} (5.22)

which indicates that the quantity \((r_d^2 - r_o^2)\) should be directly proportional to the aerosol flow rate, \(Q\). This relationship provides a means of adjusting observed deposit radii to a standard flow rate basis for comparison of experimental data. A similar rearrangement of equation 5.17 predicts an essentially linear relationship between the reciprocal of \((r_d^2 - r_o^2)\) and the temperature gradient, that is

\[\left(\frac{r_d^2 - r_o^2}{(r_d^2 - r_o^2)^{-1}}\right) = \left(\frac{S}{\phi u_0 r_d Q}\right) F_t + \left(\frac{S}{\phi u_0 r_d Q}\right) F_g\]  \hspace{1cm} (5.23)

where the symbol, \(a_{r_d}\), represents the critical particle radius evaluated at the periphery of the deposit. Since the thermal force is directly proportional to the temperature gradient, \(\frac{dT}{dy}\), the equation may be rewritten
\[ (r_d^2 - r_o^2)^{-1} = \left( \frac{C_1 S}{\rho u a_{rd} Q} \right) \frac{dT}{dy} + \left( \frac{S}{\rho u a_{rd} Q} \right) F_g \]  
\[ (5.24) \]

where \( C_1 \), the proportionality factor for the thermal force-temperature gradient relationship, is a function of all the other related variables of the basic force equation (5.32 or 5.34). Equation 5.24 expresses the quantity \((r_d^2 - r_o^2)^{-1}\) as a linear function of temperature gradient if the coefficients of \(\frac{dT}{dy}\) and \(F_g\) may be assumed constant. This assumption is precisely valid only for the case of constant particle radius. The critical particle size, i.e., that which would be observed at the maximum deposit radius, is dependent upon the relative magnitudes of the thermal and gravitational forces and is therefore subject to slight variation with changing temperature gradient. The assumption of constant coefficients is sufficiently valid, however, to permit linear interpolation of experimental data over a limited temperature gradient range. This is tantamount to linear interpolation of precipitation velocities and is permissible only as long as the gravitational component is negligible.

5. Review of Simplifying Assumptions. It should be noted that in the preceding development of equations several simplifying assumptions have been made. These are enumerated below. First, in the evaluation of the horizontal velocity component for thermal precipitation, it has been assumed (1) that fluid flow is laminar, (2) that entrance effects are negligible, (3) that fluid properties, including viscosity and density, are constant (i.e., temperature independent), and (4) that the horizontal particulate velocity component at any time is equal to that of the flowing fluid at the same point. Second, in the derivation of precipitation time
and vertical particulate velocity, it has been assumed (5) that the thermal force is constant, implying (6) a linear temperature gradient in the fluid and (7) a force directly proportional to temperature gradient, (8) that the vertical velocity is constant, implying a negligible acceleration time for the particle in beginning its descent, (9) and that the particle of concern originated at the hot plate inlet, \( r_o \). Finally, in the computation of thermal velocity and thermal force, it has been assumed (10) that the particle is spherical and (11) that its mobility is independent of the temperature of the system and the nature of the particle. These assumptions were made in order to facilitate mathematical analysis. The errors of method attributable to these simplifications give rise to inaccuracies in the absolute magnitude of thermal velocity but do not affect greatly the precision or reproducibility of data. Since relative precipitator performance is of primary concern, the complexity of a more rigorous treatment is hardly justifiable with the following exception.


When the radial velocity of the aerosol in the precipitation zone is relatively low, the pressure drop across the precipitator is negligible, and the equations derived above for an incompressible fluid are appropriate. However, in low pressure precipitation with a high aerosol throughput velocity the pressure drop may become a sizeable fraction of the absolute inlet pressure, and a significant expansion of the air may occur during flow between the plates of the precipitator. Since the air expands as it flows radially outward, its radial velocity does not decrease as rapidly with increasing radius as in the case of an incompressible fluid. The result is that a particle being swept along in the
air stream moves with a higher average horizontal velocity. The analysis of the particle trajectory is further complicated by the fact that the thermal velocity is pressure dependent. An exact analysis, providing for a variable thermal velocity has not yet been made; however, the equations have been modified for fluid expansion in the following manner.

As in chapter V, section A, the equation for the velocity profile may be written in terms of the volumetric aerosol flow rate, which in this case is a function of pressure, \( Q(P) \), defined in accordance with the perfect gas law,

\[
Q = \frac{Q_0 P_0}{P} \quad (5.25)
\]

where the subscript, \( o \), denotes the conditions at the precipitator inlet. For mathematical convenience, the pressure within the precipitator was assumed to vary linearly with the radial distance between plates from the inlet so that

\[
P = P_o + \frac{\Delta P}{\bar{R}} (r - r_o) \quad (5.26)
\]

where \( \Delta P \) is the pressure drop across the precipitator, i.e., over the radial distance \( \bar{R} \) defined by

\[
\bar{R} = r_e - r_o \quad (5.27)
\]

The subscript \( e \), denotes the exit radius. Thus the volumetric flow rate may be defined as a function of radius by

\[
Q(r) = \frac{Q_0 P_0 \bar{R}}{r(P_e - P_o) + (r_e P_0 - r_o P_e)} \quad (5.28)
\]

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and the average fluid velocity between the precipitator plates at any radius, \( r \), is given by

\[
U_{\text{avg}} = \frac{Q(r)}{A_x} = \frac{Q_o P_o \bar{R}}{2\pi L} \left\{ \frac{1}{r^2(P_e - P_o) + r(r_e P_o - r_o P_e)} \right\} \quad (5.29)
\]

Using this expression of the average velocity in a derivation of vertical particulate velocity analogous to that of chapter V, section A gives for the compressible case

\[
(V_y)_c = \frac{Q_o}{\pi(r_d^2 - r_o^2)} \left\{ \frac{3P_o \bar{R}}{3(r_e P_o - r_o P_e) (r_d^2 - r_o^2) + 2(P_e - P_o) (r_d^3 - r_o^3)} \right\} \quad (5.30)
\]

or in terms of \( V_y \) which is the vertical particulate velocity component defined by equation 5.11 for the incompressible fluid,

\[
(V_y)_c = V_y \left\{ \frac{3P_o \bar{R}}{3(r_e P_o - r_o P_e) (r_d^2 - r_o^2) + 2(P_e - P_o) (r_d^3 - r_o^3)} \right\} \quad (5.31)
\]

Once again it is noted that a constant vertical velocity has been assumed, and that a certain error of method is to be expected in using these equations for the correlation of data. Since the thermal velocity will increase with decreasing pressure, it might balance the change in the horizontal particulate velocity component due to aerosol expansion. In such a case, the correction would be superfluous.

**B. Theoretical Thermal Force and Corresponding Thermal Velocity**

The hypothetical concept of increasing precipitation effectiveness by decreasing pressure is based on the qualitative reliability of
currently accepted thermal force theory. In order to evaluate this concept more precisely and to attempt a correlation with experimental results, theoretical values must be computed.

In the region of low Knudsen numbers the data of earlier investigations best support the theory of Epstein. For this reason, Epstein's thermal force equation has been selected for computations at pressures such that the ratio of $\lambda/a$ is less than one. In this case, the thermal force, $(F_t)_E$, is described by

$$
(F_t)_E = \frac{9\pi R \lambda a}{MP(2k_g + k_p)} \frac{dT}{dy}
$$

The corresponding thermal velocity, $(V_t)_E$, can be computed by substituting the above for the force in equation 5.12 to give

$$
(V_t)_E = (\frac{9\pi R \lambda a}{6\mu a} (A + Be^{-C\lambda}) \left[ \frac{9\pi R \lambda a}{MP(2k_g + k_p)} \right] \frac{dT}{dy}
$$

In the region of large Knudsen numbers the recently developed theory of Waldmann seems to be most reliable. His equation defines the thermal force, $(F_t)_W$, as

$$
(F_t)_W = \frac{-16}{15} \pi a^2 \frac{M}{2\pi RT} (k_g)^t \frac{dT}{dy}
$$

In the foregoing discussion the mobility of a particle has been consistent with the hydrodynamic concept of the drag force in continuous fluid which is defined as

$$
(F_d)_H = \frac{6\mu Va}{S}
$$
The slip-correction factor in the denominator provides for the extended
application of this equation well into the transition region where the
Knudsen number becomes rather large.

The thermal force equation, derived by Waldmann,\textsuperscript{18} is strictly
applicable only where the mean free path length is large relative to the
size of the particle, and the appropriate drag force for the system
may be derived from kinetic theory.\textsuperscript{7,19} In this case

\[
(F_d)_K = \frac{16}{3} a^2 \pi P \sqrt{\frac{M}{2\pi RT}} (1 + \frac{\pi}{6} \alpha) V \tag{5.36}
\]

The terminal thermal velocity in this case may be computed from the equa-
tion obtainable from equations 5.34 and 5.36 above, which defines the
net force \(\overline{F}\) on the particle}\textsuperscript{20}

\[
\overline{F} = -\frac{32}{3} a^2 \frac{1}{V} \left\{ (1 + \frac{\pi}{6} \alpha) FV_t + \frac{1}{5} (k g)_tr \frac{dT}{dy} \right\} = 0 \tag{5.37}
\]

In addition to the equations presented above, two others have been de-
\[\text{rived by Einstein,}\textsuperscript{6,18} to describe thermal force-phenomena for the two
Knudsen extremes. They have been used also in computing theoretical
thermal velocities for comparison with experimental results. Einstein's
equations are

\[
\text{for } Kn \gg 1, \ (F_t)_{EL} = -\frac{8}{3} \frac{a^2 (k g)_tr}{V} \frac{dT}{dy} \tag{5.38}
\]

\[
\text{for } Kn \ll 1, \ (F_t)_{E2} = -\pi a P \frac{\lambda^2}{T} \frac{dT}{dy} \tag{5.39}
\]
VI. EXPERIMENTAL OBSERVATIONS

A. Program of Experimental Work

The experimental work in this investigation was performed in four distinct phases. Phase I was a study of the pressure-dependence of the effectiveness of thermal precipitation. Phase II dealt with the precipitation of submicron particles. Phase III was a study of the dependence of thermal precipitator performance on the distance between the hot and cold plates. Phase IV was a study of thermal precipitator performance with high aerosol throughput velocities.

B. Phase I. The Pressure-Dependence of Thermal Precipitation

1. Experimental Data. A substantial quantity of experimental data was accumulated using an aluminum oxide aerosol which contained a preponderance of particles on the order of one micron in diameter. Experimental precipitation was performed throughout the pressure range from 1.0 to 0.01 atmosphere, at a variety of aerosol flow rates in the range from 3 to 35 cc/sec, and with temperature gradients generally on the order of 1500°C/cm. Thermal velocities and precipitator effectiveness ratios have been computed from experimental observations. The experimental data, along with the corresponding computed quantities, are presented in Table I.

2. Experimental Confirmation of Linear Relationships. Experimental data have been collected for a rather wide range of flow rates at different temperature gradients. In order to illustrate the effect of each of these variables graphically and, further, to make a valid estimate of experimental deviations, it has been desirable to adjust the observed deposit radii to standard conditions. The relationships for the
### TABLE I

**EXPERIMENTAL DATA FOR THE THERMAL PRECIPITATION OF ALUMINUM OXIDE AT PRESSURES IN THE RANGE FROM 1.0 TO 0.01 ATMOSPHERE**

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Pressure (Atm)</th>
<th>Temp. Gradient (°C/Cm)</th>
<th>Aerosol Flow Rate (CC/Sec)</th>
<th>Deposit Radius (Cm)</th>
<th>Temperature Gradient Per Unit Precipitator Effectiveness</th>
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(Continued)
TABLE I (Continued)

EXPERIMENTAL DATA FOR THE THERMAL PRECIPITATION OF ALUMINUM OXIDE
AT PRESSURES IN THE RANGE FROM 1.0 TO 0.01 ATMOSPHERE

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Pressure P (Atm)</th>
<th>Temp. Gradient ΔT/L (°C/Cm)</th>
<th>Aerosol Flow Rate Q (CC/Sec)</th>
<th>Deposit Radius rd (Cm)</th>
<th>[r^2 - r_o^2]</th>
<th>Thermal Velocity VT (Cm/Sec)</th>
<th>Thermal Velocity VT X 10^4 (Cm^2/Sec°K)</th>
<th>Precipitator Effectiveness E (Dimensionless)</th>
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TABLE I (Continued)

EXPERIMENTAL DATA FOR THE THERMAL PRECIPITATION OF ALUMINUM OXIDE
AT PRESSURES IN THE RANGE FROM 1.0 TO 0.01 ATMOSPHERE

<table>
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<th>Run No.</th>
<th>Pressure P (Atm)</th>
<th>Temp. Gradient ΔT/L (°C/Cm)</th>
<th>Aerosol Flow Rate Q (CC/Sec)</th>
<th>Deposit Radius r_d (Cm)</th>
<th>[r_d^2 - r_o^2] (Cm^2)</th>
<th>Thermal Velocity V_T (Cm/Sec)</th>
<th>Thermal Velocity Per Unit Temp. Grad. V_T X 10^4 (Cm^2/Sec °K)</th>
<th>Precipitator Effectiveness E (Dimensionless)</th>
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### TABLE I (Concluded)

EXPERIMENTAL DATA FOR THE THERMAL PRECIPITATION OF ALUMINUM OXIDE
AT PRESSURES IN THE RANGE FROM 1.0 TO 0.01 ATMOSPHERE

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Pressure (Atm)</th>
<th>Temp. Gradient (°C/Cm)</th>
<th>Aerosol Flow Rate (CC/Sec)</th>
<th>Pressure Radius (Cm)</th>
<th>[r_d^2 - r_o^2]_b</th>
<th>Thermal Velocity V_T (Cm/Sec)</th>
<th>Thermal Velocity Per Unit Temp. Grad. V_T' X 10^4 (Cm^2/Sec°C)</th>
<th>Precipitator Effectiveness E (Dimensionless)</th>
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a. Using a radial flow thermal precipitator with a plate separation of 0.04 cm.
b. The precipitator inlet radius, r_o, was 0.445 cm.
c. Neglecting gravitational velocity component.
d. Thermal velocity per unit temperature gradient is defined by V_T' = V_T \cdot \frac{\Delta T}{L}.
e. Precipitator effectiveness is defined by E = \frac{Q_P}{Q_P} = 1 atm.
interpolation of experimental data, which were developed in the preceding section, have been confirmed for this application. The linear relationship of equation 5.22 between the aerosol flow rate, Q, and the quantity \( (r_d^2 - r_o^2) \) is experimentally verified in Figure 8, for pressures of 1.0 and 0.1 atmosphere. Also, the approximate linearity between the temperature gradient, \( \frac{\Delta T}{L} \), and the quantity \( (r_d^2 - r_d^2)^{-1} \) suggested by equation 5.24 is shown in Figure 9 to be adequate for extrapolation over the temperature gradient range of 500° to 2500° C/cm. Figure 9 is based on experimental data obtained in an earlier study and has been duplicated here since the data of Table I do not adequately illustrate temperature gradient dependence.

3. Effect of Temperature Gradient and Pressure. A more direct picture of the influence of temperature gradient on deposit radius is presented in Figure 10 which is also based on previously collected data. The general characteristics of the relationship are unchanged at lower pressure.

Also apparent in Figure 10 is the decrease in particle travel with pressure, a general trend observed over the entire pressure range from 1.0 to 0.01 atmosphere. Estimates of the relative effectiveness of a given precipitator at different operating pressures may be made by a direct comparison of deposit radii or area. However, in order to transform experimental data for a general interpretation of thermal precipitation effectiveness as opposed to specific observations for the particular experimental model used in this investigation, thermal velocities have been computed therefrom and plotted versus pressure. The essence of this study appears in Figure 11 where the average thermal
Figure 8. Linear Dependence of \( r_d^2 - r_o^2 \) on Aerosol Flow Rate.
Figure 9. Linear Dependence of \( (r_d^2 - r_o^2)^{-1} \) on Temperature Gradient.
Figure 10. Precipitation Distance as a Function of Temperature Gradient at 1.0 and 0.5 Atmosphere Pressure. Experimental data are for an aerosol flow rate of 200 cc/min. The theoretical curve is based on Epstein's equation for 1.0 micron magnesium oxide particles assuming a particulate thermal conductivity of 0.00146 cal/cm sec °K.
Figure 11. Relationship between Thermal Velocity and Pressure.
velocity per unit temperature gradient observed for various operating conditions at each pressure level has been plotted as point data. It has been observed that thermal velocities of air-suspended aluminum oxide particles in a temperature gradient of 1500°C/cm increase from 0.24 cm/sec at atmospheric pressure to about 170 cm/sec at 0.01 atmosphere, i.e., by a factor of 715 compared to a sampling rate increase of 100 due to the expanded volume of the aerosol. This implies an increase in effectiveness of thermal precipitation by about 700 per cent.

The thermal velocity-pressure data presentation of Figure 11 is also convenient for comparing experimental observations with theoretical analyses. The uppermost curve is based on the equation of Epstein, assuming an effective particulate thermal conductivity of zero in this case. The corresponding theoretical curve using the bulk value for the conductivity of aluminum oxide in the equation has not been shown, but it should be noted that the observed values of thermal velocity are considerably higher. It is probable that the uncertainty of the effective particulate thermal conductivity accounts for the major discrepancy between observations and Epstein's theoretical values. The thermal velocity curves based on the equations of Einstein and Waldmann are also shown, and are closer to the observed values. In general, the theoretical values lie all around the experimental points, but it is difficult to select any particular theory valid for quantitative prediction of precipitator performance. Still, the agreement between experiment and theory is acceptable in view of an estimated inaccuracy in experimental data which is on the order of a factor of two.
C. Phase II. The Precipitation of Submicron Particles

Aerosols containing particles in the diameter range from less than 20 Å to about 0.1 micron have been produced by the exploding wire technique and collected by thermal precipitation. The aerosolized materials which have been generated for use in this study include aluminum oxides, platinum, and silver. Thermal precipitation of these particulate materials was accomplished at pressures ranging from one atmosphere down to about 2 mm Hg.

In general, aerosols of the finest particles, when in concentrations sufficient to produce measurable deposits, also contain relatively large agglomerates (on the order of one micron diameter). These completely obscure the outer periphery of the deposit of small, unagglomerated, primary particles. In fact, the deposits are of such a nature that it cannot be said with certainty that a sharply defined periphery would be detectable even in the absence of the agglomerated fraction. Because of the difficulty in evaluating the thermal velocities of the very small particles it has not been possible to provide quantitative data on the particle size dependence of thermal precipitation effectiveness. It is necessary to rely on more qualitative observations as a basis for ultimate conclusions.

The most meaningful observations have been made with two different types of deposits. First, dense deposits were obtained possessing clearly defined peripheries. The measurements of radii on these deposits indicated comparable thermal velocities for all particulate materials which were generally higher than those observed in the deposition of aluminum oxide particles in the one micron diameter range. Electron micrographs of the surface films stripped from the collecting plates showed no significant frequency of particles in the region beyond the boundary of the dense central deposit.
Because of the opacity of the central core, particle size could not be determined by direct observation. The deposited particulate material was dispersed in water and subsequently examined with the electron microscope which revealed primary particles in the diameter range from 0.2 micron down as shown in Figure 12 A and B. The smallest particles were not clearly resolved in the electron microscope and were apparently smaller than 20 A in diameter (see Figure 13). Particles of this size were found throughout the deposit.

The alternate approach in this phase of study involved the collection of sparse deposits containing relatively few particles. Detailed examinations of these deposits have been performed by coating the collecting plate surfaces with a plastic film and taking electron micrographs of the stripped film at intervals of 5 to 10 mm along a radial path. Again, in the central region of the collecting plate were found both complex agglomerates and primary particles as small as a few thousand of a micron, while no significant deposition was observed in the outer region of the collection plate, i.e., a few centimeters from the precipitator inlet. Micrographs obtained in this manner are shown in Figure 12, C through F. The relative density of particulate material at various radial distances is illustrated in the sequence of micrographs at 2300X as shown in Figure 14, A through D. The collecting plate radius measured 3.75 cm; however, no particles were found beyond a distance of 2.5 cm from the inlet. The nature of particulate material collected in this case is shown more clearly at higher magnification in micrographs E and F.

Measurements at 5 mm intervals are not sufficiently precise to permit the calculation of significant thermal velocities, but do support the argument that thermal precipitation remains effective as particle size
Figure 12. Electron Micrographs of Aluminum Oxide, Silver and Platinum Deposits. Deposits A and B were collected at atmospheric pressure. Deposit C was collected at a low flow rate and a pressure of 7.6 mm Hg. Deposit D was collected at a pressure of 7.6 mm Hg, with a high aerosol throughput velocity. Deposits E and F were collected at a pressure of 2 mm Hg.
Figure 13. Electron Micrographs of Platinum Particles.
Figure 14. Electron Micrographs of Aluminum Oxide Deposit Showing the Variation of Deposit Density with Radial Distance.
decreases. At the lowest pressures (and for low flow rates) a conspicuous absence of particulate material has been noted beyond a very narrow precipitated band surrounding the inlet. The fact that particles were not collected simply by impingement has been demonstrated by the absence of such a deposit when the sample was drawn through the precipitator under isothermal conditions.

As was mentioned earlier, thermal forces and velocities are dependent upon the Knudsen number. The precipitation of a 0.005 micron particle at atmospheric pressure is characterized by a Knudsen number of 26.6, and in that respect is equivalent to the precipitation of a 0.5 micron particle at a pressure of 0.01 atmosphere. Observations in this Knudsen number region merely confirm the work of earlier investigators. The most significant results obtained in this study were achieved with the collection of aluminum oxide particles smaller than 30 Å at an operating pressure of 2 mm Hg (see Figure 12, E and F). Under these conditions the Knudsen number characteristic of the precipitation is on the order of $1 \times 10^{-4}$.

D. Phase III. The Effect of Plate Separation on Performance

Preliminary observations regarding the effectiveness of thermal precipitation as a function of the distance between the hot and cold plates indicated a pronounced influence for the close spacing, 0.01 to 0.05 cm, and relative independence of plate separation in the range between 0.05 and 0.18 cm. The experimental velocities were reasonably consistent except for data obtained at separations between 0.01 and 0.025 cm, where the thermal velocities appeared to be about twice as high as those observed for the greater plate separations. This inconsistency suggested that the higher thermal velocities might be attributed to inaccuracies in the
measurement of the temperature gradient. It should be noted that the
glass collecting-plates were not perfectly flat. In most cases the
plate distortions were on the order of 0.002 to 0.005 cm. Also, the
cold plate temperature was measured at the lower surface of the glass
collecting-plate, which was about 0.02 cm thick. Thus there is some
uncertainty in the estimate of the temperature of the exposed glass
surface. Furthermore, in order to maintain a given temperature gradient,
the temperature drop across the aerosol gap must be decreased propor-
tionally to the decrease in plate separation. At the greater plate
separations, i.e., from 0.05 cm up, the temperature drop across the
glass plate and the lack of precision in the measurement of precipitator
plate separation are negligible, leading to experimental errors of less
than 5 per cent. However, for the close plate separations, these uncer-
tainties represent significant fractions of the measurements. At best,
the inconsistent preliminary observations are not conclusive.

In an effort to improve the reliability of data, the precipitator
plate faces and spacer were remachined and recalibrated. Collecting
plates were specially selected for flatness and low surface distortion and
a single disk was used repeatedly for measurements at the closer separa-
tions. Experimental data, recorded for the precipitation of magnesium
oxide at atmospheric pressure with precipitator plate separations in the
range from 0.025 to 0.41 cm, are presented in Table II. The relative
independence of precipitator effectiveness upon plate separation is indi-
cated by equivalent values obtained for the reduced thermal velocities,
i.e., the thermal velocity per unit temperature gradient. Even though
a slight increase in the thermal velocity with increasing distance between
### TABLE II
EXPERIMENTAL DATA FOR THE PRECIPITATION OF MAGNESIUM OXIDE OVER A PRECIPITATOR PLATE SEPARATION RANGE FROM 0.025 TO 0.41 CM

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Pptr'r. Plate Separation (Cm)</th>
<th>Temp. Gradient (°C/Cm)</th>
<th>Aerosol Flow Rate (CC/Sec)</th>
<th>Deposit Radius ( r_d ) (Cm)</th>
<th>( (r_d^2 - r_o^2) ) (Cm(^2))</th>
<th>( (r_d^2 - r_o^2) ) adj. (Cm(^2))</th>
<th>( (r_d^2 - r_o^2)^{\frac{1}{2}} ) adj. (Cm(^{-1}))</th>
<th>Thermal Velocity Per Unit Temp. Grad. (Cm(^2) Sec(^{-1}) °K(^{-1}))</th>
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<td>7.75</td>
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<td>2.05</td>
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(Continued)
**TABLE II (Continued)**

EXPERIMENTAL DATA FOR THE PRECIPITATION OF MAGNESIUM OXIDE OVER A PRECIPITATOR PLATE SEPARATION RANGE FROM 0.025 TO 0.41 CM

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Plate Separation (cm)</th>
<th>Temp. Gradient (°C/cm)</th>
<th>Aerosol Flow Rate (CC/Sec)</th>
<th>Deposit Radius (rd) (cm)</th>
<th>Deposit Radius (rd) - Deposit Radius (ro) (cm)</th>
<th>Thermal Velocity Per Unit Temp. Grad. X 10^4 (cm^2Sec^-1°C^-1)</th>
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<td>0.406</td>
<td>294</td>
<td>1.618</td>
<td>2.34</td>
<td>5.28</td>
<td>8.17</td>
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</table>

a. Precipitation conducted at atmospheric pressure.
b. The inlet radius of the precipitator, ro, was 0.445 cm.
c. The values of (rd^2 - ro^2) adj. have been adjusted for an aerosol flow rate of 2.5 cc/sec.
d. Gravitational velocity component neglected.
precipitator plates is evident, it is believed that this apparent trend does not indicate an actual increase in precipitator effectiveness but may be attributed to extraneous influences such as experimental inaccuracy associated with the decreasing temperature gradient.

Due to the wide range of precipitator plate separations, it is not possible to compare results for a given temperature gradient. For example, a gradient of 1500°C/cm, ideal for a plate separation of 0.04 cm, would require a hot plate temperature of about 600°C for a separation of 0.4 cm, which is beyond the range of the experimental precipitator. Alternately, a temperature gradient of 300°C/cm, which is ideal for a plate separation of 0.4 cm, would require a temperature drop of only 7.5°C over a plate separation of 0.025 cm. In this case experimental errors would be greatly magnified. For this reason, data were obtained for progressively lower temperature gradients as the distance between plates was increased, and can be most reliably compared by taking advantage of the theoretical linear relationship between the quantity 
\[(r_d^2 - r_o^2)^{-1}\] and the temperature gradient predicted by equation 5.24 and confirmed for a fixed plate separation in Figure 9. Since the data cover a wide range of precipitator plate separations, a linear plot can be obtained for variable separation only if the deposit radius is independent of the distance between hot and cold plates. In Figure 15, the quantity 
\[(r_d^2 - r_o^2)^{-1}\] has been plotted against temperature gradient from the tabulated data of this study along with a backlog of data collected earlier in this laboratory. Thus, the linearity of the plotted results indicates that precipitator plate separation is not a significant factor within the observed range.
Figure 15. Independence of Precipitation Effectiveness and Hot and Cold Plate Separation as Indicated by the Linearity of Experimental Data Plotted versus Temperature Gradient. Since data obtained were over a wide range of precipitator plate separations, linearity may be expected only if the deposit radius is independent of the distance between plates.
The conclusion that precipitator performance is independent of the distance between plates is obviously limited to situations where entrance effects are negligible. Thus, low pressure precipitation with very high aerosol throughput velocity might be sensitive to any factor, including precipitator plate separation, which would contribute to a significant increase in the entrance length.

E. Phase IV. Precipitator Performance at High Aerosol Velocities

It has been suggested that the operation of a radial flow thermal precipitator at very high aerosol throughput velocities might result in ineffective precipitation due to exaggerated entrance effects or turbulence in the precipitation zone. In order to examine this possibility, the experimental apparatus was modified to accommodate large aerosol flow rates. With the original flow control system, observations had been made at an operating pressure of 0.01 atmosphere with average radial velocities at the precipitator inlet in the range from 60 to 315 cm/sec. It was originally intended to extend these data with increasing diverging radial velocity to the point of turbulence, which, it was supposed, would be indicated by ineffective precipitation. Thereafter, additional data were to be accumulated for converging radial flow to determine whether or not precipitator throughput capacity could be increased in that manner. It was believed that entrance effects, if significant, would be reflected by an apparent decrease in thermal velocity.

Using an aluminum oxide aerosol produced by the exploding wire technique, data were accumulated (Series A, Table III) for thermal precipitation at 0.01 atmosphere with average precipitator inlet velocities in the range from 550 to 3595 cm/sec (which represented an increase greater
# TABLE III

EXPERIMENTAL DATA FOR THE PRECIPITATION OF ALUMINUM OXIDE AT 0.01 ATMOSPHERE PRESSURE AND HIGH AEROSOL THROUGHPUT VELOCITY

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<th>A.D.P. Pressure (Mm Hg)</th>
<th>Drop Rate (CC/Sec)</th>
<th>Aerosol Flow Rate (Cm)</th>
<th>Temp. Gradient (°C/Cm)</th>
<th>Deposit Radius (Cm)</th>
<th>Average Aerosol Velocity Per Unit Temp. Grad. (Cm/Sec)</th>
<th>Thermal Velocity Per Unit Temp. Grad. (Cm °C)</th>
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<td>0.023</td>
</tr>
<tr>
<td>2</td>
<td>7.6</td>
<td>0.06</td>
<td>330</td>
<td>793</td>
<td>2.30</td>
<td>4.09</td>
<td>318</td>
<td>3.24</td>
<td>0.032</td>
</tr>
<tr>
<td>3</td>
<td>7.6</td>
<td>0.02</td>
<td>360</td>
<td>820</td>
<td>2.30</td>
<td>4.09</td>
<td>347</td>
<td>3.35</td>
<td>0.033</td>
</tr>
<tr>
<td>4</td>
<td>7.6</td>
<td>0.12</td>
<td>450</td>
<td>717</td>
<td>2.60</td>
<td>5.56</td>
<td>434</td>
<td>4.40</td>
<td>0.035</td>
</tr>
<tr>
<td>5</td>
<td>7.4</td>
<td>0.02</td>
<td>500</td>
<td>826</td>
<td>2.35</td>
<td>4.31</td>
<td>482</td>
<td>3.57</td>
<td>0.045</td>
</tr>
<tr>
<td>6</td>
<td>7.6</td>
<td>0.04</td>
<td>590</td>
<td>791</td>
<td>3.01</td>
<td>7.87</td>
<td>569</td>
<td>6.23</td>
<td>0.030</td>
</tr>
</tbody>
</table>

a. Series designation denotes change in distance between precipitating plates: Series A at 0.05 cm, Series B at 0.10 cm, and Series C at 0.15 cm.

b. Precipitator inlet radius was 1.1 cm.

c. Gravitational velocity component neglected.
than tenfold beyond the range of earlier data). Indications at this point were that the size of the experimental precipitator was the limiting factor in throughput capacity, rather than turbulence in the aerosol stream. Effective precipitation was accomplished with inlet velocities as high as 9000 cm/sec; however, increasing the velocities beyond the level of 3600 cm/sec, even at the maximum temperature gradient (≈2000°C/cm), resulted in a deposit which exceeded the periphery of the collecting plate, presumably before turbulence occurred.

A precipitator study of the stability of diverging and converging radial flow hinged upon ineffective precipitation as evidence of turbulence. According to the stability criterion derived by McGinn (Equation 3.2), the transition from laminar to turbulent flow could be approached either through an increase in flow rate or through an increase in the distance between plates. The data of Series A, referred to above, had been obtained with a precipitator plate separation of 0.05 cm. Since it was impossible to obtain quantitative measurements on deposit radii with a further increase in radial velocity, experimental precipitation was conducted at precipitator plate separations of 0.10 and 0.15 cm. Due to hot plate temperature limitation, it was necessary to operate at a lower temperature gradient with each successive increase in plate separation. Therefore, the maximum aerosol flow rate yielding quantitative precipitation data was similarly decreased. It is obvious that this approach was unsuitable for the proposed study of laminar stability due to the limitations of the existing experimental apparatus. Since no evidence of turbulence could be obtained, a useful comparative study of precipitation with diverging and converging flow could not be made.
Attention was then focused on experiments intended to evaluate entrance effects. As mentioned earlier, the entrance length, i.e., the distance over which velocity and temperature profiles develop, is dependent on the distance between the confining surfaces, as well as the velocity of the flowing fluid. For this reason, data were obtained at the greater plate separations for several different flow rates, series B and C, Table III. No conclusive evidence of significant entrance effect has been observed. Note the linearity of the plot of the quantity 
\[(r_d^2 - r_o^2) \left( \frac{\Delta T}{L} \right)^2\] versus aerosol flow rate in Figure 16. In this case, 
\[(r_d^2 - r_o^2)\] has been multiplied by the temperature gradient to eliminate its parametric effect. The consistency of experimental observations is illustrated clearly in this curve, and it is noteworthy that deviations include observations at three substantially different precipitator plate separations.

The appearance of the deposits collected under conditions of high velocity at low pressure is similar to that obtained at lower flow rates and atmospheric pressure. The main differences are (1) that irregularities in the deposit periphery are accentuated and (2) that some of the deposited material in dense deposits appears to have been swept along the surface of the collecting disk by the fast-moving airstream. In Figure 17 photographs of precipitated deposits are shown for comparison. Deposit "A" was precipitated at atmospheric pressure at an aerosol flow rate of approximately 100 cc/min while deposit "B" was collected at a flow rate of 58,500 cc/min at 0.01 atmosphere. The larger inlet radius, as well as exaggerated peripheral irregularities due to peculiarities of the exhaust system, are clearly evident in the latter. Both of these slides were
Figure 16. Independence of Precipitator Effectiveness upon Flow Rate and Precipitator Plate Separation as Indicated by Experimental Data Plotted versus Aerosol Flow Rate.
A. Deposit collected at atmospheric pressure at a flow of approximately 100 cc/min.

B. Deposit collected at 0.01 atmosphere pressure at a flow rate of 58,500 cc/min.

Figure 17. Photographs of Precipitated Deposits.
exposed to unfiltered laboratory air while measurements were being made; this accounts for the large amounts of lint and other debris visible around the deposits.

Coating the surface of the collecting disk with a nonvolatile oil has been found helpful in retaining precipitated particles. Figure 18 shows the effectiveness of the oil film in preventing the airstream from subsequently blowing particulate material off of a very dense deposit. This deposit was collected at 0.01 atmosphere, with a precipitator plate separation of 1 mm, at a temperature gradient of 1160°C/cm at an aerosol flow rate of 46,500 cc/min. The average inlet velocity in this case was 1100 cm/sec. Again the peripheral irregularity due to the unsymmetrical flow pattern is evident.
Figure 18. Effect of an Oil Film on Deposited Particle Retention.
VII. DISCUSSION OF RESULTS

A. Pressure Dependence of Thermal Precipitation Effectiveness

It has been established that a significant increase in thermal velocity results from a decrease in the operating pressure of a thermal precipitator. Precipitation effectiveness can be better appreciated, perhaps, by expressing it in terms of the deposition area required for a specific sampling rate. Consider an aerosol in rectilinear flow between flat plates where the width of the plates, \( W \), and the plate separation, \( L \), define the rectangular cross section of the flowing stream (Figure 19). The average horizontal velocity of the air stream, and therefore that of a particle being swept along in it, is defined as the distance, \( D \), traveled per unit time and is determined by the aerosol flow rate, \( Q \). Thus

\[
V_h = \frac{D}{t} = \frac{Q}{WL}
\]  

(7.1)

where \( t \) represents deposition time and the product, \( WL \), is the precipitator inlet area. Assuming a constant vertical particle velocity, \( V_y = \frac{L}{T} \), permits the elimination of \( L \) and \( T \) from the equations and makes possible the definition of the deposition area required, \( DW \), as \( Q \) divided by \( V_y \). The vertical particulate velocity (thermal velocity) has been found to be a linear function of temperature gradient, i.e.,

\[
V_y = k \left( \frac{\Delta T}{L} \right)
\]  

(7.2)

Consequently, the deposition area is inversely proportional to the temperature gradient. The proportionality constant, \( k \), has been evaluated from the data of Phase I of the experimental study. Values of the deposition
HORIZONTAL VELOCITY: \( V_D = \frac{Q}{WL} = \frac{D}{t} \) (\( t = \) Time)

VERTICAL VELOCITY: \( V_Y = \frac{L}{t} \)

DEPOSIT AREA: \( WD = \frac{Q}{V_Y} \)

\( V_Y = k \frac{\Delta T}{L} \) where \( \frac{\Delta T}{L} = \) Thermal Gradient

\( k = \) Proportionality Constant

\( k = 0.0933 \) for \( P = 0.01 \) atm

\( Q = 236,000 \text{ cm}^3/\text{sec} = 500 \text{ ft}^3/\text{min} \) (5 ft\(^3\)/min Std. Cond.)

\( WD = (2,818,000) \cdot \frac{1}{(\Delta T/L)} \)

Figure 19. Derivation of Equations for Estimation of Deposition Area.
area estimated for a flow rate of 500 cu ft/min at a pressure of 0.01 atmosphere are presented in Table IV for various temperature gradients along with temperature difference between the hot and cold plates based on a plate separation of 0.015 inch (.04 cm) which is typical for the experimental precipitators employed in this study. Values have not been tabulated here for deposition areas required at pressures other than 0.01 atmosphere; but, due to the lower thermal velocity, the area required for precipitation at the standard flow rate at an altitude of 50,000 feet (where the pressure is about 0.1 atmosphere) is approximately three times greater. Referring again to Table IV, the very slight plate temperature difference required to induce precipitation is noteworthy.

B. Thermal Precipitator Effectiveness for Submicron Particulates

It has been shown that particles as small as 0.003 micron can be thermally precipitated at pressures as low as 2 mm Hg. Furthermore, it appears that these extremely small particles are deposited with velocities which are as great, or greater than, the thermal velocities attained by particles of one micron diameter. These observations are consistent with theory, and it appears that thermal precipitation remains effective for decreasing particle size even approaching molecular dimensions.

C. Effect of Precipitator Plate Separation on Performance

Experimental observations of thermal precipitation at atmospheric pressure indicate that precipitator performance is independent of the distance between the hot and cold plates in the range from 0.025 to 0.41 cm. Effectively, these results show that entrance effects are negligible under the operating conditions at which the data were obtained. Any delay in the establishment of temperature and velocity profiles may be expected to
### TABLE IV

**DEPOSIT AREA AND TEMPERATURE DIFFERENCE REQUIRED AT A FLOW RATE OF 500 CU FT/MIN AND 0.01 ATMOSPHERE PRESSURE**

<table>
<thead>
<tr>
<th>Temperature Gradient (°C/Cm)</th>
<th>Difference in Cold and Hot Plate Temperatures (°C)</th>
<th>Deposit Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>4</td>
<td>2.82</td>
</tr>
<tr>
<td>500</td>
<td>20</td>
<td>0.564</td>
</tr>
<tr>
<td>1000</td>
<td>40</td>
<td>0.282</td>
</tr>
<tr>
<td>1500</td>
<td>60</td>
<td>0.188</td>
</tr>
<tr>
<td>2000</td>
<td>80</td>
<td>0.141</td>
</tr>
<tr>
<td>2500</td>
<td>100</td>
<td>0.113</td>
</tr>
</tbody>
</table>

*a* Equivalent to 5 std. cu ft/min.

*b* Plate spacing 0.04 cm (0.015 inch).
decrease the effectiveness of thermal precipitation. Hence, the effect of precipitator plate separation would be more pronounced for precipitator operation with high aerosol throughput rates. In this respect the low pressure data of Table III serve to give a more comprehensive picture of the influence of precipitator plate spacing. Here, again, it appears that increasing the precipitator plate separation by a factor of three (i.e., in the range from 0.05 to 0.15 cm) does not significantly affect precipitator performance. While this precipitator plate separation range may appear rather small, it includes the region of primary concern. For practical sampling rates, the pressure drop with less than 0.05 cm between plates is excessive and results in increased pumping requirements and decreased precipitator effectiveness due to the expansion of the aerosol in the precipitation zone. At the upper limit of experimental observations, (i.e., 1.5 cm), the pressure drop required to induce a rather high throughput velocity is materially reduced. For much greater plate spacing the hot plate temperature needed for an effective temperature gradient becomes too high. Thus for the most likely operating conditions it is a reasonable assumption that plate separation is not a critical factor in precipitator effectiveness.

D. Precipitator Effectiveness at High Aerosol Velocities

Here, again, one is primarily concerned with the performance of a thermal precipitator. In this respect, two factors are of foremost importance: namely, turbulence, which would make the precipitator totally ineffective, and entrance effects, which would cause an increase in the deposit area. The data obtained from experimental precipitation indicate that these factors are negligible. Neither a substantial increase in the velocity of the aerosol...
stream nor an increase in the plate separation produced evidence of turbu-
ence. The value of McGinn's stability parameter calculated for the 
maximum experimental velocity was on the order of 2, which is twice the 
value given as the criterion for laminar stability. While quantitative 
data on precipitation performance could not be reduced from the observa-
tions at this sampling rate due to the fact that the deposit radius was 
greater than the diameter of the collecting plate, it is significant 
that precipitation was accomplished. Quantitative data were obtained 
for values of \( \sigma \) on the order of 1.0. Thus there is concrete experimental 
evidence that turbulence is not a critical factor for precipitator through-
put within the range defined by McGinn's criterion, and some indication 
that it may not be a critical factor even for higher sampling rates.

It should be noted that the pressure drop between the plates of the 
thermal precipitator was considerably greater than had been anticipated 
for the runs which were made at high velocities with a plate separation 
of 0.05 cm. The fact that an acceleration of the air stream with increas-
ing radial distance occurred at the highest throughput rates may account 
for the unpredicted stability of diverging flow in this case.

The effect on the horizontal particulate velocity component of a sig-
nificant change in pressure within the precipitation zone due to the 
expansion of the aerosol carrier medium has been mentioned in chapter III, 
where a factor was derived for compensation. Attempts to apply this cor-
rection produced values for the thermal velocity which increased with 
increasing aerosol throughput velocity—an effect which is without known 
theoretical basis. Furthermore, the lack of curvature in the plotted data 
at the upper extreme of aerosol flow rates (Figure 16) indicates no
decrease in precipitator performance which would be expected to result from expansion of the fluid. Thus, it appears that the change in horizontal velocity component (which is inversely proportional to pressure) was counteracted by a corresponding increase in thermal precipitating velocity (also inversely proportional to pressure).

The plotted data of the high velocity experiments also provide the basis for the conclusion that entrance effects do not affect precipitator performance within the range of observations. If entrance effects were significant, the influence would be reflected in two ways in a plot of \( (r_d^2 - r_o^2) \cdot \frac{\Delta T}{L} \) versus aerosol flow rate. First it has been shown that in the absence of entrance effects such a plot should be linear with an intercept at the origin. Since entrance effects are proportional to the flowing fluid velocity, the deposit radius would increase with increasing aerosol flow rate for a fixed precipitator plate separation in such a way that the quantity \( (r_d^2 - r_o^2) \cdot \frac{\Delta T}{L} \) would be a nonlinear function of the flow rate exhibiting an upward curvature at the higher extreme. The relationship should still become linear at the lower extreme as the curve approaches the origin. Now, referring to the tabulated thermal velocities per unit temperature gradient presented in Table III, the decreasing trend observed with increasing aerosol throughput in the data of Series B, suggests a decrease in precipitator effectiveness which might be interpreted as the result of entrance effects. However, the plot of experimental data in Figure 16 shows that the distribution of the limited data of series B falls within the range of random experimental deviation and that the apparent trend does not constitute conclusive evidence of a significant entrance effect. On the contrary, the marked linearity of all the data, collectively,
and particularly that of series A, which includes the highest flow rates, is substantial evidence that precipitator effectiveness is not velocity dependent.

Secondly, it has been shown that, at relatively low flow rates, the deposit radius is independent of the distance between the precipitator plates. If entrance effects were significant, an increase in the plate separation would extend the entrance length and a corresponding increase in deposit radius would become evident. This effect would also be reflected in Figure 16 by a parametric elevation of the curve of plotted data for the series of points representing observations at each successive magnitude of precipitator plate separation. The fact that all points lie rather closely about a single straight line through the origin indicates that the precipitator plate separation is not a parameter and offers additional support to the conclusion that entrance effects are negligible.

This conclusion is consistent with theoretical considerations. Since the Reynolds number for a system of given geometry is a function of the mass flow rate and the viscosity only (both of which are independent of pressure), it may be assumed that flow characteristics observed at atmospheric pressure would be unchanged for the same mass flow rate at 0.1 atmosphere and that the development of the velocity profiles would be identical at either pressure. Furthermore, the Prandtl number (the dimensionless heat transfer similarity index defined by the quotient of kinematic viscosity divided by thermal diffusivity) is essentially independent of pressure so that the conclusion may be drawn from boundary layer theory the temperature profile is established as rapidly at 0.01 atmosphere as at atmospheric pressure. Thus it appears that entrance effects which are negligible at atmospheric pressure would also be insignificant at the lower pressure.
Also noteworthy is the fact that the thermal velocities tabulated for this entire series of experiments are, on the average, about thirty per cent of the value obtained for low velocity precipitator operations. Because of the observations mentioned above, it seems reasonable to attribute this discrepancy, not to entrance effects, but rather to experimental inconsistencies resulting from the use of different precipitators and operating conditions. In the low velocity experiments, the deposit radius obtained at 0.01 atmosphere was only slightly greater than the inlet radius. Since experimental thermal velocities are computed from the magnitude of the difference between the squares of the deposit and inlet radii, experimental errors are greater for smaller deposits. The deposit radii obtained with high velocity precipitator operation at 0.01 atmosphere were considerably greater than the inlet radius. Thus, more confidence may be placed in the accuracy of the data of Phase IV, especially since it more nearly approaches practical operating conditions. It is interesting that the thermal velocities observed in this phase of study are close to the value given by the equations of Waldmann and Einstein which would be expected to hold for the precipitation of very small particles at low pressure.

On the other hand, it is not advisable to base conclusions regarding the pressure dependence of thermal precipitation on the data of Phase IV comparing this value of thermal velocity with that obtained for atmospheric pressure using a different experimental system. As was mentioned earlier the absolute magnitude of the thermal velocity deduced from experimental observations is questionable and may easily by in error by a factor of two. Still, the relative effectiveness of precipitator performance indicated by
a comparison of data obtained from the operation of the original precipitator at various pressures is considered reliable on the evidence of consistent and reproducible results. In the absence of data on the pressure-dependence of precipitator performance using the modified system, the conclusion regarding the increase in precipitator effectiveness with decreasing pressure, based on the observations of Phase I, remains unchanged.
The conclusions to be drawn from this experimental study may be summarized as follows:

1. The capacity of a thermal precipitator operating at atmospheric pressure, measured in terms of volumetric sampling rate at standard conditions, will be increased upon operation at 0.01 atmosphere pressure. The increase in throughput capacity will be in the range of from 200 to 700 per cent depending upon the particle size distribution of the air-suspended material.

2. Provided its throughput capacity is not exceeded, the precipitator will operate at an efficiency of essentially 100 per cent and, at any given pressure, will be equally as effective in collecting very small particles as in collecting particles of one micron diameter. There is apparently no lower particle size limit for thermal precipitation.

3. The effectiveness of the precipitator for relatively low flow rates will be essentially independent of the distance of separation between the hot and cold plates when this distance ranges from 0.025 to 0.4 cm.

4. Within the flow rate limitation defined by McGinn's criterion for laminar stability, turbulence does not interfere with the effectiveness of the radial flow thermal precipitator. There is some indication that the upper limit defined by McGinn's stability parameter may be exceeded without precipitation becoming ineffective, however, the experimental observations do not adequately establish the maximum limit.

5. At higher aerosol flow rates (within the laminar region defined by McGinn's stability criterion), the effectiveness of the precipitator will be essentially independent of the average velocity of the aerosol in the precipitator.
the precipitation zone and independent of hot and cold plate separation when this distance is between 0.5 to 1.5 mm. Again, this conclusion may be extended to greater distances between plates and to greater inlet velocities, but it has been restricted here to the range considered practical and defined by the limits of quantitative experimental observations.

The results of this experimental study indicate that a thermal precipitator can be designed to function effectively for high altitude sampling. Thermal precipitation has been accomplished with flow rates as high as 13 cfm at a pressure of 0.01 atmosphere using a conventional radial flow experimental model. Simply by enlarging the deposition area of the precipitator its capacity could be increased still further. However, to achieve sampling rates in the neighborhood of 500 cfm at a pressure of 0.01 atmosphere, either a major modification in design will be required, or a bank of more conventional precipitators must be used.

In Table IV a deposition area of 0.113 square meters was estimated for a sampling rate of 5 scfm with a temperature gradient of 2500°C/cm. If this estimate is modified for consistency with the data of Phase IV, the required deposition area will be on the order of 0.25 square meters. From theoretical considerations an additional increase of about 25 per cent will be necessary to provide for a decrease in thermal velocity due to the ambient temperature at an altitude of 100,000 ft. Thus the deposition area becomes rather large, and the particle density per unit surface area will necessarily be low. However, the same particle density could be obtained on a much smaller area by decreasing the sampling rate.

The required deposition area is an accurate measure of precipitator effectiveness, but that alone is not sufficient for precipitator design.
In the rectilinear flow precipitator, it is immediately obvious that the dimensions of the collecting surface are determined by the distance the particle will travel before being deposited. This distance may be computed as the product of precipitation time, \( t_p = \frac{L}{V} \), multiplied by the flowing velocity of the aerosol. The flowing velocity of the aerosol is determined by the cross-sectional area of the aerosol stream (normal to the direction of flow) and the magnitude of the flow rate. The maximum flow rate will ultimately be determined either by the criteria for laminar stability or by the pressure drop which can be tolerated within the system. In the case of the rectilinear precipitator, the critical Reynold's number defines a maximum flow rate which is independent of the distance between plates. Also the distance of particle travel is independent of the distance between plates. Hence, the deposit depth is fixed for a given temperature gradient. Assuming a gradient of 2500°C/cm, the maximum deposit width is on the order of 2 cm. Therefore, an inlet width of about 15 meters would be required, regardless of the distance between the hot and cold plates of the precipitator. The precipitator plate separation then would be established by considerations of the allowable temperature difference between plates and the pressure drop which can be estimated for an incompressible fluid by

\[
\Delta P = \frac{12 \cdot Q \cdot \mu \cdot D}{L^3 \cdot W} \tag{8.1}
\]

where \( D \) is the length of the precipitator corresponding to the depth of the deposit and \( W \) is the width of the precipitator inlet. For the hypothetical case illustrated here, the pressure drop will be excessive for a plate separation of 0.05 cm, being roughly equivalent to the absolute pressure of 0.01 atmosphere. For a plate separation of one
millimeter, the pressure drop is less than one millimeter of mercury (here the assumption of a constant density fluid is fairly good). The temperature difference required for this plate separation is then 250°C, which is practicable. The width of the precipitator inlet required in this case may appear unreasonable, but it should be noted that this represents a total inlet dimension required to meet the sampling rate specification of 500 cfm. The actual precipitator inlet width may be reduced by using, for example, a stack of 15 rectilinear precipitators, each of which would be 2 cm deep and 1 meter wide with a plate separation of 1 mm. Alternately, a cylinder shell or hoop configuration could be employed with a diameter of about 5 meters for a single unit or perhaps five units with a diameter of 1 meter. Obviously, considerable flexibility in design is permissible; however, regardless of the precipitation configuration, the total deposit would be distributed over an area which is equivalent to a strip 2 cm wide by 15 meters long. Again, it should be noted that the same deposit density could be collected on a smaller surface, e.g. 2 cm by 15 cm if the sampling rate is decreased by a factor of 100.

By designing a precipitator for converging flow to increase its laminar stability and thereby to increase the maximum throughput velocity, it might be possible to increase the width of the deposit with a resulting decrease in the width of the inlet. Even this approach is limited by the pressure drop within the system, which must be less than 7.6 mm Hg if the precipitator is to function at ambient pressure. In this respect, the means of inducing flow through the precipitator will be an important factor in precipitator design.
If the airstream is to be pulled through the precipitator by decreasing the exit pressure, then the pressure drop must be less than 7.6 mm Hg. Alternately, if the precipitator is to function while sweeping a region of the atmosphere, the pressure drop within the precipitation zone must be negligible. Finally, if the airstream is to be forced through the precipitator by increasing its inlet pressure, the best approach is then to design the precipitator for the pressure drop associated with the specified sampling rate at its operating pressure, while sizing the deposition area according to precipitator performance at the inlet pressure. In the latter case, the total deposition area will be increased; however, a more compact deposit would result from an increase in deposit depth.

The foregoing discussion applies generally to a radial flow precipitator as well as to the rectilinear flow configuration. The main difference is that the sampling rate limitation established by the criterion for laminar stability in diverging radial flow is dependent on plate separation and inlet radius. Decreasing the plate separation to enhance the stability of the system results in an increased pressure drop, which is also a limiting factor in the sampling rate. Enlarging the precipitator inlet is a more likely means of increasing the throughput capacity. When this approach is employed for the same operating conditions applied in the consideration of the rectilinear precipitator, the dimensions of a single unit approach those of the cylindrical shell system suggested earlier. For example, it has been estimated that six units, each with an inlet radius of 25 cm and a plate separation of 1 mm could sample 500 cfm with a temperature gradient of 2500°C/cm. The deposit collected would be in the form of a circular band about 3 cm wide. The total length of the
band deposit would be about 9.5 meters. With smaller radial flow precipitators (comparable to the size of the experimental model) the same total surface area would be required; however, the number of units would be excessive, i.e. several hundred precipitators.

As in the case of the rectilinear flow precipitator, some advantage could be gained possibly in producing a more compact deposit by resorting to converging flow (to permit higher flow rates without turbulence), but the pressure drop again becomes a critical factor. At the present time, there is no equation available for a reliable estimate of the pressure drop at the conditions of interest. Experimental observations made during this study indicate that the maximum flow rate which can be induced by reducing the exhaust pressure from the 0.01 atmosphere level is not very much greater than the maximum flow rate established by the stability criterion for radial flow.

In the evaluation of thermal precipitation as a technique for high altitude sampling, a more fundamental consideration is of prime importance, namely, the projection of estimates of precipitator performance to altitudes above 100,000 feet. Experimental evidence shows that the thermal velocities attainable by particles moving under the influence of thermal forces increase rapidly with decreasing pressure, which is the basis for more effective precipitation at lower pressures. Waldmann's theory\(^{18}\) suggests that the thermal force exerted on a sphere suspended in a gas possessing a temperature gradient is independent of the gas pressure. However, it seems logical that there must be some point at which thermal precipitation decreases with pressure. Thus the limiting situation becomes important in resolving the question of the feasibility of thermal precipitation at
greater altitudes. The most obvious factors for consideration are the thermal force mechanism and the equation used to describe it. Waldmann's thermal force equation has been selected as the one which most nearly corresponds to the physical situation under consideration. He defines the thermal force as a mechanism of momentum transmission to a surface due to the impulses of impinging and departing gas molecules. His equation was derived by a summation of the momentum impulses over the entire surface of a spherical particle and involves an evaluation of the velocity distribution of the gas molecules corresponding to a temperature gradient in the gas. Inherent in his derivation is the assumption that the mean free path length is very much greater than the particle radius (a particulate system characterized by a very large Knudsen number) where the velocity distribution of the impinging gas molecules is not affected by collisions with gas molecules departing from the particle surface. In this respect, the model becomes more realistic as the mean free path length increases.

As the frequency of intermolecular collisions increases in the vicinity of the surface, due either to decreasing mean free path (increasing pressure) or to increasing the particle size under consideration, the velocity distribution of the gas molecules is altered significantly. Under these conditions the thermal force mechanism is that of the transition region where the fundamental model defined by Waldmann loses its validity. Hence, his equation, which suggests a pressure-independent thermal force, may be regarded as a limiting value which is approached as the pressure decreases. It may be expected to hold basically over a rather wide pressure range, provided the Knudsen number characteristic of the particulate system is always very much larger than unity.
Obviously, by definition of the model, the equation derived by Waldmann can be applied only where a temperature gradient exists within the gas. In this respect, the equation is subject to the limitations of kinetic theory. It appears that in an infinite gas volume the equation would be valid for a system of large Knudsen numbers at any pressure, as long as the changes in density, velocity, and temperature over a distance on the order of the mean free path length are small. However, if the particulate system is restricted, so that wall effects become significant, the equation cannot be expected to hold. In such a situation the intermolecular collisions are relatively infrequent compared with the frequency of molecule-wall collisions, and the mechanism for the establishment of local equilibrium within the gas itself is impaired. The methods of rigorous kinetic theory cannot then define a proper velocity distribution for the impinging gas molecules. Thus, the essential elements to be considered in low pressure thermal precipitation include not only the mechanism of thermal force, but the existence and establishment of a temperature gradient in the gas.

A convenient starting point for more specific consideration is the 100,000 ft altitude level where precipitation is known to be effective. At the ambient pressure of 7.6 mm Hg the mean free path of the gas molecules is about $4.2 \times 10^{-4}$ cm. In order to determine the characteristic Knudsen number for the thermal precipitation mechanism, the size of the particulate material must be known. A realistic estimate of the mean particle radius for atmospheric debris seems to be 0.1 micron. Hence, the Knudsen number has a value of 42. Waldmann's equation may be expected to hold provided only that a temperature gradient exists within the gas.
To support the existence of the required temperature gradient, it is necessary to consider the distance between the hot and cold plates of the precipitator. A reasonable precipitator plate separation would be 0.1 cm. Hence, the precipitator gas system is characterized by a Knudsen number of $4.2 \times 10^{-3}$. On the whole the frequency of intermolecular collisions is very large relative to the frequency of molecule-surface collisions. The thermal wall effects (from the viewpoint of kinetic theory) are insignificant and the heat transfer effects may be relegated to the continuum regime where the Navier-Stokes equations are applicable. Hence it is reasonable to stipulate the existence of a temperature gradient on a basis of thermal conduction in laminar flow provided that entrance effects are negligible.

In view of the above considerations, it is not surprising that Waldmann's equation predicts rather well the magnitude of the thermal force for this pressure, particularly where very small particles are concerned. Furthermore, the conditions under consideration are such that the particulate system approaches the mathematical force model even more closely as the pressure is decreased. At some point, however, the applicability of Waldmann's equation breaks down, as indicated above, due to the confinement of the gas between the plates of the precipitator. This point will be reached when the mean free path length approaches the distance between the plates, i.e., a systemic Knudsen number on the order of 0.1 to 0.01. This situation is encountered at altitudes well above 200,000 feet. Thus it seems safe to assume that thermal precipitation would remain effective at altitudes well above 100,000 feet.

It should be noted that the inapplicability of Waldmann's thermal
force equation does not imply a complete degeneration of the thermal force mechanism. Even though such continuum concepts as temperature gradient lose some of their meaning, the agency for heat transfer and, similarly, for thermal force remains as the system passes through the transition region into the regime of "free molecule" behavior. When the mean free path is sufficiently large it is clear that molecules which strike the particle must have come directly from the plates of the precipitator and will possess velocities which have been accommodated to some extent to the temperature of the plate surfaces. In such a situation, it is probable that thermal force, being dependent upon the frequency of molecular collisions, will decrease with decreasing pressure, as do transport phenomena which are ordinarily pressure independent. Obviously, the foregoing analysis is not absolutely complete. Since the practical sampling rates at high altitudes must be large, relatively high aerosol velocities may be expected between plates. So long as these velocities are subsonic, it is believed that this effect may be neglected. When the velocity of the flowing gas approaches the mean molecular velocity, the relative number of surface-molecule collisions will have to be revised accordingly.

In contemplating the design of a precipitator to function at pressures below 7.6 mm Hg, it should be noted that a further increase in effectiveness may occur. It cannot be predicted, however, with the same degree of confidence exhibited in the range from 1.0 to 0.01 atmosphere, since a true increase in effectiveness is essentially a characteristic of the transition region. For the precipitation of small particles at very low pressure, the increase in thermal velocity is anticipated merely to
offset the necessary increase in volumetric throughput, thereby maintaining a constant degree of effectiveness in terms of mass sampling rate. For this reason, it appears that a precipitator designed to collect particulate material from the atmosphere at an altitude of 100,000 feet could be used at higher altitudes so long as the pressure drop across the system is within prescribed limits.

In comparing the thermal precipitator with other high altitude sampling devices, again the factor of prime importance seems to be the deposition area required per unit flow rate, or, from the point of view of analyzing the sample, the particle density of the deposit. This factor is essentially independent of precipitator design, but is directly proportional to the sampling time. That is, the same particle density will be obtained with a very small precipitator as with one of the larger and necessarily more elaborate designs considered earlier. On the other hand, if the total mass of particulate material is important, it can be increased either by increasing the total deposition area or, as before, the time of sampling.

The size and weight of the sampling device is primarily a matter of design. The experimental precipitators as well as most commercially available models for sampling at atmospheric pressure, are excessively bulky and heavy. These are generally made of heavy metals with considerable space being occupied by the heating and cooling systems. The essential parts of a thermal precipitator are the hot plate, the cold plate, and a means of inducing aerosol flow. The hot and cold plates could be reduced to very thin sheets if an external source of thermal energy could be utilized. Further, if the motion of the precipitator can
be used to direct aerosol flow, the weight requirements of such a sampling device could be met.

The disadvantages of thermal precipitation at atmospheric pressure have been highly advertised. Perhaps the most popular and best justified complaint is in regard to the relatively high energy input required for the maintenance of the hot plate temperature. Certainly, the maintenance of a hot plate temperature of 100°C at atmospheric pressure when the cold plate must be cooled by water leads to an extravagant power consumption. It has been shown that precipitation can be effectively accomplished at 0.01 atmosphere by a temperature difference of only a few degrees centigrade. If the increased deposit area can be tolerated, the power consumption problem can be drastically reduced. Alternately, if solar radiation could be utilized to develop the hot plate temperature and the cold plate temperature could be maintained by the environment, the energy supply from an internal source might be small. Such a system seems feasible in view of the fact that a temperature of several hundred degrees above the ambient has been obtained in this manner at high altitudes.

The principal advantages of the thermal precipitator can be summarized briefly. First, the efficiency of the device is independent of particle size. It is capable of collecting particles less than 100 Å in diameter. Second, as far as atmospheric debris is concerned, its effectiveness in terms of mass aerosol throughput increases with decreasing pressure down to, and perhaps below, 0.01 atmosphere. Third, the basic construction of a precipitator is simple. It has no moving parts and does not require skilled operators. Finally, the deposit may be collected on a hard surface or upon a strippable film and is easily accessible for analysis.
IX. RECOMMENDATIONS

Based on the experimental results of this investigation, it is concluded that thermal precipitation is feasible for the collection of atmospheric particulate material at an altitude of 100,000 feet. Furthermore, this technique seems potentially valuable for sampling at altitudes well beyond that level. It is therefore recommended that a thermal precipitator be designed specifically for high altitude operation using the data presented herein as a guide, or that the principle of thermal precipitation be employed in conjunction with other sampling techniques as a means of collecting particles in the smaller size range. It is further recommended that a small thermal precipitator be mounted on conventional meteorological aircraft for practical preliminary testing at an altitude below 100,000 feet and that the deposits so obtained be compared with the results of impactor sampling.

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