AN INVESTIGATION OF
THE FILTERABILITY OF
DIAMOND-DRILL SLUDGES

by

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A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Mining engineering.

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ABSTRACT

Techniques in current use for the recovery of the solid material in the return water from diamond drilling operations are not completely satisfactory. To obtain information upon which improved devices for sludge recovery should be designed a study of the physical characteristics of diamond drill sludges was undertaken, using sludge from the Colorado School of Mines Experimental Mine, and, in lesser quantities, sludges originating at various other mines.

These sludges were analyzed to determine (a) the specific gravity of the contained solids, (b) the distribution of the particle sizes, and (c) the concentration of the solids in the raw return water. Tests were run to determine the effects of the following variables on the rate of fil~~trati~~on of these sludges: (a) the minus 325 mesh fraction present, (b) percentage of solids, (c) addition of flocculating reagents. From the data obtained, filtration constants were calculated. These were compared with similar data from various metallurgical operations. It was found that the sludges tested have properties similar to finely ground ores and that the filtration rates are normally slow. It appears that a single, small, simple sludge handling device, based solely on filtration, can be developed to handle the usual sludges, similar to the ones studied, but not for all types of sludges.

ACKNOWLEDGMENTS

The author wishes to express his thanks to the following members of the Faculty of the Colorado School of Mines for their valuable suggestions and advice:

Professor J. S. Rinehart, Director of Research, Mining Department

Professor J. M. Jones, Mining Department

Professor W. M. Richtmann, Head of Mechanical Engineering Department

Professor A. P. Wichmann, Metallurgical Engineering Department

Professor J. Merrin, English Department

The author is also greatly indebted to Professor C. O. Frush of the Mining Department, for his advice and guidance during the organization of the present investigation; and to Professor A. L. Pierce of the Metallurgical Engineering Department, Colorado School of Mines, for advising in the installation of filtration apparatus.

Author's sincere appreciation to the following companies for providing the diamond-drill sludges:

Sprague & Henwood, Inc., Grand Junction, Colorado
Boyles Brothers Drilling Company, Denver, Colorado
Climax Molybdenum Company, Climax, Colorado

Author's thanks are also due to Professor M. F. Ayler and Professor N. E. Grosvenor, professors-in-charge of the Colorado School of Mines' Experimental Mine, Idaho Springs, Colorado, for providing diamond-drill sludges.

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NOTE: Table 18, p. 68; Table 21, p. 71; and Table 22, p. 72 were not supplied by the Author.

INTRODUCTION

Purpose of Investigation

Diamond core drilling in bad ground may result in very poor core recovery. Consequently it is necessary to recover the drilling sludge for examination and assay. Not much can be found in the literature about sludge-collecting devices, very few of which appear to have been developed in recent years. Those presently in use are not entirely satisfactory. There is a need for mechanical devices that will process the return water rapidly, collecting the sludge continuously in such a manner as will preserve the moment-to moment fluctuations in color and character. Filtration of sludge is a possibility. But devices of sludge-collection by filtration cannot be designed properly without the knowledge of the physical characteristics of typical sludges. Since quantitative information of this subject was lacking, the immediate object of the work reported in this thesis was to determine the feasibility of filtering diamond drill sludges.

In order to understand the proposed problem the diamond drill operation and filtration theory and principles are discussed.

Outline and Plan of Investigation

The principal steps undertaken in the investigation were as follows:

1) Specific gravity determination of diamond drill sludges
2) Size distribution analysis
3) Percentage of solids determination
4) Filtration tests to determine the effect of
    (a) different percentage of solids
    (b) subsieve sizes
    (c) reagents
        (1) polyvalent
        (2) divalent

    on the filtration rates of diamond drill sludges.
5) Calculation of filtration constants and capacities from filtration tests data.

DIAMOND DRILLING OPERATION

The diamond drill is widely used as a tool of exploration, but it is an expensive tool. Thus, it is used to confirm the results of other cheaper surface exploration methods. From a diamond drilling program the geologist or prospector obtains information of the extent of an ore body, nature of ore, metal contents, average grade, and finally the value of the ore body. These data are obtained from the products of drilling, namely the core and sludge.

Construction

A diamond drill setup (Peele, 1956, p. 9-44) is made up of a boring column (Fig. 1) that consists of; bit X, set with diamonds; core shell V, containing lifter W; core barrel U; hollow rods P, rotating within casing strings M and N. The drill rod is driven by a gasoline engine, mounted on a steel frame. Water is pumped into rods through a swivel. A hose connects the pump and the swivel. The rods are raised and

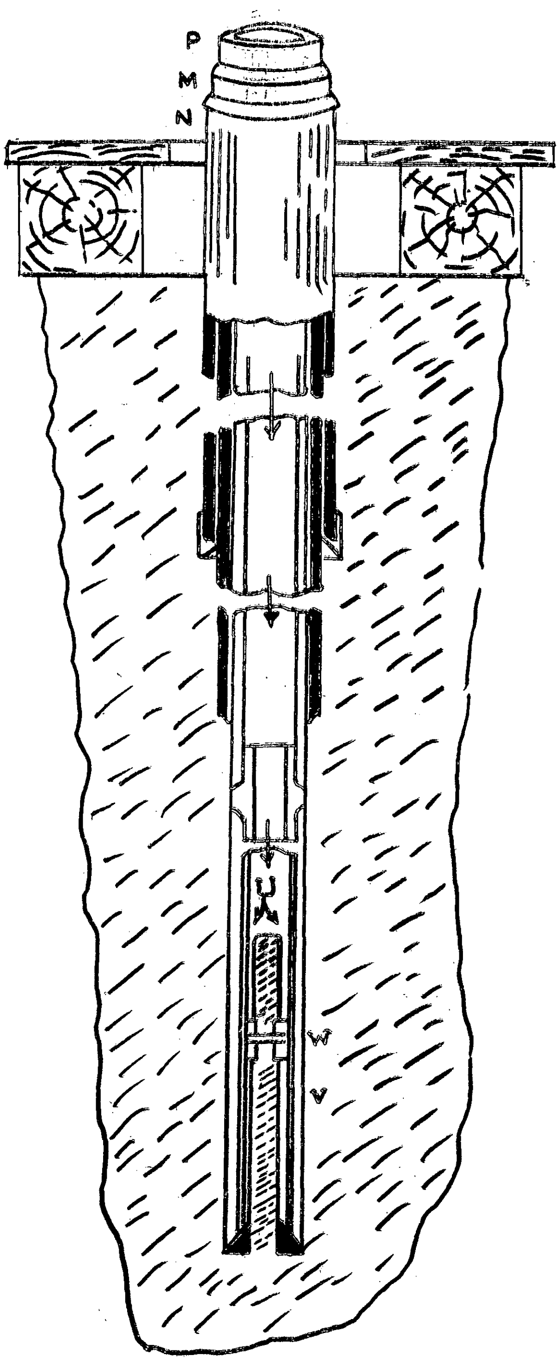


Figure 1 TYPICAL DIAMOND DRILL TOOL COLUMN

lowered by a drum and wire rope, the latter passing over a block at the top of the derrick.

Preparation

A drilling program is usually set up with drill holes in regularly-spaced intervals. Depending on the results obtained the spaced interval is reduced to a limit which both provides the best information and involves least expense. In a designated place, where a hole is to be drilled, an area of 20-25 feet square is graded. The drill and the pump are set on a plank floor. For deep holes or light machines, the derrick legs rest on the floor, to counteract upward pressure when drilling. In underground setups smaller drills are used, and drifts are widened at the drilling place.

Drilling

Peele(1956, p. 9-51) describes the sequences of drilling as follows: A standpipe is placed by wash boring. On reaching the rock, the standpipe is chopped or bored in a few inches, to make a tight joint. This is done to prevent the influx of surface material, and insure the return of drilling water to the surface. The feed mechanism is turned away from the hole. Safety clamps are set in position over the standpipe. The bit, core shell (with core lifter), core barrel, and one length of rod are connected and lowered through the safety clamps until only a few inches project. This portion of the rod is tightly gripped by the clamps. The hoisting swivel is screwed into the upper end of a section of rods. The rods are swung into place with the hoist and screwed into the rod joint projecting from the hole. The safety clamp is loosened, and the string of rods is lowered until a few inches project from the hole. The safety clamp is again tightened, and the hoisting swivel is unscrewed. These operations are repeated until the bit is within a rod's length from the bottom of the hole. The feed mechanism is brought back into place. The water swivel and lifting bail is attached to the last length. They are lowered through the drive rod, and screwed into place. The feed is adjusted to the highest position, and the chuck is tightened. The safety clamp is loosened. The water swivel is connected to the pump. After starting the pump, the drill is also started and run downward until pressure shows that the bit is against the rock. When measurement of rod indicates that the core barrel is full, or laboring of pump and engine suggest that it is blocked by broken pieces of core, the drill is stopped. But the pump is kept running until water issuing from the hole shows that the sludge has been well removed. In underground drilling the hoisting swivel is not commonly used. Rods are connected one length rod at a time.

Products of Diamond Drilling

A core and sludge are the products obtained in a diamond drilling operation.

Core: The core is the cyclindrical section of rock that has been cut and thrust into the hollow core barrel. Its length depends on the type of rock drilled. The amount of core recovered is very important in a drilling operation. The ideal result is to drill a rod length of 5 feet and obtain a 5-foot core. This is called 100% core recovery. In practice such results are uncommon. As the core recovery decreases the recovery of sludge becomes important.

Sludge: The return water from the drill hole carries up the fine rock particles formed during the cutting out of the core from the solid rock. The slurry formed by the ground rock and the drill water is called sludge. The sludge is collected to supplement the information obtained from the core. Its importance increases as the recovery of core decreases.

Sludge Collection: There are two schools of thought about sludge collection. One believes that all sludge should be collected, the other believes that none should be collected. Cummings (1956, p. 256) believes that there will be a middle ground in which sludge collection will depend on (1) economy of the situation, and (2) the personal predilection of the engineer. In determining whether to collect sludge, the engineer considers the following factors:

1) amount of core recovery
2) special physical conditions pertaining to the desired ore samples that make accuracy of results from the core recovered doubtful; or that justify the effort to recover sludge at the prevailing conditions.
3) vein material of such nature that it disintegrates, leaving only the harder and perhaps leaner sections in the recovered core.

If it is always possible in diamond drilling to obtain 100% core recovery, the sludge sample will not be of great importance except for check assays. But since favorable conditions do not prevail, the importance of sludge sample increases as core recovery decreases. This statement can be proved by the following illustration:

> In drilling an EX hole, drill rods with an outside diameter of 1 5/16-in. is used. The approximate diameter of hole made by the core barrel bit is 1 1/2 in. The core diameter is 7/8 in. (Cummings,

1956, Table 6, p. 114).

Assuming 100% core recovery (Cummings, 1956, Table 18, p. 270)

Volume of core is 35.5% of the total volume of hole

Volume of sludge is 64.5% of the total volume

Assuming 50% core recovery (Cummings, 1956, Table 17, p. 269)

Volume of core is 17.7% of total volume of hole

Volume of sludge is 82.3% of total volume of hole.

Sludge-collecting devices

There are numerous types of sludge-collecting devices, but not many have been described in the literature. Those that are described give a picture of the trend of the development of such devices.

Tub: The tub type is the crudest. The return water is allowed to run into a tub, bucket, or powder box and is permittedto overflow. Enough cuttings remain in the container to furnish a sample (Cummings, 1956, p.264).

Sludge Box: There are various designs of sludge boxes, depending on the type of material drilled and the sample requirements. A commonly used type is a box made of wooden planks, 3 to 6 feet long, 12 to 18 inches wide, and 6 to 12 inches deep (Fig. 2 and 3).Baffle plates may be used to improve settlement of the cuttings (Cummings, 1956, p263).

Swinging pipe: This is an improved methodof collecting sludge. Return water is run into three or more barrels, tubs, or sludge boxes through a pipe and launder. When one barrel is filled the pipe is swung to the next barrel, and so on (Fig. 5). If the water in the first sludge box is clear it is siphoned out and the box is filled again. This process is continued until the end of the interval to be sampled. All the material from the sludge boxes is transferred to one container and allowed to settle further. Alum is added to speed settling. The number of boxes used depends on the settling rate of the material (Cummings, 1956, p. 264).

McDonald Sludge Collector: This is a frame of welded 1-inch pipe 12 feet long, 1 3/4 feet wide, and tapering in depth from 1 foot to 2 feet (Fig. 4). Within this frame is suspended a trough of 22-gauge galvanized iron. The shallow end has a slot 10-inches wide, from which clear water overflows. The deep end is reinforced with 10-gauge galvanized iron and contains holes to drain the rough at three different levels (Sein, 1952, p. 171). The top level discharges clear water. Water coming from the middle level contains small amounts of sludge. The lowest level drains out all the sludge. The sludge is collected in 5-gallon milk cans and

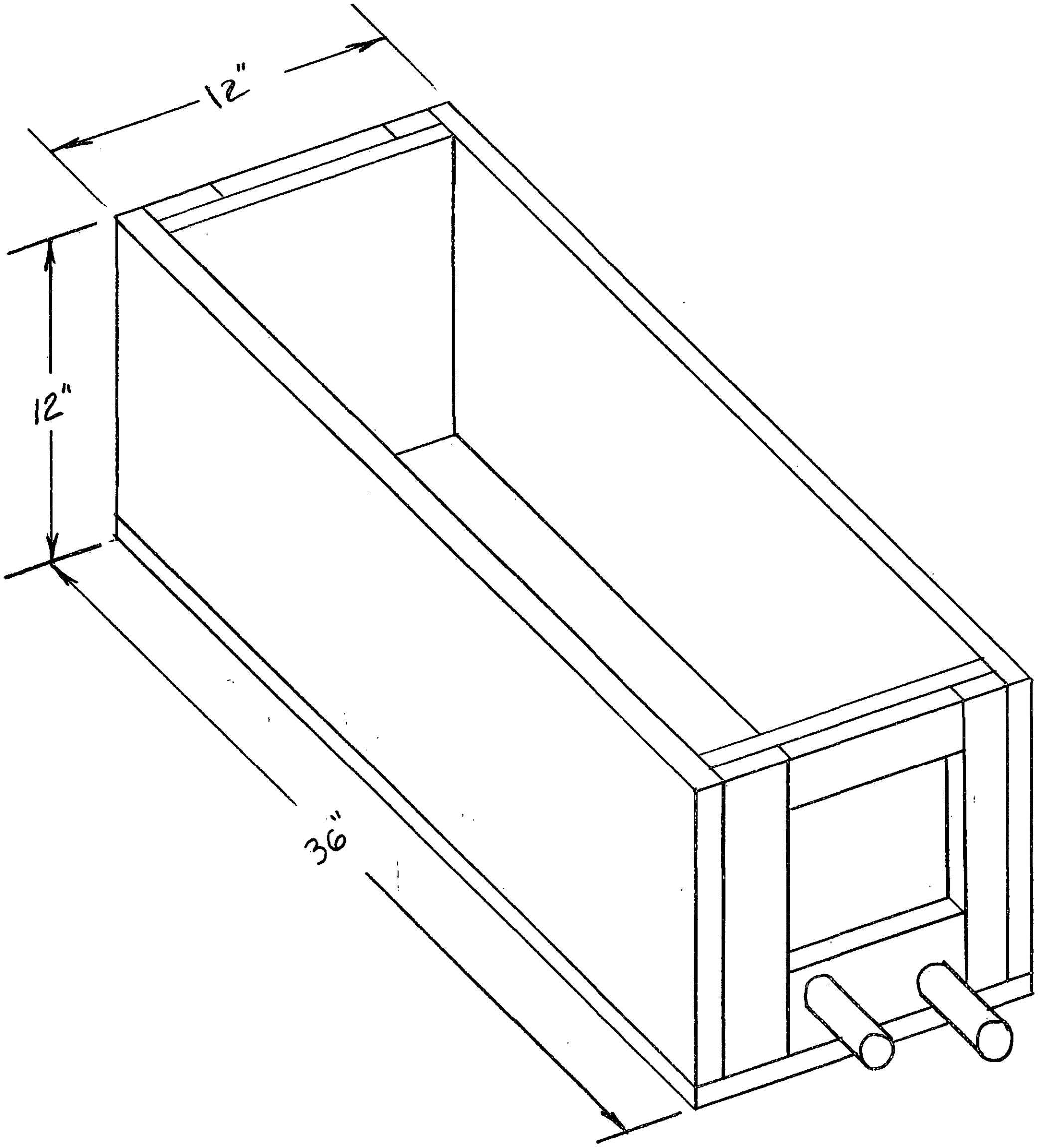


Figure 2   SLUDGE SETTLING BOX, USED IN DUPLICATE

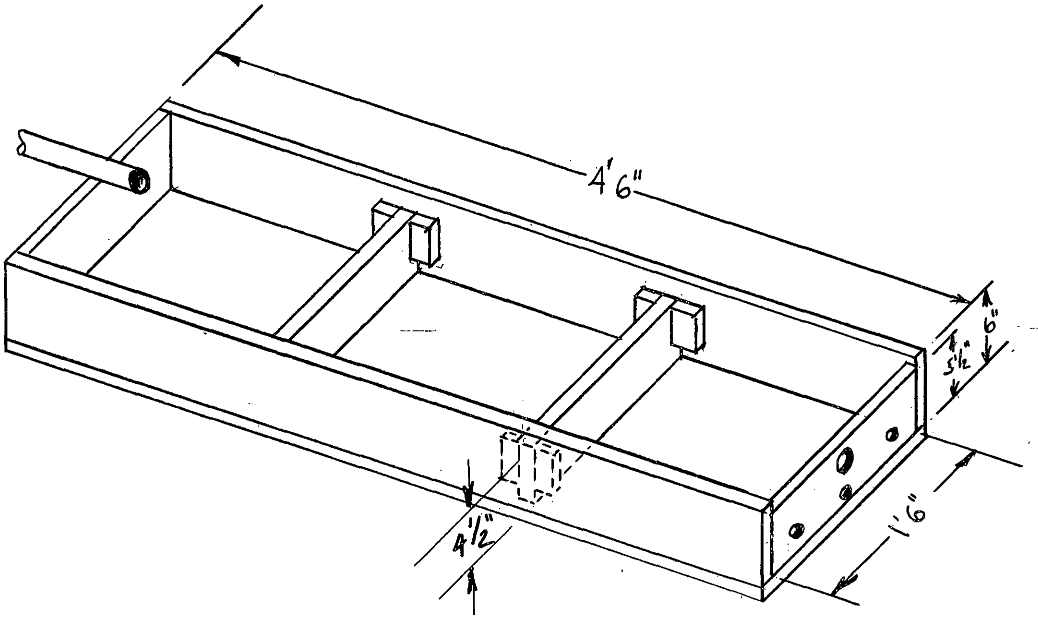
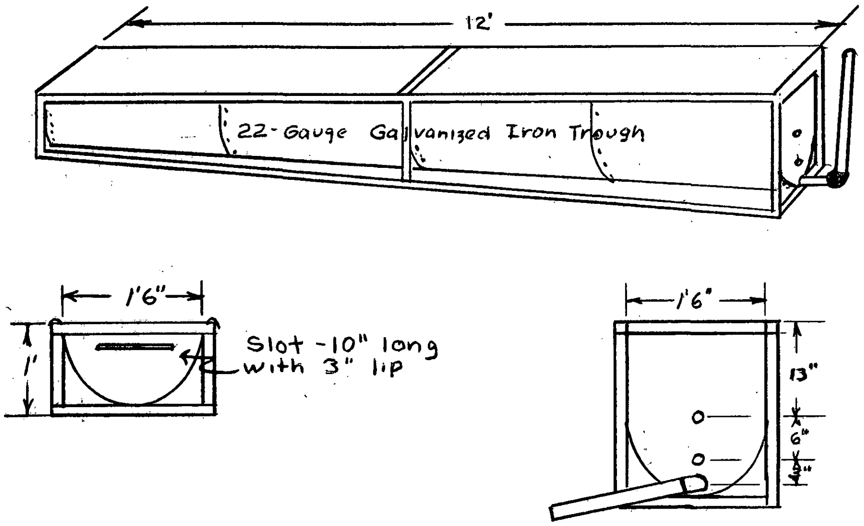


Figure 3 WOODEN SLUDGE BOX



End View - Water Recovery

End View - Sludge Recovery

Figure 4 METAL SLUDGE COLLECTING BOX - McDONALD TYPE allowed to settle out for some hours. The water is decanted and the sludge dried and weighed.

Gustafson Settling Device: This device (Cummings, 1956, p. 274; Gustafson, 1943, p. 280-285) consists of a cylindricaltank with a conical bottom. The discharge of sludge is through a valve at the bottom of the cone, assisted by hand-rotated scrapers (Fig. 5). Since the overflow of water is allowed to discharge over the entire circumference of the cylinder the velocity is low enough so that fine particles will settle and the overflow is clear.

Potential Sources of Errors in Sludge-collecting Devices: Cummings (1956, p.271) summed up the difficulties of sludge-collection. They are as follows:

1) Different proportions of ore and gangue are carried away in the sludge overflow, due to non-settlement of the lighter gangue particles.
2) In some cases 85% passes through 200-mesh and in consequence is hard to settle.
3) Fines are lost when water is siphoned from the sludge collector before settling is complete.
4) Leaks in the sludge collector reduce the validity of the sample.
5) Incomplete removal of the previous sample from a

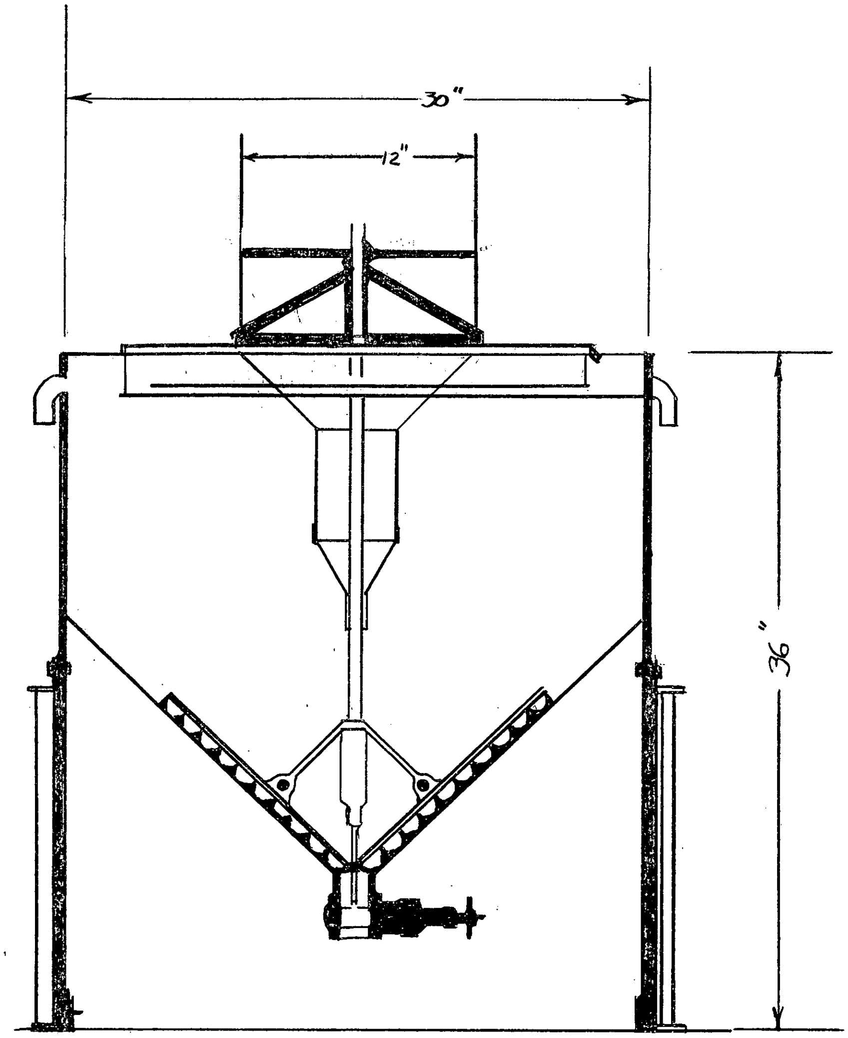


Figure 5 GUSTAFSON SETTLING DEVICE

sludge collector contiminate or salt the next sample.

Discussion: In going over the description of the above mentioned sludge-collectors one notices the trend of improvement of engineering design from tub to the Gustafson device, from draining to gravity settling and siphoning, and then to mechanical settling and thickening. This same trend of improvement can also be noticed in ore-dressing practice in attempting to separate the liquids from the solids. But in the metallurgical industry better recovery of fines is obtained by filtration and centrifuge.

FILTRATION THEORY AND PRINCIPLES

Filtration

Filtration (Taggart, 1951, p. 36) is a method of separation of fluids from solids by causing the fluids to pass through a finely perforated septum that will not pass the solids. Many useful applications have evolved from the utilization of this process; some of which are purification of water and wine, sewage removal, vitamin extraction in medicinal preparation, manufacturing of sugar and other chemical compounds, and ore dressing.

Filtration is often thought of as an extremely simple operation, consisting merely of the straining out of solids from the liquids. Unquestionably, there is some justification in this, but in reality filtration is one of the more difficult steps in chemical engineering (Dickey and Bryden, 1946, p. 30).

Poiseulle's Equation

The fundamental law for eddyless flow of liquids proposed by Poiseulle, a French anatomist, was first used by Hatschek (Dickey and Bryden, 1946, p. 31) as the fundamental equation for all flow through filter cakes, a procedure which has been followed by others. The simplified form of Poiseulle's law is as follows:

$$V = \frac{\pi P r^4}{8 L u} \qquad \frac{0.3927\, Pr^4}{L u}$$

where

P is pressure difference at tube ends	dyne cm^{-2}
r is internal capillary radius	cm
L is length of opening	cm
V is flow velocity	$cm^3\ sec^{-1}$ and
u is viscosity of fluids	gm $cm^{-1}\ sec^{-1}$

In discussing the above equation, Genter (Dickey and Bryden, 1946, p. 31-32) points out the effect of decreasing the radius of opening, e.g., by reducing it to 1/8 of its size, the pressure must be increased over 4000 times to get the same flow at the same tube length and viscosity. Conversely, doubling the radius produces 16 times as much flow with other factors constant. This equation assumes that the fluid flows through capillary channels made by the voids created during the building up of the cake. Basically this is true, but there are other factors that control the fluid flow in filtration practice.

Factors Influencing Filtration

From better understanding of the mechanics of filtration, the basic equation was transformed into a highly complicated formula by introducing many other variables to take care of the other factors that control fluid flow. These factors are listed by Genter (Dickey and Bryden, 1946, p. 31) as:

1) Effective filter area
2) Filtration pressure (pressure difference on two sides of septum).
3) Nature of solids (density, particle size, compressibility)
4) Water or solution present in sludge and filter cake and its density
5) Rate of solids deposition in filter cake (from filtrate flow rate)
6) Resistance of filter base (cloth) to filtrate flow
7) Resistance of filter cake to filtrate flow
8) Time during which rate factors are measured
9) Coefficient of viscosity of filtrate or sludge moisture
10) Temperature.

Almy and Lewis

In 1912, Almy and Lewis (Dickey and Bryden, 1946, p. 36) produced an equation which set down mathematically a formula intended to cover the process of filtration. Their investigation led to the formation of the Lewis equation expressed by the formula:

$$R = K \frac{P^m}{V^n}$$

where

P is pressure drop lb/in^2
R is rate of flow ft^3 / sec
V is volume in^3
m, n, K are constants.

In introducing this equation, Almy and Lewis insisted that the flow rate through a filter cake is not directly proportional to the pressure and inversely proportional to the thickness of the cake.

Sperry and Ruth

Sperry (Dickey and Bryden, 1946, p. 30; Sperry, 1921, p. 986) independently, without the knowledge of Lewis's work developed the Sperry Filtration equation which included septum resistance with variables in an attempt at a complete formula, while Ruth (Dickey and Bryden, 1946, p. 30; Ruth, 1935, p. 714) in his attempt gives a more tangible meaning to constants, and seems to prefer to treat them as a separate equation.

The Sperry Filtration equation is:

$$Q = \sqrt{\frac{2PKT}{R\%} + \left(\frac{KR_m}{R\%}\right)^2} - \frac{KR_m}{R\%}$$

where

Q is quantity of filtrate gal/ft^2
P is difference in pressure on two sides of the cloth lbforce/ ft^2
T is time of filtering min
K is rate of cake deposit lb/sec
% is percent of solids in sludge mixture
R_m is resistance of filter base or cloth
and R is resistance of the cake.

Ruth Filtration equation is:

$$(V + C)^2 = \frac{2A^2P}{a\ Z}\left(\frac{1 - ms}{P}\right)(\theta - \theta_o)$$

where

V is filtrate volume, liters
C is filtrate volume to produce a cake equal in resistance to the filter cloth, liters
A is filter area, cm^2
P is filtration pressure lb/in^2
a is average specific resistance of dry solids
Z is relative viscosity, centipoise
m is ratio of wet (solute free) to dry cake wt.
s is weight fraction of solids in sludge
O is filtering time, sec
O_o is theoretical time to form cake of resistance equal to cloth resistance present at start of filtration, sec.

McCabe and Smith

McCabe and Smith (1956, p. 339) following the same approach of Ruth derived an equation for filtration based on the Kozeny-Carman equation. The Kozeny-Carman equation (McCabe and Smith, 1956, p. 95) defines the friction in flow through beds of solids. The equation is used in the following form:

$$\frac{dp}{dL} = \frac{knu(1-e)^2 (sp/\ vp)^2}{g_c e^3}$$

where

dp is pressure drop lb force/ ft^2
dL is thickness of layer ft
n is viscosity of fluid-filtrate lb/ft-sec
u is linear velocity of filtrate, based on filter area ft/ sec
s_p is surface of single particle, ft^2
v_p is volume of single particle, ft^3
e is porosity of cake
k is constant
g_c is Newton's law conversion factor, 32.174 ft-lb/lb force-sec^2
For randompacked particles of definite size and shape, k is equal to 5

From the above equation McCabe and Smith formulated the following filtration equation:

$$\frac{d\theta}{dV} = K_p V + B$$

$$K_p = \frac{cna}{A^2(-\Delta p)\ g_c}$$

$$B = \frac{R_m\ n}{A\ (-\Delta p)\ g_c}$$

where

$d\theta$ is time between successive observation sec
dV is volume increment of filtrate collected over time interval $d\theta$ ft^3
c is masses of particles deposited in the filter per unit volume of filter ft^3
$(-\Delta p)$ is pressure drop lb force/ in^2
A is area of filter ft^2

a is average specific cake resistance, ft/lb
R_m is resistance of filter medium ft^{-1}
n and g_c are given in Kozeny-Carman equation
K_p and B are explained in paragraph below.

McCabe and Smith (1956, p. 344) explains the above filtration equation as follows:

> Assume that a number of observations of V vs. θ have been made. Then for any two successive observations, the quantity $\Delta\theta/\Delta V$ can be calculated, where $\Delta\theta$ is the time between observations and ΔV is the increment of filtrate collected over time period $\Delta\theta$. Since $d\theta/dV$ in the above equation is linear with V, a value of $\Delta\theta/\Delta V$ is the true slope of the θ vs. V line at a point $(V_1 + V_2)/2$, or halfway between the observed values of the V that define ΔV. Then, the arithmetic mean of each two successive observations of V can be plotted against $\Delta\theta/\Delta V$ for the same pair of readings. The best straight line is drawn through these points, and the slope of the line is K_p, and the V-axis intercept is B.
> ...... when K_p and B are known, a (the average specific cake resistance) and R_m (the filter medium resistance, ft^{-1}) are then calculated from the above given equations.

In illustrating the various equations of filtration, the writer wishes to show the trend of development---from a simple to complex and then to a much refined presentation. However different these formulas are, they all stress the importance of specific cake resistance and the resistance of the filter medium. The McCabe and Smith equation is used in the calculation of data in this thesis, not only because it is simple and straightforward, but also because it is the most widely accepted in chemical engineering.

Capacity of a Filter

In actual plant operation, equations are seldom considered, except as an indication of what effect variables may have on a filtration process. The point of liveliest interest in plant operation is the capacity of a filter. In metallurgical plants, one of the most important questions is the capacity of a filter for a certain type of material. It is expressed in terms of gallons of filtrate per unit area per unit time (e.g., gal/ft^2/24 hr) or tons of filter residue per unit area per unit time (tons/ft^2/24 hr).

Application of Filtration to Present Problem

The equations and the capacity of a filter mentioned above are the basis of the design and selection of filtration apparatus. Filtration tests used commonly in chemical and metallurgical engineering are performed on sludges obtained from various types of rock. The data obtained from these tests will help determine whether diamond drill sludges can be filtered.

EXPERIMENTAL WORK

The tests performed in the investigation were all standardized test commonly used in the engineering field. Due to the nature of material and the available facilities slight modifications were required. The experimental work is discussed under the following headings:

- Materials
- Methods
- Summary of Data

Materials

The experimental materials are sludges obtained from actual diamond-drilling operations. The materials studied consist of shale, porphyry suspended in drill-mud solution, quartz-monzonite-porphyry, granite, and gneiss.

Source: The diamond drill sludges were supplied by

Sprague and Henwood Inc., Grand Junction, Colo., Boyles Brothers Drilling Co., Denver, Colo., Climax Molybdenum Co. - Division of American Metal Climax Inc., Climax, Colo., and the Experimental Mine of the Colorado School of Mines, Idaho Springs, Colorado.

Niobrara Shale Sludge: The sludge was obtained from Sprague and Henwood Inc., drilling operations in Larimore, North Dakota. The sludge was recovered from East Central North Dakota in the Niobrara shale formation from a depth of 300-301 ft. According to the geologist's report:

> Relatively soft, very fine-textured shale formation, being cored with BX single-tube core-barrel and metal sawtooth bit.

The core recovery was approximately 100%. Casing was used --80 ft of BX casing.

Southeastern Arizona Porphyry suspended in mud solution: This sludge sample was obtained from Sprague and Henwood Inc. It was recovered from an area in Southeastern Arizona in porphyry rock. The depth from which the sludge was recovered was 1043-1044 ft. According to the geologist's report:

> Sample is from copper exploration where we are using a very thin mud solution. Mud contains 100-lb bontonite, 1-lb soda ash, 2-lb quebracho (tannic acid), 1-lb caustic soda to 500 gallons of water. Bit was special BX wireline bit cutting undersize core (1-3/8 inches).

Climax Quartz-monzonite porphyry: The sludge was provided by the Geology Department of the Climax Molybdenum Company, a Division of American Metal Climax Inc., Climax, Colo. The sludge was taken from Diamond Drill Hole #668 (surface) at the depth of 86-86½ ft. The hole was drilled in Tertiary quartz-monzonite porphyry called Elk Mountain Porphyry. According to the geologist's report:

> The ground was broken and caving in the area from which the sludge sample was taken. The area was adjacent to the foot wall of a major fault (South Fault). A little iron stain was present on fractures in the rock. The assay for the interval 80-90 ft. was: MoS_2 - 0.12%, oxide of MoS_2 - 0.3% and WO_3 - 0.16%.

A BX wireline bit was used. The core recovery was approximately 40%. BX casing was necessary from 0-86 ft. The rate of return water was 2 gpm.

LaSalle Mine granite sludge: The LaSalle Mine is situated in the vicinity of Jamestown, Colorado. With the permission of Boyles Brothers Drilling Company, the writer was able to collect the sludge personally. The drill was in granite rock during the collection. The drill hole was underground and sludge was collected at a depth of 45 ft. A BX bit was used. The approximate core recovery was 80%. No casing was necessary. The rate of return water was 5 gpm.

Idaho Springs gneiss sludge: The sludge was obtained from the diamond drill station about 2000 feet from the portal of the mine. The station is situated adjacent to the main drift. The sludge was recovered from a horizontal hole from a depth of 20-25 ft in Idaho Springs gneiss. An NX bit was used. The core recovery was 100%. No casing was necessary. The rate of return water was 3 gpm.

Methods

Four different experiments are performed in this investigation:

1) Specific Gravity determination
2) Size distribution analysis
3) Percentage of solids determination
4) Filtration Tests

Some of the experiments were performed by methods described in the Procedures for Testing Soils (April, 1958), approved by the Am. Soc. Testing Materials. The procedures were followed due to the similarities of sludge to soils - especially since both are products of disintegration of rock materials.

Experiments (1), (2), and (3) were required to provide data and information for the calculation and correlation of data obtained from the Filtration tests.

Specific Gravity Determination: This test follows the procedure described by Karol (1955, p. 3). It is considered good practice in the soil testing field (Karol, 1955, p. v).

Procedure: Karol (1955, p. 3) described the procedure as follows:

> A volumetric flask, called a pycnometer, is weighed when empty and also when filled to the reference mark with distilled water. The pycnometer is partially emptied and a known weight of soil (oven-dry soil may be used in this test) is added. Entrained air is removed from the soil, either by evacuating or heating the pycnometer, which is then filled to the initial reference mark, and the weight is recorded. ..... Temperature readings of the water should be taken to indicate whether corrections for the specific gravity of water are necessary.

The information obtained from the above porcedure permits the determination of specific gravity as shown in Table 1 (Appendix I).

Size Distribution Analysis: Size fraction of all the sludges were determined by sieve analysis. The sludges were found to contain as much as 35 to 40% of minus 325 mesh material (Table 2). A study of size fraction smaller than 325 mesh size was performed on the Idaho Springs gneiss sludge by Hydrometer method, the smallest practical sieve size being 325 mesh (each opening a square 0.044 mm on each side) of the Tyler Standard.

Sieve Analysis: Two sieve-analysis methods are commonly used in engineering, the U. S. series (A.S.T.M. Standard) and the Tyler series. The Tyler series is used almost universally. Also since 1938, owing to the range of permissible wire diameters established by the U. S. Bureau of Standards, this series can now by used interchangeably with the U. S. Standard series (Taggart, 1956, p. 19-103; Tyler Co. Catalogue 53, p. 38).

The Tyler series (Taggart, 1956, p. 19-103) is a geometrical progression with the multiplier $\sqrt{2}$ or 1.414; it starts from the standard 200-mesh testing sieve (0.0029-in. or 74 micron). In the metallurgical industries, this series has been adopted worldwide.

Before the sieve analysis test, oven-dried sludge is put on a rubberized cloth, the cloth is folded, and a rubbing action is applied on the folded cloth. This action is necessary to loosen the fines that might cling to the larger sizes. Twenty-five gram samples are taken from this pile of sludge and put into a nest of sieves (range of 48 mesh to 325 mesh). This deck of sieves is set to vibrate for exactly 5 minutes on a Rotap machine. The time of vibration is controlled by an electric timer (Tyler timer). After this process, the particles retained on each sieve are weighed and recorded. The percentage of each size fraction is calculated from the data obtained. Table 2 shows the size fraction percent cumulative weights of three sludges.

Hydrometer Method: This test was used on Idaho Springs gneiss sludge. It was used to supplement the data of minus 325 mesh (subsieve sizes). The hydrometer test (Karol, 1955, p. 7-8) is based on Stokes' Law and on another principle of sedimentation.

The Stokes' Law indicates that particles of different sizes will fall through a fluid medium with different velocities. It is expressed mathematically as:

$$v = \frac{L}{t} = \frac{R_s - R_l}{18u} D^2$$

in which

v is terminal velocity cm/min.

L is length that the particle travels cm.

t is time taken to travel L distance min.

R_s is unit weight of the sphere gm.

R_l is unit weight of the liquid gm.

D is diameter of the sphere mm.

and u is viscosity coefficient of fluid medium poises.

Stokes' Law is applicable for spheres approximately between 0.2 and 0.0002 millimeter.

The hydrometer test is based also on another principle of sedimentation. Karol (1955, p.8) describes it as follows:

> If a mass of soil is uniformly suspended in a liquid, the specific gravity of the mixture is uniform. After some time has passed, all the particles larger than a certain size (according to Stokes' Law) will have fallen below the fixed point, and the specific gravity of the mixture at that point will have decreased. By measuring the specific gravity of the mixture at the point during the uniformly suspended condition and after a certain amount of time has passed, the quantity of material no longer in solution above that point may be determined. From the elapsed time between the uniformly suspended condition and the instant of measurement, the minimum size of the particles that have dropped below the point may be determined. The quantity of material no longer in suspension is greater in size than the value thus calculated.

Before any test is performed the sludge is dispersed. A 50-gm sample of air-dry sludge is weighed out, placed in a 250-ml beaker, and covered with a deflocculating agent, 20-ml of a solution of sodium silicate crystals ($Na_2SiO_3 \cdot 9H_2O$). Distilled water is added and stirred until the sludge is thoroughly wetted. An 18-hr soaking time is allowed.

At the end of the soaking period, the mixture is further stirred by a stirring apparatus for a period of one minute. Immediately after the stirring the sludge-water slurry is transferred into a 1000-ml glass cylinder and more distilled water is added until the total volume is 1000-ml (A. S. T. M.

Procedures of Testing Soils).

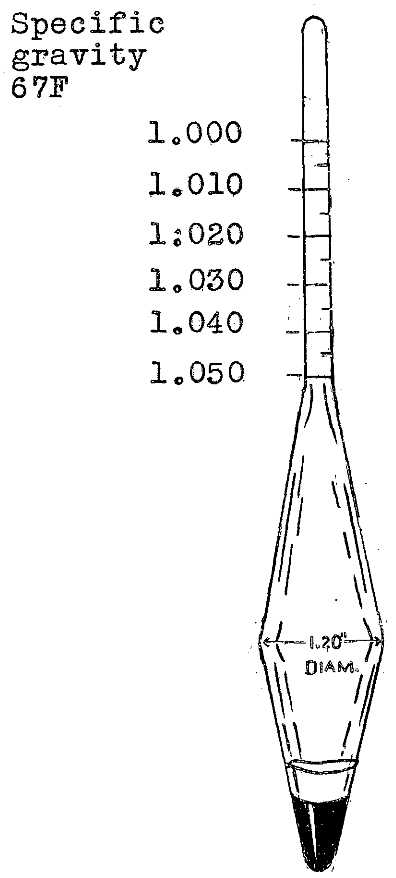
Using the palm of the hand over the open end of the cylinder, the cylinder is turned upside down and back for a period of one minute to complete the agitation of the slurry. At the end of one minute the cylinder is set in a convenient place and the hydrometer readings are taken at predetermined intervals.

In taking readings, the hydrometer (Fig. 6) is carefully inserted about 20 to 25 seconds before the reading is due, to approximately the depth it will have when the reading is taken. As soon as the reading is taken, the hydrometer is carefully removed and placed with a spinning motion in a graduate of clean distilled water. Readings are taken at the top of the meniscus formed by the suspension around the stem; also it is important to remove the hydrometer immediately after each reading. After each reading, a thermometer is inserted into the suspension for the temperature.

The method of calculation adopted is given in the A.S.T.M. Procedures of Testing Soils, April, 1958, p. 90. This method is used for the hydrometer 151H, the type of hydrometer used in this investigation. The percentage of soil (sludge) remaining in suspension at the level at which the hydrometer is measuring the density of the suspension

Figure 6

Hydrometer Type 151H used in Size distribution analysis



may be calculated as follows:

$$P = \frac{100,000}{W} \times \frac{G}{G - G_1} \ (R - G_1)$$

where

P is percentage of soil (sludge) remaining in suspension at the level at which the hydrometer measures the density of the suspension

R is hydrometer reading with composite correction applied

W is oven-dry weight of soil (sludge) in a total test sample represented by weight of soil (sludge) dispersed, gm

G is specific gravity of the soil (sludge) particles, and

G_1 is specific gravity of the liquid in which the particles are suspended.

The diameter of a particle corresponding to the percentage indicated by a given hydrometer reading is calculated according to Stokes' Law, on the basis that a particle of this diameter was at the surface of the suspension at the beginning of sedimentation and had settled to the level at which the hydrometer is measuring the density of the suspension. The Stokes' Law for this calculation is expressed as:

$$D = \sqrt{\frac{30\ u}{980\ (G - G_1)} \times \frac{L}{T}} = K\sqrt{\frac{L}{T}}$$

where

D is diameter of particle, mm

u is coefficient of viscosity of the suspending medium, poises

L is the effective depth, which is the distance from the surface of the suspension to the level at which the density of the suspension is being measured, cm, (for a given hydrometer and sedimentation cylinder, values vary according to the hydrometer readings; are given in Table II, p. 91, above mentioned reference).

T is interval of time from beginning of sedimentation to the taking of reading, min

G is specific gravity of soil (sludge) particles,

and G_1 is specific gravity of suspending medium.

Since Stokes' Law considers the terminal velocity of a single sphere falling in an infinity of liquid, the sizes calculated represent the diameter of spheres that would fall at the same rate as the sludge particles.

Values of "P" and "D" for Idaho Springs gneiss sludge are tabulated and sample calculations are illustrated in Appendix II.

Percentage of Solids Determination: Percent solids is the ratio of the weight of sludge particles to the weight of slurry. This test is carried out in order to get the information on the percent solids of sludges from actual diamond drilling operations.

Procedure: A sludge sample was weighed on a tared pan. The pan and its content is dried in an electric oven. When the content is dry the pan is weighed and dried until a constant weight is obtained. From the data recorded the percent solids can be calculated. Table 4 gives the percent solids of the sludges.

Filtration Test: The filtration test was the main test of the investigation. The object of such test was to determine whether it is feasible to filter sludges under drilling conditions. Thus, the capacity, the rate of filtration in relation with time, the average specific cake resistance, and the filter-medium resistance were the data sought after. Also, the effects of different pulp density, sub-sieve sizes and addition of flocculating reagents were also studied.

The amount of sludge obtained from each type of rock was a controlling factor in performing the test. All sludges except the Idaho Springs gneiss sludge, were obtained in insufficient quantity. The result was that only the Idaho Springs gneiss sludge was studied completely.

The following outline shows the different types of tests in which the other sludges were studied:

- Shale (Niobrara)
    - Funnel (gravity) filtration
        - 4-in. diam. inverted-conical funnel
    - Pressure filtration

18-in diam Stearn and Rogers pressure filter

Vacuum filtration

3.37-in diam. Buchner filter

Granite (LaSalle Mine)

Vacuum filtration

6-in diam. Buchner filter

1) Filtrate volume vs Time Test
2) Filtration Rate vs Cake thickness (Batch)
3) Effects of Sepran 2610

Porphyry suspended in drill-mud solution (S.E. Arizona)

Funnel (gravity) filtration

4-in diam. funnel

1) Filtration rate test
2) Different percentage of solids

Climax Porphyry

Vacuum filtration

12-in diam. metallurgical Laboratory filter.

From the outline given, one sees that various types of filtration methods were used. Also, tests were performed in different sizes of filter. The reason for this arrangement was to discover the method and size best suited for the investigation considering the nature of sludge and the quantity of sludge available.

From this preliminary investigation, it was found that vacuum filtration with a 6-in diameter Buchner filter was the best way.

Funnel (gravity) filtration resulted in very slow filtration rate as compared to the other two methods. Also, it is only used commonly in chemical laboratory where the material to be filtered is small in quantity and time is not an important factor.

The pressure filters available were too large for the quantity of sludges available. They also provided many technical difficulties in operating conditions. Considerable time was required to prevent leakage.

Vacuum filtration provided best operating conditions, and is one commonly used in filtration studies. The method chosen for the study of Idaho Springs gneiss is similar to that used by Hassett (1957, p. 139). Of the three different diameter Buchner filters available the 6-in diameter filter was chosen. The 6-in diameter Buchner filter provided ample room for a 1000-ml test sample.

The results of the various tests on the four sludges are also presented in the Discussion of Data chapter along with those of Idaho Springs gneiss sludge. These results though obtained from various methods do bring out many significant facts.

Idaho Springs gneiss sludge was studied in full detail due to the following reasons:

1) Sufficient quantity was available
2) Freshness of sludge (tests were made a day following collection of the sludge.
3) Sludge was collected personally
4) Size distribution of the sludge was that between the finest and the coarsest.

Filtration tests were performed on the sludge to determine:

1) The filtration rate and capacity of normal sludge (sludge in conditions as obtained from drill hole)
2) The effects on filtration rate by
   a) Removal of minus 325 particles
   b) Filtration of sludges of different percentage of solids
   c) Addition of flocculating reagents
      polyvalent -- Separan 2610 (Appendix III)
      divalent -- Lime (CaO)

All the results for the five sludges are tabulated into tables and illustrated in graph forms (see Appendix I).

<u>Preparation of test sample</u>: Samples of sludges were transported in 5-gal "G.I" cans from the source. The sludges were poured into 5-gal crocks in the laboratory before the test. Vigorous mixing was required to break up the settled mud to obtain a uniform sample. A dip sample was taken for every test. Compressed air was used for stirring when a dip sample was to be taken. Stirring by hand or

wooden paddle tend to concentrate larger particles at the bottom due to centrifugal action.

Filtration apparatus: Filtration apparatus used in the study of the Idaho Springs gneiss sludge is shown in Fig. 7. The apparatus assembly is similar to that described by Hassett (Hassett, 1957, p. 139) shown in Fig. 8.

The apparatus consists of a 6-in. diameter Buchner filter attached tightly by a rubber stopper to a graduated bottle. The vacuum was introduced into the bottle through a rubber tube attached to the stopper. The available vacuum in the distribution system was 22.5-in. of mercury. The pressure at which the filtration was conducted was read from a gage installed near the rubber stopper. An inverted conical container was used to introduce the sludge into the filter. The sludge was stirred or agitated constantly during introduction by compressed air. The rate of sludge flow into the filter was regulated by a screw-type clasp at the bottom of the container.

Filtration procedure: One liter samples are taken from the crock and added into the "introductory" container.

A filter paper was placed on the filter. The flow of sludge was regulated by the stop clock at a rate always slightly higher than the filtration rate. Time was read

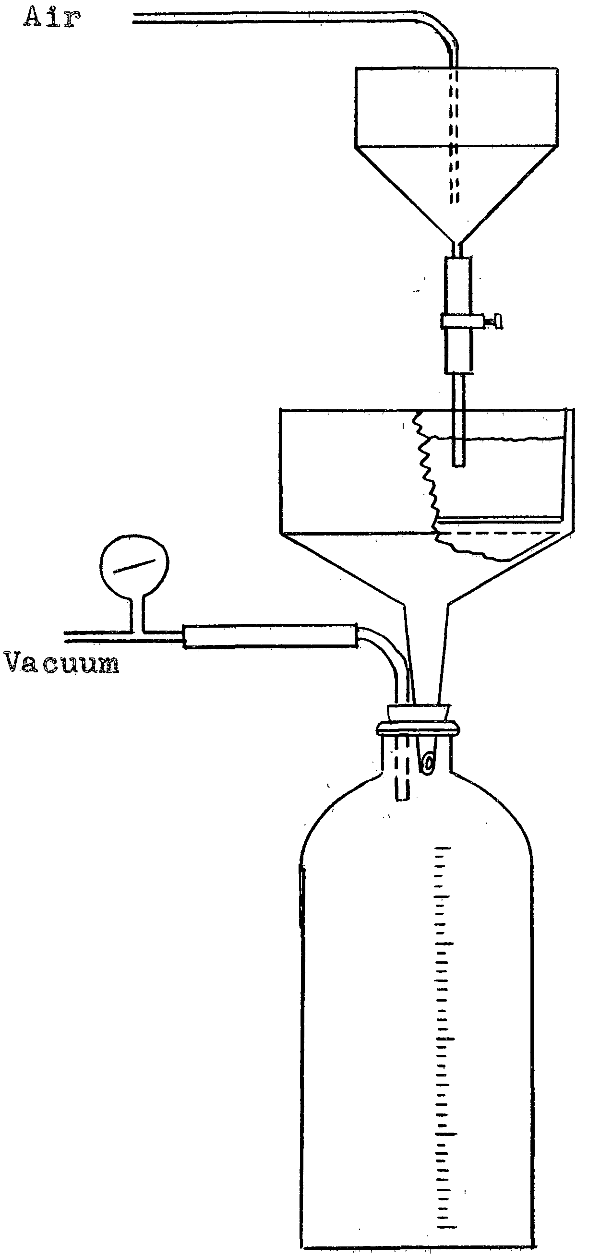


Figure 7 FILTRATION TEST APPARATUS USED FOR IDAHO SPRINGS GNEISS SLUDGE SAMPLES

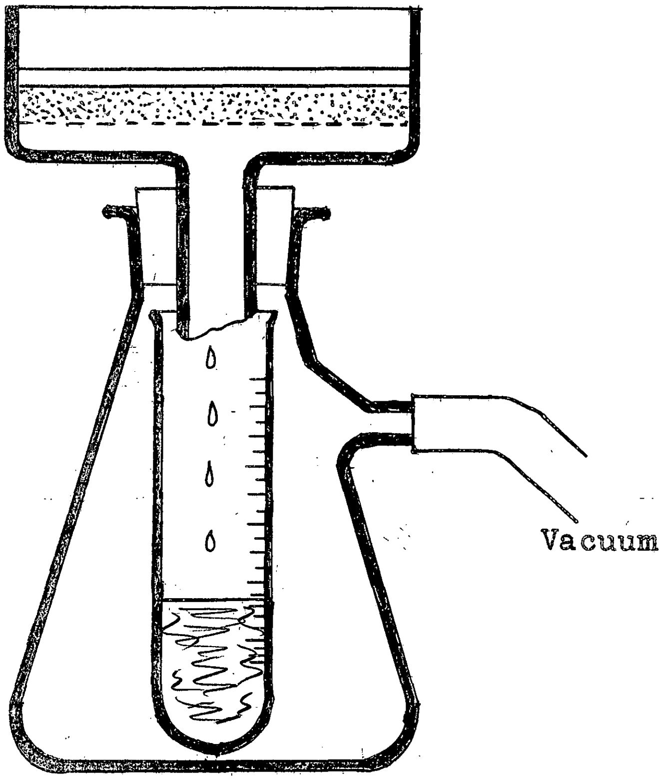


Figure 8 FILTRATION APPARATUS USED BY HASSETT

from a stop watch as the filtrate volume approached each 100-ml interval in the filtrate receiving bottle. The reading on the gage was also recorded following the recording of time.

Calculation of Data: Three important values were sought after from the data obtained in the test. They were (a) the filter capacity and filtration rate, (b) average specific cake resistance, and (c) resistance of filter medium.

The filtration rate was obtained by dividing the filtrate volume of sludge by the time required to filter. It is expressed in terms of milliliter per second. The capacity in terms of gallons of filtrate per square foot per hour can be calculated by a conversion factor from the filtration rate. This is shown in Appendix II.

The average specific cake resistance and the filter medium resistance are calculated from McCabe and Smith filtration equation (given in p.20), where

$$\text{average specific cake resistance} = \frac{K_p\, A^2\, (-\Delta p)\, g_c}{c\, n}$$

$$\text{filter medium resistance} = \frac{B\, A(-\Delta p)\, g_c}{n}$$

DISCUSSION OF DATA

The data obtained in this work are summarized in Appendix I.

Table 1 shows the specific gravity of solids found in the sludges from the various sources. It is not surprising to find that they are very little different from those of the natural rock. The exception is porphory sludge from southestern Arizona. In this case drilling had been done with a highly prepared drill mud suspension, previously described, which is believed to have effected adversely the method used for the determination of the specific gravities.

Table 2 shows size distribution by sieve analysis of the sludge particles from the various sources. It will be observed that a large portion of the total dry weight is concentrated in the minus 200 mesh sizes.

Table 3 shows the distribution of the sizes in the minus 325 mesh fraction of the sludge from the Idaho Springs gneiss, as determined by the hydrometer method of size determination. The calculations required by this method are shown in Appendix II.

Table 4 shows the percentage of solids by weight in the raw sludges, as received. A low percentage of solids appears to be characteristic of raw return sludge from diamond drilling operations.

Tables 5 to 14 present the results of filtration tests on the raw sludges, modified only by varying the percentage of solids in the filter feed. Table 5 shows that the sludge from the Niobrara shale cannot be filtered effectively, even in diluted form.

Table 6 shows that the Arizona porphyry, drilled with the mud suspension instead of water, is only very slightly more filterable.

Table 7 shows similar filtration data for the LaSalle Mine granite sludge. It filters much better. Table 8 shows the effect of increasing cake thickness on the filtration rate of this sludge.

Tables 9, 10, and 11 present information on the filterability of sludge from Climax, originating in a quartz-monzonite-porphyry.

Tables 12, 13, and 14 present similar information for sludge coming from the Idaho Springs gneiss.

Table 15 shows the results obtained on the Idaho Springs gneiss sludge after removal of the minus 325-mesh fraction. The filtration rate increased by an amount varying from 10 to 30%.

The effects of various flocculating reagents is shown in Tables 16, 17, and 18. Lime increased the filtration rate of the Idaho Springs gneiss sludge by 10 to 15% but Separan 2610 decreased it. Smaller amounts, used with the granite sludge, appeared to be beneficial.

Table 19 shows the approximate filtering area that would be required to filter the full return flow of sludge at the rate reported by the drillers.

Table 20 presents, by contrast, information taken from the literature on the character and filterability of various metallurgical pulps. These have much the same distribution of particle sizes, but the data is for much thicker slurries. This data provides some indication of the filtration rates to be expected with thick cakes.

Table 21 shows observed values of K_p, $\left(\frac{\Delta T/\Delta V}{V}\right)$ and B (y-intercept) obtained from the graphs of the results of the various tests on Idaho Springs gneiss.

Table 22 presents the calculated data of average specific cake resistance and filter medium resistance, based on the values given in Table 21.

Summary and Conclusion:

Examination of the experimental results and comparision of the physical properties of these sludges with those of finely ground ores indicates that diamond drill sludges are similar in many ways to the pulps treated in metallurgical plants.

Most typical diamond drill sludges appear to filter rather easily, but some, such as that from the Niobrara shale and those from holes in which mud has been used as the drilling fluid, filter very poorly, if at all. For the usual sludges, similar to the ones studied, not more than 20 square feet of filtering area would be necessary to handle the full return flow.

Attention should be called to the difficulty of obtaining reliable particle size values for the minus 325-mesh fraction. When using sedimentation techniques the rate of settling of the particles is effected by their specific gravity, shape, and degree of dispersion. The specific gravity of the solid particles is of importance only as it effects the settling rates. Normal rocks are composed of an assortment of minerals differing in their specific gravities and normal particle shape. Consequently sedimentation analysis and screen analysis on the same material do not exactly coincide.

The sludges, as they come from the diamond drill holes, are normally rather dilute, most of the ones tested ranging from 3 to 10% solids by weight. The Niobrara shale sludge, containing 22.1% solids by weight, was not a typical sample, having been cut by a metal sawtooth bit. When similarly dilute slurries occur in metallurgical practice they are commonly thickened prior to filtration so as to reduce the size of the filters required. This is not considered practical in the processing of diamond-drill sludges because of the time required for thickening, the volume of fluid required, and the consequent mixing of the returning sludge. In any case, the amount of filtering area normally required would be relatively small and thickening would give no advantage.

The increased rate of filtration of sludges from which the minus 325-mesh fraction had been removed is only to be expected, as the resulting cake will have a higher percentage of voids. However, removal of this fraction is not practical because (a) it is a difficult and time consuming operation in itself, and (b) the minus 325-mesh fraction constitutes from 35 to 40% of the total weight of solids. As the only reason for separating the solids, aside from recovery of the water for re-use, is to obtain material for assay, it is entirely undesirable to discard an unrepresentative fraction.

The addition of flocculating agents for the purpose of increasing the filtration rates seems like a logical operation. As a matter of fact, improved filtration rates are obtained when suitable flocculants are added in right amounts. However, various minerals react differently to various flocculants and certain flocculants may be detrimental to filtration, particularly if used in the wrong concentration. For example, 0.03 gram of Separan 2610 per liter of granite sludge from the LaSalle Mine devreased the time required to filter 500 milliliters from 230 seconds to 50 seconds. On the other hand, the addition of 0.2 gram of Separan 2610 to each liter of Idaho Springs gneiss sludge increased the time required for the filtration of 500 milliliters from 45 seconds to 72 seconds. Increasing the amount of Separan 2610 to 1.0 gram per liter of sludge caused the time needed to increase to 150 seconds. It must be concluded that the use of flocculants may be very desirable, but they must be chosen with care and used with discretion. Lime appears to be the best general purpose flocculant and the easiest to use. A number of graphs are presented in Appendix I, showing the effects of varying amounts of different flocculants on the various sludges tested.

From the practical point of view the most important measure of sludge filterability is the amount of equipment required for satisfactory operation. Any filtration operation requires some source of differential pressure, vacuum or otherwise. From the point of view of sludge utilization it would be most desirable to produce a very small cake whose thickness was proportional to the distance drilled. In such a cake the moment-to-moment variations in color and volume would be apparent and could be related to the nature of the ground being drilled. The results of the experimental work reported here indicate that typical sludges filter much too slowly for any simple device to produce this result. To keep up with normal rates of sludge return a filtering surface of not less than 15 square feet of filtering surface will be necessary, using vacuum filtration. The resulting thickness of cake, for a 10-foot run, even with very poor core recovery, would be less than one-half of an inch. This would not produce the desired columnar effect if all the filtering surface were used simultaneously in batch-type filtration.

A simple batch-type filter is the simplest arrangement, requiring onlu a simple pan filter, a filtrate reciever, and a source of vacuum. This arrangement has many advantages, among them simplicity, ease of sludge handling, and minimal equipment. Any type of continous filtering equipment capable of approximating the desired columnar result would necessarily be much more complex mechanically, but nothing shown by this work indicates that such an apparatus could not be built.

Suggestions for future work

The experimental work reported in this thesis is only the groundwork in understanding the filtration characteristics of diamond-drill sludges. To fully understand these characteristics, additional studies in the following fields would be desirable:

1). Similar studies on additional diamond-drill sludges from a wider assortment of rock and ore types; in order to determine more accurately the limiting parameters.

2). A study similar to the one reported her on rotary-drill sludges.

3). A design study of appropriate continous pressure filtration devices.

APPENDIX I

Table 1

Specific Gravity of Solids in Suspension

Idaho Spring Gneiss	2.575
Climax Quartz-monzonite porphyry	2.50*
LaSalle Mine Granite (Jamestown, Colo.)	2.60*
Niobrara Shale (Larimore, N.D.)	2.15*
Southeastern Arizona Porphyry Suspended in drill-mud solution #	1.35*

* Determined by same method as Idaho Spring Gneiss.

Detail description of mud solution in p.

Table 2

Size Distribution (by Sieve Analysis) of Sludges
Percent Cumulative Weights

Tyler Screen Mesh	Niobrara Shale	Porphyry Suspended in Drill-mud Solution	LaSalle Mine Granite	Climax Quartz-Monzonite Porphyry	Idaho Spring Gneiss
+48	0	0	1.4%	0.4%	1.4%
65	0	0	8.0	1.2	3.6
100	0	0	14.0	8.3	7.2
150	0	0	22.0	32.3	17.2
200	~~100~~		28.8	42.5	23.6
(-200)	100%	100%			
230	~~100~~	~~100~~	32.4	48.8	28.0
270	~~100~~	~~100~~	45.2	59.0	38.8
325	~~100~~	~~100~~	59.2	64.5	60.8
-325	~~100~~	~~100~~	100.0	100.0	100.0

Table 3

Size Distribution of Idaho Springs gneiss sludge

Results of Size analysis of minus 325 mesh fraction by Hydrometer Method (A.S.T.M.)

larger than	.058 mm*	2.92%
	.043 *	3.75
	.032	5.00
	.023.4	2.66
	.017	2.54
	.012	1.57
	.0099	1.06
	.0082	1.45
	.0071	0.44
smaller than	.0071	17.81

* The overlapping of size values of sieve method and hydrometer method are discussed in the Discussion of Data Chapter.

Table 4

Percent solids by weight in raw sludges, as received

Idaho Springs gneiss	3.25%
Climax Quartz-monzonite porphyry	8.45%
LaSalle Mine granite (Jamestown, Colo.)	7.50%
Niobrara shale (Larimore, N.D.)	22.10%
Southeastern Arizona porphyry suspended in drill-mud solution	4.6%

Table 5

Filtration of Niobrara Shale

	Funnel (gravity) Filtration	Pressure Filtration	Vacuum Filtration
Sludge of 22.1% (by wt.) Pulp density			
Amount:	50-ml sludge	2500-ml sludge	50-ml sludge
Condition:	4-in. diam. funnel Gravity	18-in. diam. Stearn-Rogers pressure filter; 40 psi	3.77-in. diam. Buchner filter; 22.5-in. Hg
Observation:	No visible filtrate at end of 24 hrs.	No filtrate	No filtrate
5% solids by weight of sludge			
Amount:	50-ml	2500-ml	50-ml
Condition:	4-in. diam. funnel Gravity	Same apparatus as above; From 20-40 psi	Same as above
Observation:	5-ml of turbid filtrate in first minute	At low pressure, no filtrate; at 40 psi 100-ml turbid filtrate, and also enormous leakage.	5-ml in 1-min No further filtrate appear.

Table 6

Filtration of Porphyry (S.E.Ariz.)
with drill mud solution

Funnel (gravity) filtration, 4-in. diam. 50-ml sludge

4.6% solids by weight		3.8% solids by weight		3% solids by weight	
Time	Vol	Time	Vol	Time	Vol
No filtrate		20-min	1-ml	20-min	4-ml
		100-min	4.8	100	10

Table 7

Filtration of LaSalle Mine granite sludge

6-in. diam. Buchner filter, 22.5-in. Hg vacuum pressure

7.5% solids by weight

Filtrate volume, V, ml	Time, T, sec	$\frac{V}{T}$ ml/sec	ΔV ml	ΔT sec	$\Delta V/\Delta T$ $\frac{\text{ml}}{\text{sec}}$	$\frac{\Delta T}{\Delta V}$ $\frac{\text{sec}}{\text{ml}}$	$\bar{V}$ ml	Capacity, gal/sq. ft per hr
0	0							
100	25	4.00	100	25	4.00	0.25	50	19.5
200	65	3.08	100	40	2.50	0.40	150	15.0
300	112	2.68	100	47	2.13	0.47	250	13.0
400	165	2.43	100	53	1.90	0.53	350	11.8
500	230	2.18	100	65	1.54	0.65	450	10.6

Table 8

The Effect of Increase in Cake Thickness

100-ml sludge is added after the previous 100-ml has been filtered. Time T' is time for each 100-ml filtered.

Sludge volume, V' ml	Filtrate volume, V, ml	Time, T', sec	$\frac{V}{T'}$ ml/sec	Cake Thickness inch
100	92.5	25	3.7	0.04
100	92.5	60	1.54	0.08
100	92.5	135	0.69	0.12
100	92.5	150	0.62	0.16
100	92.5	180	0.52	0.20

Table 9

Filtration of Climax Quartz-monzonite porphyry sludge

12-in. diam. metallurgical laboratory filter
22.5-in. Hg vacuum pressure

4.2% solids by weight sludge, [illegible]

Filtrate volume, V, ml	Time, T, sec	$\frac{V}{T}$ ml/sec	ΔV ml	ΔT sec	$\Delta V/\Delta T$ $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$ $\frac{sec}{ml}$	$\bar{V}$ ml	Capacity, gal/sq.ft per hr
0	0							
200	0		0	0				
400	3	133.31	400	3	133.3	.0075	300	162.0
600	9	61.7	200	6	33.3	.030	500	81.0
800	15	53.0	200	6	33.3	.030	700	64.0
1000	20	50.0	200	5	40.0	.025	900	60.5
1200	25	48.0	200	5	40.0	.025	1100	58.0
1400	35	40.0	200	10	20.0	.050	1300	48.5
1600	40	40.0	200	5	40.0	.025	1500	48.5
1800	45	40.0	200	5	40.0	.025	1700	48.5
1900	47	40.0	100	2	50.0	.020	1850	48.5

Table 10

Filtration of Climax Quartz-monzonite porphyry sludge

12-in. diam. metallurgical laboratory filter
22.5-in. Hg vacuum pressure

6.3% solids by weight sludge, [illegible]
[illegible] read [illegible]

Filtrate volume, V, ml	Time, T, sec	$\frac{V}{T}$	ΔV	ΔT	ΔV/ΔT $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$	$\bar{V}$	Capacity, gal/sq.ft per hr
0	0			0			0	
200	0			0			100	
400	6	66.7	400	6	66.7	.015	300	81.0
600	10	60.0	200	4	50.0	.020	500	72.5
800	20							
800	17	47.0	200	7	28.6	.035	700	57.0
1000	23	43.5	200	6	33.3	.030	900	52.5
1190	30							
1200	31	38.7	200	7	28.6	.035	1100	47.0
1400	37	38.0	200	6	33.3	.030	1300	46.0
1550	40							
1600	44	36.3	200	7	28.6	.035	1500	44.0
1800	50	36.0	200	6	33.3	.030	1700	43.5
1900	54	35.2	100	4	25.0	.040	1850	42.5

Table 11

Filtration of Climax Quartz-monzonite porphyry sludge

12-in. diam. metallurgical laboratory filter
22.5-in. Hg vacuum pressure

8.45% solids by weight sludge, [illegible]
[illegible] fr[illegible]

Filtrate volume, V, ml	Time, T, sec	$\frac{V}{T}$	ΔV	ΔT	ΔV/ΔT $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$	$\bar{V}$	Capacity, gal/sq. ft per hr
0	0							
200	2	100	200	2	100	.01	100	113
400	8	50.0	200	6	33.3	.03	300	60.5
600	15	40.0	200	7	28.6	.035	500	48.5
800	23	34.7	200	8	25.0	.040	700	42.0
1000	30	33.3	200	7	28.3	.035	900	40.4
1200	38	31.6	200	8	25.0	.040	1100	38.3
1250	40							
1400	47	29.8	200	9	22.2	.045	1300	36.2
1500	50							
1600	55	29.0	200	8	25.0	.040	1500	35.2
1700	60							
1800	63	28.6	200	8	25.0	.040	1700	34.7
1900	70	27.2	100	7	14.3	.070	1850	33.0

Table 12

Filtration of Idaho Springs gneiss sludge

6-in. diam. Buchner filter, 22.5-in. Hg Vac. Press.

1% solids by weight sludge

Filtrate volume, V, ml	Time T, sec	$\frac{V}{T}$ $\frac{ml}{sec}$	ΔV ml	ΔT sec	$\frac{\Delta V}{\Delta T}$ $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$ $\frac{sec}{ml}$	$\bar{V}$ ml	Capacity gal/sq.ft per hr
0	0							
200	15	13.4	200	15	13.4	.075	100	65.0
300	25	12.0	100	10	10.0	.10	250	58.0
400	30	13.3	100	5	20.0	.05	350	64.5
500	45	11.1	100	15	6.7	.15	450	54.0
600	55	10.9	100	10	10.0	.10	550	53.0
700	70	10.0	100	15	6.7	.15	650	48.6
800	80	10.0	100	10	10.0	.10	750	48.6
900	90	10.0	100	10	10.0	.10	850	48.6

Table 13

Filtration of Idaho Springs gneiss sludge

6-in. diam. Buchner filter, 22.5-in. Hg Vac. Press.

3.25% solids by weight sludge

Filtrate volume, V, ml	Time T, sec	$\frac{V}{T}$ $\frac{ml}{sec}$	ΔV ml	ΔT sec	$\frac{\Delta V}{\Delta T}$ $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$ $\frac{sec}{ml}$	$\bar{V}$ ml	Capacity gal/sq.ft per hr
0	0							
100	8	12.5	100	8	12.5	.08	50	60.8
200	18	11.1	100	10	10.0	.10	150	54.0
300	30	10.0	100	12	8.3	.12	250	48.6
400	45	8.9	100	15	6.7	.15	350	43.0
500	60	8.5	100	15	6.7	.15	450	41.2
600	78	7.8	100	18	5.6	.18	550	37.8
700	96	7.3	100	18	5.6	.18	650	35.4
800	115	7.0	100	19	5.3	.19	750	33.9
900	135	6.7	100	20	5.0	.20	850	32.4

Table 14

Filtration of Idaho Springs gneiss sludge

6-in. diam. Buchner filter Vacuum pressure, 22.5-in.Hg

5% solids by weight sludge

Filtrate volume, V, ml	Time T, sec	$\frac{V}{T}$ $\frac{ml}{sec}$	ΔV ml	ΔT sec	$\frac{\Delta V}{\Delta T}$ ml/sec	$\frac{\Delta T}{\Delta V}$ $\frac{sec}{ml}$	$\bar{V}$ ml	Capacity gal/sq. ft per hr
0	0							
200	20	10.0	200	20	10.0	.10	100	48.6
300	35	8.6	100	15	6.7	.15	250	41.7
400	60	6.7	100	25	4.0	.25	350	32.4
500	75	6.7	100	15	6.7	.15	450	32.4
600	90	6.7	100	15	6.7	.15	550	32.4
700	105	6.7	100	15	6.7	.15	650	32.4
800	140	5.7	100	35	2.9	.35	750	27.6
900	160	5.6	100	20	5.0	.20	850	27.2

Table 15

Effect of Subsieve Sizes

Filtration of Idaho Springs gneiss sludge
6-in.diam. Buchner filter, 22.5-in.Hg Vac. Press.

Filtration volume, V, ml	Time, T, sec	$\frac{V}{T}$ $\frac{ml}{sec}$	ΔV ml	ΔT sec	$\frac{\Delta V}{\Delta T}$ $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$ $\frac{sec}{ml}$	$\bar{V}$ ml	Capacity gal/sq. ft/hr
1% solids by weight sludge								
200	10	20.0	200	10	20.0	.05	100	97.2
300	16	18.8	100	6	16.7	.06	250	91.0
400	22	18.2	100	6	16.7	.06	350	88.2
500	27	18.6	100	5	20.0	.05	450	90.5
600	33	18.2	100	6	16.7	.06	550	88.2
700	45	15.5	100	8	12.5	.08	650	75.5
800	53	15.1	100	8	12.5	.08	750	73.5
900	60	15.0	100	7	14.3	.07	850	73.0
3.25% solids by weight sludge								
200	14	14.3	200	14	14.3	.07	100	69.5
300	23	13.0	100	9	11.1	.09	250	63.3
400	35	11.4	100	12	8.3	.12	350	55.2
500	44	11.35	100	9	11.1	.09	450	55.2
600	54	11.1	100	10	10.0	.10	550	54.0
700	64	10.9	100	10	10.0	.10	650	53.0
800	76	10.5	100	12	8.3	.12	750	51.0
900	95	9.5	100	19	5.3	.19	850	46.2

Table 16

Effect of Lime (CaO)

Filtration of Idaho Springs gneiss sludge
6-in. diam. Buchner filter, 22.5-in. Hg Vac. Press.

Fil-trate volume, V, ml	Time, T, sec	$\frac{V}{T}$ $\frac{ml}{sec}$	ΔV ml	ΔT sec	$\frac{\Delta V}{\Delta T}$ $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$ $\frac{sec}{ml}$	$\bar{V}$ ml	Capacity gal/sq.ft per hr
1% solid by weight sludge, adding 3g of CaO per liter of sludge								
200	10	20.0	200	10	20.0	.05	100	97.2
300	18	16.7	100	8	12.5	.08	250	81.0
400	28	14.3	100	10	10.0	.10	350	69.5
500	38	13.1	100	10	10.0	.10	450	63.6
600	50	12.0	100	12	8.4	.12	550	58.2
700	62	11.3	100	12	8.4	.12	650	54.8
800	72	11.1	100	10	10.0	.10	750	54.0
900	81	11.1	100	9	11.1	.09	850	54.0
3.25% solid by weight sludge, adding 3g of CaO per liter of sludge								
100	6	16.7	100	6	16.7	.06	50	81.0
200	13	15.4	100	7	14.3	.07	150	74.8
300	22	13.6	100	9	11.1	.09	250	66.0
400	32	12.5	100	10	10.0	.10	350	60.5
500	44	11.35	100	12	8.35	.12	450	55.2
600	63	9.5	100	19	5.25	.19	550	46.2
700	78	8.95	100	15	6.67	.15	650	43.5
800	94	8.5	100	16	6.25	.16	750	41.2
900	110	8.2	100	16	6.25	.16	850	39.8

Table 17

Effect of Separan 2610

Filtration of Idaho Springs gneiss sludge

6-in. diam. Buchner filter, 22-in. Hg Vac. Press.

Filtrate volume, V, ml	Time, T, sec	$\frac{V}{T}$	ΔV	ΔT	$\Delta V/\Delta T$ $\frac{ml}{sec}$	$\frac{\Delta T}{\Delta V}$	$\bar{V}$	Capacity gal/sq.-ft/hr
1% solids by weight sludge, adding 0.2 g Separan 2610 per liter of sludge								
0	0							
250	30	8.3	250	30	8.3	.12	125	40.0
500	72	6.95	250	42	6.0	.17	375	33.8
750	125	6.	250	53	4.7	.21	625	29.0
990	240	4.1	240	115	2.1	.48	870	20.0
3.25% solids by weight sludge, adding 0.2g Separan 2610 per liter of sludge								
0	0							
250	52	4.8	250	52	4.8	.208	125	23.3
500	114	4.4	250	62	4.04	.248	375	21.4
750	186	4.0	250	72	3.48	.288	625	19.4
970	330	2.94	220	144	1.53	.655	860	14.3

Table 19

Filter Capacities

Type of sludge	% solids	Minimal Filter Capacity gal/ft^2/min	Rate of flow from drill hole gal/min	Approx. size of filter - ft^2
LaSalle Mine granite	7.5	0.18	5	10
Climax porphyry	8.45	0.5	2	4
Idaho Springs gneiss	3.25	0.55	2.5	5

Table 20

Data of some Metallurgical Pulps

Type of pulps	Capacity of filters on some flotation concentrates			Capacity of filters on cyanide pulps		
Plant	Climax	St. Joseph Lead Co. Bonne Terre	Bonne Terre	Hollinger	Madsen Red Lake	Idaho, Maryland
Filter diam. x length, ft.	Oliver 5 1/3 x 8	Oliver 11 1/2 x 12	Dorrco 4 x 1 1/2	Oliver 14 x 16	Oliver 11 1/2 x 12	Oliver 8 x 6
Vac. Inches Hg	16	21	10	22-26	23	24
Feed Nature	Molybdenite	Lead	Lead	Siliceous	Siliceous	Sulphides
Size, % minus 200-m	90	94	68	78	77	100
Solids, %	50	70	60	55	57	50
Cake Thickness	1-in.	3/8-in.	¼-in.	7/16-½in.	½-in.	3/8-in.
Capacity gal. filtrate per sq. ft per min	0.011	0.0083	0.35	0.038	0.34	0.015

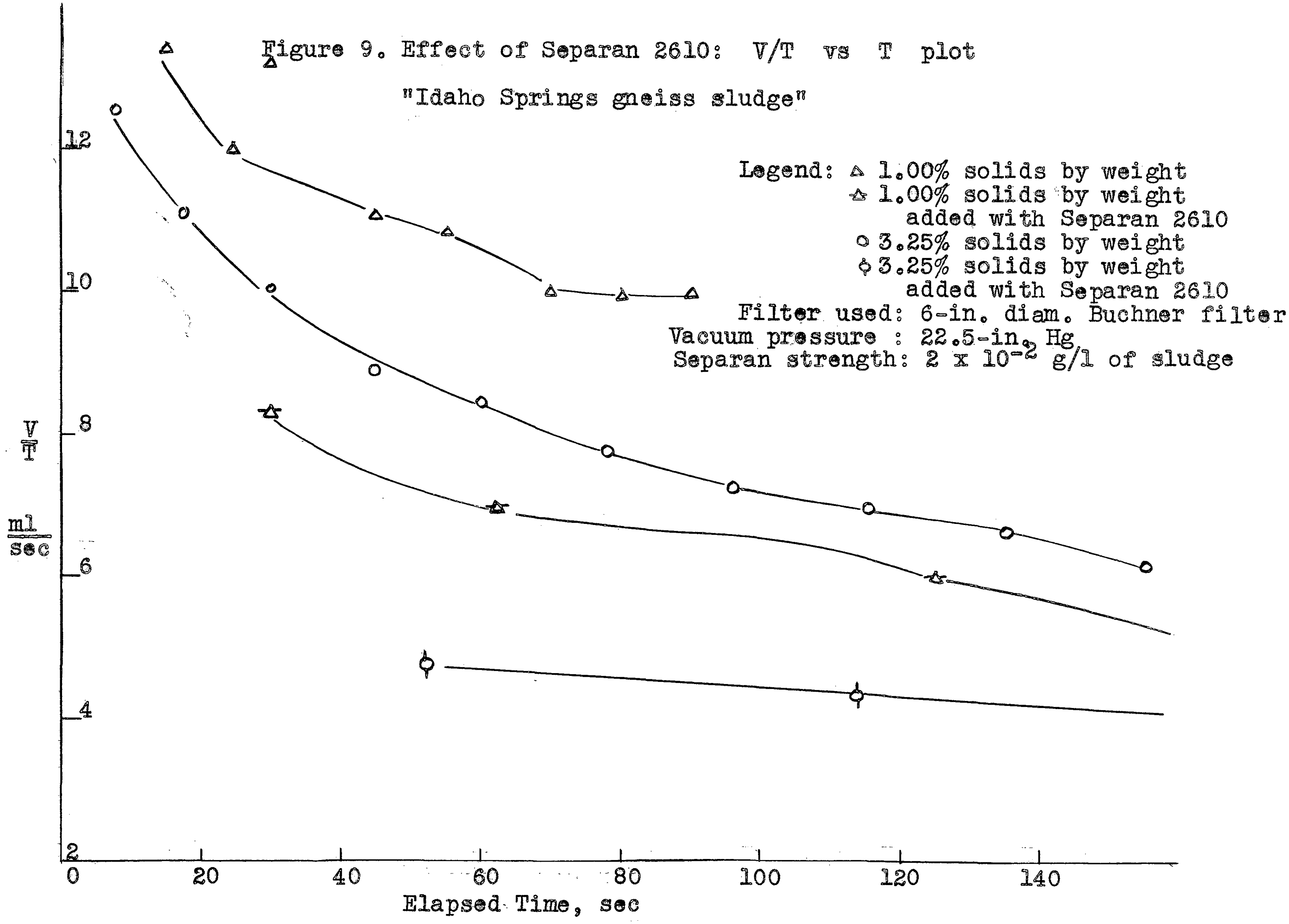


Figure 9. Effect of Separan 2610: V/T vs T plot

"Idaho Springs gneiss sludge"

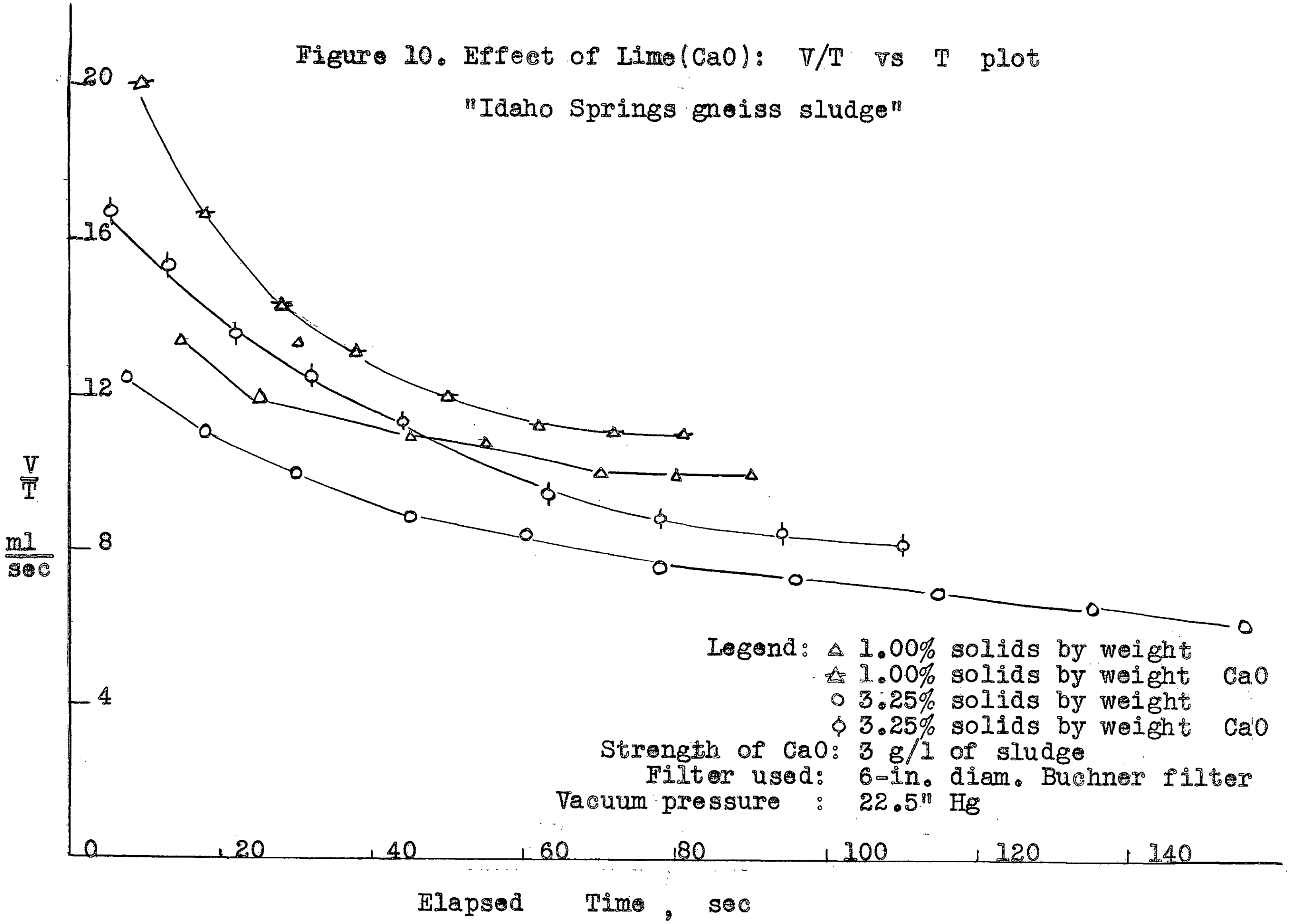


Figure 10. Effect of Lime(CaO): V/T vs T plot

"Idaho Springs gneiss sludge"

Figure 11. Effect of different percentage of solids:
$\Delta T/\Delta V$ vs $\overline{V}$ plot

"Idaho Springs gneiss sludge"

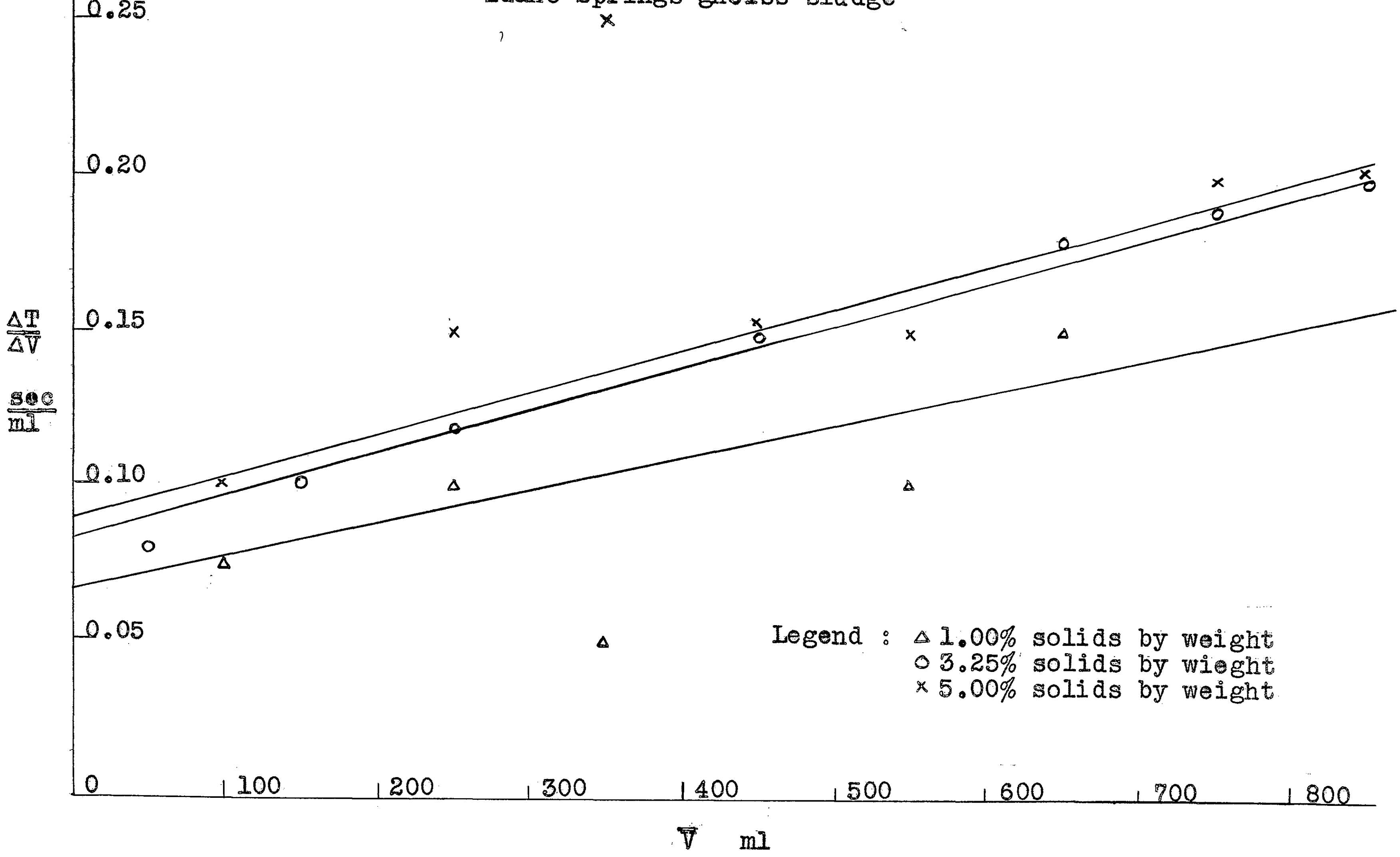


Figure 12. Effect of Separan 2610: ΔT/ΔV vs $\overline{V}$ plot

"Idaho Springs gneiss sludge"

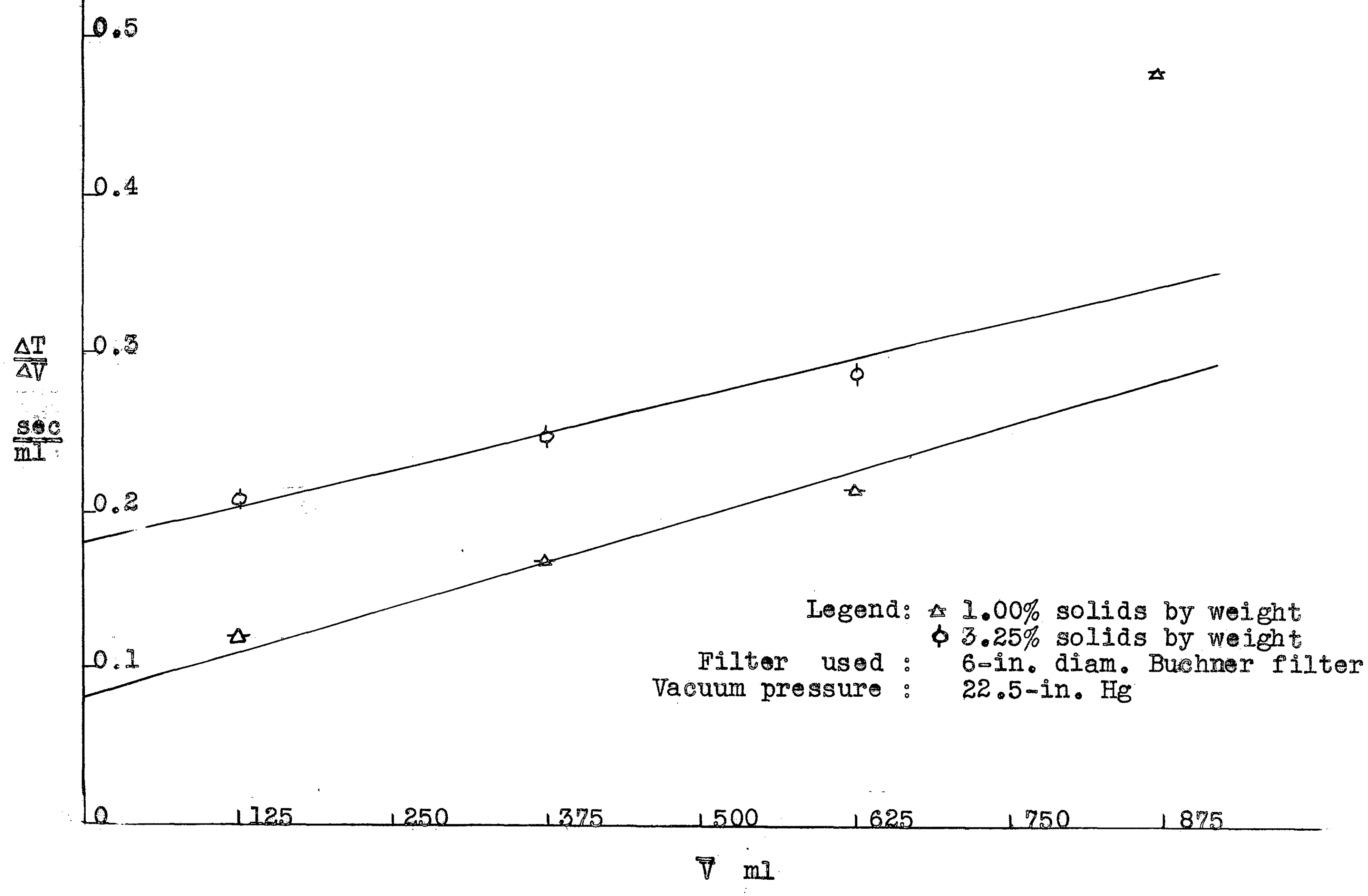


Figure 13 Effect of Lime (CaO): Relationship between filtration rate, V/T, and elapsed time

IdahoSprings gneiss sludge

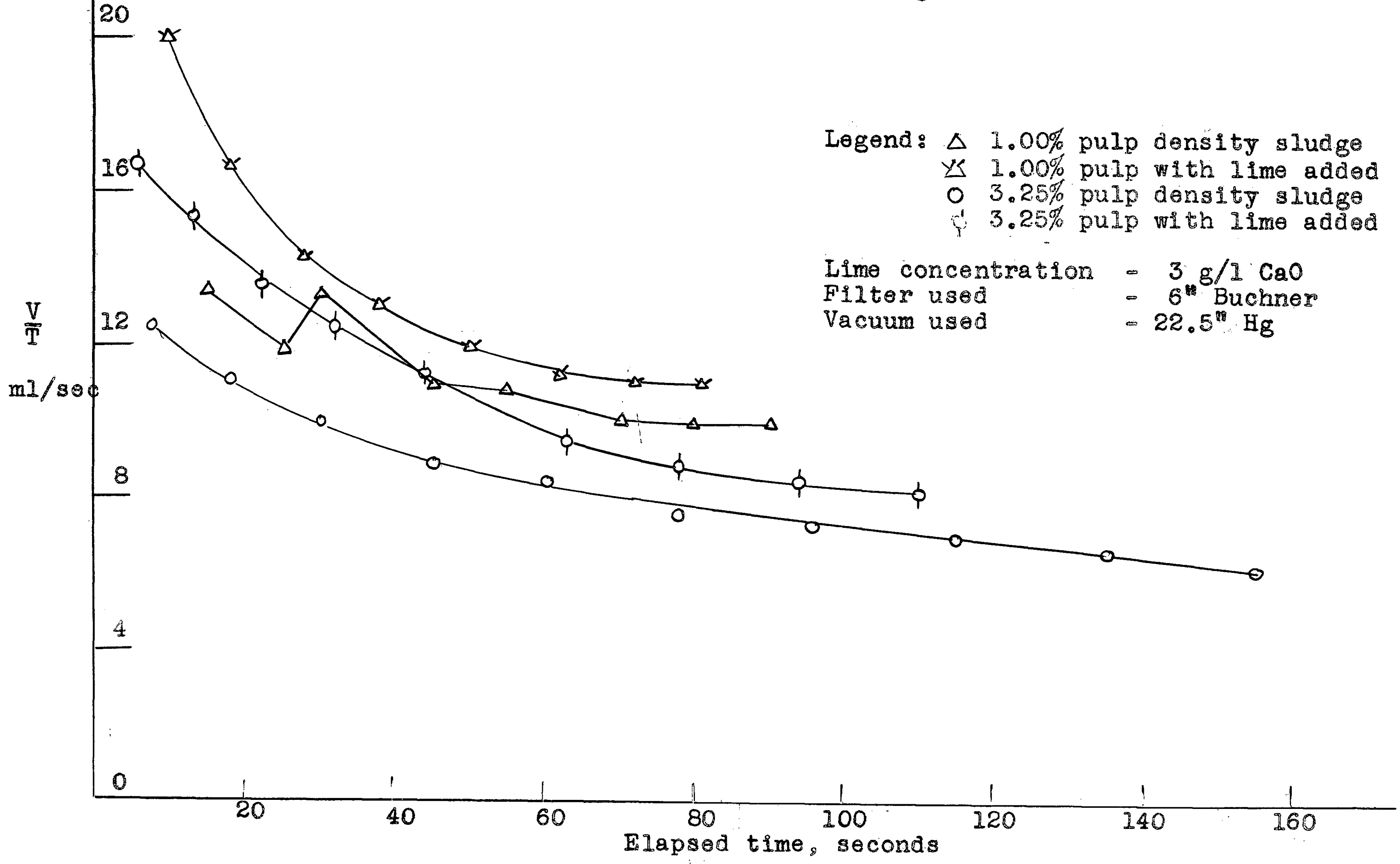
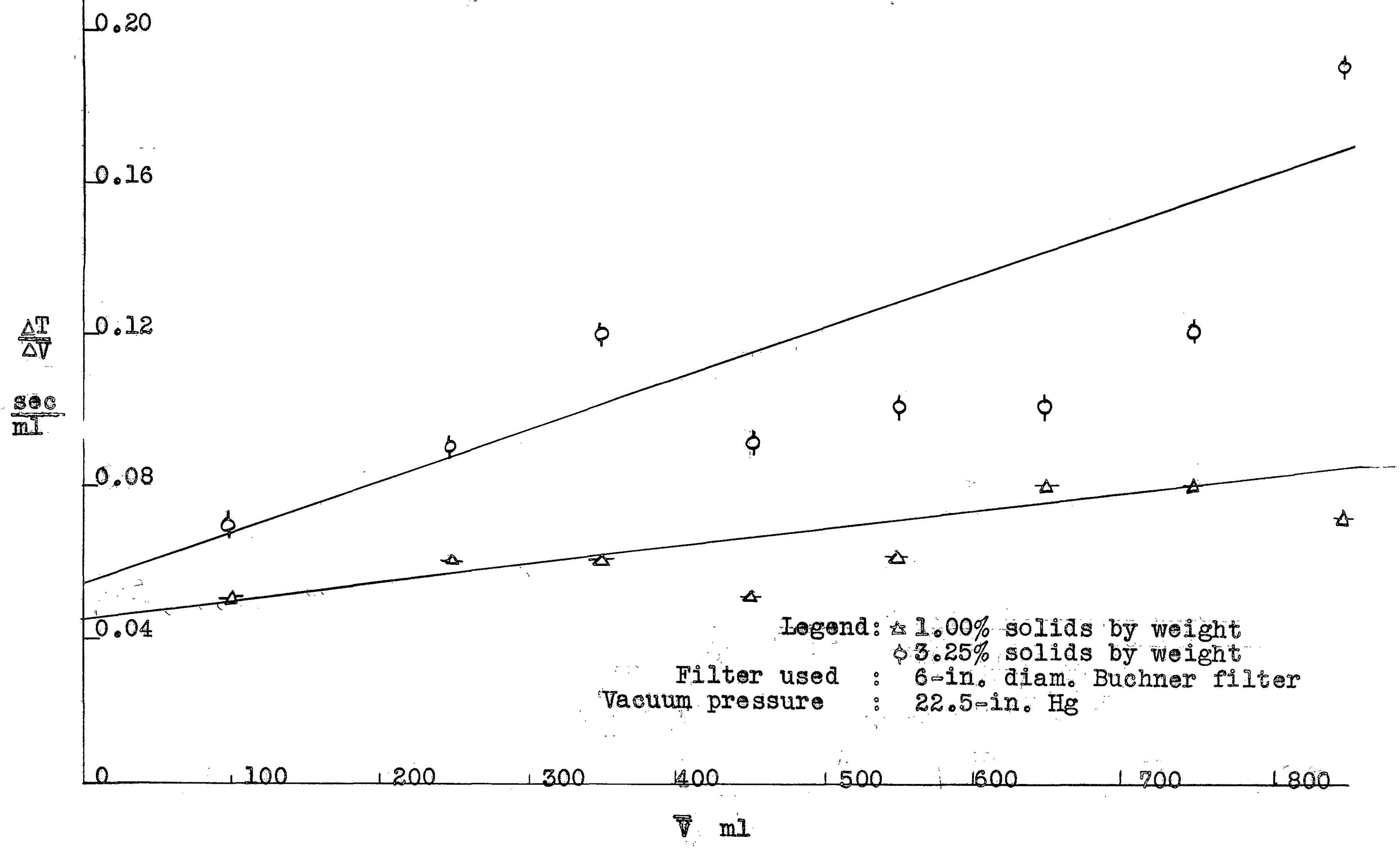


Figure 14. Effect of Subsieve sizes: $\Delta T/\Delta V$ vs $\overline{V}$ plot

"Idaho Springs gneiss sludge"



APPENDIX II

SAMPLE CALCULATIONS

I). Specific gravity of solids in suspension: Idaho Springs gneiss sludge

Wt. of flask plus water	621.76 gm
Wt. of flask	121.76
Wt. of water to fill flask	500.00
Wt. of flask plus sludge plus water	661.45
Volume of flask	500.00 ml
Wt. of flask	121.76 gm
Wt. of water plus sludge	539.69
Wt. of dry sludge	64.87
Wt. of water	474.82
Volume of water	474.82 ml
Volume of sludge	25.18 ml
Specific gravity	2.575

II). Calculation of "P" and "D" values of Hydrometer Test: Idaho Springs gneiss sludge

$$P_{\frac{1}{2}\text{ min}} = \frac{100,000}{W} \times \frac{G}{G - G_1}(R - G_1)$$

$$= \frac{100,000}{50} \times \frac{2.575}{2.575-1}(1.0284 - 1)$$

$$= 92.6\%$$

$$D_{\frac{1}{2}\,min} = \frac{30\ u}{980(G - G_1)} \times \frac{L}{T}$$

$$= \frac{30 \times 1.0114 \times 10^{-2}}{980(2.575-1)} \times \frac{8.72}{0.5}$$

$$= 1.4 \times 10^{-2} \times (4.16)$$

$$= 0.0585\ mm.$$

Values of "P" and "D" of Idaho Springs gneiss sludge by Hydrometer(151H Type) size analysis on minus 325 mesh size are tabulated as follows:

Time, min	Temp. F	Hydrometer readings Test 1	Test 2	Ave.	L	D	P%
0							
$\frac{1}{2}$	68	1.0287	1.0281	1.0284	8.72	0.058	92.6
1		1.0258	1.0251	1.0254	9.52	0.043	83.0
2		1.0217	1.0214	1.0215	10.60	0.032	70.3
4		1.0198	1.0192	1.0195	11.15	0.023	63.5
8		1.0178	1.0172	1.0175	11.65	0.017	57.0
16		1.0167	1.0158	1.0162	11.86	0.012	53.0
24		1.0157	1.0151	1.0154	12.18	0.0099	50.3
36		1.0144	1.0142	1.0143	12.39	0.0082	46.6
48		1.0139	1.0139	1.0139	12.63	0.0071	45.4

III). Calculation of percentage of solids in suspension:

Idaho Springs gneiss sludge

Wt. of sludge plus pan	1469 gm
Wt. of pan	399
Wt. of wet sludge	1070
Wt. of oven dried sludge plus pan	434
Wt. of pan	399
Wt. of oven dried sludge	35
Percentage of solids in sludge	3.25%

IV). Calculation of Capacity of the 6-in diameter Buchner filter:

$$\text{Capacity (gallons per ft}^2\text{ per hr)} = \frac{V\,\text{ml}}{T\,\text{sec}} \times \frac{0.265 \times 10^{-3}}{\text{ml}} \; \frac{3600\text{sec}}{\text{hr}} \; \frac{1 \quad \text{gal}}{(\frac{1}{4})^2\text{ft}^2}$$

$$= \frac{V}{T} \times 1.35 \times 3.6$$

$$\text{Capacity } 200\text{ml}^* = \frac{200}{20} \times 1.35 \times 3.6$$

$$= 48.6 \text{ gals per ft}^2 \text{ per hr}$$

(* values taken from Table 14, p. 64)

V). Calculation of Average specific cake resistance and Filter medium resistance: Idaho springs gneiss sludge of 3.25% solids by weight

Data:

$K_p = 1.33 \times 10^2$ sec per liter per liter (Table 21)

$= 1.33 \times 28.31^2 \times 10^2$ sec per ft^3 per ft^3

$= 107{,}000$ sec per cubic foot per cubic foot

$B = 82.5$ sec per liter (Table 21)

$= 82.5 \times 28.31$ sec per cubic foot

$= 2330$ sec per cubic foot

$A = (\frac{1}{4})^2$ square foot 0.196 square foot

$g_c = 32.17$ ft-lb/lb-force-sec^2

$(-\Delta p) = 22.5$-in. Hg $= 22.5/12 \times 13.6 \times 62.5$ lb/ft^2

$= 1600$ lb per square foot

$n = 1.0114$ centipoise (67 F)

$= 1.0114 \times 6.72 \times 10^{-4}$ lb/ft-sec

$= 6.8 \times 10^{-4}$ lb/ft-sec

c = mass of solids per unit volume

= gram of solids per liter of filtrate

$= (3.25/96.75) \times 1000$ g/l

$= (33.6 \times 28.31)/454$ lb/ft^3

$= 2.10$ lb per cubic foot

Average specific cake resistance $= \dfrac{A^2 gc(\ p)}{c\ n} K_p$

$$= \frac{0.196^2 \times 32.17 \times 1600}{2.10 \times 6.8 \times 10^{-4}} \times 1.07 \times 10^5$$

$$= 14.0 \times 10^5 \times 1.07 \times 10^5$$

$$= 1.5 \times 10^{11} \text{ ft/lb}$$

Filter medium resistance $= \dfrac{A\ g_c\ (-\Delta p)}{n} B = \dfrac{0.196 \times 32.17 \times 1600}{6.8 \times 10^{-4}} B$

$$= 1.48 \times 10^7 \times 2330$$

$$= 3.46 \times 10^{10} \text{ ft}^{-1}$$

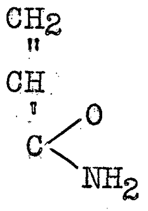
APPENDIX III

DESCRIPTION OF SEPARAN 2610

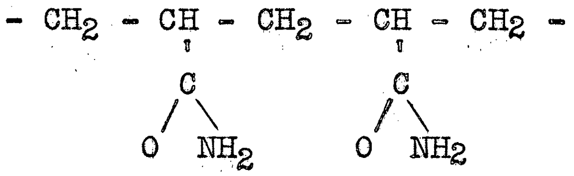
According to the information described in "Separan 2610" , a pamphlet issued by the Dow Chemical Company, Separan is composed of "acrylamide polymer hydrolytes" having from 0.8 to 10 percent of the amide groups replaced by carboxyl groups. Acrylamide polymer hydrolytes are composed of hydrolytes of the homopolymer of acrylamide plus hydrolytes of water-soluble copolymers of acrylamide with different monomers.

Davies(1954, p. 28) describes the structural formulas as follows:

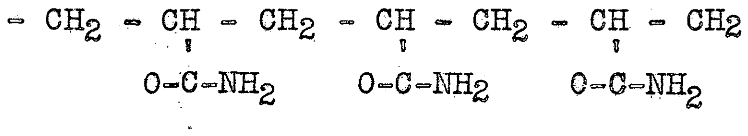
Acrylamide



Homopolymer of Acrylamide



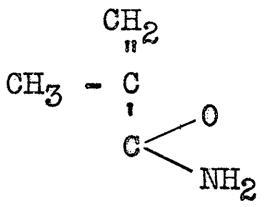
Hydrolyte of Homopolymer of Acrylamide



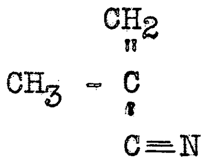
$$-CH_2-\underset{O-C-NH_2}{\underset{|}{CH}}-CH_2-\underset{O-C-NH_2}{\underset{|}{CH}}-CH_2-\underset{O-C-NH_2}{\underset{|}{CH}}-CH_2$$

The monomers becoming copolymerized with Acrylamide result into:

Metacrylamide



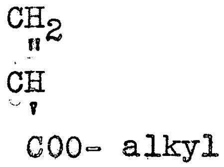
Methacrylonitrile



$CH_3 - \underset{\overset{|}{C \equiv N}}{\overset{\overset{CH_2}{\|}}{C}}$

Alkyl Ester of

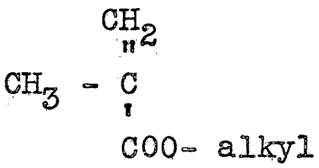
Acrylic acid



$\underset{\overset{|}{COO- \text{alkyl}}}{\overset{\overset{CH_2}{\|}}{CH}}$

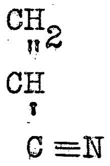
Alkyl Ester of

Methacrylic acid



$CH_3 - \underset{\overset{|}{COO- \text{alkyl}}}{\overset{\overset{CH_2}{\|}}{C}}$

Acrylonitrile

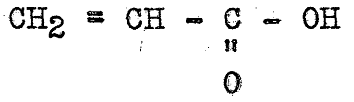


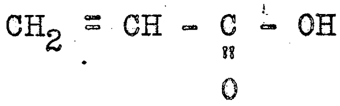
$\underset{\overset{|}{C \equiv N}}{\overset{\overset{CH_2}{\|}}{CH}}$

Vinyl acetate

$CH_2 = CH -$ acetate

From the description given, Separan 2610 may be described as follows:

acrylamide,  $CH_2 = CH - \underset{\overset{\|}{O}}{C} - OH$ contains the double bond of the acryl groups, also the amide function, which can be regarded as derived from the carboxyl function by replacement of - OH with $-NH_2$. It polymerizes readily.



Acrylic acid, $CH_2 = CH - \underset{\underset{O}{\|}}{C} - OH$, also polymerizes readily.

Acrylamide polymer hydrolytes represent polymers of acrylamide with acrylic acid. Those containing the relatively small proportion of 0.8 to 10 percent of the acid function, and are at the appropriate stages of aggregation make up "Separan 2610".

BIBLIOGRAPHY

ASTM, 1944, Standard method for mechanical analysis of soils: ASTM Procedures for testing soils, Designation D422-39, September, p. 19.

__________, 1958, Grain analysis of soils: ASTM Procedures for testing soils, Designation D422-54T, April, p. 83.

Cummings, J. D., 1956, Diamond drill handbook: Toronto, Ontario, J. K. Smith and Sons of Canada Ltd.

Davies, O. L., 1954, Statistical methods in research and production: New York, Hafner Publishing Co.

Dickey, G. D. and Bryden, C. L., 1946, Theory and practice of filtration: New York, Reinhold Publishing Corporation.

Gustafson, A. A., 1943, Settling device for sludge samples: Trans. A.I.M.E., v. 153, p. 280-285.

Hassett, N. J., 1957, Filtration theory and practice: British Chem. Eng., v. 2, March, p. 136-142.

Karol, R. H., 1955, Engineering properties of soils: New York, Prentice Hall Inc.

McCabe, W. L., and Smith, J. C., 1956, Unit operations of chemical engineering: New York, McGraw-Hill Book Co., Inc.

Peele, R., 1956, Mining engineers' handbook: Third edition, sixth printing, New York, John Wiley and Sons Inc.

Sein, M. S., 1952, Exploration of mineral deposits by diamond drilling: Thesis No. 759, Colorado School of Mines.

Taggart, A. F., 1951, Elements of ore dressing: New York, John Wiley and Sons Inc.

__________, 1956, Handbook of mineral dressing: New York, John Wiley and Sons Inc.