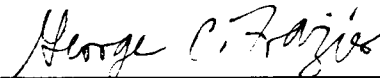


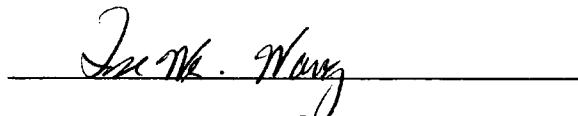
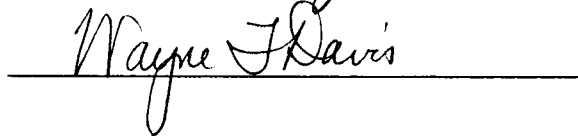
To the Graduate Council:

I am submitting herewith a thesis written by Kwang Song Chua entitled "Condensation of Lead Dichloride Fume on Silica Particles in a Hot Gas Stream." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.



George C. Frazier, Major Professor

We have read this thesis and
recommend its acceptance:

Accepted for the Council:



Associate Vice Chancellor and
Dean of the Graduate School

**CONDENSATION OF LEAD DICHLORIDE FUME ON SILICA
PARTICLES IN A HOT GAS STREAM**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Kwang Song Chua

December 1997

Dedication

I dedicate this work to my parents, Mr. Kim Chong Chua (deceased) and Mrs. Ho Kiang Chia, who have brought me to this beautiful world with love. Furthermore, I appreciate my oldest brother, Mr. Chaw Song Chua, for providing me this invaluable educational opportunity.

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Abstract

Incinerators are capable of destroying hazardous industrial waste forever in a large volume. However, they can cause air pollution such as heavy metal emissions if the feed stocks contain such metals. Particulates less than one micron in size are difficult to remove with current technologies. These fine hazardous metal emissions limit the application of incineration as a way of waste disposal. Since removal efficiency is a lot higher for larger particles, it is desirable to increase the particle size of the metal fumes generated when feed materials containing heavy metals are incinerated.

A process has been developed where selected particles are introduced into a hot gas stream contaminated with metal fumes. It is anticipated that these particles serve as agglomeration agents or condensation sites for the hazardous vapor. Lead dichloride, produced by hydrochloridation of a lead oxide pellet, is chosen as a test model fume; whereas silica particles, generated *in situ* by the combustion of hexamethyldisiloxane vapor in air, act as the agglomeration or condensation agent.

This work studies the effect of silica particles on the size distribution of lead dichloride fumes at temperatures 350, 450, 550 and 650°C. A general increase in the size distribution toward the larger particles has been observed at 350, 450, and 550°C, but not at 650°C. For instance, the peak shifts from 0.02 μm to 0.07 μm at 450°C. In conclusion, this study has identified a possible agglomeration or condensation agent that can result in the shift of the particle size distribution to larger sizes, which in turn may result in higher removal efficiencies in scrubbers such as the venturi types.

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List of Symbols

a ,	radius, cm
d_p ,	particle diameter, cm
D ,	diffusion coefficient, cm^2/s
k ,	mass transfer coefficient, cm/s
K ,	collision frequency function of a mono-disperse aerosol, cm^3/s {Eq. (2.3)}
m ,	mass of particle or molecule, g
n ,	concentration, cm^{-3}
N_∞ ,	total particle number concentration, cm^{-3}
p ,	pressure, dyne/cm^2
p_1 ,	partial pressure of the condensing vapor far from the droplet
p_d ,	equilibrium vapor pressure above a drop of diameter d_p
p_s ,	equilibrium vapor pressure above a flat surface
r ,	radial coordinate, cm
S ,	saturation ratio, dimensionless
t ,	time, s
T ,	absolute temperature, $^\circ\text{K}$
u ,	velocity component in x direction, cm/s
v ,	particle volume, cm^3
v_m ,	molecular volume, cm^3

Subscripts

i , pertaining to particle i

j , pertaining to particle j

Greek Letters

β , collision frequency function, cm^3/s

λ , wavelength of light, cm

μ , viscosity, $\text{g}/\text{cm}\cdot\text{s}$

ρ_p , particle density, g/cm^3

Chapter 1 Introduction

Air pollution by fine metal-containing particles formed during hazardous waste incineration has been less studied than other incineration emissions such as noxious organic partial oxidation products, for example. The 1990 Clean Air Act Amendment (CAAA) empowers the Environmental Protection Agency (EPA) to tighten the control of metal emissions. In response, the EPA identified twelve toxic metals (arsenic, beryllium, cadmium, hexavalent chromium, nickel, antimony, barium, lead, mercury, selenium, silver, and thallium) which are considered to pose an unreasonable risk to human health and to the environment. Control of the emission of these metals from incinerators is now mandated under current and pending regulations [refer to, for example, Section 3005(c)(3) and Part 264, subpart O, of the Resource Conservation and Recovery Act (RCRA) regulations].

Hazardous industrial waste can contain organic sludge and many metals in various chemical and physical forms. The organic materials may contain halogens, chlorine in particular, in polymers such as polyvinyl chloride (PVC). When such mixtures are incinerated, the combustion process converts the organic chlorides to hydrogen chloride which can react with metals, even in oxide form at incineration temperatures, forming metal chlorides. The metal chlorides generally possess relatively high vapor pressures and therefore can appear in the combustion gases in appreciable amounts. A metal fume of very fine particles forms from these vapors as the gas cools (Shor, 1994). These fumes typically contain particles in the sub-micron range [mean particle sizes in the range of

from about 0.1 to 0.2 μm have been observed in this laboratory (Shor, 1994)]. Particulates less than one micron (1 μm) in diameter are very difficult to remove from gas streams even with the use of technically advanced equipment such as electrostatic precipitators (ESP) and bag filters (Wark and Warner, 1981).

The EPA's mandated control of the emissions of the RCRA metals from industrial incinerators is therefore of considerable concern to incinerator designers and operators. It now appears that the use of incinerators for the processing of hazardous industrial wastes may be severely limited, unless a method is developed which can significantly reduce the production of fine metal-containing fumes during the combustion process.

1.1 Objective

The purpose of this experimental work is to determine if selected fumes of sub-micron particles can be agglomerated or otherwise grown to larger size by introducing controlled amounts of carefully selected fine particles to the gas stream which can act as a agglomerating agents or surfaces on which metal-containing vapors can condense. Promoted agglomeration may suppress the fume formation and/or lead to fumes with substantially larger particle sizes, which are more readily removed in the air pollution control system down stream of the incinerator than fumes consisting mainly of sub-micron particles.

If successful, the results of this investigation may be applicable to the control of heavy metal emissions from incinerators.

1.2 Methodology

Certain aspects of the incineration process can be simulated in a laboratory-scale, tubular furnace in which a “model” metal fume, lead dichloride, is generated by the reaction of a suspended lead oxide pellet with hydrogen chloride in a stream of air. A series of experimental runs will then be conducted in an effort to agglomerate this fume on silica oxide generated *in situ* by the combustion of a volatile organometallic compound introduced directly to the hot zone of the furnace through a specially designed, small, air cooled probe. The fine particles of silica oxide are formed as a product of the combustion of hexamethyldisiloxane in air.

The lead dichloride system is chosen as a model fume for these studies because appreciable quantities of vapor and fume can be produced in the readily accessible temperature range of about 400 to 700°C and because of the previously gained experience with this system in this laboratory (Shor, 1994).

Particles from all experimental runs are collected and analyzed for size distribution. An electrical aerosol analyzer, Model No. 3030 manufactured by TSI Incorporated (St. Paul, MN) and provided by the courtesy of Dr. Wayne Davis of The Department of Civil and Environmental Engineering, are used for the particle size determinations.

Chapter 2 Literature Review

2.1 Legislative Background

Increasing industrialization, urban growth, the burning of soft coal for domestic and commercial space heating, and local atmospheric conditions are important factors that contributed to decreasing urban air quality in the United States during the latter part of the 19th century. By the turn of the 20th century the air quality was so poor in some cities at times that elected municipal officials, reacting to an aroused public, considered and debated methods for restoring air quality in order to protect the health of the public.

The earliest municipal ordinance aimed at protecting air quality appears to be that enacted by the city of Albany, New York in 1913. This ordinance placed restrictions on the sale or use of high-volatile coal for use in hand-fired fuel burning equipment (Magill, et al., 1956). By 1950 seventy three cities including Knoxville and Kingsport, Tennessee have fuel restrictions ordinances providing inspection requirements and penalties for noncompliance. Ordinances were also enacted by numerous municipalities based on smoke density classifications (Magill, et al., 1956), as determined by a Ringlemann Chart, for example.

These early ordinances were aimed principally at controlling the release of particulate matter (dust or "smoke") to the atmosphere. However, eighteen cities including Knoxville, Kingsport, and Chattanooga, Tennessee enacted prior to 1950 ordinances aimed at controlling fume emissions, defined according to the American

Society of Mechanical Engineers (ASME) model ordinance as “gases or vapors that are of such character as to create an uncleanly, destructive, offensive or unhealthy condition”. Note that this definition does not explicitly include ultra-fine particles formed by condensation from the gaseous state, which is an essential part of technical definitions of fumes today (refer to, for example, Parker, 1984). The only ordinance enacted by 1950 or before which attempts to regulate specific materials other than dusts is that due to the city of Los Angeles, and was directed at limiting the discharge of sulfur compounds to the atmosphere. Sulfur compounds, expressed as SO_2 , could not be legally emitted to the atmosphere if present in gas streams in excess of 0.2 percent by volume.

Attempts to maintain or protect air quality by regulatory processes prior to 1950 appear to have been restricted to the local level (municipality, or county-wide at most). Concern generally was limited to particulates and to fumes defined more or less as above, although an ordinance was enacted by the city of Detroit, Michigan in 1947 which did make explicit reference to metallic dusts in its definition of fumes. However, this ordinance did not consider classifications of metals such as those which are especially toxic (such as arsenic and beryllium) or heavy metals (such as lead, mercury, and cadmium) in general.

The first state-wide law aimed at regulating air quality is that enacted by the State of Oregon in 1951, according to Magill, et al. (1956). Wark and Warner (1981, ch 2), however, state that California was the first to take measures against air pollution. Many other states were actively involved in creating state-wide legislation in 1953, presumably as a result of the disastrous London smog of December, 1952.

The Oregon act created an Air Pollution Authority, "charged with the development of a comprehensive program for the prevention and control of all sources of pollution in the air in the state, cooperating with other agencies, encouraging air pollution studies, collecting and disseminating information, making rules and regulations, considering complaints, making investigations, and holding hearings".

The history of federal involvement in air quality regulation began in 1955 with the enactment of the Air Pollution Control Act of 1955 (Public Law 84-159). This particular act was narrow in scope, "primarily because of the federal government's hesitation to encroach on states' rights" (Wark and Warner, ch 2, 1981). The 1955 act initiated the following actions, according to Wark and Warner:

1. Research on the effects of air pollution by the Public Health Service.
2. Provision for technical assistance to the states by the federal government.
3. Training of individuals in the area of air pollution.
4. In-house and out-of-house research on air pollution control.

The scope of the Act of 1955 was expanded by congress during the course of the next thirty five years through the process of amendment. The following paragraphs provide a brief summary of the amendments enacted through 1990 along with some of their important features.

- **Air Pollution Control Act Amendments of 1960 and 1962**, Public Laws 86-463 and 87-761. This act directed the surgeon general to conduct a thorough study relating the effects of motor vehicle exhausts to human health.

- **The Clean Air Act of 1963**, Public Law 88-206. This act for the first time provided federal financial aid and technical assistance, encouraging state, regional and local programs for the control and abatement of air pollution.
- **Motor Vehicle Air Pollution Control Act of 1965**, Public Law 89-272. The California state emission standards for hydrocarbons and carbon monoxide were mandated nation wide.
- **The Air Quality Act of 1967**, Public Law 96-148. Among other things, this act provided for the development and issuance of air quality criteria (AQC's) for specific pollutants that have identifiable effects on human health and welfare, and required that state and local agencies establish air quality standards consistent with AQC's on a fixed time schedule.
- **The Clean Air Act Amendments of 1970**, Public Law 91-604. This act created the Environmental Protection Agency (EPA) and authorized this agency to set national ambient air quality standards (NAAQS), among other things. The act also requested additional research on clean fuels for stationary sources (\$350 million to be spent over a 3-year period), authorized additional state and regional grant programs, provided for standards of performance for new plants (NSPS), and national emission standards for hazardous air pollutants (NESHAP) were to be set and would apply to existing as well as new plants (Wark and Warner, 1981). Lead, mercury, cadmium, and asbestos were included in the list of hazardous agents.

- **The Clean Air Act Amendment of 1977**, Public Law 95-95. This act established the Prevention of Significant Deterioration (PSD) for attainment areas and specified that each major new plant must install best available control technology (BACT) in addition to PSD. It also established “emission offset policy” to make industrial growth in non-attainment areas possible.
- **The Clean Air Act Amendment of 1990**, Public Law 101-549. The most substantive set of regulations adopted since 1970, this act contained eleven major provisions including Title I non-attainment, Title III Air Toxics, Title IV Acid Rain, and Title V Permitting.

Title I increased the offset requirements and required state and/or local agencies to develop comprehensive emission inventory tracking systems to ensure that progress was made toward the standard. Title III established a list of 189 hazardous air pollutants (HAPs) which are associated with approximately 300 major source categories. Phase I under this title required each major source to meet maximum achievable control technology (MACT) standards within 10 years. A second phase evaluated the significance of any residual risk in order to set the risk-based standards 8 years after the promulgation of MACT standards.

The intent of Title IV was to achieve a 10 million ton reduction in SO₂ emissions from 1980 levels that would place a cap of approximately 8.9 million tons per year on SO₂ emissions. A national permitting program, established under Title V, required approximately 40,000 sources to submit applications for Title V permits to EPA.

2.2 Technologies for Removing Particulate Matter (Dust) from Gas Streams

The ordinances enacted beginning early in this century and the Congressional Clean Air Act and amendments of 1955-1990 provided an enormous incentive for the development of new and improvement of existing gas cleaning technologies, both for removing particulate matter (dusts and aerosols) and for removing undesirable chemical contaminants such as acid gases (e.g., SO_2 and NO_x) and organic vapors.

A brief overview of dust removal technologies is provided in this section, in view of the fact that the heavy metal contaminations of interest in this work are in particulate form. The removal of gaseous and vapor contaminations is not included in the scope of this work and will not be considered further. Refer to Kohl and Riensenfeld (1985) for a comprehensive presentation of technologies suitable for cleaning gas streams of gaseous chemical contaminants.

Dust removal technologies may be grouped into four classes (Wark and Warner, 1981): cyclones, wet scrubbers, fabric filters, and electrostatic precipitators.

Cyclones have relatively low dust removal efficiency and are useful when the dust is "coarse" and the dust loading is relatively high (e.g. $>1 \text{ gr/ft}^3$).

Wet scrubbers such as the venturi or spray tower type are especially useful for applications where high removal efficiency of fine particles are required and the cooling of and the addition of moisture to the stream are acceptable. Soluble gaseous contaminants as well as particulates can be removed by these devices.

Typical applications of fabric filters (bag house) include those situations where the gas temperature is relatively low but always above its dew point, and very high removal efficiency is required.

Electrostatic precipitators are typically used when very high efficiencies are required for the removal of fine dust, and very large volumes of gas are to be handled (Wark and Warner, 1981).

In spite of the many advantages of each of these dust removal technologies, they all have relatively low fractional removal efficiencies for particles whose diameters are less than about a few tenths of a micrometer, as shown by the typical curves provided in Figure 2.1. Unfortunately, this is the size range associated with many fumes. As a consequence, these technologies are not well suited for the removal of fume particles if it should be mandated that 80 to 90 percent, or more, of the particles are to be removed from a stream contaminated with heavy metals or radionuclides.

It should be pointed out that the curves in Figure 2.1 for spray tower and dry ESP are in error in the particle size range below about 0.08 micrometers (Davis, 1997).

2.3 Particle Formation and Growth in Gas Streams

The nucleation and growth of particles (aerosols), especially with respect to atmospheric processes, has received the attention of numerous scientists during the course of the last century. One goal of the research has been to formulate the general dynamic equation for the particle size distribution function, $N(v)$, under the influence of interacting particle force fields and to test predictions of this theory against experimental

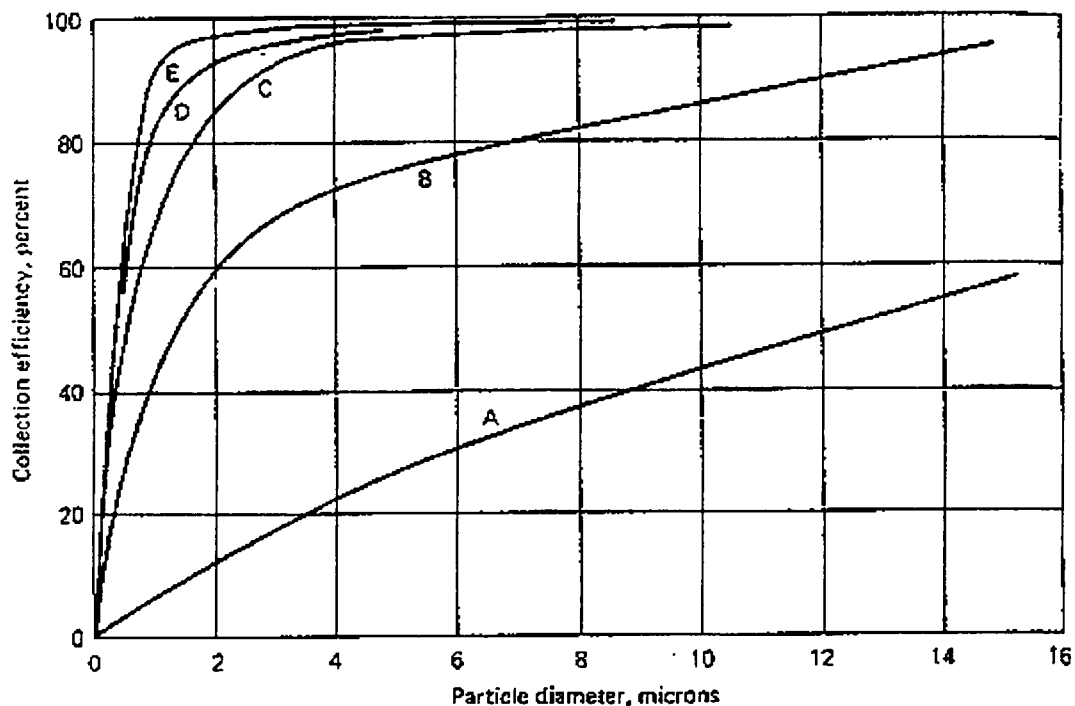


Figure 2.1 Typical Collection Efficiency Curves for Various Types of Dust Collectors: (A) High-Throughput Cyclone; (B) High-Efficiency Cyclone; (C) Spray Tower; (D) Dry ESP; (E) Venturi Scrubber (Source: Wark & Warner, 1981).

observations. The processes leading to the evolution of the so-called stationary size distribution function are nonlinear, which leads to considerable difficulty in extracting reasonably general, useful results from the mathematical theory. A relatively recent summary of the current state of the knowledge in this area is provided by Friedlander (1977) in his book, *Smoke, Dust, and Haze*. This book is the principal source of the material presented in this section.

Growth (in size) of the particles in a given distribution of particles suspended in a gas can occur by collision and coagulation and by condensation from the gas phase (gas-

to-particle conversion). These processes are independent and are generally treated separately. Collision and coagulation will be considered first.

Collisions between particles may occur due to diffusive, or Brownian, motion and/or fluid shear. Brownian motion is the principal mechanism by which collisions take place when the particles are less than about 1 μm in diameter but appreciably larger than the mean free path of the gas molecules and when the gas is essentially shear-free (e.g., a stagnant system). This process is of special interest in fumes, because their particles are in this size range in many instances. For gas streams undergoing shear, collision may also be shear induced, and this mechanism can contribute significantly to the total collision rate, depending on the magnitude of the shear and on the particle sizes.

2.3.1 Brownian Coagulation

Friedlander (1977) derives the following equation for the stationary state collision frequency function, $\beta(v_i, v_j)$, between particles whose volumes are v_i and v_j , for the restrictions that the particle diameters are much larger than the mean free path of the gas molecules, that the Stokes-Einstein result holds for the diffusion coefficient, that all collisions result in coagulation, and that inter-particle force fields are negligible:

$$\beta(v_i, v_j) = \frac{2kT}{3\mu} \left(\frac{1}{v_i^{1/3}} + \frac{1}{v_j^{1/3}} \right) (v_i^{1/3} + v_j^{1/3}) \quad (2.1)$$

For particles much smaller than the mean free path of the gas molecules, the kinetic theory of gases leads to the following result for collisions between rigid, elastic spheres:

$$\beta(v_i, v_j) = \left(\frac{3}{4\pi} \right)^{1/6} \left(\frac{6kT}{\rho_p} \right)^{1/3} \left(\frac{1}{v_i} + \frac{1}{v_j} \right)^{1/2} (v_i^{1/3} + v_j^{1/3})^2 \quad (2.2)$$

Considering the simple case of a mono-disperse aerosol, where $v_i = v_j$, Eq (2.1)

reduces to: $(v_i = v_j) \equiv K = 8kT/(3\mu)$ (2.3)

The dynamic equation for the total number of particles per unit volume of gas, according to Friedlander (1977) is:

$$\frac{dN_{\infty}}{dt} = \frac{K}{2} \sum_{k=1}^{\infty} \sum_{i+j=k} n_i n_j - KN_{\infty}^2 \quad (2.4)$$

which for a mono-disperse aerosol reduces to:

$$\frac{dN_{\infty}}{dt} = -\frac{K}{2} N_{\infty}^2 \quad (2.5)$$

Using the initial condition that $N_{\infty} = N_{\infty}(0)$ at $t = 0$ and integrating Eq (2.5) leads to the following result,

$$N_{\infty} = \frac{N_{\infty}(0)}{1 + \left(\frac{KN_{\infty}(0)t}{2} \right)} \quad (2.6)$$

where K is given by Eq (2.3). Eq (2.6) may be used to estimate, for example, the time required for a given mono-disperse, stationary state particle population, N_{∞} , to be reduced to a specified fraction of its initial value, $N_{\infty}(0)$. Using the result calculated by Hidy and Brock (1970) for $K = \beta \approx 14.4 \times 10^{-10}$ cm³/sec for particles in air at 23°C and one atm pressure, and an initial population of 10^8 particles/cm³, Friedlander estimates that about 125 seconds are required for the population to be reduced to one-tenth of its initial value. Similar estimates are not known for particles in combustion gases at incineration temperatures.

The results obtained above are restricted to the case where force fields between particles are negligible. Inter-particle forces of principal interest are van der Waals forces, which are always present, and Coulomb forces, due to charge on the particles. A correction factor must be included in the coagulation theory to account for these forces.

As van der Waals forces are attractive, the correction factor for this case results in an increased coagulation rate compared with the force-free results summarized above. However, for colliding particles of the same size, the correction factor is dependent only on an interaction energy, Q , defined as,

$$Q = \frac{4\varepsilon\sigma^6}{v_m^2} \quad (2.7)$$

where ε and σ are parameters in the Lennard-Jones attractive potential function, with units of energy and length, respectively. Using collisions between small ethyl acetate droplets under ambient conditions as an example, Friedlander calculates that the value of the van der Waals collisional correction factor is about 25%. This value is suggested to be relatively unimportant in view of uncertainties resulting from convection and deposition of particles on walls of containment vessels.

The effect of electric charge on colliding particles can be such that the collision frequency is increased or decreased, depending on whether the product of the charges is positive or negative. The correction factor depends on the dimensionless parameter,

$$y = \frac{z_i z_j e^2}{\varepsilon k T (a_i + a_j)} \quad (2.8)$$

where z_i and z_j are the number of charges on the interacting particles, e is the electronic charge, ϵ is the dielectric constant of the medium, k is Boltzmann's constant, T is the absolute Kelvin temperature, and a_i and a_j are the particle radii. Colliding particles of like charge (unipolar charging) give a positive value for y and the effect of the charge is to cause a reduction in collision rate. The parameter y will be negative for particles of opposite (bipolar) charge, and the effect is to increase the collision rate over the rate given by Eq (2.5).

It is not known to what extent if any heavy metal particles formed in incinerators are charged, and if so, whether particles carry like or unlike charges. Friedlander points out that for weak bipolar charging, the effect of the charge on the collision correction factor is to more or less cancel out. However for strong bipolar aerosols ($|y| \gg 1$), this compensation does not take place (Friedlander, 1977). Should heavy metal particles in incineration gas streams be similarly charged, the effect is that their collision frequency is reduced, the extent of which is a function of the magnitude of the charge product.

2.3.2 Coagulation by Laminar Shear

Particles dispersed in a fluid undergoing shear collide because of their relative motion. In practice, shear fields can be complex, ranging in difficulty from those encountered in three-dimensional laminar motion to those produced by turbulent motion. The simplest known model for the effect of shear on particle collision is that of a rectilinear laminar shear, characterized by a single velocity gradient, du/dx . Friedlander (1977, ch 7) shows that the collision frequency function for coagulation in such a shear field is:

$$\beta(v_i, v_j) = \frac{4}{3}(a_i + a_j)^3 \frac{du}{dx} \quad (2.9)$$

The dynamic equation, based on this result for the case of a mono-disperse aerosol ($a_i = a_j = a$) becomes:

$$\frac{dN_\infty}{dt} = -\frac{16}{3} \frac{du}{dx} a^3 N_\infty^2 \quad (2.10)$$

Assuming that the total volume of the aerosol particles is constant (no losses from the system),

$$\frac{4}{3} \pi a^3 N_\infty = V = \text{const} \quad (2.11)$$

and integrating from the initial condition of $N_\infty = N_\infty(0)$, the equation for the stationary state decay rate in the particle numbers becomes:

$$\ln\left(\frac{N_\infty(0)}{N_\infty}\right) = \frac{4V}{\pi} \frac{du}{dx} t \quad (2.12)$$

This result was tested in part against experimental data by Swift and Friedlander (1964), with the experimental data in good agreement with the theory.

2.3.3 Coagulation by Simultaneous Laminar Shear and Brownian Motion

Assuming that collision rates by Brownian motion and by rectilinear laminar shear are independent and additive, the particle dynamic equation becomes (Friedlander, 1977, ch 7):

$$\frac{dN_\infty}{dt} = -\frac{4\alpha_0}{3} \frac{kT}{\mu} N_\infty^2 - \frac{4G\alpha_1 V}{\pi} N_\infty \quad (2.13)$$

where $G = du/dx$, α_0 is an empirical collision efficiency for Brownian motion, and α_1 is the collision efficiency for laminar shear. Assuming $\alpha_0 = \alpha_1 = \alpha$, the integrated result is:

$$\ln \left[\left(\frac{N_{\infty} + R}{N_{\infty}} \right) \left(\frac{N_{\infty}(0)}{N_{\infty}(0) + R} \right) \right] = \frac{4\alpha G V t}{\pi} \quad (2.14)$$

where $R = 3GV\mu/(\pi kT)$. Note that Eq (2.14) reduces to Eq (2.12) at high shear rates.

Swift and Friedlander (1964) tested Eqs (2.12) and (2.14) against experimental data obtained for a mono-disperse population ($a = 0.871 \mu\text{m}$) of polystyrene latex particles suspended in water. The data correlated remarkably well with this simple theory and further showed that $\alpha = 0.375$ for this system under the experimental conditions and that $\alpha_1 = 0.364$, consistent within experimental error with the assumption that $\alpha_1 = \alpha$.

It is not known whether or not the theory as outlined above has ever been tested in complex, reactive gas streams at incineration temperatures.

2.3.4 Particle Growth by Condensation from the Gas Phase

Gas-to-particle conversion mechanisms include homogeneous nucleation and heterogeneous condensation (Friedlander, 1977, ch 9). Both chemical and physical processes may play a role in each of these mechanisms. A review of the role of chemical processes is not provided here because these processes are not likely to be significant under the condensation conditions of the experimental work, where attempts will be made to condense lead dichloride vapor on silica particles introduced up stream of the source of the PbCl_2 vapor.

Physical processes involved in homogeneous nucleation are those that produce supersaturation, such as cooling by expansion or thermal conduction or radiation. Mixing can also be a factor. Heterogeneous condensation is the process of condensation of vapor on nuclei or particles already present in the system. The physical process, in the absence

of surface or particulate-phase chemical reactions, is transport limited. Classical diffusion controls when the particle sizes, a_p , are much larger than the mean free path of the gas molecules, $a_p \gg \lambda$, and molecular bombardment of the particles control when $a_p \ll \lambda$.

Homogeneous Nucleation. The kinetic equation for the continuous particle size distribution function $n(g)$ may be written according to Friedlander (1977, ch 9) as:

$$\frac{\partial n}{\partial t} = - \frac{\partial I}{\partial g} \quad (2.15)$$

where $n(g)$ is the number density of the particles (clusters) of size g and I is the so-called droplet, or particle, current in c.g.s. units of particles/(cm³ sec). An approximate solution of Eq (2.15) has been obtained by use of the following assumptions:

1. The non-equilibrium size distribution function approaches the equilibrium distribution, n_e , as $g \rightarrow$ small,

$$\frac{n}{n_e} \rightarrow 1 \text{ as } g \rightarrow 0$$

2. For very large values of g , $n/n_e \rightarrow 0$, which implies that the nuclei concentration for the non-equilibrium distribution is much smaller than that for the equilibrium distribution.
3. The droplet current $I(g)$ is independent of the droplet size, which implies that a quasi-steady state exists such that as many nuclei enter a size range as leave.

The solution of Eq (2.15) for the particle current consistent with these assumptions may be written according to Friedlander as:

$$I = 2 \left[\frac{p_i}{(2\pi mkT)^{1/2}} \right] \left(n_1 v_m^{2/3} \right) \left(\frac{\sigma v_m^{2/3}}{kT} \right)^{1/2} \exp \left[-\frac{16\pi\sigma^3 v_m^2}{3(kT)^3 (\ln S)^2} \right] \quad (2.16)$$

where p_i is the partial pressure of the condensing vapor far from the droplet, n_1 is the nuclei density, v_m is the molar volume of the vapor molecules, and S is the vapor saturation ratio, defined as p_i/p_s , where p_s is the vapor pressure at the surface of the droplet.

Careful experiments performed in cloud chambers have confirmed this simple theory for the case of selected organic vapors, such as toluene, over the temperature range of about 230 - 320°K. The data for condensing water vapor is in poorer agreement with the theory. In all cases, care must be taken to remove nuclei from the cloud chamber that are generated by cosmic rays which pass through the apparatus.

The area that is least developed is that of the nucleation process itself. One reason that the nucleation process is relatively undeveloped is that experimental methods have not been developed which are capable of following the development of molecular clusters in the size range of the order of 100 Angstroms ($10^{-2} \mu m$) or less.

Heterogeneous Condensation. This process occurs when both the supersaturation is low and also large concentrations of particles are present. Under these conditions and neglecting chemical reaction, the growth law in terms of the particle volume, v , may be written as:

$$\frac{dv}{dt} = m_v F \quad (2.17)$$

where F , the molecule flow rate to the particle, depends on the driving force ($p_1 - p_d$) and the form of the transport law, and m_v is the molecular volume.

For the case of $a_p \gg \lambda$ (continuum behavior), the transport law is obtained by solving Fick's second law in spherical coordinates,

$$\frac{\partial n}{\partial t} = \frac{D}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial n}{\partial r} \right) \quad (2.18)$$

and using the result to form the equation for the molecule flow rate:

$$F = \pi d_p^2 D \left. \frac{\partial n}{\partial r} \right|_{r=\frac{d_p}{2}} = \frac{2\pi d_p D (p_1 - p_d)}{kT} \quad (2.19)$$

For Knudsen transport ($a_p \ll \lambda$), the transport law can be gotten from kinetic theory, with the result:

$$F = \frac{\alpha(p_1 - p_d) \pi d_p^2}{(2\pi m k T)^{1/2}} \quad (2.20)$$

An equation for interpolation between these limits is given by Fuchs and Sutugin (1971).

If the droplets are sufficiently small that the Kelvin effect is important, the partial pressure driving force is of the form:

$$p_1 - p_d = p_1 - p_s \exp\left(\frac{d_p^* \ln S}{d_p}\right) \quad (2.21)$$

A relatively simple equation may be derived for the growth in time of droplets in the Knudsen size range by neglecting the Kelvin effect. Using $v = \pi d_p^3/6$, and combining Eqs (2.17) and (2.20) and integrating, the result as given by Friedlander (1977, ch 9) is:

$$d_p = d_{p0} + \int_0^t \frac{2v_m (p_1 - p_s)}{(2\pi m k T)^{1/2}} dt' \quad (2.22)$$

Note in this result that none of the quantities on the right hand side is a function of droplet size. As a consequence, all the droplets will develop to about the same size as they grow, independent of the nuclei size distribution, so long as $d_p \gg d_{p0}$ and all droplets experience the same temperature and driving force ($p_1 - p_s$). These conditions can be expected to produce a mono-disperse distribution (Friedlander, 1977).

In summary, the literature contains a substantial body of theoretical results for aerosol growth by gas-to-particle conversion. The theory has been tested against results obtained in cloud chambers in some cases. It is not known that the theory has been tested under conditions approaching those encountered in incinerators, and as discussed in the next section, data suitable for test of the theory at high temperatures does not appear to be available.

2.4 Fumes and Particles in Hot Gas Streams

Particles formed in gas streams in incinerators may be classified as those which are principally carbonaceous in content such as "soot" and those which are principally inorganic such as metal oxides and chlorides. Carbonaceous particles may contain inorganic occlusions.

Soot formation in flames is a very complex phenomenon, depending on fuel type and state of aggregation (e.g., pulverized coal, fuel oil, natural gas), air-to-fuel ratio, temperature, heat transfer, and ion formation and loss from the system, among other things. While there may be commonalities in the processes of soot and inorganic particle nucleation and growth, it is thought that soot formation is sufficiently different from that

of metal oxide or chloride formation that attention here can be focused on the literature reporting on inorganic particle formation and growth alone. For a model and discussion on the mechanism of carbon formation in flames, refer to Howard (1969), for example.

2.4.1 Fumes Produced in Flames

Most of the work in this area has been devoted to investigating and describing the fine particles produced during the combustion of coal, and to a lesser extent, incineration of wastes. A limited number of studies have been made on fumes produced in bench-scale laboratory flames.

The early work was focused on particulate matter found in the flue gases of coal-fired utility boilers. Both Flagon and Friedlander (1971) and also Damle et al. (1982), on reviewing this work, concluded that condensation of vaporized species is the probable mechanism for the formation of the sub-micron particles. Davison et al. (1974) and Gladney et al. (1976) report that the sub-micron particles formed during coal combustion are preferentially enriched in volatile metal species such as antimony, lead, cadmium, silver, copper, and zinc. Vogg (1986) reported enrichment factors of 20 for Pb, 60 for Sb, 100 for Cd, and 600 for Hg in emission from municipal waste incinerators. Toxic metals (e.g., Sb, As, Cu, Pb, Ag, Zn) are concentrated on sub-micron particles. These results raise the question of to what extent the volatile species may be condensing on heterogeneous nuclei.

Fume formation in laboratory scale, tubular furnaces, produced by burning pulverized coal, has been studied by Neville et al. (1981), Neville and Sarofim (1982), and Quann and Sarofim (1982). Neville et al. found that the temperatures of burning coal

particles are much higher than the surrounding gas temperature and that the quantity of submicron fume generated correlated with the burning particle temperature. It was hypothesized that submicron inorganic matter within the coal particles is reduced to elemental metals which have relatively high vapor pressures, and that these metal vapors later oxidize and condense, forming the fume. Quann and Sarofim as well as Neville and Sarofim developed models based on these and other observations which provide results at least in qualitative agreement with experimental findings.

Lin et al. (1992) studied the kinetics of the formation of lead oxide fume in a bench scale premixed methane-air flame, with peak temperatures in the range of 900-1300°C. The lead was introduced to the flame in the form of a lead acetate aerosol, along with the air-fuel mixture. The aerosol was produced by atomizing a solution of lead acetate in water, and drying the droplets prior to their introduction to the burner. Particles were removed from selected axial positions in the flame by use of a suitable probe and analyzed, after dilution, by use of a Model 3030 TSI analyzer. Data interpretation was in terms of a model based on the assumption that the lead acetate aerosol decomposes quickly to yield lead in gaseous form which subsequently reacts reversibly with oxygen to form gaseous lead oxide, PbO(g), according to the global stoichiometric equation:



Both Pb(g) and PbO(g) are assumed to nucleate and condense according to classical theory as summarized by Friedlander (1977). Lin et al. further assumed Eq (2.23) is elementary, so that the rate law can be written as:

$$r = -2k_f[\text{Pb}]^2[\text{O}_2] + 2k_r[\text{PbO}]^2 \quad (2.24)$$

The rate coefficients k_f and k_r in Eq (2.24) are not known, so Lin et al. used estimated values and investigated the sensitivity of their model results to these parameters. Rough agreement with the experimental data was achieved, in spite of the many assumptions involved.

2.4.2 Sorption of Metal Fumes from Hot Gas Streams

The sorption of heavy metal fumes from hot gas streams appears to date from 1972, when Cantwell, et al. (1972) reported that particulate lead emissions from automobile exhaust gas could be reduced by the use of alumina pellets.

More recently, Uberoi and Shadman (1990) demonstrated that lead chloride vapor is absorbed in hot beds (700°C) of pellets (60-80 mesh) of each of the following materials: silica, alumina, kaolinite, bauxite, emathlite, and lime. Kaolinite and emathlite are natural alumino-silicate clays. Kaolinite and bauxite were found to be the most effective at removing the lead chloride vapor from the hot simulated flue gas stream, with up to 80% removed. Silica, alumina and emathlite were intermediate in effectiveness, with removal efficiencies in the range of 50 to 60%, while lime was least efficient, with an efficiency of 20%. Details of the experiment, such as bed depth and mean residence time of the gas in the bed, were not provided.

Srinivasachar et al. (1992) working at PSI Technology Company also used a fixed bed of sorbent to chemically capture lead chloride vapor, produced in a hot gas stream by the reaction of HCl, in concentrations of 400 or 1000 ppm, with lead shot. Their sorbent was also shown to successfully trap vapor phase species of arsenic oxide, zinc chloride, and cadmium chloride. Detail of their fixed bed and sorbent were not reported; the

sorbent is presumed to be proprietary. The removal efficiency for the lead chloride varied from 65 to 100% and depended on bed temperature and the HCl concentration in the inlet gas stream. They attempted to capture lead chloride at two temperatures, 725 and 940°C, with 400 ppm HCl in the gas. The highest capture efficiency (100%) occurred at a bed temperature of 725°C and the efficiency drops to 65% at the higher temperature (940°C). The capture efficiency of CdCl_2 , As_2O_3 , and ZnCl_2 ranged from 88 to 91%.

Ho et al. (1992) studied the extent to which lead chloride could be captured on selected sorbents in a laboratory scale fluid bed during incineration of synthetic "waste" (wood pellets contaminated with lead chloride), in the temperature range of 400°C to 950°C. The bed consisted of sand, or sand with limestone or aluminum oxide particles, which served as both the fluidized particles and the capture agents, although most of the work was performed with sand alone. The percent of the lead captured by sand was strongly dependent on the bed temperature, with the maximum of about 70% occurring in the temperature range of about 600 - 700°C. The capture falls off sharply both below and above this temperature range. They suspected that the low efficiency at the higher temperatures was due to the excessive volatilization of metals while the incomplete combustion of wood decreased the efficiency at lower temperatures. They also suggested that there is an optimum incinerator temperature for the capturing of metal vapor. Capture efficiencies of as high as 90% were achieved in some cases. This work shows that lead chloride vapor can condense in appreciable quantities under the right conditions (e.g. temperature, residence time, contacting method) on certain sorbents.

Chapter 3 Experimental Method

The limited amount of data in the literature suggest that some metal oxide vapors are capable of heterogeneous condensation from hot gas streams on fine particulate matter. Also certain metal chloride vapors can be removed on some sorbents. It has not been demonstrated so far as known that metal chloride vapors can be removed from hot gas streams by heterogeneous condensation. An experiment has been designed to determine the extent to which one metal chloride, lead dichloride, can be condensed on silica particles in a hot gas stream by heterogeneous condensation and/or agglomeration in the temperature range of about 350 - 650°C.

Fine particles of silica, formed as a product of the combustion of hexamethyldisiloxane (HMDS) vapor in air, have been chosen as potential condensation sites for the lead dichloride vapor in the hot gas stream. The organic form of silicon is chosen as a means of introducing this metal to the hot zone of the furnace because it is liquid under ambient conditions and possesses sufficient vapor pressure so that it can volatilize into a carrier stream of nitrogen which sweeps the vapor into the furnace.

3.1 Description of the Overall Process

A flow sheet for the experimental process is provided as Figure 3.1. The description of the overall process will in general proceed in the direction of gas flow as indicated by the arrows on the schematic flow diagram.

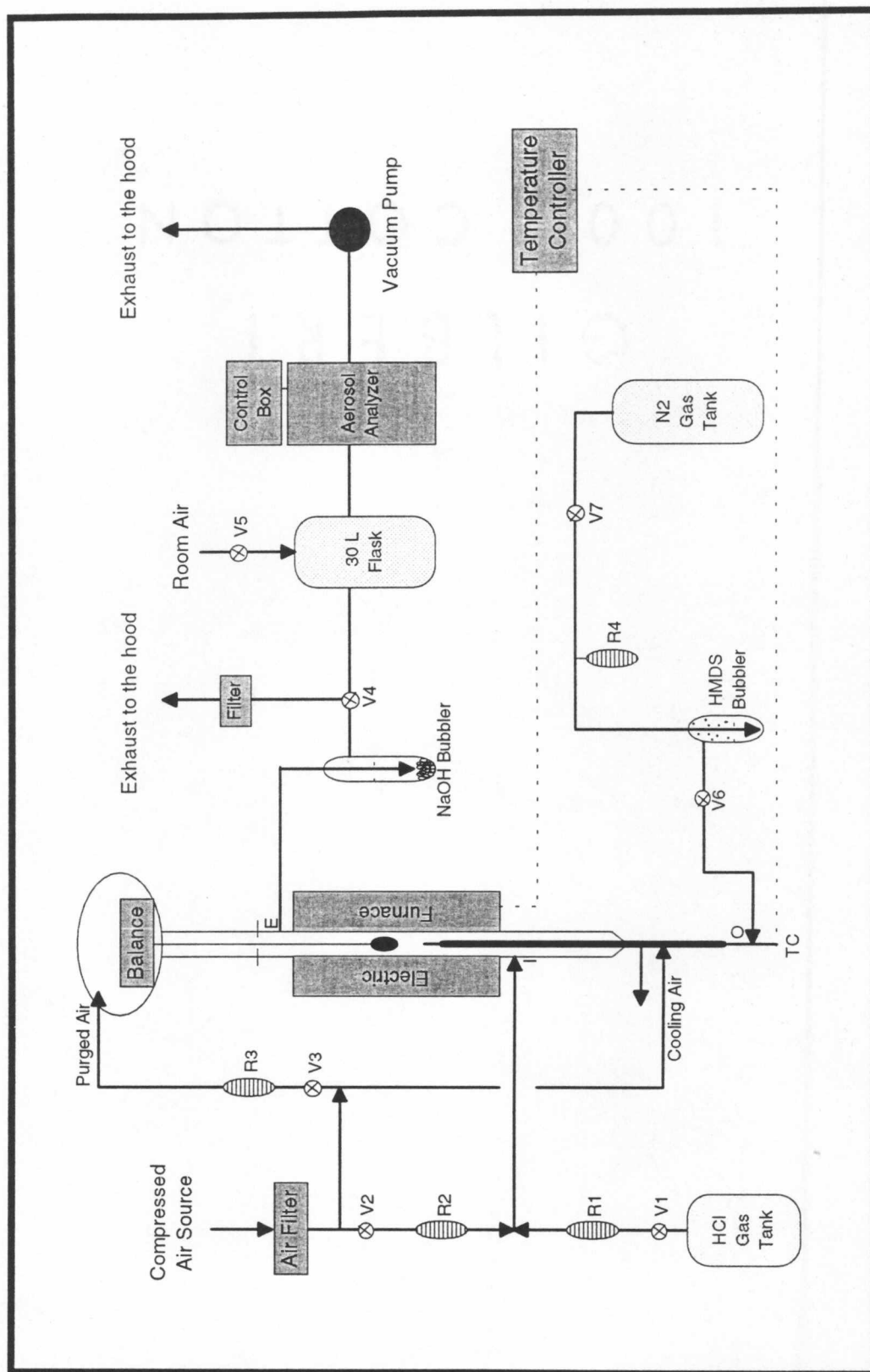


Figure 3.1 Schematic Flow Diagram of the Particle Analyzing Experiment.

3.1.1 Air Stream

Clean air is needed in this experiment to provide a source of oxygen for the combustion of the HMDS vapor, to dilute the reactive HCl gas, to purge the balance chamber, and to serve as cooling air for the HMDS vapor. It was obtained by passing the compressed building air through an air filter. The valve V2 was adjusted to give a rotameter reading of 60 on R2, which corresponds to about 786 ml/min, in order to let air flow continuously into the system. This air provided a source of oxygen for the combustion of HMDS vapor and was essential for the dilution of HCl gas that was to be reacted with the PbO pellet.

The purge gas is set at a flow rate of about 2 l/min (rotameter reading of 50 on R3) and flowed at all times through the balance chamber. The design of the balance chamber can be found in Shor (1994). The purpose of the purge air is to prevent the reactive gas from reaching the balance chamber and corroding the balance. Also, some of the air is diverted into an air cooled probe described later in Section 3.1.3. The cooling air is necessary in order to prevent the decomposition of the HMDS vapor before it reaches the tip of the air cooled probe.

Besides that, room air is used to dilute the particles collected in the 30 liter glass storage reservoir and to ensure sufficient aerosol flow to the Electrical Aerosol Analyzer provided by the calibration sheet. The introduction of room air was controlled by the valve V5 on Figure 3.1.

3.1.2 Production of Lead Dichloride

A mixture of gaseous HCl and air is introduced to the reaction section of the furnace through the opening at point "T" by adjusting the valve V1. Meanwhile, the flow rate of HCl is read from the rotameter R1. At the rotameter reading of 30, air containing about 2000 ppm HCl is introduced to the reaction tube where the acid gas contacted a lead oxide pellet suspended by a fine platinum wire from a balance located above the furnace. This flow rate of HCl was chosen based on the experience of Shor (1994). The HCl reacts with the pellet, producing lead dichloride, which is relatively volatile at about 400°C and above.

3.1.3 Combustion of Hexamethyldisiloxane (HMDS)

The HMDS vapor is introduced to the air stream just upstream of the lead oxide pellet through an air cooled quartz probe, 19 inches long and 18 mm in diameter, specially designed for this purpose. This is accomplished by opening the valve V6 and adjusting the valve V7 at the nitrogen tank that causes the nitrogen to bubble through the liquid HMDS compound and carries with it some HMDS vapor. The vapor in nitrogen passed through the air cooled probe to the point of combustion while being air cooled. The details of the probe are provided in Figure 3.2 and show how it was designed to keep the HMDS vapor relatively cool before it reaches the tip of the tube.

The HMDS vapor is highly combustible in the hot air stream, reacting to form silica oxide which resulted in a fine fume of sub-micron particles. Some of these particles may be converted to the chloride form in the experimental temperature range because of the presence of the hydrogen chloride. Thus, the lead dichloride vapor and the

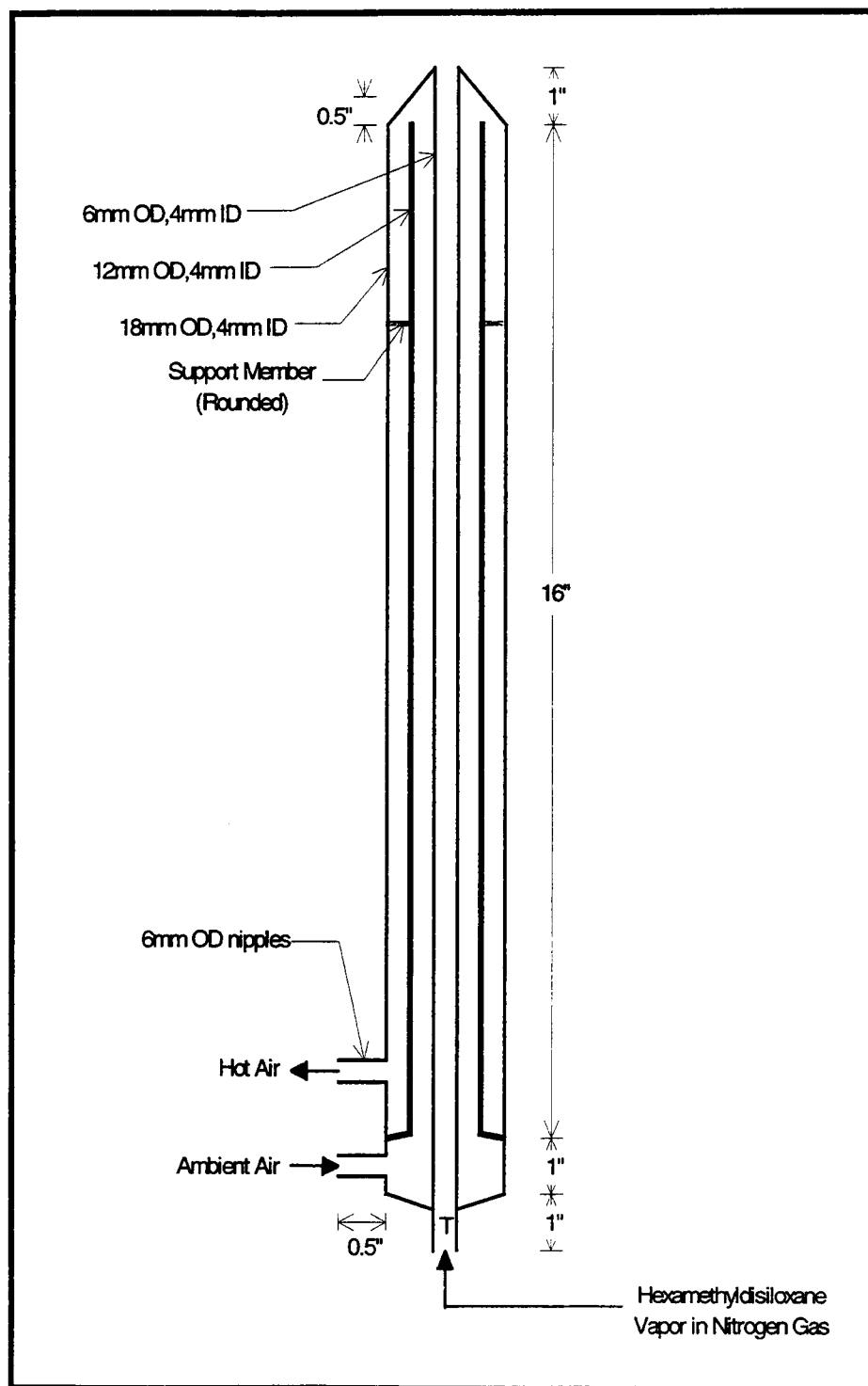


Figure 3.2 Air Cooled Probe Used for the Delivering of the HMDS Vapor to the Point of Combustion.

silica fume mixed in the zone immediately down stream of the lead oxide pellet and the entire mixture cooled as the gas moved toward the exit end of the furnace tube. It was anticipated that lead dichloride vapor would condense in this zone and we expected that more or less of it may condense on the silica fume.

3.1.4 Reaction Section of the Furnace

A vertically mounted high temperature Lindberg Model 54081-A, 800 W electric furnace with a 20-in. heating zone, equipped with a one-inch i.d. quartz tube, serves as the reaction zone of the experiment. The detailed design of the quartz reaction tube can be found in Shor (94). A Type K NiCr versus NiAl thermocouple (not shown in Figure 3.2) was contained in the probe inserted at point TC, with the bead located at the tip of the tube, where the vapor-nitrogen stream mixed with the central air stream. Alumina sleeve spacers were used to prevent the thermocouple wires from crossing (Shor, 94). This thermocouple, along with an Omega model CN310KF temperature controller with self-tuning capability, was used to measure the temperature in the reaction zone of the furnace. Inside this section, a lead oxide sample pellet was hung from a platinum wire connected to the bottom hook of a balance. The distance from the sample pellet to the tip of the air cooled probe and thermocouple was about 3 inches.

3.1.5 Treatment of the Particle-Laden Exit Gas

After the reaction, the particle-laden gas is mixed with the purge gas and exited a side arm of the quartz reaction tube at point "E", Figure 3.1. The exit gas thence passed through a 12-in. glass bubbler that contained 500 ml sodium hydroxide solution to neutralize any residual HCl gas. The 3-way valve V4 diverted the gas either to the

California hood or to the 30 liter glass storage reservoir, where the particle-laden gas was collected for a specified period of time. A 0.1 micron Headline cartridge filter with a stated 99.9% particle collection efficiency at 0.1 micron removed the particles before the gas was exhausted through a fume hood. Particles collected on the filter were saved for elemental analysis.

The purpose of the storage reservoir was to dilute the particles with room air and to ensure that the particles were well-mixed in the gas before being introduced to the electrical aerosol analyzer (EAA). Room air was admitted into the storage reservoir via the valve V5. A vacuum pump was used to pull the gas-particle mixture through the analyzer and to exhaust the waste gas through the hood.

Some of the particles generated in the furnace were deposited on the walls of the tube of the furnace and down stream piping. Additional particles were lost in the acid gas scrubber, but preliminary experiments indicated that a sufficient quantity of particles was collected in the reservoir for size distribution analysis.

3.2 Sample Pellets Production Techniques

Shor (1994) developed the “inert gas technique” that makes possible the reproduction of small lead oxide sample pellets required for the generation of lead dichloride fume. The idea behind this technique was to ease the sample removal from the mold through the slow cooling of the sample pellets in an inert atmosphere. The sintering procedure is described in the following paragraphs.

First of all, approximately 8 grams of the analytical reagent grade lead oxide powder (CAS#1317-36-8) from Mallinckrodt Specialty Chemicals Co. was poured into a Standard Sieve no. 270 with opening of 53 micron (0.0021") by the W. S. Tyler Company. The sieve was fitted to a pan with the same size that had a 6"×6" weighing paper in it. The powder was then crushed into finer PbO particles with a ceramic pestle and collected on the weighing paper. The resultant fine PbO powder was loosely placed in a cylindrical nickel mold, the dimensions of which was shown in Figure 3.3 and can be found in Shor (1994) as well.

Filled with PbO powder, the mold was shaken in order to produce a more compact PbO pellet. After that, a platinum wire, 2.5 cm long and 0.1 mm in diameter, was

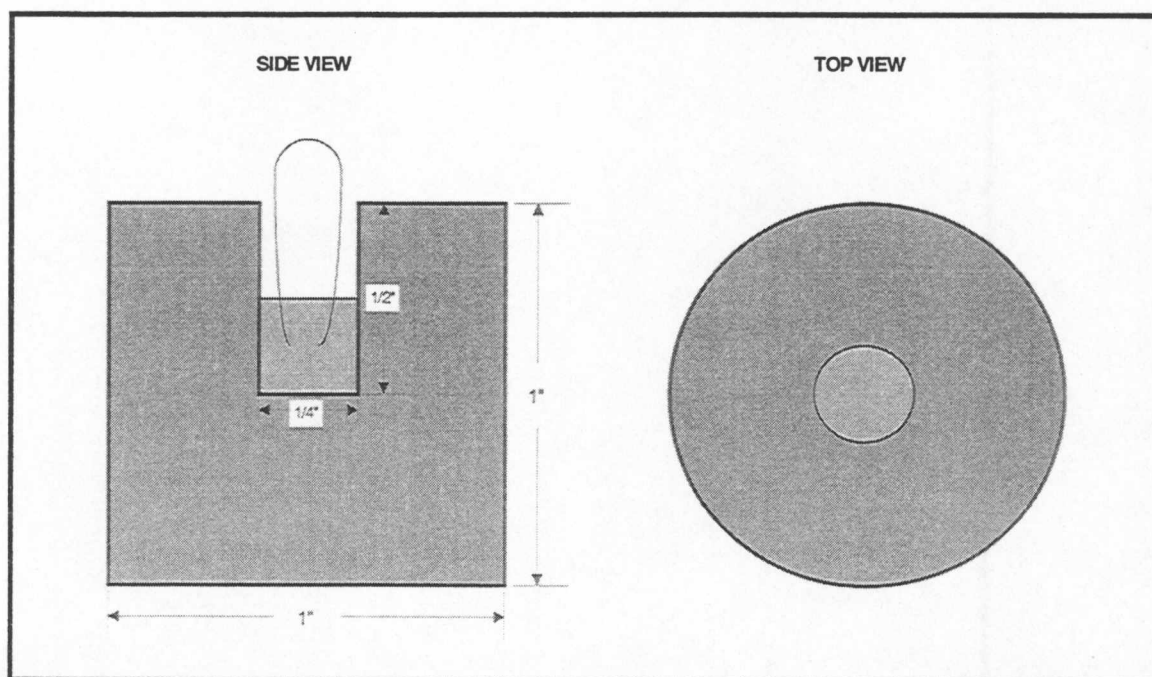


Figure 3.3 Sketch of the Mold Used for Producing the Lead Oxide Sample Pellets.

inserted into the powder. A total of six molds was assembled in a quartz boat that can hold six molds at a time. The assembly was now ready for the thermal treatment.

Figure 3.4 illustrates the sintering of PbO pellets in a tubular furnace fitted with a 3-in quartz tube. The thermal treatment process was started by heating the furnace up to a temperature of 850°C with the help of a temperature controller. Next, the valve located at the argon tank was adjusted to let the argon gas flow through the furnace. The assembly was slid to the middle of the furnace at position A from the open end of the quartz tube. It was heated there for 12 minutes while the open end of the tube was covered with some glassy fiber to reduce heat loss. Then, the assembly was moved to the edge of the furnace at position B to cool the molds down slowly for 24 minutes and removed from the furnace afterward. The resulting PbO pellets removed from the molds were dense and compact with the average heights, measured with a micrometer, of about 5 mm.

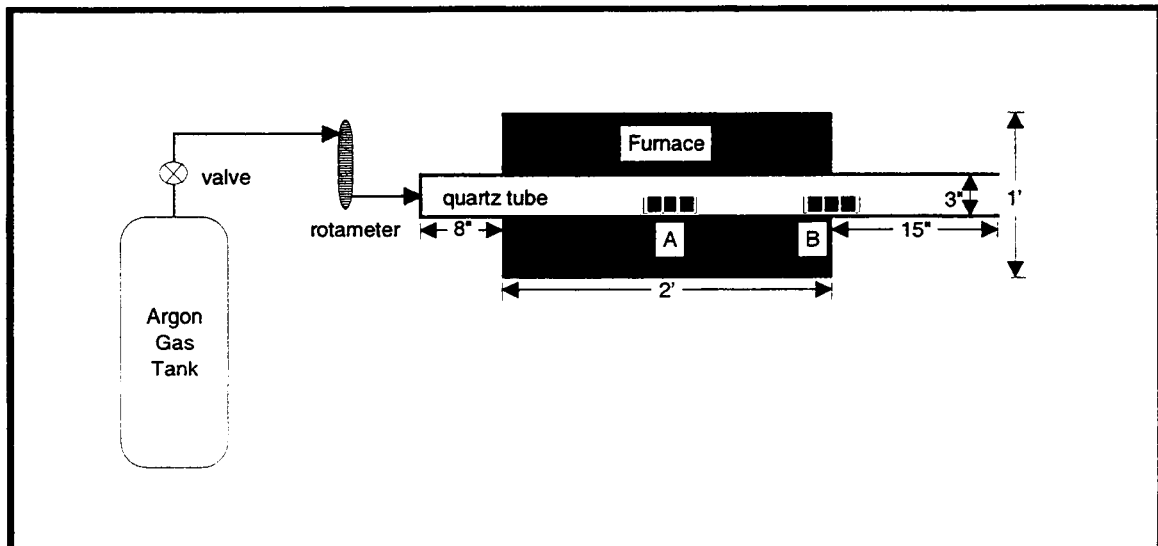


Figure 3.4 Sintering of PbO Sample Pellets with the Inert Gas Technique.

3.3 Description of Electrical Aerosol Analyzer

The aerosol particle size distribution is determined by a Model 3030 electrical aerosol analyzer (EAA) manufactured by TSI Incorporated of St. Paul, Minnesota. This instrument is capable of determining ten size fractions of the total distribution in the range of about 0.01 to 1 micrometer. It samples aerosols at the rate of 4 LPM and requires 1 LPM of charger sheath air. An additional 45 LPM of air is needed for the mobility analyzer, making a total of 50 LPM of air needed for the instrument system. A vacuum pump has been used to pull air through the analyzer and provide a pressure drop across the analyzer that is greater than 45" H₂O.

The total flow, aerosol flow, ionizer current, ionizer voltage, and charger sheath air flow all have a single value and a tolerance that are given on the calibration sheet provided by TSI (see Table 1 in Appendix A). Figure 3.5 shows the schematic flow diagram of the analyzer copied from *The Operating and Service Manual* published by the manufacturer, which is the source of information to this section. The instrument consists of three major parts: the aerosol charger, the particle precipitator, and the electrometer current sensor.

3.3.1 Aerosol Charger

The aerosol is first sampled into the aerosol charger to expose the particles to unipolar ions produced by corona discharge from a fine tungsten wire held at a high potential. The flow of ions through the screen surrounding the corona wire into the charging region creates a corona wind effect that might draw the aerosol into the corona discharge region. Therefore the charger sheath air is used to keep the aerosol away from

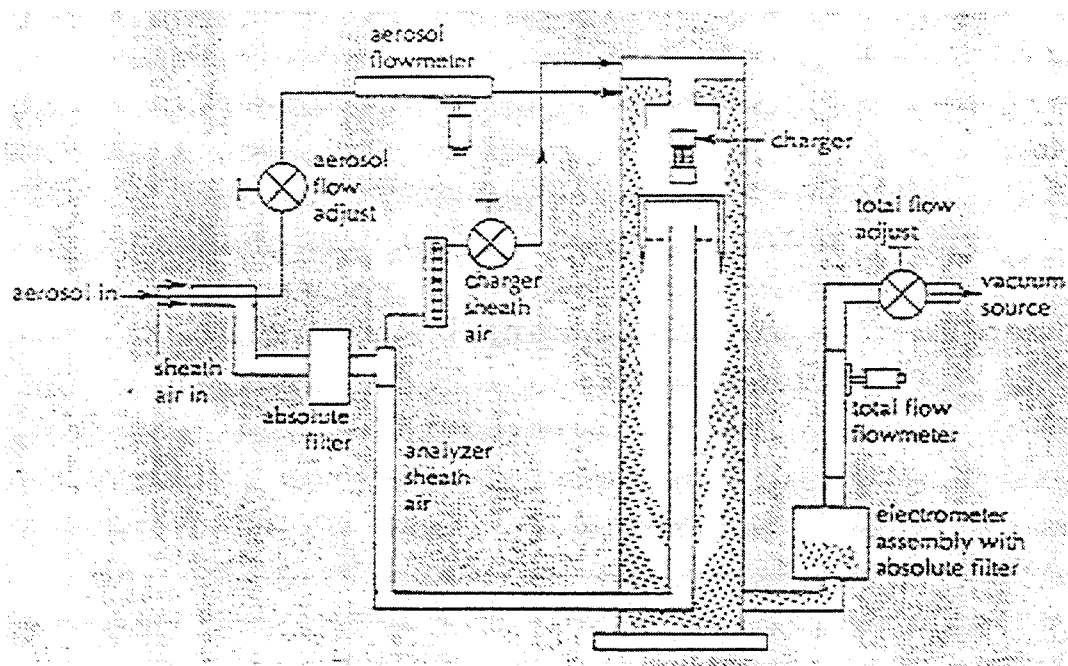


Figure 3.5 Schematic Flow Diagram of the Electrical Aerosol Analyzer (Source: TSI Incorporated).

the high-voltage wire and screen to ensure uniform charging. To insure that the charger is working properly, both ionizer current and ionizer voltage have to be within tolerances. The ionizer current is the ion currents picked up on an insulated metal ring on the outside wall of the charger section and the ionizer voltage is simply the screen voltage.

3.3.2 Particle Precipitator

From the charger, the aerosol is introduced into the precipitator through an annular space where it joins a laminar core flow of filtered air, which serves to improve the resolution of the instrument. The precipitator is in the form of a flow condenser with concentric cylindrical electrodes. In the precipitator, the charged particles are deflected by the electric field toward the collecting rod. Particles with a sufficiently high electrical

mobility are precipitated while those with lower mobilities escape collection and sensitized by the electrometer sensor.

3.3.3 Electrometer Current Sensor

These particles are removed from air stream by an absolute filter. The current flows to the filter carried by the charged particles is measured by an electrometer. The size distribution is determined by varying the voltage on the collecting rod incrementally and measuring the current coming off the filter. The measured current, called the Analyzer Current, is the fundamental variable of interest that depends only on the analyzer voltage and particle concentration of the aerosol being sampled.

3.4 Experimental Procedures

3.4.1 Procedures of Lead Dichloride Production

1. Turn on California hood and check rotameters R2 and R3 for correct air flows.
2. Introduce fresh lead oxide sample pellet into the reaction section of the quartz furnace tube and save the used pellet for elemental analysis.
3. Turn on furnace and heat reaction section up to the desired temperature. Wait for steady state, which may take from 20-75 minutes depending on temperature.
4. Turn on vacuum pump and EAA simultaneously; with valve V5 open, check the analyzer for proper setting, comparing to the values in Table 1.
5. Turn off vacuum pump and EAA simultaneously and close valve V5.

6. Open valve V1 to introduce hydrogen chloride gas into reaction section at rotameter reading of 30, approximately 2000 ppm in air.
7. Wait for 10 minutes for the system to come to steady state and generate sufficient particles for collection.
8. Turn on pump and EAA simultaneously for 3 minutes; with valve V5 closed now, the suction of the vacuum pump generates a vacuum in the 30 L flask.
9. Open 3-way valve V4 to let the air-particles mixture flow into the evacuated 30 L flask for 20 seconds.
10. Turn on vacuum pump and EAA simultaneously in order to pull the sample aerosol through the analyzer and open valve V5.
11. Record the peak analyzer current and the analyzer currents from stage 3 to 11.
12. Pump down the flask for 10 minutes and then turn off pump .
13. Repeat steps 8 to 12 two more times to give a total of 3 runs.
14. Close valve V1 and turn off furnace.
15. Turn off hood just as the temperature of reaction section is cooled down to 150°C, when the lead dichloride vapor is relatively not volatile.
16. After completion of lead dichloride production, change aerosol filter and scratch particles off filter and save for chemical analysis.
17. Change sodium hydroxide solution, wash and dry tubes and storage reservoir.

The system is now free of lead dichloride particles and ready for silica production.

3.4.2 Procedures of Silica Oxide Production

1. Turn on California hood and check rotameters R2 and R3 for correct air flows.
2. Make Sure that the HMDS bubbler is filled with sufficient HMDS solution.
3. Same as steps 3 to 5 in section 3.4.1.
4. Adjust valve V7, then open V6 to let nitrogen gas flow through HMDS solution and carry with it some HMDS vapor into reaction section.
5. Record nitrogen gas rotameter reading on R4 that signifies the amount of HMDS vapor introduce into the reaction section.
6. Same as steps 7 to 13 in section 3.4.1.
7. Close valve V6, and then V7 to stop the nitrogen gas flow.
8. Turn off the furnace and California hood.
9. Same as steps 16 to 17 in section 3.4.1. The system is now free of silica oxide particles and ready for simultaneous lead dichloride and silica oxide production.

3.4.3 Simultaneous Lead Dichloride and Silica Production Procedures

1. Turn on California hood and check rotameters R2 and R3 for correct air flows.
2. Introduce fresh lead oxide sample pellet into the reaction section of the quartz furnace tube and save the used pellet for elemental analysis.
3. Make Sure that the HMDS bubbler is filled with sufficient HMDS solution.
4. Same as steps 3 to 5 in section 3.4.1.
5. Open valve V1 to introduce hydrogen chloride gas into reaction section at rotameter reading of 30, approximately 2000 ppm in air.

6. Same as steps 4 to 5 in section 3.4.2.
7. Same as steps 7 to 13 in section 3.4.1.
8. Close valve V6, and then V7 to stop the nitrogen gas flow.
9. Same as steps 14 to 17 in section 3.4.1.

3.5 Experimental Difficulties

The most significant difficulty in this experiment was the failure to collect sufficient particles on the particle filter. The collection of particles observed during the preliminary experiment was probably due to hundreds of runs leftover from Shor (94). Also the small rotameter R4 did not give consistent readings at lower flow rate of nitrogen. To overcome this problem the number of bubbles that bubbled through the bubbler for 10 seconds was observed and recorded rather than recording the rotameter reading. The rotameter reading on the original data sheet was just an estimation.

Besides, the fine thermocouple wire was broken after wear and tear and has to be joined together by thermal welding. Collecting data without opening valve V5 was a bad idea because it did not give sufficient aerosol flow to satisfy the EAA requirement. Lead oxide was a good solvent (Shor 94) and fused the quartz reaction tube making it impossible to clean the tube with tap water. The vacuum pump could get overheated if not being air cooled by an external fan. The NaOH bubbler could be saturated with particles and giving false readings to the EAA if it was not cleaned after a few runs.

Chapter 4 Results and Discussion

4.1 Data Treatment

This section shows the results of the experimental work. The analyzer current readings have been recorded from the Electrical Aerosol Analyzer, with the procedures described in the previous chapter and the original data presented in Appendix B. These data, after conversion to particle size distribution, characterize the lead dichloride and silica fumes generated in the experiment. Appendix C converts these data to the number of particles with the results of each run summarized in Appendix D.

The presence of room air in the sampling of aerosols makes it necessary to correct the particle size distribution of the above chemical fumes with that of room air. Appendix E shows the particle size distribution of the chemical species before and after the correction with room air. The total number of particles sampled by the electrical aerosol analyzer from the storage reservoir during the two-minute interval at each temperature is summarized in Table 4.1.

Table 4.1 Total Number of Particles Sampled by the Electrical Aerosol Analyzer from the Storage Reservoir during the Two-Minute Interval at 350, 450, 550, and 650°C.

Temperature (°C)	PbCl ₂ Fumes	Silica Fumes	Sum of Both Fumes	Simultaneous Production	Change in Number	Percent Change
350	171,475	159,281	330,756	208,012	-122,744	-37
450	261,876	215,547	477,423	321,450	-155,973	-33
550	380,397	318,744	699,140	466,553	-232,587	-33
650	487,414	337,626	825,039	672,052	-152,987	-19

The following approach has been applied in order to see the effects of the introduction of silica fumes on the size distribution of lead dichloride and the possible agglomeration/condensation of particles. The sum of the size distribution for lead dichloride fumes and silica fumes is computed and compared to the size distribution of the simultaneous production of lead dichloride and silica fumes. The total number of particles for the latter distribution, however, is less than that of the sum (see Table 4.1). To correct for this discrepancy in the comparison, the latter distribution is normalized to the sum by the multiplication of a constant factor that equalizes the total number of particles of both distributions. The change in the number of particles as well as its percent change at each diameter is then computed by subtracting the normalized distribution from the sum. Finally, the particle size distributions for the sum and the normalized simultaneous production are plotted on a semi-log graph.

The results can also be interpreted semi-quantitatively, such as grouping the particles into three different classes: small, medium and large, with particle size ranging from 0.0100 to 0.0562, 0.0562 to 0.1780, and 0.1780 to 1.0000 μm , respectively. The change in the number of particles within each class is then computed by subtracting the normalized simultaneous distribution from the sum of the separate production. The total percent change of particles in each class is the difference between the percent of particles in each class in the sum distribution and that of the normalized distribution. It should be pointed out that the small, medium, and large particles correspond to the first three rows, rows 4 and 5, and the last three rows on pages 45, 48, 51, and 54, respectively. Section 4.2 presents the results qualitatively, quantitatively, and semi-quantitatively.

4.2 General Observations

This section attempts to analyze and discuss the results in three different ways. First, the size distributions between the sum of particles generated from two separate experiments and the simultaneous production of particles are compared graphically or qualitatively. Second, some important changes in the number of particles at their corresponding particle sizes, along with the changes in the total number of particles, are shown qualitatively. Third, the changes in the number of particles are compared in three different size ranges. The following subsections show the effects of the introduction of silica particles on the size distribution of lead dichloride at 350, 450, 550, and 650°C.

4.2.1 Particle Size Distribution at 350°C

Figure 4.1 shows the shift of the size distribution to the right or to the larger particle size qualitatively. The peak of the size distribution for the sum and for the simultaneous production all occurs at about 0.02 μm . The number of particles decreases at the peak and a new peak is developing at about 0.07 μm . Moreover, the number of particles declines below about 0.035 μm and increases above that diameter. Therefore, there is a trend of smaller particles being replaced by larger particles.

Table 4.2 reveals that 42,484 particles, the greatest number of particles lost, diminish at 0.0133 μm . This corresponds to 53 percent fewer particles compared to the sum. Table 4.2 also indicates that 34,742 particles have disappeared at 0.0237 μm , coincides with the decline at the peak observed qualitatively. The new peak observed earlier (Figure 4.1) occurs at 0.0750 μm and receives the greatest increase in particles, which are 41,441. Interestingly, the greatest percent increase, 164 percent, takes place at

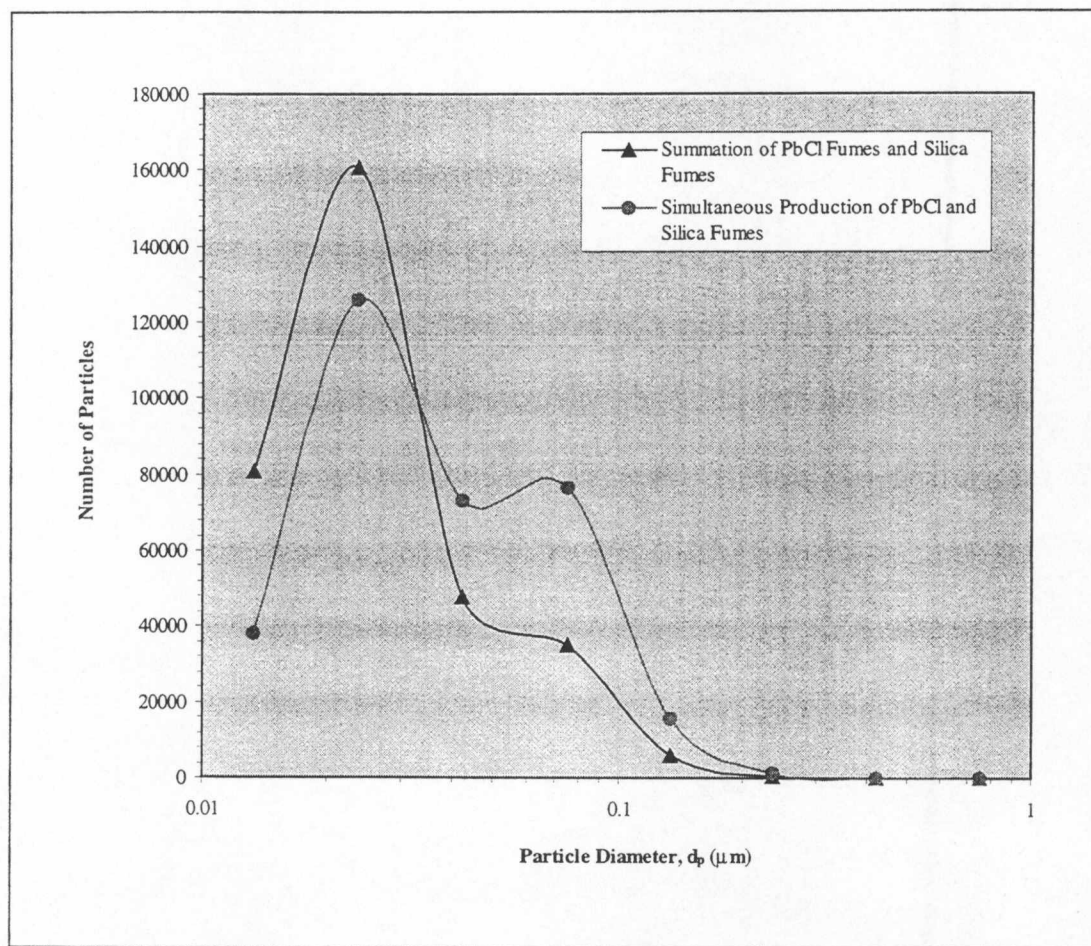


Figure 4.1 Qualitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 350°C .

Table 4.2 Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 350°C .

Mean Particle Diameter d_p (μm)	Sum of PbCl_2 Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Percent Change between Sum and Norm. Sim
0.0133	80574	38089	-42484	-53
0.0237	160728	125986	-34742	-22
0.0422	47889	72996	25107	52
0.0750	34893	76334	41441	119
0.1330	6003	15826	9823	164
0.2370	580	1343	764	132
0.4220	71	154	83	116
0.7500	17	27	9	53
Total # of Particles	330756	330756	0	N/A

0.1330 μm although it does not gain the most number of particles. The same trend happens at the larger particle sizes, signifies that many particles are formed at this size range.

The total number of particles for the sum and simultaneous production are equal to 330,756 and 208,012, respectively (refer to Table 4.1). Thus 122,744 fewer particles, a reduction of 37 percent, have been observed with the method of simultaneous production than with the sum. Apparently, it takes many small particles to form a few large particles.

Now, the shift of particle distribution between the small and medium sized classes in the presence of silica will be analyzed. Table 4.3 shows that 52,120 small particles have disappeared and 51,263 additional medium particles are formed. This corresponds to a decrease of 7.5 percent and an increase of 7.3 percent, respectively in each class. Even though the number of large particles have more than doubled as a result of the introduction of silica particles, the total percent change (0.1%) at this size range is relatively insignificant.

Table 4.3 Semi-Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl₂ and Silica Fumes at 350°C.

Particle Size Classification	Range of Particle Diameter d _p (μm)	Sum of PbCl ₂ Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Total Percent Change (%)	Relative Percent Change (%)
small	0.0100 - 0.0562	289191	237071	-52120	-7.5	-18
medium	0.0562 - 0.1780	40897	92160	51263	7.3	125
large	0.1780 - 1.0000	668	1525	856	0.1	128

4.2.2 Particle Size Distribution at 450°C

Figure 4.2 shows the shift of the size distribution to the larger size. A bimodal distribution has been observed for the sum with the taller peak occurring at about 0.02 μm and the shorter peak at 0.07 μm. The peak at 0.02 μm essentially vanishes for the simultaneous production, and a distinctly new peak emerges around 0.07 μm. The number of particles declines below about 0.04 μm and increases above that diameter.

Table 4.4 indicates that 72,029 particles, the greatest number of particles lost, occurs at 0.0237 μm. This is 45 percent fewer particles compared to the sum and coincides with the decline at the peak observed qualitatively. The new peak observed earlier occurs at 0.0750 μm and receives the greatest increase in particles, which are 47,400. The greatest percent increases take place at 0.4220 and 0.7500 μm.

The total number of particles for the sum and simultaneous production are equal to 477,423 and 321,450, respectively (refer to Table 4.1). Thus 155,973 fewer particles, a reduction of 33 percent, have been observed with the method of simultaneous production than with the sum. Agglomeration of particles might have contributed to this reduction.

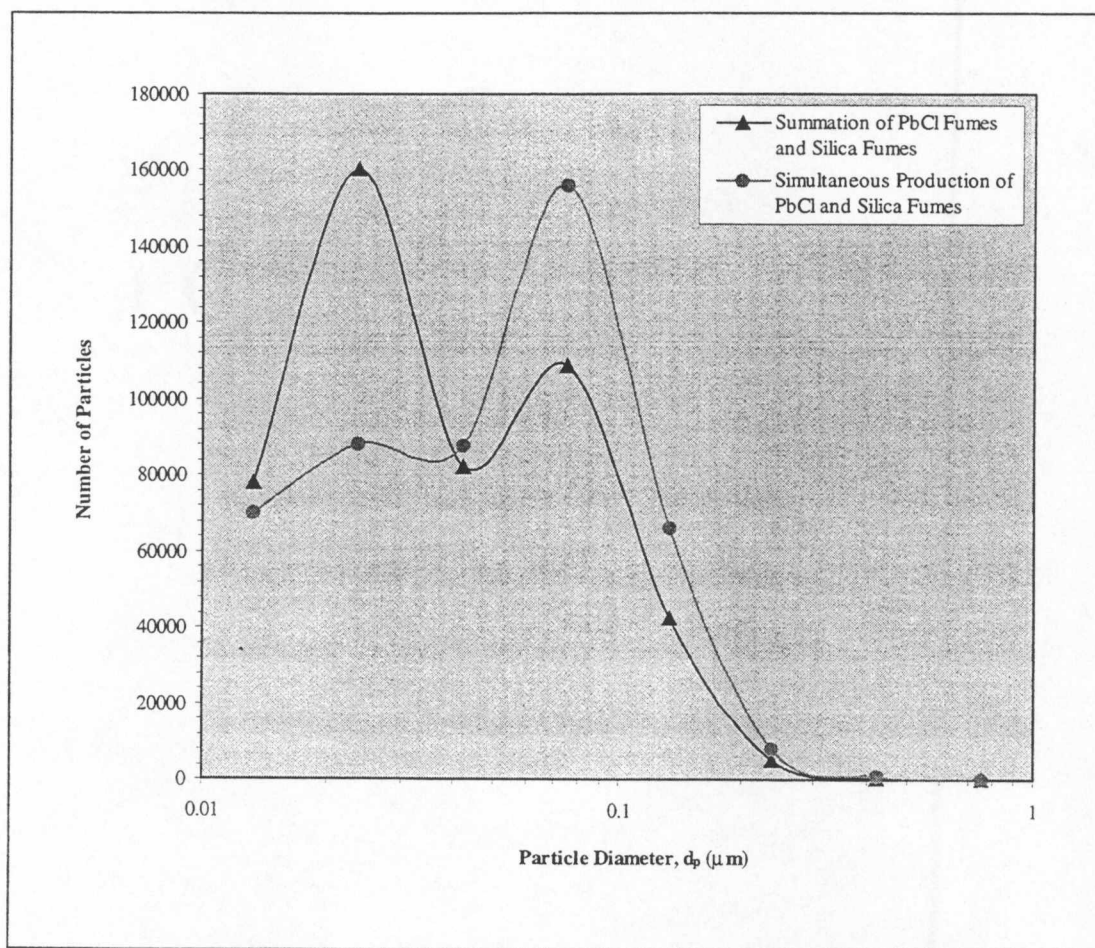


Figure 4.2 Qualitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of $PbCl_2$ and Silica Fumes at $450^\circ C$.

Table 4.4 Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl₂ and Silica Fumes at 450°C.

Mean Particle Diameter d_p (μm)	Sum of PbCl ₂ Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Percent Change between Sum and Norm. Sim
0.0133	78164	70123	-8042	-10
0.0237	160218	88189	-72029	-45
0.0422	82152	87880	5727	7
0.0750	108629	156029	47400	44
0.1330	42538	66059	23521	55
0.2370	5099	8036	2937	58
0.4220	529	941	412	78
0.7500	94	166	72	77
Total # of Particles	477423	477423	0	N/A

Now, the shift of particle distribution between the small and medium sized classes in the presence of silica will be analyzed. Table 4.5 shows that 74,343 small particles have disappeared and 70,921 additional medium particles are formed. This corresponds to a decrease of 10.6 percent and an increase of 10.1 percent, respectively in each class. The small particles lost might have agglomerated to form the medium particles here.

4.2.3 Particle Size Distribution at 550°C

Figure 4.3 shows the shift of the size distribution to the larger size with the number of particles declining below 0.1 μm and increasing above that diameter, except at 0.01 μm . Both the sum and the simultaneous production exhibit a bimodal distribution. The sum has its peaks at 0.02 and 0.07 μm , while the simultaneous production peaks at 0.01 and 0.07 μm . Although the peak at 0.01 μm is not clearly understood, there is a general trend that smaller particles are agglomerating to form larger particles.

Table 4.5 Semi-Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 450°C .

Particle Size Classification	Range of Particle Diameter d_p (μm)	Sum of PbCl_2 Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Total Percent Change (%)	Relative Percent Change (%)
small	0.0100 - 0.0562	320535	246192	-74343	-10.6	-23
medium	0.0562 - 0.1780	151167	222089	70921	10.1	47
large	0.1780 - 1.0000	5721	9143	3422	0.5	60

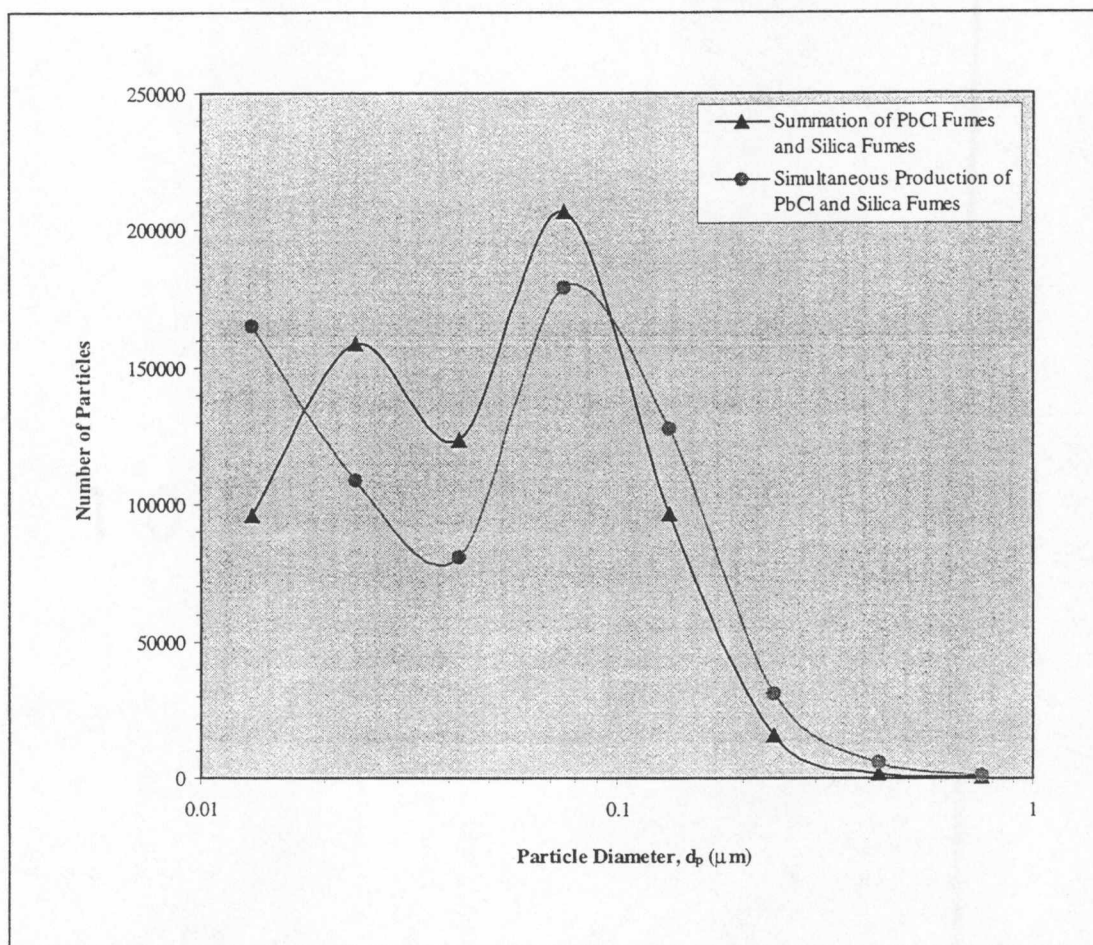


Figure 4.3 Qualitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 550°C .

Table 4.6 indicates that 49,762 particles, the greatest number of particles lost, diminish at 0.0237 μm . This corresponds to 31 percent fewer particles compared to the sum and coincides with the decline at the peak as shown in Figure 4.3. The new peak observed at 0.0133 μm receives the greatest increase in particles, which are 68,781. The greatest percent increase, 230 percent, takes place at 0.7500 μm .

The total number of particles for the sum and simultaneous production are equal to 699,140 and 466,553, respectively (refer to Table 4.1). Thus 232,587 fewer particles, a reduction of 33 percent, have been observed with the method of simultaneous production than with the sum. Again, the addition of silica particles might have caused the agglomeration or condensation of lead dichloride fumes, which depresses the total number of particles in the system.

The shift of particle distribution between the small and large sized classes in the

Table 4.6 Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 550°C.

Mean Particle Diameter d_p (μm)	Sum of PbCl_2 Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Percent Change between Sum and Norm. Sim
0.0133	96188	164969	68781	72
0.0237	158761	108999	-49762	-31
0.0422	123395	80512	-42883	-35
0.0750	206425	179015	-27411	-13
0.1330	96502	127572	31070	32
0.2370	15587	31305	15719	101
0.4220	1922	5580	3658	190
0.7500	361	1189	828	230
Total # of Particles	699140	699140	0	N/A

presence of silica will now be analyzed. Table 4.7 shows that 23,864 small particles have disappeared and 20,204 additional large particles are formed. This corresponds to a decrease of 3.4 percent and an increase of 2.9 percent, respectively, lower than that observed at the two lower temperatures presented previously. The number of large particles have more than doubled as a result of the introduction of silica particles, and unlike what happens at 350°C, the total percent change (2.9%) at this size range is more significant. However, the low total percent change observed, with the high of 3.4 percent, seems to suggest that agglomeration may be negligible at this temperature.

4.2.4 Particle Size Distribution at 650°C

Figure 4.4 shows the shift of the size distribution to the left or to the smaller size, except at 0.01 μm . This is the exact opposite of what was observed at 550°C. A bimodal distribution has been observed for the simultaneous production, most noticeably the peak arises at about 0.02 μm . The shorter period of time, 10 seconds as opposed to 20 (see Table B.3), to collect particles into the storage reservoir might be the cause to this unusual and unexplainable result.

Table 4.7 Semi-Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 550°C.

Particle Size Classification	Range of Particle Diameter d_p (μm)	Sum of PbCl_2 Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Total Percent Change (%)	Relative Percent Change (%)
small	0.0100 - 0.0562	378344	354480	-23864	-3.4	-6
medium	0.0562 - 0.1780	302927	306587	3660	0.5	1
large	0.1780 - 1.0000	17869	38074	20204	2.9	113

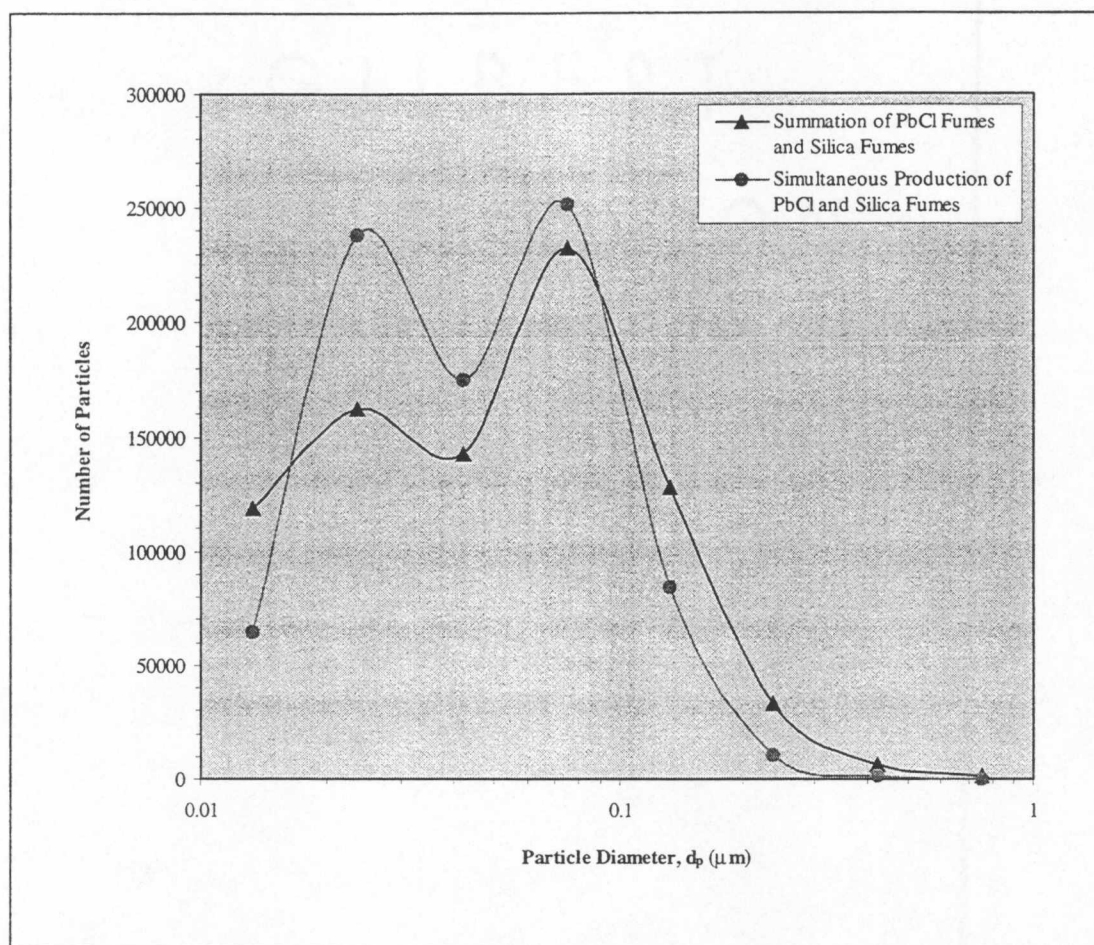


Figure 4.4 Qualitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 650°C .

Table 4.8 indicates that 75,591 new particles, the greatest number of particles gain, are generated at 0.0237 μm . This corresponds to 47 percent more particles compared to the sum and coincides with the sharp increase at the new peak as observed qualitatively. The greatest percent drops, 78 percent, occur at 0.4220 and 0.7500 μm .

The total number of particles for the sum and simultaneous production are equal to 825,039 and 672,052, respectively (refer to Table 4.1). Thus 152,987 fewer particles, a reduction of 19 percent, have been observed with the method of simultaneous production than with the sum. The percent reduction in the number of particles is significantly less than the reductions at the lower temperatures, perhaps due to lack of agglomeration.

The shift of particles distribution among three sized classes in the presence of silica will again be analyzed. Table 4.9 shows that 25,394 medium and 28,074 large particles have disappeared and 53,468 additional small particles are formed, in apparent contrast to the trend in shift exhibited at lower temperatures. However, the total percent change is less significant than that at 350 and 450°C.

Table 4.8 Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl_2 and Silica Fumes at 650°C.

Mean Particle Diameter d_p (μm)	Sum of PbCl_2 Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Percent Change between Sum and Norm. Sim
0.0133	118706	64730	-53976	-45
0.0237	162547	238138	75591	47
0.0422	142738	174590	31852	22
0.0750	232903	251273	18370	8
0.1330	127848	84084	-43764	-34
0.2370	33090	10644	-22446	-68
0.4220	6024	1323	-4701	-78
0.7500	1184	257	-927	-78
Total # of Particles	825039	825039	0	N/A

Table 4.9 Semi-Quantitative Comparison of the Particle Size Distribution between the Sum and the Normalized Simultaneous Production of PbCl₂ and Silica Fumes at 650°C.

Particle Size Classification	Range of Particle Diameter d _p (μm)	Sum of PbCl ₂ Fumes and Silica Fumes	Normalized Simultaneous Production	Change in Number of Particles	Total Percent Change (%)	Relative Percent Change (%)
small	0.0100 - 0.0562	423991	477459	53468	6.5	13
medium	0.0562 - 0.1780	360751	335357	-25394	-3.1	-7
large	0.1780 - 1.0000	40298	12224	-28074	-3.4	-70

Observations of the results have shown that if agglomeration indeed occurs, the distribution should shift to the larger size with less total number of particles. The next section concludes the effects of silica particles on lead dichloride fumes based on the observations discussed in this section.

4.3 Conclusions

An experiment has been conducted with simulated hazardous waste incinerator conditions at temperatures of 350, 450, 550, and 650°C. Data have been collected on particle size distribution of silica fumes, lead dichloride fumes, and simultaneous fume production of both chemicals. The data reveal the important effects of silica particles on the size distribution of lead dichloride fumes:

1. At 350°C, a peak corresponding to larger particle size is developing. Many more large particles are formed as indicated by a 37 percent reduction in total number of particles. Semi-quantitative analysis also indicate the reduction of small particles and the increase of particles in the medium class.

2. At 450°C, a clear shift of the peak from diameter size of 0.0237 μm to that of 0.0750 μm in particle size has been observed. A 33 percent reduction in total particles supports this shift. Furthermore, semi-quantitative analyses seem to suggest that the small particles have agglomerated or grown by condensation to form medium particles.
3. At 550°C, there is a general shift of distribution to the larger particle size except in the size range near 0.0133 μm . Values of percent reduction in total particles resemble that at 450°C. Furthermore, semi-quantitative analysis seem to suggest that some small particles have agglomerated or grown by condensation to form large particles.
4. At 650°C, there appears to be a shift of distribution to the smaller particle size except in the size range near 0.0133 μm , in contrast to the direction of the shift observed at lower temperatures. A peak at the smaller size near 0.0237 μm emerges. A significantly less percent reduction has been observed. This phenomenon is unexplainable at this time.

Thus, there is a general increase in the average particle size of lead dichloride fumes at all temperatures except at 650°C, where it is inconclusive. The semi-quantitative analysis shows that agglomeration of particles is significant at the lower temperatures of 350 and 450°C, with small particles agglomerate to form medium particles. At the higher temperatures of 550 and 650°C, however, the total percent changes are relatively insignificant. Therefore, the results appear to suggest that there is a

temperature dependence of the condensation of lead dichloride fumes on silica particles, similar to those observed in the literature, such as the results observed by Ho et al. (1992).

Therefore, this work has identified possible agglomeration or condensation of lead dichloride fumes on silica particles, as a mechanism of increasing particle size, subject to pilot scale test. This process may result in higher removal efficiency of lead dichloride fumes in scrubbers such as venturi type. However, increased overall efficiency in other types of scrubbers, such as spray towers and ESP, may not be realized unless the particle sizes can be increased substantially above that achieved in this work. This is the first known instance of size increase of a hot heavy metal fume by purposeful introduction of a second fume of small particles which can act as an agglomerating agent or condensation sites.

4.4 Significance to Incineration and Future Work

Although agglomeration/condensation of lead dichloride fumes on silica particles occurs in this lab, practical application remains in question. However, if the trend of particle growth observed here holds true at the actual incineration conditions, it may be possible to remove hazardous fumes from hot gas streams at a much higher efficiency with this method.

There are many improvements which can be made to this experimental process. A larger storage reservoir, such as a huge plastic bag, could reduce particle lost while collecting data and possibly eliminate the need for room air dilution. In addition, a longer reaction or furnace tube would allow longer residence time for agglomeration. It would

be interesting to see the effects of some basic particles, such as zinc oxides, on the lead dichloride fumes.

Finally, the data can be interpreted with different approaches. For instance, the number of particles can be converted to a volume (or mass) basis. Then, the extent of any inconsistency in the data, if any, can be determined by a comparison of the volume (mass) of particles lost from one size range and gained by another. A volume (or mass) balance was not made in this work because only a few data points (8) were measured over the entire size range and because of the relatively large scatter in the data.

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APPENDICES

Appendix A

Calibration Data for the Electrical Aerosol Analyzer (EAA)

Table A.1 Calibration Data for the Electrical Aerosol Analyzer.

Model 3030 Electrical Aerosol Analyzer		
Serial No. 212		
Thermal-Systems Inc.		
Calibration Data*:		
<u>Quantity</u>	<u>Value</u>	<u>Setting</u>
Aerosol Flow	4 L/min.	0.992 ± 0.012 v
Total Flow	50 L/min.	2.215 ± 0.044 v
Charger Sheath Air Flow ⁺	1 L/min.	44 ± 5 div.
Ionizer Current		0.76
Ionizer Voltage		0.69 - 0.70
* Provided by Dean Lowe of TSI, Telephone 612 490 3866 (April 94)		
⁺ Rotameter Setting		

Appendix B

Original Data: Analyzer Current Readings Recorded from EAA

Table B.1 Analyzer Current Readings for Lead Dichloride Fumes Produced from 350 to 650°C.

	Step	Run 1			Run 2			Run 3		
		Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading
		#1	#2	#3	#1	#2	#3	#1	#2	#3
350 °C	3	2.389	2.155	1.833	2.773	2.531	2.169	2.733	2.412	2.055
	4	2.356	2.106	1.795	2.714	2.463	2.123	2.668	2.346	2.012
	5	1.953	1.725	1.499	2.262	2.034	1.781	2.012	1.758	1.513
	6	1.483	1.324	1.154	1.703	1.542	1.341	1.412	1.260	1.098
	7	0.601	0.561	0.516	0.668	0.632	0.563	0.549	0.508	0.471
	8	0.273	0.261	0.248	0.275	0.270	0.258	0.257	0.250	0.237
	9	0.200	0.193	0.190	0.196	0.191	0.192	0.194	0.188	0.187
	10	0.177	0.175	0.174	0.177	0.176	0.174	0.173	0.171	0.172
	11	0.170	0.169	0.165	0.166	0.165	0.163	0.169	0.166	0.165
	Peak	2.47			2.82			2.94		
450 °C	3	5.575	5.060	4.169	6.534	5.924	4.945	6.525	5.373	4.276
	4	N/A	4.910	4.099	6.440	5.758	4.868	6.457	5.303	4.155
	5	N/A	4.718	3.856	6.221	5.435	4.575	6.036	4.856	3.821
	6	N/A	4.292	3.497	5.583	4.883	4.069	5.286	4.185	3.303
	7	N/A	2.505	2.061	2.991	2.622	2.238	2.710	2.209	1.771
	8	N/A	0.733	0.620	0.856	0.777	0.679	0.798	0.662	0.581
	9	N/A	0.297	0.274	0.339	0.325	0.295	0.338	0.308	0.284
	10	N/A	0.218	0.209	0.236	0.232	0.216	0.239	0.229	0.218
	11	N/A	0.195	0.187	0.205	0.196	0.190	0.210	0.197	0.196
	Peak	5.69			6.64			6.68		
550 °C	3	7.833	6.967	5.849	9.110	7.969	6.845	9.306	8.485	7.237
	4	7.795	6.825	5.733	9.066	7.896	6.714	9.189	8.258	7.085
	5	7.242	6.333	5.334	8.543	7.495	6.293	8.829	7.888	6.607
	6	6.338	5.559	4.660	7.499	6.621	5.629	8.086	7.121	6.044
	7	3.242	2.847	2.419	3.947	3.479	2.915	4.421	3.919	3.342
	8	0.919	0.847	0.726	1.093	0.963	0.835	1.163	1.051	0.935
	9	0.366	0.343	0.308	0.388	0.352	0.337	0.410	0.381	0.340
	10	0.252	0.238	0.227	0.259	0.245	0.231	0.257	0.247	0.234
	11	0.205	0.202	0.197	0.211	0.201	0.197	0.211	0.203	0.194
	Peak	8.33			9.50			9.65		
650 °C	3	9.59	8.50	7.19	9.87	8.60	7.20	10.26	9.03	7.65
	4	9.47	8.48	7.10	9.82	8.35	7.03	10.11	8.76	7.37
	5	8.51	7.48	6.32	9.02	7.87	6.53	9.61	8.37	7.02
	6	6.94	6.13	5.21	7.69	6.67	5.43	8.43	7.41	6.25
	7	2.70	2.42	2.13	3.10	2.76	2.43	4.52	3.93	3.37
	8	0.59	0.53	0.48	0.67	0.62	0.55	1.19	1.09	0.94
	9	0.24	0.22	0.22	0.28	0.24	0.23	0.39	0.38	0.34
	10	0.18	0.18	0.17	0.21	0.17	0.18	0.24	0.23	0.20
	11	0.16	0.15	0.15	0.15	0.14	0.14	0.19	0.18	0.17
	Peak	10.15			10.31			10.82		

Table B.2 Analyzer Current Readings for Silica Fumes Produced from 350 to 650 °C.

350 °C	Step	Run 1			Run 2			Run 3		
		Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading
		#1	#2	#3	#1	#2	#3	#1	#2	#3
	3	1.027	0.923	0.800	1.331	1.205	1.068	1.415	1.269	1.097
	4	0.845	0.766	0.684	1.138	1.052	0.943	1.260	1.134	0.993
	5	0.343	0.342	0.325	0.452	0.442	0.420	0.533	0.508	0.474
	6	0.262	0.269	0.262	0.321	0.317	0.310	0.358	0.349	0.333
	7	0.209	0.209	0.210	0.223	0.224	0.223	0.225	0.222	0.221
	8	0.170	0.169	0.171	0.180	0.180	0.180	0.169	0.176	0.173
	9	0.153	0.152	0.149	0.161	0.161	0.161	0.154	0.155	0.157
	10	0.147	0.146	0.144	0.157	0.155	0.154	0.148	0.150	0.145
	11	0.143	0.142	0.144	0.154	0.152	0.152	0.146	0.145	0.142
	Peak	1.11			1.39			1.51		
	*****	No ice blanket is put around HMDS (Hexamethyldisiloxane) bubbler.								
	*****	Rotameter R4 reading = 20.								
450 °C										
	3	2.219	1.984	1.693	2.653	2.367	2.048	3.000	2.473	2.018
	4	2.055	1.837	1.596	2.600	2.306	1.956	2.911	2.429	1.956
	5	1.147	1.057	0.939	1.727	1.554	1.345	2.204	1.837	1.531
	6	0.770	0.714	0.651	1.142	1.036	0.909	1.608	1.359	1.142
	7	0.338	0.324	0.308	0.408	0.387	0.358	0.685	0.597	0.519
	8	0.208	0.206	0.202	0.217	0.211	0.205	0.285	0.266	0.250
	9	0.177	0.173	0.174	0.177	0.173	0.171	0.196	0.185	0.182
	10	0.167	0.167	0.166	0.166	0.164	0.163	0.172	0.167	0.165
	11	0.164	0.164	0.161	0.162	0.159	0.158	0.164	0.158	0.156
	Peak	2.35			2.83			3.23		
		*****	No ice blanket is put around HMDS bubbler.							
	*****	Rotameter R4 reading = ~10 and nitrogen gas bubbles through the HMDS solution at 1 bubble/sec.								
550 °C										
	3	5.675	4.983	4.204	7.174	6.643	5.693	7.231	6.537	5.540
	4	5.485	4.849	4.068	7.132	6.447	5.555	7.206	6.332	5.522
	5	5.096	4.466	3.734	6.282	5.719	4.915	6.581	5.876	5.008
	6	4.579	4.000	3.373	5.281	4.831	4.154	5.819	5.150	4.408
	7	3.331	2.889	2.481	2.888	2.652	2.321	3.440	3.113	2.673
	8	1.460	1.301	1.109	1.201	1.103	0.969	1.347	1.213	1.050
	9	0.565	0.499	0.434	0.480	0.442	0.400	0.541	0.501	0.445
	10	0.318	0.306	0.276	0.283	0.271	0.255	0.316	0.303	0.289
	11	0.238	0.224	0.212	0.226	0.213	0.202	0.240	0.230	0.222
	Peak	6.32			7.41			7.80		
		*****	A blanket of ice is put around HMDS bubbler in order to lower the vapor pressure of HMDS.							
	*****	Rotameter R4 reading = ~10 and nitrogen gas bubbles through the HMDS solution at 1 bubble/sec.								
650 °C										
	3	10.32	9.40	8.17	10.68	9.80	8.30	11.85	10.04	8.25
	4	10.25	9.30	8.01	10.65	9.61	8.27	11.73	9.70	8.08
	5	9.76	8.83	7.45	10.43	9.24	7.93	11.33	9.47	7.80
	6	9.15	8.21	6.99	9.83	8.77	7.50	10.79	9.04	7.44
	7	7.44	6.70	5.71	7.50	6.79	5.82	8.85	7.34	6.17
	8	4.28	3.89	3.35	3.61	3.26	2.80	5.13	4.33	3.63
	9	1.65	1.58	1.38	1.35	1.21	1.07	2.22	1.86	1.52
	10	0.81	0.68	0.59	0.65	0.61	0.51	1.00	0.84	0.67
	11	0.42	0.40	0.38	0.38	0.35	0.30	0.52	0.45	0.40
	Peak	10.98			11.37			12.47		
		*****	A blanket of ice is put around HMDS bubbler in order to lower the vapor pressure of HMDS.							
	*****	Rotameter R4 reading = ~5 and nitrogen gas bubbles through the HMDS solution at .5 bubble/sec.								

Table B.3 Analyzer Current Readings for Simultaneous Production of Lead Dichloride and Silica Fumes from 350 to 650°C.

350 °C	Step	Run 1			Run 2			Run 3		
		Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading	Reading
		#1	#2	#3	#1	#2	#3	#1	#2	#3
	3	3.225	2.929	2.553	3.303	2.911	2.533	3.528	3.216	2.776
	4	3.188	2.850	2.479	3.247	2.900	2.476	3.446	3.122	2.725
	5	2.530	2.269	1.982	2.733	2.437	2.087	2.959	2.662	2.324
	6	1.889	1.697	1.484	2.118	1.883	1.629	2.364	2.132	1.876
	7	0.695	0.650	0.600	0.816	0.743	0.666	0.967	0.903	0.806
	8	0.277	0.264	0.253	0.305	0.293	0.276	0.339	0.320	0.304
	9	0.200	0.195	0.193	0.208	0.207	0.200	0.213	0.214	0.209
	10	0.174	0.178	0.176	0.187	0.182	0.181	0.188	0.189	0.187
	11	0.173	0.171	0.169	0.178	0.177	0.175	0.180	0.176	0.173
	Peak	3.45			3.47			3.63		
450 °C	3	6.274	5.602	4.848	7.135	6.324	5.433	8.030	7.006	6.136
	4	6.187	5.486	4.787	6.998	6.232	5.303	7.831	6.956	5.965
	5	5.643	5.095	4.408	6.763	5.930	5.065	7.297	6.524	5.640
	6	4.905	4.371	3.828	6.045	5.287	4.536	6.445	5.738	4.927
	7	2.533	2.291	2.002	3.294	2.880	2.511	3.266	2.948	2.567
	8	0.776	0.705	0.624	0.965	0.853	0.749	0.912	0.840	0.760
	9	0.336	0.319	0.297	0.381	0.350	0.334	0.366	0.353	0.315
	10	0.238	0.228	0.222	0.254	0.240	0.233	0.247	0.240	0.228
	11	0.212	0.204	0.198	0.206	0.204	0.194	0.206	0.198	0.195
	Peak	6.58			7.59			8.35		
550 °C	3	11.64	9.62	7.76	12.31	10.98	9.58	13.03	11.16	9.13
	4	11.34	9.30	7.67	12.25	10.82	9.28	12.65	10.70	8.80
	5	10.92	8.98	7.31	11.69	10.26	8.76	12.04	10.34	8.41
	6	10.38	8.46	6.87	10.62	9.42	8.03	11.53	9.67	8.01
	7	7.74	6.42	5.20	6.61	6.04	5.25	8.24	6.96	5.82
	8	3.89	3.14	2.63	2.66	2.45	2.14	3.53	3.05	2.50
	9	1.64	1.35	1.13	1.09	0.97	0.81	1.38	1.16	1.00
	10	0.83	0.74	0.59	0.49	0.51	0.45	0.69	0.61	0.53
	11	0.48	0.44	0.39	0.33	0.32	0.30	0.42	0.37	0.33
	Peak	12.30			12.94			13.60 !		
! This is the upper limit of the particle analyzer (the actual value should be a little bit higher).										
650 °C	3	6.213	5.533	4.763	6.613	5.904	5.125	7.143	6.530	5.626
	4	6.164	5.440	4.641	6.539	5.864	5.017	7.102	6.492	5.610
	5	5.322	4.761	4.041	6.075	5.399	4.660	6.436	5.823	5.035
	6	4.331	3.790	3.258	5.292	4.688	4.028	5.494	4.936	4.298
	7	1.869	1.682	1.472	2.577	2.336	2.040	2.608	2.399	2.140
	8	0.614	0.553	0.516	0.806	0.714	0.646	0.816	0.756	0.664
	9	0.297	0.286	0.272	0.354	0.320	0.316	0.348	0.326	0.307
	10	0.225	0.211	0.207	0.246	0.241	0.231	0.246	0.234	0.225
	11	0.196	0.191	0.188	0.205	0.206	0.199	0.206	0.198	0.195
	Peak	6.84			7.14			7.32		
!!! Collect particles in storage reservoir for 10 seconds instead of 20 due to the limit found at 550 C.										

Table B.4 Analyzer Current Readings for the Room Air Introduced into the Glass Storage Reservoir.

<u>Step</u>	<u>Run 1</u>	<u>Run 2</u>	<u>Run 3</u>
3	0.361	0.348	0.374
4	0.358	0.345	0.372
5	0.335	0.325	0.355
6	0.322	0.311	0.328
7	0.266	0.260	0.270
8	0.211	0.208	0.211
9	0.191	0.190	0.191
10	0.183	0.184	0.183
11	0.180	0.181	0.180
Peak	0.39	0.38	0.40

Appendix C

Conversion of Analyzer Currents to the Number of Particles

Table C.1 Conversion of Analyzer Currents to the Number of Particles for Lead Dichloride Fumes Produced at 350°C.

Run 1	d_p(μm)	I			dI			dN			dN
<u>dN/dI</u>	<u>mean</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>mean</u>
		#1	#2	#3	#1	#2	#3	#1	#2	#3	
4.17E+05	0.0133	2.389	2.155	1.833	0.033	0.049	0.038	13761	20433	15846	16680
1.67E+05	0.0237	2.356	2.106	1.795	0.403	0.381	0.296	67301	63627	49432	60120
8.70E+04	0.0422	1.953	1.725	1.499	0.470	0.401	0.345	40890	34887	30015	35264
4.44E+04	0.0750	1.483	1.324	1.154	0.882	0.763	0.638	39161	33877	28327	33788
2.41E+04	0.1330	0.601	0.561	0.516	0.328	0.300	0.268	7905	7230	6459	7198
1.23E+04	0.2370	0.273	0.261	0.248	0.073	0.068	0.058	898	836	713	816
6.67E+03	0.4220	0.200	0.193	0.190	0.023	0.018	0.016	153	120	107	127
3.51E+03	0.7500	0.177	0.175	0.174	0.007	0.006	0.009	25	21	32	26
		0.170	0.169	0.165				170093	161032	130931	154019
Run 2											
4.17E+05	0.0133	2.773	2.531	2.169	0.059	0.068	0.046	24603	28356	19182	24047
1.67E+05	0.0237	2.714	2.463	2.123	0.452	0.429	0.342	75484	71643	57114	68080
8.70E+04	0.0422	2.262	2.034	1.781	0.559	0.492	0.440	48633	42804	38280	43239
4.44E+04	0.0750	1.703	1.542	1.341	1.035	0.910	0.778	45954	40404	34543	40300
2.41E+04	0.1330	0.668	0.632	0.563	0.393	0.362	0.305	9471	8724	7351	8515
1.23E+04	0.2370	0.275	0.270	0.258	0.079	0.079	0.066	972	972	812	918
6.67E+03	0.4220	0.196	0.191	0.192	0.019	0.015	0.018	127	100	120	116
3.51E+03	0.7500	0.177	0.176	0.174	0.011	0.011	0.011	39	39	39	39
		0.166	0.165	0.163				205282	193042	157440	185255
Run 3											
4.17E+05	0.0133	2.733	2.412	2.055	0.065	0.066	0.043	27105	27522	17931	24186
1.67E+05	0.0237	2.668	2.346	2.012	0.656	0.588	0.499	109552	98196	83333	97027
8.70E+04	0.0422	2.012	1.758	1.513	0.600	0.498	0.415	52200	43326	36105	43877
4.44E+04	0.0750	1.412	1.260	1.098	0.863	0.752	0.627	38317	33389	27839	33182
2.41E+04	0.1330	0.549	0.508	0.471	0.292	0.258	0.234	7037	6218	5639	6298
1.23E+04	0.2370	0.257	0.250	0.237	0.063	0.062	0.050	775	763	615	718
6.67E+03	0.4220	0.194	0.188	0.187	0.021	0.017	0.015	140	113	100	118
3.51E+03	0.7500	0.173	0.171	0.172	0.004	0.005	0.007	14	18	25	19
		0.169	0.166	0.165				235140	209544	171587	205424

Table C.2 Conversion of Analyzer Currents to the Number of Particles for Lead Dichloride Fumes Produced at 450°C.

Run 1	d_p(μm)	I			dI			dN			dN
<u>dN/dI</u>	<u>mean</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>mean</u>
		<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	
4.17E+05	0.0133	5.575	5.060	4.169	N/A	0.150	0.070	N/A	62550	29190	45870
1.67E+05	0.0237	N/A	4.910	4.099	N/A	0.192	0.243	N/A	32064	40581	36323
8.70E+04	0.0422	N/A	4.718	3.856	N/A	0.426	0.359	N/A	37062	31233	34148
4.44E+04	0.0750	N/A	4.292	3.497	N/A	1.787	1.436	N/A	79343	63758	71551
2.41E+04	0.1330	N/A	2.505	2.061	N/A	1.772	1.441	N/A	42705	34728	38717
1.23E+04	0.2370	N/A	0.733	0.620	N/A	0.436	0.346	N/A	5363	4256	4809
6.67E+03	0.4220	N/A	0.297	0.274	N/A	0.079	0.065	N/A	527	434	480
3.51E+03	0.7500	N/A	0.218	0.209	N/A	0.023	0.022	N/A	81	77	79
		N/A	0.195	0.187				N/A	259694	204257	231976
Run 2											
4.17E+05	0.0133	6.534	5.924	4.945	0.094	0.166	0.077	39198	69222	32109	46843
1.67E+05	0.0237	6.440	5.758	4.868	0.219	0.323	0.293	36573	53941	48931	46482
8.70E+04	0.0422	6.221	5.435	4.575	0.638	0.552	0.506	55506	48024	44022	49184
4.44E+04	0.0750	5.583	4.883	4.069	2.592	2.261	1.831	115085	100388	81296	98923
2.41E+04	0.1330	2.991	2.622	2.238	2.135	1.845	1.559	51454	44465	37572	44497
1.23E+04	0.2370	0.856	0.777	0.679	0.517	0.452	0.384	6359	5560	4723	5547
6.67E+03	0.4220	0.339	0.325	0.295	0.103	0.093	0.079	687	620	527	611
3.51E+03	0.7500	0.236	0.232	0.216	0.031	0.036	0.026	109	126	91	109
		0.205	0.196	0.190				304970	322346	249272	292196
Run 3											
4.17E+05	0.0133	6.525	5.373	4.276	0.068	0.070	0.121	28356	29190	50457	36001
1.67E+05	0.0237	6.457	5.303	4.155	0.421	0.447	0.334	70307	74649	55778	66911
8.70E+04	0.0422	6.036	4.856	3.821	0.750	0.671	0.518	65250	58377	45066	56231
4.44E+04	0.0750	5.286	4.185	3.303	2.576	1.976	1.532	114374	87734	68021	90043
2.41E+04	0.1330	2.710	2.209	1.771	1.912	1.547	1.190	46079	37283	28679	37347
1.23E+04	0.2370	0.798	0.662	0.581	0.460	0.354	0.297	5658	4354	3653	4555
6.67E+03	0.4220	0.338	0.308	0.284	0.099	0.079	0.066	660	527	440	542
3.51E+03	0.7500	0.239	0.229	0.218	0.029	0.032	0.022	102	112	77	97
		0.210	0.197	0.196				330787	292227	252171	291728

Table C.3 Conversion of Analyzer Currents to the Number of Particles for Lead
Dichloride Fumes Produced at 550°C.

Run 1	d_p(μm)	I			dI			dN			dN
<u>dN/dI</u>	<u>mean</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>mean</u>
		#1	#2	#3	#1	#2	#3	#1	#2	#3	
4.17E+05	0.0133	7.833	6.967	5.849	0.038	0.142	0.116	15846	59214	48372	41144
1.67E+05	0.0237	7.795	6.825	5.733	0.553	0.492	0.399	92351	82164	66633	80383
8.70E+04	0.0422	7.242	6.333	5.334	0.904	0.774	0.674	78648	67338	58638	68208
4.44E+04	0.0750	6.338	5.559	4.660	3.096	2.712	2.241	137462	120413	99500	119125
2.41E+04	0.1330	3.242	2.847	2.419	2.323	2.000	1.693	55984	48200	40801	48329
1.23E+04	0.2370	0.919	0.847	0.726	0.553	0.504	0.418	6802	6199	5141	6048
6.67E+03	0.4220	0.366	0.343	0.308	0.114	0.105	0.081	760	700	540	667
3.51E+03	0.7500	0.252	0.238	0.227	0.047	0.036	0.030	165	126	105	132
		0.205	0.202	0.197				388019	384355	319732	364035
Run 2											
4.17E+05	0.0133	9.110	7.969	6.845	0.044	0.073	0.131	18348	30441	54627	34472
1.67E+05	0.0237	9.066	7.896	6.714	0.523	0.401	0.421	87341	66967	70307	74872
8.70E+04	0.0422	8.543	7.495	6.293	1.044	0.874	0.664	90828	76038	57768	74878
4.44E+04	0.0750	7.499	6.621	5.629	3.552	3.142	2.714	157709	139505	120502	139238
2.41E+04	0.1330	3.947	3.479	2.915	2.854	2.516	2.080	68781	60636	50128	59848
1.23E+04	0.2370	1.093	0.963	0.835	0.705	0.611	0.498	8672	7515	6125	7437
6.67E+03	0.4220	0.388	0.352	0.337	0.129	0.107	0.106	860	714	707	760
3.51E+03	0.7500	0.259	0.245	0.231	0.048	0.044	0.034	168	154	119	147
		0.211	0.201	0.197				432708	381970	360283	391654
Run 3											
4.17E+05	0.0133	9.306	8.485	7.237	0.117	0.227	0.152	48789	94659	63384	68944
1.67E+05	0.0237	9.189	8.258	7.085	0.360	0.370	0.478	60120	61790	79826	67245
8.70E+04	0.0422	8.829	7.888	6.607	0.743	0.767	0.563	64641	66729	48981	60117
4.44E+04	0.0750	8.086	7.121	6.044	3.665	3.202	2.702	162726	142169	119969	141621
2.41E+04	0.1330	4.421	3.919	3.342	3.258	2.868	2.407	78518	69119	58009	68548
1.23E+04	0.2370	1.163	1.051	0.935	0.753	0.670	0.595	9262	8241	7319	8274
6.67E+03	0.4220	0.410	0.381	0.340	0.153	0.134	0.106	1021	894	707	874
3.51E+03	0.7500	0.257	0.247	0.234	0.046	0.044	0.040	161	154	140	152
		0.211	0.203	0.194				425238	443755	378334	415776

Table C.4 Conversion of Analyzer Currents to the Number of Particles for Lead Dichloride Fumes Produced at 650°C.

Run 1	d _p (μm)	I			dI			dN			dN
dN/dI	mean	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	mean
4.17E+05	0.0133	9.59	8.50	7.19	0.12	0.02	0.09	50040	8340	37530	31970
1.67E+05	0.0237	9.47	8.48	7.10	0.96	1.00	0.78	160320	167000	130260	152527
8.70E+04	0.0422	8.51	7.48	6.32	1.57	1.35	1.11	136590	117450	96570	116870
4.44E+04	0.0750	6.94	6.13	5.21	4.24	3.71	3.08	188256	164724	136752	163244
2.41E+04	0.1330	2.70	2.42	2.13	2.11	1.89	1.65	50851	45549	39765	45388
1.23E+04	0.2370	0.59	0.53	0.48	0.35	0.31	0.26	4305	3813	3198	3772
6.67E+03	0.4220	0.24	0.22	0.22	0.06	0.04	0.05	400	267	334	334
3.51E+03	0.7500	0.18	0.18	0.17	0.02	0.03	0.02	70	105	70	82
		0.16	0.15	0.15				590832	507248	444479	514186
Run 2											
4.17E+05	0.0133	9.87	8.60	7.20	0.05	0.25	0.17	20850	104250	70890	65330
1.67E+05	0.0237	9.82	8.35	7.03	0.80	0.48	0.50	133600	80160	83500	99087
8.70E+04	0.0422	9.02	7.87	6.53	1.33	1.20	1.10	115710	104400	95700	105270
4.44E+04	0.0750	7.69	6.67	5.43	4.59	3.91	3.00	203796	173604	133200	170200
2.41E+04	0.1330	3.10	2.76	2.43	2.43	2.14	1.88	58563	51574	45308	51815
1.23E+04	0.2370	0.67	0.62	0.55	0.39	0.38	0.32	4797	4674	3936	4469
6.67E+03	0.4220	0.28	0.24	0.23	0.07	0.07	0.05	467	467	334	422
3.51E+03	0.7500	0.21	0.17	0.18	0.06	0.03	0.04	211	105	140	152
		0.15	0.14	0.14				537994	519234	433008	496745
Run 3											
4.17E+05	0.0133	10.26	9.03	7.65	0.15	0.27	0.28	62550	112590	116760	97300
1.67E+05	0.0237	10.11	8.76	7.37	0.50	0.39	0.35	83500	65130	58450	69027
8.70E+04	0.0422	9.61	8.37	7.02	1.18	0.96	0.77	102660	83520	66990	84390
4.44E+04	0.0750	8.43	7.41	6.25	3.91	3.48	2.88	173604	154512	127872	151996
2.41E+04	0.1330	4.52	3.93	3.37	3.33	2.84	2.43	80253	68444	58563	69087
1.23E+04	0.2370	1.19	1.09	0.94	0.80	0.71	0.60	9840	8733	7380	8651
6.67E+03	0.4220	0.39	0.38	0.34	0.15	0.15	0.14	1001	1001	934	978
3.51E+03	0.7500	0.24	0.23	0.20	0.05	0.05	0.03	176	176	105	152
		0.19	0.18	0.17				513583	494105	437054	481581

Table C.5 Conversion of Analyzer Currents to the Number of Particles for Silica Fumes
Produced at 350°C.

Run 1	d_p(μm)	I			dI			dN			dN
<u>dN/dI</u>	<u>mean</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>mean</u>
		<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	
4.17E+05	0.0133	1.027	0.923	0.800	0.182	0.157	0.116	75894	65469	48372	63245
1.67E+05	0.0237	0.845	0.766	0.684	0.502	0.424	0.359	83834	70808	59953	71532
8.70E+04	0.0422	0.343	0.342	0.325	0.081	0.073	0.063	7047	6351	5481	6293
4.44E+04	0.0750	0.262	0.269	0.262	0.053	0.060	0.052	2353	2664	2309	2442
2.41E+04	0.1330	0.209	0.209	0.210	0.039	0.040	0.039	940	964	940	948
1.23E+04	0.2370	0.170	0.169	0.171	0.017	0.017	0.022	209	209	271	230
6.67E+03	0.4220	0.153	0.152	0.149	0.006	0.006	0.005	40	40	33	38
3.51E+03	0.7500	0.147	0.146	0.144	0.004	0.004	0.000	14	14	0	9
		0.143	0.142	0.144				170331	146519	117359	144736
Run 2											
4.17E+05	0.0133	1.331	1.205	1.068	0.193	0.153	0.125	80481	63801	52125	65469
1.67E+05	0.0237	1.138	1.052	0.943	0.686	0.610	0.523	114562	101870	87341	101258
8.70E+04	0.0422	0.452	0.442	0.420	0.131	0.125	0.110	11397	10875	9570	10614
4.44E+04	0.0750	0.321	0.317	0.310	0.098	0.093	0.087	4351	4129	3863	4114
2.41E+04	0.1330	0.223	0.224	0.223	0.043	0.044	0.043	1036	1060	1036	1044
1.23E+04	0.2370	0.180	0.180	0.180	0.019	0.019	0.019	234	234	234	234
6.67E+03	0.4220	0.161	0.161	0.161	0.004	0.006	0.007	27	40	47	38
3.51E+03	0.7500	0.157	0.155	0.154	0.003	0.003	0.002	11	11	7	9
		0.154	0.152	0.152				212098	182020	154223	182780
Run 3											
4.17E+05	0.0133	1.415	1.269	1.097	0.155	0.135	0.104	64635	56295	43368	54766
1.67E+05	0.0237	1.260	1.134	0.993	0.727	0.626	0.519	121409	104542	86673	104208
8.70E+04	0.0422	0.533	0.508	0.474	0.175	0.159	0.141	15225	13833	12267	13775
4.44E+04	0.0750	0.358	0.349	0.333	0.133	0.127	0.112	5905	5639	4973	5506
2.41E+04	0.1330	0.225	0.222	0.221	0.056	0.046	0.048	1350	1109	1157	1205
1.23E+04	0.2370	0.169	0.176	0.173	0.015	0.021	0.016	185	258	197	213
6.67E+03	0.4220	0.154	0.155	0.157	0.006	0.005	0.012	40	33	80	51
3.51E+03	0.7500	0.148	0.150	0.145	0.002	0.005	0.003	7	18	11	12
		0.146	0.145	0.142				208755	181727	148725	179736

Table C.6 Conversion of Analyzer Currents to the Number of Particles for Silica Fumes

Produced at 450°C.

Run 1	d_p(μm)	I			dI			dN			dN
<u>dN/dI</u>	<u>mean</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>mean</u>
		<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	
4.17E+05	0.0133	2.219	1.984	1.693	0.164	0.147	0.097	68388	61299	40449	56712
1.67E+05	0.0237	2.055	1.837	1.596	0.908	0.780	0.657	151636	130260	109719	130538
8.70E+04	0.0422	1.147	1.057	0.939	0.377	0.343	0.288	32799	29841	25056	29232
4.44E+04	0.0750	0.770	0.714	0.651	0.432	0.390	0.343	19181	17316	15229	17242
2.41E+04	0.1330	0.338	0.324	0.308	0.130	0.118	0.106	3133	2844	2555	2844
1.23E+04	0.2370	0.208	0.206	0.202	0.031	0.033	0.028	381	406	344	377
6.67E+03	0.4220	0.177	0.173	0.174	0.010	0.006	0.008	67	40	53	53
3.51E+03	0.7500	0.167	0.167	0.166	0.003	0.003	0.005	11	11	18	13
		0.164	0.164	0.161				275595	242016	193423	237012
Run 2											
4.17E+05	0.0133	2.653	2.367	2.048	0.053	0.061	0.092	22101	25437	38364	28634
1.67E+05	0.0237	2.600	2.306	1.956	0.873	0.752	0.611	145791	125584	102037	124471
8.70E+04	0.0422	1.727	1.554	1.345	0.585	0.518	0.436	50895	45066	37932	44631
4.44E+04	0.0750	1.142	1.036	0.909	0.734	0.649	0.551	32590	28816	24464	28623
2.41E+04	0.1330	0.408	0.387	0.358	0.191	0.176	0.153	4603	4242	3687	4177
1.23E+04	0.2370	0.217	0.211	0.205	0.040	0.038	0.034	492	467	418	459
6.67E+03	0.4220	0.177	0.173	0.171	0.011	0.009	0.008	73	60	53	62
3.51E+03	0.7500	0.166	0.164	0.163	0.004	0.005	0.005	14	18	18	16
		0.162	0.159	0.158				256559	229689	206974	231074
Run 3											
4.17E+05	0.0133	3.000	2.473	2.018	0.089	0.044	0.062	37113	18348	25854	27105
1.67E+05	0.0237	2.911	2.429	1.956	0.707	0.592	0.425	118069	98864	70975	95969
8.70E+04	0.0422	2.204	1.837	1.531	0.596	0.478	0.389	51852	41586	33843	42427
4.44E+04	0.0750	1.608	1.359	1.142	0.923	0.762	0.623	40981	33833	27661	34158
2.41E+04	0.1330	0.685	0.597	0.519	0.400	0.331	0.269	9640	7977	6483	8033
1.23E+04	0.2370	0.285	0.266	0.250	0.089	0.081	0.068	1095	996	836	976
6.67E+03	0.4220	0.196	0.185	0.182	0.024	0.018	0.017	160	120	113	131
3.51E+03	0.7500	0.172	0.167	0.165	0.008	0.009	0.009	28	32	32	30
		0.164	0.158	0.156				258938	201756	165797	208830

Table C.7 Conversion of Analyzer Currents to the Number of Particles for Silica Fumes

Produced at 550°C.

Run 1	d _p (μm)	I			dI			dN			dN
dN/dI	mean	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	mean
4.17E+05	0.0133	5.675	4.983	4.204	0.190	0.134	0.136	79230	55878	56712	63940
1.67E+05	0.0237	5.485	4.849	4.068	0.389	0.383	0.334	64963	63961	55778	61567
8.70E+04	0.0422	5.096	4.466	3.734	0.517	0.466	0.361	44979	40542	31407	38976
4.44E+04	0.0750	4.579	4.000	3.373	1.248	1.111	0.892	55411	49328	39605	48115
2.41E+04	0.1330	3.331	2.889	2.481	1.871	1.588	1.372	45091	38271	33065	38809
1.23E+04	0.2370	1.460	1.301	1.109	0.895	0.802	0.675	11009	9865	8303	9725
6.67E+03	0.4220	0.565	0.499	0.434	0.247	0.193	0.158	1647	1287	1054	1330
3.51E+03	0.7500	0.318	0.306	0.276	0.080	0.082	0.064	281	288	225	264
		0.238	0.224	0.212				302611	259420	226148	262726
Run 2											
4.17E+05	0.0133	7.174	6.643	5.693	0.042	0.196	0.138	17514	81732	57546	52264
1.67E+05	0.0237	7.132	6.447	5.555	0.850	0.728	0.640	141950	121576	106880	123469
8.70E+04	0.0422	6.282	5.719	4.915	1.001	0.888	0.761	87087	77256	66207	76850
4.44E+04	0.0750	5.281	4.831	4.154	2.393	2.179	1.833	106249	96748	81385	94794
2.41E+04	0.1330	2.888	2.652	2.321	1.687	1.549	1.352	40657	37331	32583	36857
1.23E+04	0.2370	1.201	1.103	0.969	0.721	0.661	0.569	8868	8130	6999	7999
6.67E+03	0.4220	0.480	0.442	0.400	0.197	0.171	0.145	1314	1141	967	1141
3.51E+03	0.7500	0.283	0.271	0.255	0.057	0.058	0.053	200	204	186	197
		0.226	0.213	0.202				403839	424117	352753	393570
Run 3											
4.17E+05	0.0133	7.231	6.537	5.540	0.025	0.205	0.018	10425	85485	7506	34472
1.67E+05	0.0237	7.206	6.332	5.522	0.625	0.456	0.514	104375	76152	85838	88788
8.70E+04	0.0422	6.581	5.876	5.008	0.762	0.726	0.600	66294	63162	52200	60552
4.44E+04	0.0750	5.819	5.150	4.408	2.379	2.037	1.735	105628	90443	77034	91035
2.41E+04	0.1330	3.440	3.113	2.673	2.093	1.900	1.623	50441	45790	39114	45115
1.23E+04	0.2370	1.347	1.213	1.050	0.806	0.712	0.605	9914	8758	7442	8704
6.67E+03	0.4220	0.541	0.501	0.445	0.225	0.198	0.156	1501	1321	1041	1287
3.51E+03	0.7500	0.316	0.303	0.289	0.076	0.073	0.067	267	256	235	253
		0.240	0.230	0.222				348844	371366	270409	330207

Table C.8 Conversion of Analyzer Currents to the Number of Particles for Silica Fumes
Produced at 650°C.

Run 1	d_p(μm)	I			dI			dN			dN
<u>dN/dI</u>	<u>mean</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>mean</u>
		<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	
4.17E+05	0.0133	10.32	9.40	8.17	0.07	0.10	0.16	29190	41700	66720	45870
1.67E+05	0.0237	10.25	9.30	8.01	0.49	0.47	0.56	81830	78490	93520	84613
8.70E+04	0.0422	9.76	8.83	7.45	0.61	0.62	0.46	53070	53940	40020	49010
4.44E+04	0.0750	9.15	8.21	6.99	1.71	1.51	1.28	75924	67044	56832	66600
2.41E+04	0.1330	7.44	6.70	5.71	3.16	2.81	2.36	76156	67721	56876	66918
1.23E+04	0.2370	4.28	3.89	3.35	2.63	2.31	1.97	32349	28413	24231	28331
6.67E+03	0.4220	1.65	1.58	1.38	0.84	0.90	0.79	5603	6003	5269	5625
3.51E+03	0.7500	0.81	0.68	0.59	0.39	0.28	0.21	1369	983	737	1030
		0.42	0.40	0.38				355491	344294	344205	347997
Run 2											
4.17E+05	0.0133	10.68	9.80	8.30	0.03	0.19	0.03	12510	79230	12510	34750
1.67E+05	0.0237	10.65	9.61	8.27	0.22	0.37	0.34	36740	61790	56780	51770
8.70E+04	0.0422	10.43	9.24	7.93	0.60	0.47	0.43	52200	40890	37410	43500
4.44E+04	0.0750	9.83	8.77	7.50	2.33	1.98	1.68	103452	87912	74592	88652
2.41E+04	0.1330	7.50	6.79	5.82	3.89	3.53	3.02	93749	85073	72782	83868
1.23E+04	0.2370	3.61	3.26	2.80	2.26	2.05	1.73	27798	25215	21279	24764
6.67E+03	0.4220	1.35	1.21	1.07	0.70	0.60	0.56	4669	4002	3735	4135
3.51E+03	0.7500	0.65	0.61	0.51	0.27	0.26	0.21	948	913	737	866
		0.38	0.35	0.30				332066	385025	279825	332305
Run 3											
4.17E+05	0.0133	11.85	10.04	8.25	0.12	0.34	0.17	50040	141780	70890	87570
1.67E+05	0.0237	11.73	9.70	8.08	0.40	0.23	0.28	66800	38410	46760	50657
8.70E+04	0.0422	11.33	9.47	7.80	0.54	0.43	0.36	46980	37410	31320	38570
4.44E+04	0.0750	10.79	9.04	7.44	1.94	1.70	1.27	86136	75480	56388	72668
2.41E+04	0.1330	8.85	7.34	6.17	3.72	3.01	2.54	89652	72541	61214	74469
1.23E+04	0.2370	5.13	4.33	3.63	2.91	2.47	2.11	35793	30381	25953	30709
6.67E+03	0.4220	2.22	1.86	1.52	1.22	1.02	0.85	8137	6803	5670	6870
3.51E+03	0.7500	1.00	0.84	0.67	0.48	0.39	0.27	1685	1369	948	1334
		0.52	0.45	0.40				385223	404174	299142	362847

Table C.9 Conversion of Analyzer Currents to the Number of Particles for Simultaneous Production of Lead Dichloride and Silica Fumes at 350°C.

Run 1	d_p(μm)	I			dI			dN			dN
dN/dI	mean	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	mean
4.17E+05	0.0133	3.225	2.929	2.553	0.037	0.079	0.074	15429	32943	30858	26410
1.67E+05	0.0237	3.188	2.850	2.479	0.658	0.581	0.497	109886	97027	82999	96637
8.70E+04	0.0422	2.530	2.269	1.982	0.641	0.572	0.498	55767	49764	43326	49619
4.44E+04	0.0750	1.889	1.697	1.484	1.194	1.047	0.884	53014	46487	39250	46250
2.41E+04	0.1330	0.695	0.650	0.600	0.418	0.386	0.347	10074	9303	8363	9246
1.23E+04	0.2370	0.277	0.264	0.253	0.077	0.069	0.060	947	849	738	845
6.67E+03	0.4220	0.200	0.195	0.193	0.026	0.017	0.017	173	113	113	133
3.51E+03	0.7500	0.174	0.178	0.176	0.001	0.007	0.007	4	25	25	18
		0.173	0.171	0.169				245293	236510	205671	229158
Run 2											
4.17E+05	0.0133	3.303	2.911	2.533	0.056	0.011	0.057	23352	4587	23769	17236
1.67E+05	0.0237	3.247	2.900	2.476	0.514	0.463	0.389	85838	77321	64963	76041
8.70E+04	0.0422	2.733	2.437	2.087	0.615	0.554	0.458	53505	48198	39846	47183
4.44E+04	0.0750	2.118	1.883	1.629	1.302	1.140	0.963	57809	50616	42757	50394
2.41E+04	0.1330	0.816	0.743	0.666	0.511	0.450	0.390	12315	10845	9399	10853
1.23E+04	0.2370	0.305	0.293	0.276	0.097	0.086	0.076	1193	1058	935	1062
6.67E+03	0.4220	0.208	0.207	0.200	0.021	0.025	0.019	140	167	127	145
3.51E+03	0.7500	0.187	0.182	0.181	0.009	0.005	0.006	32	18	21	23
		0.178	0.177	0.175				234184	192809	181817	202937
Run 3											
4.17E+05	0.0133	3.528	3.216	2.776	0.082	0.094	0.051	34194	39198	21267	31553
1.67E+05	0.0237	3.446	3.122	2.725	0.487	0.460	0.401	81329	76820	66967	75039
8.70E+04	0.0422	2.959	2.662	2.324	0.595	0.530	0.448	51765	46110	38976	45617
4.44E+04	0.0750	2.364	2.132	1.876	1.397	1.229	1.070	62027	54568	47508	54701
2.41E+04	0.1330	0.967	0.903	0.806	0.628	0.583	0.502	15135	14050	12098	13761
1.23E+04	0.2370	0.339	0.320	0.304	0.126	0.106	0.095	1550	1304	1169	1341
6.67E+03	0.4220	0.213	0.214	0.209	0.025	0.025	0.022	167	167	147	160
3.51E+03	0.7500	0.188	0.189	0.187	0.008	0.013	0.014	28	46	49	41
		0.180	0.176	0.173				246194	232262	188181	222212

Table C.10 Conversion of Analyzer Currents to the Number of Particles for Simultaneous Production of Lead Dichloride and Silica Fumes at 450°C.

Run 1	d_p(μm)	I			dI			dN			dN
<u>dN/dI</u>	<u>mean</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>Reading</u>	<u>mean</u>
		<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	
4.17E+05	0.0133	6.274	5.602	4.848	0.087	0.116	0.061	36279	48372	25437	36696
1.67E+05	0.0237	6.187	5.486	4.787	0.544	0.391	0.379	90848	65297	63293	73146
8.70E+04	0.0422	5.643	5.095	4.408	0.738	0.724	0.580	64206	62988	50460	59218
4.44E+04	0.0750	4.905	4.371	3.828	2.372	2.080	1.826	105317	92352	81074	92914
2.41E+04	0.1330	2.533	2.291	2.002	1.757	1.586	1.378	42344	38223	33210	37925
1.23E+04	0.2370	0.776	0.705	0.624	0.440	0.386	0.327	5412	4748	4022	4727
6.67E+03	0.4220	0.336	0.319	0.297	0.098	0.091	0.075	654	607	500	587
3.51E+03	0.7500	0.238	0.228	0.222	0.026	0.024	0.024	91	84	84	87
		0.212	0.204	0.198				345150	312671	258081	305301
Run 2											
4.17E+05	0.0133	7.135	6.324	5.433	0.137	0.092	0.130	57129	38364	54210	49901
1.67E+05	0.0237	6.998	6.232	5.303	0.235	0.302	0.238	39245	50434	39746	43142
8.70E+04	0.0422	6.763	5.930	5.065	0.718	0.643	0.529	62466	55941	46023	54810
4.44E+04	0.0750	6.045	5.287	4.536	2.751	2.407	2.025	122144	106871	89910	106308
2.41E+04	0.1330	3.294	2.880	2.511	2.329	2.027	1.762	56129	48851	42464	49148
1.23E+04	0.2370	0.965	0.853	0.749	0.584	0.503	0.415	7183	6187	5105	6158
6.67E+03	0.4220	0.381	0.350	0.334	0.127	0.110	0.101	847	734	674	751
3.51E+03	0.7500	0.254	0.240	0.233	0.048	0.036	0.039	168	126	137	144
		0.206	0.204	0.194				345312	307507	278268	310363
Run 3											
4.17E+05	0.0133	8.030	7.006	6.136	0.199	0.050	0.171	82983	20850	71307	58380
1.67E+05	0.0237	7.831	6.956	5.965	0.534	0.432	0.325	89178	72144	54275	71866
8.70E+04	0.0422	7.297	6.524	5.640	0.852	0.786	0.713	74124	68382	62031	68179
4.44E+04	0.0750	6.445	5.738	4.927	3.179	2.790	2.360	141148	123876	104784	123269
2.41E+04	0.1330	3.266	2.948	2.567	2.354	2.108	1.807	56731	50803	43549	50361
1.23E+04	0.2370	0.912	0.840	0.760	0.546	0.487	0.445	6716	5990	5474	6060
6.67E+03	0.4220	0.366	0.353	0.315	0.119	0.113	0.087	794	754	580	709
3.51E+03	0.7500	0.247	0.240	0.228	0.041	0.042	0.033	144	147	116	136
		0.206	0.198	0.195				451817	342946	342115	378960

Table C.11 Conversion of Analyzer Currents to the Number of Particles for Simultaneous Production of Lead Dichloride and Silica Fumes at 550°C.

Run 1	$d_p(\mu\text{m})$	I			dI			dN			dN
dN/dI	mean	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	mean
4.17E+05	0.0133	11.64	9.62	7.76	0.30	0.32	0.09	125100	133440	37530	98690
1.67E+05	0.0237	11.34	9.30	7.67	0.42	0.32	0.36	70140	53440	60120	61233
8.70E+04	0.0422	10.92	8.98	7.31	0.54	0.52	0.44	46980	45240	38280	43500
4.44E+04	0.0750	10.38	8.46	6.87	2.64	2.04	1.67	117216	90576	74148	93980
2.41E+04	0.1330	7.74	6.42	5.20	3.85	3.28	2.57	92785	79048	61937	77923
1.23E+04	0.2370	3.89	3.14	2.63	2.25	1.79	1.50	27675	22017	18450	22714
6.67E+03	0.4220	1.64	1.35	1.13	0.81	0.61	0.54	5403	4069	3602	4358
3.51E+03	0.7500	0.83	0.74	0.59	0.35	0.30	0.20	1229	1053	702	995
		0.48	0.44	0.39				486527	428883	294769	403393
Run 2											
4.17E+05	0.0133	12.31	10.98	9.58	0.06	0.16	0.30	25020	66720	125100	72280
1.67E+05	0.0237	12.25	10.82	9.28	0.56	0.56	0.52	93520	93520	86840	91293
8.70E+04	0.0422	11.69	10.26	8.76	1.07	0.84	0.73	93090	73080	63510	76560
4.44E+04	0.0750	10.62	9.42	8.03	4.01	3.38	2.78	178044	150072	123432	150516
2.41E+04	0.1330	6.61	6.04	5.25	3.95	3.59	3.11	95195	86519	74951	85555
1.23E+04	0.2370	2.66	2.45	2.14	1.57	1.48	1.33	19311	18204	16359	17958
6.67E+03	0.4220	1.09	0.97	0.81	0.60	0.46	0.36	4002	3068	2401	3157
3.51E+03	0.7500	0.49	0.51	0.45	0.16	0.19	0.15	562	667	527	585
		0.33	0.32	0.30				508744	491850	493120	497904
Run 3											
4.17E+05	0.0133	13.03	11.16	9.13	0.38	0.46	0.33	158460	191820	137610	162630
1.67E+05	0.0237	12.65	10.70	8.80	0.61	0.36	0.39	101870	60120	65130	75707
8.70E+04	0.0422	12.04	10.34	8.41	0.51	0.67	0.40	44370	58290	34800	45820
4.44E+04	0.0750	11.53	9.67	8.01	3.29	2.71	2.19	146076	120324	97236	121212
2.41E+04	0.1330	8.24	6.96	5.82	4.71	3.91	3.32	113511	94231	80012	95918
1.23E+04	0.2370	3.53	3.05	2.50	2.15	1.89	1.50	26445	23247	18450	22714
6.67E+03	0.4220	1.38	1.16	1.00	0.69	0.55	0.47	4602	3669	3135	3802
3.51E+03	0.7500	0.69	0.61	0.53	0.27	0.24	0.20	948	842	702	831
		0.42	0.37	0.33				596282	552543	437075	528633

Table C.12 Conversion of Analyzer Currents to the Number of Particles for Simultaneous Production of Lead Dichloride and Silica Fumes at 650°C.

Run 1	d _p (μm)	I			dI			dN			dN
dN/dI	mean	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	Reading #1	Reading #2	Reading #3	mean
4.17E+05	0.0133	6.213	5.533	4.763	0.049	0.093	0.122	20433	38781	50874	73392
1.67E+05	0.0237	6.164	5.440	4.641	0.842	0.679	0.600	140614	113393	100200	236138
8.70E+04	0.0422	5.322	4.761	4.041	0.991	0.971	0.783	86217	84477	68121	159210
4.44E+04	0.0750	4.331	3.790	3.258	2.462	2.108	1.786	109313	93595	79298	188138
2.41E+04	0.1330	1.869	1.682	1.472	1.255	1.129	0.956	30246	27209	23040	53663
1.23E+04	0.2370	0.614	0.553	0.516	0.317	0.267	0.244	3899	3284	3001	6790
6.67E+03	0.4220	0.297	0.286	0.272	0.072	0.075	0.065	480	500	434	943
3.51E+03	0.7500	0.225	0.211	0.207	0.029	0.020	0.019	102	70	67	159
		0.196	0.191	0.188				391303	361310	325034	718432
Run 2											
4.17E+05	0.0133	6.613	5.904	5.125	0.074	0.040	0.108	30858	16680	45036	61716
1.67E+05	0.0237	6.539	5.864	5.017	0.464	0.465	0.357	77488	77655	59619	143175
8.70E+04	0.0422	6.075	5.399	4.660	0.783	0.711	0.632	68121	61857	54984	123308
4.44E+04	0.0750	5.292	4.688	4.028	2.715	2.352	1.988	120546	104429	88267	208828
2.41E+04	0.1330	2.577	2.336	2.040	1.771	1.622	1.394	42681	39090	33595	76911
1.23E+04	0.2370	0.806	0.714	0.646	0.452	0.394	0.330	5560	4846	4059	9643
6.67E+03	0.4220	0.354	0.320	0.316	0.108	0.079	0.085	720	527	567	1209
3.51E+03	0.7500	0.246	0.241	0.231	0.041	0.035	0.032	144	123	112	253
		0.205	0.206	0.199				346118	305207	286240	625043
Run 3											
4.17E+05	0.0133	7.143	6.530	5.626	0.041	0.038	0.016	17097	15846	6672	26410
1.67E+05	0.0237	7.102	6.492	5.610	0.666	0.669	0.575	111222	111723	96025	212647
8.70E+04	0.0422	6.436	5.823	5.035	0.942	0.887	0.737	81954	77169	64119	148828
4.44E+04	0.0750	5.494	4.936	4.298	2.886	2.537	2.158	128138	112643	95815	224398
2.41E+04	0.1330	2.608	2.399	2.140	1.792	1.643	1.476	43187	39596	35572	78903
1.23E+04	0.2370	0.816	0.756	0.664	0.468	0.430	0.357	5756	5289	4391	10291
6.67E+03	0.4220	0.348	0.326	0.307	0.102	0.092	0.082	680	614	547	1227
3.51E+03	0.7500	0.246	0.234	0.225	0.040	0.036	0.030	140	126	105	248
		0.206	0.198	0.195				388176	363006	303246	702952

Table C.13 Conversion of Analyzer Currents to the Number of Particles for Room Air Introduced into the Glass Storage Reservoir.

dN/dI	d _p (μm)	I			dI			dN			dN
	<u>mean</u>	<u>Run #1</u>	<u>Run #2</u>	<u>Run #3</u>	<u>Run #1</u>	<u>Run #2</u>	<u>Run #3</u>	<u>Run #1</u>	<u>Run #2</u>	<u>Run #3</u>	<u>mean</u>
4.17E+05	0.0133	0.361	0.348	0.374	0.003	0.003	0.002	1251	1251	834	1112
1.67E+05	0.0237	0.358	0.345	0.372	0.023	0.020	0.017	3841	3340	2839	3340
8.70E+04	0.0422	0.335	0.325	0.355	0.013	0.014	0.027	1131	1218	2349	1566
4.44E+04	0.0750	0.322	0.311	0.328	0.056	0.051	0.058	2486	2264	2575	2442
2.41E+04	0.1330	0.266	0.260	0.270	0.055	0.052	0.059	1326	1253	1422	1334
1.23E+04	0.2370	0.211	0.208	0.211	0.020	0.018	0.020	246	221	246	238
6.67E+03	0.4220	0.191	0.190	0.191	0.008	0.006	0.008	53	40	53	49
3.51E+03	0.7500	0.183	0.184	0.183	0.003	0.003	0.003	11	11	11	11
		0.180	0.181	0.180				10345	9599	10329	10091

Appendix D

Summary of Particle Size Distribution for Each Run

Table D.1 Summary of Lead Dichloride Particle Size Distribution for Each Run and the Average Particle Size Distribution from 350 to 650°C.

350 °C	<u>mean d_p (μm)</u>	<u>Run 1</u>	<u>Run 2</u>	<u>Run 3</u>	<u>Mean</u>
	0.0133	16680	24047	24186	21638
	0.0237	60120	68080	97027	75076
	0.0422	35264	43239	43877	40793
	0.0750	33788	40300	33182	35757
	0.1330	7198	8515	6298	7337
	0.2370	816	918	718	817
	0.4220	127	116	118	120
	0.7500	26	39	19	28
	Total # of Particles	154019	185254	205425	181566
450 °C	0.0133	45870	46843	36001	42905
	0.0237	36323	46482	66911	49905
	0.0422	34148	49184	56231	46521
	0.0750	71551	98923	90043	86839
	0.1330	38717	44497	37347	40187
	0.2370	4809	5547	4555	4970
	0.4220	480	611	542	544
	0.7500	79	109	97	95
	Total # of Particles	231977	292196	291727	271967
550 °C	0.0133	41144	34472	68944	48187
	0.0237	80383	74872	67245	74167
	0.0422	68208	74878	60117	67734
	0.0750	119125	139238	141621	133328
	0.1330	48329	59848	68548	58908
	0.2370	6048	7437	8274	7253
	0.4220	667	760	874	767
	0.7500	132	147	152	144
	Total # of Particles	364036	391652	415775	390488
650 °C	0.0133	31970	65330	97300	64867
	0.0237	152527	99087	69027	106880
	0.0422	116870	105270	84390	102177
	0.0750	163244	170200	151996	161813
	0.1330	45388	51815	69087	55430
	0.2370	3772	4469	8651	5631
	0.4220	334	422	978	578
	0.7500	82	152	152	129
	Total # of Particles	514187	496745	481581	497504

Table D.2 Summary of Silica Particle Size Distribution for Each Run and the Average Particle Size Distribution from 350 to 650°C.

350 °C	<u>mean d_p (μm)</u>	<u>Run 1</u>	<u>Run 2</u>	<u>Run 3</u>	<u>Mean</u>
	0.0133 0.0237 0.0422 0.0750 0.1330 0.2370 0.4220 0.7500	63245 71532 6293 2442 948 230 38 9	65469 101258 10614 4114 1044 234 38 9	54766 104208 13775 5506 1205 213 51 12	61160 92333 10227 4021 1066 226 42 10
	Total # of Particles	144737	182780	179736	169084
450 °C	0.0133 0.0237 0.0422 0.0750 0.1330 0.2370 0.4220 0.7500	56712 130538 29232 17242 2844 377 53 13	28634 124471 44631 28623 4177 459 62 16	27105 95969 42427 34158 8033 976 131 30	37484 116993 38763 26674 5018 604 82 20
	Total # of Particles	237011	231073	208829	225638
550 °C	0.0133 0.0237 0.0422 0.0750 0.1330 0.2370 0.4220 0.7500	63940 61567 38976 48115 38809 9725 1330 264	52264 123469 76850 94794 36857 7999 1141 197	34472 88788 60552 91035 45115 8704 1287 253	50225 91275 58793 77981 40260 8809 1253 238
	Total # of Particles	262726	393571	330206	328834
650 °C	0.0133 0.0237 0.0422 0.0750 0.1330 0.2370 0.4220 0.7500	45870 84613 49010 66600 66918 28331 5625 1030	34750 51770 43500 88652 83868 24764 4135 866	87570 50657 38570 72668 74469 30709 6870 1334	56063 62347 43693 75973 75085 27935 5543 1077
	Total # of Particles	347997	332305	362847	347716

Table D.3 Summary of Particle Size Distribution for the Simultaneous Production of Lead Dichloride and Silica Fumes for Each Run and the Average Particle Size Distribution from 350 to 650°C.

350 °C	<u>mean d_p (μm)</u>	<u>Run 1</u>	<u>Run 2</u>	<u>Run 3</u>	<u>Mean</u>
	0.0133	26410	17236	31553	25066
	0.0237	96637	76041	75039	82572
	0.0422	49619	47183	45617	47473
	0.0750	46250	50394	54701	50448
	0.1330	9246	10853	13761	11287
	0.2370	845	1062	1341	1083
	0.4220	133	145	160	146
	0.7500	18	23	41	27
	Total # of Particles	229158	202937	222213	218103
450 °C	0.0133	36696	49901	58380	48326
	0.0237	73146	43142	71866	62718
	0.0422	59218	54810	68179	60736
	0.0750	92914	106308	123269	107497
	0.1330	37925	49148	50361	45811
	0.2370	4727	6158	6060	5648
	0.4220	587	751	709	682
	0.7500	87	144	136	122
	Total # of Particles	305300	310362	378960	331541
550 °C	0.0133	98690	72280	162630	111200
	0.0237	61233	91293	75707	76078
	0.0422	43500	76560	45820	55293
	0.0750	93980	150516	121212	121903
	0.1330	77923	85555	95918	86465
	0.2370	22714	17958	22714	21129
	0.4220	4358	3157	3802	3772
	0.7500	995	585	831	804
	Total # of Particles	403393	497904	528634	476644
650 °C	0.0133	73392	61716	26410	53839
	0.0237	236138	143175	212647	197320
	0.0422	159210	123308	148828	143782
	0.0750	188138	208828	224398	207121
	0.1330	53663	76911	78903	69826
	0.2370	6790	9643	10291	8908
	0.4220	943	1209	1227	1126
	0.7500	159	253	248	220
	Total # of Particles	718433	625043	702952	682143

Appendix E

Particle Size Distribution before and after Corrected with Room Air Size Distribution

Table E.1 Summary of Lead Dichloride Particle Size Distribution before Corrected with Room Air Particle Size Distribution from 350 to 650°C.

Mean d_p (μm)	350 °C	450 °C	550 °C	650 °C	Air
0.0133	21638	42905	48187	64867	1112
0.0237	75076	49905	74167	106880	3340
0.0422	40793	46521	67734	102177	1566
0.0750	35757	86839	133328	161813	2442
0.1330	7337	40187	58908	55430	1334
0.2370	817	4970	7253	5631	238
0.4220	120	544	767	578	49
0.7500	28	95	144	129	11
Total # of Particles	181566	271967	390488	497504	10091

Table E.2 Summary of Silica Particle Size Distribution before Corrected with Room Air
Particle Size Distribution from 350 to 650°C.

Mean d_p (μm)	350 °C	450 °C	550 °C	650 °C	Air
0.0133	61160	37484	50225	56063	1112
0.0237	92333	116993	91275	62347	3340
0.0422	10227	38763	58793	43693	1566
0.0750	4021	26674	77981	75973	2442
0.1330	1066	5018	40260	75085	1334
0.2370	226	604	8809	27935	238
0.4220	42	82	1253	5543	49
0.7500	10	20	238	1077	11
Total # of Particles	169084	225638	328834	347716	10091

Table E.3 Summary of Particle Size Distribution for the Simultaneous Production of Lead Dichloride and Silica Fumes before Corrected with Room Air Particle Size Distribution from 350 to 650°C.

Mean d_p (μm)	350 °C	450 °C	550 °C	650 °C	Air
0.0133	25066	48326	111200	53839	1112
0.0237	82572	62718	76078	197320	3340
0.0422	47473	60736	55293	143782	1566
0.0750	50448	107497	121903	207121	2442
0.1330	11287	45811	86465	69826	1334
0.2370	1083	5648	21129	8908	238
0.4220	146	682	3772	1126	49
0.7500	27	122	804	220	11
Total # of Particles	218103	331541	476644	682143	10091

Table E.4 Summary of Lead Dichloride Particle Size Distribution after Corrected with Room Air Particle Size Distribution from 350 to 650°C.

Mean d_p (μm)	350 °C	450 °C	550 °C	650 °C
0.0133	20526	41793	47075	63755
0.0237	71736	46565	70827	103540
0.0422	39227	44955	66168	100611
0.0750	33315	84397	130886	159371
0.1330	6003	38853	57575	54096
0.2370	580	4733	7015	5393
0.4220	71	495	718	529
0.7500	17	84	133	118
Total # of Particles	171475	261876	380397	487414

Table E.5 Summary of Silica Particle Size Distribution after Corrected with Room Air
Particle Size Distribution from 350 to 650°C.

Mean d _p (μm)	350 °C	450 °C	550 °C	650 °C
0.0133	60048	36372	49113	54951
0.0237	88993	113653	87935	59007
0.0422	8661	37197	57227	42127
0.0750	1579	24232	75539	73531
0.1330	0	3684	38927	73751
0.2370	0	366	8572	27697
0.4220	0	33	1204	5494
0.7500	0	9	227	1066
Total # of Particles	159281	215547	318744	337626

Table E.6 Summary of Particle Size Distribution for the Simultaneous Production of Lead Dichloride and Silica Fumes after Corrected with Room Air Particle Size Distribution from 350 to 650°C.

Mean d_p (μm)	350 °C	450 °C	550 °C	650 °C
0.0133	23954	47214	110088	52727
0.0237	79232	59378	72738	193980
0.0422	45907	59170	53727	142216
0.0750	48006	105055	119461	204679
0.1330	9953	44478	85132	68492
0.2370	845	5411	20891	8670
0.4220	97	633	3723	1077
0.7500	17	112	793	209
Total # of Particles	208012	321450	466553	672052

Vita

Kwang Song Chua was born in Pulau Ketam, Malaysia on August 9, 1971. He attended the Methodist (A.C.S) High School, Klang, where he graduated in 1989. He entered The University of Tennessee, Knoxville during August of 1990 where in August, 1993 he received the Bachelor of Science in Chemical Engineering. He went on to pursue the Master of Science in Chemical Engineering at The University of Tennessee the same month he graduated with a bachelor degree. The master degree was officially received in December, 1997. He has been known as "Vic" while he was attending college.