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***Project Title*: Attrition and Changes in Size Distribution of Lime Sorbents During Fluidization in a Circulating Fluidized Bed Absorber**

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Abstract

The experimental data of lime sorbent attrition obtained from attriton tests in a circulating fluidized bed absorber (CFBA) are represented. The results are interpreted as both the weight-based attrition rate and size-based attrition rate. The weight-based attrition rate constants are obtained from a modified second-order attrition model, incorporating a minimum fluidization weight, W_{min}, and excess velocity. Furthermore, this minimum fluidization weight, or W_{min} was found to be a function of both particle size and velocity. A plot of the natural log of the overall weight-based attrition rate constants ($ln\ K_a$) for Lime 1 (903 MMD) at superficial gas velocities of 2 m/s, 2.35 m/s, and 2.69 m/s and for Lime 2 (1764 MMD) at superficial gas velocities of 2 m/s, 3 m/s, 4 m/s and 5 m/s versus the energy term, $1/(U-U_{mf})^2$, yielded a linear relationship. And, a regression coefficient of 0.9386 for the linear regression confirms that K_a may be expressed in Arrhenius form.

In addition, an unsteady state population model is represented to predict the changes in size distribution of bed materials during fluidization. The unsteady state population model was verified experimentally and the solid size distribution predicted by the model agreed well with the corresponding experimental size distributions. The model may be applicable for the batch and continuous operations of fluidized beds in which the solids size reduction is predominantly resulted from attritions and elutriations. Such significance of the mechanical attrition and elutriation is frequently seen in a fast fluidized bed as well as in a circulating fluidized bed.

I. Work Performed/Results Obtained

<u>Experimental Procedure.</u> The lime attrition tests were conducted in a bench scale circulating fluidized bed absorber (CFBA) shown in Figure 1, which was primarily constructed for the purpose of study on sulfur uptake of solid sorbents under low temperature conditions. Two discrete ranges of Dravo limes were used as solid sorbents for the attrition tests. The sizes of Lime 1 ranged between 595 μm (30 mesh) and 1095 μm (16 mesh), while those of Lime 2 ranged between 1095 μm (16 mesh) and 2380 μm (8 mesh). Since the lime samples supplied by the Dravo lime company were as big as about 1.3 cm in diameter, the sorbents were ground to two mass mean diameters (MMD) of 903 μm (Lime 1) and 1764 μm (Lime 2) with a Bico pulverizer (BICO co.). The fractional size distribution for the lime samples are shown in Figure 2. In addition, the lime sample is a high calcium quicklime formed by calcining limestone so that CO_2 is liberated. Its available lime was measured as about 90%, and a slaking test confirmed that the lime is very reactive. The physical and chemical properties of lime samples were measured or obtained from Dravo Company; results are shown in Figure 3.

For a single particle size attrition test, 500 g. of either Lime 1 or Lime 2 were charged into the CFBA so that the initial pressure drop in the bed reactor reached about 15.24 cm H_20. Air was used as the fluidizing gas at superficial gas velocities of 1.54 m/s - 2.69 m/s for Lime 1 and 2 m/s - 5 m/s for Lime 2, respectively. Since the gas velocities were much less than the terminal velocities (8 m/s for Lime 1 and 10 m/s for Lime 2), no elutriation of the parent solids was expected during fluidziation. All bed weight reduction was, therefore, attributed to attrition. During the test, the recirculating valve was closed to prevent the attritted fines from reentering the bed, which enabled the first cyclone to capture them. At regular time intervals (30 min., 1 hour, 2 hours, 3 hours, 5 hours, and 16 hours), the fluidization was stopped, and all the samples were collected from the bed and the first and second cyclone. These samples were then weighed and the extent of attrition was determined. Finally, the size distributions of bed materials were measured by a sieving method and a Coulter counter (Model TA II, Coulter Electronics, Inc.). For the measurement of size distribution, the lime samples ranging from 200 g. to 400 g. were placed onto the sievers and sieved for a fixed time of two minutes to prevent the size reduction of samples in the process of sieving. The lime samples are coarse enough to be separated by two minutes of sieving.

In addition to single particle sizes, three mixtures of Lime 1 and Lime 2 were studied:

**1/3 Lime 1 + 2/3 Lime 2
**1/2 Lime 1 + 1/2 Lime 2
**2/3 Lime 1 + 1/3 Lime 2

For these attrition tests, 500 g. of the mixture were charged into the CFBA and fluidized at regular time intervals (30 min., 1 hour, 2 hours, and 3 hours). With the exception of using air as the fluidizing gas with superficial gas velocities of 2 m/s - 3 m/s, the same procedure used for the single particle sizes was implemented for the mixture attritions.

Results and Discussion.

Attrition Rates

Attrition tests were carried out at room temperature with lime samples in a CFBA at a batch mode to see the fluid-induced attrition tendency. The fluidizing gas was air with superficial velocities of 1.54 m/s - 2.69 m/s for Lime 1, 2 m/s - 5 m/s for Lime 2, and 2 m/s- 3 m/s for mixtures of Lime 1 and Lime 2. Figures 4 and 5 show the weight reduction of the parent solids due attrition during fluidization in the CFBA for Lime 1 and Lime 2, respectively. This weight reduction occurs rapidly at the beginning of fluidization, continues, and finally levels off to reach a minimum weight, W_{min}, after 15 hours. Different Wmins were obtained for the different particle sizes at the same velocities (76% of the initial weight or 380 g. for Lime 1 at 2 m/s and 59% or 295 g. for Lime 2 at 2 m/s) and for the same particle size at different velocities (See Table 1). Thus, as shown in Figure 6, W_{min} is apparently a function of both particle size and velocity.

Table 1. Velocity dependence of Wmin for Lime 1 and Lime 2.

Lime 1		Lime 2	
Velocity	Wmin	Velocity	Wmin
1.54 m/s	78%	2 m/s	59%
2.0 m/s	76%	3 m/s	52%
2.35 m/s	71%	4 m/s	40%
2.69 m/s	56%	5 m/s	21%

The experimental data presented in Figures 4 and 5 suggest an exponential decrease of the weight of parent solids in a bed during fluidization. After evaluating several different attrition models, the best fit was obtained with the following second order model:

$$-\frac{dW}{dt}=k_a(W^2-W_{\min}^2) \tag{1}$$

where W is the weight of the parent solids in the bed (g.), W_{min} is the minimum weight with which the attrition may be negligible after a long fluidization (g.), and k_a is the attrition rate constant (sec^{-1}).

Because W_{min} is a strong function of velocity, an overall attrition rate constant, K_a, proportional to both the attrition rate constant, k_a, and the square of the excess velocity is suggested:

$$K_a=k_a(U-U_{mf})^2 \tag{2}$$

where U is the superficial gas velocity (m/sec), U_{mf} is the minimum fluidization velocity (m/sec), and K_a has units of ($m^2/(sec^3)$).

Substituting Equation (2) into Equation (1) yields the desired modified second-order attrition model:

$$-\frac{dW}{dt}=K_a\frac{(W^2-W_{\min}^2)}{(U-U_{mf})^2} \tag{3}$$

This modified second-order model satisfies four important conditions:

1. When $W = W_{min}$, $-dW/dt = 0$
2. When $U = U_{mf}$, $-dW/dt = 0$
3. The overall attrition rate increases with increasing velocity.
4. Higher attrition rates are obtained for smaller particle sizes at constant velocity, since Umf is smaller for the smaller sizes.

Integrating Equation (3) with the boundary conditions of $t=0, W=W_o$ and $t=t, W=W$ gives;

$$\frac{(U-U_{mf})^2}{2W_{\min}}\ln[\frac{W_o-W_{\min}}{W_o+W_{\min}}]-\ln[\frac{W-W_{\min}}{W+W_{\min}}]=K_at \tag{4}$$

The overall attrition rate constant, K_a, therefore, can be obtained from the slope of plotting Equation (4) versus time, t. The overall attrition rate constants, K_a, obtained from the slopes as shown in Figures 7 and 8 are listed in Table 2.

Table 2. Summary of Attrition Rate Constants for Lime 1 and Lime 2

Lime 1		Lime 2	
Velocity	K_a (sec^{-1})	Velocity	K_a (sec^{-1})
1.54 m/s	3.11e-07	2 m/s	7.99e-08
2.0 m/s	5.27e-07	3 m/s	6.43e-07
2.35 m/s	1.10e-06	4 m/s	1.52e-06
2.69 m/s	1.78e-06	5 m/s	2.67e-06

The experimental data obtained from the present attrition tests were compared with an attrition model expressing the overall attrition rate constant in an Arrhenius form, as described by Equations (5) and (6).

$$K_a = K_o \exp^{\frac{-E_a}{(U-U_{mf})^2}} \qquad (5)$$

$$-\frac{dW}{dt} = K_o \exp^{\frac{-E_a}{(U-U_{mf})^2}} \frac{(W^2 - W_{\min}^2)}{(U-U_{mf})^2} \qquad (6)$$

Finally, the linear relationship between $ln\ (K_a)$ and $-1/(U-U_{mf})^2$ as shown in Figure 9, indicates that the overall attrition rate constant, K_a, may be expressed in an Arrhenius form, and from the slope and y-intercept the attrition activation energy, E_a and K_o can be obtained as: $E_a = 3.8925 \times 10^{-3}$ KJ/kg and $K_o = 2.89 \times 10^{-6}$ sec^{-1}.

Comparisons between the mechanical attrition data obtained experimentally and the theoretical values computed with the attrition activation energy, E_a and K_o are illustrated in Figure 10-13. Figures 10 show the results for Lime 1, while those for Lime 2 are represented in Figures 11, 12, and 13. Based on these graphs, the theoretical weight loss of solids during fluidization at different gas velocities and solid sizes is in good agreement with observations.

Size Distributions of Lime Sorbents During Fluidization

A Fortran computer program, based on an unsteady state population model applicable to batch operation, was written to predict the changes in size distributions of lime sorbents during fluidization. The main program and output are listed in the Appendix. In the computer program, the fractional weights measured at discrete sizes are divided by the difference between the lower and upper ranges and multiplied by the size increment to give the initial fractional weight, $W_{i,0}$, at time, $t=0$ and each size, d_{pi}. In other words, the initial fractional weight at each size within the lower and upper ranges is assumed as the same. The terminal velocities for the computations of the elutriation rate at each size and time interval are obtained by trial and error, depending on the Reynolds number. The size and time interval may be smaller to give more accurate results, depending on the computer's capacity; size intervals greater than 40 μm and time increments greater 20 sec. may cause an unacceptable computation result.

The fractional size distribution curves obtained from the computations and corresponding measured size distribution after fluidizations of 30 minutes, 1 hour, 2 hours, and 3 hours are shown in Figures 14 -17. The size distributions computed by the unsteady state population model agree well with the experimental data, while slightly lower estimations occur at the lower size ranges because elutriations of solids are considered in the model.

The effect of gas velocity on the size distribution of solids is shown in Figures 18 and 19. For the output, the same operating conditions and an arbitrary initial size distribution are used at the different velocities. As shown in Figure 18, the initial fractional weight with normal gaussian distribution was chosen for the purpose of illustration. Figures 18 and 19 show that decreasing the rate of the mass mean diameter at the lower velocity (2 m/s) is greater than that at the higher velocity (4 m/s), while the size range at 2 m/s becomes much wider than at 4 m/s. This suggests that the solids that become smaller by attrition at the higher velocity are easily elutriated, and only relatively coarse solids remain in the bed as the fluidization time increases. As a result, the decreasing rate in MMDs of the remaining parent solids may be relatively slower at the higher velocity.

II. Unusual Problems/Circumstances

If a superficial gas velocity of less than 2 m/s (1.54 m/s) was used for Lime 2, about 75% -80 % of the lime sorbents would fall out of the bed through the gas distribution grid or screen after two - three hours of fluidization. Since a superficial gas velocity of 2 m/s or greater provided sufficient excess energy to prevent a significant amount of particles from falling through the screen, only the 2 m/s, 2.35 m/s, and 2.69 m/s attrition rate constants were used in the Arrhenius Plot; the 1.54 m/s attrition rate constant was neglected. Furthermore, considering the great influence of the type and size of holes of the gas distribution system on the attrition rate, the screen was not changed to accommodate lower velocities for Lime 1.

III. Tasks/Work to be Performed

An attrition model for various mixtures of Lime 1 and Lime 2 needs to be develop to describe both changes in final bed weight and changes in size distribution of the lime sorbents during fluidization. For both models, the dependence or independence of W_{min} and K_a for various compositions of Lime 1 and Lime 2 needs to analyzed.

List of Figure Captions

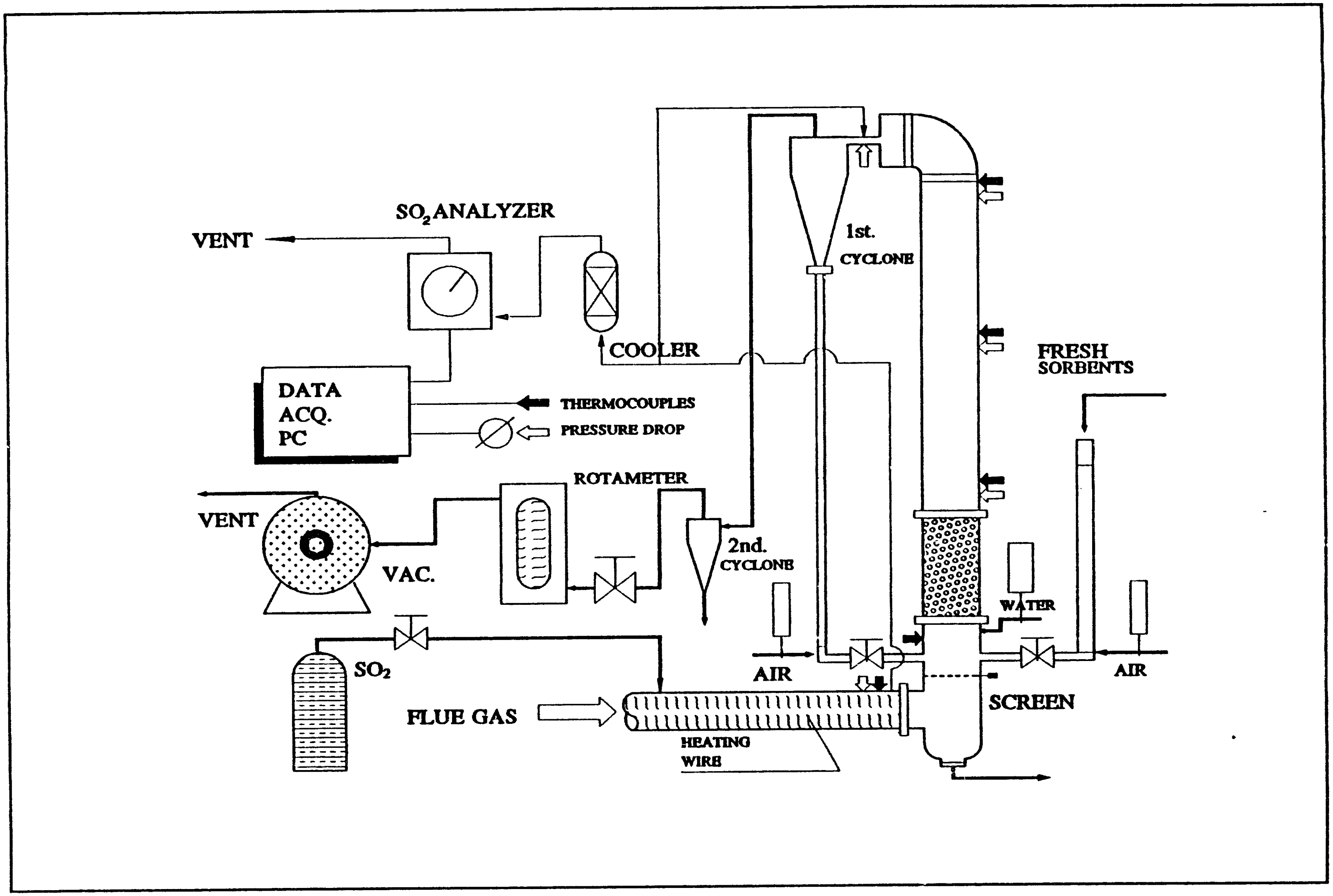


Figure 1. Scheme of bench scale CFBA unit

Figure 2. Fractional Size Distribution of Lime Samples

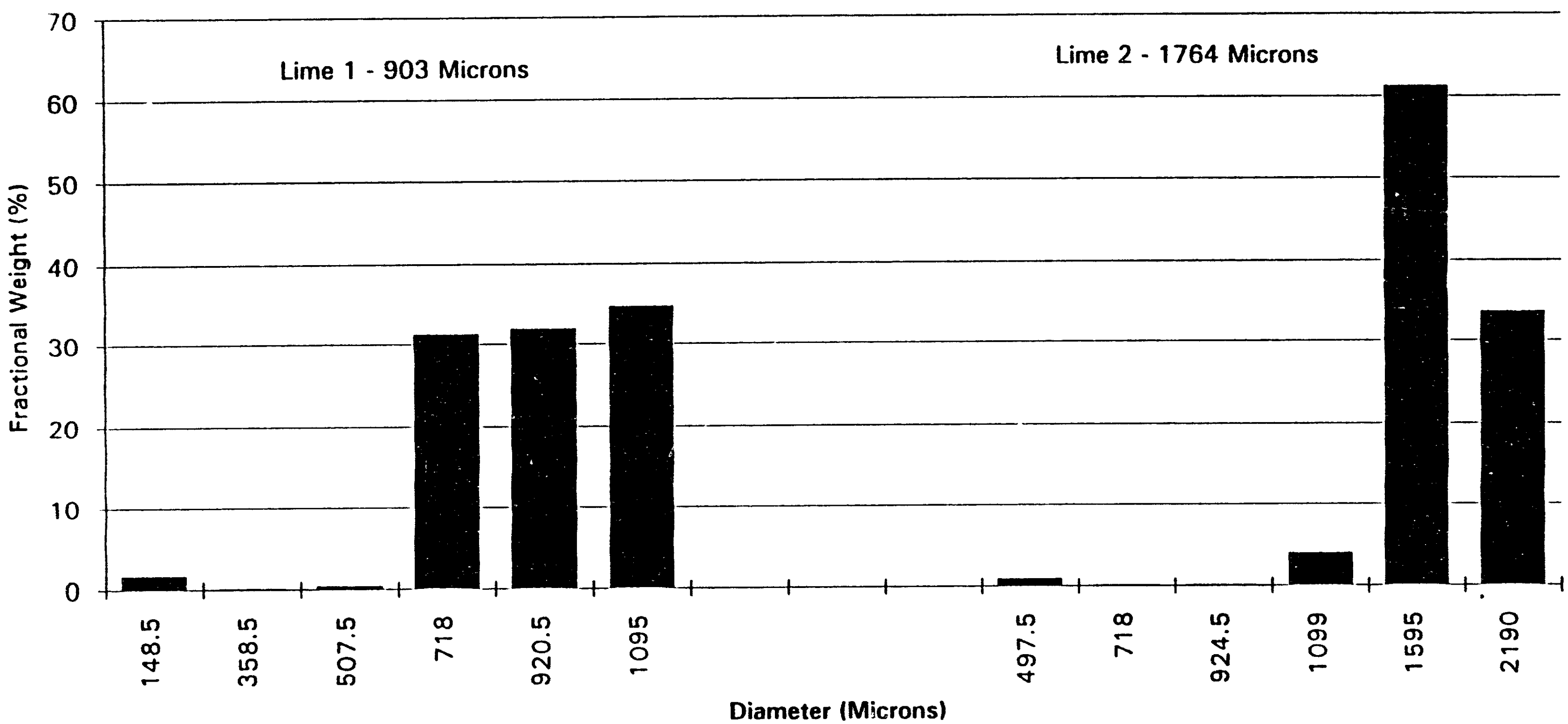


Figure 3. Physical and Chemical Properties of Lime Samples

Table 3.1 *Physical Properties of Lime Samples

Sample Numer	Mass Mean Dameter (Microns)	Surface Mean Diameter	Specific BET Surface Area (m^2/kg)	Bulk Density (kg/m^3)
Lime 1	903	820	1.36×10^3	1.28×10^3
Lime 2	1764	1682	1.27×10^3	1.45×10^3

* Measured

Table 3.2 **Chemical Properties of Lime Samples

Chemical Components	Weight %
Total CaO	93
Available CaO	87.5 - 88.5 (95*)
MgO	2.65 - 2.75
Sulfur	0.045 - 0.050
$CaCO_3$	1.1 - 1.2
H_20	0.4
SiO_2	1.95 - 2.05

* Measured
** Obtained from Dravo Lime Co.

Figure 4. Weight Remaining vs. Time for Attrition of 900 Micron Lime at Different Velocities

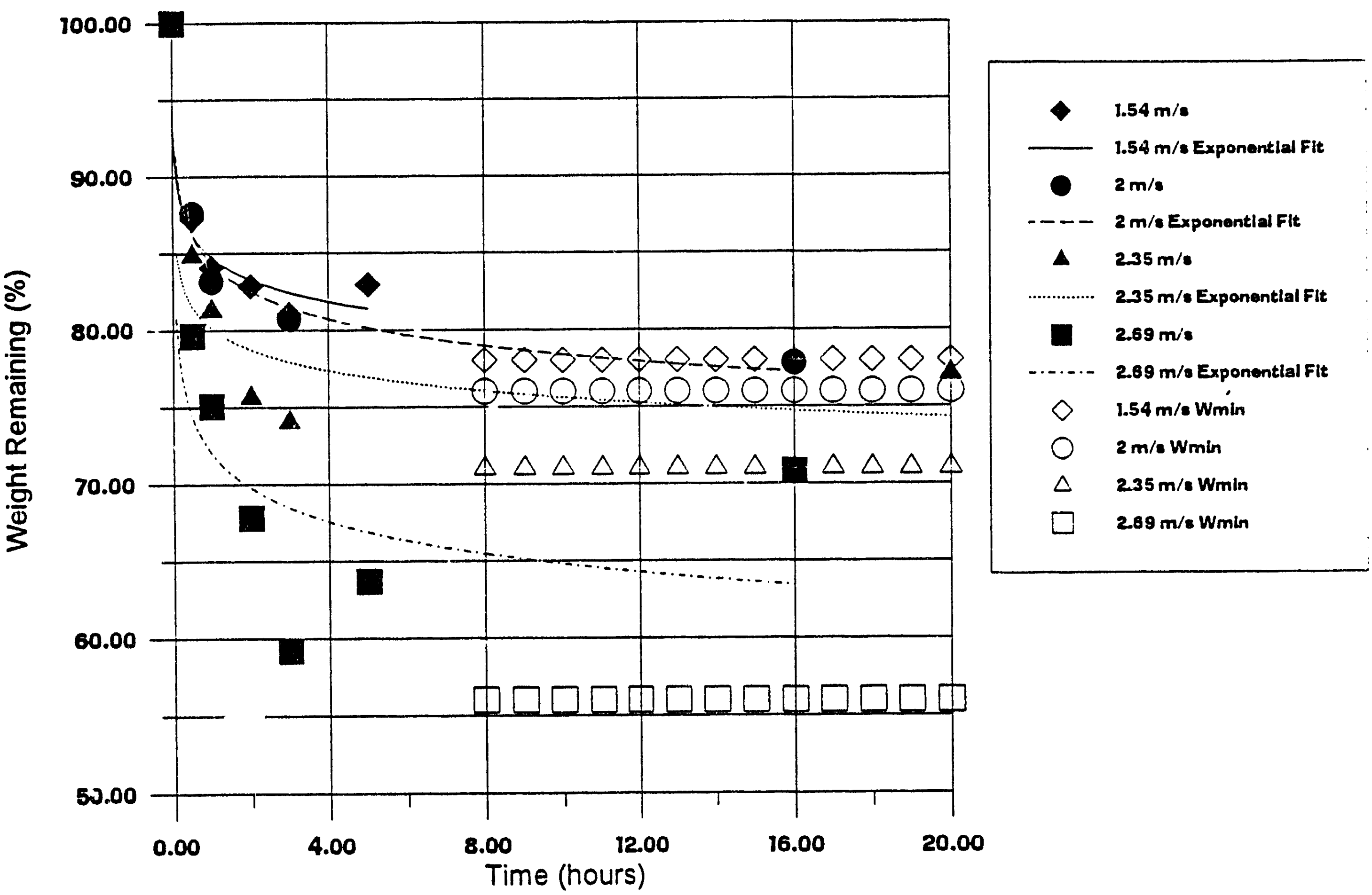


Figure 5. Weight Remaining vs. Time for Attrition of 1764 Micron Lime at Different Velocities

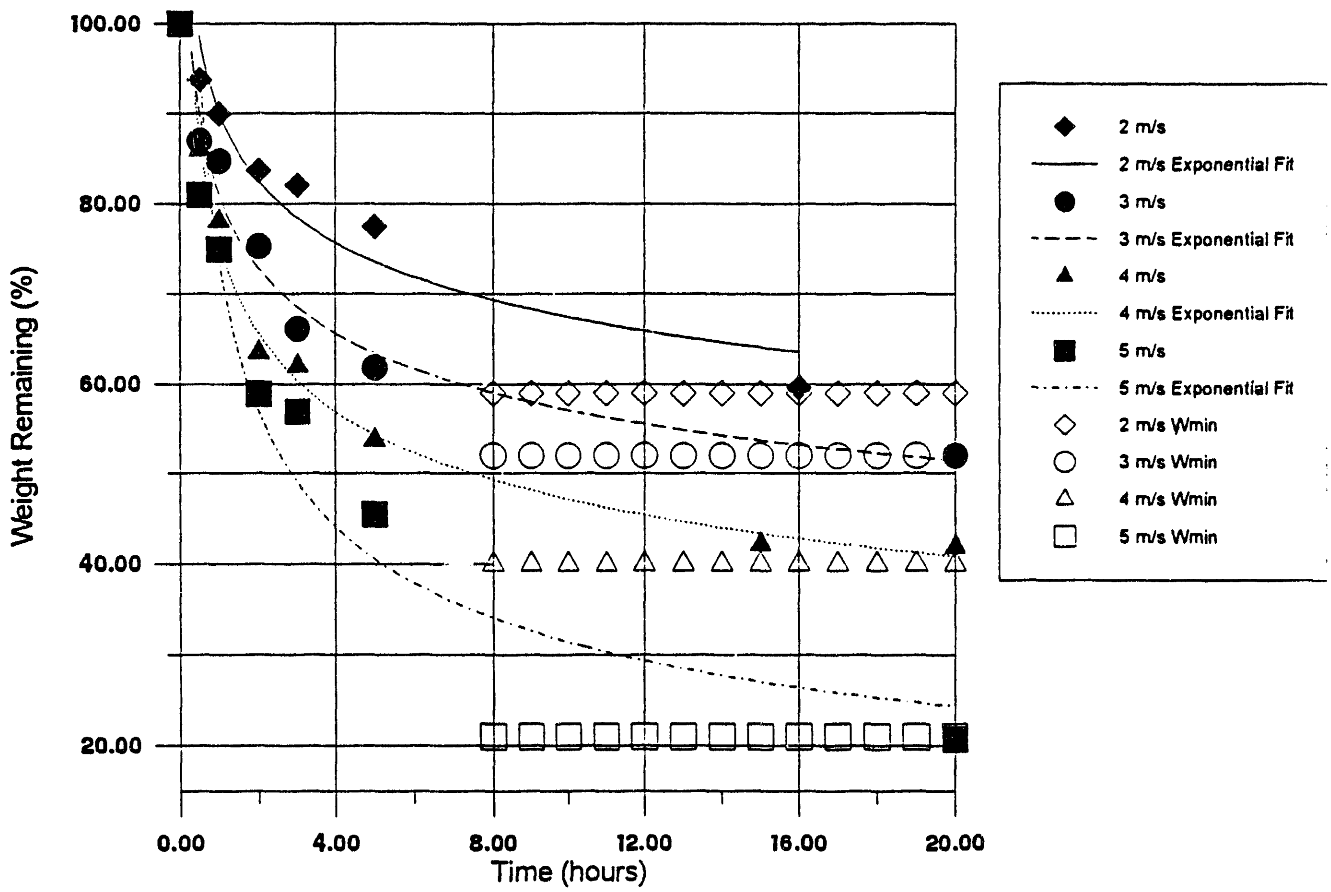


Figure 6. Wmin Dependence on Particle Size and Velocity

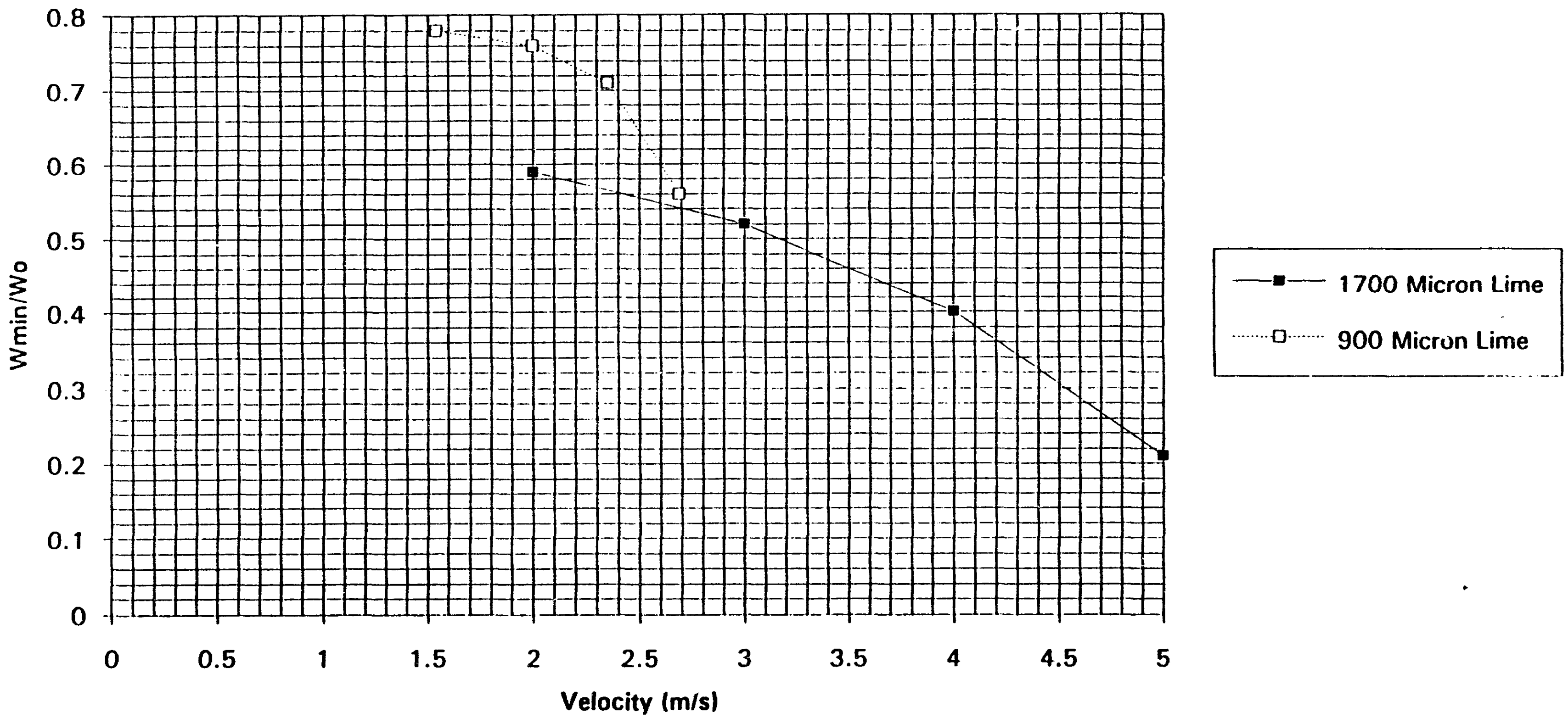


Figure 7. Modified Second Order Model for 900 Micron Lime with Experimental Wmins

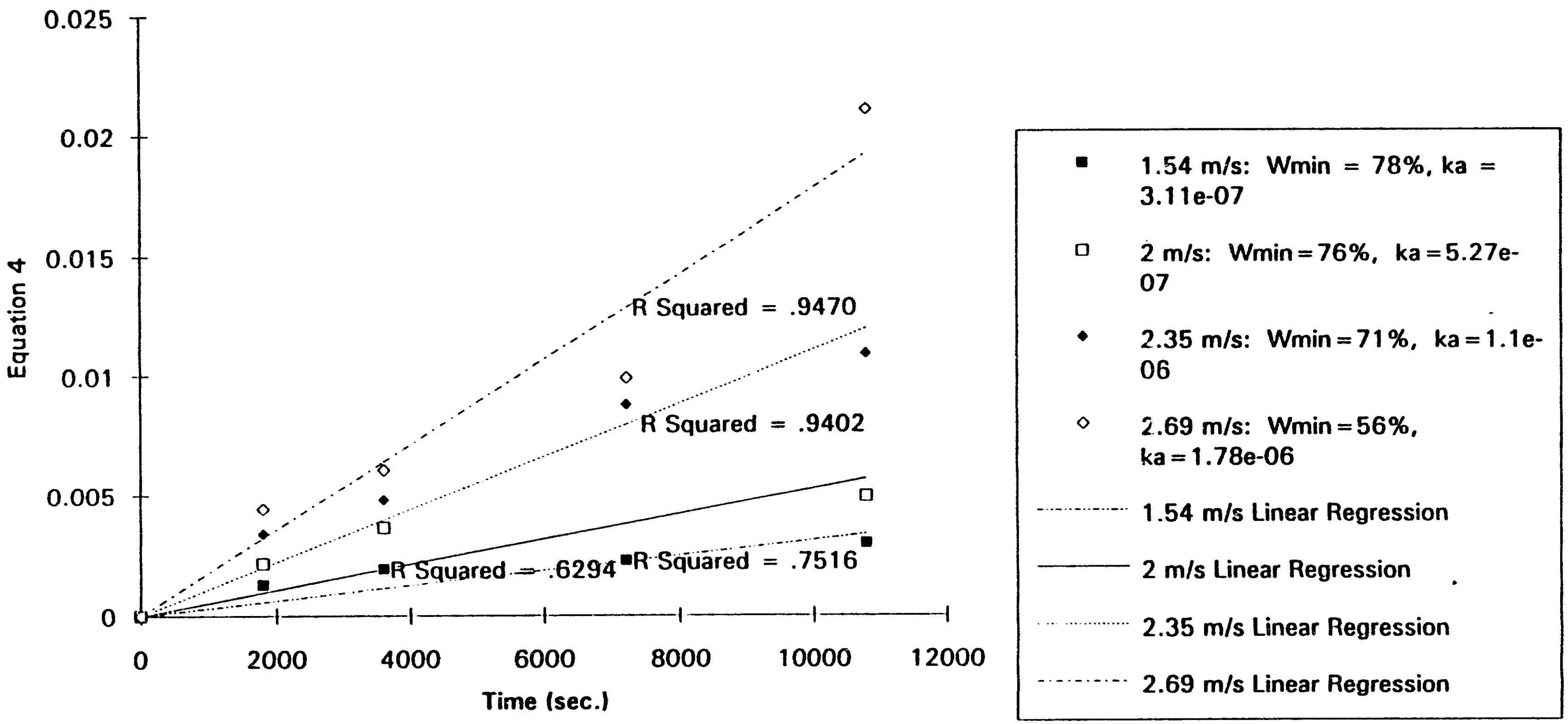
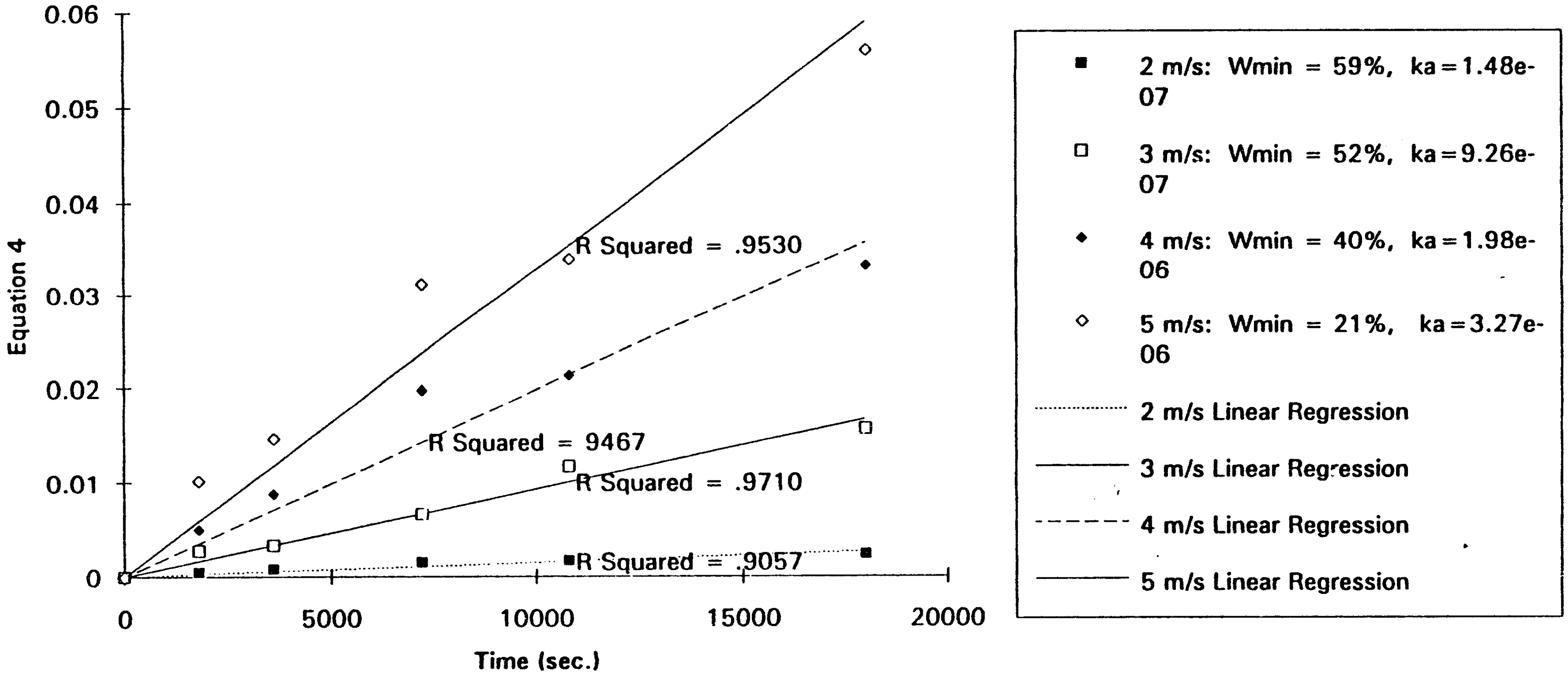


Figure 8. Modified Second Order Model for Attrition Rate Constants for 1764 Micron Lime with Experimental Wmins



Intercept = -12.7559 Slope = -4.22468 R Squared = .9386

Figure 9. Arrhenius Form for the Modified Second Order Model with Experimental Wmins for 1700 and 900 Micron Lime

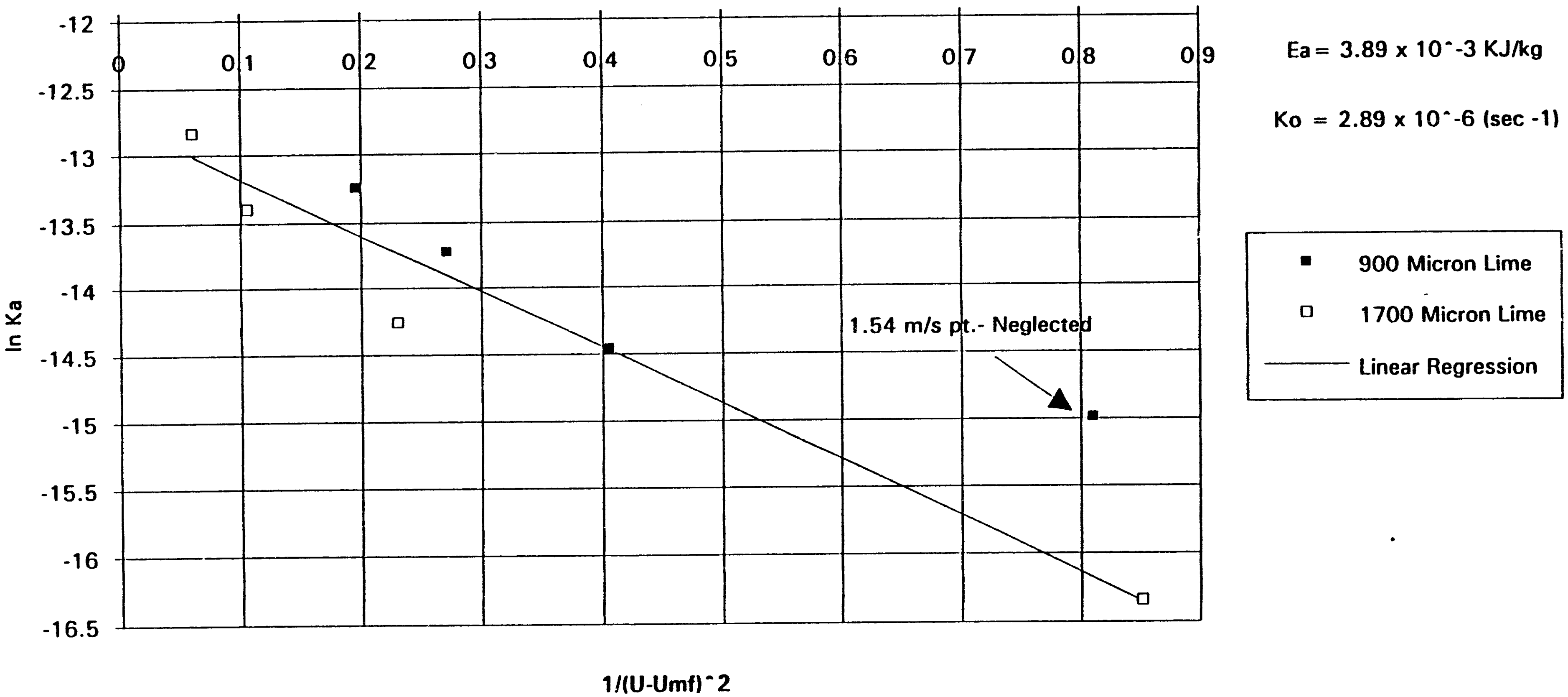


Figure 10. Weight Remaining vs. Time for 900 Micron Lime

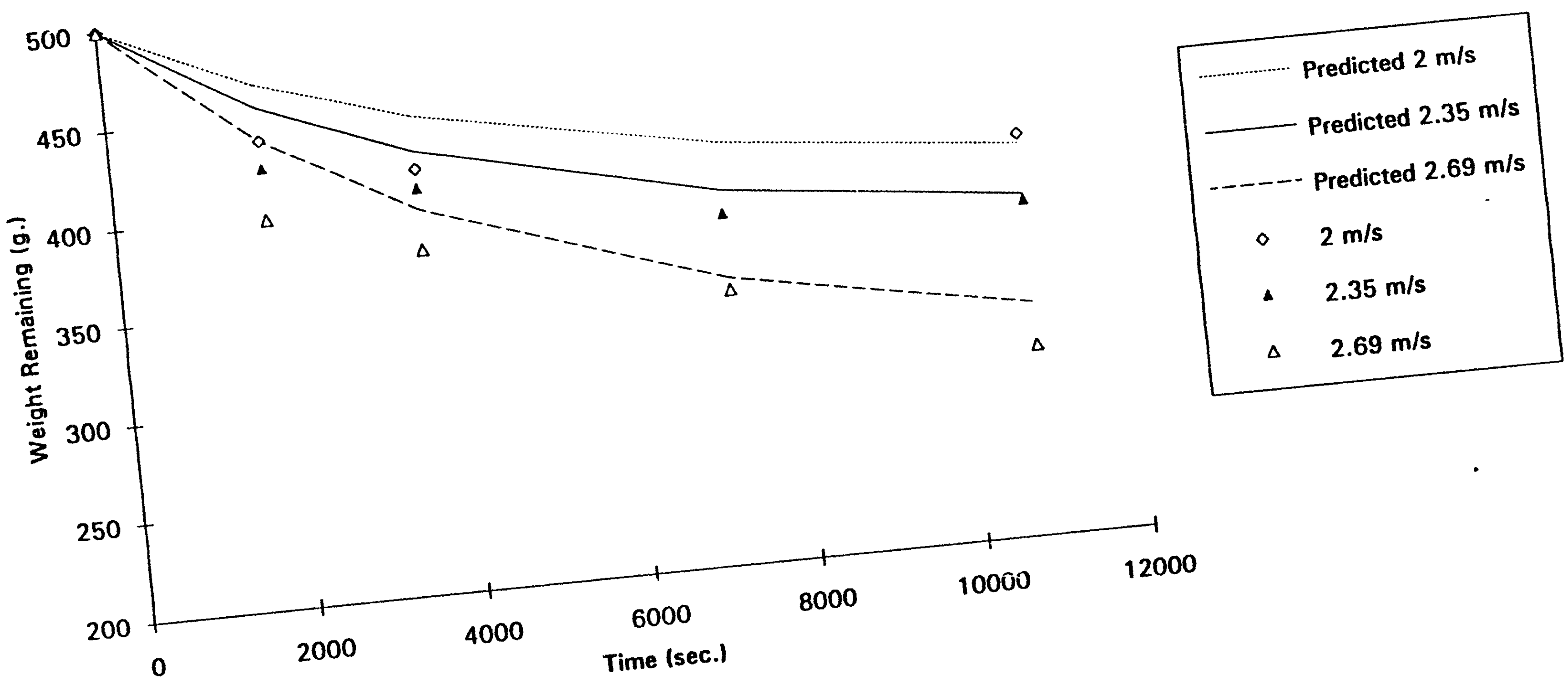


Figure 11. Weight Remaining vs. Time for 1764 Micron Lime at 2 m/s and 4 m/s

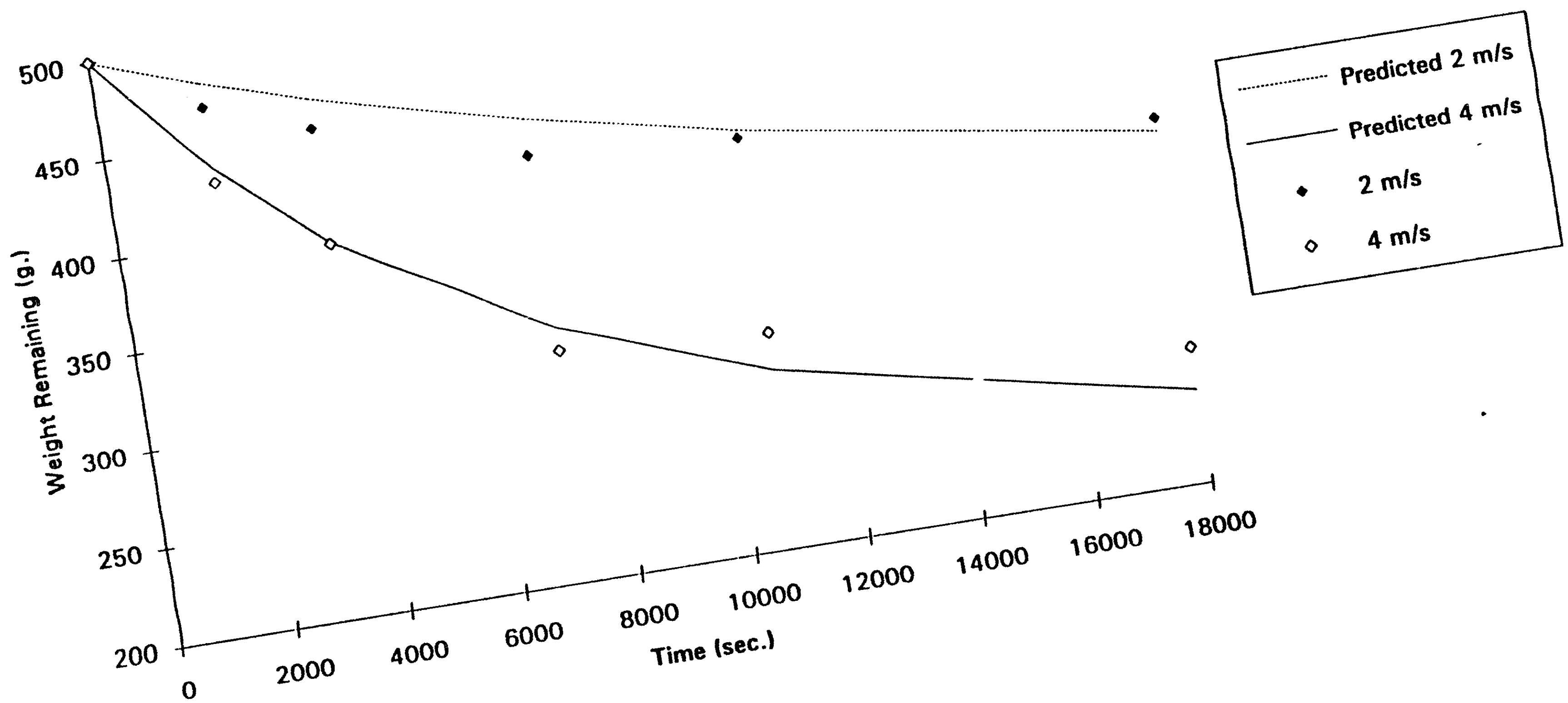


Figure 12. Weight Remaining vs. Time for 1764 Micron Lime at 3 m/s

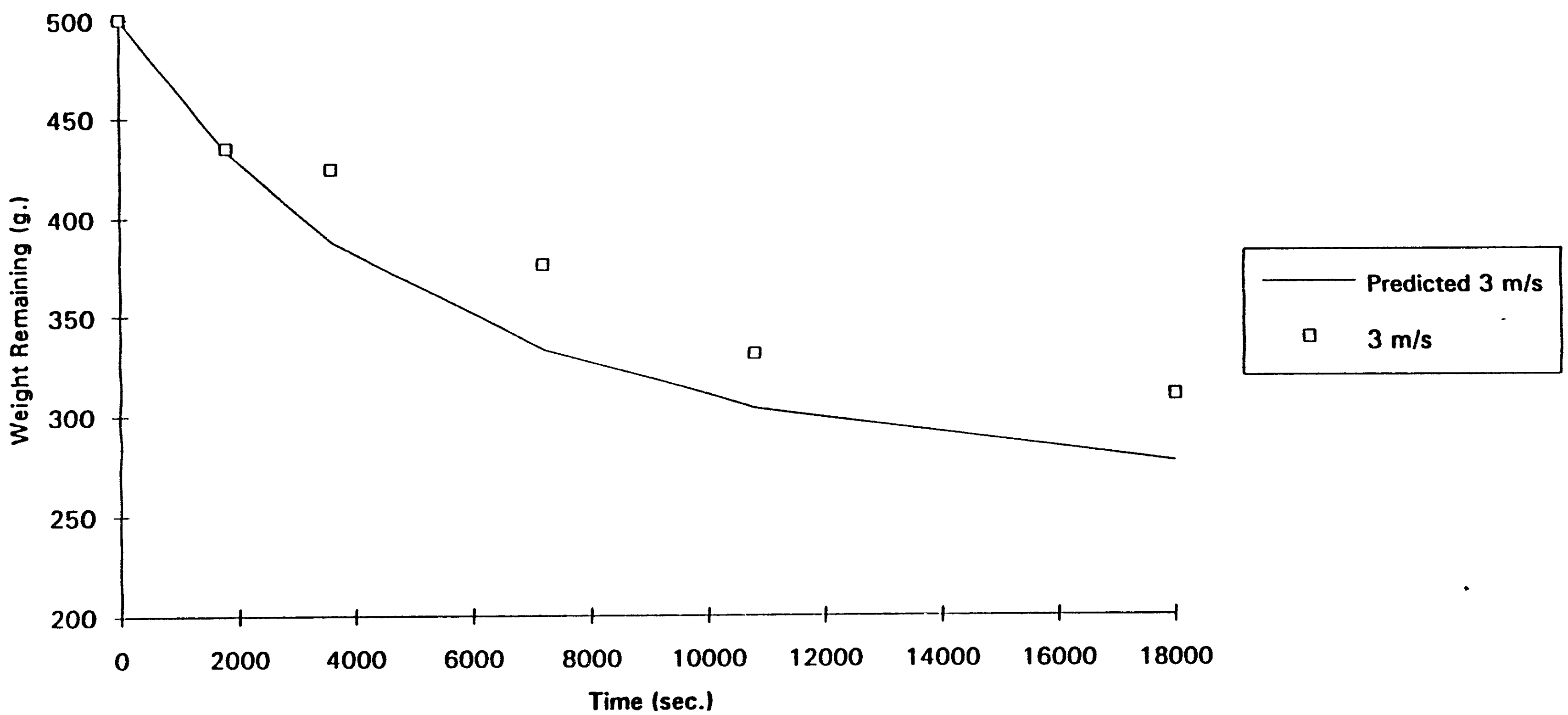


Figure 13. Weight Remaining vs. Time for 1764 Micron Lime at 5 m/s

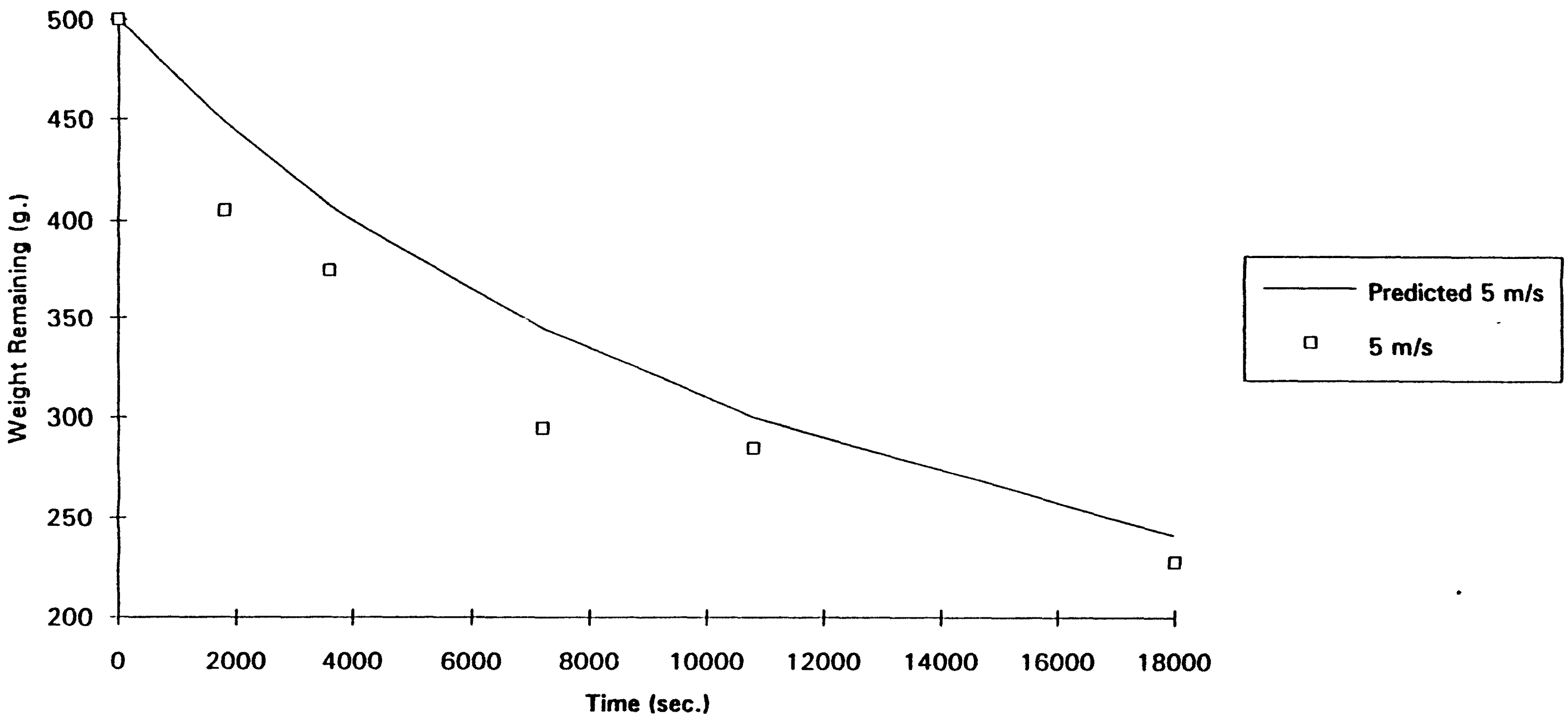
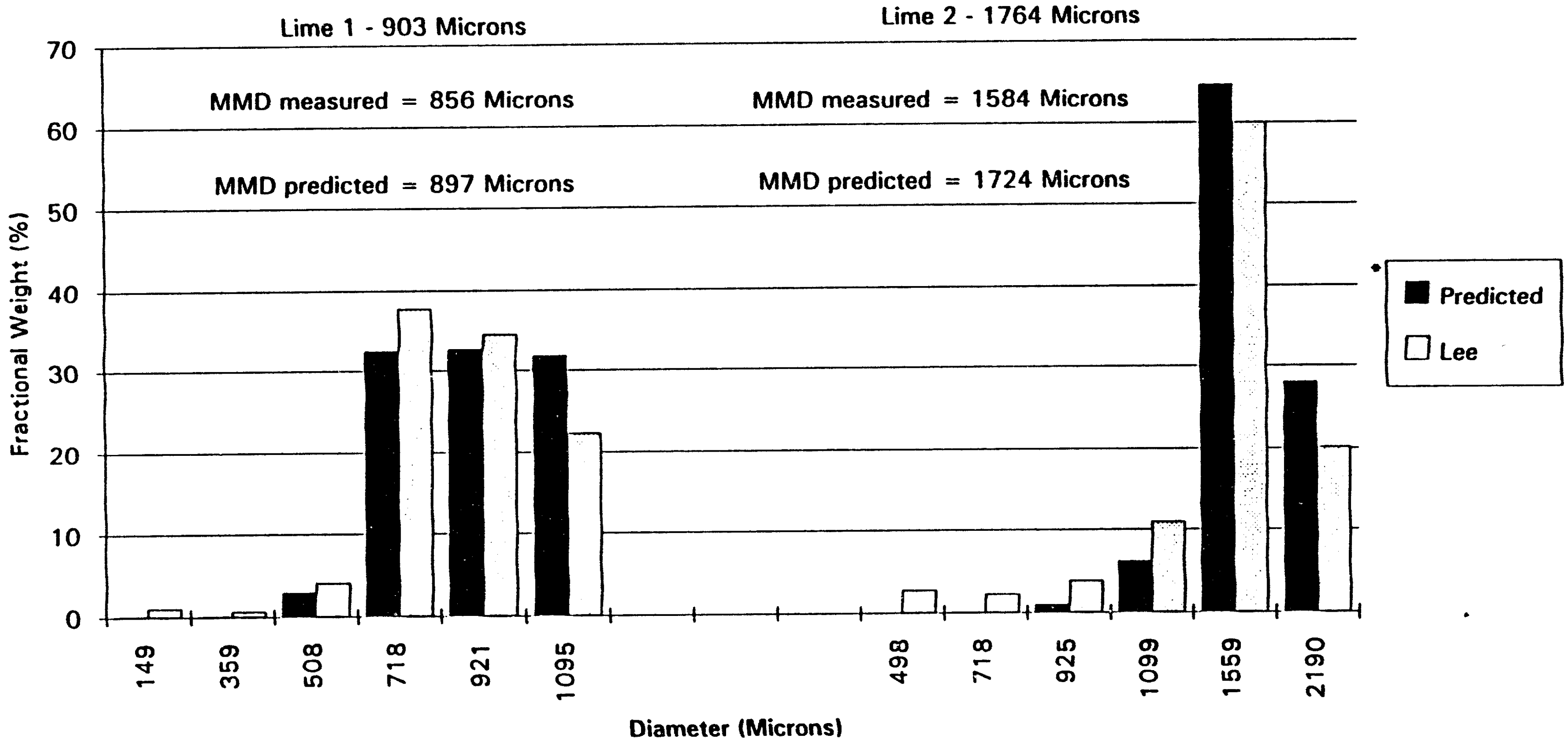


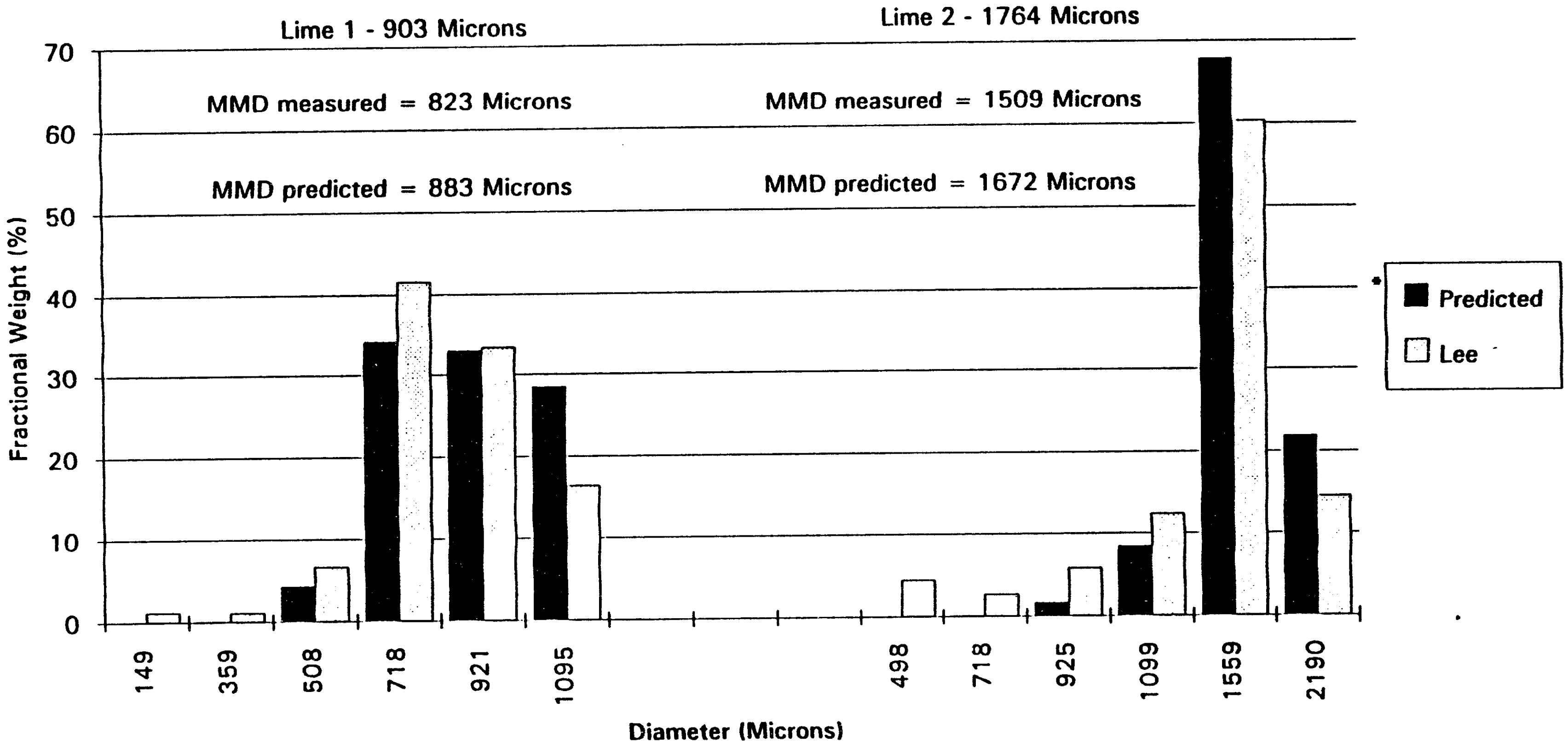
Figure 14. Size Distribution of Lime Sorbents after 30 Minutes of Fluidization



* Data from Sang-Kwun Lee's Dissertation, 1993

(u = 2 m/s for Lime 1 and u = 4 m/s for Lime 2)

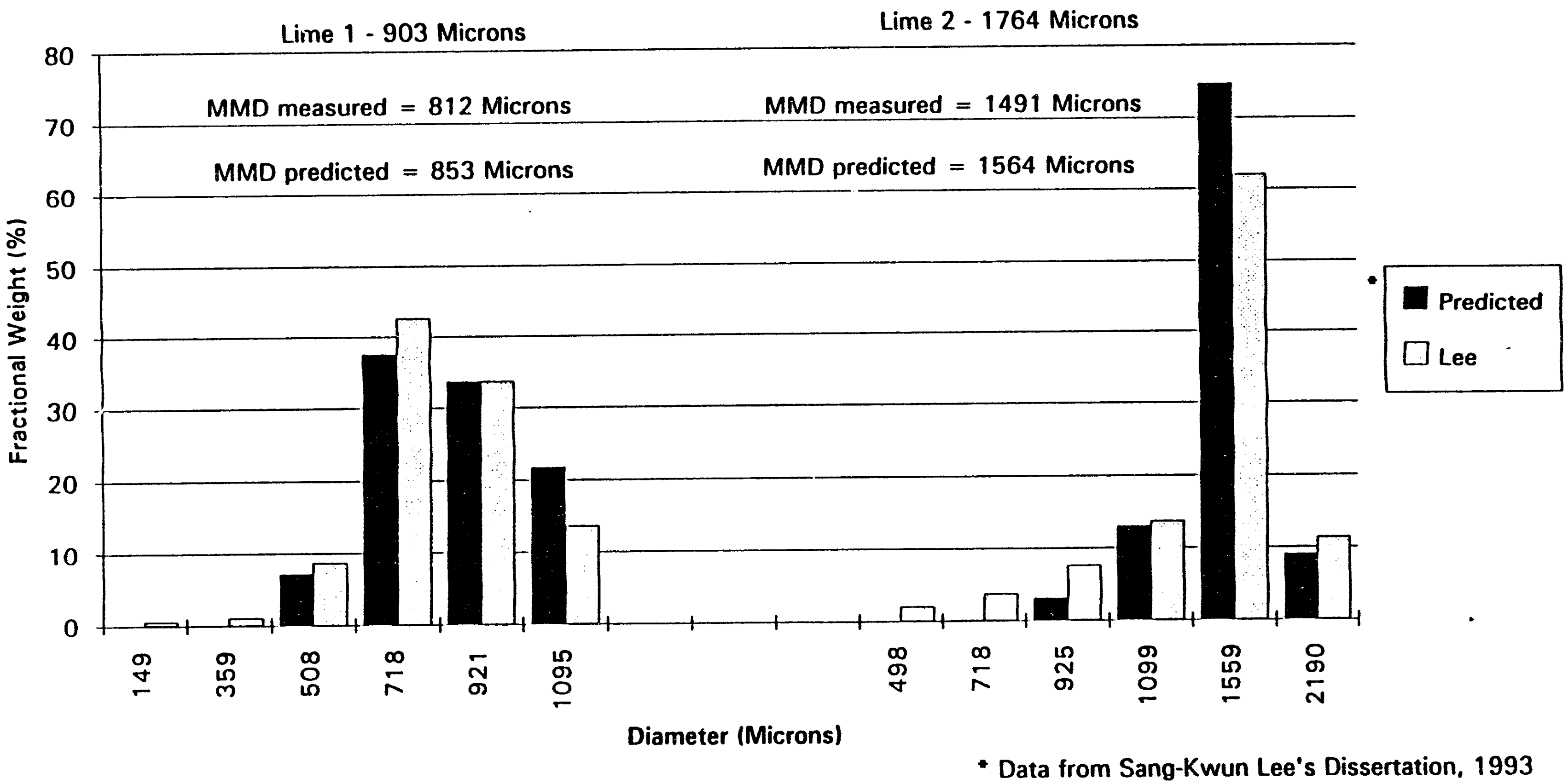
Figure 15. Size Distribution of Lime Sorbents after 1 Hour of Fluidization



* Data from Sang-Kwun Lee's Dissertation, 1993

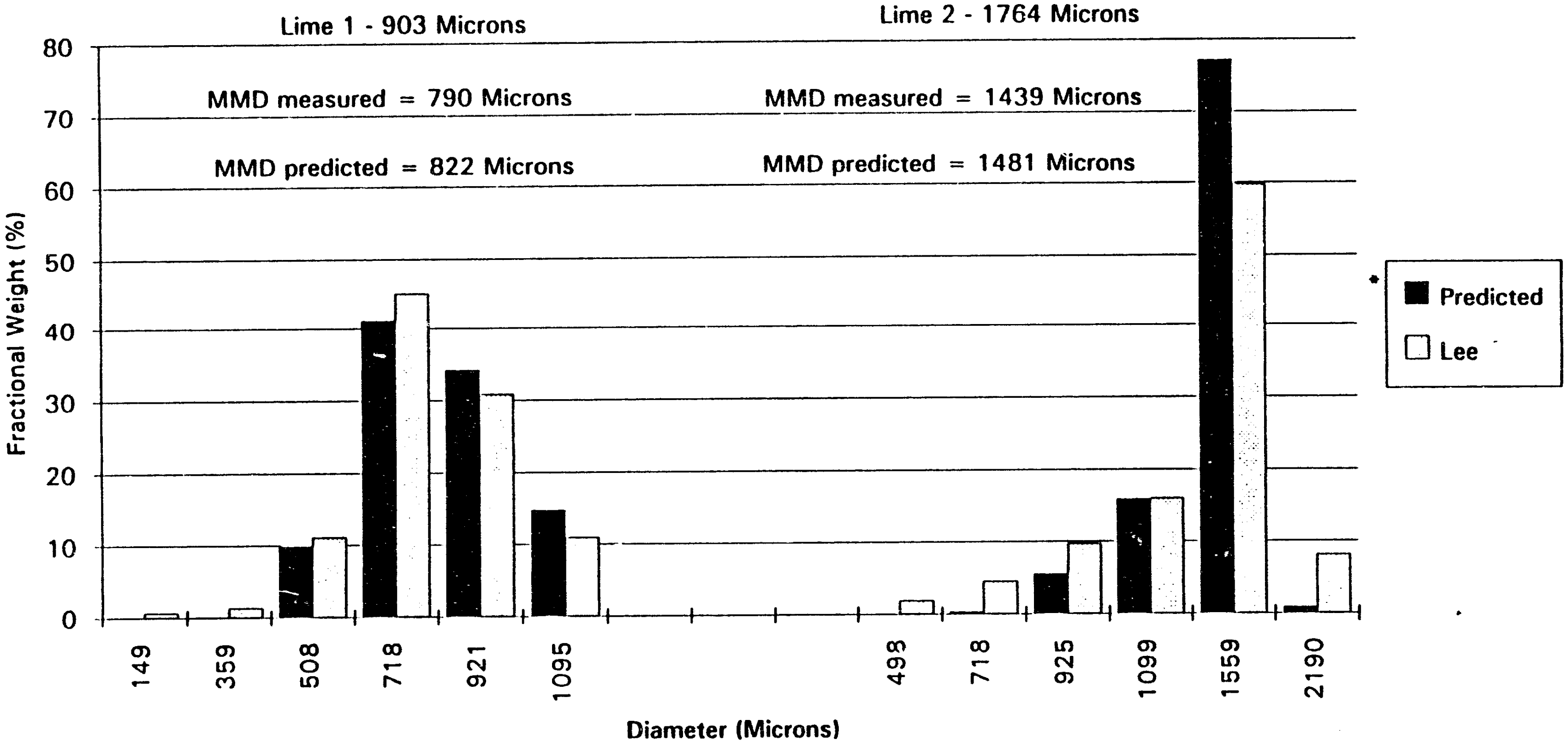
(u = 2 m/s for Lime 1 and u = 4 m/s for Lime 2)

Figure 16. Size Distribution of Lime Sorbents after 2 Hours of Fluidization



(u = 2 m/s for Lime1 and u = 4m/s for Lime 2)

Figure 17. Size Distribution of Lime Sorbents after 3 Hours of Fluidization



* Data from Sang-Kwun Lee's Dissertation, 1993

(u = 2 m/s for Lime 1 and u = 4 m/s for Lime 2)

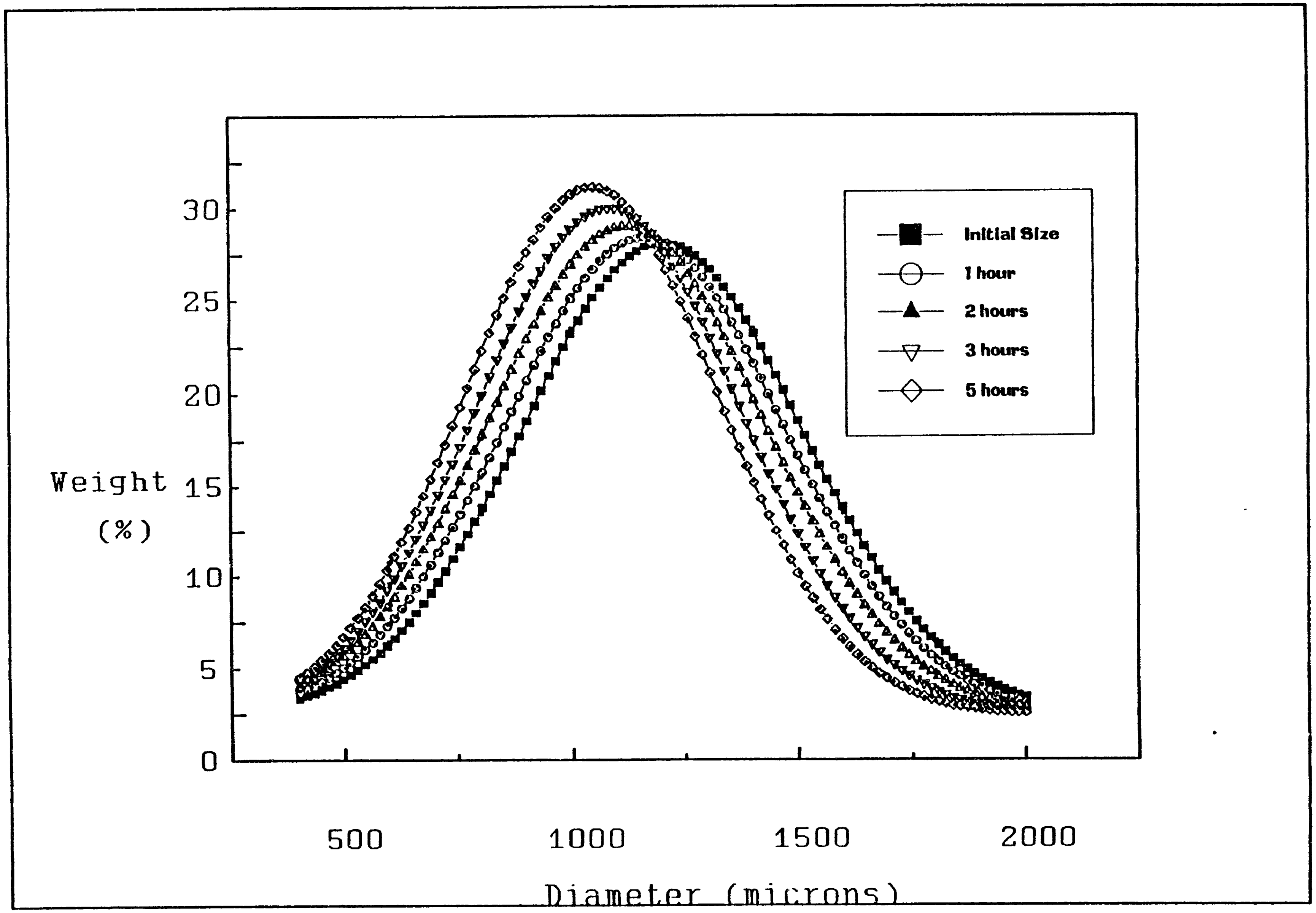


Figure 18. Changes of Solid Size Distribution at the Velocity of 2 m/s.

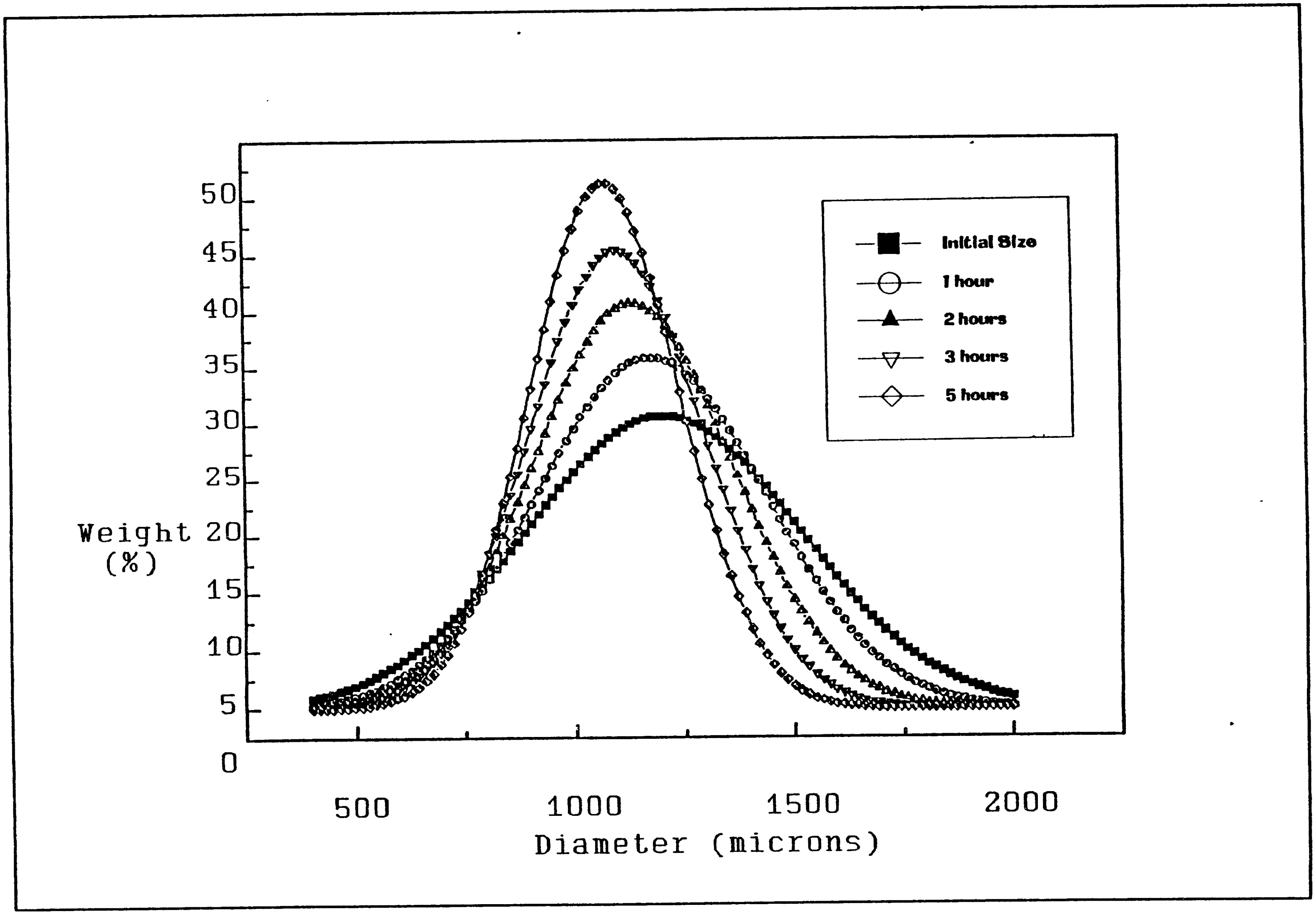


Figure 19. Changes of Solid Size Distribution at the Velocity of 4 m/s.

Appendix

Fortran Program

```fortran
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     THIS IS A MAIN PROGRAM FOR CFBA MODEL.  THE PROGRAM CALLS THE    C
C     FOLLOWING SUBROUTINES TO COMPUTE THE REMOVAL EFFICIENCY OF       C
C     SULFUR DIOXIDE IN A Circulating Fluidized Bed Absorber (CFBA).   C
C                                                                      C
C     CFBADAT : READ INPUT DATA                                        C
C     CFBAOUT : WRITE COMPUTATION RESULTS                              C
C     UMFTERM : COMPUTE MINIMUM FLUIDIZATION VELOCITY AND TERMINAL     C
C               VELOCITY                                               C
C     UNPOPUL : COMPUTE THE PARTIAL DIFFERENTIAL EQUATION IN AN        C
C               UNSTEADY-STATE POPULATION MODEL                        C
C     DIAG    : SOLVE THE TRIDIAGONAL EQUATIONS.  CALLED BY UNPOPUL.   C
C     CFBASO2 : DETERMINE THE SO2 REMOVAL EFFICIENCY                   C
C     CFBAWET : COMPUTE WETTING EFFICIENCY                             C
C     CFBADRY : COMPUTE EVAPORATION RATE OF DROPLETS                   C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


      IMPLICIT REAL*8 (A-H,O-Z)


      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
      COMMON/A3/N,Ntime
      COMMON/A4/dpAve,dpL1,dpH1,dpW1
      COMMON/A5/TITLE
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK


      REAL*8 dpAve(10),W(1000),dp(10),Ut(10),ReUt(10)
      REAL*8 dpL1(10),dpH1(10),dpW1(10),dpL(10),dpH(10),dpW(10)
      REAL*8 Umf(10),Umf1(10),Umf2(10)
      CHARACTER TITLE*60,WHICH1*6,WHICH2*6,WHICH3*6,CHECK*6

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     READ INPUT DATA                                                  C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBADAT

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     WRITE INPUT DATA                                                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBAOUT

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     COMPUTATION OF MINIMUM FLUIDIZATION AND TERMINAL VELOCITY        C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      Ndp=N
      DO 10 I=1,N
   10 dp(I)=dpAve(I)

      CALL UMFTERM(dp,Ndp,Ut,ReUt,Umf1,Umf2,Umf,0)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     WRITE Umf and Ut                                                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      CALL CFBAOUT
```

```
        DO 20 I=1,N
   20 WRITE(6,15)dpAve(I),Umf1(I)/100.,Umf2(I)/100.,ReUt(I),
     *Ut(I)/100.
   15 FORMAT(5X,3(F10.3),5X,2(F10.3)/)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     SOLUTION OF THE UNSTEADY STATE POPULATION MODEL                  C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
        CALL CFBAOUT

        Ddp=Ddp1
        Dt=Dt1
        DO 30 I=1,N
        dpL(I)=dpL1(I)
        dpH(I)=dpH1(I)
   30 dpW(I)=dpW1(I)

        CALL UNPOPUL(dpL,dpH,dpW,Ndp,W,Ddp,Dt)

        STOP
        END


CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     THIS SUBROUTINE READS INPUT DATA NECESSARY FOR COMPUTATIONS.     C
C     THE DATA CAN BE GIVEN THROUGH THE SCREEN OR DATA FILE.  THE      C
C     VARIABLES FOR INPUT DATA ARE DESCRIBED AS FOLLOWS :              C
C                                                                      C
C     dpAve(I)  : MEAN DIAMETER (microns)                              C
C     dpL(I)    : LOW LIMITS OF SIZE RANGES (microns)                  C
C     dpH(I)    : HIGH LIMITS OF SIZE RANGES (microns)                 C
C     dpW(I)    : WEIGHT OF SOLIDS AT EACH DISCRETE SIZE (g)           C
C     pDensity  : DENSITY OF SOLIDS (g/cm3)                            C
C     gDensity  : GAS DENSITY (g/cm3)                                  C
C     Viscosity: VISCOSITY OF GAS (g/cm/sec)                           C
C     Gravity   : GRAVITATIONAL CONSTANT (cm/sec2)                     C
C     BedDiam   : DIAMETER OF BED REACTOR (cm)                         C
C     BedHeight: HEIGHT OF BED REACTOR (cm)                            C
C     ETAc      : COLLECTION EFFICIENCY OF THE FIRST CYCLONE (%)       C
C     gVelocity: GAS VELOCITY (cm/sec)                                 C
C     N         : NUMBER OF DISCRETE SIZES                             C
C     Ka        : ATTRITION RATE CONSTANT (/sec)                       C
C     Ddp1      : SIZE INTERVAL FOR POPULATION MODEL (microns)         C
C     Dt1       : TIME INTERVAL FOR POPULATION MODEL (sec)             C
C     Ntime     : NUMBER OF ITERATION FOR POPULATION MODEL             C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC



        SUBROUTINE CFBADAT

        IMPLICIT REAL*8 (A-H,O-Z)

        COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
        COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
        COMMON/A3/N,Ntime
        COMMON/A4/dpAve,dpL1,dpH1,dpW1
        COMMON/A5/Title
```

```
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

      REAL*8 dpAve(10),dpL1(10),dpH1(10),dpW1(10),Ka

      CHARACTER TITLE*60,WHICH1*6,WHICH2*6,WHICH3*6,CHECK*6

      WRITE(*,1)
    1 FORMAT(////////////////
     *       5X,'                                                    '/
     *       5X,'                                                    '/
     *       5X,'THIS PGM IS USED FOR OPERATIONS OF FLUIDIZED BED.  '/
     *       5X,'                          by                        '/
     *       5X,'                     SANG-KWUN LEE                  '/
     *       5X,'                UNIVERSITY OF CINCINNATI            '/
     *       5X,'      CIVIL & ENVIRONMENTAL ENGINEERING DEPT.       '/
     *       5X,'                 CINCINNATI, OH 45219               '/
     *       5X,'                    (513) 556-3687                  '/
     *       5X,'                                                    '/
     *       5X,'                                                    '/
     *       5X,'                                                    '///
     *       5X,'      Strike the RETURN key to continue....     '/////)
      READ(*,*)
   50 FORMAT(A6)
      WRITE(*,2)
    2 FORMAT(//////////4X, '                                      '/
     *       5X, '           DO YOU WANT TO RUN THIS PROGRAM          '/
     *       5X, '         WITH DATA FILE NAMED AS "CFBA.DAT" ?       '/
     *       5X, '                                                    '/
     *       5X, '                       Enter (Y/N)        '///////////)

      READ(*,3)WHICH1
    3 FORMAT(A6)
      IF(WHICH1.EQ.'Y'.OR.WHICH1.EQ.'y')GO TO 100
    9 WRITE(*,12)
   12 FORMAT(/////////////////////////////////1X,'Enter TITLE, and strike
     * RETURN key to continue... ')
      READ(*,150)TITLE
  150 FORMAT(A60)
      WRITE(*,*)'How many dpAve (MMD or SMD) do you have ?'
      READ(*,*)N
      DO 10 I=1,N
      WRITE(*,11)I
   11 FORMAT(1X,'Enter (',I2,') Low and High Limits, Mean (microns), and
     * Weight (g) of discrete sizes')
   10 READ(*,*)dpL1(I),dpH1(I),dpAve(I),dpW1(I)
      WRITE(*,*)'Enter Particle Density (g/cm3)'
      READ(*,*)pDensity
      WRITE(*,*)'Enter Gas Density : 1.2046E-3(g/cm3)'
      READ(*,*)gDensity
      WRITE(*,*)'Enter Viscosity : 1.78E-4 (g/cm/sec)'
      READ(*,*)Viscosity
      WRITE(*,*)'Enter Gravitational Constant : 980.66(cm/sec2)'
      READ(*,*)Gravity
      WRITE(*,*)'Enter Bed Diameter (cm)'
      READ(*,*)BedDiam
      WRITE(*,*)'Enter Bed Height (cm)'
      READ(*,*)BedHeight
      WRITE(*,*)'Enter collection efficiency of the first cyclone (%)'
      READ(*,*)ETAc
      WRITE(*,*)'Enter Gas Velocity (cm/sec)'
```

```
      READ(*,*)gVelocity
      WRITE(*,*)'Enter Attrition Rate Constant (/sec)'
      READ(*,*)Ka
      WRITE(*,*)'Enter size interval (microns) for the population model'
      READ(*,*)Ddp1
      WRITE(*,*)'Enter time interval (sec) for the population model'
      READ(*,*)Dt1
      WRITE(*,*)'Enter number of iteration based on time for P-Model'
      READ(*,*)Ntime
      CHECK='CHECK'

      CALL CFBAOUT

      WRITE(*,*)'The input data are correct? (Y or N)'
      READ(*,50)CHECK
      IF(CHECK.EQ.'N'.OR.CHECK.EQ.'n')GO TO 9

      WRITE(*,22)
 22   FORMAT(//////////,4X,'    Which equation do You want to use for'/,
     *       5X,'   MINIMUM FLUIDIZATION VELOCITY ?                     '/,
     *       5X,'                                                       '/,
     *       5X,'   Enter -"Y" for YEN & YU"s eqn OR "B" for BABU"s eqn'
     */////////////)
      READ(*,50)WHICH2
      WRITE(*,23)
 23   FORMAT(///////////,4X,'    Do You want to write the MINIMUM FLUIDI
     *ZATION'/5X,'   VELOCITY & TERMINAL VELOCITY ?                  '/,
     *       5X,'                                                    '/,
     *       5X,'      Enter (Y/N)   '/////////////)
      READ(*,50)WHICH3
      WRITE(*,24)
 24   FORMAT(////////////////1X,'                     Please wait.............'
     *//////////////)
      GO TO 200

100   READ(5,150)TITLE
      READ(5,*)N
      DO 20 I=1,N
 20   READ(5,*)dpL1(I),dpH1(I),dpAve(I),dpW1(I)
      READ(5,*)pDensity
      READ(5,*)gDensity
      READ(5,*)Viscosity
      READ(5,*)Gravity
      READ(5,*)BedDiam
      READ(5,*)BedHeight
      READ(5,*)ETAc
      READ(5,*)gVelocity
      READ(5,*)Ka
      READ(5,*)Ddp1
      READ(5,*)Dt1
      READ(5,*)Ntime
      READ(5,50)CHECK
      READ(5,50)WHICH2
      READ(5,50)WHICH3

200   RETURN
      END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     THIS SUBROUTINE WRITES THE COMPUTATION RESULTS AS WELL AS INPUT  C
C     DATA.                                                            C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

         SUBROUTINE CFBAOUT

         IMPLICIT REAL*8 (A-H,O-Z)

         COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
         COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
         COMMON/A3/N,Ntime
         COMMON/A4/dpAve,dpL1,dpH1,dpW1
         COMMON/A5/TITLE
         COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

         REAL*8 dpAve(10),dpL1(10),dpH1(10),dpW1(10),Ka

         CHARACTER TITLE*60,WHICH1*6,WHICH2*6,WHICH3*6,CHECK*6

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     WRITE THE INPUT DATA                                             C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
         IF(CHECK.EQ.'POPUL1')GO TO 15
         IF(CHECK.NE.'CHECK')GO TO 3
         WRITE(*,4)TITLE
         WRITE(*,6)
         DO 1 I=1,N
    1 WRITE(*,5)I,dpL1(I),dpH1(I),dpAve(I),dpW1(I)
         WRITE(*,8)pDensity,gDensity,Viscosity,Gravity,BedDiam,BedHeight,ET
     *Ac,gVelocity,Ka,Ddp1,Dt1,Ntime
         GO TO 100

    3 IF(CHECK.EQ.'N'.OR.CHECK.EQ.'n')GO TO 10
         WRITE(6,4)TITLE
    4 FORMAT(/75('-')/5X,'TITLE = ',A60/75('-')//)
         WRITE(6,6)
    6 FORMAT(///75('-')/5X,'DATA INPUT'/75('-')//29x,'Minimum ',4x,
     *'Maximum ',2x,'Mean (um) ',2x,'Weight (%)  ')
         DO 2 I=1,N
    2 WRITE(6,5)I,dpL1(I),dpH1(I),dpAve(I),dpW1(I)
         WRITE(6,8)pDensity,gDensity,Viscosity,Gravity,BedDiam,BedHeight,ET
     *Ac,gVelocity,Ka,Ddp1,Dt1,Ntime
    5 FORMAT(5X,'Particle Dia.(',I2,')   =',4(F10.3,2x))
    8 FORMAT(/5X,'Density of Particle        =',F15.3,'    (g/cm3)'/
     *       5X,'Density of Gas             =',E15.3,'    (g/cm3)'/
     *       5X,'Viscosity                  =',E15.3,'    (g/cm/sec)'/
     *       5X,'Gravitational Constant     =',F15.3,'    (cm/sec2)'/
     *       5X,'Bed Diameter               =',F15.3,'    (cm)'/
     *       5X,'Bed Height                 =',F15.3,'    (cm)'/
     *       5x,'Efficiency of 1st cyclone  =',F15.3,'    (%)'/
     *       5x,'Gas Velocity               =',F15.3,'    (cm/sec)'/
     *       5x,'Attrition Rate Constant    =',F15.8,'    (/sec)'/
     *       5x,'Size Interval              =',F15.3,'    (microns)'/
     *       5x,'Time Interval              =',F15.3,'    (sec)'/
     *       5x,'Number of Iteration        =',I11)
         CHECK='N'
         GO TO 100
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     PRINT Umf, and TERMINAL VELOCITY                                 C
```

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

   10 IF(WHICH3.EQ.'N'.OR.WHICH3.EQ.'n')GO TO 100
      WRITE(6,11)
   11 FORMAT(1H1///70('-')/5X,'MINIMUM FLUIDIZATION VELOCITY AND TERMINA
     *L VELOCITY'/70('-')//)
      WRITE(6,12)
   12 FORMAT(5X,'  Particle   Minimum Fluidization    Terminal  Velocity
     *'/5X,'  Diameter   Velocity (m/sec)              (m/sec)'/
     *5X,'  (microns)  -------------------      -------------------'/
     *5X,'                  Yen       Babu          Re #         Ut    '/
     *5X,'  ------------------------------------------------------------'/)
      CHECK='POPUL1'
      GO TO 100
   15 WRITE(6,16)('MMD =',dpAve(I),I=1,N)
   16 FORMAT(1H1////5x,'Changes in size distributions of solids in a bed
     * as a function of time'/5x,70('-')///2x,'Time(min)',1x,'Tot-Wt(g)'
     *,1x,9(A6,F5.0,2x))

  100 RETURN
      END
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C     THE SUBROUTINE, DIAG(A,B,C,NR) SOLVES THE TRIDIAGONAL EQUATION,  C
C     WHICH CONSISTS OF A TRIDIAGONAL MATRIX.                          C
C     A(NR) AND B(NR) ARE COEFFICIENTS OF ELEMENTS, AND C(NR) ARE THE  C
C     N-UNKNOWN VARIABLES TO BE DETERMINED.  AFTER THE COMPUTATION IS  C
C     COMPLETED, THE SOLUTION IS STORED IN ARRAY C(1), C(2)...C(NR).   C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      SUBROUTINE DIAG(A,B,C,NR)
      REAL*8 A(NR),B(NR),C(NR)

      C(NR)=C(NR)/A(NR)
      DO 100 I=NR-1,1,-1
  100 C(I)=(C(I)-B(I)*C(I+1))/A(I)
      RETURN
      END

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C     THIS SUBROUTINE COMPUTES THE MINIMUM FLUIDIZATION VELOCITY AND   C
C     TERMINAL VELOCITY.  TWO EMPIRICAL EQUATIONS FOR THE MINIMUM      C
C     FLUIDIZATION VELOCITY IS GIVEN AND CAN BE CHOSEN BY USER.        C
C     THE SUBROUTINE NEEDS THE FOLLOWING VARIABLES :                   C
C                                                                      C
C     dp(Ndp)= DIAMETER OF SOLIDS                                      C
C     Ndp    = NUMBER OF DIAMETERS GIVEN FOR COMPUTATIONS              C
C     Nterm  = "1" FOR COMPUTATION OF TERMINAL VELOCITY ONLY           C
C            = "0" FOR BOTH COMPUTATIONS OF Umf AND Ut                 C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      SUBROUTINE UMFTERM(dp,Ndp,Ut,ReUt,Umf1,Umf2,Umf,Nterm)

      IMPLICIT REAL*8 (A-H,O-Z)

      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,Time,Ka,ETAc
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

      REAL*8 dp(10),Ut(10),ReUt(10),Umf1(10),Umf2(10)
```

```
      REAL*8 Ar(10),ReMF1(10),ReMF2(10),Umf(10)

      CHARACTER WHICH2*6


      IF(Nterm.EQ.1)GO TO 250

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c     MINIMUM FLUIDIZATION VELOCITY : Umf(1) and Umf(2)               c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      DO 3 I=1,Ndp
      dp(I)=dp(I)/10**4
      Ar(I)=dp(I)**3*gDensity*(pDensity-gDensity)*Gravity/
     *Viscosity**2
      ReMF1(I)=(33.7**2+0.0408*Ar(I))**0.5-33.7
      ReMF2(I)=(25.25**2+0.0651*Ar(I))**0.5-25.25
      Umf1(I)=ReMF1(I)*Viscosity/gDensity/dp(I)
    3 Umf2(I)=ReMF2(I)*Viscosity/gDensity/dp(I)
      IF(WHICH2.EQ.'Y'.OR.WHICH2.EQ.'y')GO TO 200
      DO 5 I=1,Ndp
    5 Umf(I)=Umf2(I)
      GO TO 250
  200 DO 6 I=1,Ndp
    6 Umf(I)=Umf1(I)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c     COMPUTATION OF TERMINAL VELOCITY (Ut)                           c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
  250 DO 20 I=1,Ndp
   21 Ut(I)=Gravity*(pDensity-gDensity)*dp(I)**2/18.0/Viscosity
      ReUt(I)=dp(I)*gDensity*Ut(I)/Viscosity
      IF(ReUt(I).LT.0.4)GO TO 20
      Ut(I)=(4.0/225.0*(pDensity-gDensity)**2*Gravity**2/gDensity/
     *Viscosity)**(1.0/3.0)*dp(I)
      ReUt(I)=dp(I)*gDensity*Ut(I)/Viscosity
      IF(ReUt(I).GE.0.4.AND.ReUt(I).LT.500.0)GO TO 20
      Ut(I)=(3.1*Gravity*(pDensity-gDensity)*dp(I)/gDensity)**0.5
      ReUt(I)=dp(I)*gDensity*Ut(I)/Viscosity
      IF(ReUt(I).GE.500.0)GO TO 20
      GO TO 21
   20 CONTINUE
      RETURN
      END

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c     THE SUBROUTINE, UNPOPUL(W,Dt,Ddp) SOLVES A PARTIAL DIFFERENTIAL c
c     EQUATION OF THE UNSTEADY STATE POPULATION MODEL BY THE FINITE   c
c     DIFFERENTIAL METHODS.  IT RETURNS WITH W(I,J), WHICH IS SOLID   c
c     WEIGHT OF EACH SIZE, dp(I) AT AN ARBITARY TIME,t.               c
c                                                                     c
c     THE VARIABLES ARE DEFINED AS ;                                  c
c                                                                     c
c     W(I)    = WEIGHT OF SOLIDS WITH DIAMETER OF dp(I) AT AN ARBITARY c
c               TIME IN A BED                                         c
c     Dt      = TIME INTERVAL                                         c
c     Ddp     = SIZE INTERVAL                                         c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      SUBROUTINE UNPOPUL(dpL,dpH,dpW,Ndp,W,Ddp,Dt)
```

```
      IMPLICIT REAL*8 (A-H, O-Z)

      COMMON/A1/pDensity,gDensity,Viscosity,Gravity,gVelocity
      COMMON/A2/BedDiam,BedHeight,Ddp1,Dt1,TIME,Ka,ETAc
      COMMON/A3/N,Ntime
      COMMON/A4/dpAve,dpL1,dpH1,dpW1
      COMMON/A5/TITLE
      COMMON/A6/WHICH1,WHICH2,WHICH3,CHECK

      REAL*8 dp(1000),W(1000),A(1000),B(1000),DD(10)
      REAL*8 KAPA(1000),Ka,Umf(10),Umf1(10),Umf2(10),Wmin
      REAL*8 dpW(10),dpH(10),dpL(10),Ut(10),ReUt(10),dp0(1000)
      REAL*8 dpWprt(20,10),TimePrint(20),Wsum(20),dpAve(10)

      CHARACTER CHECK*6

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C       SET INITIAL CONDITIONS                                       C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      J=0
      TimeOut=30.
      TT=0.
      Wtotal=500.
      W(0)=0.
      dp(0)=dpL(1)-Ddp
      I=1
      DO 100 IN=1,Ndp
   10 dp(I)=dp(I-1)+Ddp
      dp0(I)=(dp(I)+dp(I-1))/2.
      IF(dp(I).GT.dpH(IN))GO TO 100
      W(I)=dpW(IN)/(dpH(IN)-dpL(IN))*Ddp*Wtotal/100.
      I=I+1
      dpWprt(0,IN)=dpW(IN)
      GO TO 10
  100 CONTINUE
      Time=0.
      K=0
      Timeprint(0)=0.
      Wsum(0)=Wtotal
      WRITE(6,700)TIME,Wtotal,(dpW(IN),IN=1,Ndp)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C     SET BOUNDARY CONDITIONS                                        C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      NR=I
      W(NR)=0.

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C     ITERATION OF FINITE DIFFERENCE EQUATION BY IMPLICIT METHOD :   C
C                                                                    C
C     THE IMPLICIT METHOD IS BASED ON THE BACKWARD EULER METHOD, AND C
C     CALLS THE SUBROUTINE, DIAG(A,B,W,I) TO DETERMINE UNKNOWN VALUES. C
C     THE SUBROUTINE, UMFTERM IA ALSO CALLED TO DETERMINE THE TERMINAL C
C     VELOCITY NECESSARY FOR THE COMPUTATION OF ELUTRIATION RATE     C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
    1 J=J+1

      DO 300 I=1,NR-1
```

```
      DD(1)=dp(I)

      CALL UMFTERM(DD,1,Ut,ReUt,Umf1,Umf2,Umf,0)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C     Levenspiel's eqn for elutriation constant (see p.179,Fuildi.Eng) C
C                                                                      C
C      IF(Ut(1).LT.gVelocity)GO TO 2                                   C
C      KAPA(I)=0.                                                      C
C      GO TO 3                                                         C
C                                                                      C
C   2 KAPA(I)=1.1*10**(-5)*pDensity*(3.1415/6*BedDiam**2)/Wtotal*(1-   C
C    *Ut(1)/gVelocity)**2                                              C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C     Geldart's equation for elutriation constant, KAPA(I)             C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

    2 KAPA(I)=gVelocity*gDensity*23.7*(3.1415/6.*BedDiam**2)/Wtotal*
     *DEXP(-5.4*Ut(1)/gVelocity)

      Wmin=260
    3 ALPA=Ka*Dt/Ddp*(-ka*500**2/((gvelocity-umf(i))**2*dp0(I)**6))*
     *(dp(I)-wmin**2/500**2*dp0(I)**6/dp(I)**5)
      BETA=1.-((1.-ETAc/100.)*KAPA(I)+3*Ka/(gvelocity-umf(i))**2*
     *(500**2/dp0(I)**6)*(1-wmin**2/500**2*dp0(I)**3/dp(I)**6))

      A(I)=(1+ALPA)/BETA
  300 B(I)=-ALPA/BETA

      CALL DIAG(A,B,W,NR-1)

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C     WRITES THE COMPUTATION RESULTS BY CALLING SUBROUTINE, CFBAOUT    C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      Wtotal=0.
      I=0
      DO 800 IN=1,Ndp
      dpWb=0.
  900 IF(dp0(I).GT.dpH(IN))GO TO 801
      dpWb=dpWb+W(I)
      I=I+1
      GO TO 900
  801 Wtotal=Wtotal+dpWb
  800 dpW(IN)=dpWb
      TIME=J*Dt/60
      IF(TIME.EQ.TT+TimeOut)GO TO 701
      GO TO 702
  701 WRITE(6,700)TIME,Wtotal,(dpW(I)/Wtotal*100,I=1,Ndp)
  700 FORMAT(1x,F9.3,2x,F8.3,3x,F10.5,3x,F10.5,3x,F10.5,3x,F10.5,3x,
     *F10.5,3x,5(F10.5,3x))
      K=K+1
      TimePrint(K)=TIME
      Wsum(K)=Wtotal
      DO 703 I=1,Ndp
  703 dpWprt(K,I)=dpW(I)/Wtotal*100
      TT=TimeOut+TT
  702 IF(J.GT.Ntime)GO TO 1000
      GO TO 1
```

```
1000 WRITE(6,706)(TimePrint(KK),KK=0,K)
 706 FORMAT(1h1//1x,'Time (min)',1x,20(F10.1,3x))
       WRITE(6,707)(Wsum(KK),KK=0,K)
 707 FORMAT(/1x,'Total Wt(g)',1x,20(F10.1,3x))
       WRITE(6,708)
 708 Format(/1x,'Fractional weight (g) as a function of time'/)
       DO 705 I=1,Ndp
 705 WRITE(6,704)dpAve(I),(dpWprt(KK,I),KK=0,K)
 704 FORMAT(1x,F9.3,2x,20(F10.5,3x))

       RETURN
       END
```

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END