ABSTRACT

MING-TA HSIEH  Preliminary Study of the Growth of Metallic Aerosols under Reduced Pressure Environment. (Under the direction of Dr. PARKER C. REIST and Dr. PHIL A. LAWLESS)

The growth behavior of metallic aerosols under normal and reduced pressure environments was investigated. Particles grown at both environments exhibit very irregular profiles. Particles' growth, in general, can be categorized into three types in this study, they are: cluster-cluster aggregation, particle-cluster aggregation, and ballistic aggregation.

A descriptor, called fractal dimension, is applied to quantifying the effect of reducing the pressure on the growth of particles. According to the measurements of fractal dimension, at higher pressure, 0.1 and 1.0 atm., cluster-cluster aggregation occurred at the early stage of growth; while particle-cluster aggregation occurred at the later stage of growth. Opposite phenomenon was found when pressure decreased to 0.01 atm.
ACKNOWLEDGMENTS

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Ming-Ta Hsieh
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Aerosol growth is an area of study most interesting to aerosol technologists. For the past few decades much of research has been concentrated on particle coagulation due to Brownian motion. However, almost all studies considered the atmospheric pressure parameter as a constant having a value of one atmosphere, so that these studies were only applicable to the atmosphere near the surface of the earth. The pressure in the upper level of the atmosphere is less than 1 atm, decreasing exponentially as the altitude increases. Thus in the upper reaches of the atmosphere the gas mean free path is no longer the same as used in the traditional growth model. In other words, to study aerosol growth in the upper atmosphere, it is necessary to take into account the parameter of gas mean free path, i.e. gas pressure.

One of the major goals of this report is to investigate the growth behavior of metallic aerosols at several reduced pressure environments. To do this we have explored the use of a recently developed descriptor to characterize the shape of grown aerosols, called the fractal dimension of the particle.

Traditionally, the term most often used in characterizing aerosols is aerodynamic diameter. In many cases, however, aerodynamic diameter is hard to describe the irregular aggregates very well and cannot tell much characteristics of the irregular aggregates. It is the fractal dimension that can describe certain rugged profiles.
Fractal dimensions are numbers between the classical whole number dimensions of 1, 2, and 3. This term was first introduced by Mandelbrot in 1977. He suggested that the concept of dimension can be extended from integer values of 1, 2, and 3 by the addition of a fractional value describing the space filling power of a boundary or a surface. Thus a line of fractal dimension 1.4 would fill space more efficiently than an extremely straight line, whose fractal dimension is 1.0, even though both would be topologically of dimension 1. Similarly, a rugged surface with fractal dimension 2.4 would fill space more than a surface of fractal dimension 2.0 or 2.2.

1.1 Growth of Metallic Aerosols

Metallic aerosols investigated in this report were generated by the Exploding Wire Generator (EUG), which will be described in Section II. The first step of growth is the nucleation of aerosols from the vapor phase, the second step is the liquid metal coagulation, and the third step is the growth of solid aerosol particles. The time needed for the first two steps to go to completion is extremely short, so that observation is very difficult. Only the growth of solid aerosols could be "seen" via filter sampling at different times (see electron micrographs).

According to the literature, formation of aggregates can be characterized in two categories: particle-cluster growth model, and cluster-cluster growth model.

For more than two decades, computer simulations have been
applied to the formation of aggregates in a wide variety of systems. This approach has been particularly successful in developing a better understanding of aggregation phenomena. In the 1960s, the earliest model for computer simulation of floc formation in colloidal systems were carried out by Vold[23,24] and Sutherland et al.[25,26] In these studies, particles were added to growing clusters of particles via randomly oriented trajectories, without including the effects of Brownian motion. A reasonable model of cluster formation in the colloidal systems should include the effects of long- and short-range interactions, particle size distribution and irregular shapes, hydrodynamic interactions, clustering of clusters, etc.[12] Recently, Witten and Sander[20] have introduced a particle-cluster aggregation model where the effects of Brownian motion were included.

Witten and Sander start with a single-seed particle at the origin of a lattice. A second particle is added a long distance from the origin and undergoes a random walk on the lattice until it reaches a site adjacent to the seed and becomes part of the growing cluster. Then, a third particle is introduced at a random distant point and undergoes a random walk until it also becomes part of the growing cluster. The procedure is repeated until a cluster of sufficiently large size is formed.

As the case of particle-cluster aggregation, the earliest models for cluster-cluster aggregation were carried out also
using linear trajectories. In recent years, Paul Meakin has explored a series of investigations[11-17] regarding the diffusion-limited aggregation in two- and three-dimensional simulations, in which both linear and random walk (Brownian) trajectories are considered and in which both particle-cluster growth model and cluster-cluster growth model are taken into consideration.

In the original Witten-Sander model, all growth originates from a single immobile growth site and only one particle is allowed in the vicinity of the growing cluster at any time. These features are unrealistic for many real colloidal systems. [14] In Meakin's model, clusters of particles, as well as single particles, are allowed to diffuse; clusters of all sizes stick together on contact.[14]

Meakin uses two-dimensional simulations on a simple square lattice with periodic boundary conditions. At the start of the simulation, a fraction of the lattice sites are picked at random and occupied (avoiding multiple occupancy). Particles at nearest neighbor positions are considered to belong to the same cluster. Clusters, including single-particle clusters, are picked randomly and moved with a probability proportional to their mobility by one lattice spacing in one of four equally probable directions. If a cluster contacts other clusters, they are merged to form a single cluster. In this manner, the clusters grow larger and larger until only one large cluster remains.
1.2 Fractal Dimension

Before discussing the fractal dimension, it is necessary to know what "fractals" are. Fractals are mathematical entities which have been developed to describe the geometrical similarities between irregular systems. This is a relatively new branch of mathematics and is increasingly applied to the problems dealing with irregular shapes.

According to Mandelbrot [27], fractals can be categorized into two kinds: mathematical fractals and natural fractals. An ideal fractal mathematical curve has two important properties. First, it has an indeterminate boundary magnitude approaching to infinity. Secondly, it is mathematically self-similar at any two different scales of scrutiny; in other words, the boundary looks the same whatever magnification is used in the examination of the structure of the curve. A natural fractal is a curve whose structure appears indeterminate at a series of resolutions but may ultimately exhibit other significant geometrical behavior when measured at a sufficiently high level of resolution. Methodology for measuring the fractal dimension will be discussed in Section III.

An approach to the description of rugged profiles using the concepts of fractal dimension to describe irregular profile of a fine particle has been widely developed by Brian H. Kaye and co-workers. [28-33] The concept of the fractal dimension of a non-Euclidean boundary is introduced by Mandelbrot. [10] The origin
of "fractal" comes from the Latin adjective "fractus", meaning "irregular" or "fragmented". In his book Mandelbrot describes the ruggedness of a line as its space filling ability and assigns a dimension between one and two to the structure of a line depending on its ability to fill space. A simple example is a straight line of traditional Euclidean geometry, which has a fractal dimension of 1; the trajectory of Brownian motion on a flat plane has a fractal dimension of 2.

Those studies dealing with computer simulations of growth models, as discussed previously, also worked out the measurements of fractal dimension of corresponding growth model. Table 1.1 summarizes these characteristic values of fractal dimension for different growth models.
Table 1.1 Fractal Dimensions Obtained from Two-Dimensional Aggregation Models

<table>
<thead>
<tr>
<th>Model</th>
<th>D</th>
<th>Reference</th>
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<tr>
<td>Linear trajectory,</td>
<td>1.95 ± 0.002</td>
<td>[12]</td>
</tr>
<tr>
<td>particle-cluster</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brownian trajectory,</td>
<td>5/3</td>
<td>[20]</td>
</tr>
<tr>
<td>particle-cluster</td>
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<td></td>
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<tr>
<td>Brownian trajectory,</td>
<td>1.73 ± 0.06</td>
<td>[12, 13]</td>
</tr>
<tr>
<td>particle-cluster</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear trajectory,</td>
<td>1.50 ± 0.05</td>
<td>[15]</td>
</tr>
<tr>
<td>cluster-cluster</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brownian trajectory,</td>
<td>1.44 ± 0.02</td>
<td>[15]</td>
</tr>
<tr>
<td>cluster-cluster</td>
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II. Experimental Apparatus

II.1 Introduction to the Exploding Wire Generator

Metallic aerosols to be studied in this report are generated by the Exploding Wire Generator (EWG). The principle of aerosol generation is that the EWG supplies enough energy to vaporize a piece of wire mounted on two electrodes. After the wire is vaporized, i.e. exploded, condensation proceeds right away, and aerosols are condensed from the vapor phase. Figure 2.1 shows the basic scheme of an EWG. [34]

Fig. 2.1 Basic Scheme of An Exploding Wire Generator

C: Low inductance capacitor
HV: High voltage power supply
S1: Trigger switch
W: Wire inside exploding chamber E
T: Timer for automatic dumping switch
S2: Dumping switch
The physics of the exploding wire phenomena is well investigated in the literature.[34-37] In general, the previous studies indicated that aerosols generated by the EWG have the following characteristics:

1) The primary particles form chain-like structures of smooth spherical particles, whose size distribution can be characterized by a log normal distribution.

2) The mean diameter of these primary particles are between 0.01 and 0.1 micrometers in size, depending on the parameters used in their generation, such as electrical energy or diameter of wire.

3) The aerosols are reproducible if they are generated under the same operating conditions.

The EWG used for this study is a Tobe Deutschmann Laboratories Model ESB-118 energy Storage System. It is a self-contained 9 kilojoule system consisting of three main assemblies: Capacitor Bank, Power and Relay Tank, and Control Console.

This system is designed around a 45 μf, 20 KV capacitor and a high voltage trigger unit. The capacitor may be charged up to 25 KV as desired. A push-button switch is used to remotely trigger the capacitor to discharge the stored energy through a wire mounted across two electrodes. A dumping switch can be used to discharge the capacitor without exploding the wire when the test is to be aborted. Pushing the "Start Charge" button connects the
high voltage power supply to the capacitor and starts the two-minute time delay automatic dump circuit which is provided for safety purposes. This assures that no charge will accidentally be left on the Capacitor Bank. The circuit is designed so that it allows 15 seconds for the operator to trigger the capacitor for explosion before the system automatically dumps the charges on the capacitor. After wire explosion, the circuit will automatically dump the residual charge left on the capacitor through a grounded wire. The distance between two electrodes is adjustable; the mass of wire exploded may be altered by changing the relative positions of electrodes, because sometimes it is necessary to obtain higher mass concentration or number concentration of particles.

II.2 Sampling Devices

1. Laser Aerosol Spectrometer

   This is an optical particle counter manufactured by Particle Measuring System, Inc. It is used to monitor particle size distribution and, roughly, number concentration. A size range of 0.09 to 3.0 micrometers is covered by this counter.

2. 47-mm Filter Holder

   A 47-mm, 0.05 micrometer nuclepore filter is used to collected particles for Scanning Electron Microscope (SEM) analyses, and then image analyses on computer.

3. Main Chamber (Exploding Chamber)
This is a large stainless steel pipe tee, mounted on the top of the Exploding Wire Generator, with a volume of 74.6 liters. Fig. 2.2 shows a side-view of this chamber.

Fig. 2.2 Side-View of the Main Chamber

4. Extractive Sampling Chamber

This is a small chamber, with a volume of 145 cc, located near the center of the exploding chamber (main chamber). Extractive sampling is used because of the difficulties of collecting particles without disturbing the gas pressure in exploding chamber. Particles captured in this chamber can be quickly raised to atmospheric pressures and flushed through.
several sampling devices described above.

5. In Situ Sampler

When the operating pressure is reduced to lower values, the problem of particle settling would become more severe, and extractive sampling would become more difficult also. Therefore, an in situ sampler is designed to overcome this difficulty. This sampler has been added, but not been applied, to the bottom of exploding chamber to collect timed particles samples directly on SEM substrates by settling. By this sampler, however, the time resolution may not be so good as with other samplers. Fig. 2.3 shows the outline of this in situ sampler.

![In Situ Sampler](image)

(a) Opened (b) Closed

Fig. 2.3 In Situ Sampler. (a) Opened (b) Closed
There are six positions, where SEM substrates are located, on the sampler to collect settled particles, i.e. this sampler is designed such that only six samples can be obtained in an experiment. Essentially, this sampler consists of two round plates; one of them has one hole on it, and the other one has six. The one, having one hole, amounts atop the other one. When sample is to be taken, turn the plate on the top so that the hole on the top coincides one of six holes on the bottom plate; otherwise, turn it to the "blind" area as illustrated in Fig. 2.3.

II.3 Pumping and Pressure Measuring System

The pumping and pressure measuring system are interfaced to the exploding chamber through vacuum-tight flanges on the arms of this chamber. A mechanical vacuum pump, direct drive vacuum pump, manufactured by Precision Scientific Group, is applied to provide reduced pressure. This pump can provide an ultimate low pressure down to 0.1 μm Hg absolute. System pressure is monitored by the Barocel Electronic Manometer which can be calibrated by a Mcleod gauge if necessary.

II.4 Other Equipment

1. Faraday Cage Filter and Electrometer

This assembly was used in the early stage of experiment to measure total charges on aerosols. In practice, a metallic aerosol which would have a low residual electrostatic charge is desired.
2. Video Capture System -- PC-EYE, Computer Software

This system has been set up in order to analyze the fractal dimensions of particles. It consists of a video camera, an image analyzer board and a software package for the IBM-PC. A particle image on an electron micrograph is digitized by this system and then stored as a file to the floppy disk for further analyses. This video capture system, called PC-EYE, is a commercial product distributed by Chorus Data Systems, Inc.

II.5 System Assembly

Figure 2.4 shows the assembly of entire chamber and monitoring system (top view).

II.6 Sampling Technique

It was readily known that aerosols generated from EWG were oxidized in normal air. In this study oxidized metallic aerosols are not desired, so that pure nitrogen is used as the gas medium to prevent metallic aerosols from being oxidized. Before the wire is exploded, it is required to "clean" the exploding chamber such that no particles other than exploded aerosols exist. This was done by evacuating the exploding chamber and filling it with pure, filtered nitrogen at least three times, and then adjusting the pressure to the desired value.

After the wire has exploded, particles diffuse into the open extractive sampling chamber. After several seconds, which is enough time for particles to enter this sampling chamber, the
Fig 2.4 Assembly of Experimental Apparatus

F : 47-mm Filter Holder
FV: Four-way Valve
G : Vacuum Gauge
L : Laser Spectrometer
M : Manometer
N : Needle Valve
Q : Flow Meter
T : Toggle Valve
VP: Vacuum Pump
VT: Vacuum Tank
X : Extractive Sampling Chamber
    (Inside Main Chamber)
chamber's door is closed, the pressure is raised with nitrogen gas, and then nitrogen flushes the particles out to the sampling devices, laser spectrometer, and nuclepore filter. The nitrogen flushing rate is 10 cc/sec, of which 1 cc/sec is applied to laser counter; the remaining 9 cc/sec of aerosol is collected by the filter.

After all of the particles in the sampling chamber have been flushed out (this can be monitored by the laser counter), the sampling chamber is pumped out to the pressure of main chamber. Then sampling chamber's door is opened to receive particles again.
III. Analyses

III.1 Scanning Electron Microscope

Every filter sample is examined by scanning electron microscopy (SEM). On the SEM in use, the maximum magnification for a picture with good resolution is about 20,000x. On certain electron micrographs, the primary particles are hard to identify, but appears to be about 0.04 - 0.05 micrometer spheres. Even so, this is not a major limitation, because in this study the measurement of size distribution of primary particles is not crucial.

For each filter sample, cut off about 1 square centimeter of this sample. Stick it on a specimen stub with carbon substrate, and then examine it by the scanning electron micrometer.

III.2 Fractal Analysis

There are two ways applicable to fractal analysis: perimeter method (or compass walk method), and dilation method (or covering squares method).

1. Perimeter (Compass Walk) Method

The basic concept of this method is to estimate the perimeter of a profile by drawing a polygon around this profile. If \( P \) represents the estimated perimeter of the profile, i.e. exact perimeter of corresponding polygon, and \( S \) represents the length of each side of polygon; the plot of \( \ln(P) \) versus \( \ln(S) \) would be a straight line with a slope of \( m \). The fractal dimension of this
profile is then calculated by

\[ D = 1 - m \]

To measure it practically, take a drafting compass and open it to a stride length \( S \). Starting at one end of Feret's diameter, swing the legs of the compass from the outside inwards to meet the profile, and then make repeated swings, until the compass returns to the starting point. There is a brief discussion of alternate ways to swing the compasses. It should be noted, however, that a consistent method must be used throughout the entire analyses.

This analytical method seems easier than dilation method (to be described in the next section), but is a tedious process and will consume much more time than the dilation method because it can not be easily computerized.

2. Dilation (Covering Squares) Method

Consider an arbitrary planar profile, as illustrated in Fig. 3.1 outlined by the heavy line. The figure is then covered with a plane covering pattern of different scales, such as regular triangles, squares, pentagons, or hexagons (squares are usually used), until the figure is either completely covered or one pattern covers the figure exactly. The smaller the covering cell (triangle, square, etc.), the more the number of cells will be. Similar to perimeter method, the logarithmic plot of the number required to cover versus the length of the covering cell will show a straight line, whose negative slope can be used to
express the fractal dimension. That is, the negative slope of the line will be:

$$D = -\frac{d \ln (N)}{d \ln (b)}$$

where $N$ is the number of covering squares, $b$ is the length of the side of the corresponding square, and $D$ will be termed as the fractal dimension.

Fig. 3.1 Shape Representing an Image of a Particle for Fractal Analysis
Fig. 3.2 Tiling of Shape by (a) Unit Square, (b) Squares of Side 2, (c) Squares of Side 3
Fig. 3.2 shows the processes for three sizes of squares. It is possible for this method to be applied to computer. But it was found that a fractal analysis for a single picture would require more than two hours on the computer available. This leads to the consideration of applying another dilation method described below.

This alternative dilation method was addressed by S. R. Forrest and T. A. Witten in 1979.[38] A digitized electron micrograph presents a matrix of "ones" and "zeros" (or "blanks"), the "ones" ("zeros") corresponding to the presence (absence) of one point of a particle. This digitized image is analyzed by computer (IBM PC); the computer program is written by BetterBASIC, an improved version of the BASIC language, and is listed in the Appendix. When analyzing, a smallest box was picked such that its geometric center is near the center of mass of particle, then a series of nested squares of different sizes was placed around it and the number of "ones" in each square was counted. This analysis would yield a powerlaw relationship between the length B of the square and the number of pixels Np within it, i.e. $N_p \propto B^D$, where D is fractal dimension.[38] Forrest and Witten also found that results were most reproducible when squares were chosen whose centers of mass coincided with their geometric centers.

In order to verify the availability and accuracy of this procedure, a Koch curve (see, e.g., Mandelbrot[27]) with known
fractal dimension of 1.500 was analyzed. A mean value for this test was 1.509, within 1% of accuracy. There are two limitations for this method, which were also stated by Forrest and Witten. One is due to the finite total number of pixels in the image analyzed, the other is due to the finite size of digitized image. The first limitation will cause the exponent of the power law, D (fractal dimension), approaching 0. The second limitation results in the data span being limited to a range of B. Despite these two limitations, this approach spends much less time than the one described at the beginning of this section.
IV. Results

IV.1 Selection of Metallic Wire

The earliest experiments were engaged in the selection of metallic wire. Two criteria are required: low melting point and low residual charge on the particles generated from wire explosion. The higher melting point metals appear to become thermally ionized during the explosion, while the low melting point metals could be easily dispersed without ionization. Besides, it is also necessary to have a wire that low residual electrostatic charges can be built up on the particles after explosion, such that electrically dominant forces would not influence the growth of particles. The charges on numerous metal aerosols were measured with a Faraday cage filter. After trying Cu, Ag, Mo, and Al, Ag wire was chosen. Table 4.1 lists the measurements of the charge levels on different aerosols.

Table 4.1 Measurements of the Charge Levels on Different Aerosols

<table>
<thead>
<tr>
<th>Material</th>
<th>Charge/Mass (C/g)</th>
<th>Space Charge (C/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>3.5 E-8</td>
<td>2.9 E-9</td>
</tr>
<tr>
<td>Ag</td>
<td>3.9 E-8</td>
<td>2.1 E-9</td>
</tr>
<tr>
<td>Ag</td>
<td>1.1 E-8</td>
<td>7.5 E-10</td>
</tr>
<tr>
<td>Cu</td>
<td>4.3 E-9</td>
<td>1.0 E-9</td>
</tr>
</tbody>
</table>
IV.2 Electron Micrographs Made by SEM

Fig. 4.1 through 4.10 show the electron microscope (SEM) pictures of particles at different pressures and times. Four different pressures were conducted: 1 atm, 0.1 atm, 0.01 atm, and 0.001 atm. There is no problem to collecting particles by using extractive sampler when the pressure was equal to or higher than 0.01 atm, although particles settled more quickly at the lower pressures. Even with repeated attempts, no particles were observed at 0.001 atm. Beside the pressure, other parameters were fixed. They are: wire material, Ag; wire diameter, 0.012"; electric energy, 15 KV; distance between two electrodes, 3 cm.

After realizing that no particles could be collected at the pressure of 0.001 atm, it was desired to know the lower limit for particle formation. Another two pressure settings were performed, 0.004 atm and 0.002 atm. In these two tests, it was only desired to know the "threshold" of pressure, and no pictures were taken. The PMS counter did show the presence of particles within one hour after wire explosion for these two pressures.

From the electron microscope pictures (Fig. 4.1 to Fig. 4.10), the primary particles reveal a diameter of 0.04 - 0.05 micrometer at all levels of pressure. It was also seen that some primary particles remained molten long enough to coalesce into larger spheres at 0.01 atm (not shown in the figures).
IV.3 Fractal Analysis

Fig. 4.11 to Fig. 4.20 are the plots of fractal analysis for the particles grown at different pressures (1.0 atm, 0.1 atm, and 0.01 atm). The fractal dimension revealed in the figures, as determined by one of dilation methods, do show a pressure dependent as well as time dependent tendencies.

For the particles grown at one atmosphere, the fractal dimension in the range of 0.07 to 0.5 micrometer is about 1.3 at short times after wire explosion, and increased to about 1.45 two hours later. The value of 1.45 is characteristic of cluster-cluster agglomeration,[11] i.e. the particle growth is due largely to the coagulation of clusters of particles of comparable sizes. Also in one atmosphere, particles grown above 0.5 micrometer have a fractal dimension of 1.7, which is close to the value of 5/3 expected for particle-cluster agglomeration.

In 0.1 atmosphere, particles exhibited the same general trend; where the range of cluster-cluster growth was from 0.08 to 0.3 micrometer, and the particle-cluster growth range was from 0.5 micrometer and higher.

In 0.01 atmosphere, however, there was an opposite trend. The smaller size range (from 0.07 to 0.5 micrometer) showed a fractal dimension in a range from 1.4 to almost 1.7. While at size of 0.5 micrometer and up to about 1.0 micrometer, the fractal dimension was about 1.35. This will be discussed later.
Fig. 4.1 Electron Micrograph of Agglomerates, 1 atm.
Sample Taken at 37 sec. after Explosion. 20,000x

Fig. 4.2 Electron Micrograph of Agglomerates, 1 atm.
Sample Taken at 26.3 min. after Explosion.
(a) 20,000x, (b) 2,000x
Fig. 4.3 Electron Micrograph of Agglomerates, 1 atm.
Sample Taken at 129.5 min. after Explosion.
(a) 20,000x, (b) 2,000x

Fig. 4.4 Electron Micrograph of Agglomerates, 1 atm.
Sample Taken at 194.8 min. after Explosion. 20,000x
Fig. 4.5 Electron Micrograph of Agglomerates, 0.1 atm. Sample Taken at 30 sec. after Explosion. (a), (b) 20,000x, (c) 4,000x
Fig. 4.6  Electron Micrograph of Agglomerates, 0.1 atm.
Sample Taken at 30 min. after Explosion.
(a) 20,000x, (b), (c) 4,000x
Fig. 4.7 Electron Micrograph of Agglomerates, 0.1 atm. Sample Taken at 60 min. after Explosion. (a) 20,000x, (b) 4,000x, (c) 800x
Fig. 4.8 Electron Micrograph of Agglomerates, 0.1 atm.
Sample Taken at 120 min. after Explosion.
(a) 4,000x, (b) 800x

Fig. 4.9 Electron Micrograph of Agglomerates, 0.1 atm.
Sample Taken at 180 min. after Explosion.
(a) 4,000x, (b) 800x
Fig. 4.10  Electron Micrograph of Agglomerates, 0.01 atm.
Sample Taken at (a) 26 sec., 20,000x, (b) 29.8 min.,
12,000x, after Explosion.
Fig. 4.11 Fractal Analysis for the Particle in Fig. 4.1
Fig. 4.12 Fractal Analysis for the Particle in Fig. 4.2(a)
Fig. 4.13 Fractal Analysis for the Particle in Fig. 4.3(a)
Fig. 4.14 Fractal Analysis for the Particle in Fig. 4.5(b)
Fig. 4.15 Fractal Analysis for the Particle in Fig. 4.6(a)
Fig. 4.16 Fractal Analysis for the Particle in Fig. 4.7(a)
Fig. 4.17 Fractal Analysis for the Particle in Fig. 4.9(a)
Fig. 4.18 Fractal Analysis for the Particle in Fig. 4.10(a)
Fig. 4.19 Fractal Analysis for the Particle in Fig. 4.10(b)
Fig. 4.20 Fractal Analysis for the Particle Taken at 66.7 min. after Explosion at 0.01 atm
V. Discussion

From the electron micrographs (Fig. 4.1 to Fig. 4.10), it is seen that at normal pressure (1 atm) particles tend to form a plane, chain-like agglomerate (Fig. 4.1 to Fig. 4.4). At short time after wire explosion, the agglomerates exhibit an outline of linear chain (Fig. 4.1). At the later stage of growth, branched chain agglomerates appeared (Fig. 2 to Fig. 4). These branched chain agglomerates, obviously, are built up from a linear chain base. Besides, those branches are not long compared to their parent chain. Comparing these chain-like agglomerates it is found that the chains formed at earlier stage of growth are opened and smaller than those formed at later stage of growth, in that closed chains were observed (Fig. 4.1 and Fig. 4.2 versus Fig. 4.3 and Fig. 4.4).

As the pressure was reduced, distinct differences were observed. At 0.1 atm (Fig. 4.5 to Fig. 4.9), agglomerates are still chain-like. Nonetheless, these chain-like agglomerates are more compact, or "thicker" (i.e. no longer in two dimensional pattern but three dimensional), than those formed at 1 atm; and the formation of closed chain agglomerates seemed to be earlier. As pressure went even lower, at 0.01 atm, grown particles were still in the form of chain; however, they became more and more compact, i.e. space among particles was less, than those grown at higher pressures (see Fig. 4.10). The reason is that the growth at lower pressure, say 0.01 atm, is due largely to ballistic collision of particles rather than Brownian motion. This leads to the fact that either individual
particles or clusters of particles are more likely to penetrate inside a growing cluster of particles than to stick around it, such that a very compact structure of aggregate is formed. On the other hand, at higher pressure, say 0.1 atm and 1.0 atm, the interaction of the gas molecules with the particles is essential in the aggregation process in which particles are more likely to stick around the periphery of a growing aggregate than to penetrate into it, such that an open structured aggregate is formed.

From the SEM micrographs, it is obvious that the major effect of reducing gas pressure on particles' growth is that particles will grow into more compact structures. To quantify this effect, a descriptor named fractal dimension is applied.

Before measuring fractal dimensions, it should be noted that fractal dimension can be used to describe the ruggedness of an object only when this object exhibits fractal characteristics. It is necessary to realize whether or not the grown particles generated in this study reveal fractal characteristics.

Consider, for example, Fig. 4.6. Fig. 4.6(a) is a magnified picture of the particle laid on the left side of Fig. 4.6(b). Compare these two pictures, it is found that the structure of the particle shown on Fig. 4.6(a) is similar to that of the particle laid on right side of Fig. 4.6(b). They are constructed by the base of closed-chain structure. If we take a closer look at this particle, however, the fundamental structure of this particle would be changed. It will be
found that this agglomerate is added up with spherical primary particles even though the resolution gets higher and higher. Beyond this magnification, probably 25,000x or more, the boundary of the agglomerate becomes a smooth finite profile and exhibits Euclidean structure rather than fractal structure, since spheres are Euclidean objects. By definition (see Section I) particles exhibiting the above described behavior are characterized as natural fractals, provided they also exhibit scale invariance of some properties.

Fig. 5.1 Fractal Dimension Measured by Compass Walk Method
If we use compass walk technique (perimeter method) to measure the fractal dimension of a natural fractal, the plot on log-log scale would show two linear regions (e.g. see Fig. 5.1). The linear region at higher resolution describes the general structure of the profile, the other region at lower resolution describes the packing texture of the subunits (i.e. primary particles). Kaye suggests the former be described as structural fractal and the latter as textural fractal. Furthermore, the break-point between these two linear regions should be theoretically at the dimension of the discernible subunit.

The method used to measure fractal dimension in this study is dilation method which is described in Section III.2. Fig. 4.11 through Fig. 4.20 are log-log plots derived from the analysis of the digitized images of SEM micrographs. Unlike the plot shown in Fig. 5.1 which is obtained from the analysis using compass walk method, these plots show positive slopes. This is true because they are based on the relation described in Section III.2: \( N_p \propto R^D \). More actually, this relation can be written into

\[ M \propto R^D \]

where \( M \) is the mass enclosed within a sphere of radius \( R \). In this relation it assumes that the center of mass of the particle be the center of the circle.

According to the experience derived from analyzing those digitized images, there are some problems to which one has to pay attention. First and the most important, the boxes enclosing the
object should be expanded around the center of mass of the object. This requires at least an evaluation of the center of mass. Secondly, the slope of the plot is very sensitive to the initial location of the smallest box. In other words, small changes in the location of the smallest box will result in fluctuating slopes. This occurs even though the largest boxes contain the whole image; in that case the total number of pixels (which are coded "1") is the same. To overcome these problems, an averaging technique has been applied. Several expansion centers were chosen in order to derive an averaged plot. That is to say, Fig. 4.11 to Fig. 4.20 are all averaged plots.

Table 5.1 Fractal Dimensions Determined by Dilation Method

<table>
<thead>
<tr>
<th>Time*</th>
<th>D</th>
<th>Time</th>
<th>D</th>
<th>Time</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>1.267 (0.07-0.5)</td>
<td>0.5</td>
<td>1.227 (0.08-0.3)</td>
<td>0.5</td>
<td>1.425 (0.07-0.2)</td>
</tr>
<tr>
<td>1.713</td>
<td>( &gt; 0.5)</td>
<td></td>
<td>1.469 ( &gt; 0.3)</td>
<td></td>
<td>1.167 ( &gt; 0.2)</td>
</tr>
<tr>
<td>26.3</td>
<td>1.370</td>
<td>30</td>
<td>1.414 (0.08-0.2)</td>
<td>30</td>
<td>1.492 (0.1-0.5)</td>
</tr>
<tr>
<td>129.5</td>
<td>1.451</td>
<td>60</td>
<td>1.392 (0.06-0.5)</td>
<td>67</td>
<td>1.699 (0.1-0.4)</td>
</tr>
<tr>
<td>1.628</td>
<td>( &gt; 0.5)</td>
<td></td>
<td></td>
<td>1.389 ( &gt; 0.4)</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>1.617 (0.3-0.9)</td>
<td></td>
<td></td>
<td>1.882 ( &gt; 0.9)</td>
<td></td>
</tr>
</tbody>
</table>

* Time is counted after wire explosion and is in a unit of minute.
** Unit in the parentheses is in micrometers.
Table 5.1 lists the measures of fractal dimensions determined by the dilation method. In this table, most of the values of fractal dimensions exhibit two regions. There is no evidence showing that, like the plot of compass walk method, the break point is near the size of primary particles. However, this can be described as two stages of growth. For example, let us take a look at the fractal dimension of a grown particle at 30 minutes after explosion under 0.1 atmosphere of pressure. At the early stage of growth (growing from 0.08 to 0.2 micrometers), the fractal dimension of 1.414 manifests a cluster—cluster aggregation. While at the later stage of growth (growing from 0.2 micrometers and larger), the fractal dimension of 1.717 reveals that particle growing at this stage is in particle—cluster aggregation.

For the particles grown at one atmosphere, at short time after explosion, the fractal dimension in the range of 0.07 to about 0.5 micrometer is about 1.3, and is about 1.7 for the range above 0.5 micrometers. Two hours later, it increases to about 1.45 which is a characteristic value of cluster—cluster aggregation (see Table 1.1). The value of 1.7 is close to the value of 5/3 which is an anticipated value for particle—cluster aggregation (see also Table 1.1). The trend of growth at this pressure manifests that cluster—cluster agglomeration will be dominated for long-term coagulation.

At 0.1 atmosphere, particles’ growth reveals similar features as they grow at one atmosphere. The data presented in Table 5.1 show that there is a transition to particle—cluster aggregation during the
coagulation times. The cluster-cluster aggregation occurs for the size ranging from 0.08 to 0.3 micrometers, and from 0.5 micrometers and larger reveals particle-cluster aggregation.

Unlike 0.1 and 1 atmosphere, particles grown at 0.01 atmosphere exhibit another character. For the size ranging from 0.07 to 0.5 micrometers the fractal dimension is from 1.43 to 1.70, and is from 1.2 to 1.4 for the size of 0.5 micrometers and larger. This tells us that at the early stages of growth cluster-cluster aggregation is dominated within 30 minutes after wire explosion; and particle-cluster aggregation begins dominating at one hour after explosion and later. At the later stages of growth, the growth will approach to cluster-cluster aggregation with longer coagulation time, say, one hour after explosion.

The reason that growth switches from cluster-cluster aggregation to particle-cluster aggregation can be described as follows. As the size of cluster increases, its Brownian motion will become slow because this cluster is large enough that the bombardments of gas molecules on it could not affect its motion; that is to say, this cluster is "stable". In that case, the motion of this cluster is much less than the background particles or small clusters of much smaller size. Therefore those background particles and small clusters are more likely to collide with the relatively large clusters rather than stick themselves. This is the characteristics of particle-cluster aggregation.
As gas density is low, for example, 0.01 atmosphere, the fractal
dimension for early stage of growth is larger than that for later
stage of growth for the entire sampling time. The micrographs of the
particles grown at 0.01 atmosphere (Fig. 4.10) can demonstrate these
measurements. In the figures, the structure of the particles shows
that it becomes more compact and solid as looking from the periphery
inward. From another point of view, particles collide together by
cluster-cluster aggregation at the early stage of growth; since the
gas density is low these clusters of particles can contact one
another tightly, such that a compact structure forms. In the limit of
purely ballistic aggregation, a nearly solid structure will have a
fractal dimension of 2.0.

The method used to measure fractal dimension in this study is
dealing with two-dimensional projecting shapes which are electron
micrographs of the particles generated. However, the real particles
are three-dimensional, which is apparent in low angle micrographs or
stereo-pairs. However, in the literature reported by Weitz and
Huang,[40] it was demonstrated that as long as the particles are
sparse enough, the two dimensional projection of a three-dimensional
particle will have the same fractal characteristics as the particle
itself. Therefore, it is unnecessary to do a three-dimensional
analysis, except perhaps in the ballistic limit.
VI. Summary

In this report, the growth behavior of metallic aerosols under normal and reduced pressure environments was investigated. Particles grown at both environments exhibit very irregular outlines, as shown in the electron microscope pictures from Fig. 4.1 to Fig. 4.10. It was found that the basic structure of agglomerates in all three pressure conditions performed is a chain with some branches. At normal pressure, the agglomerates look like several branched chains stuck together end to end and, constructing an open-chain agglomerate. As pressure decreases, particles' profile is changing from open-chain to closed-chain and their structure becomes more compact and solid.

The growth of particles is characterized into three types in this study, they are: cluster-cluster aggregation, particle-cluster aggregation, and ballistic aggregation, according to the measured fractal dimensions.

According to the observations in this study, the agglomerates under normal and reduced pressure exhibit fractal characteristics, and can be categorized as natural fractals.

A descriptor, called fractal dimension which is used to describe a fractal object, is applied to quantifying the effect of reducing the pressure on the growth of particles. The measures of fractal dimensions of experimentally generated and grown particles are
summarized in Table 5.1.

Particles grown at 1.0 atmosphere exhibit cluster-cluster aggregation in the early stage of growth, and particle-cluster aggregation for the later stage of growth at short time after wire explosion. Then the growth tends to be a cluster-cluster aggregation.

At 0.1 atmosphere, like at one atmosphere, the growth is attributed to forming small clusters of particles initially. After that, these small clusters of particles aggregate one another by cluster-cluster aggregation to form a larger cluster with a characteristic fractal dimension of about 1.4. The later stage of growth is dominated by particle-cluster aggregation and is characterized by a fractal dimension of about 1.7.

At even lower pressure, 0.01 atmosphere, the initial growth is changing from cluster-cluster aggregation to particle-cluster aggregation. While the later stage of growth will approach a cluster-cluster aggregation, but will presumably change to particle-cluster aggregation at longer times.

Throughout this report, it is obvious that gas mean free path is an important factor to the growth of particles. Although the pressure does not decrease to very low value, it seems clear that the aggregation of particles will tend toward forming more compact structures with fractal dimensions approaching to a limit value of 2. The most important point in this report is the concept and application of
fractal dimension. The fractal analysis is able to interpret the structural informations of agglomerates about their growth history.
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8. Tolfo, Flavio


10. Mandelbrot, B. B.

11. Meakin, Paul

12. Meakin, Paul

13. Meakin, Paul

14. Meakin, Paul
"Formation of Fractal Clusters and Networks by Irreversible
15. Meakin, Paul

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23. Vold, M. J.

24. Vold, M. J.

25. Sutherland, D. N.

26. Sutherland, D. N.

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APPENDIX
SOURCE
PRECISION 6
PROCS=44
BYTE ARRAY (16384): Ba/X
BYTE ARRAY (320, 200): A/X
INTEGER ARRAY (100): X1, X2, X3, X4, Y1, Y2, Y3, Y4
INTEGER ARRAY (100): W
REAL ARRAY (100): P
BYTE: Inc, Boxnum
INTEGER: Rb, Lb, Ul, Ll

PROCEDURE: Acqpic
END PROCEDURE

PROCEDURE: Shrink
END PROCEDURE

PROCEDURE: SetWidth
END PROCEDURE

PROCEDURE: Anykey
END PROCEDURE

PROCEDURE: Showpic
END PROCEDURE

PROCEDURE: Counting
END PROCEDURE

PROCEDURE: DefineWindow
END PROCEDURE

PROCEDURE: Plot
END PROCEDURE

PROCEDURE: Setbound
END PROCEDURE

PROCEDURE: Message1
END PROCEDURE

PROCEDURE: Result
END PROCEDURE

PROCEDURE: Acqpic
EXTERNAL: Ba, Anykey
INTEGER: I
STRING: File$(16)

PROCEDURE: Mes
END PROCEDURE

PROCEDURE: Mes
EXTERNAL: File$, Anykey
10 CLS
20 SET CURSOR 10, 25: INPUT "Picture file name? " ; File$
30 CLS
40 SET CURSOR 2, 19: PRINT "For picture to appear it needs 22 seconds."
50 SET CURSOR 5, 27: COLOR LTGREEN: PRINT "When picture appears .......
60 SET CURSOR 6, 13: COLOR YELLOW: PRINT "Use arrow keys and hit certain keys to set boundaries"
70 SET CURSOR 9, 25: COLOR LTGREEN: PRINT "After setting boundaries .......
80 SET CURSOR 10, 17: COLOR YELLOW: PRINT "The picture will then be stored into an array."
90 SET CURSOR 11, 28: COLOR YELLOW: PRINT (It needs a few minutes)"
100 SET CURSOR 14, 19: COLOR LTCEAN: PRINT "Hit the following keys to set boundaries."
110 SET CURSOR 16, 13: COLOR YELLOW
120 PRINT "'L': Left boundary"; SPC(15) "'R': Right boundary"
130 SET CURSOR 17, 13: COLOR YELLOW
140 PRINT "'U': Upper boundary"; SPC(14) "'D': Lower boundary"
142 SET CURSOR 18, 29: COLOR YELLOW
144 PRINT "<ESC> : Finish setting"
150 SET CURSOR 21, 28: COLOR LTRED: PRINT "Type any key to continue.";
160 Anykey
170 SET CURSOR 21, 28: COLOR LTRED: PRINT "Acquiring Picture .......
END PROCEDURE
10 Mes
30 OPEN File$ AS I LEN 16384
40 READ RECORD #1,1,Ba
50 CLOSE 1
60 FOR I = 4 TO 16003 : Ba(I) = Ba(I*252) : NEXT
70 Ba(0) = 128: Ba(1) = 2: Ba(2) = 200: Ba(3) = 0
END PROCEDURE

PROCEDURE: Shrink
EXTERNAL: A, Ul, Ll, Rb, Lb, Definewindow, Anykey
INTEGER: I, J

PROCEDURE: Modify
END PROCEDURE

PROCEDURE: Mes
END PROCEDURE

PROCEDURE: Modify
EXTERNAL: Rb, Lb
10 IF Rb MOD 2 = 1 THEN Rb = Rb + 1
20 IF Lb MOD 2 = 1 THEN Lb = Lb - 1
END PROCEDURE

A - 2
COMPUTER PROGRAM

PROCEDURE: Mes
EXTERNAL: Definewindow, Anykey
10 Definewindow
20 SET CURSOR 10,14:PRINT "The picture has been stored into
a 320 x 200 array."
30 SET CURSOR 12,12:PRINT "Next step is to set width and
number of counting boxes."
40 SET CURSOR 15,27:COLOR LTRED:PRINT "Type any key to
continue."
50 Anykey
END PROCEDURE

10 Modify
20 CLEAR(A)
30 FOR J = U1 TO L1
40 FOR I = Lb TO Rb
50 A(I/2,J) = POINT(I,J) * POINT(I+1,J)
60 NEXT
70 NEXT
80 SOUND 1000,2
90 Mes
END PROCEDURE

PROCEDURE: SetWidth
INTEGER: X, Y
BYTE ARRAY(5): Ptr
EXTERNAL: W, X1, X2, X3, X4, Y1, Y2
EXTERNAL: Y3, Y4, Showpic, Inc, Definewindow, Boxnum, Anykey
STRING: K0[5]
EXTERNAL: Ba

PROCEDURE: Init
END PROCEDURE

PROCEDURE: MovePtr
END PROCEDURE

PROCEDURE: Boxinit
END PROCEDURE

PROCEDURE: Box
END PROCEDURE

PROCEDURE: Mes
END PROCEDURE

PROCEDURE: Valreset
END PROCEDURE

PROCEDURE: Mes1
END PROCEDURE

PROCEDURE: Init
EXTERNAL: Ptr
COMPUTER PROGRAM

10 PSET(10,10),1
20 GET(10,10)-(10,10),Ptr
30 PRESET(10,10)

END PROCEDURE

PROCEDURE: MovePtr
STRING: K$[5],R$[5],L$[5],U$[5],D$[5]
EXTERNAL: X,Y,Ptr,Showpic
EXTERNAL: Boxinit,Init
10 Showpic
20 Init
30 R$=CHR$(0)+CHR$(77):L$=CHR$(0)+CHR$(75):
   U$=CHR$(0)+CHR$(72):D$=CHR$(0)+CHR$(80)
40 X = 300 : Y = 50
50 PUT(X,Y),Ptr,XOR
60 DO
70  K$=INKEY$:IF K$="*" THEN GOTO 70
80  IF K$ = CHR$(27) THEN Boxinit
90  IF K$ = "*" THEN EXIT
100 IF K$ = R THEN PUT(X,Y),Ptr,XOR : X = X + 5:
80  PUT(X,Y),Ptr,XOR
110 IF K$ = L THEN PUT(X,Y),Ptr,XOR : X = X - 4:
80  PUT(X,Y),Ptr,XOR
120 IF K$ = U THEN PUT(X,Y),Ptr,XOR : Y = Y - 4:
80  PUT(X,Y),Ptr,XOR
130 IF K$ = D THEN PUT(X,Y),Ptr,XOR : Y = Y + 5:
80  PUT(X,Y),Ptr,XOR
140 REPEAT

END PROCEDURE

PROCEDURE: Boxinit
EXTERNAL: X,Y,X1,X2,X3,X4,Y1,Y2
EXTERNAL: Y3,Y4
STRING: K$[5]
10 K$=INKEY$: IF K$="*" THEN GOTO 10
20 IF K$ = "1" THEN X1(0) = X : Y1(0) = Y
30 IF K$ = "2" THEN X2(0) = X : Y2(0) = Y
40 IF K$ = "3" THEN X3(0) = X : Y3(0) = Y
50 IF K$ = "4" THEN X4(0) = X : Y4(0) = Y

END PROCEDURE

PROCEDURE: Box
EXTERNAL: W,X1,X2,X3,X4,Y1,Y2,Y3
EXTERNAL: Y4,Inc,Boxnum
INTEGER: I
10 CLS
20 W(0)=Y2(0)-Y1(0)
30 X3(0)=X1(0)+2*W(0) : Y3(0)=Y2(0)
40 X4(0)=X3(0) : Y4(0)=Y1(0)
50 FOR I = 0 TO Boxnum
60  X1(I+1)=X1(I)-2*Inc : Y1(I+1)=Y1(I)-Inc
70  X2(I+1)=X2(I)-2*Inc : Y2(I+1)=Y2(I)-Inc
80  X3(I+1)=X3(I)-2*Inc : Y3(I+1)=Y3(I)-Inc
90  X4(I+1)=X4(I)-2*Inc : Y4(I+1)=Y4(I)-Inc
PROCEDURE: Mes
EXTERNAL: Inc, Boxnum
STRING: K$[5]
10 CLS : COLOR YELLOW
20 SET CURSOR 8,12:PRINT "Hit <CR> to choose number of boxes and increment value."
30 SET CURSOR 9,23:PRINT "Other keys will use default values."
40 SET CURSOR 13,19:PRINT "Default values are: Number of boxes = 20"
50 SET CURSOR 14,19:PRINT "Box increment = 4"
60 SET CURSOR 18,24:COLOR LTGREEN:PRINT "<ESC> will use earlier values."
70 K$=INKEY$:IF K$ = "" THEN GOTO 70
80 DO IF K$=CHR$(13)
90  CLS : COLOR YELLOW
100 SET CURSOR 9,16:INPUT "Number of boxes wanted ?";Boxnum
110 SET CURSOR 11,16:INPUT "Box increment ?";Inc
120 END DO
130 DO IF K$<>CHR$(13) AND K$<>CHR$(27)
140  Boxnum = 20 : Inc = 4
150 END DO
END PROCEDURE

PROCEDURE: Valreset
EXTERNAL: Inc, Boxnum, Definewindow
STRING: K$[5]
10 Definewindow
20 SET CURSOR 10,8
30 PRINT "Want to reset number of boxes and box increment values ? (Y/N)"
40 K$=INKEY$:IF K$="" THEN GOTO 40
50 DO IF K$="y" OR K$="Y"
60  CLS
70 SET CURSOR 9,29:INPUT "Number of boxes ?";Boxnum
80 SET CURSOR 11,29:INPUT "Box increment ?";Inc
90 END DO
END PROCEDURE

PROCEDURE: Mesl
EXTERNAL: Anykey
STRING: K$[5]
10 CLS : COLOR YELLOW
20 SET CURSOR 3,24:PRINT "Use arrow keys to move pointer."
30 SET CURSOR 5,15:PRINT "The pointer should be moved to the position where"
40 SET CURSOR 6,15:PRINT "is one of the four corners of the most inner box."
50 SET CURSOR 7,15:PRINT "The corners can be set by doing
the following way:

60   SET CURSOR 9,12:PRINT "Hit <ESC> and 1 to set the upper left corner of that box."
70   SET CURSOR 10,12:PRINT "Hit <ESC> and 2 to set the lower left corner of that box."
80   SET CURSOR 12,15:PRINT "The upper and lower left corners should be set."
90   SET CURSOR 13,15:PRINT "before viewing the boxes. After setting these"
100  SET CURSOR 14,15:PRINT "corners, hit SPACE bar to view how those boxes"
110  SET CURSOR 15,15:PRINT "look like and how do you like them. You could"
120  SET CURSOR 16,15:PRINT "either reset box number and box increment values"
130  SET CURSOR 17,15:PRINT "or remain these values but change the positions"
140  SET CURSOR 18,15:PRINT "of those boxes."
150  SET CURSOR 21,27:COLOR LTRED:PRINT "Type any key to continue.";
160  Anykey
END PROCEDURE

10   Mes
20   CLS:COLOR YELLOW
30   SET CURSOR 10,27:PRINT "Need instructions ? (Y/N)"
40   K$=INKEY$:IF K$="" THEN GOTO 40
50   IF K$="y" OR K$="Y" THEN Mes1
60   MovePtr
70   Box
80   PUT(0,0),Ba,XOR
90   LOCATE 24,65:PRINT "OK ? (Y/N)  ";
100  K$=INKEY$:IF K$="" THEN GOTO 100
110  IF K$<>"Y" AND K$<>"y" THEN Valreset : GOTO 60
120  LOCATE 24,65:PRINT "Computing .... ";
END PROCEDURE

PROCEDURE: Anykey
STRING: S(5)
10   S = INKEY$ : IF S = "" THEN GOTO 10
END PROCEDURE

PROCEDURE: Showpic
EXTERNAL: Ba
10   SCREEN 2
15   'LINE(2,0)-(639,191),1,BF
20   PUT(0,0),Ba,XOR
END PROCEDURE

PROCEDURE: Counting
EXTERNAL: A,X1,X2,X3,X4,Y1,Y2,P
EXTERNAL: Boxnum
INTEGER: I,J,K
PROCEDURE: Modify
PROCEDURE: Modify

INTEGER: I
EXTERNAL: X1, X2, X3, X4, Boxnum
10 DO IF X1(0) MOD 2 = 1
20 FOR I = 0 TO Boxnum-1
30 X1(I) = X1(I) - 1
40 X2(I) = X2(I) - 1
50 X3(I) = X3(I) - 1
60 X4(I) = X4(I) - 1
70 NEXT
80 END DO

PROCEDURE: DefineWindow

10 CLS : SCREEN 0 : STATUSLINE OFF
20 DEFINE WINDOW 1,0,0,23,79,YELLOW,ON BLUE
30 FRAME WINDOW 1,10
40 SOUND 1000,0.5
PROCEDURE: Plot
EXTERNAL: W, P, Anykey, Boxnum, Definewindow
INTEGER: L, Vc, Hc, Pmin

PROCEDURE: Coord
END PROCEDURE

PROCEDURE: Scale
END PROCEDURE

PROCEDURE: Regression
END PROCEDURE

PROCEDURE: Plot4x3
END PROCEDURE

PROCEDURE: Plot3x3
END PROCEDURE

PROCEDURE: Plot3x2
END PROCEDURE

PROCEDURE: Plot2x2
END PROCEDURE

PROCEDURE: Plot2x3
END PROCEDURE

PROCEDURE: Coord
EXTERNAL: Hc, Vc

PROCEDURE: FourxThree
END PROCEDURE

PROCEDURE: ThreexThree
END PROCEDURE

PROCEDURE: ThreexTwo
END PROCEDURE

PROCEDURE: TwoxTwo
END PROCEDURE

PROCEDURE: TwoxThree
END PROCEDURE

PROCEDURE: FourxThree
INTEGER: I, J
10 LINE(170, 0)-(470, 180), 1, B
20 FOR I = 0 TO 1
30 LINE(270+100*I, 0)-(270+100*I, 4), 1
COMPUTER PROGRAM

40 LINE(270+100*I,176)-(270+100*I,180),1
50 NEXT
60 FOR I = 0 TO 2
70 LINE(170,135-45*I)-(177,135-45*I),1
80 LINE(463,135-45*I)-(470,135-45*I),1
90 NEXT
100 FOR J = 2 TO 5 STEP 3
110 FOR I = 0 TO 2
120 LINE(170+100*(I*LOG(J)/2.3),0)-(170+100*(I*LOG(J)/2.3),176),1
130 LINE(170+100*(I*LOG(J)/2.3),180),1
140 NEXT
150 FOR I = 0 TO 3
160 LINE(170,180-60*(I+LOG(J)/2.3))-(177,180-60*(I+LOG(J)/2.3)),1
170 LINE(463,180-60*(I+LOG(J)/2.3))-(470,180-60*(I+LOG(J)/2.3)),1
180 NEXT
190 NEXT
200 END PROCEDURE

PROCEDURE: ThreexThree
INTEGER: I,J
10 LINE(125,0)-(515,180),1,B
20 FOR I = 0 TO 1
30 LINE(255+130*I,0)-(255+130*I,4),1
40 LINE(255+130*I,176)-(255+130*I,180),1
50 NEXT
60 FOR I = 0 TO 1
70 LINE(125,180-60*I)-(132,180-60*I),1
80 LINE(508,60-60*I)-(515,60-60*I),1
90 NEXT
100 FOR J = 2 TO 5 STEP 3
110 FOR I = 0 TO 2
120 LINE(125+130*(I*LOG(J)/2.3),0)-(125+130*(I*LOG(J)/2.3),176),1
130 LINE(125+130*(I*LOG(J)/2.3),180),1
140 NEXT
150 FOR I = 0 TO 3
160 LINE(125,180-60*(I+LOG(J)/2.3))-(132,180-60*(I+LOG(J)/2.3)),1
170 LINE(508,180-60*(I+LOG(J)/2.3))-(515,180-60*(I+LOG(J)/2.3)),1
180 NEXT
190 NEXT
200 END PROCEDURE

PROCEDURE: ThreexTwo
INTEGER: I,J
10 LINE(190,0)-(450,180),1,B
20 LINE(320,0)-(320,4),1
30 LINE(320,176)-(320,180),1
COMPUTER PROGRAM

40 FOR I = 0 TO 1
50  LINE(190, 120-60*I)-(197, 120-60*I), 1
60  LINE(443, 120-60*I)-(450, 120-60*I), 1
70 NEXT
80 FOR J = 2 TO 5 STEP 3
90  FOR I = 0 TO 1
  100   LINE(190+130*(I+LOG(J)/2.3), 0)-(190+130*(I+LOG(J)/2.3), 4), 1
  110   LINE(190+130*(I+LOG(J)/2.3), 176)-(190+130*(I+LOG(J)/2.3), 180), 1
120 NEXT
130  FOR I = 0 TO 2
  140   LINE(190, 180-60*(I+LOG(J)/2.3))-(197, 180-60*(I+LOG(J)/2.3)), 1
  150   LINE(443, 180-60*(I+LOG(J)/2.3))-(450, 180-60*(I+LOG(J)/2.3)), 1
160 NEXT
170 NEXT
180 END PROCEDURE

PROCEDURE: TwoxTwo
INTEGER: I, J
10  LINE(120, 0)-(520, 180), 1, B
20  LINE(320, 0)-(320, 4), 1
30  LINE(320, 176)-(320, 180), 1
40  LINE(120, 90)-(127, 90), 1
50  LINE(513, 90)-(520, 90), 1
60 FOR J = 2 TO 5 STEP 3
70  FOR I = 0 TO 1
  80   LINE(120+200*(I+LOG(J)/2.3), 0)-(120+200*(I+LOG(J)/2.3), 4), 1
  90   LINE(120+200*(I+LOG(J)/2.3), 176)-(120+200*(I+LOG(J)/2.3), 180), 1
100 NEXT
110 NEXT
120 FOR I = 0 TO 1
130  LINE(120, 180-90*(I+LOG(J)/2.3))-(127, 180-90*(I+LOG(J)/2.3)), 1
140  LINE(513, 180-90*(I+LOG(J)/2.3))-(520, 180-90*(I+LOG(J)/2.3)), 1
150 NEXT
160 NEXT
170 END PROCEDURE

PROCEDURE: TwoxThree
INTEGER: I, J
10  LINE(20, 0)-(620, 180), 1, B
20 FOR I = 0 TO 1
30  LINE(220+200*I, 0)-(220+200*I, 4), 1
40  LINE(220+200*I, 176)-(220+200*I, 180), 1
50 NEXT
60  LINE(20, 90)-(27, 90), 1
70  LINE(613, 90)-(620, 90), 1
80 FOR J = 2 TO 5 STEP 3
90  FOR I = 0 TO 2

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COMPUTER PROGRAM

100     LINE(20•200•(I•LOG(J)/2.3),0)-(20•200•(I•LOG(J)/2.3),4),1
110     LINE(20•200•(I•LOG(J)/2.3),176)-(20•200•(I•LOG(J)/2.3),180),1
120   NEXT
130   FOR I = 0 TO 1
140     LINE(20,180-90•(I+LOG(J)/2.3))-(27,180-90•(I+LOG(J)/2.3)),1
150   LINE(613,180-90•(I•LOG(J)/2.3))-(620,180-90•(I•LOG(J)/2.3)),1
160   NEXT
170   NEXT
END PROCEDURE

10    DO IF Vc=4 AND Hc=3
20      FourxThree
30    END DO
40    DO IF Vc=3 AND Hc=3
50      ThreexThree
60    END DO
70    DO IF Vc=3 AND Hc=2
80      ThreexTwo
90    END DO
100   DO IF Vc=2 AND Hc=2
110     TwoxTwo
120   END DO
130   DO IF Vc=2 AND Hc=3
140     TwoxThree
150   END DO
END PROCEDURE

PROCEDURE: Scale
EXTERNAL: Vc,Hc,W,Pmin

PROCEDURE: FourxThree
END PROCEDURE

PROCEDURE: ThreexThree
END PROCEDURE

PROCEDURE: ThreexTwo
END PROCEDURE

PROCEDURE: TwoxTwo
END PROCEDURE

PROCEDURE: TwoxThree
END PROCEDURE

PROCEDURE: FourxThree
EXTERNAL: Pmin
10    DO IF INT(LOG(Pmin)/2.3)=1
20      LOCATE 1,14:PRINT "100,000";
30      LOCATE 1,15:PRINT "10,000";
40      LOCATE 1,16:PRINT "1,000";

50 LOCATE 17,18:PRINT "100";
60 LOCATE 23,19:PRINT "10";
70 END DO
80 DO IF INT(LOG(Pmin)/2.3)=0
90 LOCATE 1,15:PRINT "10,000";
100 LOCATE 6,16:PRINT "1,000";
110 LOCATE 12,18:PRINT "100";
120 LOCATE 17,19:PRINT "10";
130 LOCATE 23,20:PRINT "1";
140 END DO
150 LOCATE 24,22:PRINT "1";
160 LOCATE 24,34:PRINT "10";
170 LOCATE 24,46:PRINT "100";
180 LOCATE 24,58:PRINT "1,000";
END PROCEDURE

PROCEDURE: ThreexThree
EXTERNAL: Pmin
10 DO IF INT(LOG(Pmin)/2.3)=2
20 LOCATE 1,9:PRINT "100,000";
30 LOCATE 8,10:PRINT "10,000";
40 LOCATE 16,11:PRINT "1,000";
50 LOCATE 23,13:PRINT "100";
60 END DO
70 DO IF INT(LOG(Pmin)/2.3)=1
80 LOCATE 1,10:PRINT "10,000";
90 LOCATE 8,11:PRINT "1,000";
100 LOCATE 16,13:PRINT "100";
110 LOCATE 23,14:PRINT "10";
120 END DO
130 LOCATE 24,16:PRINT "1";
140 LOCATE 24,32:PRINT "10";
150 LOCATE 24,48:PRINT "100";
160 LOCATE 24,63:PRINT "1,000";
END PROCEDURE

PROCEDURE: ThreexTwo
EXTERNAL: W,Pmin
10 DO IF INT(LOG(Pmin)/2.3)=2
20 LOCATE 1,17:PRINT "100,000";
30 LOCATE 8,18:PRINT "10,000";
40 LOCATE 16,19:PRINT "1,000";
50 LOCATE 23,21:PRINT "100";
60 END DO
70 DO IF INT(LOG(Pmin)/2.3)=1
80 LOCATE 1,18:PRINT "10,000";
90 LOCATE 8,19:PRINT "1,000";
100 LOCATE 16,21:PRINT "100";
110 LOCATE 23,22:PRINT "10";
120 END DO
130 DO IF INT(LOG(W(0))/2.3)=1
140 LOCATE 24,24:PRINT "10";
150 LOCATE 24,40:PRINT "100";
160 LOCATE 24,55:PRINT "1,000";
COMPUTER PROGRAM

170 END DO
180 DO IF INT(LOG(W(0))/2.3)=0
190  LOCATE 24,25:PRINT "1";
200  LOCATE 24,41:PRINT "10";
210  LOCATE 24,57:PRINT "100";
220 END DO

END PROCEDURE

PROCEDURE: TwoxTwo
EXTERNAL: W,Pmin
10 DO IF INT(LOG(Pmin)/2.3)=3
20  LOCATE 1, 8:PRINT "100,000";
30  LOCATE 12, 9:PRINT "10,000";
40  LOCATE 23,10:PRINT "1,000";
50 END DO
60 DO IF INT(LOG(Pmin)/2.3)=2
70  LOCATE 1, 9:PRINT "10,000";
80  LOCATE 12,10:PRINT "1,000";
90  LOCATE 23,12:PRINT "100";
100 END DO
110 DO IF INT(LOG(W(0))/2.3)=1
120  LOCATE 24,15:PRINT "10";
130  LOCATE 24,39:PRINT "100";
140  LOCATE 24,63:PRINT "1,000";
150 END DO
160 DO IF INT(LOG(W(0))/2.3)=0
170  LOCATE 24,16:PRINT "1";
180  LOCATE 24,40:PRINT "10";
190  LOCATE 24,65:PRINT "100";
200 END DO

END PROCEDURE

PROCEDURE: TwoxThree
EXTERNAL: Pmin
10 DO IF INT(LOG(Pmin)/2.3)=3
20  LOCATE 24,15:PRINT "10",";
30  LOCATE 24,39:PRINT "100",;
40 END DO
50 DO IF INT(LOG(Pmin)/2.3)=2
60  LOCATE 24,16:PRINT "10",";
70  LOCATE 24,27:PRINT "10",;
80  LOCATE 24,52:PRINT "100",;
90  LOCATE 24,75:PRINT "1,000",;
100 END DO

END PROCEDURE

10 DO IF Vc=4 AND Hc=3
20  FourxThree
30 END DO
40 DO IF Vc=3 AND Hc=3
50  ThreexThree
60 END DO
70 DO IF Vc=3 AND Hc=2
80  ThreexTwo
90 END Two

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COMPUTER PROGRAM

100 DO IF Vc=2 AND Hc=2
110   TwoxTwo
120 END DO
130 DO IF Vc=2 AND Hc=3
140   TwoxThree
150 END DO
END PROCEDURE

PROCEDURE: Regression
EXTERNAL: W, P, Boxnum
INTEGER: I
REAL ARRAY(100): RegX, RegY
REAL: Xsum, Ysum, U, Xysum, X2sum, Y2sum
REAL: Y2sum, Numer, Denom, R, B
10 CLEAR(RegX, RegY, U, Xsum, Ysum, Xysum, X2sum, Y2sum)
20 FOR I = 0 TO Boxnum-1
30  DO IF W(I) > 0 AND P(I) > 0
40    RegX(I) = LOG(W(I))/2.3 : RegY(I) = LOG(P(I))/2.3
50  END DO
60  Xsum = Xsum + RegX(I) : Ysum = Ysum + RegY(I)
70  U = RegX(I)*RegY(I) : Xysum = Xysum + U
80  U = RegX(I)^2 : X2sum = X2sum + U
90  U = RegY(I)^2 : Y2sum = Y2sum + U
100 NEXT
110 Numer = Xysum - Xsum*Ysum/Boxnum
120 Denom = (SQR(X2sum-Xsum^2/Boxnum))*(SQR(Y2sum-
130   Ysum^2/Boxnum))
140 R = Numer/Denom
150 B = (Xysum-Xsum*Ysum/Boxnum)/(X2sum-Xsum^2/Boxnum)
160 DO IF ABS(R) > 0.98
170 LOCATE 21,42:PRINT "Slope =";:PRINT USING 
180   "#.###•;B
190 LOCATE 22, 42:PRINT " R =";:PRINT USING 
200   "#.####•;R
210 END DO
END PROCEDURE

PROCEDURE: Plot4x3
EXTERNAL: W, P, L, Pmin
10 DO IF INT(LOG(Pmin)/2.3)=1
20    CIRCLE(170+100*LOG(W(L))/2.3,180-45*(LOG(P(L))/2.3-
210   1)),2,1
30 END DO
40 DO IF INT(LOG(Pmin)/2.3)=0
50    CIRCLE(170+100*LOG(W(L))/2.3,180-45*LOG(P(L))/2.3),2,1
60 END DO
END PROCEDURE

PROCEDURE: Plot3x3
EXTERNAL: W, P, L, Pmin
10 DO IF INT(LOG(Pmin)/2.3)=2
20    CIRCLE(125+130*LOG(W(L))/2.3,180-60*(LOG(P(L))/2.3-
210   2)),2,1
30 END DO
40 DO IF INT(LOG(Pmin)/2.3)=1
50    CIRCLE(125+130*LOG(W(L))/2.3,180-60*LOG(P(L))/2.3-\n220   1),2,1
50 END DO
50 END DO
END PROCEDURE
PROCEDURE: Plot3x2
EXTERNAL: W, P, L, Pmin
10 DO IF INT(LOG(Pmin)/2.3) = 1 AND INT(LOG(W(0))/2.3) = 1
20 CIRCLE(190+130•(LOG(W(L))/2.3-1),180-60•(LOG(P(L))/2.3-1)),2,1
30 END DO
40 DO IF INT(LOG(Pmin)/2.3) = 1 AND INT(LOG(W(0))/2.3) = 0
50 CIRCLE(190+130•LOG(W(L))/2.3,180-60•LOG(P(L))/2.3-1)),2,1
60 END DO
70 DO IF INT(LOG(Pmin)/2.3) = 2 AND INT(LOG(W(0))/2.3) = 1
80 CIRCLE(190+130•LOG(W(L))/2.3-1),180-60•LOG(P(L))/2.3-2)),2,1
90 END DO
100 DO IF INT(LOG(Pmin)/2.3) = 2 AND INT(LOG(W(0))/2.3) = 0
110 CIRCLE(190+130•LOG(W(L))/2.3,180-60•LOG(P(L))/2.3-2)),2,1
120 END DO
END PROCEDURE

PROCEDURE: Plot2x2
EXTERNAL: W, P, L, Pinin
10 DO IF INT(LOG(Pmin)/2.3) = 2 AND INT(LOG(W(0))/2.3) = 1
20 CIRCLE(120+200•(LOG(W(L))/2.3-1),180-90•(LOG(P(L))/2.3-2)),2,1
30 END DO
40 DO IF INT(LOG(Pmin)/2.3) = 2 AND INT(LOG(W(0))/2.3) = 0
50 CIRCLE(120+200•LOG(W(L))/2.3,180-90•LOG(P(L))/2.3-2)),2,1
60 END DO
70 DO IF INT(LOG(Pmin)/2.3) = 3 AND INT(LOG(W(0))/2.3) = 0
80 CIRCLE(120+200•LOG(W(L))/2.3,180-90•LOG(P(L))/2.3-3)),2,1
90 END DO
100 DO IF INT(LOG(Pmin)/2.3) = 3 AND INT(LOG(W(0))/2.3) = 1
110 CIRCLE(120+200•LOG(W(L))/2.3-1),180-90•LOG(P(L))/2.3-3)),2,1
120 END DO
END PROCEDURE

PROCEDURE: Plot2x3
EXTERNAL: W, P, L, Pmin
10 DO IF INT(LOG(Pmin)/2.3) = 2
20 CIRCLE(20+200•LOG(W(L))/2.3,180-90•LOG(P(L))/2.3-2)),2,1
30 END DO
40 DO IF INT(LOG(Pmin)/2.3) = 3
50 CIRCLE(20+200•LOG(W(L))/2.3,180-90•LOG(P(L))/2.3-3)),2,1
60 END DO
END PROCEDURE
10 FOR L = 0 TO Boxnum-1
20 DO IF P(L) > 0
30 Vc = INT(LOG(P(Boxnum-1))/2.3) - INT(LOG(P(L))/2.3) + 1
40 Pmin = P(L) : EXIT 2 LEVELS
50 END DO
60 NEXT
70 Hc = INT(LOG(W(Boxnum-1))/2.3) - INT(LOG(W(0))/2.3) + 1
80 CLS : SCREEN 2
90 Coord
100 Scale
110 DO IF Vc=4 AND Hc=3
120 FOR L = 0 TO Boxnum-1
130 DO IF P(L)>0
140 Plot4x3
150 END DO
160 NEXT
170 END DO
180 DO IF Vc=3 AND Hc=3
190 FOR L = 0 TO Boxnum-1
200 DO IF P(L)>0
210 Plot3x3
220 END DO
230 NEXT
240 END DO
250 DO IF Vc=3 AND Hc=2
260 FOR L = 0 TO Boxnum-1
270 DO IF P(L)>0
280 Plot3x2
290 END DO
300 NEXT
310 END DO
320 DO IF Vc=2 AND Hc=2
330 FOR L = 0 TO Boxnum-1
340 DO IF P(L)>0
350 Plot2x2
360 END DO
370 NEXT
380 END DO
390 DO IF Vc=2 AND Hc=3
400 FOR L = 0 TO Boxnum-1
410 DO IF P(L)>0
420 Plot2x3
430 END DO
440 NEXT
450 END DO
460 Regression
470 Anykey
480 Definewindow
END PROCEDURE

PROCEDURE: Setbound
BYTE ARRAY(200): B,C
EXTERNAL: Rb,Lb,U1,L1
PROCEDURE: Init
END PROCEDURE

PROCEDURE: Leftright
END PROCEDURE

PROCEDURE: Updown
END PROCEDURE

PROCEDURE: Init
EXTERNAL: B, C
10 LINE(0, 25)-(0, 175), 1 : GET(0, 25)-(0, 175), B
20 LINE(0, 25)-(0, 175), 0
30 LINE(170, 0)-(470, 0), 1 : GET(170, 0)-(470, 0), C
40 LINE(170, 0)-(470, 0), 0
END PROCEDURE

PROCEDURE: Leftright
EXTERNAL: B, Rb, Lb
STRING: R[5], L[5], A[5]
INTEGER: X
10 R=CHR$(0)+CHR$(77) : L=CHR$(0)+CHR$(75)
20 X=50
30 PUT(X, 25), B, XOR
40 DO
50 A=INKEY$: IF A="" THEN GOTO 50
60 IF A=CHR$(27) THEN PUT(X, 25), B, XOR : EXIT
70 IF A=R THEN PUT(X, 25), B, XOR : X = X + 5 :
   PUT(X, 25), B, XOR
80 IF A=L THEN PUT(X, 25), B, XOR : X = X - 4 :
   PUT(X, 25), B, XOR
90 IF A="R" THEN Rb=X
100 IF A="L" THEN Lb=X
110 REPEAT
END PROCEDURE

PROCEDURE: Updown
EXTERNAL: C, U1, L1
STRING: U[5], D[5], A[5]
INTEGER: Y
10 U=CHR$(0)+CHR$(72) : D=CHR$(0)+CHR$(80)
20 Y=0
30 PUT(170, Y), C, XOR
40 DO
50 A=INKEY$: IF A="" THEN GOTO 50
60 IF A=CHR$(27) THEN PUT(170, Y), C, XOR : EXIT
70 IF A=D THEN PUT(170, Y), C, XOR : Y = Y + 5 :
   PUT(170, Y), C, XOR
80 IF A=U THEN PUT(170, Y), C, XOR : Y = Y - 4 :
   PUT(170, Y), C, XOR
90 IF A="U" THEN U1=Y
100 IF A="D" THEN L1=Y
110 REPEAT
PROCEDURE: Hessagel
EXTERNAL: Definewindow
STRING: K$[5]

PROCEDURE: Directory
END PROCEDURE

PROCEDURE: Directory
STRING: K$[5]
10 CLS
  20 PRINT "Which drive ? (A/B)"; SPC(20) "Hit <CR> to continue"
  30 K$=INKEY$: IF K$="" THEN GOTO 30
  40 IF K$=CHR$(13) THEN EXIT
      50 IF K$<>"A" AND K$<>"a" AND K$<>"B" AND K$<>"b" THEN GOTO 10
  60 IF K$="A" OR K$="a" THEN FILES"a:«.«" ELSE FILES"b:».»
  70 PRINT : PRINT : PRINT "Once Again ? (Y/N)"
  80 K$=INKEY$: IF K$="" THEN GOTO 80
  90 IF K$="Y" OR K$="y" THEN GOTO 10
END PROCEDURE

10 Definewindow
  20 SET CURSOR 10,14:PRINT "Hit 'd' for directory, any other keys to continue"
  30 K$=INKEY$: IF K$="" THEN GOTO 30
  40 IF K$="D" OR K$="d" THEN Directory
END PROCEDURE

PROCEDURE: Result
EXTERNAL: Definewindow, Anykey, P, W, Boxnum
INTEGER: I
STRING: K$[5]
10 Definewindow
  20 SET CURSOR 10,14:PRINT "Hit 'd' for directory, any other keys to continue"
  30 SET CURSOR 11,26:COLOR LTRED:PRINT "Counting has completed."
  40 SET CURSOR 18,25:COLOR LTGREEN:PRINT "Type any key to see result."
  40 SET CURSOR 18,25:COLOR LTGREEN:PRINT "<ESC> will bypass to the plot."
  50 K$=INKEY$: IF K$="" THEN GOTO 50
  60 IF K$=CHR$(27) THEN EXIT
  70 CLS : COLOR YELLOW
  80 FOR I = 0 TO Boxnum-1
  90 PRINT SPC(24) "W(";I;") =";W(I), "P(";I;") = ";P(I)
 100 NEXT
110 SET CURSOR 21,27:COLOR LTRED:PRINT "Type any key to see plot."
120 Anykey
END PROCEDURE
'MAIN Program:

10 '**** This is a Dilation Fractal Analysis. ****
20 Message1
30 Acqpic
40 Showpic
50 Setbound
60 Shrink
70 SetWidth
80 Counting
90 Result
100 Plot
110 GOTO 70

ENDFILE