AN INVESTIGATION OF THE EFFECTS OF AIR VELOCITY AND PROPERTIES OF DRILL CUTTINGS ON THE CARRYING CAPACITY OF AIR

By

JOHN E. HANSFORD

Bachelor of Science

Oklahoma Agricultural and Mechanical College

Stillwater, Oklahoma

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THE CARRYING CAPACITY OF AIR

Thesis Approved:

J. H. Boggs
Thesis Adviser

C. M. Leonard
Major Adviser

Robert MacVicar
Dean of the Graduate School

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LIST OF ILLUSTRATIONS AND CURVES

LIST OF SYMBOLS AND ABBREVIATIONS

A = area, sq. ft.
b = base, in.
C_d = coefficient of drag, dimensionless
D = drag, lb.
d = diameter, in.
d_n = diameter of sphere having the same volume as particle, in.
g = the acceleration of gravity, ft/sec.^{2}
h = height, in.
N_{Re} = Reynolds number, dimensionless
P = pressure, lb./sq. in.
q_c = quantity of air at measured conditions, lb./cu.ft.
T = temperature, degrees Fahrenhiet absolute
t = thickness, in.
v = volume, cu. ft.
V_a = air velocity, ft./sec.
V_p = particle velocity, ft./sec.
V_s = slip velocity, ft./sec.
w = gravimetric rate of flow--, lb./sec.
μ = absolute viscosity, $\frac{\text{lb.-sec}}{\text{ft}^2}$
ν = kinematic viscosity $\frac{\text{ft}^2}{\text{sec.}}$
ρ = density as indicated, $\frac{\text{lb.-sec}^2}{\text{ft}^4}$

CHAPTER I

STATEMENT OF PROBLEM

The object of this research was to investigate the effect that variations in particle size, shape, and density and variation in air velocity have on the carrying capacity of air.

Almost all available field data which have included air volumes and velocities used in drilling with air as a circulating medium for rotary drilling indicates that an air velocity of 3000ft./min. is a minimum value for keeping the hole clean of drill cuttings using conventional circulation. Therefore, variation of air and particle properties with air velocities of 3000 ft./ min. and up are of the most interest.

Using the Reynolds number as a criterion of dynamic similarity, the variation of size, shape and density of the particle and the variation in air velocity on lifting capacity of air has been investigated and discussed.

CHAPTER II

INTRODUCTION

When a rotary drilling rig is used for drilling a hole in the earth's surface in the never ending search for petroleum, a significant portion of the cost of drilling is the expense of furnishing the drilling mud. Drilling fluid is used to cool and lubricate the bit and drill pipe, to form an impermeable supporting filter cake on the walls of the hole, and to transport the drilled cuttings to the surface.

If a cheaper fluid could be used to perform these same functions, at the same or faster rate, a great saving could be made in drilling operations.

Air has been used since the turn of the century for various drilling and mining operations which require the removal of drill cuttings. However, little has been done on a scientific approach for using air as a drilling fluid.

As early as 1909, air was used to clean the hole for percussion type drills. The air was conveyed to the bottom of the hole by a separate drop pipe along the side of the drill until 1913 when the hollow drill was introduced and the air was then circulated through the drill.

The first use of air as a drilling fluid for a rotary drilling rig was in 1949 when it was used in the strip mining and quarry industries for drilling blast holes which average from 30-70 feet deep.

The use of air as a drilling fluid spread rapidly to many applications in exploratory drilling in 1950. At the same time, the Engineer

Research and Development Board, U. S. Corps of Engineers, presented an original idea to use air to core drill in regions so cold that ordinary mud would freeze. Some successful work was done along this line.

In the last few years, air drilling has found other new applications. Air has been used extensively in drilling seismic shot holes, especially in arid regions where water is difficult to obtain in quantities required to mix mud. Also, air has found application in drilling for petroleum, especially in regions where loss of circulation is a problem. An example of this situation is drilling the Spraberry sand in Martin County, Texas. Here air was found to be superior to mud in every respect since the loss of circulation was a major problem. By using air as a drilling fluid, faster drilling rates, less loss of oil, and less contamination of the producing formation was experienced. The greatest difficulties experienced were that the dust particles were too small for geological interpretation and the fine dust combined with water to clog the annulus when a small amount of water was encountered. Both of these conditions were greatly improved when reverse circulation was used; that is, sending the air down the annulus between the hole and the drill stem and the cuttings traveling up the inside of the drill pipe. In almost every case of using air as the drilling fluid, the life of the drill bit was increased and the drilling rate greatly increased. Field studies verify the fact that air drilling has two major disadvantages: (1) less primary control of well pressures and (2) less support for sloughing formations.

At the present time it is known that air drilling has taken place in West Virginia, Pennsylvania, Mississippi, Arkansas, Texas, Oklahoma, New Mexico, Colorado, Wyoming, Oregon, Utah, California, and Canada.

In an average hole 10,000 feet deep filled with an average mud, the pressure on bottom varies between five and ten thousand pounds per square inch. This pressure is due in part to the weight of the column of mud above the bottom of the hole. It has been found by several investigators that many rock formations which are so brittle the chips virtually explode from the parent rock when drilled at atmospheric pressure, become plastic and the chips are squeezed out like lead when drilled under high hydrostatic pressures. Therefore, if the density of the column of drilling fluid above the bottom of the hole could be reduced, there would be an increased drilling rate with decreased bit weight and thereby an increase in bit life. One avenue of approach which is being investigated is to lighten the fluid column by mixing air with the drilling mud. This compromise overcomes some of the disadvantages of both air and mud drilling. At the present time very little information has been reported on the results of aerated mud drilling. It stands to reason that if both mud and air were available at the wellhead, then any desirable mixture could be used depending upon the circumstances. However, the cost of providing both air and mud would be higher in any case than if only one were required.

Other theories which have been advanced to explain why drilling with air is faster than drilling with mud are:

1. Faster drilling rates, especially in hard and dry formations.
2. Less loss of oil.
3. Less contamination of producing formations.
4. Increased bit life.
5. Water availability presents no problem.
6. In cold regions no problem of freezing mud exists.
7. Less circulation loss in cavernous formations.

8. Less possibility of overlooking productive formations.

9. Well samples obtained are more representative of the material being drilled, at the time the sample is obtained because of faster circulation rates.

10. Air drilling is not limited to depth any more than when drilling with mud.

11. Cuts costs where applicable.

Example: Cost comparison on well in South Mountain and Oat Mountain Field in California

(This well was drilled through cavernous formations)

For a minimum 1000 foot hole air drilling costs versus mud drilling costs are:

	Mud	Air
Rig-up costs	$6,000.00	$7,500.00
Drilling costs	$11,220.00	$7,000.00
Total Costs	$17,220.00	$14,500.00

Total saving with air $2,720.00

12. Can go to greater depths than drilling with mud without a great increase in horsepower at the surface.

13. Re-drilling of cuttings believed to be eliminated to a great extent since many cuttings one-half inch in diameter are reported.

14. Satisfactory penetration rates can be maintained with bit weights of one-half those used in drilling with mud. This conceivably minimizes crooked hole problems (opinions differ here).

15. Excellent core recovery.

16. Less cement needed because of better gauged holes.

Some disadvantages experienced when using air drilling are:

1. Less primary control of well pressures.

2. Less support for sloughing formations.

3. Well particles too fine for geological interpretation (reports vary greatly; this probably depends on the return air velocities being used).

4. Eliminating dust hazards is difficult.

5. Dust particles accumulate inside the drill pipe when a small amount of liquid is encountered but not if a large volume of liquid is produced. Air pressure has to be increased if any quantity of liquid is produced.

6. There is some wear at places of reduced area in exhaust conveying lines.

7. Large volume of air is required for operation (especially true if bit and drill stem differ in size greatly).

8. Education of drilling crews (a minor problem).

9. Rotary table speeds usually reduced because of excessive 'kelly' packing wear. This packing is necessary to seal the air and cuttings from the derrick floor.

10. Rig is put under greater stress since the drill pipe is more free to move in the dry hole.

11. There exists a remote possibility of an explosive mixture of air and gas forming. However, reports of such explosions state that little damage was done.

12. Compressor manufacturers know little as yet of the requirements of air drilling.

13. Limited in electric log information that can be obtained in a dry hole.

14. Compressor efficiency reduced somewhat at high altitudes.

From the foregoing list, it can be seen that at the present time, air or gas drilling seems to have advantages when one of the following conditions exists:

1. Severe loss of circulation is encountered.

2. Producing formations are susceptible to injury from drilling fluid or particle penetration.

3. Drilling mud is expensive or non-available.

4. Extremely hard formations encountered.

5. Areas of extremely low temperatures.

The conventional method of rotary drilling using mud as a drilling fluid seems to have the advantage when one of the following conditions exists:

1. High pressure formations are encountered.

2. Sloughing formations are encountered.

CHAPTER III

THEROTICAL ANALYSIS OF THE PROBLEM

If the gravity force on a particle is less than the "drag" on the particle exerted by the vertical fluid stream, the particle will move in the direction of the stream. When the particle is in equilibrium, the force of gravity equals the "drag" force.

The maximum free fall velocity is known as the terminal velocity. The determination of the terminal velocity is important because it is approximately the same as that required of an upward air stream to float or hold the particle at constant elevation. It follows that the particle will rise or fall in an air stream, depending on the velocity of the air.

There are many practical situations where relative motion exists between a fluid and a solid. One such situation is a solid particle in a fluid stream.

The different size, shape, and density combinations of particles are infinite in number. If every linear dimension of a particle is a constant ratio of the same linear dimension of another particle, then the two particles are geometrically similar. Geometrically similar particles have the same shape but differ only in size and position.

Two systems having dynamic similarity have motion of the same form and differ only in size and shape. Therefore, before a system can be dynamically similar, it must be geometrically similar. For example, two flow systems whose streamlines of fluid flow can be superimposed on each other without alteration other than magnification of one, is said to be dynamically similar.

It is a known fact that when dynamic similarity exists in two fluid-solid systems, the product of any characteristic dimension, any velocity, the density, and the reciprocal of the viscosity is the same for both systems when these variables are chosen at corresponding locations. This dimensionless product is called the Reynolds number after Osborne Reynolds, who applied it to the problem of flow inside pipes. It is applicable however in all cases of relative motion between solids and fluids except in the presence of appreciable gravitational or elastic effects.

The drag against a solid object in a fluid stream is given (1) as:

$$F = C_d \rho \frac{AV^2}{2} \qquad (1)$$

Therefore:

$$C_d = \frac{2F}{\rho AV^2} \qquad (2)$$

F = drag, lb.

C_d = coefficient of drag, dimensionless

ρ = mass density of fluid, $\frac{\text{lb. sec}^2}{\text{ft}^4}$

A = projected area of particle, sq. ft.

V = velocity of solid relative to fluid, ft./sec.

g = acceletation due to gravity, 32.2 ft./sec./sec.

The coefficient of drag is a function of the Reynolds number and is plotted as such in many scientific works.

There are several methods of approximating the terminal velocity of particle in a viscous medium. One of the more accurate ways is to express the fluid resistance to motion of a spherical particle as a function of the Reynolds Number (N_{Re}), density of the fluid, and the square of the velocity.

$f\ (N_{Re})^2$ can be found by (2)

$$f\ (N_{Re})^2 = \frac{4}{3} g \left(\frac{\sigma - \rho}{\rho}\right) \frac{D^3}{3} \qquad (3)$$

where:

f = resistance factor, dimensionless

N_{Re} = Reynolds number, dimensionless

σ = mass density of particle, $\frac{lb.\ sec^2}{ft^4}$

D = diameter of sphere, ft.

μ = absolute viscosity of fluid, $\frac{lb.\ sec}{ft^2}$

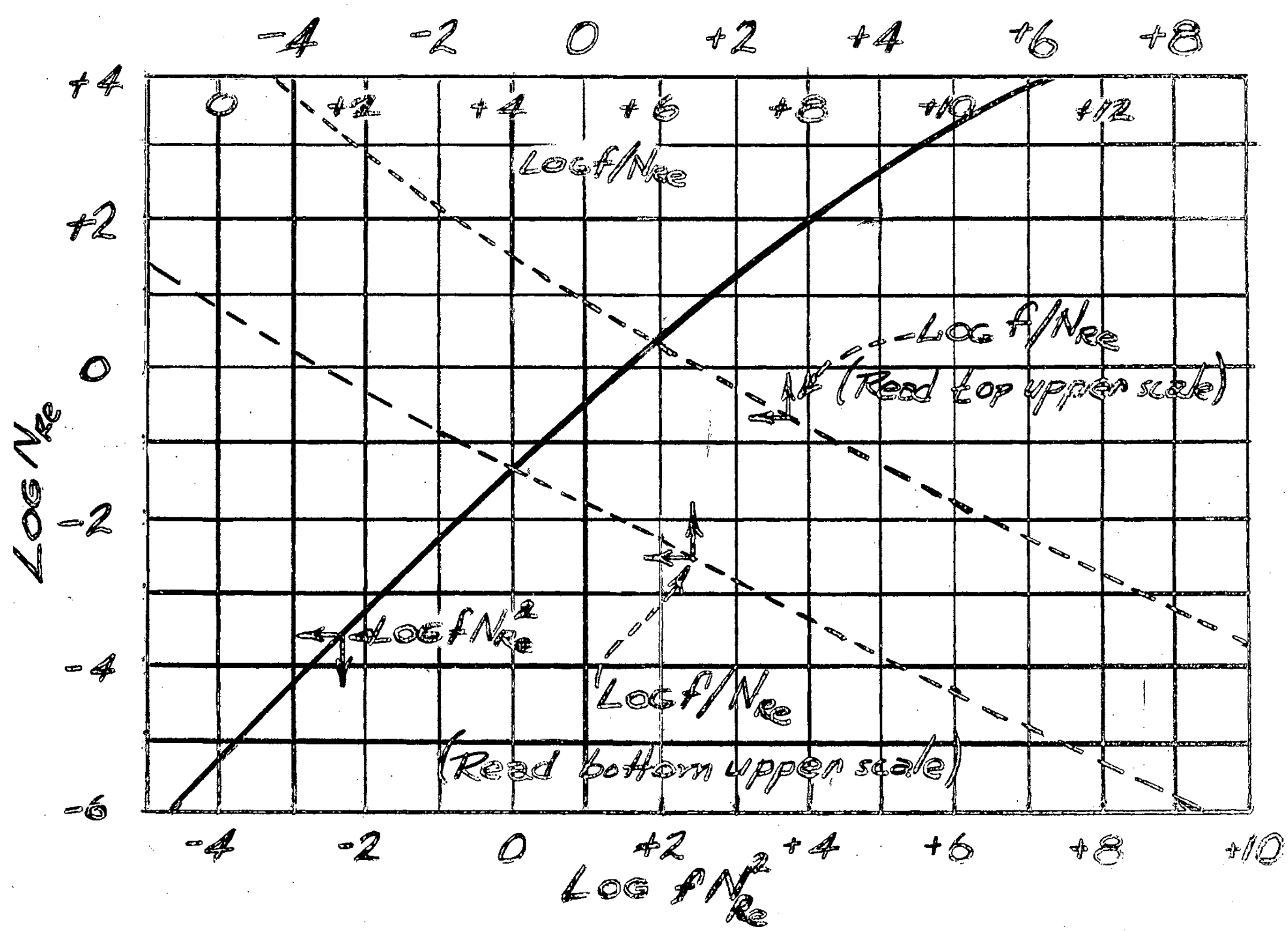
ν = kinematic viscosity, $\frac{ft^2}{sec}$

Then from a plot of Log $f\ (N_{Re})^2$ vs. Log N_{Re}, (see Fig. A, p. 11) N_{Re} can be found. The terminal velocity can then be found by the relation

$$U_t = \frac{N_{Re}\,\nu}{D} \qquad (4)$$

This is the terminal velocity since equation (3) was obtained by equating the net gravity force, F, to the fluid resistance of a moving particle.

To find the terminal velocity of a particle non-spherical in shape, a factor called the sphericity of the particle is introduced. The sphericity of a particle, Σ, is equal to $\frac{s}{S}$ where s is the surface area of a sphere having the same volume as a particle whose surface is equal to S. Then to compute the terminal velocity of a non-spherical particle:



VARIATION OF RESISTANCE FUNCTIONS WITH REYNOLDS NUMBER FOR SPHERES (2)

FIG. A

1. Compute the terminal velocity, (U_t), for a sphere having the same volume as the particles.

2. Find D_n, where D_n equals the diameter of a sphere having the same volume as the particle in question.

3. Find Σ and $(N_{Re})_n$ which is equal to the N_{Re} of a sphere having the same volume as the particle.

4. From a plot of $(N_{Re})_n$ vs. f, the resistance factor, at given (see Fig. B), the resistance factor f_n can be found.

5. From a plot of Σ vs. V/A where V equals the volume and A equals largest projected area, at different shapes, the value of V/A can be found. (See Fig. C)

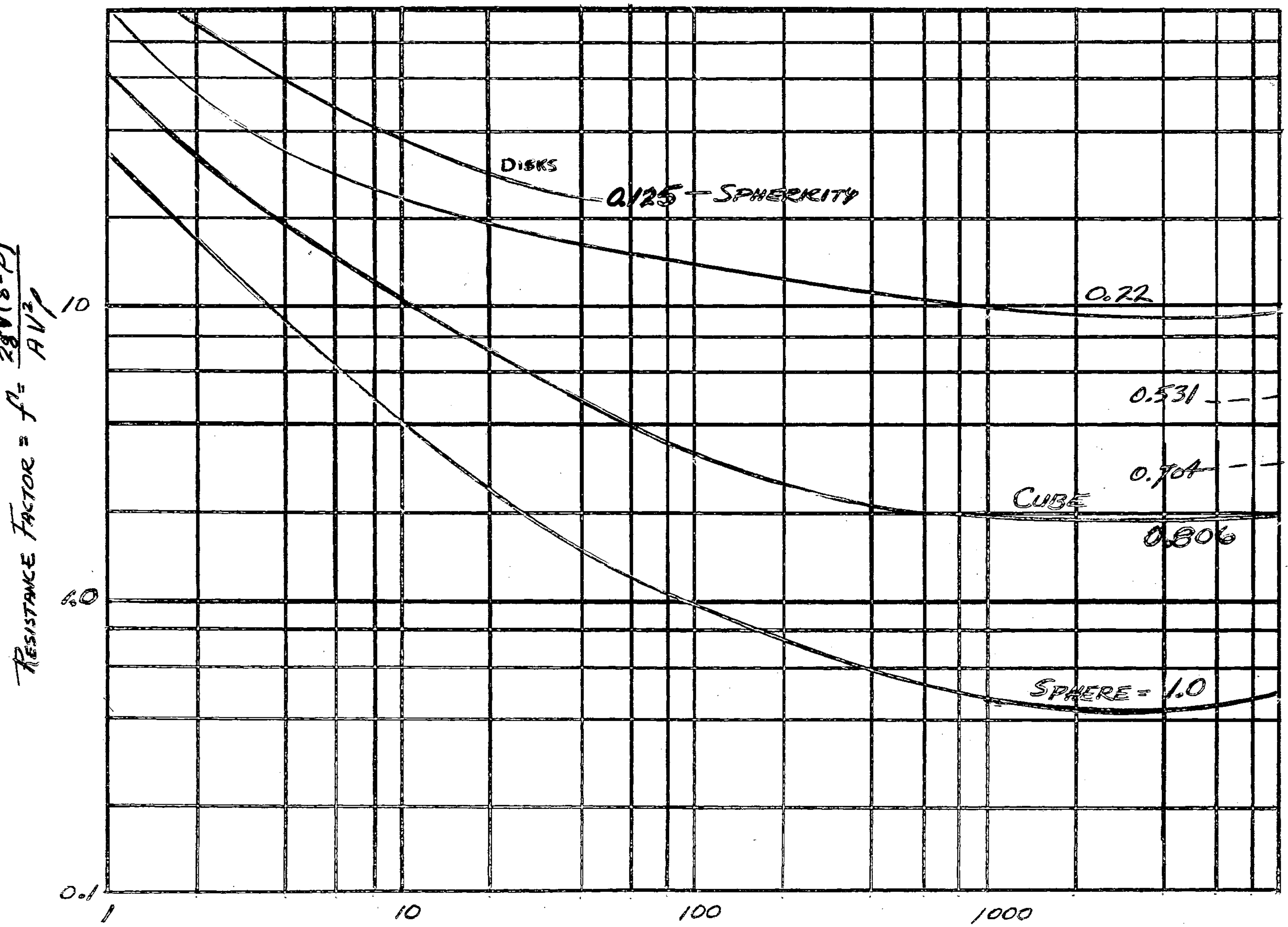
The terminal velocity can now be found from:

$$(U_t)_p = (U_t)_n \sqrt{\left(\frac{V_p}{A_p}\right)\left(\frac{A_n}{V_n}\right)\left(\frac{f_n}{f_p}\right)} \qquad (5)$$

where the subscript p refers to the particle and the subscript n refers to a spherical particle having the same volume.

The curves for the above calculation are limited to cubical and cylindrical disks.

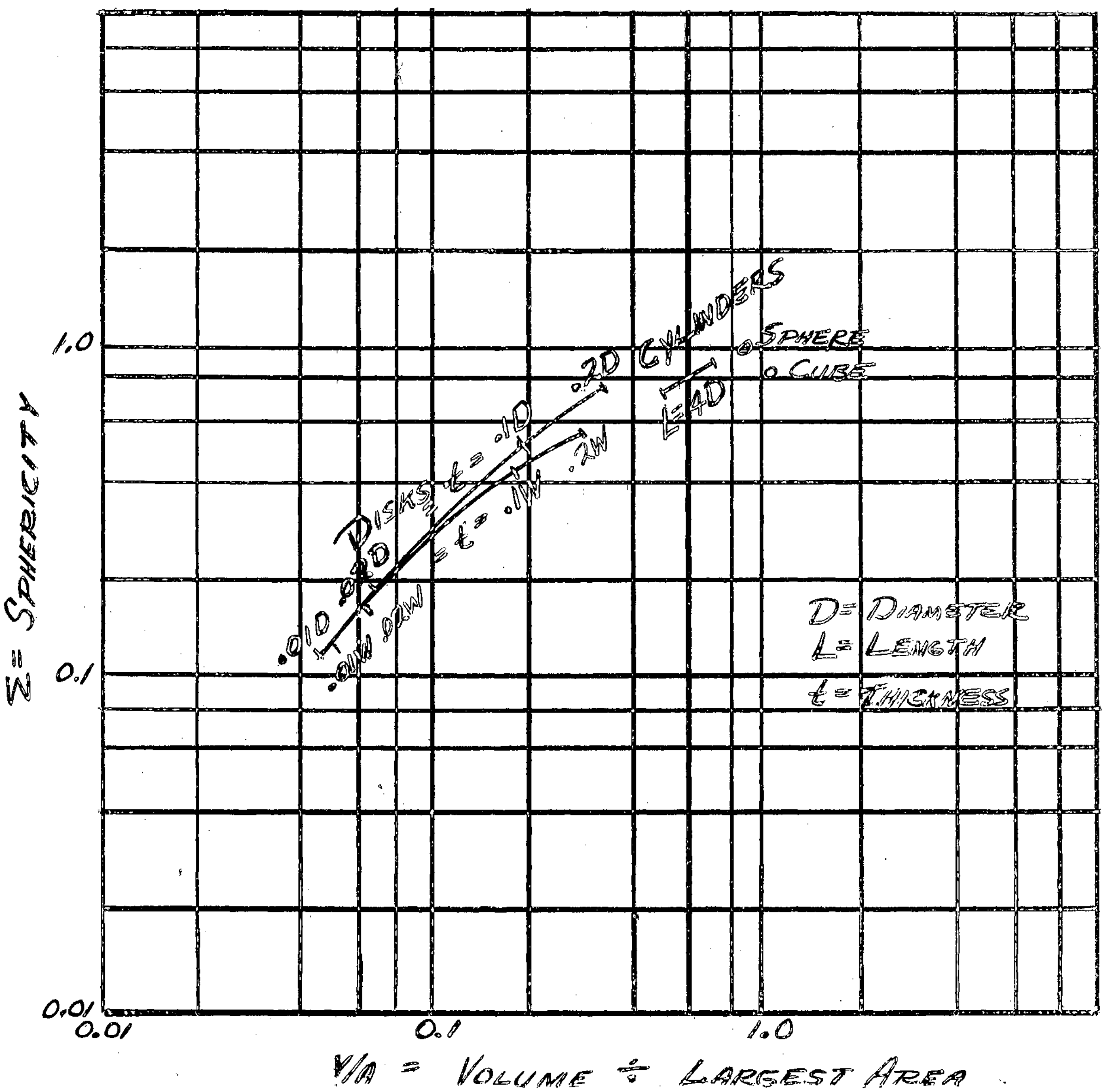
A method of approximating the terminal velocity has been derived neglecting the friction effect (2). If p_t is equal to the total pressure, p_s is equal to the static pressure, A is equal to the projected cross-sectional area (largest) of the particle, V is equal to the volume of the particle, and D is equal to the diameter of the particle, then the upward force acting on the particle is (p_sA) plus $V(\sigma-\rho)$.



$N_{Re} = \frac{DV\rho}{\mu}$

Reynolds Number vs. Resistance Factor (2)

Fig. B


Σ = SPHERICITY
1.0
0.1
0.01
0.01
0.1
1.0
V/A = VOLUME ÷ LARGEST AREA
CYLINDERS
SPHERE
CUBE
L=4D
D = DIAMETER
L = LENGTH
t = THICKNESS

V/A vs. Σ (2)

FIG. C

At the terminal velocity conditions:

$$(P_s + \frac{U}{2}\rho)\, A = P_s A + V_g\, (\delta - \rho) \qquad (6)$$

$$U = \sqrt{\frac{2g}{A}\left(\frac{\delta - \rho}{\rho}\right)} \qquad (7)$$

Then for spheres:

$$U = 6.55\sqrt{D\left(\frac{\delta - \rho}{\rho}\right)} \qquad (8)$$

For circular disks of thickness t equal to V/A

$$U = 8.03\sqrt{t\,\left(\frac{\delta - \rho}{\rho}\right)} \qquad (9)$$

As previously mentioned, these equations do not include friction effect and result in values approximately ten percent higher than the experimental results.

CHAPTER IV

APPARATUS

An apparatus consisting of an injector, stand, and a ten foot length of transparent two inch plastic pipe was built to study the vertical motion of particles in an air stream (See Fig. 1).

The air supply was a two-stage Fairbanks Morse air compressor, (Fig. 2) regulated by a Fisher "99" gas regulator (Fig. 3). Air volume was measured by an ASME flow nozzle having throat taps (Fig. 4).

The air compressor was driven by an electric motor and the air discharged into an air tank equipped with an oil and moisture trap. A two inch pipe carried the air from the tanks to the apparatus. A globe valve was used in conjunction with the gas regulator to regulate the flow of air.

Two cross type air flow vanes were installed to straighten the air flow before it came into the test section.

A Bell-Howell 16mm spring-wound movie camera was used to record the motion of the particles as they traveled up the transparent plastic pipe.

An electric timer utilizing a synchronous electric motor was used to calibrate the camera (Fig. 5).

A fine mesh bag was attached to the end of the plastic pipe to catch the particles as they left the tube.

A Bell-Howell 16mm projector was used to view the results of the experiments. This projector was equipped with a manual film ejector and a frame counter.

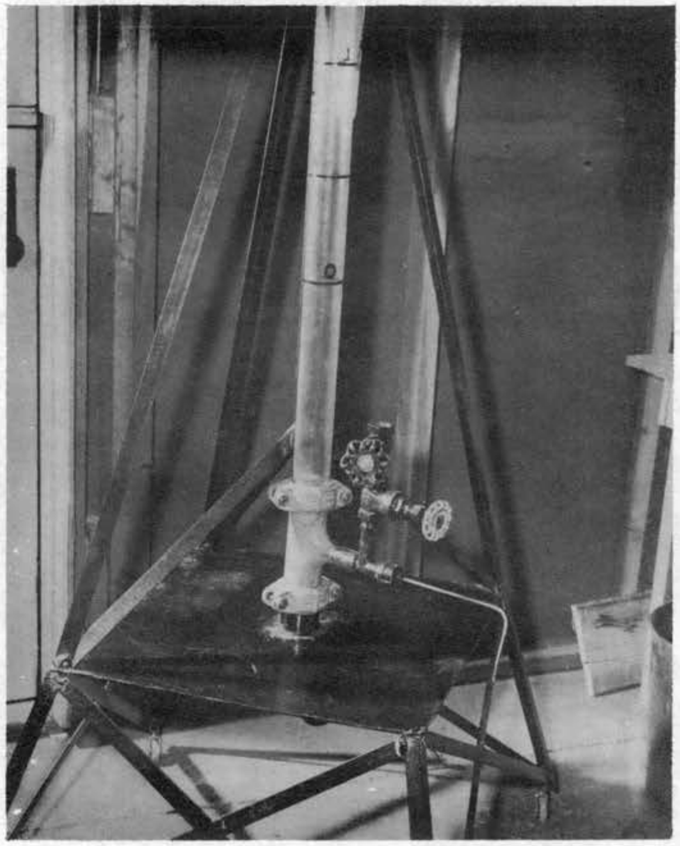


Figure 1.
Injector and Eductor Tube

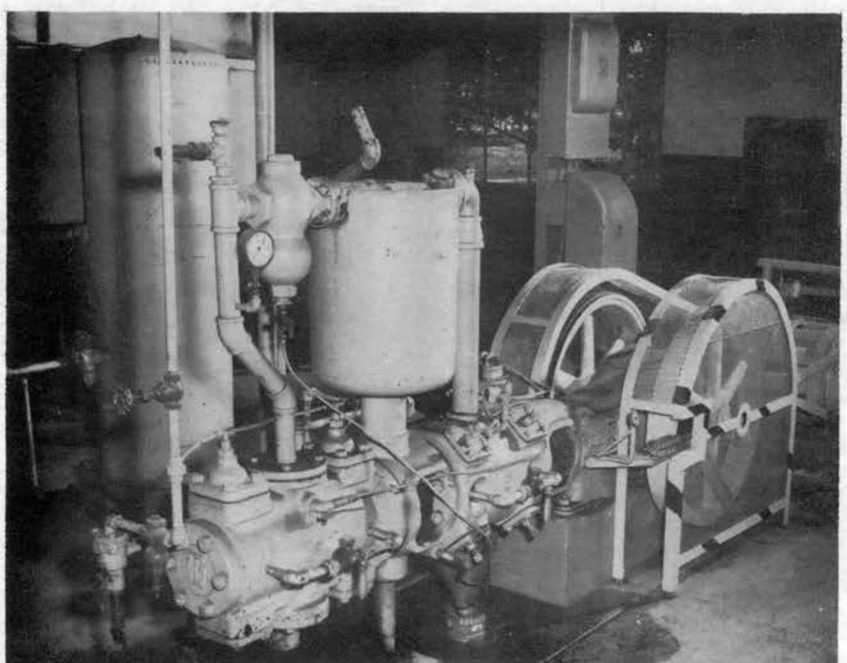


Figure 2.
Air Compressor

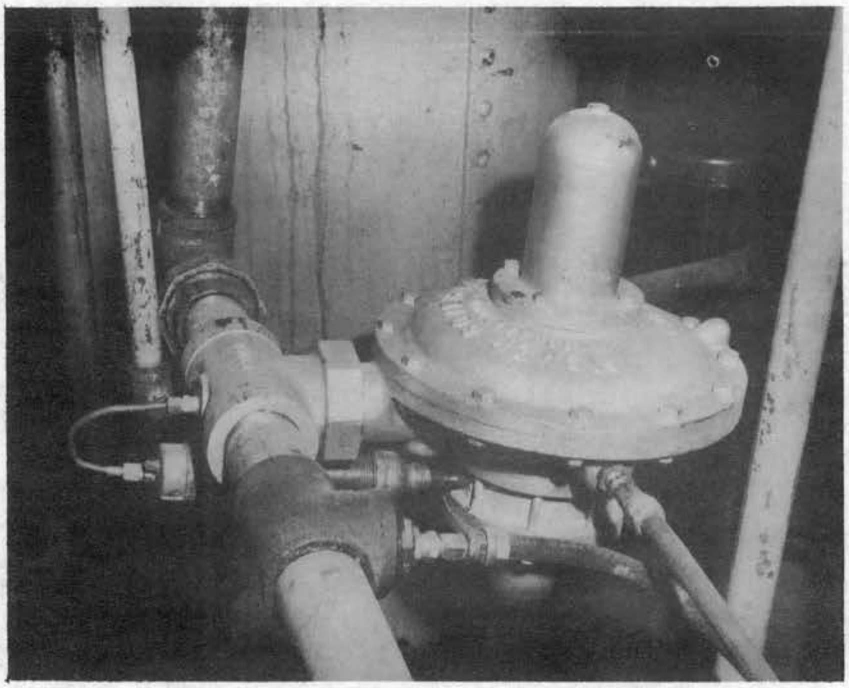


Figure 3.
Gas Regulator

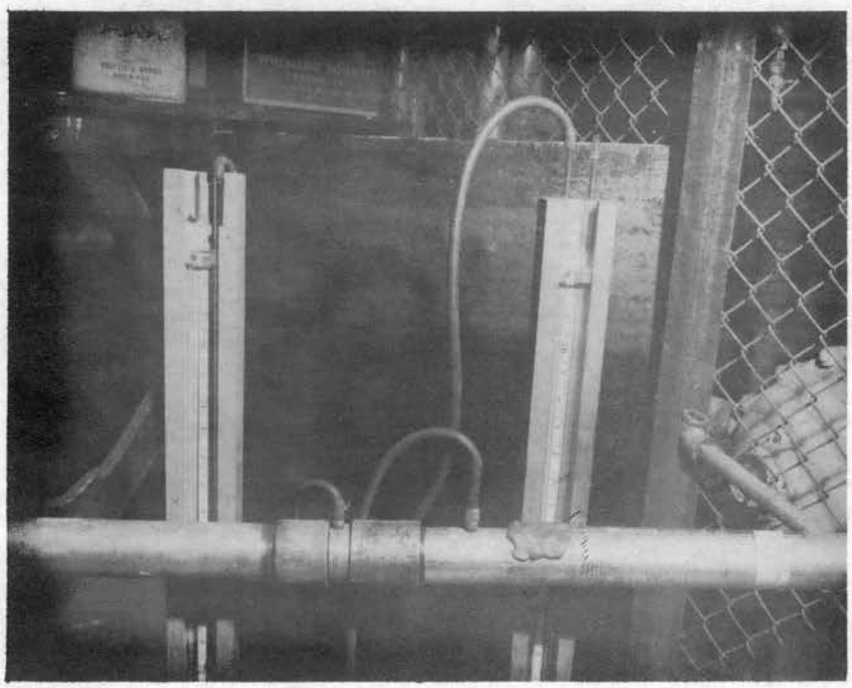


Figure 4.
ASME Flow Nozzle and Manometers

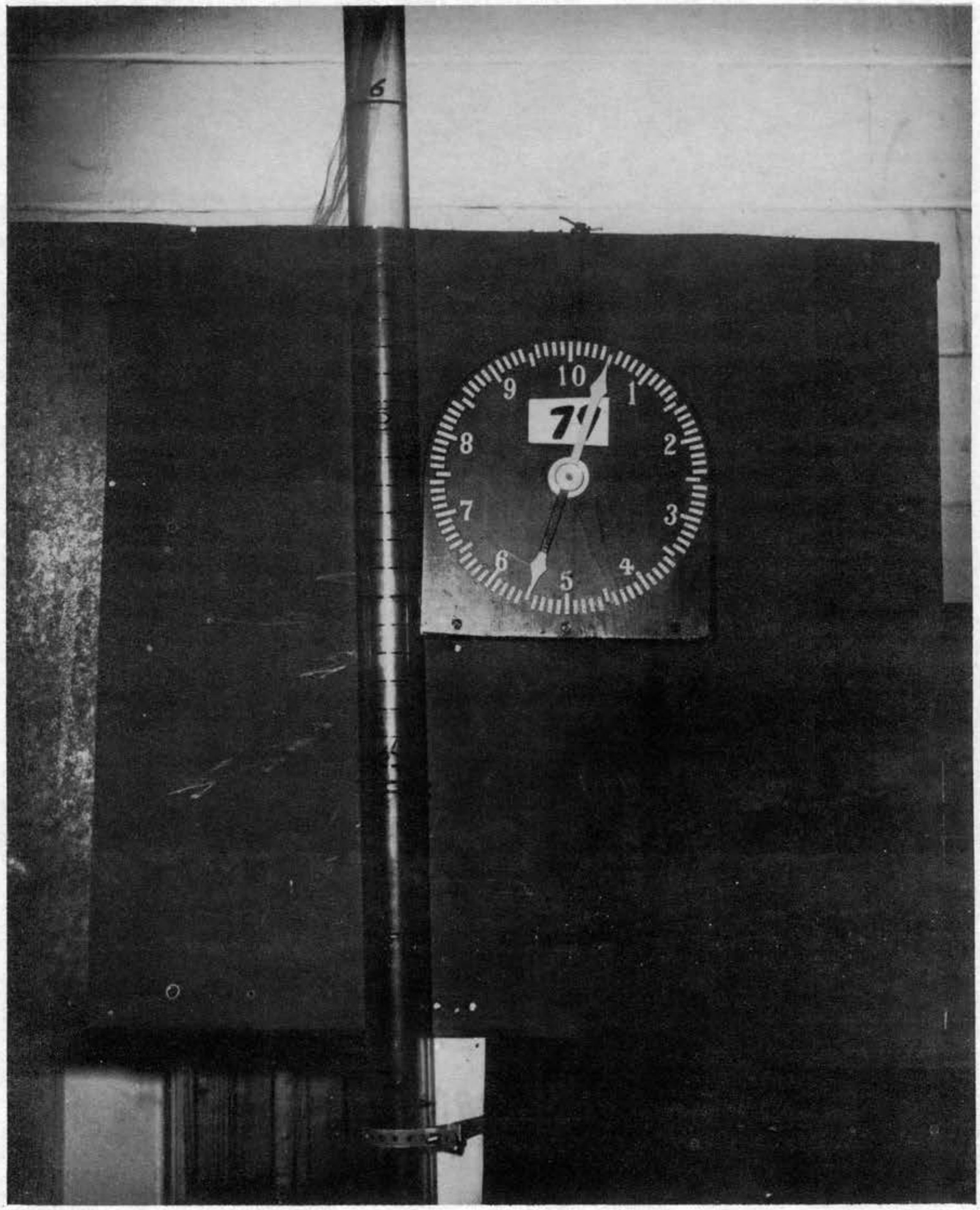


Figure 5.
Electric Timer

Two sets of particles were made. There were 11 particles in each set each having a counterpart in the other set (Fig. 6 & 7). One set was cut from a limestone core and the other was made of ceramic clay and oven baked. These particles are:

Sphere - $d = \frac{1}{2}$

Sphere - $d = \frac{1}{4}$

Rectangular prism - $\frac{1}{2} \times \frac{1}{4} \times \frac{1}{4}$

Rectangular prism - $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{4}$

Rectangular prism - $3/4 \times \frac{1}{4} \times 1/16$

Rectangular prism - $\frac{1}{2} \times \frac{1}{4} \times 1/8$

Cylinder - $d = \frac{1}{2}, t = \frac{1}{4}$

Cylinder - $d = \frac{1}{2}, t = 1/16$

Cylinder - $d = \frac{1}{4}, t = \frac{1}{4}$

Triangular prism - $b = \frac{1}{2}$, $h = \frac{1}{2}$, $t = \frac{1}{4}$

Triangular prism - $b = \frac{1}{2}$, $h = \frac{1}{4}$, $t = \frac{1}{4}$

where:

d = diameter, in.

t = thickness, in.

h = height, in.

b = base, in.

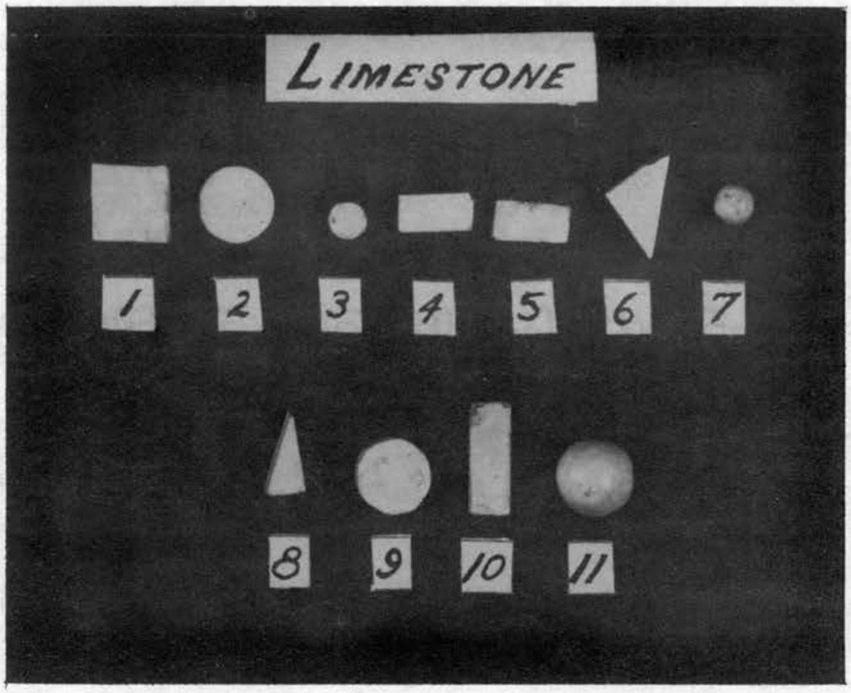


Figure 6.
Limestone Particles

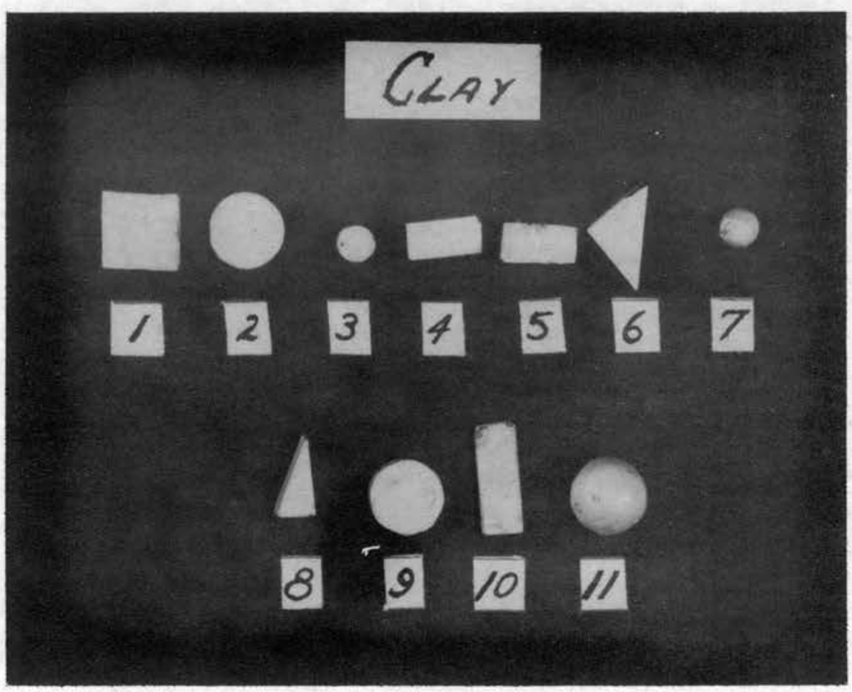


Figure 7.
Clay Particles

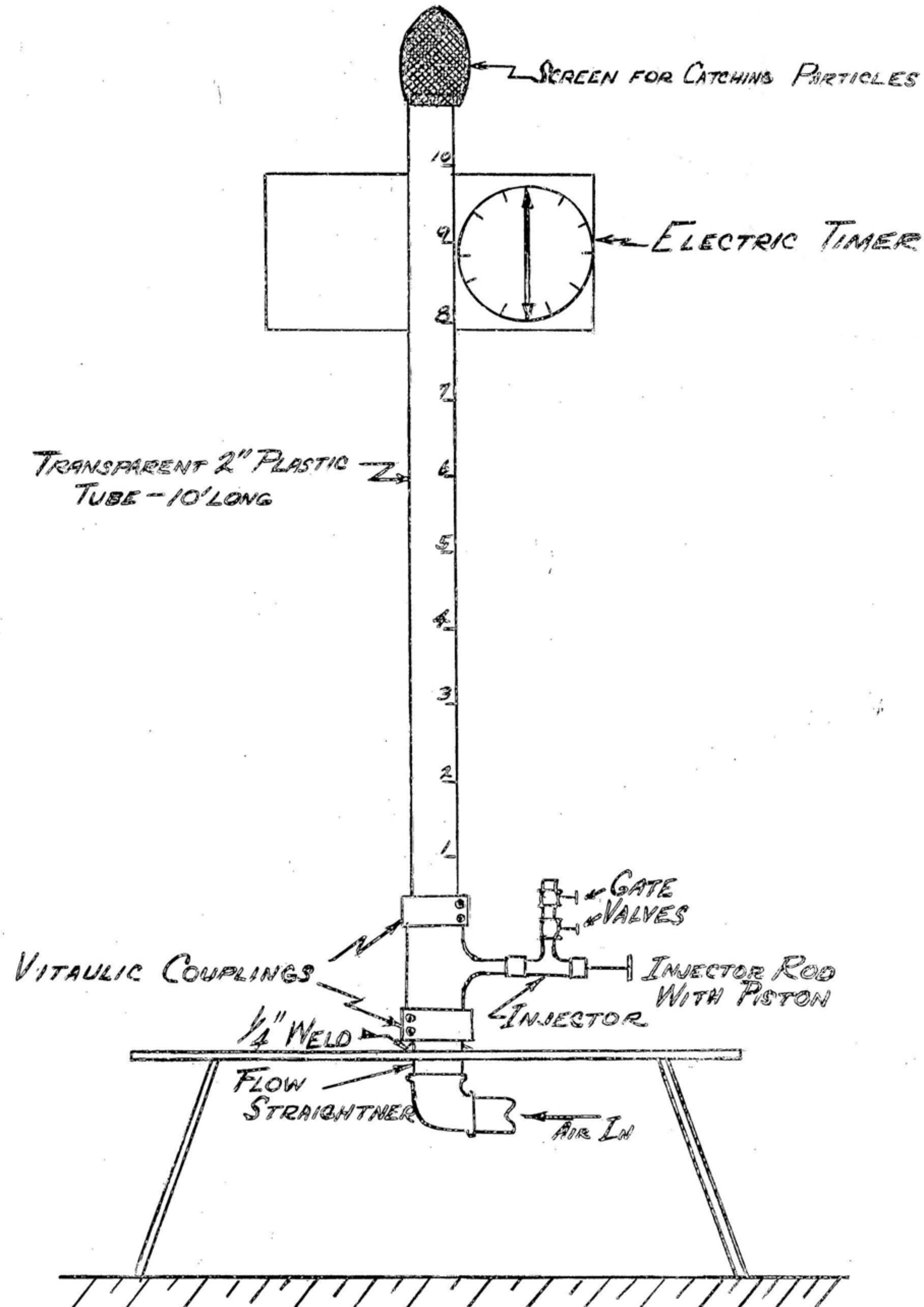


FIG. No. 8
EXPERIMENTAL APPARATUS

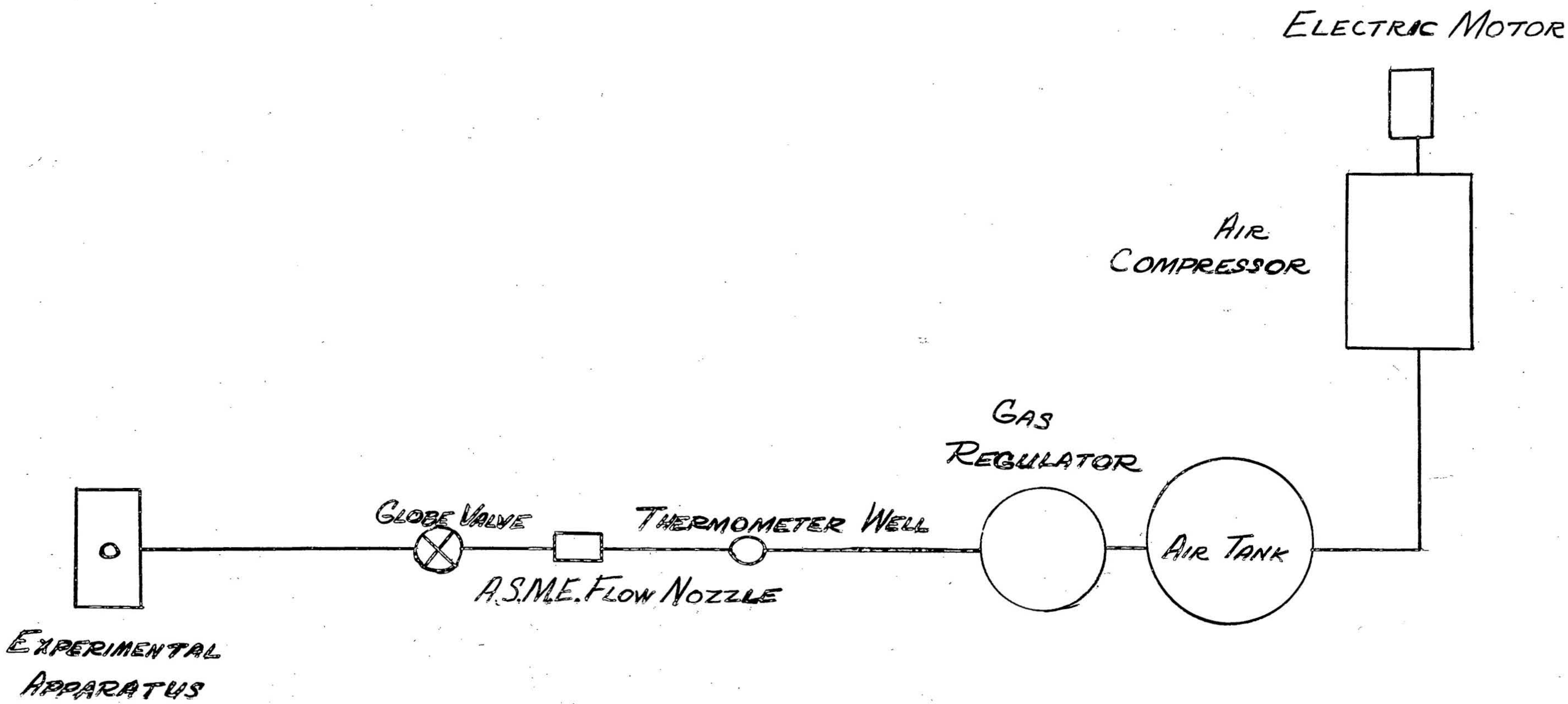


FIG. NO. 9

SCHEMATIC DIAGRAM OF EXPERIMENTAL EQUIPMENT

CHAPTER V

PROCEDURE

Several preliminary runs were made to ascertain the maximum length of tubing that could be photographed and still obtain data from all of the small particles. This length was found to be two feet. The top portion of the tube was photographed as the initial accelerative effects of injection would be negligible by the time the particles reached the top.

For a typical test run the air compressor was started and a small amount of air was circulated through the system until the air reached a temperature which did not vary more than a few degrees over a ten minute interval. The gas regulator and globe valve were set for the desired air velocity.

The top valve of the injector was opened. The particle size and shape, the air temperature, and the static and differential pressure of the flow nozzle were noted. Then the particle was dropped in the injector, the top valve closed, and the bottom valve opened. Upon pushing the piston plunger forward, the motion picture camera was started at a speed of 64 frames per second and run until the particle was caught by the fine mesh bag. This procedure was repeated until all of the particles were in the bag. Then the particles were retrieved and the cycle started again. Seventy-nine runs were made in all. At least two and many times three runs at the same conditions were made to determine whether the results could be duplicated. A total of 500 feet of film was used; 100 feet being used in making test runs.

The ASME Power Test Code (3) gives the following formula for calculating the air quantity passing through an ASME flow nozzle using throat tap and static pressure readings when $\Delta P < (.1)$ of P_s.

$$w = 0.8596\ Cd_2^2 \sqrt{\frac{\frac{P_2 \Delta P}{T_1}}{1 - \left(\frac{d_2}{d_1}\right) \quad \frac{1 - 1.434\Delta P}{P_1}}} \qquad (10)$$

where:

w = gravimetric rate of flow, lb./sec.

P_2 = Absolute outlet static pressure, lb./sq. in.

P_1 = absolute inlet static pressure, lb./sq. in.

P = differential pressure across element, lb./sq. in.

$\frac{d_2}{d_1}$ = diameter ratio, $\frac{\text{nozzle diameter}}{\text{pipe diameter}}$

T_1 = absolute inlet temperature, degrees Rankine

Then to obtain rate of flow in cubic feet per second

$$q_c = w/\rho_c \qquad (11)$$

where ρ_c is the density at q_c conditions in lb./cu. ft. Using the continuity equation yields:

$$V = q_c/A \qquad (12)$$

To determine the particle velocities, the film was run through the projector one frame at a time. The speed of the camera was calibrated by noting, from the electric clock in the photograph, the amount of time lapsed between five frames before and five frames after any position of the particle. Each division on the clock was 0.001 of a minute. Thus, the frames per second could be determined. The plastic pipe was marked off in increments of one inch and the number of frames were counted while the particle traveled the two feet. Thus the speed of the particle in feet per second was found. The difference between the air velocity and particle velocity is known as the slip velocity of the particle. This is the relative velocity of the particle with respect to the air stream. This dimension appears in the Reynolds number as follows:

$$N_{Re} = \frac{d_n V_s \rho}{\mu} = \frac{d_n V}{\nu} \tag{13}$$

where:

d_n = diameter of a sphere having the same volume as the particle in question, ft.

V_s = slip velocity, ft./sec.

The force acting against an object in a fluid stream is given by Rouse (10) as:

$$D = C_d \frac{w A V_s^2}{2g} \tag{14}$$

where:

D = drag force, lb.

C_d = the coefficient of drag which varies with the size, shape, and slip velocity, dimensionless

w = weight of the fluid, lb./cu.ft.

A = the projected area of the object, sq.ft.

V_s = velocity of the object with respect to the fluid, commonly called the slip velocity, ft./sec.

Therefore:

$$C_d = \frac{D 2g}{A V_s^2 w} \tag{15}$$

The Reynolds number and the coefficient of drag was computed for each of the runs made and a curve of C_d vs. N_{Re} was plotted on log paper for each shape of particle and a comparison made with values given by Wadell (4).

To gain some information on the value of increasing the air velocity above the minimum to raise the particles, air velocity vs. particle velocity and air velocity vs. slip velocity curves were plotted.

CHAPTER VI

RESULTS AND CONCLUSIONS

The results compare favorably with Wadell's values for spheres (see Figure 10).

Only point comparison (dashed curves) is available on some particles but results are consistant and the slope of curves drawn through two or three points are equal to the slope of the solid lines where more data was available.

The shape and material of the particle and the air velocity being constant, the slip velocity is proportional to size and the particle velocity is inversely proportional to size.

The closer the approach of the sphericity to unity, the harder the particle is to lift. For example, in curve 11, although the rectangular prism is heavier, it is easier to lift than the lighter cylinder.

$$W_R = 0.00534 \text{ lb.} \qquad \Sigma_R = 0.761$$

$$W_C = 0.00453 \text{ lb.} \qquad \Sigma_C = 0.805$$

Therefore a desirable particle shape would be a thin, flat chip with a sphericity approaching zero. This is fortunate since most drill cuttings are angular in shape.

The slip velocity is directly proportional to the density and the particle velocity is inversely proportional to the density.

An increase in air velocity results in an increase in particle velocity. The slope of the particle velocity vs. air velocity curve

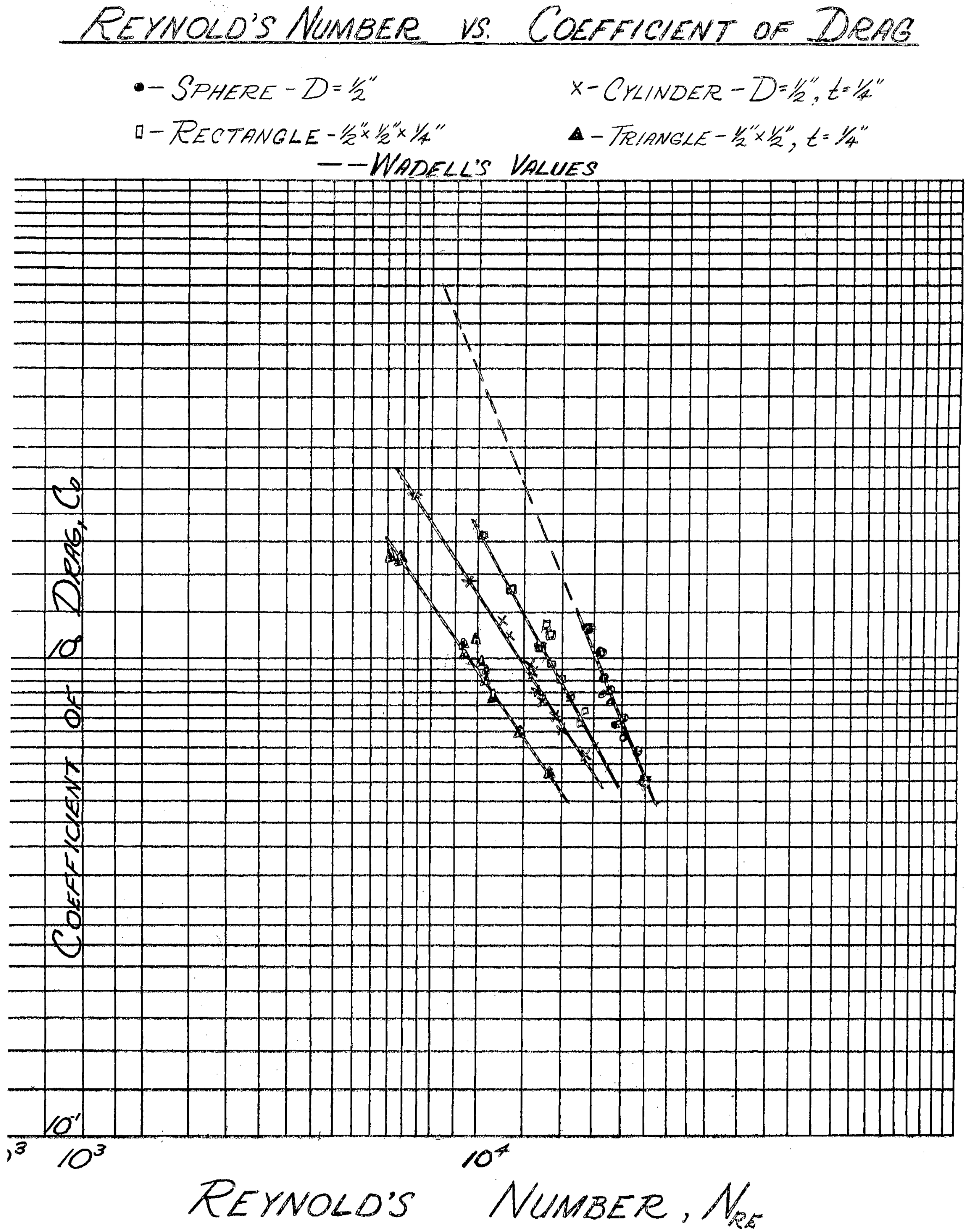

REYNOLD'S NUMBER VS. COEFFICIENT OF DRAG
• - SPHERE - D = ½"
× - CYLINDER - D = ½", t = ¼"
□ - RECTANGLE - ½" × ½" × ¼"
▲ - TRIANGLE - ½" × ½", t = ¼"
-- WADELL'S VALUES
COEFFICIENT OF DRAG, C_D
10
10^{-1}
10^3
10^4
REYNOLD'S NUMBER, N_{RE}

FIG. 10

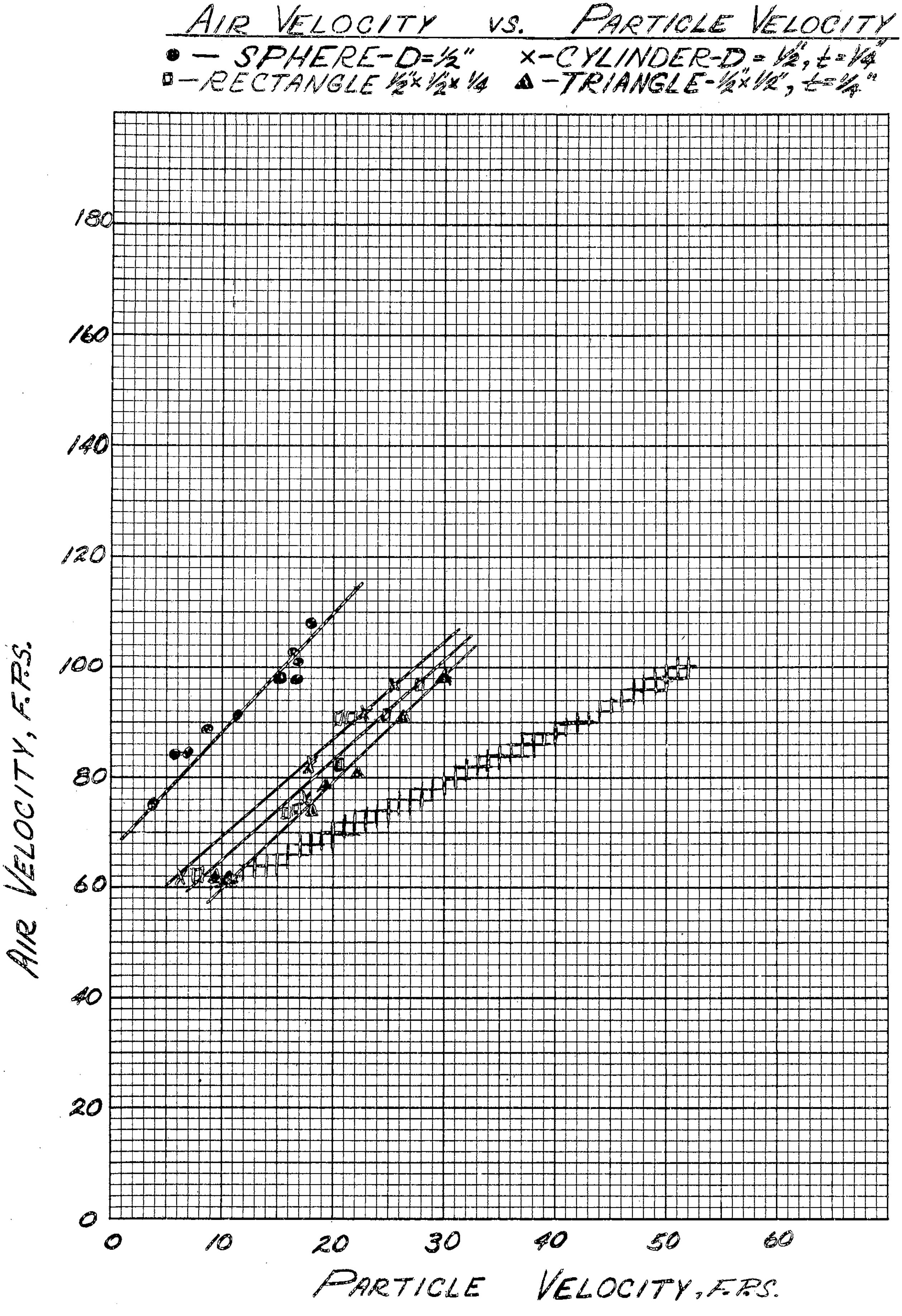

AIR VELOCITY VS. PARTICLE VELOCITY
● — SPHERE-D=½"
×-CYLINDER-D=½", t=¼"
□-RECTANGLE ½"×½"×¼
▲-TRIANGLE-½"×½", t=¼"
AIR VELOCITY, F.P.S.
PARTICLE VELOCITY, F.P.S.
0
20
40
60
80
100
120
140
160
180
10
30
50

FIG. 11

(see curve 11) is two for air velocity between 3000 ft./min. and 6180 ft./min. Within these limits the ratio of the change of the particle velocity to the change in air velocity is 0.5 which gives a lifting efficiency of 50 percent.

REYNOLD'S NUMBER VS. COEFFICIENT OF DRAG FOR SPHERES

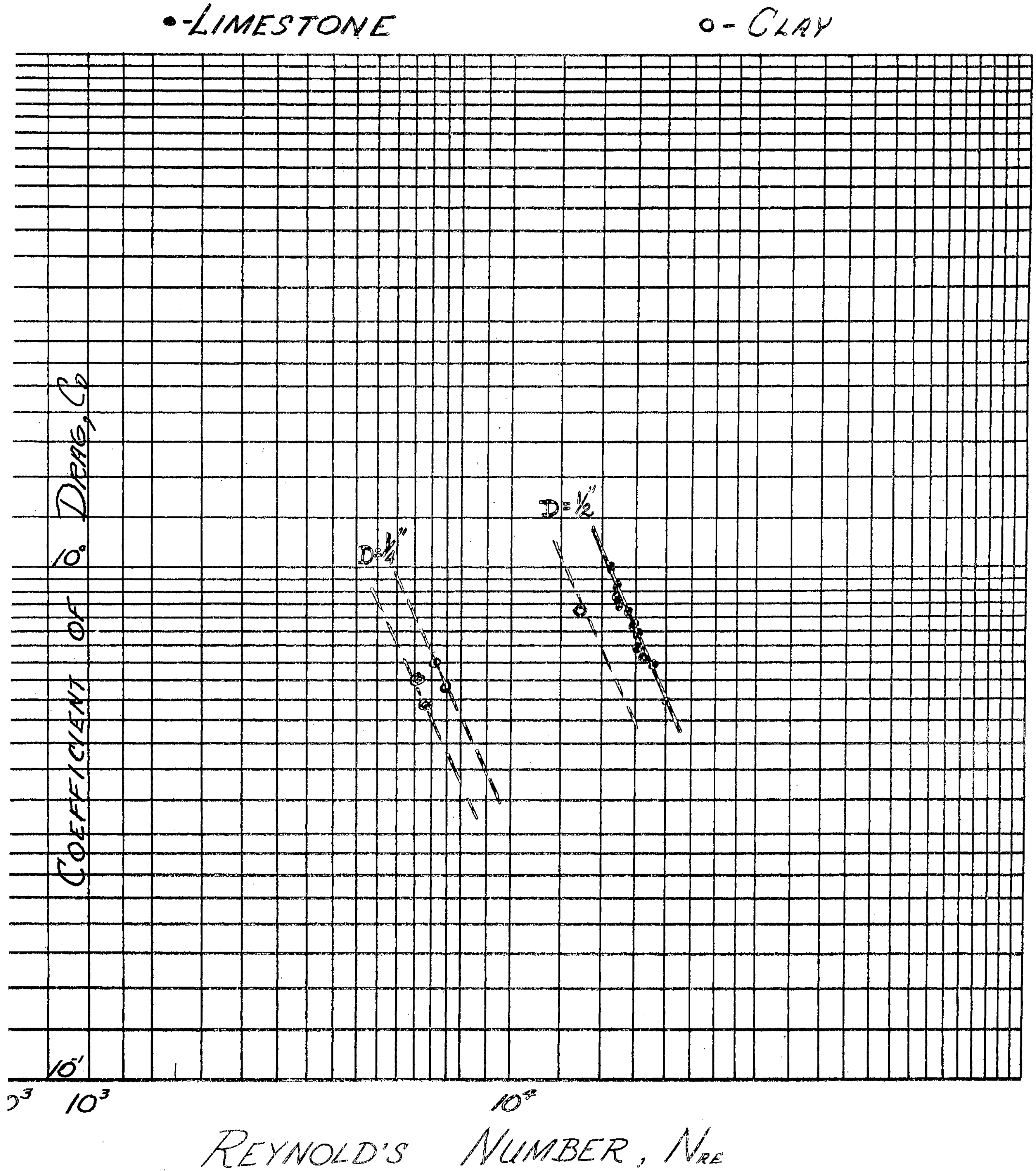


FIG. 12

REYNOLD'S NUMBER VS. COEFFICIENT OF DRAG FOR CYLINDERS

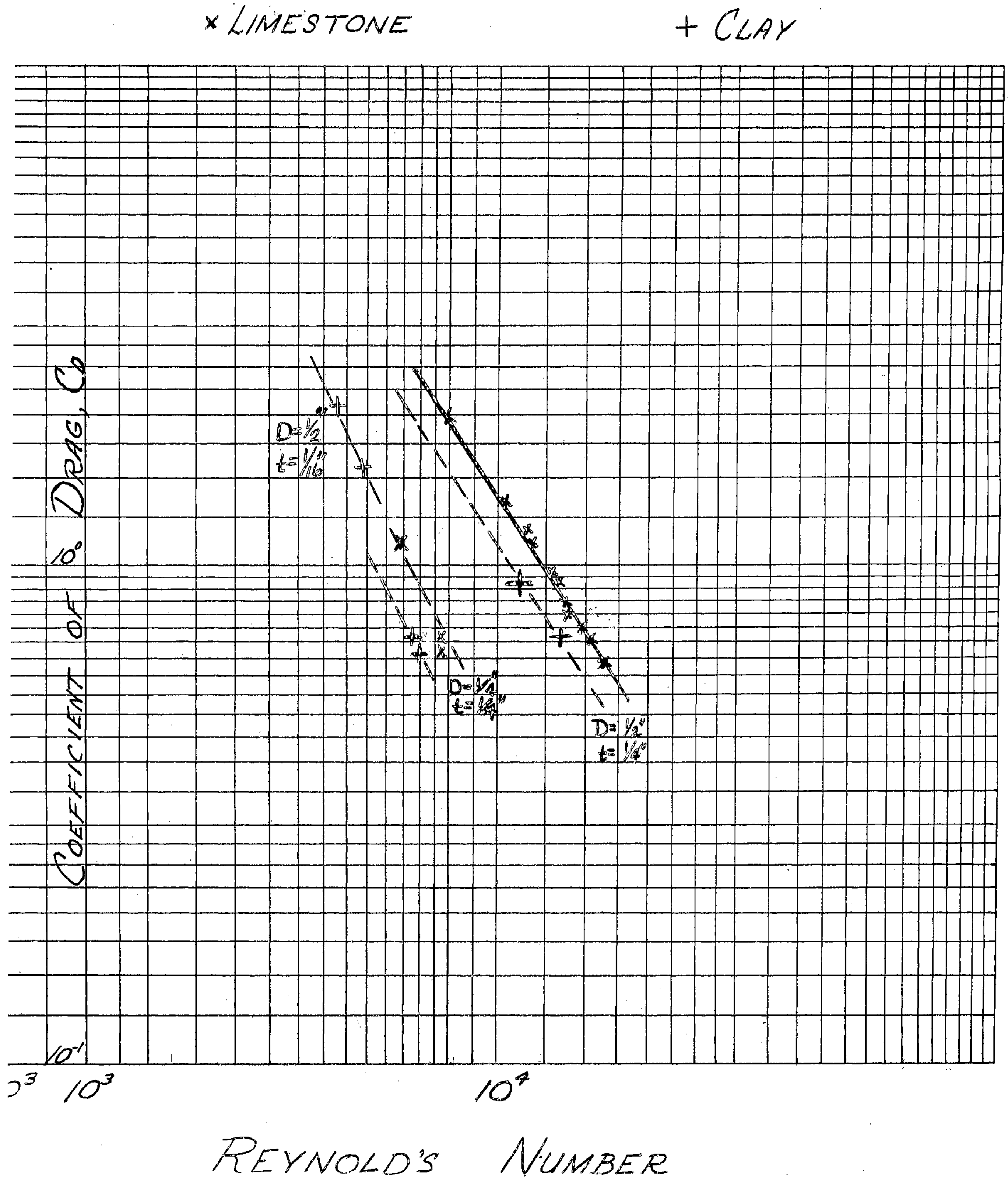
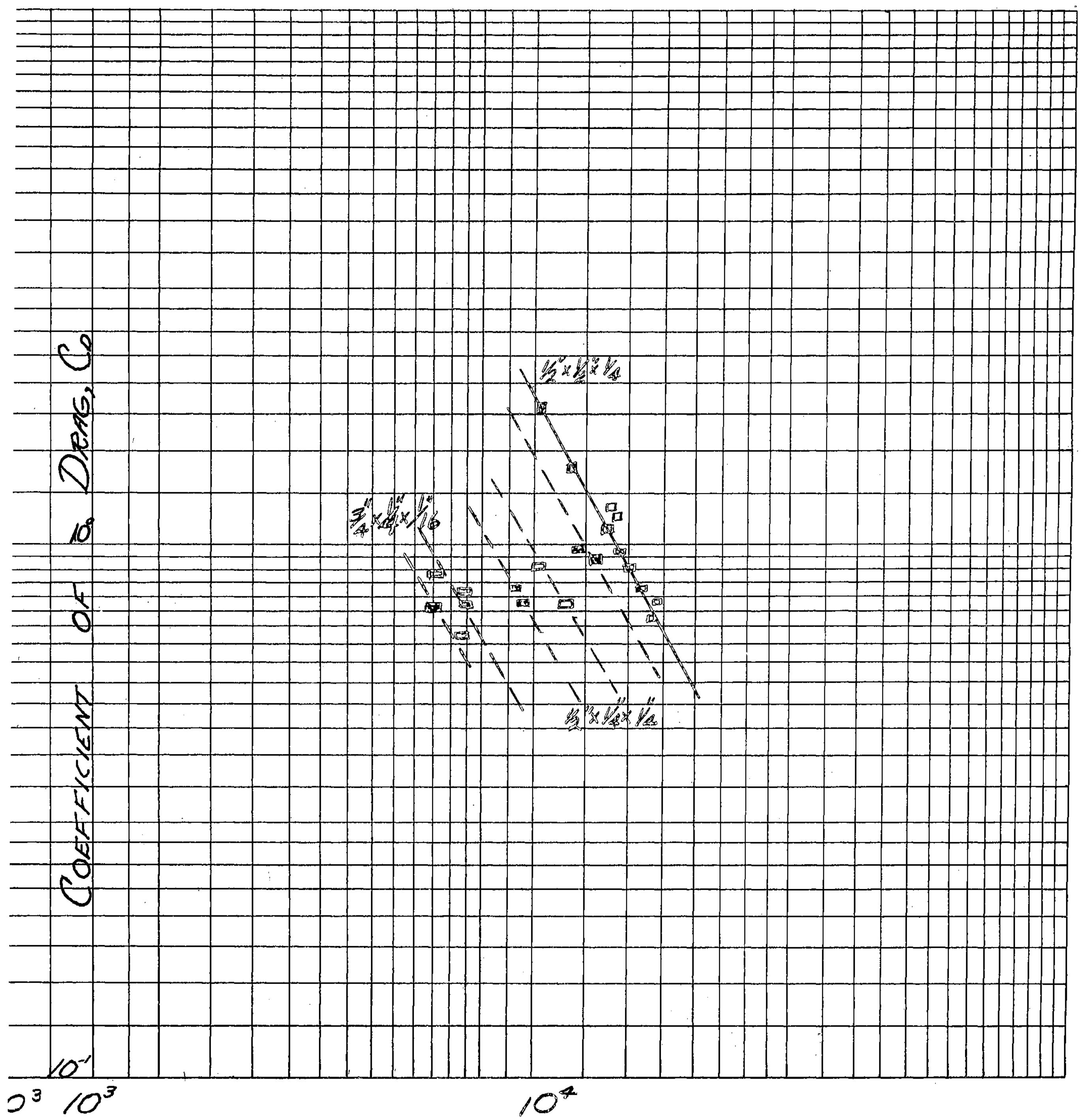


FIG. 13

REYNOLD'S NUMBER VS. COEFFICIENT OF DRAG

FOR RECTANGLES

▭ - LIMESTONE ▬ - CLAY



REYNOLD'S NUMBER, N_{RE}

FIG. 14

REYNOLD'S NUMBER VS. COEFFICIENT OF DRAG FOR TRIANGLES

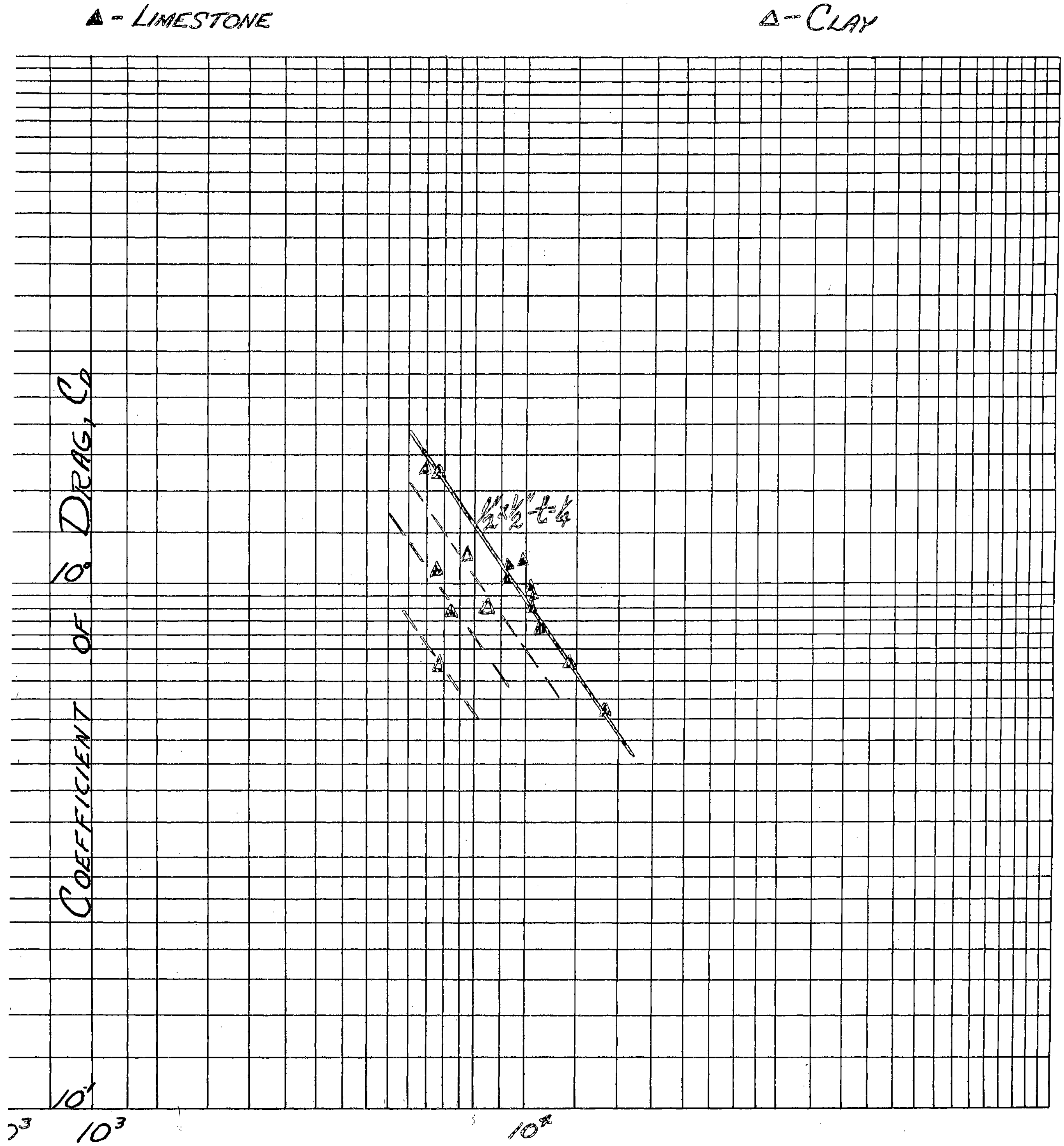


FIG. 15

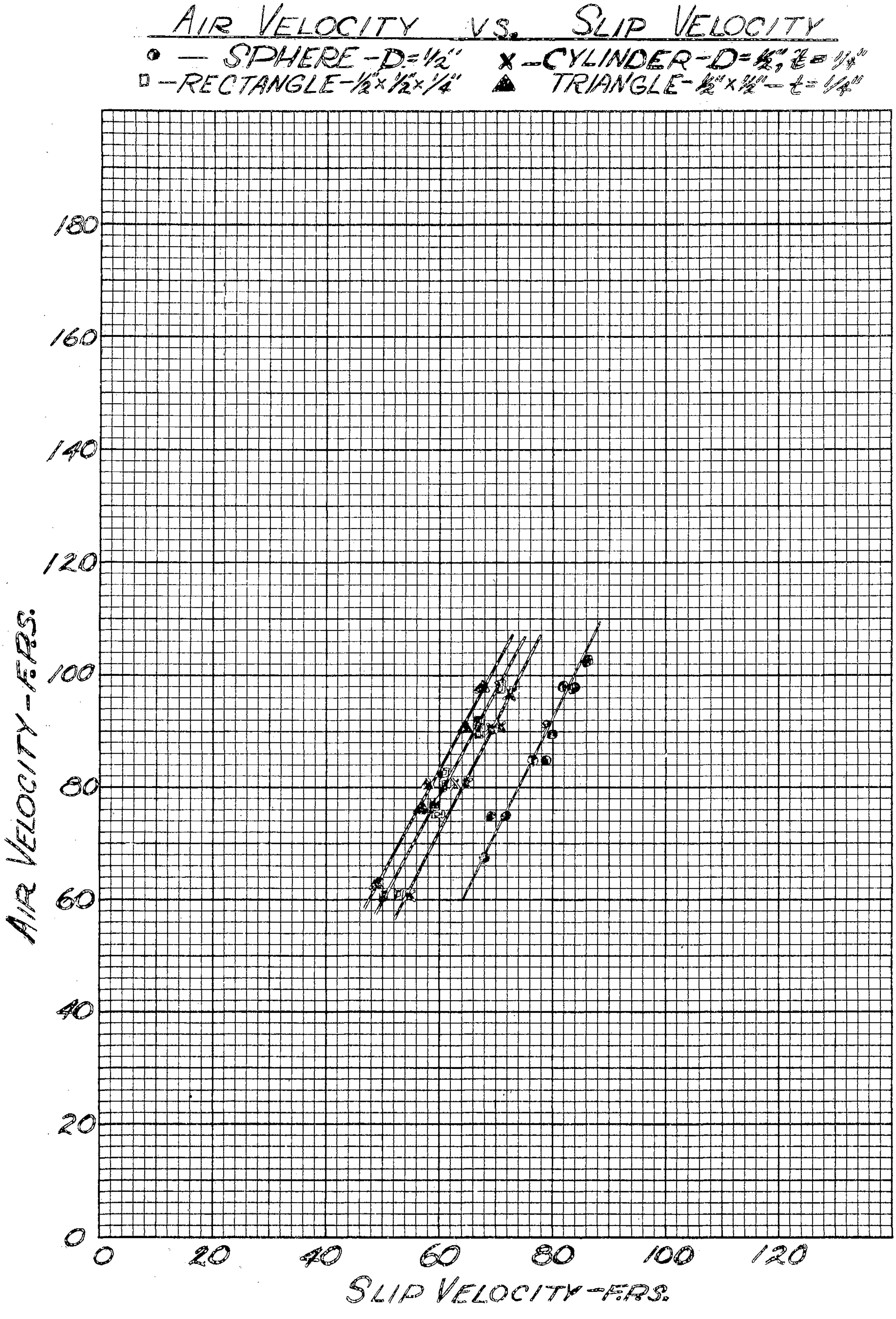

AIR VELOCITY VS. SLIP VELOCITY
• — SPHERE - D = 1/2"
x — CYLINDER - D = 1/2", t = 1/4"
□ — RECTANGLE - 1/2" x 1/2" x 1/4"
▲ TRIANGLE - 1/2" x 1/2" - t = 1/4"
AIR VELOCITY - F.P.S.
0
20
40
60
80
100
120
140
160
180
0
20
40
60
80
100
120
SLIP VELOCITY - F.P.S.

FIG. 16

APPENDIX I

Sample Calculations

Camera Calibration: (Done for each run on basis of 0.005 min. on each side of particle.)

Run No. 6 Frames = 38.5
Seconds = 0.60

$$\text{Camera Speed} = \frac{38.5}{0.60} = 64.1 \ \frac{\text{frames}}{\text{sec.}}$$

Particle Velocity:

Distance covered = 1.0416 ft.

Time = 4 frames = 0.06240 sec.

$$V_p = \frac{1.0416 \text{ ft}}{0.06240 \text{ sec.}} = 16.70 \text{ fps.}$$

Air Velocity:

From ASME code for $\Delta p < (.1)\, P_s$

$$W = 0.8596\, CD_2^2 \sqrt{\frac{\dfrac{P_2 \Delta P}{T_1}}{1 - \left(\dfrac{D_2}{D_1}\right)\left(1 - \dfrac{1.434\Delta p}{P_2}\right)}}$$

Run No. 46:

ΔP = 2 ft. of water = 0.866 psi P_1 = 0.410 ft. of H_g = 0.242
+14.42
14.662 psia

P_2 = 14.662
-0.866
13.796 psia

T_1 = 135°F
+ 459.7
594.7°R

from curve in Power Test Code) = 0.980

Therefore:

$$W = (0.8596)(0.980)(1)\sqrt{\frac{\frac{(13.797)(0.866)}{594.7}}{1 - (0.0625)(1 - \frac{(1.434)0.866}{(14.662)}}}$$

$$= 0.842 \quad 0.02135$$

$$= 0.123 \text{ lb./sec}$$

$$\rho_a \text{ @ } 135^o = 0.0667 \text{ lb/ft}^3$$

$$q = \frac{0.123 \text{ lb/sec}}{0.0667 \text{ lb/ft}^3} = \text{ft}^3/\text{sec} = 1.846$$

$$A_{pipe} = 0.0218 \text{ ft}^2$$

$$V_a = \frac{1.846 \text{ ft}^3/\text{sec}}{0.0218 \text{ ft}^2} = 84.7 \text{ fps}$$

Slip Velocity (V_s)

Run No. 46 $\quad V_s = V_{air} - V_{particle}$

$$V_s = 84.7 - 6.69 = 78.01 \text{ fps.}$$

Reynolds Number:

$$N_{Re} = \frac{D_n V_s \rho_a}{\mu_a} = \frac{D_n V_s}{\nu_a}$$

Run No. 46:

$$D_n = 4.17 \times 10^{-2} \text{ ft.}$$

$$V_s = 78.01 \text{ ft/sec.}$$

$$\nu = 1.980 \times 10^{-4} \text{ ft}^2/\text{sec}$$

$$N_{Re} = \frac{(4.17)(78.01) \times 10^{-2}}{1.980 \times 10^{-4}} = 16{,}450$$

Coefficient of Drag:

$$C_d = \frac{2F}{A_n \rho_a V_s^2}$$

And when particle is in equilibrium,

$$F = v(\rho_p - \rho_a)g$$

since $(v_p)(\rho_a)g$ is so small, (it can be neglected and $v_p \rho_p g = W_p$ = lb. of the particle can be used, thus avoiding use of ρ_p and consequent introduction of errors due to inaccurate dimensions of the particle.

Therefore:

$$C_d = \frac{2W}{A_p \rho_a V_s^2} = \frac{lb}{(ft^2)\left(\frac{lb\text{-}sec^2}{ft^4}\right)\left(\frac{ft^2}{sec^2}\right)} = \text{dimensionless}$$

<u>Run No. 46:</u>

$$C_d = \frac{(2)\ (6.59 \times 10^{-3})}{13.62 \times 10^{-4})(20.945 \times 10^{-4})(7801)}$$

$$= 0.760$$

EXPERIMENTAL DATA

Particle	D_n(ft.)	An	W.(lb.)
Ls.-Sphere -D = $\frac{1}{2}$"	0.0417	13.62×10^{-4}	6.59×10^{-4}
Ls.-Sphere -D = $\frac{1}{4}$"	0.0208	3.42	.737
Ls.-Cylinder -D = $\frac{1}{2}$" t = $\frac{1}{4}$"	0.0379	11.28	4.53
Ls.-Cylinder -D = $\frac{1}{2}$" t = 1/16"	0.02385	4.47	1.14
Ls.-Cylinder -D = $\frac{1}{4}$" t = $\frac{1}{4}$"	0.02385	4.47	1.075
Ls.-Rectangular prism - $\frac{1}{2}$" x $\frac{1}{2}$" x $\frac{1}{4}$"	0.0411	13.28	5.34
Ls.-Rectangular prism - $\frac{1}{2}$" x $\frac{1}{4}$" x $\frac{1}{4}$"	0.0326	8.34	2.58
Ls.-Rectangular prism -3/4" x $\frac{1}{4}$" x 1/16"	0.0235	4.33	1.119
Ls.-Rectangular prism - $\frac{1}{2}$" x $\frac{1}{4}$" x 1/8"	0.0258	5.22	1.383
Ls.-Triangular prism -b = $\frac{1}{2}$", h = $\frac{1}{2}$", t = $\frac{1}{4}$"	0.0326	8.34	3.07
Ls.-Triangular prism -b = $\frac{1}{2}$", h = $\frac{1}{4}$", t = $\frac{1}{4}$"	0.0258	5.22	1.857
Clay-Sphere -D = $\frac{1}{2}$"	0.0417	13.62×10^{-4}	4.93×10^{-3}
Clay-Sphere -D = $\frac{1}{4}$"	0.0208	3.42	.634
Clay-Cylinder -D = $\frac{1}{2}$" t = $\frac{1}{4}$"	0.0379	11.28	3.36
Clay-Cylinder -D = $\frac{1}{2}$" t = 1/16"	0.02385	4.47	.891
Clay-Cylinder -D = $\frac{1}{4}$" t = $\frac{1}{4}$"	0.02385	4.47	.88
Clay-Rectangular prism $\frac{1}{2}$" x $\frac{1}{2}$" x $\frac{1}{4}$"	0.0411	13.28	4.125

Clay-Rectangular prism $\frac{1}{2}$" x $\frac{1}{4}$" x $\frac{1}{4}$"	0.0326	8.34	2.15
Clay-Rectangular prism 3/4" x $\frac{1}{4}$" x 1/16"	0.0235	4.33	.777
Clay-Rectangular prism $\frac{1}{2}$" x $\frac{1}{4}$" x 1/8"	0.0258	5.22	1.09
Clay-Triangular prism $b = \frac{1}{2}$", $h = \frac{1}{2}$", $t = \frac{1}{4}$"	0.0326	8.34	2.32
Clay-Triangular prism $b = \frac{1}{2}$", $h = \frac{1}{4}$", $t = \frac{1}{4}$"	0.0258	5.22	1.255

EXPERIMENTAL DATA

Run No.	Particle	Air Temp.	V_a	V_p	V_s	N_{Re}	C_d
1	Ls.-Sphere D = ½"	111°F	75.35	3.92	71.43	16,000	0.873
2	Ls.-Sphere D = ¼"	112	75.5	15.42	60.08	6,740	0.552
3	Ls.-Cylinder D = ½" t = ¼"	117	76.2	17.75	58.45	11,800	1.09
4	Ls.-Cylinder D = ½" t = 1/16"	118	76.35	31.00	45.35	5,750	1.153
5	Ls.-Cylinder D = ¼" t = ¼"	118	76.35	17.02	59.33	7,525	0.635
6	Ls.-Rectangular prism ½" x ½" x ¼"	118	76.35	16.70	59.65	13,030	1.050
7	Ls.-Rectangular prism ½" x ¼" x ¼"	119	76.50	14.05	62.45	10,800	0.739
8	Ls.-Rectangular prism 3/4" x ¼" x 1/16"	119	76.50	14.57	61.93	7,720	0.627
9	Ls.-Rectangular prism ½" x ¼" x 1/8"	120	76.65	20.05	56.60	7,730	0.772
10	Ls.-Triangular prism ½" x ½" x ¼" = t	105	74.50	18.45	56.05	10,010	1.072
11	Ls.-Triangular prism ½" x ½" x ¼" = t	108	74.95	20.00	54.95	7,730	1.080
12	Ls.-Sphere D = ½"	110	75.20	6.20	69.00	15,590	0.934
13	Ls.-Sphere D = ¼"	105	74.50	13.30	61.20	6,980	0.528
14	Ls.-Cylinder D = ½" t = ¼"	105	74.50	17.68	56.82	11,810	1.136
15	Ls.-Cylinder D = ½" t = 1/16"	116	No particle record on film				
16	Ls.-Cylinder D = ¼" t = ¼"	116	74.65	14.96	59.69	7,605	0.627

17	Ls.-Rectangular prism ½" x ½" x ¼"	116	76.05	16.71	59.34	13,020	1.059
18	Ls.-Rectangular prism ½" x ¼" x ¼"	116	76.05	18.36	57.69	10,020	0.862
19	Ls.-Rectangular prism	116	76.05	22.70	53.35	6,685	0.884
20	Ls.-Rectangular prism ½" x ¼" x 1/8"	116	76.05	20.35	55.70	7,680	0.793
21	Ls.-Triangular prism ½" x ½" x ¼" = t	116-	76.05	17.20	58.85	10,220	0.985
22	Ls.-Triangular prism ½" x ¼" x ¼" = t	116	76.05	16.22	59.83	8,250	0.910
23	Clay-Sphere D = ½"	116	76.05	10.00	66.05	14,690	0.767
24	Clay-Sphere D = ¼"	116	76.05	17.45	58.60	6,515	0.499
25	Clay-Cylinder D = ½" t = ¼"	116	76.05	20.00	56.05	11,320	0.880
26	Clay-Cylinder D = ½" T = 1/16"	116	76.05	41.2	34.85	4,440	1.518
27	Clay-Cylinder D = ¼" T = ¼"	116	76.05	22.33	53.72	6,840	0.631
28	Clay-Rectangular prism ½" x ½" x ¼"	115	75.95	21.35	54.60	12,010	0.965
29	Clay-Rectangular prism ½" x ¼" x ¼"	115	75.95	19.94	56.01	9,790	0.763
30	Clay-Rectangular prism 3/4" x ¼" x 1/16"	115	No particle record on film				
31	Clay-Rectangular prism ½" x ¼" x 1/8"	98	73.6	29.1	44.5	6,430	0.958
32	Clay-Triangular prism ½" x ½" x ¼"	101	74.0	26.45	47.55	8,580	1.132
33	Clay-Triangular prism ½" x ¼" x ¼"	103	No particle record on film				
34	Clay-Sphere D = ½"	107	74.75	10.00	73.75	16,760	0.609
35	Clay-Sphere D = ¼"	108	74.9	17.83	57.07	6,470	0.524

36	Clay-Cylinder D = ½" t = ¼"	110	75.2	14.27	60.93	12,505	0.760
37	Clay-Cylinder D = ½" t = 1/16	112	75.4	42.3	33.10	4,265	1.840
38	Clay-Cylinder D = ¼" t = ¼"	112	75.4	21.6	53.8	6,920	0.626
39	Clay-Rectangular prism ½" x ½" x ¼"	115	75.8	21.65	54.15	11,910	0.981
40	Clay-Rectangular prism ½" x ¼" x ¼"	116	75.9	206	55.3	9,620	0.782
41	Clay-Rectangular prism ½" x ¼" x 1/8"	125	77.25	25.70	51.55	6,930	0.740
42	Clay-Triangular prism ½" x ½" x ¼"	126	77.40	21.10	56.30	9,520	0.826
43	Clay-Triangular prism ½" x ¼" x ¼"	128	77.55	23.75	53.80	7, 175	0.783
44	Clay-Rectangular prism 3/4" x ¼" x 1/16"	120	67.20	24.40	42.80	5,330	0.910
45	Ls.-Sphere D = ½"	135	84.70	5.66	79.04	16,670	0.738
46	Ls.-Sphere D = ½"	135	84.70	6.69	78.01	16,450	0.760
47	Ls.-Rectangular prism ½" x ½" x ¼"	135	61.20	12.00	49.20	10,190	1.589
48	Ls.-Cylinder D = ½" t = ¼"	135	61.20	11.60	46.93	8,990	1.742
49	Ls.-Triangular prism ½" x ½" x ¼"	135	61.20	11.60	49.60	8, 150	1.433
50	Ls.-Rectangular prism ½" x ½" x ¼"	133	61.10	6.44	54.66	11,420	1.283
51	Ls.-Cylinder D = ½" t = ¼"	133	61.10	6.60	54.50	10,505	1.285
52	Ls.-Triangular prism ½" x ½" x ¼"	133	61.10	10.84	50.26	8,310	1.388
53	Ls.-Sphere D = ½"	126	89.30	9.90	79.40	17,180	0.724

54	Ls.-Rectangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	130	80.40	17.15	63.25	13,330	0.953
55	Ls.-Cylinder D = $\frac{1}{2}"$ t = $\frac{1}{4}"$	133	80.80	18.49	62.31	12,030	0.984
56	Ls.-Triangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	133	80.80	18.48	62.32	10,320	0.904
57	Ls.-Sphere D = $\frac{1}{2}"$	136	90.60	11.82	78.78	16,550	0.747
58	Ls.-Rectangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	136	81.25	20.50	60.75	12,585	1.043
59	Ls.-Cylinder D = $\frac{1}{2}"$ t = $\frac{1}{4}"$	136	81.25	17.82	63.43	12,100	0.960
60	Ls.-Triangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	136	81.25	22.45	58.80	9,630	1.018
61	Ls.-Sphere D = $\frac{1}{2}"$	136	98.70	15.44	83.26	17,480	0.668
62	Ls.-Rectangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	136	90.60	21.65	68.95	14,275	0.811
63	Ls.-Cylinder D = $\frac{1}{2}"$ t = $\frac{1}{4}"$	137	90.70	23.75	66.95	12,720	0.858
64	Ls.-Triangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	138	90.80	26.40	64.40	10,495	0.855
65	Ls.-Sphere D = $\frac{1}{2}"$	136	98.70	15.88	82.82	17,410	0.674
66	Ls.-Rectangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	137	90.70	18.00	72.70	14,990	0.730
67	Ls.-Triangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	137	90.30	16.70	73.60	12,015	0.651
68	Ls.-Cylinder D = $\frac{1}{2}"$ t = $\frac{1}{4}"$	137	90.60	24.65	65.95	12,520	0.884
69	Ls.-Sphere D = $\frac{1}{2}"$	138	103.80	16.70	87.10	18,175	0.612
70	Ls.-Rectangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	136	98.70	27.65	71.05	14,710	0.766
71	Ls.-Cylinder D = $\frac{1}{2}"$ t = $\frac{1}{4}"$	136	98.70	25.70	73.00	13,930	0.721

72	Ls.-Triangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	136	98.70	29.10	69.60	13,930	0.721
73	Ls.-Sphere D = $\frac{1}{2}"$	138	102.00	16.29	85.71	17,880	0.632
74	Ls.-Rectangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	138	90.80	25.10	65.70	13,520	0.896
75	Ls.-Cylinder D = $\frac{1}{2}"$ t = $\frac{1}{4}"$	138	90.80	21.03	69.77	13,240	0.793
76	Ls.-Triangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	138	90.80	31.70	59.10	9,640	1.013
77	Ls.-Cylinder D = $\frac{1}{2}"$ t = $\frac{1}{4}"$	142	91.10	21.12	69.98	13,120	0.793
78	Ls.-Triangular prism $\frac{1}{2}" \times \frac{1}{2}" \times \frac{1}{4}"$	142	91.10	26.40	64.70	10,415	0.854
79	Clay-Rectangular prism 3/4" x $\frac{1}{4}"$ x 1/16"	142	No particle record on film				

APPENDIX II

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VITA

John Ed Hansford
candidate for the degree of
Master of Science

Thesis: AN INVESTIGATION OF THE EFFECTS OF AIR VELOCITY AND PROPERTIES OF DRILL CUTTINGS ON THE CARRYING CAPACITY OF AIR

Major: Mechanical Engineering

Biographical and Other Items:

Born: November 9, 1930, at Wetumka, Oklahoma.

Undergraduate Study: East Central State College, 1950-1951
Oklahoma Agricultural and Mechanical College, 1951-1954

Graduate Study: Oklahoma Agricultural and Mechanical College, 1954-1955

Date of Final Examination: April 1957

THESIS TITLE: AN INVESTIGATION OF THE EFFECTS OF AIR VELOCITY AND PROPERTIES OF DRILL CUTTINGS ON THE CARRYING CAPACITY OF AIR

AUTHOR: John E. Hansford

THESIS ADVISER: Dr. James H. Boggs

The content and form have been checked and approved by the author and thesis adviser. The Graduate School Office assumes no responsibility for errors either in form or content. The copies are sent to the bindery just as they are approved by the author and faculty adviser.

TYPIST: Eula M. Haack