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DEVELOPMENT OF PROCEDURES FOR PROCESS INSPECTION OF HEAVY MEDIA BENEFICIATION PLANTS FOR COARSE AGGREGATE

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and
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THE MICHIGAN DEPARTMENT OF STATE HIGHWAYS
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IN COOPERATION WITH
U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAYS ADMINISTRATION
BUREAU OF PUBLIC ROADS

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Final Report

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The Michigan Department of State Highways was responsible for general direction of the project and review of progress. In the first and second phases, W. W. McLaughlin, Testing and Research Engineer; E. M. Noble, Manager, Highway Planning and Research; and F. E. Legg, Jr., Materials Consultant, Testing Laboratory Division, provided guidance to the work. In the third stage, R. L. Greenman took over responsibility for general direction of the work upon Mr. McLaughlin's retirement.

The project was carried out by the Institute of Mineral Research, a department of the Michigan Technological University, Houghton, Michigan. E. L. Michaels, Research Engineer, was in charge of the first and second phases of the project, under the general supervision of M. E. Volin, Director. Dr. L. Valentik, Research Engineer, was in charge during the third stage of the work. R. A. Campbell, Pilot Plant Supervisor, assisted in the design and assembly of the pilot plant used in the study, and W. A. Hockings, Research Engineer, contributed to developments which were vital to the objectives of the study. G. J. Peterson, Technician, carried out much of the routine work.

The Michigan Sand and Gravel Producers Association provided a magnetic drum and two pumps for the pilot plant.

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SUMMARY

The process most widely used for beneficiating gravel aggregate in Michigan is heavy media separation (HMS). The objective of this study is to develop and demonstrate HMS plant controls that will assure an aggregate product of sufficiently high quality that sampling inspection can be supplanted by occasional process inspection. This final report describes the work done in the three years of the study.

Michigan HMS plants were visited to observe operational practices. It was found that control practices varied to such an extent that comparisons between plants were not meaningful. In general, plant control was based upon measurements of the specific gravity of the medium made on samples periodically withdrawn from one or more points in the circuit and upon visual observation of the separatory system, but also upon the results of sampling inspection.

Samples of sink and float products were collected at one of the plants for evaluation of performance and for the experimental work to be done later.

A literature search was made to obtain information about automatic recording, control, and warning devices that might be used in process inspection. Some information was found about methods of measuring the specific gravity of heavy mediums on a continuous basis and methods of measuring the consistency and stability of medium samples periodically withdrawn from the circulation system.

Preliminary work done to establish experimental procedures and to prepare for the pilot plant tests comprised: (1) investigations of the measurement of specific gravity, consistency and stability of mediums; (2) heavy liquid separations to determine the specific gravity distributions of the plant samples for evaluation of performance and for making up feed samples to be used in the experimental work; (3) measurements of size, shape, and surface characteristics of the gravel particles in the plant samples; (4) measurements

of the effects of medium contaminants and of media particle size on consistency and stability; and (5) preliminary batch tests to determine the effect of different size structures of media on the consistency and stability of circulating mediums and to determine the relationships of consistency and stability to the efficiency of separation.

A heavy media pilot plant was set up with a three-foot diameter cone separator, a Venturi meter for continuous measurement of flow rate of the circulating medium, and a Nuclear-Chicago Qualicon density gauge for the continuous measurement of the specific gravity of the medium. A typical feed sample of approximately 1,000 pounds was made up for the pilot plant tests with deleterious particles marked for positive identification and with the specific gravity distributions of the sound and deleterious particles known. Fifteen tests were made at 5 levels of specific gravity of the medium and at two feed rates, and with the consistency and stability of the medium varied by additions of clay. In these tests, consistency and stability were measured on samples withdrawn from the circulating medium. While the Nuclear-Chicago gauge provided satisfactory control of the specific gravity of the medium, it was found that measurements of apparent viscosity and of stability made on samples periodically withdrawn from the medium were subject to error and did not provide the degree of control necessary for process inspection.

A consistometer was developed and installed in the pilot plant circuit to measure continuously the consistency of the circulating medium. As the final phase of the project, pilot plant tests were made with both the specific gravity and the consistency of the medium continuously monitored. A typical feed sample of known specific gravity and particle type composition was used, and the feed rate was closely controlled. The conditions for best separation were established and maintained so as to provide optimum yield for a given quality of product. The tests demonstrated that measurement and control of both the specific gravity and the consistency of the circulating medium are essential in maintaining a sharp separation and optimum efficiency.

On the basis of the final pilot plant tests, it can be concluded that continuous monitoring of the specific gravity and consistency of the medium along with regulation of the feed rate will provide adequate process and quality control, and that the records of operations under these conditions would be sufficient for process inspection of HMS plants.

INTRODUCTION

Problem

Natural gravels beneficiated in some degree make up a large part of the coarse aggregate used in concrete going into highways and highway structures in Michigan. Beneficiation of the natural gravels is commonly accomplished by the heavy media separation (HMS) process.

The Michigan Department of State Highways accepts gravel aggregate on the basis of sampling inspection performed in the field by trained inspectors. The procedure involves selection and testing of a sample from each lot of aggregate (100-150 tons) offered to the Department of State Highways. This procedure is costly and it temporarily interrupts the flow of aggregate to the mixing plants. Furthermore, the sampling and testing procedure as now practiced is subject to significant errors.(1) Erroneous acceptance of inferior aggregate for use in concrete going into highways and structures ultimately results in a loss to the public, while erroneous rejection of a lot of good aggregate causes a loss to the producer.

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Quality control is widely used in industry for monitoring production processes so that product quality will be sufficiently high that the risk of rejection will be kept to an acceptable level. Michigan aggregate producers apply some degree of quality control, but most of the plants are operated on the basis of the results of sampling inspection. It is the policy of the Department of State Highways to warn the producer when sampling results approach or exceed specification limits so that corrective action can be taken to bring the quality of the aggregate within limits again. Although this sampling plan provides a measure of quality control along with inspection, it is inefficient in that inferior quality is recognized only after the product is sampled.

It would be desirable to establish and maintain operating conditions such that aggregate of high quality would be assured and only occasional samples would need to be taken and tested. The problem is to maintain a specified quality of aggregate through plant control and process inspection rather than by sampling inspection of the product.

Objectives

The ultimate objective set up for this research project was to develop and demonstrate HMS process control such that a product of sufficiently high quality would be assured and frequent sampling inspection could be supplanted by occasional process inspection. Individual objectives were:

1. A literature study of automatic recording, control, and warning devices that might be used in process control and inspection.
2. A survey of heavy media gravel plants to observe operating practices, the controls exercised, and the variation in product quality under existing production conditions.
3. A study of control methods applicable to the HMS process.
4. Demonstration of control methods and procedures for process inspection under continuous operating conditions.

Scope

This is a final report covering the three years of work on the project. The research was originally scheduled for completion in two years, but unforeseen difficulties in obtaining equipment caused delays in assembly of the pilot plant. Objectives 1, 2, and 3 were substantially completed in the first two years and work was initiated towards objective 4, but when the initial pilot plant results indicated that medium consistency was a critical variable in process control it was necessary to continue into the third year to reach the final objective. Work in the third year comprised development and testing of a continuous recording consistometer, pilot plant tests under controlled conditions of medium specific gravity and consistency, and a further survey of operating plants to collect additional samples for the purpose of evaluating plant performance and adapting control methods.

HEAVY MEDIA PROCESS

Description of Process

Heavy media separation is a widely used mineral beneficiation process. Application of the process in the beneficiation of natural gravels has grown rapidly in Michigan as a result of increasing consumption of coarse aggregate in highways and structures and because acceptance specifications have become progressively rigorous.

Separation is accomplished in a suspension of heavy particles in water. A mixture of fine ferrosilicon and magnetite is commonly used as the media in Michigan gravel plants to make up the suspension, or medium, to the desired specific gravity. Gravels heavier than the medium sink, and those lighter float. The separation vessels in principal use are the horizontal rotating drum and the vertical stationary cone. The drum has a relatively shallow pool stirred by peripheral blades which also lift the sink gravels onto a conveyor belt for their removal. The cone has a deep pool with a specific gravity gradient from top to bottom; the medium is stirred primarily by the streaming action to overflow and underflow.

A schematic diagram of a typical HMS flowsheet utilizing a cone vessel is shown in Figure 1. Gravel particles of low specific gravity overflow at the float discharge weir, while high gravity particles sink to the bottom of the cone and are air-lifted to overflow the sink discharge weir. The sink and float products discharge separately onto a divided vibrating screen, where most of the media particles separate from the gravel particles and drop through the screen into a collection sump to be pumped back to the cone. As the gravels move to the lower part of the screen, they are washed by water sprays to free them of the rest of the media and any adhering clays or other fine contaminant particles. This portion of the medium is collected in another sump and circu-

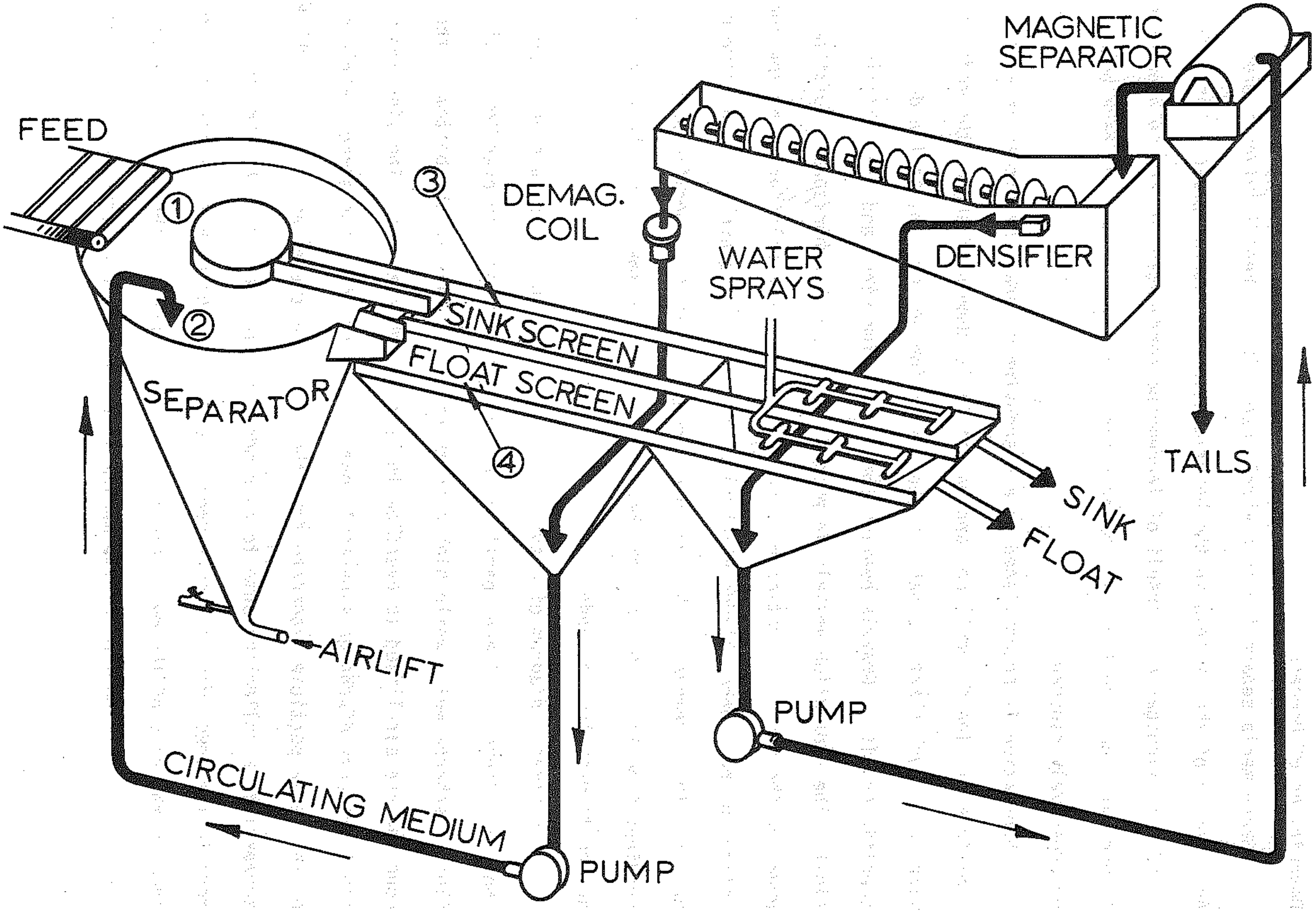

Figure I. Schematic diagram and flowsheet of cone type heavy media separator.

lated to a magnetic drum where the ferrosilicon and magnetite are separated from the contaminants. The cleaned medium is then densified and returned to the cone. The proportion of the medium to be cleaned is controlled by baffles placed on the screens.

Process Variables

The most important variable affecting the separation is the specific gravity of the medium. This is closely related to but not necessarily the same as the effective specific gravity of separation, which depends upon other characteristics of the medium as well as of the feed.

Other important variables are the viscosity of the medium and a related variable, the stability of the medium. These variables are influenced mostly by the amounts and kinds of contaminants, but also by the size structure of the media. If the medium is too viscous, stratification of gravel particles does not take place rapidly enough for efficient separation, especially of the smaller particles of specific gravity near that of the medium. If the medium is not sufficiently viscous, the media particles settle too rapidly for efficient separation to be realized within the short retention time in the zone of separation. The right viscosity provides the stability of medium necessary to maintain the proper specific gravity differential between the top and bottom of the separation zone for optimum separation efficiency.

Feed rate is as important in the HMS as in other mineral beneficiation processes. The feed rate should be optimum for the desired separating conditions, and it should not fluctuate greatly. If the feed rate is excessive for the volume of the separatory vessel, the separation zone becomes congested, and sharpness of separation and product quality will be impaired. Other factors also may enter into the separatory action such as the manner of feeding the vessel; it is undesirable for the feed to enter the separatory pool with excessive momentum.

The flow rate of the medium influences the motions of individual particles and thus their stratification. The flow of the medium in a cone vessel has a somewhat different effect on stratification than the flow through a drum, and thus the same medium specific gravity may not produce the same separation in the two types of vessels.

Feed particle size, shape, and roughness affect the separation. Large particles stratify at different rates than smaller ones of the same specific gravity but tend to pull along the latter by interference or other action. Flat or elongated particles, or angular ones, settle at slower rates than spheroidal or rounded ones. The media tends to cling more to particles with rough surfaces, thus increasing their apparent specific gravity.

PLANT PRACTICES

As the first step in the study, a number of Michigan aggregate plants using the HMS process were visited. Fourteen plants were selected to provide a geographical cross section of the gravels processed and to cover the various types of separatory vessels in use. The names of the plants, their locations, and the types and rated capacities of the HMS vessels are listed in Table 1. During these visits, plant control measures were observed, and the operators were questioned about practices and operational problems. Samples were taken at one of the plants for the purpose of evaluating performance and for use later in the experimental work. For purposes of comparison, two HMS plants on the Mesabi range in Minnesota were visited to observe practices in the beneficiation of iron ore and obtain information about the recording, control, and warning devices in use. The observations made during the plant visits are summarized here as an introduction to succeeding steps in the study.

The gravel feeds varied widely in size structure and deleterious content; moreover, practices in excavating the gravels, in preliminary washing and screening, and in feeding the separatory vessels were different at each plant. At some pits the natural gravels were small enough for direct processing; at others, oversize gravels were picked or screened out and either crushed or discarded. Furthermore, local modifications had been made to the separatory vessels so that operating practices were not the same even at those plants with the same type of vessel. For these reasons, comparisons between plants were not meaningful.

The plants used a media mixture of 50 to 80 percent by weight of minus 65 mesh ferrosilicon and the remainder minus 100 mesh ground magnetite. Most plants used ground (angular) ferrosilicon but one used atomized (spherical) ferrosilicon, which though higher in cost was found to impart better fluidity,

Table 1

Michigan HMS Plants Visited in Preliminary Survey

Name	Location	Type of Vessel	Rated Capacity Tons/Hour
American Aggregate Corp., Green Oaks	Brighton	Drum (2)*	500
American Aggregate Corp., Oxford	Oxford	Drum (2)*	750
American Aggregate Corp., Romeo	Romeo	Drum	200
Bundy Hill Gravel Co.	Somerset Center	Drum	100
Burroughs Corp.	Holly	Drum	100
Cheney Gravel Co.	Holt	Cone	50
Construction Aggregate Corp.	Ferrysberg	Drum	200
Hastings Gravel Co.	Assyria	Drum	100
Killins Gravel Co.	Ann Arbor	Drum	100
Koenig Gravel Co.	Oxford	Cone	200
Lyon Sand and Gravel	Brighton	Cone	225
Mickelson Corp.	Oxford	Cone	100
Natural Aggregate Corp.	Romeo	Cone	100
Whittaker-Gooding	Dexter	O.C.C. sweep	100

*Number of vessels

have better cleaning characteristics, and to undergo less attrition than the angular type. Furthermore, with the atomized ferrosilicon it was possible to use a higher proportion of magnetite which costs less than ferrosilicon.

The specific gravity of the medium was not monitored continuously at any plant. Instead samples were withdrawn at 15-minute to hourly intervals for measurement of the specific gravity, but practices varied in the location at which the samples were taken and in the method of making the measurement. Samples might be taken at a designated point below the surface of the bath, from either the sink or the float screen underflow, from the medium sump, or at the point of discharge into the separatory vessel. At some plants, samples were taken from both the float and sink screen underflows to determine the specific gravity differential between the top and bottom of the bath. A direct reading pulp density balance was in general use for measuring the specific gravity of the medium, but operator variations were noted.

Because of the widely different gravel feeds, practices varied in the level of specific gravity maintained, and also practices varied in the gravity differential maintained. Some plants operated at a float specific gravity as low as 2.52, and others at a sink specific gravity as high as 2.73, and some plants maintained the gravity differential in a narrow range of four points (0.04 in specific gravity). Specific gravity was controlled by adding water to the circuit when the gravity became too high or by lowering the densifier screw in the cleaning circuit to add more media when the gravity became too low.

Consistency of the medium was not measured at any plant, but the stability was sometimes measured as the rate of drop of media in a glass beaker or column. The specific gravity differential, if measured, was taken as an indication of the consistency and stability.

The amounts of contaminants in the medium were normally estimated only by observation of the nonmagnetic product of the magnetic drum and the action of the bath, but grab samples were sometimes taken from the bath for visual examination of contaminants. The amount of contaminant was controlled by adjusting the baffles on the sink and the float screens so as to send more or less medium to the cleaning circuit.

The size structure of the media was analyzed occasionally at some plants, but not at others. Fresh media was added either at regular intervals or as needed to make up for attrition of particle size and for losses which averaged about 0.4 pounds per ton of aggregate produced. Concern about the effect of attrition of media was expressed by one plant operator. He noted that as the media became finer in size it was more difficult to dewater with the result that the densifier could not return enough media to the circuit to maintain the desired specific gravity. Either fresh media had to be added, or it was necessary to reduce the feed rate to produce acceptable aggregate. This operator was experimenting with ferrosilicon containing some coarser sizes than 65 mesh.

Weightometers to measure the feed were not in use at any plant, and the feed rate was estimated only by observing the loading of the converyor belts. At one plant, the feed rate was noted to be very sporadic; at another, the feed rate exceeded the manufacturer's designated capacity of the HMS vessel. There was a general impression among the operators, apparently on the basis of claims made by HMS equipment manufacturers, that the efficiency of the process is not affected by variations in feed rate or even by fluctuations in the amount of deleterious gravels in the feed, provided that the rated capacity of the vessel is not exceeded. Evidence to substantiate such claims is lacking, and in fact it is more reasonable to believe that both the feed rate and the amounts of low specific gravity gravels affect the separations. Obviously, the retention time of gravels in the separatory zone must be sufficient to achieve separation, and thus if the feed rate is excessive for the capacity of the zone, separation is impaired. On the other hand, if the plant is not operated at optimum capacity for the quality of product desired, the operator does not realize the lowest production cost.

Provisions for varying the medium circulation rate were not found at any plant, but in those using a cone vessel some control of the rate of circulation was provided by adjusting the amount of air used in lifting the sink product to overflow. The air flow was regulated manually by a valve according to the reading on a pressure gauge.

Sizing of feed was practiced at one plant, and four sizes of product were stockpiled; amounts were withdrawn as required to make up a final product to meet a given specification. This practice appeared to have advantages in plant control, recovery efficiency, and flexibility. No plant provided for elimination of flat or elongated particles, but only minor amounts of these particles were noted in the natural gravels. Most of the gravels, except some of the hard absorbent ones, were observed to have relatively smooth surfaces. However, there is a lack of information about the variation in shape and surface roughness of natural gravels, and the effects of shape and roughness upon separation efficiency have not been investigated.

Many plant operators added lime to the medium to prevent acidity which causes corrosion of the media, and to assist in fluidization of the settled solids when starting up after a shutdown. At one plant, small amounts of trisodium phosphate were added to correct water hardness and retard corrosion of the ferrosilicon.

Most of the plants practiced quality control in some degree, and a few plants had a quality control staff. At some plants both feed and products were sampled and picked, but at most of the plants only the products were picked either regularly or occasionally.

In the third phase of the project, nine Michigan HMS plants including some of those previously visited, were again surveyed. The purpose was to collect additional samples for evaluation of plant performance and to assess problems of adapting automatic monitoring of medium specific gravity and consistency to existing circuits. As a result of this survey, modifications were made to the IMR pilot plant to improve the diversion of medium from the recirculation system to the consistometer. This same method could be used in full scale plants for diversion of medium to the automatic specific gravity gauge as well as to the consistometer.

EXPERIMENTAL MATERIALS

Samples

Samples for experimental uses were taken at one of the plants included in the visits. This plant was selected because the circuit was readily accessible for sampling and the operating conditions were variable; also, the plant was small enough (50 tons per hour) to be used for demonstration purposes if this should become desirable later.

Samples were taken in two separate periods of about two weeks each. The plant feed, the sink product, and the float product were sampled simultaneously and for the same length of time so that the amounts collected provided a weight recovery balance. In the first period, eight samples of approximately 110 pounds each were taken, and in the second period five samples of 200 to 400 pounds each were taken. All feed and product samples were placed in separate marked bags and shipped to IMR.

During both periods, specific gravity measurements were made periodically on samples of medium taken at four points in the circuit designated by number in Figure 1 and described as follows: 1) just below the surface of the bath in the cone, 2) point of discharge of return medium into the cone, 3) screen underflow on the sink side, and 4) screen underflow on the float side. Two medium samples were brought back to IMR for further study. The temperature and pH of the bath were measured at first, but they varied little and these measurements were discontinued. Attempts to measure the viscosity of the medium with a spindle-type viscometer were not successful.

Media

A media mixture of 50% by weight ground ferrosilicon and 50% ground magnetite was used in the experimental work. This was more magnetite than is used in most plants, but it was not expected to undergo much attrition in the limited experimental work. The ferrosilicon and magnetite used in the early batch tests had the size analyses listed in Table 2; these media were supplied by American Aggregate Corp. In the pilot plant tests Carborundum Co. 65 mesh ferrosilicon and Mineral Mills, Inc. type D magnetite were used. The size analysis of a 50/50 weight percent mixture of these media is listed in Table 3.

Table 2

Size Analyses of Ground Ferrosilicon and Ground Magnetite Used in Batch Tests

Mesh Size	Ferrosilicon, Wt. Pct. Ind.	Ferrosilicon, Wt. Pct. Cum.	Magnetite, Wt. Pct. Ind.	Magnetite, Wt. Pct. Cum.
+35			0.16	0.16
+48			0.63	0.79
+65	1.25	1.25	5.53	6.32
+100	7.13	8.38	15.24	21.56
+150	19.93	28.31	19.31	40.87
+200	23.94	52.25	13.35	54.22
+270	16.59	68.84	11.57	65.79
+325	6.72	75.56	5.69	71.48
-325	24.44	100.00	28.52	100.00

Table 3

Size Analysis of 50/50 Weight Percent Mixture of Ferrosilicon and Magnetite Used in Pilot Plant Tests

Mesh Size	Mixture, Wt. Pct. Ind.	Mixture, Wt. Pct. Cum.
+28	0.04	0.04
+35	0.21	0.25
+48	1.32	1.57
+65	3.43	5.00
+100	6.91	11.91
+150	11.52	23.43
+200	14.44	37.87
+270	14.40	52.27
+325	7.05	59.32
-325	40.68	100.00

Clay Contaminant

A local clay was used as a medium contaminant in the preliminary tests, and a clay obtained from the end of a washing flume at one of the Michigan HMS plants was used in the batch and pilot plant tests. Other contaminants such as sand particles which are present in plant mediums were not added in these tests.

LITERATURE SEARCH

Starting in the first year and continuing concurrently with the laboratory and pilot plant work, a literature search was made for information on recording, control, and warning devices that might have application to process control in heavy media plants, with particular attention to methods of continuously measuring and controlling the variables considered to be most important, the specific gravity, consistency, and stability of the medium.

Nesbitt and Weavind (2) described a simple instrument for continuously measuring the density of the medium in a cone. This consisted essentially of two vertical tubes of different length extending into the top of the bath. Purge water flowed through the tubes to maintain static water columns, and a standard technique of bubbling air through the columns was used to measure the difference in water height by means of the differential air pressure, which was converted to density of the medium. It was claimed that the instrument required little attention, and that its accuracy was ±0.01 specific gravity units.

Bean (3) described a density meter for continuous measurement of the specific gravity of a heavy media suspension. This instrument was similar to the one described by Nesbitt and Weavind but had added features providing automatic control of the specific gravity.

A gauge sold by Nuclear-Chicago Corp. (4) continuously measures the density of a circulating medium by monitoring the absorption of radiation from a gamma source. This gauge is claimed to have an accuracy of ±0.003 specific gravity units, and it is easily integrated into existing plants without changes in design or interruption of production. It was in use in conjunction with a Ramsey periodic error integrating controller in the two Minnesota iron ore HMS plants. In these installations, any drift from the designated gravity was automatically corrected either by changing the amount of water added to the circulating medium or by raising or lowering the densifier screw.

Devaney and Shelton (5) gave a detailed description of a consistometer used to measure the apparent viscosity of samples periodically withdrawn from the circulating medium.

Geer, et al (6) described methods of measuring the viscosity of dense mediums used in cleaning coal and discussed the effect of various medium contaminants on viscosity as well as the influence of viscosity on consumption of media. They also described a method of measuring the stability of suspensoids in samples periodically withdrawn from the circulating medium.

Many other publications were reviewed, but only those pertinent to this investigation were studied in detail and are referred to by number in the BIBLIOGRAPHY. Other references listed without numbers provide access to some of the useful literature on heavy media plant operations. The unnumbered references also include reports of previous studies of gravel aggregate done by the Institute of Mineral Research.

PRELIMINARY WORK TO ESTABLISH EXPERIMENTAL PROCEDURES

Measurement of Specific Gravity

Since heavy media separation takes advantage of differences in specific gravity, control of the specific gravity of the medium is essential. This is the most important process variable, and in practice it is controlled largely by measuring the specific gravity of medium samples periodically withdrawn from the circuit. The standard method is to weigh a known volume of medium with a direct reading pulp density balance.

Repeated measurements were made to determine the accuracy of a Marcy pulp density balance in measuring specific gravity. Samples of medium were taken under the pilot plant sink drain screen and under the float drain screen with steady state circulation of the medium. For reproducible results, it was found that the samples must be taken to a given volume without permitting overflow from the container. With this procedure, the standard deviation of a single measurement was ±0.016 specific gravity units.

In the pilot plant tests the Marcy balance was used only to determine the specific gravity differential between the top and bottom of the bath by periodic measurements made on samples taken as described above, while the specific gravity of the circulating medium was measured continuously by the Nuclear-Chicago Qualicon gauge. In the batch tests, however, the Marcy container was found to be unsuitable for taking samples from the laboratory cone, and a smaller receptacle was devised for withdrawing 200 cubic centimeters of medium 3 inches below the surface of the bath. The variation in repeated measurements with this device was insignificant at the 95% confidence level.

Measurement of Consistency

Another variable entering into the heavy media process is the apparent viscosity, or consistency, of the medium. As Taggart (7) states "...the viscosity, real or pseudo, of the medium is an important element in the motion of the solid particles therein, and time may be an element in the separation".

It is worthwhile at this point to define viscosity and explain the difference between Newtonian and non-Newtonian fluids. The viscosity of a fluid is its resistance to flow, and the coefficient of viscosity is the ratio of the shearing stress to the rate of strain. Newtonian fluids exhibit a constant coefficient as shown in Figure 2. However, many fluids including most suspensions do not have this simple relationship, and they are called non-Newtonian. They fall into classifications of dilatant, pseudoplastic, and Bingham plastic, as illustrated in Figure 2. For these fluids, the coefficient determined for a given strain rate by the slope of the line to the origin is not the true viscosity, but the apparent viscosity, or consistency. In spite of its restrictions, the measurement of apparent viscosity has been widely used in the mineral industries for characterizing the rheological properties of heavy media suspensions.

As a result of the plant visits, it was decided that the consistency of the medium should be studied as an important process variable for measurement and control. A method of continuous measurement would be desirable, but the literature search did not reveal any means by which this could be done. Spindle-type viscometers were tried, but they were not found useful. A consistometer similar to that described by Devaney and Shelton (5) was built and calibrated with liquids of known viscosity. As illustrated in Figure 3, this instrument consists of a capillary tube attached to the bottom of a cylindrical reservoir in which an impeller rotates at a speed sufficient to keep the media in suspension. The time required for gravity flow of 100 cubic centimeters of medium is measured, and the consistency is determined by the following formula derived from the Poiseuille equation:

$$n = kdt$$

where n = consistency, centipoises
k = instrument constant taken from a calibration curve established with Newtonian liquids of known viscosity
d = density of medium, grams per cubic centimeter
t = time, seconds

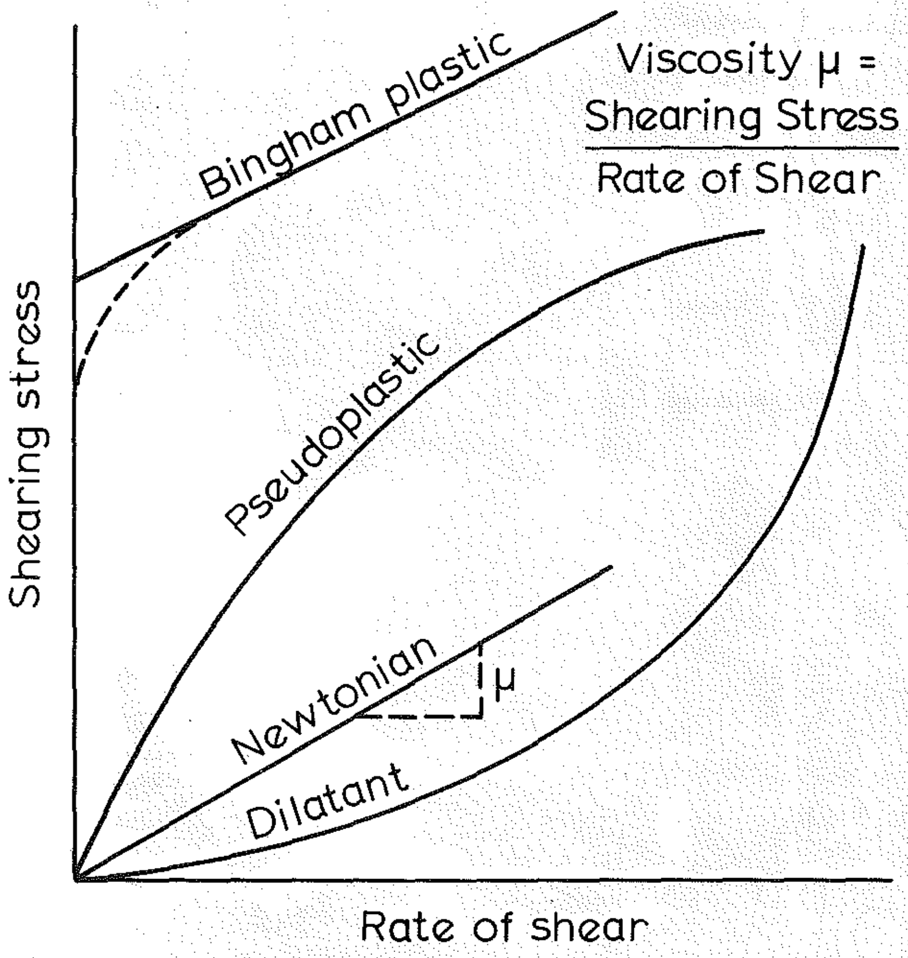

Figure 2. Shear diagrams characteristic of Newtonian and non-Newtonian fluids.

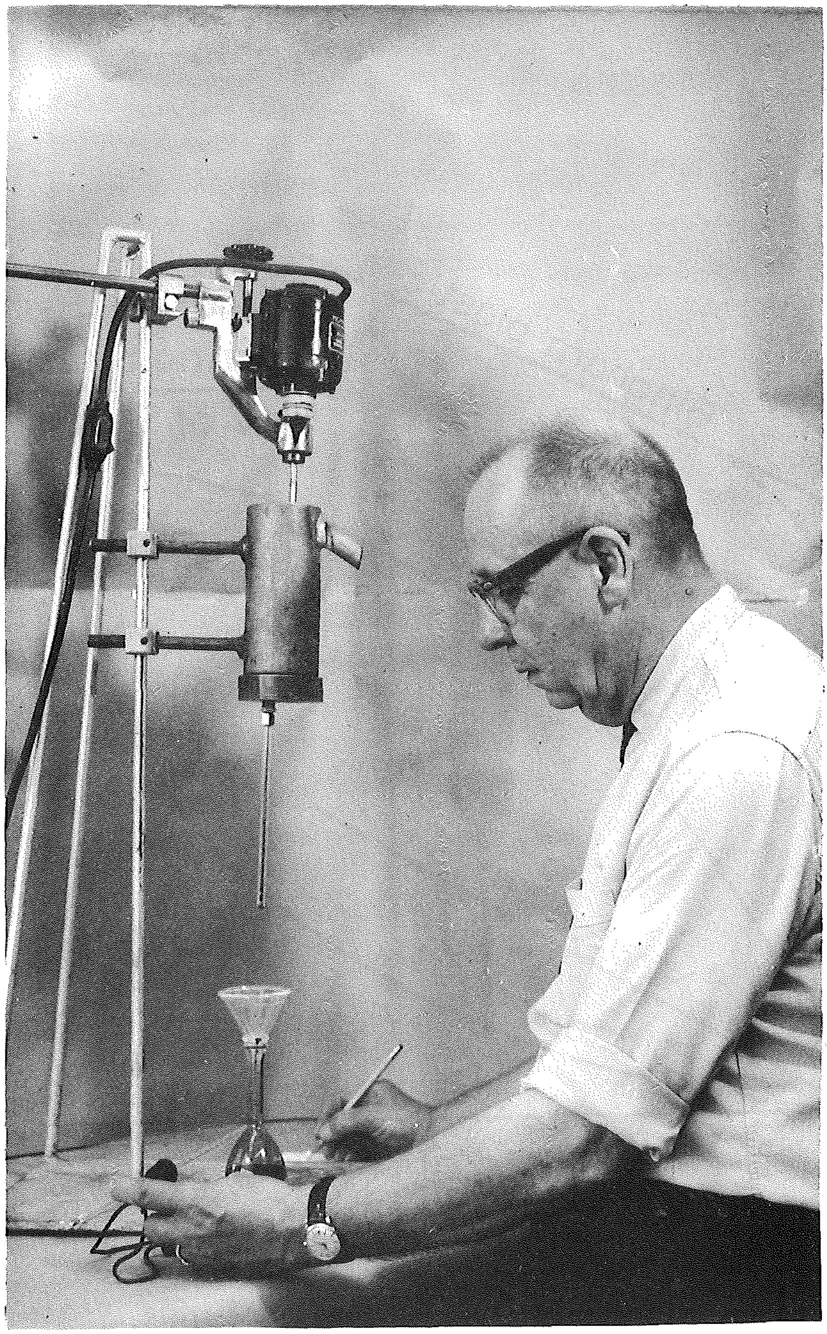

Figure 3. DeVaney-Shelton consistometer.

Before making a measurement the plus 28 mesh portion of the media was removed to prevent plugging of the capillary tube. Preliminary tests established that removal of this portion of the media had a negligible effect. All determinations, both for the batch and the continuous tests, were made with the temperature of the suspension maintained at 25°. In replicated measurements with mediums made up to 2.35 specific gravity with 50/50 weight percent mixtures of clean ferrosilicon and magnetite of four different size structures, the standard deviation of a single measurement was ±0.35 centipoises.

Development of an instrument for the continuous measurement of consistency of circulating heavy media suspensions was undertaken as a separate project. An experimental instrument designed and built by IMR was tested in the pilot plant in the third phase of the study.

Measurement of Stability

A device similar to that developed by Geer et al (6) for measuring the stability of a medium was built. It consists of a 10-inch length of 3/4 inch pipe with a base on which the pipe stands vertically; a drain hole is located about a third of the distance from the upper or open end of the pipe. In making a measurement, the pipe with the drain hole closed is filled with medium and weighed. After vigorous shaking of the pipe, the media is allowed to settle for one minute. Then the medium in the upper part is drained off, and the pipe with the remaining medium is weighed again. From the weights before and after settling, the known tare weight of the pipe, and the known volumes full and drained, the stability is computed by the empirical formula:

$$\text{Stability, \%} = \frac{100\,(2.96\,W_d - 86.6)}{W_1 - 86.6}$$

where $W_d = W_1 - W_2$

W_1 = initial weight, grams　　pipe volume full = 86.6 cubic centimeters

W_2 = final weight, grams　　pipe volume drained = 57.3 cubic centimeters

Stability thus is defined as the change in specific gravity after one minute of settling time, and it is expressed as a percentage taking 100 as the index of a medium from which no settling takes place. It is to be noted that this expression is the complement of that proposed by Geer et al (6). In replicated measurements with mediums made up to 2.35 specific gravity with 50/50 weight percent mixtures of clean ferrosilicon and magnetite in three different size structures, the standard deviation of a single measurement was ±2.65 percent.

Specific Gravity Distributions of Aggregate Types

It was necessary to determine the specific gravity distributions of the aggregate types in the samples collected at the Michigan HMS plant as a basis for evaluating plant performance and also for evaluating the results of the experimental work to be undertaken. The sink and float products were picked by a trained technician to separate the sound, soft, hard absorbent and chert particles into type fractions, and the deleterious particles were individually marked with a small amount of durable paint for positive identification in repeated tests. The specific gravity composition of each fraction was determined by heavy liquid separations made at gravities of 2.15 to 2.96 in increments of 0.10. Mixtures of carbon tetrachloride and tetrabromoethane were used for this purpose, and the specific gravity of the mixture was checked often so that it was constant during each separation.

To avoid an excessive amount of work, the specific gravity compositions of only the first five plant samples (nos. 1-5) were determined. Heavy liquid separations were made of the sink and float products, and the results were combined on the assumption that the composite of the two products was representative of the feed at the time the samples were taken. These five samples were used in the batch tests, but for the pilot plant tests, a larger sample (no. 6) was prepared by combining the five samples with three of the larger samples taken in the second sampling period. These three larger samples were picked to segregate the four aggregate types, and heavy liquid separations of the deleterious fractions were made at gravities of 2.15 to 2.96 in increments of 0.10. However, to avoid the cost of making heavy liquid separations of the large amount of sound gravels, four three-pound samples were split out and heavy liquid separations were made at gravities of 2.25 to 2.85 in increments of 0.10. The weights of the fractions were averaged to arrive at the specific gravity composition of the sound gravels.

The heavy liquid separation data for the sink and the float products making up samples nos. 1-5 are listed in Tables A1-A5, respectively (Appendix). The heavy liquid separation data for sample no. 6 are in Table A6 (Appendix).

During the second plant survey, grab samples were collected simultaneously from the sink and float discharge screens so as to have approximately 20 pounds. These samples were brought to IMR for heavy liquid separations and evaluation of plant performance.

Aggregate Particle Size, Shape, and Surface Characteristics

Since the settling rate of a particle in a fluid is influenced by its size, shape, and surface roughness, preliminary measurements were made in an attempt to evaluate the effects of these factors on the heavy media separations.

Particle size distributions were determined for two of the samples, nos. 4 and 5. Each heavy liquid fraction obtained from the specific gravity determinations was sized into minus 1 1/2 plus 1 inch, minus 1 plus 1/2 inch, and minus 1/2 plus 3/8 inch classes. The weights of the aggregate types in each size class at the various levels of specific gravity for both the sink and the float products of samples nos. 4 and 5 are listed in Tables A7 and A8, respectively (Appendix).

The particle index described by Huang (8) was selected for characterization of shape, angularity, and surface roughness. This is a numerical index which for a mass of single sized, polished aluminum spheres is zero and which increases numerically as the particles become more irregular in shape, angularity, and surface roughness.

The procedure used for measuring the particle index was to split out portions from the samples and size them into minus 3/4 plus 1/2 inch and minus 1/2 plus 3/8 inch fractions; larger sizes were not found in the portions. Gravels from each size fraction were rodded into a specially designed rhombohedron split mold in three equal layers with a standard tamping rod, first at 10 strokes per minute and then at 50 strokes. The percentage voids was computed from the net weight of the aggregate in the mold for each tamping rate as follows:

$$V_n = 1 - \frac{(W\ )}{sv}\ 100$$

Where V_n = percentage voids at n strokes per layer

W_n = net weight of aggregate in the mold at n strokes per layer, grams

s = bulk specific gravity of the aggregate

v = volume of rhombohedron mold, cubic centimeters

The particle index was computed from the percentages of voids at 10 and 50 strokes as follows:

$$I_a = 1.25\ V_{10} - 0.25\ V_{50} - A$$

where I_a = particle index for size a

V_{10} = percentage voids at 10 strokes per layer

V_{50} = percentage voids at 50 strokes per layer

A = constant dependent upon the size (32.0 for the minus 3/4 plus 1/2 inch size and 31.0 for the minus 1/2 plus 3/8 inch size).

Measurements of particle index were made on portions split out from samples nos. 2 and 5. The measurements were not repeated to obtain an assessment of error because the procedure was found to be time consuming and the value of the measurement was uncertain. The particle indices for the two samples were:

Sample No.	Minus 3/4 plus 1/2 inch	Minus 1/2 plus 3/8 inch
2	8.6	8.0
5	8.6	7.7

Effect of Contaminants on Consistency and Stability of Mediums

Although the natural gravels are washed and screened before HMS treatment, minor amounts of adhering clay and fine sand particles are carried into the HMS circuit to become a part of the circulating medium. Fine rock particles from attrition during processing of the gravels also become a part of the medium. As the slimes affect the consistency and stability of the medium and thus the specific gravity of separation, a cleaning circuit is provided to prevent a build-up of these contaminants.

Preliminary tests were made to determine the effect of clay contaminants on the consistency and stability of the medium. A heavy media mixture of 50/50 weight percent ferrosilicon and magnetite was used in the tests. Mediums were made up to specific gravities of 2.50 to 2.65 in 0.05 increments, and consistency and stability measurements were made as previously described. Then the consistency and stability measurements were made again after incremental additions of a local clay. The clay additions were continued until the measurements became difficult to make. The consistency and stability measurements are listed in Table A9 (Appendix).

Effect of Media Particle Size on Consistency and Stability of Mediums

Salzmann (9) pointed out that the medium has a "consistence" because of friction between the particles suspended in the liquid, and this "consistence" influences the stability of a suspension depending upon the grain size of the heavy particles, finer particles imparting higher "consistence".

Preliminary tests were made to determine the effect of media size structure on the consistency and stability of the medium. Four mixtures of equal weights of ferrosilicon and magnetite were made up in size structures having linear log-log distributions with the same distribution modulus (slope) but progressively finer size moduli (top size intercept). These mixtures were used to make up mediums of 2.35 specific gravity, and the consistency and stability of each were determined by the procedures previously described. The results are listed in Table A10 (Appendix.)

Later it became apparent that the media size structures and medium conditions in the preliminary tests were not really representative of those in actual plant operations, and new tests were made. Four mixtures of ferrosilicon and magnetite in the weight ratio of 2:1, respectively, were made up to have progressively finer size structures with distributions similar to media mixtures normally used in plant operations. The necessary amount of water was added to have a medium of 2.55 specific gravity, and the consistency and stability were measured by the procedures previously described. The measurements were repeated after the media mixture was filtered, screened and again made up with water to 2.55 specific gravity. These measurements are listed in Table A10-1 (Appendix).

Since a plant medium contains both clay and fine rock particles, additional tests were made to determine the effect of media size structure on the consistency and stability of a medium containing a normal amount of these contaminants. Media of 2:1 weight percent ferrosilicon to magnetite of the same size structures as previously used were thoroughly admixed with 4.5 weight percent clay plus rock sand obtained from a washing flume at one of the Michigan HMS plants; four mixtures were made up with the clay varying from one to four weight percent of the mixture and the remainder of the total contaminant rock sand. Water was added to each mixture to form a medium with a specific gravity of 2.55, and the consistency and stability were measured by the procedures previously described. The measurements were repeated after the media mixture was filtered, screened and again made up with water to 2.55 specific gravity. These measurements are listed in Table A10-2 (Appendix).

BATCH TESTS

Batch tests were undertaken to study the control of specific gravity, consistency, and stability of the medium within the ranges to be investigated in the continuous pilot plant tests. The laboratory separator illustrated in Figure 4 was used in making the batch tests. This separator holds approximately eight gallons of medium, which is circulated at a rate of 15 gallons per minute by a one inch pump with a 3/4 hp 1800 rpm motor.

Samples nos. 1 and 4 were used in the tests; the sink and float portions were combined to make up each feed sample. These samples had been picked, and the deleterious particles had been marked by type with a small amount of durable paint so that they could be positively identified after each test. After the sink and float products from a test were picked and the fractions weighed, the products were recombined again so as to have the same feed sample for the next test. Only a negligible amount of degradation of gravel particles occurred during the tests.

The media was made up of equal parts by weight of ground ferrosilicon and magnetite as described under EXPERIMENTAL MATERIALS. A clay collected from a tailings flume at one of the Michigan HMS plants was used as a contaminant. Five tests were made with each of the two samples, first without clay and then with increasing additions of clay to vary the consistency and stability.

In starting a series of tests, steady state circulation of the water in the cone system was established; then media was added until the specific gravity of the medium as determined by measurement was 2.34. This level had been established as equivalent to an effective specific gravity of separation of about 2.50 in the pilot plant cone. Then the gravel sample was fed by hand into the upper cone, a small amount at a time. Float gravels passed out of the upper cone by overflow and were collected in the basket of the lower cone while the sink gravels remained in the basket in the upper cone. The baskets were emptied frequently to permit proper circulation of the medium.

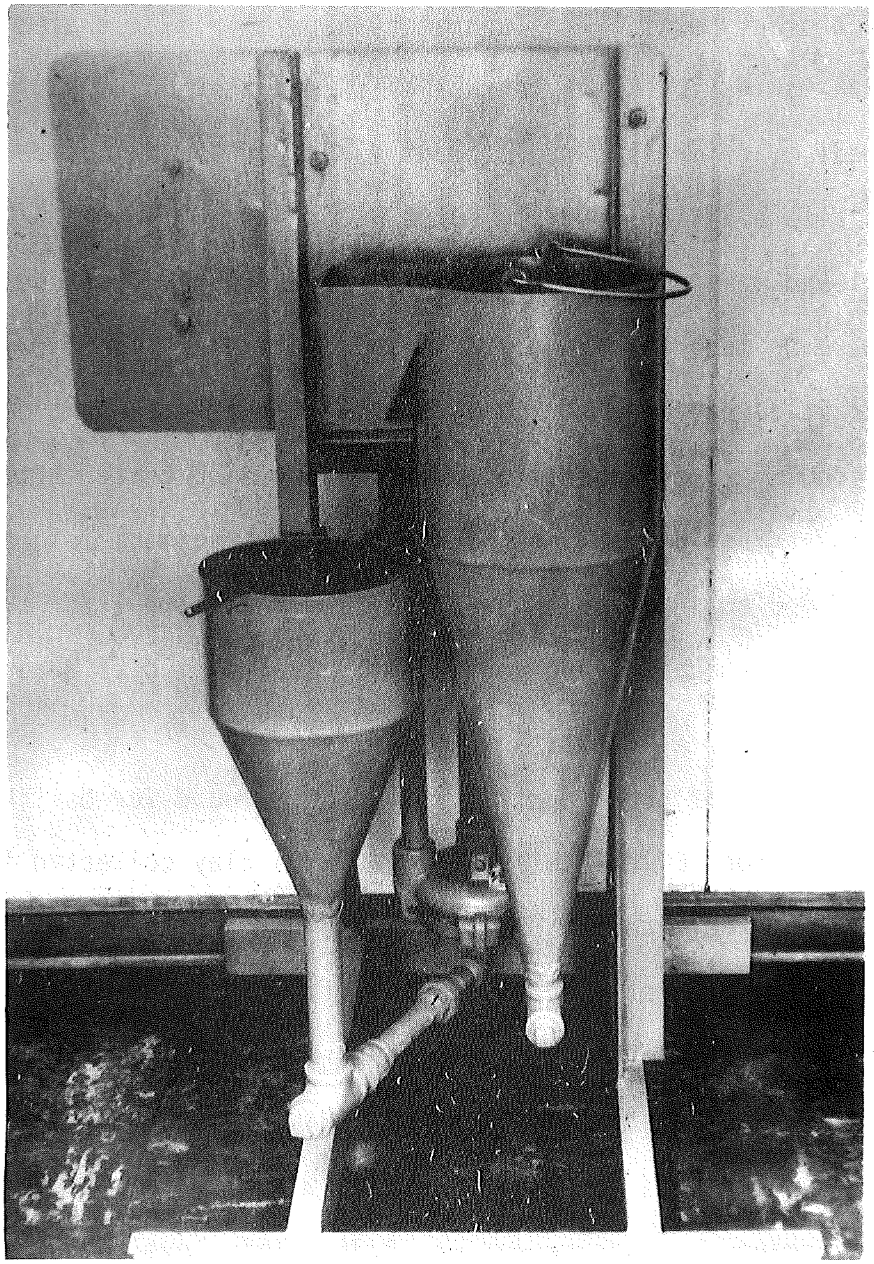

Figure 4. Laboratory separator for HMS batch tests.

Medium samples for measurement of specific gravity, consistency, and stability were taken from the upper cone at the end of each test. The samples for measurement of specific gravity were taken at the surface, middle, and bottom of the bath with a specially designed container of fixed volume as described under PRELIMINARY WORK TO ESTABLISH EXPERIMENTAL PROCEDURES, Measurement of Specific Gravity.

The batch test conditions and results are listed in Table A11 (Appendix).

PILOT PLANT TESTS, PHASES I AND II

Pilot plant tests were undertaken as a necessary step towards the final objective of demonstrating methods of process control under continous conditions. The preliminary tests were made to investigate the effects of the process variables on product yield and quality, to determine the levels of the variables for optimum yield and product quality, and to establish control of the variables. The process variables of interest were the specific gravity, consistency, and stability of the medium, the specific gravity differential of the bath, and the feed rate. Fifteen preliminary tests were made. The medium specific gravity was controlled at five levels and the feed rate at two levels. The consistency and stability were varied by adding clay to the medium; the clay additions were made only at the higher feed rate. The specific gravity differential was measured as a random variable. The medium circulation rate was held as constant as possible. The dependent variables were the yield and deleterious content of the sink product, the loss of sound gravel, and the efficiency.

Pilot Plant Circuit and Equipment

A diagram of the pilot plant circuit is shown in Figure 5, and a photograph of the assembled equipment in Figure 6. The principal items of equipment were:

Wemco cone separator, 3-foot diameter
Symons type F horizontal vibrating screen, 2x4-foot
Wemco densifier, 12-inch x 9-foot
Dings XW3 magnetic separator, 24x12-inch
Eriez Hi-Vi type 40A vibrating feeder
Wemco model C torque flow and CAM Warman pumps, 4x3-inch
Wemco model BM Warman pump, 1 1/2x1-inch

The specific gravity of the circulating medium was continuously measured and recorded by a Nuclear-Chicago Qualicon density gauge connected to a Fisher Scientific Recordall, series 129, and the rate of circulation was measured by a Venturi flow meter with a 20-inch Merriam manometer.

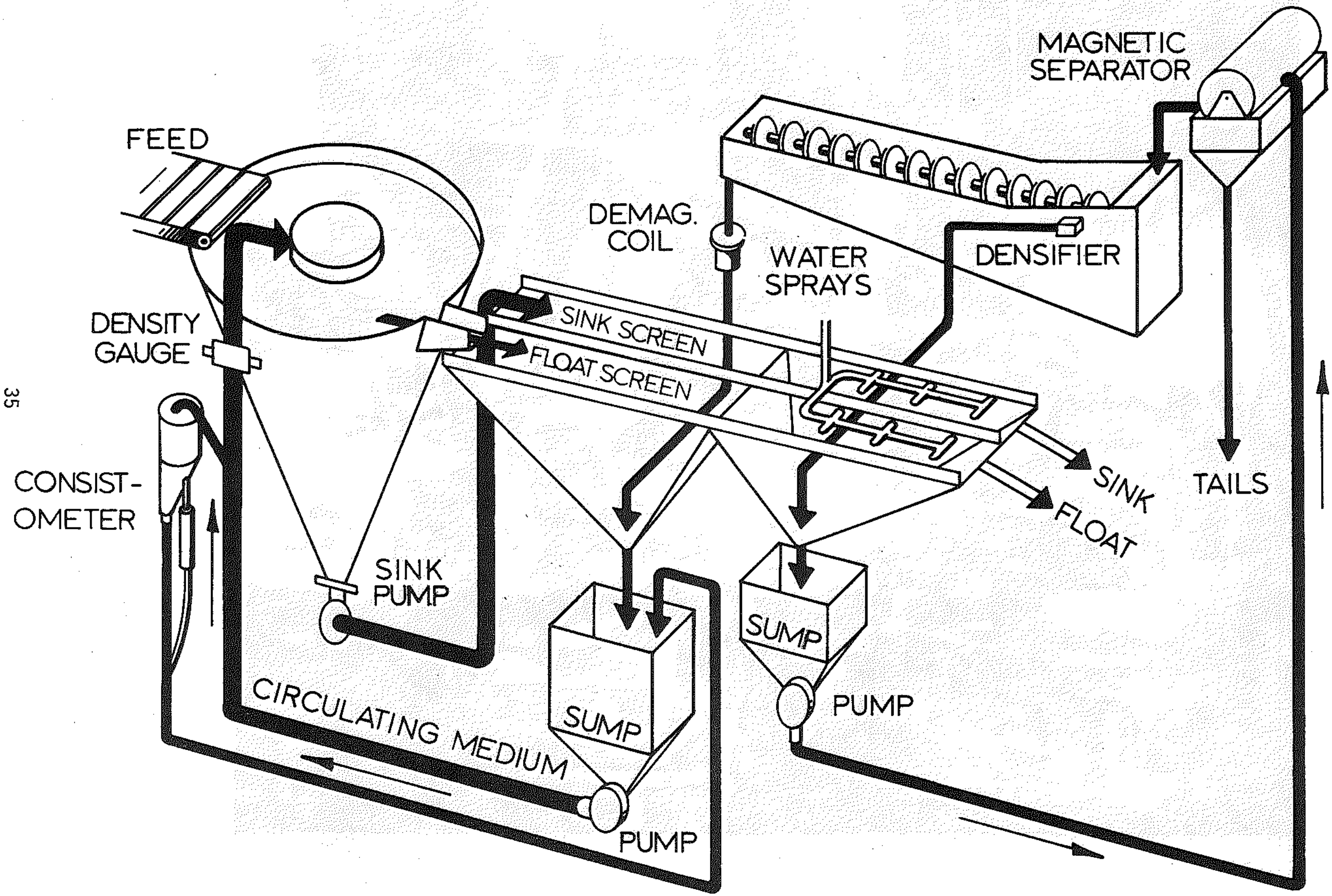

Figure 5. Schematic diagram and flowsheet of pilot plant heavy media separator.

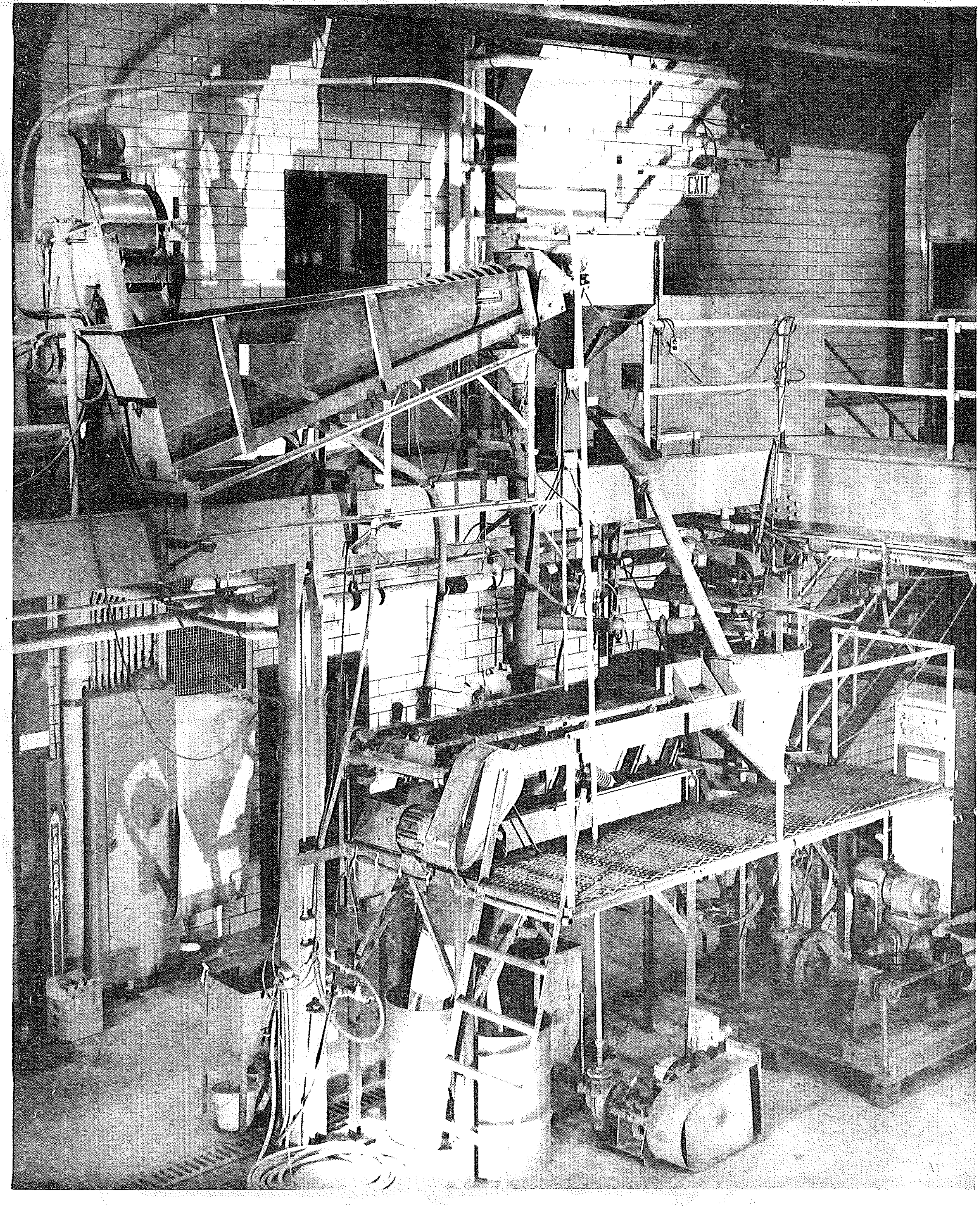

Figure 6. View of HMS pilot plant.

Feed Sample

The pilot plant feed sample (no. 6) was made up as described under EXPERIMENTAL MATERIALS. The deleterious particles in the feed had been marked according to type with a small amount of durable paint so that they could be quickly and positively identified after each test. The sink and float products from each test were picked to segregate the particles by type, and the fractions were weighed; then all fractions were combined to reconstitute the same feed sample for the next test. The feed sample was kept water saturated, and all weights of test products were determined with the gravel particles in the saturated surface dry condition.

Media and Contaminant

The media used in the pilot mill tests was a 50/50 weight percent mixture of ferrosilicon and magnetite, as described under EXPERIMENTAL MATERIALS. Clay obtained from a washing flume at one of the Michigan HMS plants was used as a contaminant; its specific gravity was measured and an amount was added so that the clay made up 5 percent by weight of the solids in the media mixture.

Operation of Pilot Plant and Sampling

The initial step in operation of the pilot plant was to establish a steady circulation rate, and then additions of media were made to the circulation sump until the desired specific gravity was registered on the density gauge recorder. Samples were taken under the sink and the float drain screens and measurements were made with a Marcy pulp balance to determine the specific gravity differential. For the tests in which clay was used, the computed amount was added to the sump. Samples for consistency and stability measurements were then taken from the sink and float drain screen underflows and from the circulating medium at the inlet to the sump.

After the desired test conditions were reached, the feed was introduced to the separatory vessel. When input-output equilibrium had been established, which took only 3 to 4 minutes, sampling of the sink and float products was begun and continued until the total weight of the two products was about 200 pounds. The specific gravity of the circulating medium was maintained throughout each test by adding water when the gravity increased or by lowering the densifier screw when the gravity decreased.

At the conclusion of the five tests made without clay additions and two of the tests with clay additions, samples of medium were taken from the sink and float screen underflows and from the sump to determine if there was any significant change in the specific gravity, consistency, or stability during a test. These terminal measurements were not found to be significantly different from those made at the start of any test. A sample of the circulating medium was taken at the end of each test in which clay additions had been made, and the clay content was measured by removing the ferrosilicon and magnetite by Davis tube magnetic separator.

The sink and float products were picked to segregate the particle types according to their markings, and the weight of each type in each product was recorded. The conditions for the 15 tests are listed in Table A12 (Appendix), and the weights of the aggregate types in the sink and float products are shown in Table A13 (Appendix).

DEVELOPMENT OF CONSISTOMETER

The preliminary pilot plant tests indicated that while the automatic density gauge provided satisfactory control of the specific gravity of the medium, consistency and stability measurements on samples periodically withdrawn from the medium were subject to errors and time lapses which made them ineffective for plant control. Thus, attainment of the principal objective of the program depended upon development of an instrument for continuously measuring the consistency of the circulating medium. As no such instrument was available on the market nor revealed in the literature search, IMR undertook to develop one. A relatively simple and low cost device which could be used with either cone or drum types of vessels was deemed necessary, and it would need to have operational stability and reliability over long periods of time. For the purposes of process inspection, it was considered desirable to have the consistency continuously recorded on a chart.

Description of Consistometer

The principal of the consistometer is that a fluid in flowing over a surface exerts a drag force which is directly proportional to the viscosity and velocity of the fluid and to the area of the surface. If the velocity and surface area are constant, any change in viscosity will cause a change in the drag on the surface, and measurement of this change provides a quantitative indication of the change in viscosity.

A diagram of the consistometer and feeding system finally developed is shown in Figure 7 and a photograph of the apparatus as integrated into the pilot plant circuit is shown in Figure 8. The consistometer proper is made up of three concentric cylinders connected by fins and suspended by a fine wire from a sensitive vertical transducer, the output of which is millivolts. The transducer is housed and protected by a streamlined chamber supported in the center of the enlarged part of the consistometer so that the medium can

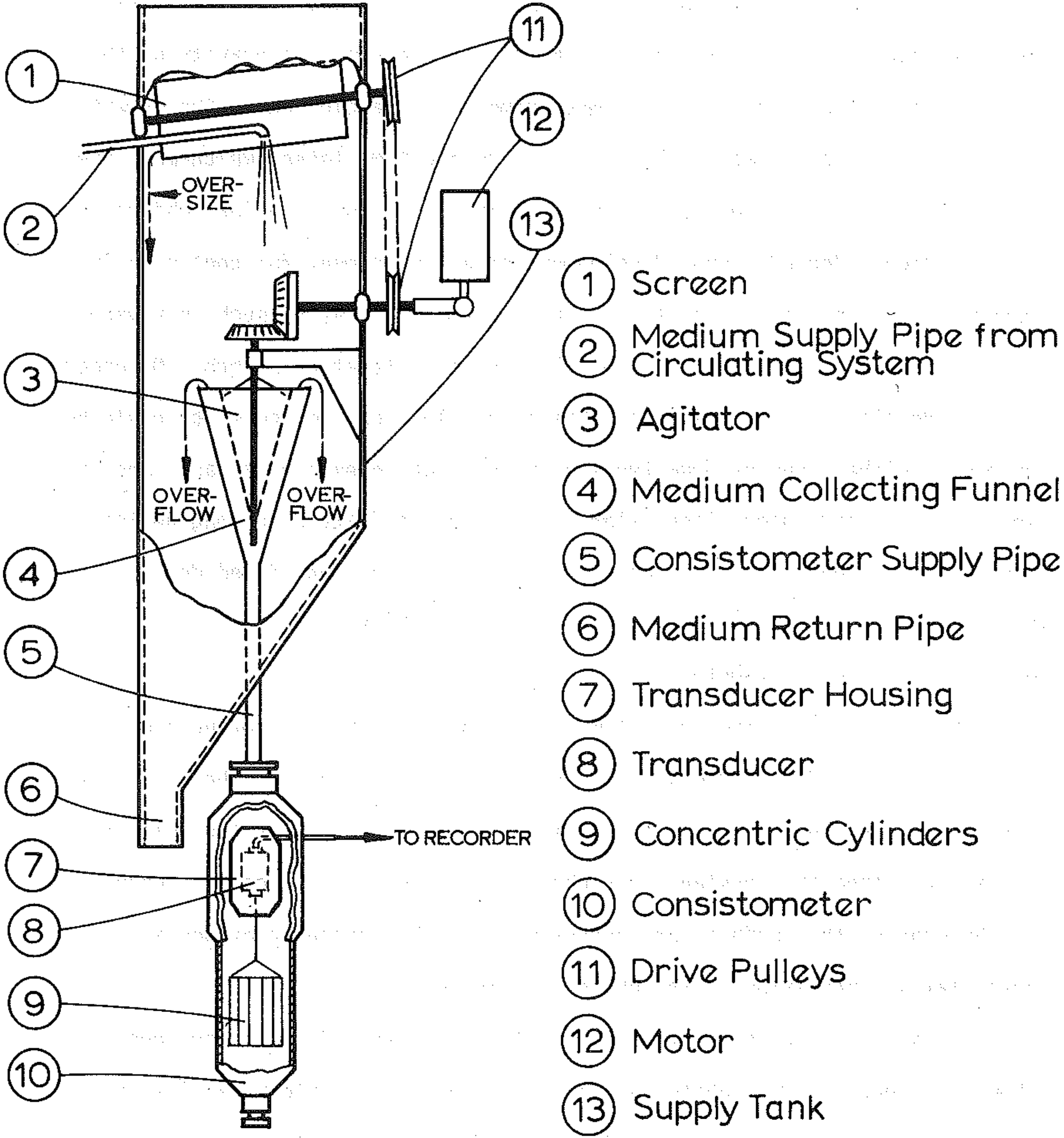

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Figure 7. Diagram of automatic consistometer and feeding system.

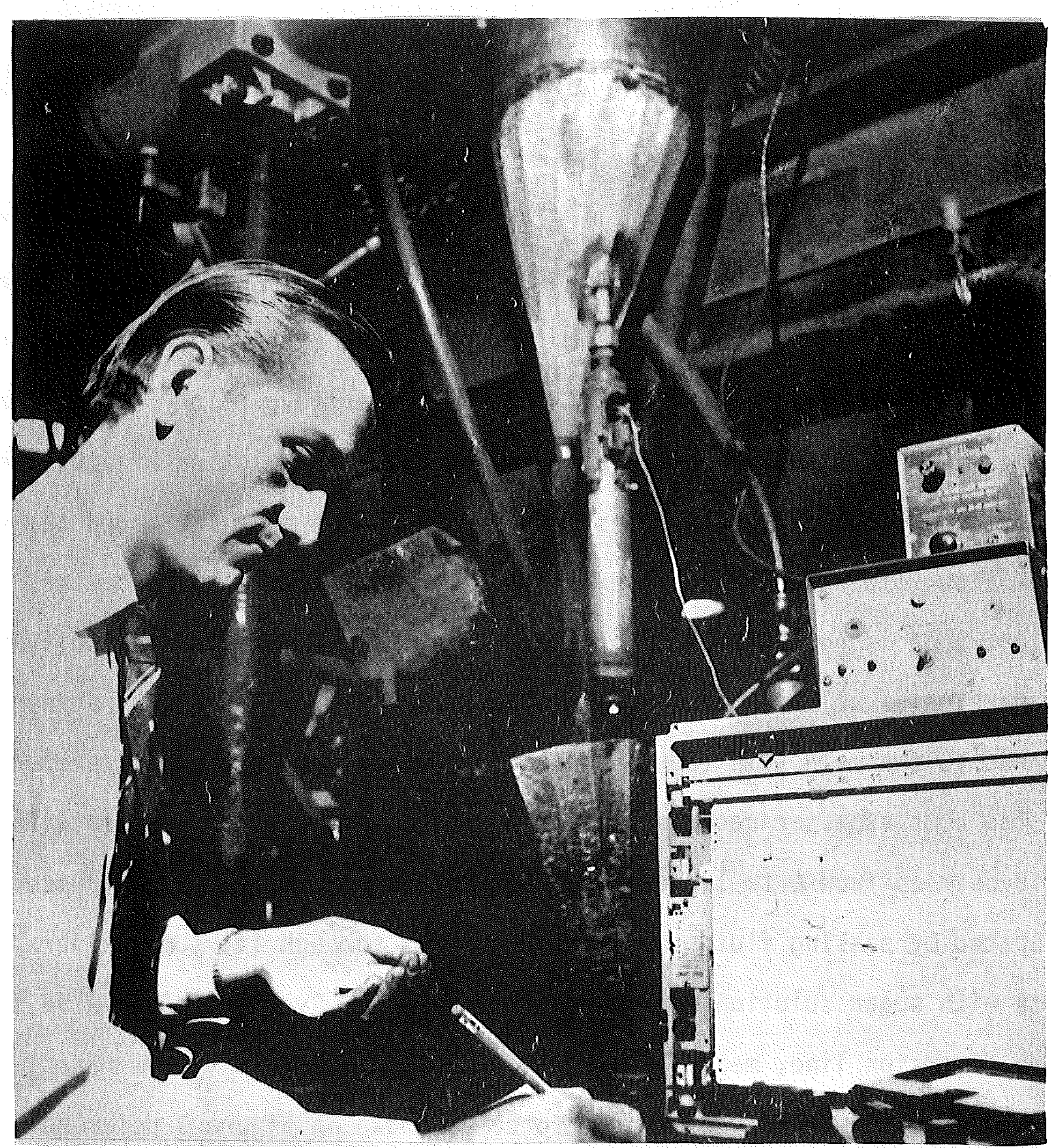


Figure 8. Consistometer and density gauge connected to pilot plant medium circulation system.

flow unhindered around it. The housing chamber is filled with special transformer oil free of contaminants which prevents medium from entering through the small hole (0.030 in. diam.) at the bottom of the chamber and causing corrosion of the transducer. The medium enters the top of the consistometer and flows around the chamber and through the concentric cylinders to exert a constant load on the transducer. Any change in the drag force on the cylinders is transmitted as a change in the electrical output to the recorder.

The feeding apparatus shown in Figure 7 was devised to supply the consistometer with screened, homogenous medium under constant head. A portion of the circulating medium is diverted by a supply pipe properly positioned in the circulation system as shown in Figure 5. The diverted portion is fed to a 10 mesh inclined cylindrical screen 6 inches in diameter rotating at approximately 20 rpm. The screened medium drops into a funnel with a stirrer, and the stirred medium flows downward through a one-half inch pipe to the consistometer. Constant head is provided by maintaining an overflow condition in the funnel. The overflow is collected along with the coarse particles from the screen and returned to the main sump together with the medium from the consistometer.

The consistometer records apparent viscosity at a given flow rate; a range of viscosities from 0 to 120 centipoises can be measured. The instrument is calibrated by passing fluids of known viscosity through it; some calibration points with sugar solutions are shown in Figure 9. By means of a valve in the medium diversion line, measurements can be made at different flow rates, and the graphs of flow rate versus drag force as shown in Figure 9 describe the plastic viscosity and yield stress of a given medium. Thus the consistometer may be used as a viscosity measuring device as well as for plant control.

The instrument has distinct advantages for process control in that any change in consistency of the medium is instantly recorded; also it provides a continuous chart record which would serve process inspection. After 2 months of continual testing of the consistometer, no difficulty was experienced because of settling of the media particles, and no wear of the concentric cylinders was apparent, thus indicating a negligible abrasive effect of the medium.

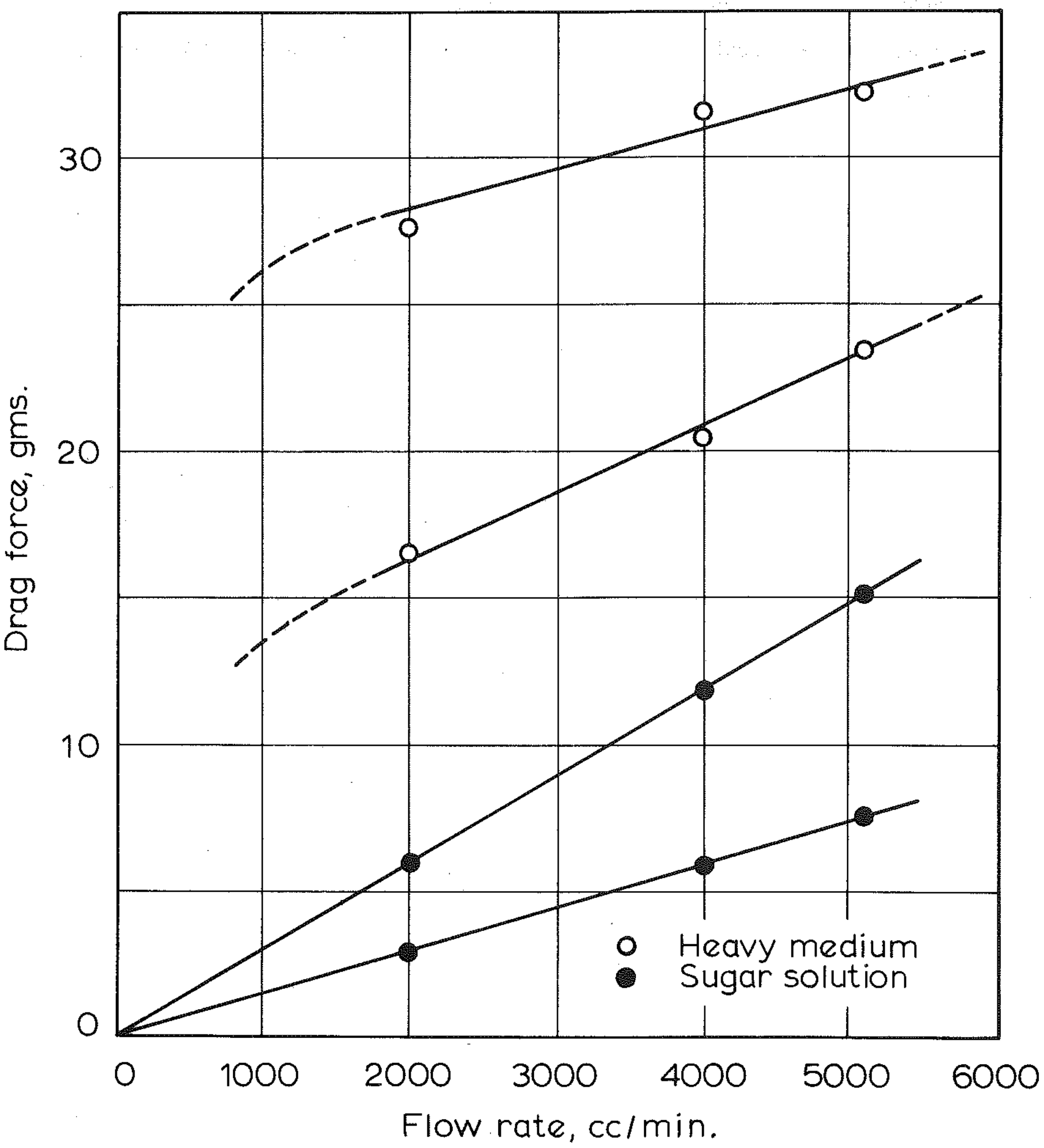


Figure 9. Consistometer measurements at different flow rates for sugar solutions and ferrosilicon - magnetite mediums contaminated with clay.

PILOT PLANT TESTS, PHASE III

The final pilot plant tests were made with both the specific gravity and consistency of the medium continuously measured and automatically recorded. The tests were made in the same pilot plant circuit previously used except that the automatic consistometer was connected to the medium return pipe as shown in Figure 8 and the cleaning circuit was bypassed by collecting the wash screen underflow in a separate sump.

The objective was to demonstrate that the automatic density gauge and consistometer would provide adequate control of the medium specific gravity and consistency under various operating conditions so as to realize a desired quality of product along with optimum yield. Six tests were performed to define the conditions for best separation and to optimize product yield and quality; each test was repeated once. The feed rate was constant and the medium circulation rate was held as constant as possible. The medium specific gravity at the top of the bath was held constant by adjustment of the media, while the consistency and stability were varied by additions of clay. The specific gravity of the circulating medium and that of the sink screen underflow were measured variables.

Feed Sample and Media

The nine samples collected at Michigan HMS plants during the second survey were picked to segregate the sound and deleterious gravels, and the specific gravity composition of each type fraction was determined by heavy liquid separations as previously described. These specific gravity compositions were necessary for plant performance evaluations. The gravels were washed with acetone after each heavy liquid separation instead of with carbon tetrachloride as in the previous practice. The acetone is nontoxic and also inexpensive, and although consumption was about a gallon for 40 pounds of gravel, nearly all of the tetrabromoethane, which is the expensive heavy liquid component, was recovered by this washing technique.

The feed sample was made up by combining all of the sound gravels exceeding 2.53 in specific gravity into one fraction and all of the deleterious gravels less than 2.53 in specific gravity into another fraction. Other gravels from previous tests were divided by specific gravity in the same way, and all gravels were blended into a feed sample of approximately 1,000 pounds containing 70% sound gravels and 30% deleterious gravels. The deleterious gravels were then marked by spraying them with a small amount of durable paint so that they could be easily picked.

The media was made up of two thirds ground ferrosilicon and one third ground magnetite; the size distribution was similar to that of the media mixture used in the earlier pilot plant tests. The same clay was added to the medium to vary the consistency and stability.

Operation of Pilot Plant and Sampling

Initially the medium circulation system was brought to a steady flow rate as shown by the Venturi meter, and the specific gravity and consistency were brought to the desired levels as shown by the density gauge and consistometer. Measurements of specific gravity were made on samples taken from the sink and float screen underflows and from the circulation sump. Then the gravels were introduced by vibrating feeder at a rate of two tons per hour. After input-output equilibrium was attained, which took only a minute, samples of the sink and the float products were taken simultaneously for 15 seconds in each minute of operation. It took about 20 minutes to run the feed sample through and recover over 95 percent of the gravels.

After each test, the sink and float composite samples were weighed and picked to determine the amounts of sound (unmarked) and deleterious (marked) gravels in each product and arrive at a weight balance. Then the gravels were combined to reconstitute the feed sample for the next test.

The amount of clay for each test condition was computed on the basis of relationships established earlier. A composite of medium samples taken during replicated tests was put through a Davis magnetic tube to separate the clay from the ferrosilicon and magnetite and thus determine the average weight percent of clay in the media solids. Clay additions were made in successive tests until the consistency and stability became so high that separations were severely impaired.

RESULTS AND DISCUSSION

Analysis of Plant Performance

Yield and quality of product are of primary interest to the HMS gravel plant operator because these factors translate directly into the economics of operation. The operator strives to produce as much acceptable aggregate as possible from his pit run gravels, and for plant control he depends largely upon experience in meeting specifications and on the results of inspection sampling which warn him when the percentage deleterious in his product is near specification limits. The operator periodically measures the specific gravity of the medium, observes the character of the bath, and estimates the deleterious content of the sink product. However, the plant feed and products are not routinely weighed and analyzed as is normally done in mineral beneficiation operations.

Criteria for the evaluation of heavy media plant performance have been discussed in many publications dealing with the cleaning of coal. The First International Coal Preparation Congress (1950) was primarily concerned with the evaluation of coal washery performance, including heavy media coal washing. (10) However, applications of the heavy media process in the beneficiation of gravel aggregate have not been extensively described, and although gravel plant performance may be evaluated by the same criteria applied to coal washery performance, comparisons based on such evaluations must take into consideration fundamental differences in the two feed materials. Whereas coal generally is not completely liberated from ash constituents, gravel particles are classified as either sound or deleterious. However, the specific gravity distributions of the two gravel types may overlap, and thus complete separation of sound from deleterious gravels may not be realized on the basis of specific gravity even though a sharp separation is achieved. It must be pointed out that gravel soundness is determined by visual inspection rather than by measurement of specific gravity, and although soundness is well correlated with specific gravity, the degree of the correlation will vary in gravels from different sources.

From the performance standpoint, an ideal HMS process for the beneficiation of gravels would be one in which all of the sound gravels would be recovered in the sink product and all of the deleterious gravels would be collected in the float product. However, this kind of separation is not realized even when all of the sound gravels in the feed are of higher specific gravity than the deleterious gravels. While sound gravels of high specific gravity and deleterious gravels of low specific gravity generally report to their proper product, the proportions reporting improperly increase among those gravels of specific gravity approaching the effective specific gravity of separation (sgs), which is defined as the gravity of the gravels in the feed that are distributed equally between sink and float products. Thus, the separation becomes more difficult for feeds in which considerable amounts of the natural gravels have densities near the sgs.

The sharpness of separation is defined by the amounts of the misplaced gravels, that is, the gravels of higher specific gravity than the sgs that report to the float product and those of lower specific gravity that report to the sink product. Misplacement of gravel particles can be attributed to a number of factors, most of which are related to the way the separatory system is operated. Important factors obviously are the specific gravity of the medium and the gravity differential of the bath. Other important factors are the amount of contaminants in the medium and the size structure of the media. Regulation of the feed rate so as not to overload the separation zone and thus cause interference in stratification is important. Flat or elongated heavy particles tend to become misplaced into the float product to a degree depending upon the medium circulation rate and turbulence.

Plant performances are often compared on the basis of efficiency, which has been defined in a number of ways with the common objective of comparing performance in a manner that does not depend directly upon the specific gravity composition of the feed. However, not all of these definitions conform to the usual engineering concept of efficiency, that is, the ratio of output to input. The formula advanced by Fraser and Yancey (11) has achieved the widest acceptance as an expression of coal washery performance:

$$\text{Efficiency, \%} = \frac{\text{yield washed coal x 100}}{\text{yield float coal of same ash content}}$$

It is apparent that this expression of efficiency requires a knowledge of the specific gravity compositions of the feed and of the sink and float products.

The analysis of plant performance presented here is based upon the heavy liquid separation data of Tables A1-A5 (Appendix) for five of the samples taken at a Michigan HMS plant. When the samples were taken, measurements were made of the specific gravity of the circulating medium, and that of the sink and float screen underflows, and two medium samples were brought back for determinations of composition, size structure, consistency, and stability. The small number of samples and relatively short sampling period limit the scope of the analysis in characterizing plant performance over an extended time, and the evaluation of the one plant cannot be taken as typical of all Michigan HMS plants.

The criteria for performance are the sharpness of separation, the yield of gravels in the sink product, the quality of the sink product as defined by the percentages of total deleterious and soft nondurable gravels, and the efficiency. The standards for quality are set by the Michigan Department of State Highways specifications (May 1, 1965), which limit the percentages by weight of total deleterious and of soft particles in 6A class coarse aggregate to 9 and 2.5 percent, respectively, and 6AA class aggregate to 4 and 2 percent, respectively.

The specific gravity data for the five samples and distributions of gravels to sink products are shown in Table 4, and the plant performance data are listed in Table 5 along with the measurements made to characterize the two medium samples. The cumulative weight percent distributions by specific gravity of the gravels in each of the five samples are shown in Figures 10-14, respectively; the distribution curves are additive for each type of gravel so that the total deleterious is the sum of the three deleterious types and the total feed is the sum of the total deleterious and sound gravels. Figures 10-14 also show the partition curves of recovery of the gravels in each specific gravity fraction in the sink product (data from Table 4).

The effective specific gravity of separation is defined by the midpoint of the distribution curve, and the sharpness of separation is defined by the probable error or by the error area. The probable error is taken from the partition curve as half of the specific gravity interval between the 25 and 75 weight percentiles. The error area is that lying between the partition curve and the line of perfect separation (vertical line through sgs).

The efficiency is computed by:

$$\text{Efficiency, \%} = \frac{\text{output}}{\text{input}} \times 100 = \frac{\text{yield of sink gravel} \times 100}{\text{theoretical yield of sink gravels exceeding sgs}}$$

The input, or amount of feed gravels of specific gravity greater than the sgs, is taken from the cumulative specific gravity distribution of the composite feed. The percentage of the feed within the limits of probable error also is taken from the specific gravity distribution; this is a measure of the amount of feed gravels of specific gravity near the sgs, which are the gravels having the greatest effect on the sharpness of separation.

During the period in which the samples were taken, the plant was producing aggregate for uses other than in concrete for highway construction. It is apparent from the performance data that the plant was not in control at the time that sample no. 2 was taken and that it was approaching an out of control condition at the time sample no. 1 was taken. Records made at the time help

Table 4 - Specific Gravity Analyses of HMS Plant Composite Feeds and Distributions by Percent of Specific Gravity Fractions to Sink Products

	Sample No.									
	1		2		3		4		5	
Spec. Grav.	Comp. Feed, Wt. %	Distr. to Sink,%	Comp. Feed, Wt. %	Distr. to Sink,%	Comp. Feed, Wt. %	Distr. to Sink,%	Comp. Feed, Wt. %	Distr. to Sink,%	Comp. Feed, Wt. %	Distr. to Sink,%
2.96	4.45	94.5	2.76	88.5	3.88	99.2	3.46	98.7	2.18	99.6
2.96-2.85	2.39		1.83		2.78		2.68		1.66	
2.84-2.75	14.05	91.7	14.87	82.7	16.33		17.00		14.21	98.7
2.74-2.65	26.23		23.07		24.64	98.6	23.69	97.9	23.77	98.0
2.64-2.55	28.10		34.54		28.91		27.27	97.7	26.47	90.4
2.54-2.45	5.91		6.99	79.5	4.45	89.4	5.90	90.8	13.98	13.5
2.44-2.35	3.54	84.5	4.96	76.2	5.77	10.9	3.80	30.5	9.45	0.
2.34-2.25	6.48	13.9	4.07	59.7	6.72	3.4	7.65	0.9	4.96	0.
2.24-2.15	5.39	0.2	1.93	7.8	3.91	0.8	3.96	0.	2.59	0.
2.15	3.46	0.	4.98	0.	2.61	0.	4.59	0.	0.73	0.

Table 5

HMS Plant Performance Data and Medium Characteristics

	Plant Sample No.				
	1	2	3	4	5
Spec. Grav. of Sepn.	2.350	2.275	2.455	2.430	2.550
Spec. Grav. of Medium	2.42	2.43	2.57	2.45	2.59
Spec. Grav. Dif.	0.10	0.17	0.06	0.10	0.08
Prob. Error	0.032	0.079	0.029	0.038	0.028
Error Area	40.62	82.05	23.00	26.63	19.97
% Feed within PE	3.16	5.73	2.96	3.75	11.33
Efficiency, %	92.7	84.4	99.6	98.7	97.1
Product Yield, %	78.5	76.0	80.45	79.3	67.0
Delet. in Sink, %	9.0	12.5	4.3	7.0	3.9
SND in Sink, %	1.9	3.0	1.0	1.3	0.8

Characteristics of Two Medium Samples

	1	2
Spec. Grav.	2.61*	2.54**
Consistency, cP	5.49	13.5
Stability, %	71.4	77.8
Solids, %	74.5	72.4
Magnetics, wt. %	95.26	96.53
Nonmagnetics, wt. %	4.74	3.47
Size Analysis of Magnetics, Wt. % in Mesh Size		
+48	0.02	0.16
48/65	0.02	4.87
65/100	0.10	4.51
100/150	0.81	3.94
150/200	4.52	6.98
200/270	12.60	7.70
270/325	8.73	11.65
-325	73.20	60.90
Size Analysis of Nonmagnetics, Wt. % in Mesh Size		
+28	46.76	19.02
28/35	2.93	5.45
35/48	4.02	6.03
48/65	5.73	8.88
65/100	6.12	9.70
100/150	4.53	8.07
150/200	3.68	5.37
200/270	3.12	2.77
270/325	1.38	2.07
-325	21.73	32.64

* Measured by pulp density balance
** Estimated

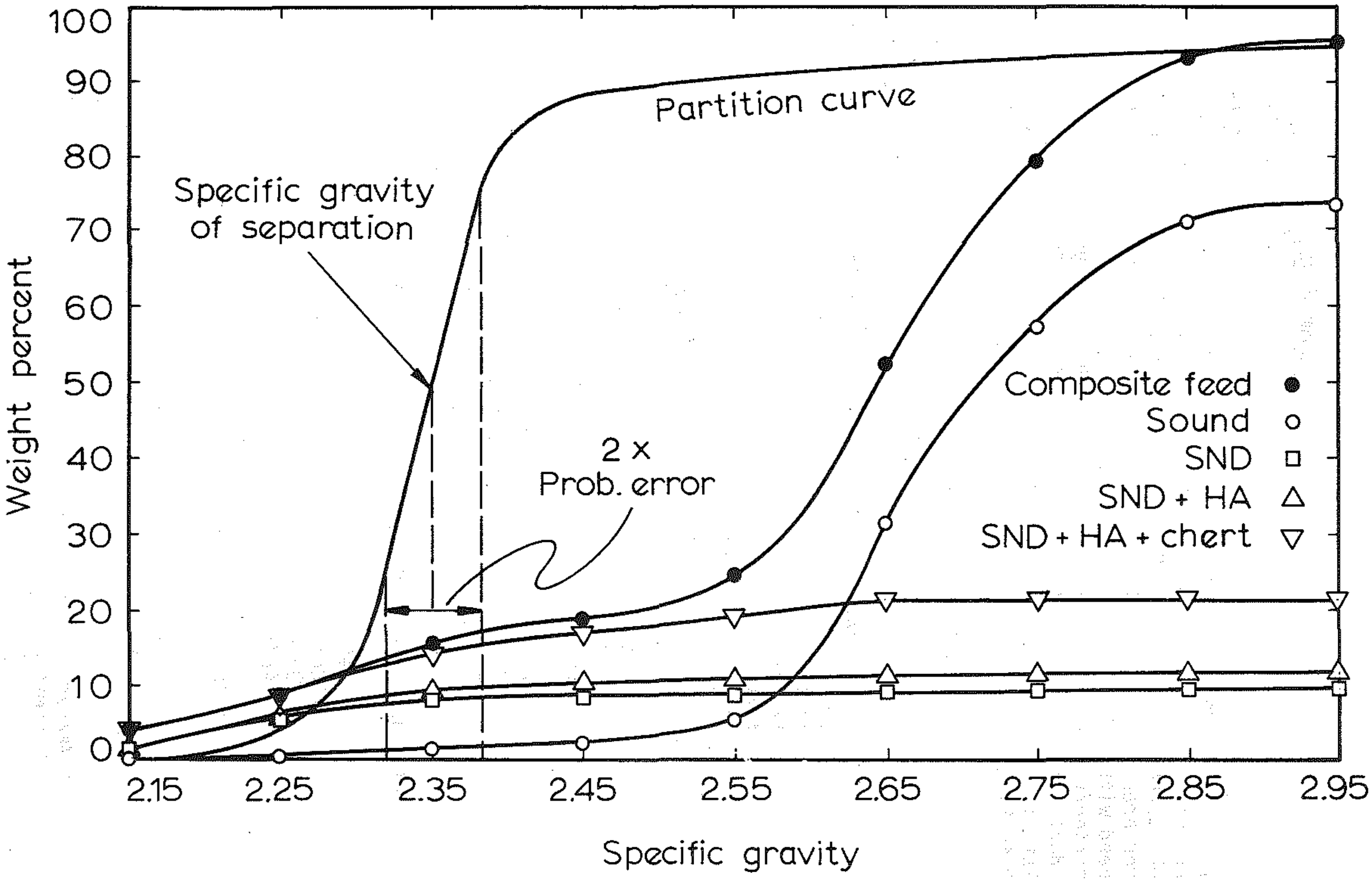


Figure 10. Cumulative weight percent distributions by specific gravity of aggregate types in HMS plant composite feed sample no. 1, and partition curve of percent recovery of specific gravity fractions in sink product.

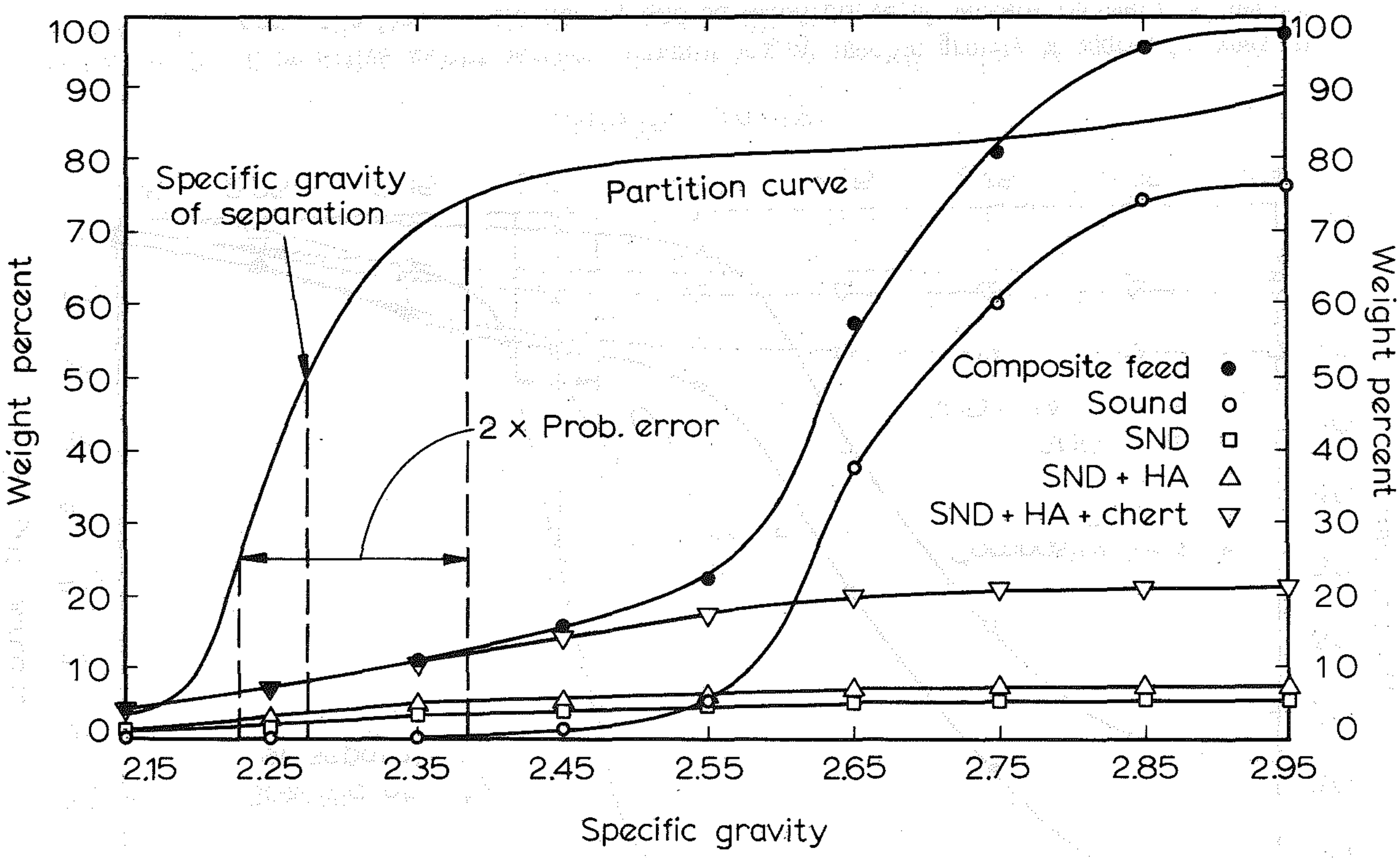


Figure 11. Cumulative weight percent distributions by specific gravity of aggregate types in HMS plant composite feed sample no. 2, and partition curve of percent recovery of specific gravity fractions in sink product.

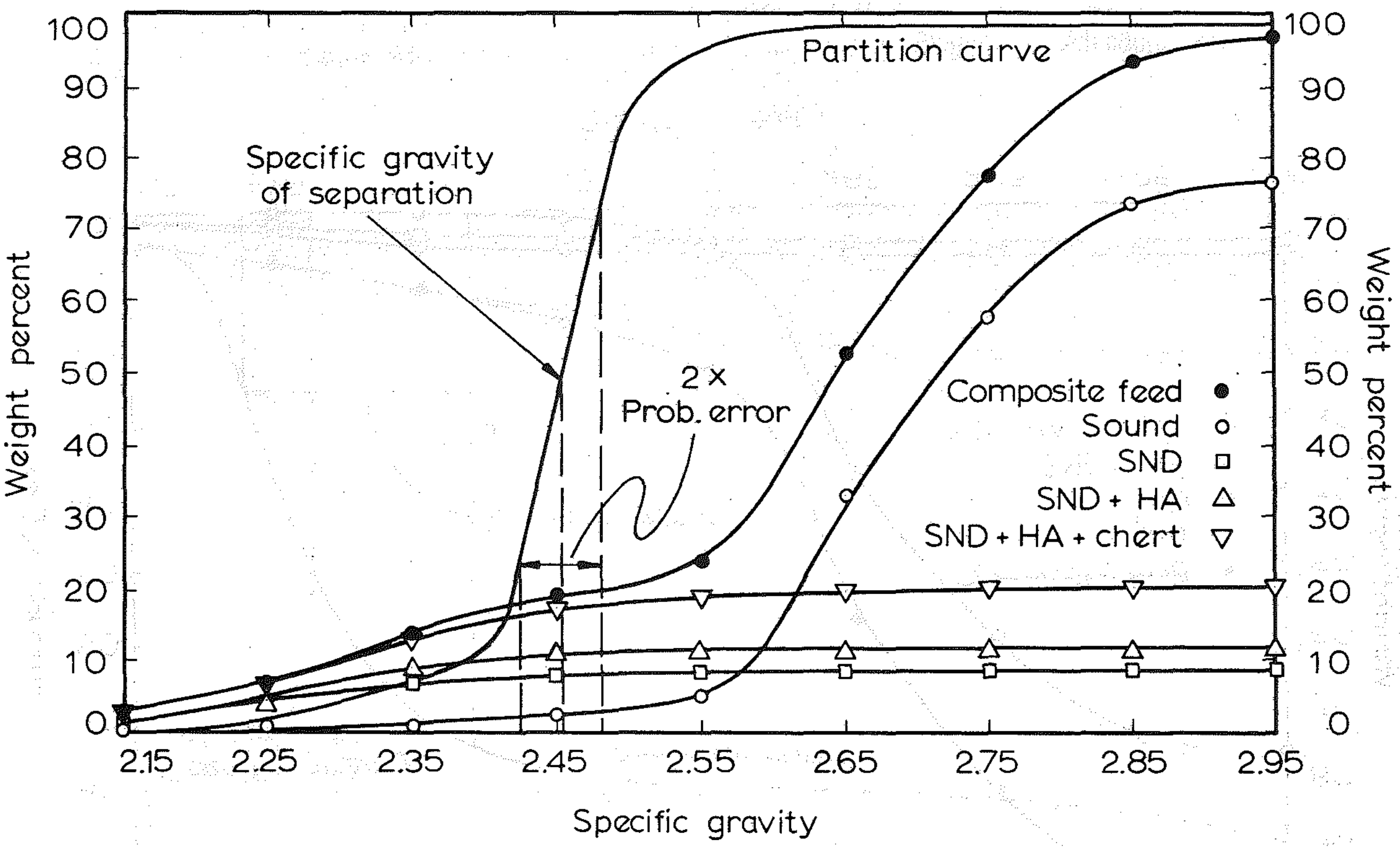


Figure 12. Cumulative weight percent distributions by specific gravity of aggregate types in HMS plant composite feed sample no. 3, and partition curve of percent recovery of specific gravity fractions in sink product.

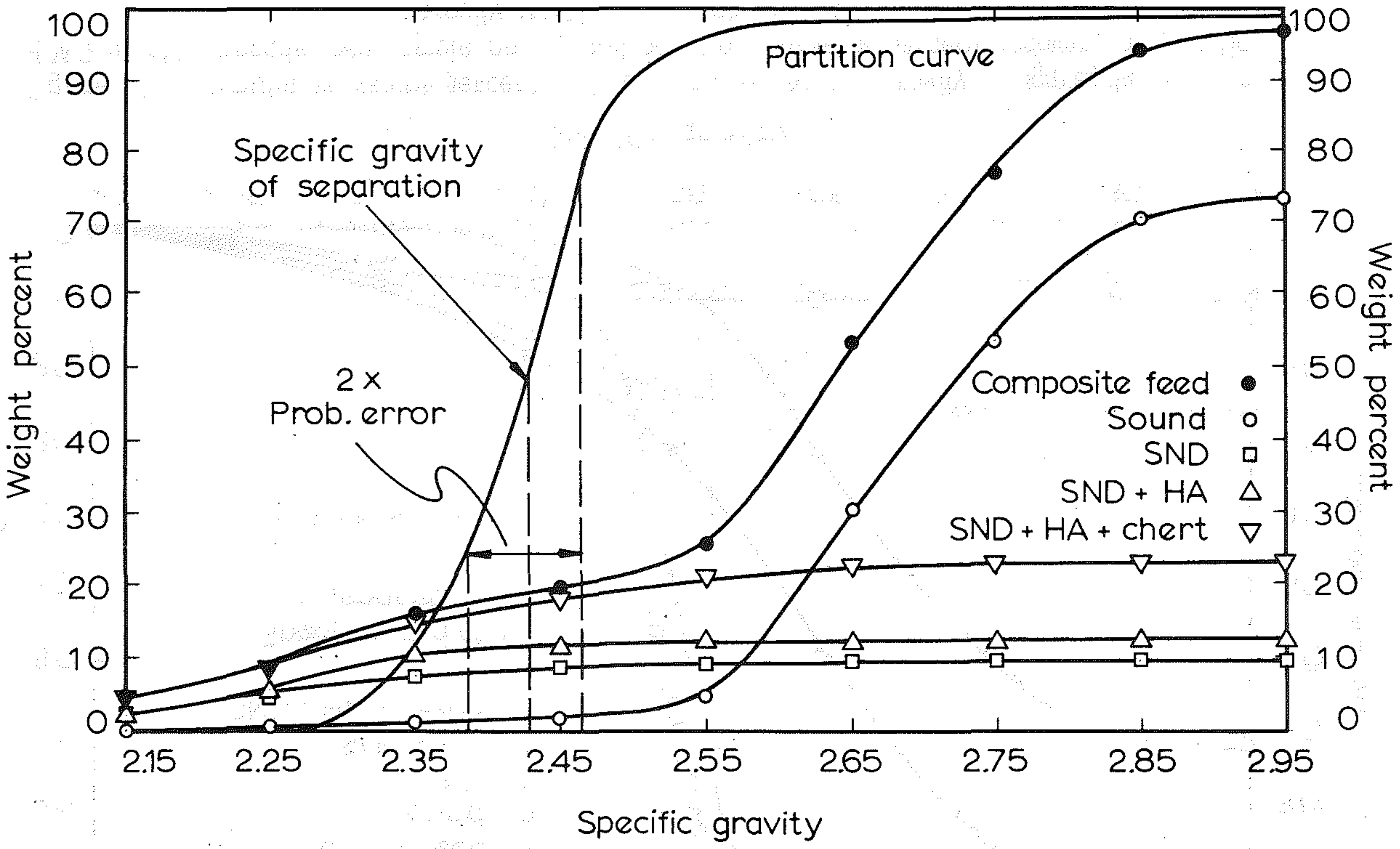


Figure 13. Cumulative weight percent distributions by specific gravity of aggregate types in HMS plant composite feed sample no. 4, and partition curve of percent recovery of specific gravity fractions in sink product.

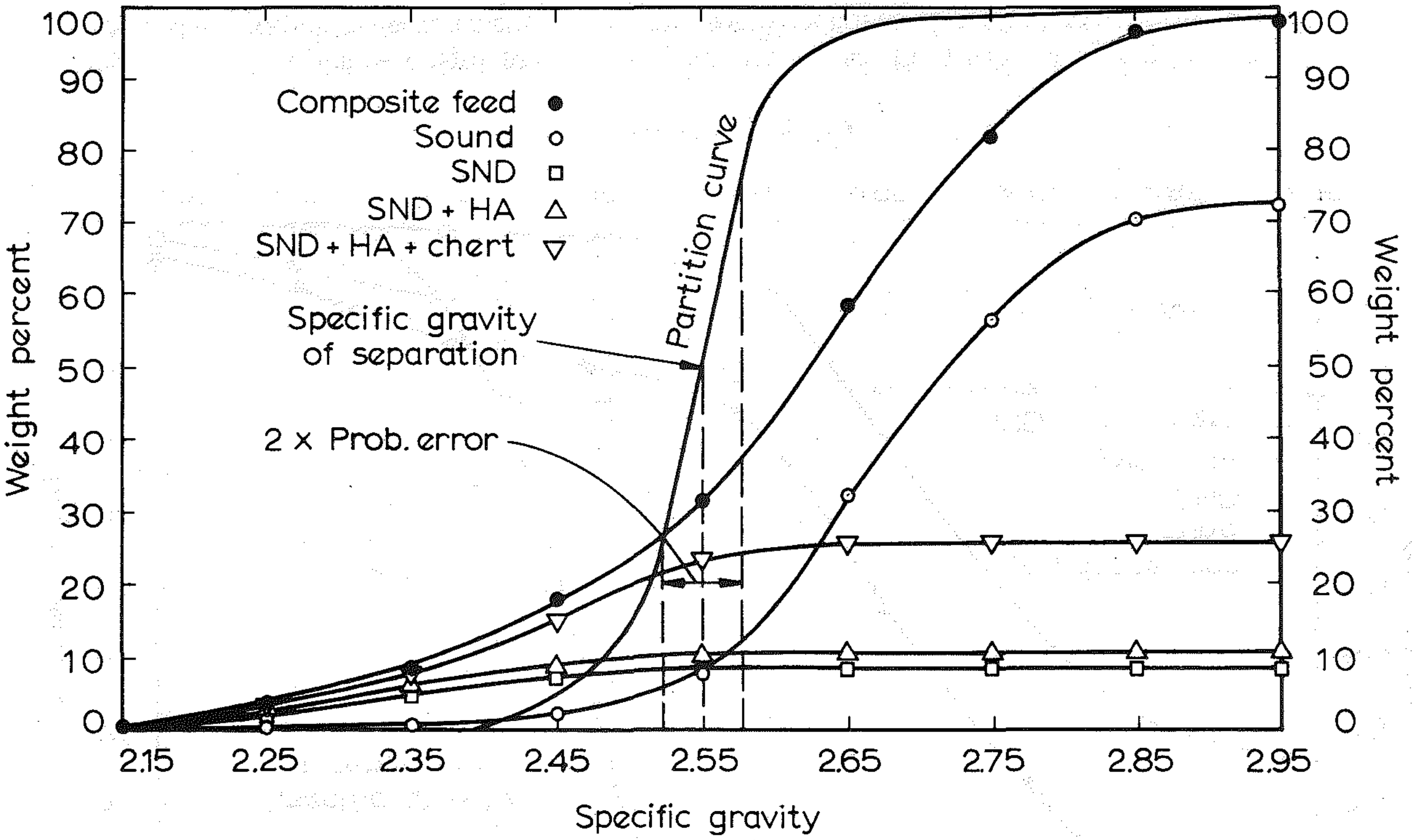


Figure 14. Cumulative weight percent distributions by specific gravity of aggregate types in HMS plant composite feed sample no. 5, and partition curve of percent recovery of specific gravity fractions in sink product.

to explain the poor results. The specific gravity of the medium was found to be abnormally low when the measurement was made at the time sample no. 1 was taken. The operator corrected this condition by lowering the densifier screw so as to add media to the circulation system. Furthermore, the feed rate was variable at the time because of periodic stoppages in the dredge line. When sample no. 2 was taken, too much wash water was being retained in the circuit with the result that the specific gravity at the top of the bath was too low, as evidenced by the large gravity differential. Thus the lighter, deleterious gravels rode at a lower level in the cone than desirable, causing congestion and poor stratification in the zone of separation which resulted in a low sgs and much deleterious gravel in the sink product.

The partition curve in Figure 11 is notably skewed towards the high specific gravity side showing that much gravel of higher gravity than the sgs reported improperly in the float product. Misplacement of the heavier gravels apparently occurred mostly in the minus one half inch sizes; this will be discussed further under Gravel Feed Effects. As noted above, when sample no. 2 was taken the separation zone was congested, and with this condition increased misplacement of heavy small particles into the float product would be expected.

Taking Michigan Department of State Highways specifications as a basis for aggregate quality, the plant was producing acceptable 6A class aggregate when samples 3 and 4 were taken, and it was producing acceptable 6AA class aggregate when sample no. 5 was taken. The performance data for samples 3 and 4 indicate that the best medium specific gravity for producing 6A class aggregate from feed gravels of the character being processed at the time would be 2.52-2.54. With the media structure and contaminant condition that existed at the time, this level of medium specific gravity would provide an sgs of 2.46-2.50 and a gravity differential of about 0.08.

The medium conditions when sample no. 5 was taken exemplify those for production of a high quality product; however, a lower yield of gravel was realized, as would be expected, with a medium of 2.59 specific gravity. It is noteworthy that a sharp separation was achieved even though 11.33 percent of the feed was within the limits of the probable error. It is of interest to compare the sharpness of separation, probable error 0.028 and error area 19.97, with that achieved in HMS coal washeries, where a probable error of 0.02 and an error area of 11 would be characteristic of the best operating practices. (12)

High efficiencies were being realized when samples 3, 4, and 5 were being taken; in particular, the plant conditions when samples 3 and 5 were taken would appear to exemplify good operating practices for producing 6A or 6AA class aggregate from natural gravels of the specific gravity composition processed at this plant.

It was noted that the plant operator took medium samples for measurement of specific gravity by dipping the one liter pulp density balance container to a depth of about 3 inches below the surface of the bath. The samples carried some float gravels which were not removed before the container was weighed. Measurements made in this manner showed a significant amount of variation.

The two medium samples were taken in the week preceding the first sampling period, and thus it is uncertain to what extent the medium characteristics can be related to the evaluation based on the samples. It is apparent that the size structure of media in the second medium was coarser than that in the first; possibly an addition of coarse media was made just before the second sample was taken. The nonmagnetic particles had about the same size structure in intermediate sizes but differed considerably in the plus 28 and minus 325 mesh sizes. Microscopic study showed that the coarsest fraction was made up of rock fragments of the same mineralogical character as the gravels; these fragments probably came from attrition of the gravels. The minus 325 mesh fraction was made up of rock flour and clay; the clay probably was introduced with the feed and the rock flour probably was the product of further attrition of the intermediate rock sizes. It might be expected that the medium with the finer media and higher percent solids would have the higher consistency and stability, but the coarse size structure and higher percentages of nonmagnetics apparently exerted some offsetting effects. It must be pointed out that the mediums were dehydrated for shipment and then repulped for the consistency and stability measurements, and this may have changed their rheological properties to some extent. There is a lack of information about the effects of size structure and specific gravity composition of the nonmagnetic particles upon the rheological properties of dense mediums.

Gravel Feed Effects

The usefulness of the HMS process depends primarily upon the specific gravity differences of the sound and deleterious gravels. The size, shape, and surface roughness of gravels also affect the separation in some degree. The widespread use of the HMS process for the production of gravel aggregate is evidence that most of the deleterious gravels are of lower specific gravity than the sound ones, but there is a lack of information about the specific gravity distributions of the natural gravels by types. This study furnishes a limited amount of information based upon the results of heavy liquid separations made on plant samples.

The five large samples collected in the first survey furnish accurate information about the feed to one plant. Figures 10-14 show that the deleterious gravels made up 20-26 percent of the feed at the time the samples were taken, and that 3-11 percent of the feed in the deleterious classification exceeded 2.45 in specific gravity while 5-8 percent of the feed in the sound classification was less than 2.55 in specific gravity. Separations are normally made in the specific gravity range from 2.45 to 2.55. The specific gravity compositions of the sound, total deleterious and soft nondurable gravels in the range 2.35 to 2.65 are shown in Figure 15 for sample no. 3, for which the sgs was 2.455, and in Figure 16 for sample no. 5, for which the sgs was 2.55. The predicted and actual separation results are listed in Table 6. For sample no. 3, the actual results were near the predicted ones, and the separation gravities for the sound, total deleterious, and soft nondurable gravels were in the narrow range of 2.45-2.475 bracketing the sgs of 2.455 for all gravels. For sample no. 5, the actual results were much the same as predicted except for the greater loss of sound gravel. The separation gravities for the individual types were in the narrow range of 2.53 to 2.55.

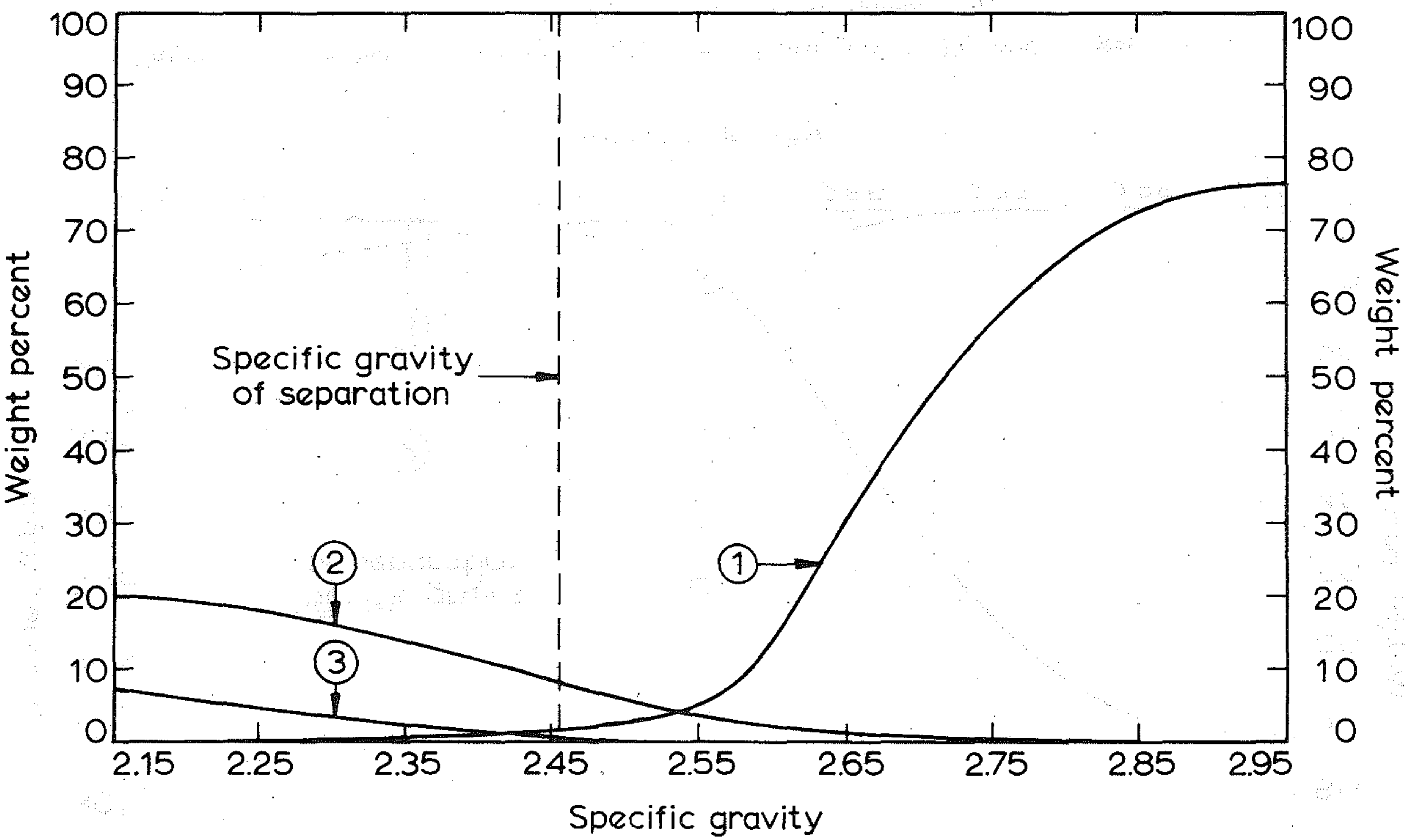


Figure 15. The specific gravity compositions of the sound (1), total deleterious (2) and soft nondurable gravels (3) for sample no. 3.

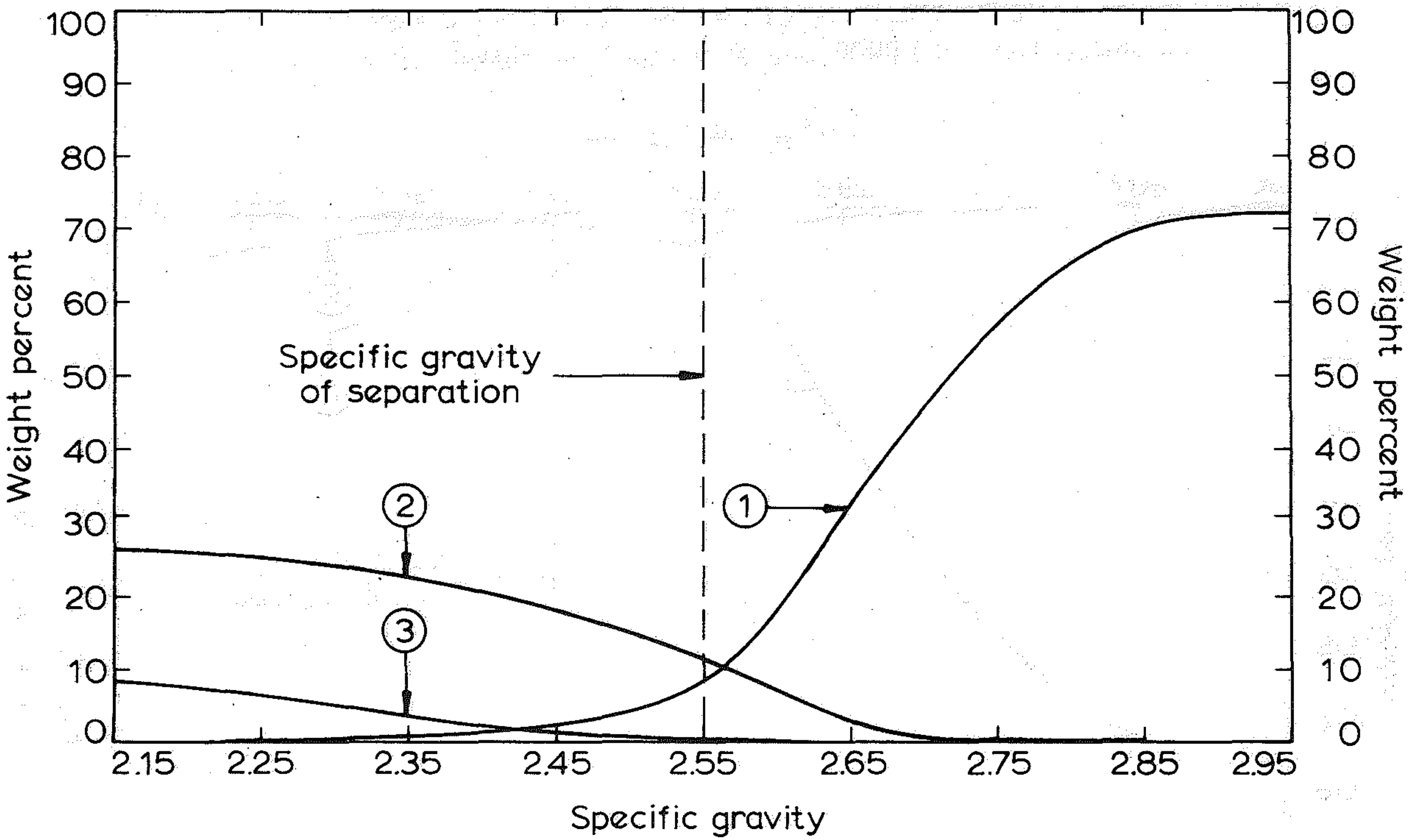


Figure 16. The specific gravity compositions of the sound (1), total deleterious (2) and soft nondurable gravels (3) for sample no. 5.

Table 6

Separation Results for Samples 3 and 5

	Sample No. 3		Sample No. 5	
	Predicted(1)	Actual	Predicted(1)	Actual
Product Yield, %	81	80.45	68.5	67.0
Deleterious in sink, %(2)	3.7	4.3	3.3	3.9
SND in sink, %(2)	0.9	1.0	0.7	0.8
Sound gravel not recovered, %(3)	2.2	3.8	7.5	15.1
Efficiency, %	97.8		91.0	

(1) taken from graphs

(2) % of sink product

(3) % of sound gravel in feed

The partition curves are not as well defined as would be desirable. However, they indicate that the gravities of separation are similar for the gravel types, that sharp separation of the soft nondurable gravels is difficult, that misplacement of sound gravels occurs to a greater extent among those of lower specific gravity than the sgs, and that as the sgs increases, misplacement of the constituents making up the higher proportions of the feed will increase.

The graphs of specific gravity composition suggest a method for estimating the best sgs for obtaining a product of given quality with maximum yield and of computing a meaningful efficiency. This would be based on specific gravity determinations at 2.45 and 2.55 of the sound, total deleterious, and soft nondurable gravels in the feed; only two such determinations should be necessary for most Michigan natural gravels. Efficiency of separation expressed as an index would be defined as the ratio of actual to predicted separation results, thus

$$\text{Efficiency} = \frac{100 - (a_1 + b_1)}{100 - (a_2 + b_2)}$$

where a = % sound gravels not recovered

b = % total deleterious gravels in sink product x % product yield

subscript 1 designates actual results

subscript 2 designates predicted results

This definition of efficiency is similar to that presented by Valentik (13). The efficiency index is one for a perfect separation, and in general it will be less than one. There could be cases in which the index would exceed one, such as when the shape effect of heavy deleterious particles would cause them to go into the float instead of the sink product.

The distribution curves also indicate what can be gained theoretically by operating at a higher or a lower sgs. It is evident that a higher sgs than 2.55 would result in increasing losses of sound gravels in the float product, and that a higher sgs than 2.50 would bring increasing amounts of the gravels near the sgs, which makes the separation more difficult. This emphasizes the need for a very sharp separation when operating at higher gravities where more of the gravels are of specific gravity near the sgs, and as a consequence they stratify more slowly and are more likely to become misplaced. The relationship of specific gravity composition of the gravels to sgs and the sharpness of separation are well illustrated in Figure 16. To maintain a high separation efficiency at the sgs of 2.55, it was necessary to limit the range of specific gravity in which the separation was difficult to ±0.028 thereby limiting the amount of gravels falling within this range to 11.33 percent of the feed (Table 5, sample no. 5).

Since a sharp separation requires sufficient time for good stratification, lower feed rates would be required when higher proportions of the gravels are near the sgs, such as would be the case at high separation gravities. Although the settling rates of particles in Newtonian fluids have been extensively documented, there is relatively little literature on settling rates of individual particles in non-Newtonian fluids, and there is a lack of information about the settling rates of particles in dense mediums under conditions of interference. Quantitative information was not found about the effect of feed rate on the efficiency of separation by the HMS process. Valentik and Whitmore (14) noted in a study of the performance of magnetite, shale, and clay mediums that at high throughput large mats formed and entrapped particles in spite of their densities. They also observed that the sgs declined with increasing feed rate in a flocculated media. To achieve good separations, they observed that the feed rate should be such as to ensure free movement for all particles so as to eliminate "rafting", and that conditions at the feed point should be such as to permit the entering material to be spread smoothly on the surface of the medium, thus avoiding an excessive vertical fall which would immerse light particles to the point where they would be carried into the sink product.

An indication of the specific gravity compositions of gravels from various locations is afforded by the results of heavy liquid separations made on samples collected from nine different plants in the second survey; these necessarily were smaller samples than those taken earlier at one plant, but they nevertheless furnish a general evaluation of the amounts of deleterious gravels, the specific gravity characteristics of gravels, and plant performance. The essential data are presented in Table 7, and the average weight percent distributions by specific gravity of the sound and deleterious gravels with ranges in each specific gravity class are shown in Figure 17. It is apparent that the average gravel feed does not have as favorable a specific gravity composition as that represented by Figure 15. While these average distributions do not apply to the situations at individual plants, they do emphasize the need for close control of the sgs based upon the specific gravity composition of the feed. It would appear from Table 7 that plants are operated at high separation gravities to ensure product quality in spite of large losses of sound gravels which might have been recovered by improved sharpness of separation.

Although it is known that feed particle size has an important effect upon HMS efficiency, there is not much information to quantify this effect in the range of sizes in which most gravel aggregate is produced. Whitmore (15) showed that the probable error, a measure of sharpness of separation, is roughly proportional to the reciprocal of the square root of the diameter of feed particles. Therefore, separation efficiency would be expected to increase with particle size. Both the mean size and the size range are important in separation. If the size range is wide, large pieces of feed drag along small pieces to decrease efficiency in the separation of small sizes. Thus, a large particle in movement will drag along a small particle near to it and thus the narrower the size range of the feed the higher the efficiency of separation for the small particles. Furthermore, as the size range of the feed increases, the specific gravity range over which separation is achieved is increased.

Table 7

Characteristics of Samples from Nine Michigan HMS Plants

Sample no.	Medium s.g.	Wt. % A	Wt. % B	Wt. % C	Wt. % D	Approx. yield wt. %
1	2.584	18.2	7.5	33.70	6.95	70
2	2.635	21.6	3.4	24.11	5.96	65
3	2.580	16.2	5.3	26.46	14.00	75
4	2.658	24.5	7.0	26.41	12.87	65
5	2.575	16.0	3.6	31.59	9.67	80
6	2.570	17.2	4.8	21.52	13.68	82.5
7	2.585	18.5	6.9	29.07	17.13	----
8	2.685	23.4	3.9	37.70	6.42	65
9	2.600	17.9	3.7	40.44	9.34	75

Explanation:

A - Deleterious gravels in feed
B - Deleterious gravels in feed exceeding s.g. 2.45
C - Sound gravels in feed less than s.g. 2.55
D - Deleterious gravels in sink product

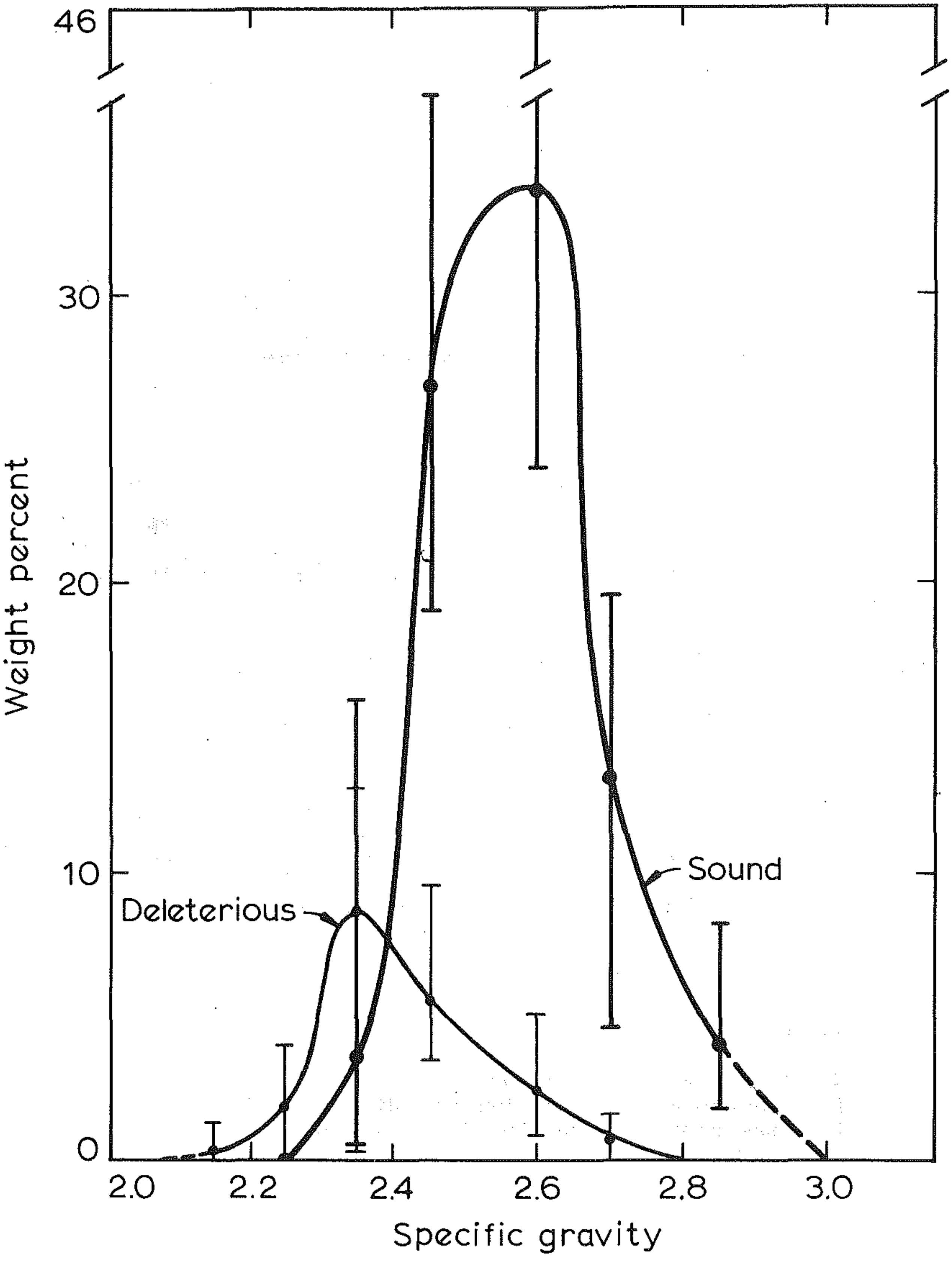


Figure 17. Average weight percent distributions by specific gravity of sound and deleterious gravels in feed samples to nine different H M S plants, with ranges in each specific gravity class.

Davies et al (16) found in a great number of coal washing tests with heavy media cyclones that there was a correlation between probable error and the particle size of the coal. Their graph of particle size versus the ratio of probable error for a given particle size to the probable error for 10 millimeters size was a nearly linear relationship. They found that this relationship was reasonably accurate in predicting the probable error of separation of different minerals in various sizes and provided an approximate prediction of probable error for a given feed size fraction. In tests under identical conditions, they found that the finer feed size fractions appeared to have a higher specific gravity of separation than the coarse sizes but only the probable error was affected above a certain size. This emphasizes the need for a very sharp separation when operating at high gravities where more of the feed gravels are of specific gravity near the sgs. Since a sharp separation requires sufficient time for good stratification of the gravels, lower feed rates would be indicated.

Medium Effects

The efficiency of the HMS process depends primarily upon the properties of the medium, mainly its specific gravity, viscosity, stability, and flow rate. The specific gravity depends upon the amount and type of media particles. As previously noted, Michigan HMS plants use mixtures of ferrosilicon (specific gravity 6.90) and magnetite (specific gravity 4.87) in which the ferrosilicon may be 50-80 percent by weight. An amount of media mixture is added to water to make up a medium of the desired specific gravity. However, the specific gravity of the medium is not necessarily the specific gravity of separation because of other factors in the dynamic process.

The medium exerts a viscous effect on the movement of the gravels, and since separation takes place by stratification, the viscosity of the medium must be considered. Viscosity depends upon the concentration of the media particles (the specific gravity of the medium), the size, shape and magnetization of the media particles and in minor degree the temperature of the medium. In practical applications, clay slimes and fine rock particles tend to build up in the separatory vessel, and the amount, size, shape and mineralogical character of these contaminant particles affect the viscosity of the medium. The presence of slimes results in a non-Newtonian character such that resistance to motion has two components, the yield stress due to the rigidity of the medium which must be overcome before movement takes place, and the plastic viscosity or resistance after movement starts. It has been shown that the separation efficiency is affected more by the plastic viscosity than the yield stress. (14)

The medium is an unstable suspension and it must have motion to keep the heavy media particles suspended; a certain amount of stability is required to have a useful medium. The stability is highly influenced by the concentration, size and shape of media particles and the concentration, size, and mineralogical character of contaminant particles. Since these same factors influence the apparent viscosity, or consistency of the medium, it is necessary to maintain the right balance to have sufficient stability for a useful medium yet not a level of consistency such that the separation is impaired.

The relationships of consistency and stability to medium specific gravity are shown in Figure 18, with clay additions to vary the consistency and stability. In the range of specific gravity investigated, it is apparent that the clean, fresh media was highly unstable and imparted low consistency. Additions of clay up to two percent did not materially increase the consistency but amounts approaching six percent raised the consistency to levels such that gravel separations would become impaired in the range of medium specific gravity within which gravel plants are normally operated (2.50 to 2.65). Depending upon the specific gravity, clay in amounts of 3.5 to 5 percent of the media solids imparted a desirable degree of stability to the medium. With the type, composition, and size structure of media in general use in HMS gravel plants, clay contaminant in the amount of about 3.5 percent by weight of the suspended solids is desirable to have a suspension of workable stability but amounts exceeding 5 percent increasingly impair separation efficiency.

The contaminants in plant media are clay and rock flour acquired from the feed gravels in amounts depending upon the thoroughness of washing prior to HMS treatment; also rock particles are produced by attrition of the gravels. The two medium samples taken from an HMS plant are characterized by the data in Table 8. The size structure of the magnetics in the second sample was coarser than that of the first, possibly because of media additions just before the sample was taken. The lower consistency and stability of this medium is a reflection of the coarser size structure of the media. The contaminant particles had similar structure in intermediate sizes but differed in the amounts of plus 28 mesh sizes; these sizes were necessarily removed before making the measurements of consistency by the DeVaney-Shelton device.

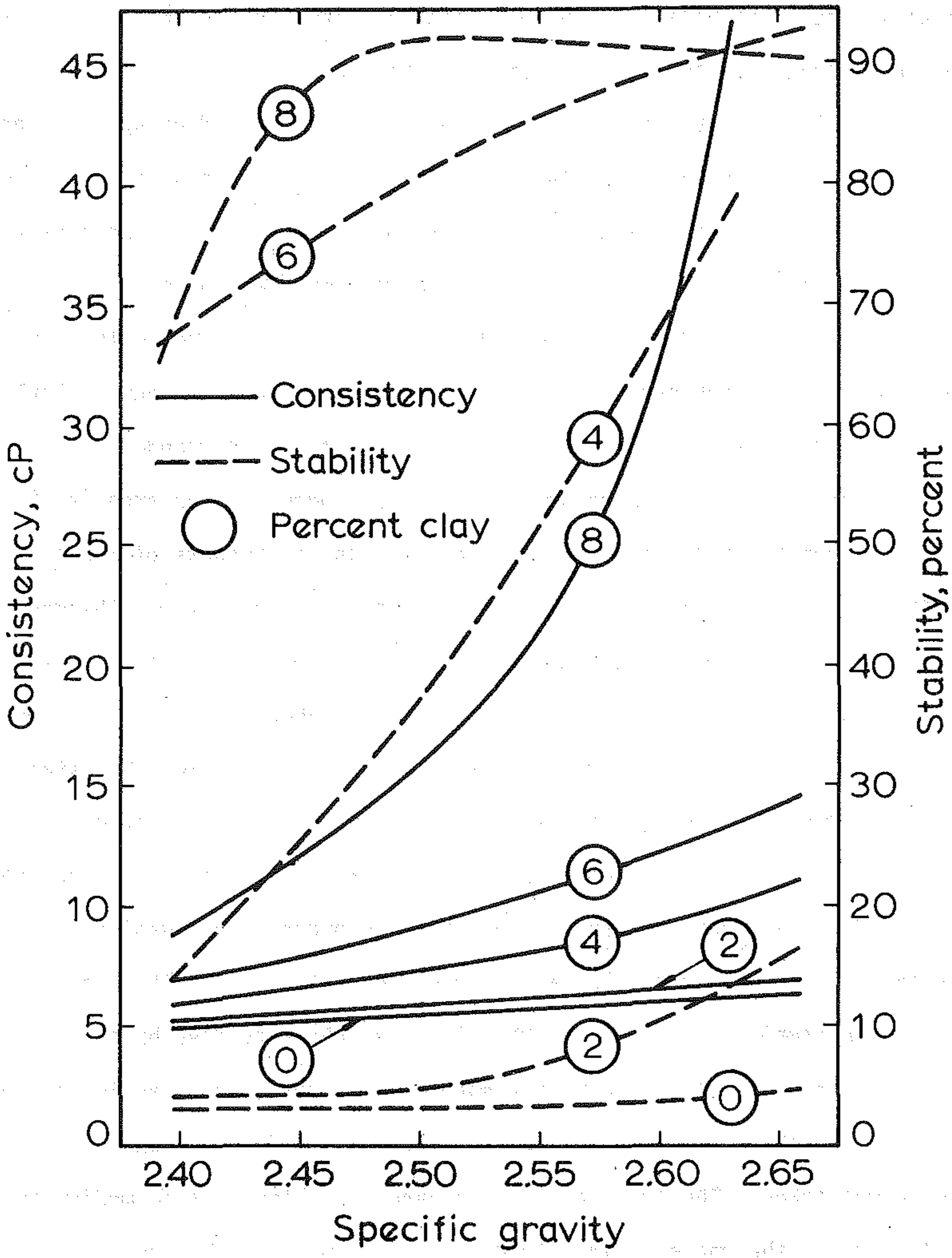


Figure 18. Consistency and stability versus specific gravity of clean and contaminated ferrosilicon - magnetite mediums.

Table 8

Characteristics of Two Medium Samples from HMS Plant

	1	2
Spec. Grav. (a)	2.51	2.50
Consistency, cP (b)	7.05	5.49
Stability, % (c)	71.4	61.7
Solids, %	72.4	74.5
Magnetics, wt. %	95.26	96.53
Nonmagnetics, wt. %	4.74	3.47
Size Analysis of Magnetics, Wt. % in Mesh Size		
+48	0.02	0.16
48/65	0.02	4.87
65/100	0.10	4.51
100/150	0.81	3.94
150/200	4.52	6.98
200/270	12.60	7.70
270/325	8.73	11.65
-325	73.20	60.90
Size Analysis of Nonmagnetics, Wt. % in Mesh Size		
+28	36.76	19.02
28/35	2.93	5.45
35/48	4.02	6.03
48/65	5.73	8.88
65/100	6.12	9.70
100/150	4.53	8.07
150/200	3.68	5.37
200/270	3.12	2.77
270/325	1.38	2.07
-325	31.73	32.64

(a) By pulp density balance
(b) By DeVaney-Shelton consistometer
(c) Geer apparatus

Note: Media mixture 1:1 weight percent ground ferrosilicon and magnetite

Microscopic examination showed that the coarser fractions were made up of rock particles of the same mineralogical character as the gravels, indicating that these particles came from attrition of the gravels. The minus 325 mesh sizes were clay and rock flour introduced with the gravels. X-ray and chemical analyses of the slimes showed that they were composed mostly of illite-chlorite and only a minor amount of alkali montmorillinite. Geer et al (6) noted that montmorillinite increased the consistency of magnetite suspensions more than kaolinite and that the effect was greater for the sodium as compared with calcium montmorillinite. Aplan and Spedden (17) investigated the effects of different kinds and amounts of slime contaminants upon the consistency and stability of spherical and ground ferrosilicon suspensions. However, more quantitative information is needed about the effects of mineralogical composition and size structure of contaminants upon the rheological properties of heavy mediums.

The size structure and shape of the media particles change through attrition in the circulation system, thus changing the consistency and stability of the medium. As the particles become smaller, their settling rate decreases and they exert more drag on the movement of the gravels. However, as the media particles become rounded, they settle faster and exert less drag. In starting up a plant, new media generally is worked for an initial period to remove the sharp edges and stabilize the consistency and stability before introducing the feed. When the media particles become fine enough, they leave the circuit through attachment to the gravels or by overflow from the classifier with the contaminant particles discarded from the cleaning circuit. There is a lack of information about the sizes of media lost in these ways. Furthermore, as the media particles become finer than 325 mesh, they become so stable that they do not readily densify in the cleaning circuit. Thus, plant economics and facility of operation require cognizance of the media structure. Some operators use coarser sizes in making additions to compensate for losses so that the media will be retained in the circuit longer and densification will be facilitated.

The media size structures used in the preliminary tests to determine the effect of size on consistency and stability of the medium are shown in Figure 19, and the test results are shown in the graphs of Figure 20. As previously noted, the aritifical size structures were not representative of those normally used in actual plant practices. While the trends shown in Figure 20 are what would be expected, the graphs might not afford accurate predictions of consistency and stability of a normal plant medium.

The size distributions of clean media used in later measurements to determine the relationships of consistency and stability to size are shown in Figure 21, and of contaminated media in Figure 22. In these figures, A designates the coarsest size structure and D the finest, while the two intermediate size structures are not shown. The test results (Tables A10-1 and A10-2) show that changes in the size structure primarily affected the stability and did not significantly change the consistency; medium A with the coarsest size structure had low stability while medium D with the finest size structure exhibited high stability. The data for contaminated mediums (Table A10-2) must be evaluated with respect to the proportions of clay and rock sand, which had their own sizes. It is apparent that the slimes had a dominant effect on stability. Disparities in the original and duplicate stability measurements are evident. The replication technique of filtering and sieving caused changes in the size structure of the media particles; it is apparent that attrition of coarser sizes and agglomeration of fine sizes took place.

To have a medium of satisfactory stability with an acceptable densification rate in the cleaning circuit, a compromise has to be found in using commercial media of various size distributions. Figure 22 shows how this compromise may be achieved by the addition of suitable contaminants; the

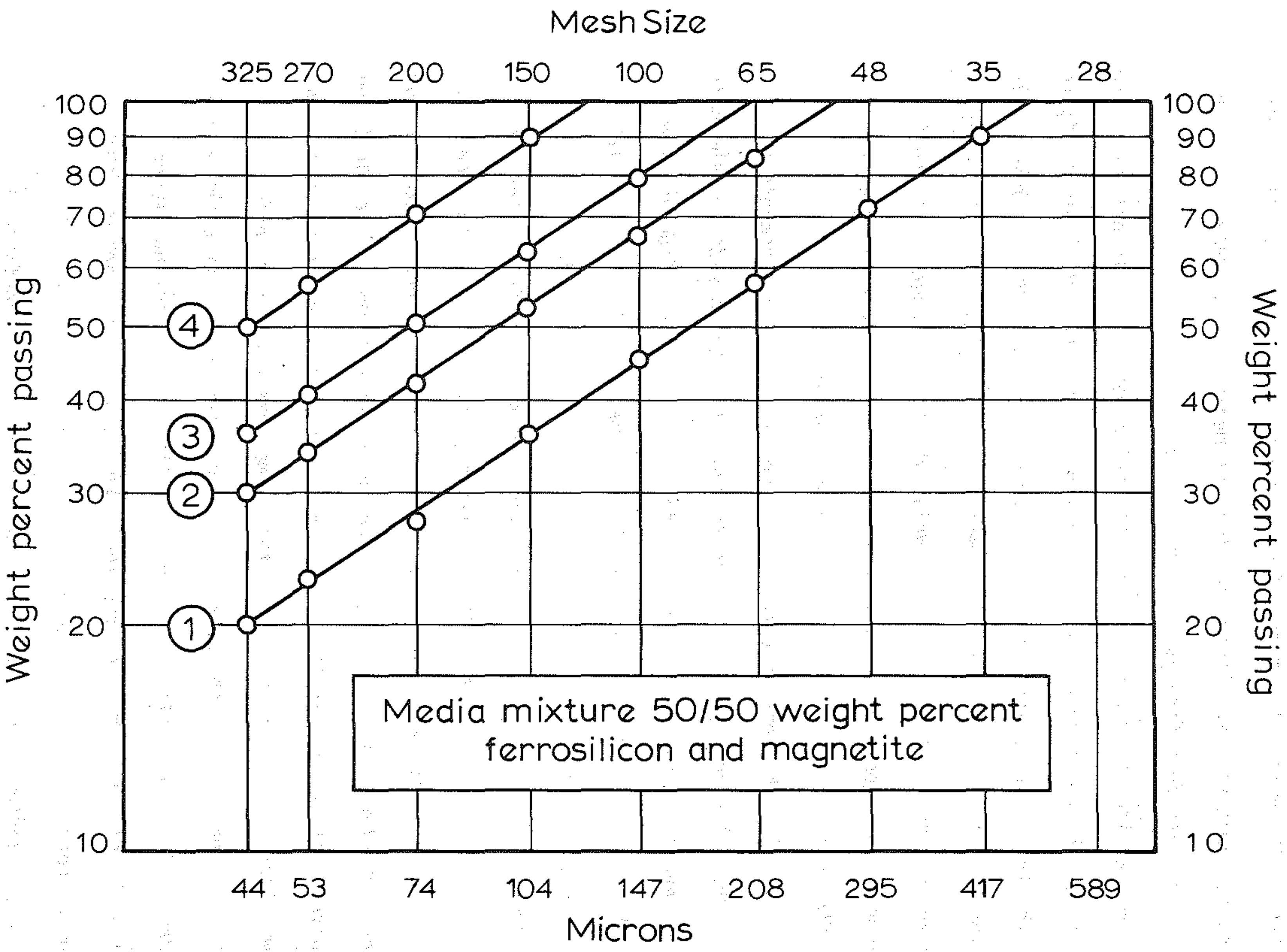


Figure 19. Size distributions of media mixtures used to determine effect of media particle size on consistency and stability of mediums.

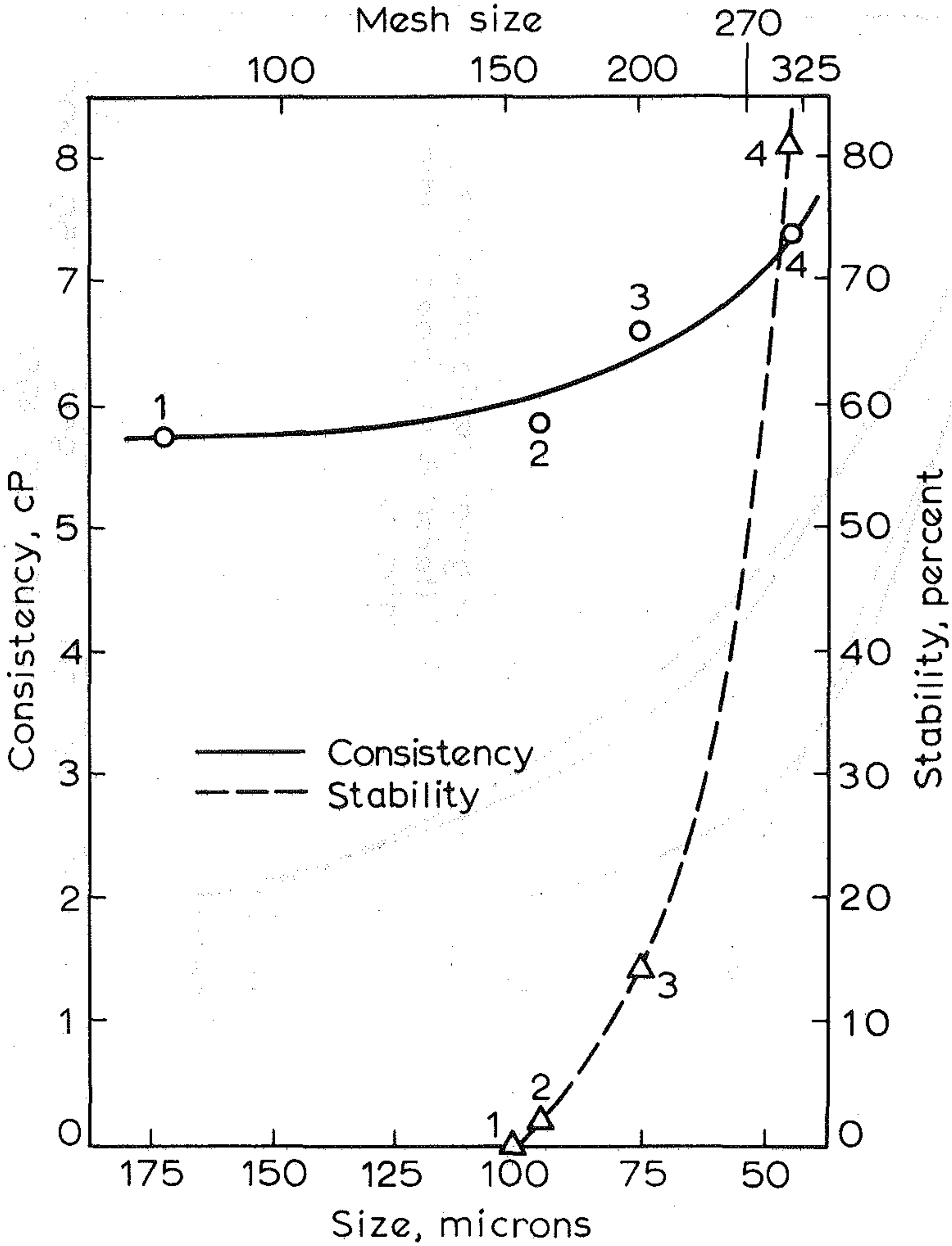


Figure 20. Consistency and stability versus media particle size.

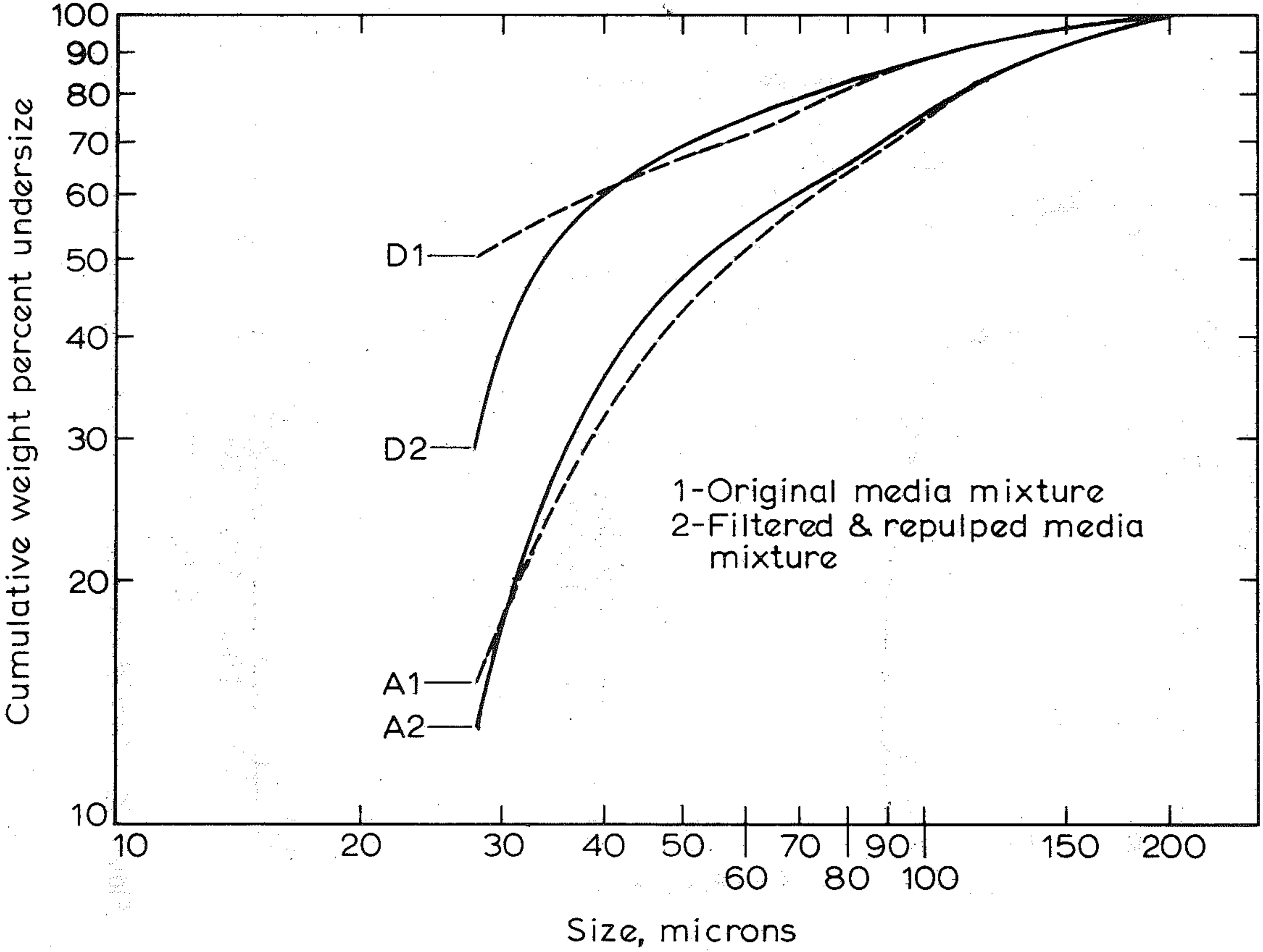


Figure 21. Size structures of media mixtures containing 2:1 weight percent ferrosilicon to magnetite.

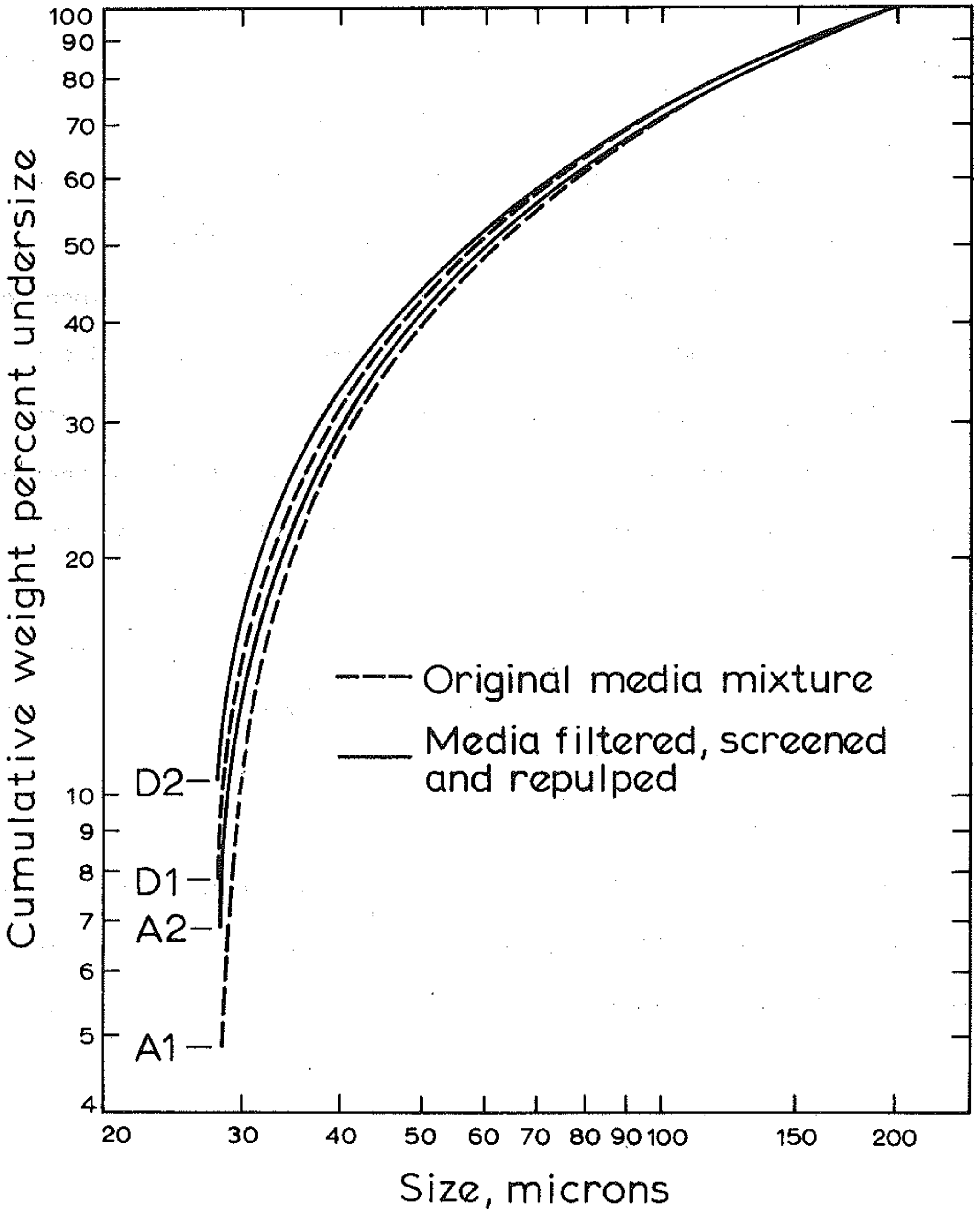


Figure 22. Size structures of media mixtures containing 2:1 weight percent ferrosilicon to magnetite and varying amounts of clay and rock sand.

addition of 1-4% clay to identical media size structures improved stability with a very small increase in consistency. This indicates that coarser media, which is less costly, easier to recover, and wears longer, can be used under controlled conditions.

The use of chemical dispersants to improve the properties of ferrosilicon suspensions so as to minimize viscosity while retaining stability, particularly at the higher specific gravities, has been well documented. Aplan and Spedden (17) made a detailed study of the effects of chemical dispersants on the viscosity and stability of ground and spherical ferrosilicon suspensions, both clean and contaminated with various mineral slimes, and found that the dispersants effectively lowered the yield stress of the mediums so that under proper conditions it was possible to have both a very stable suspension and a low viscosity. They found that sodium hexametaphosphate in amounts of 0.2 pounds per ton of media was particularly effective in increasing the sharpness of separation, increasing mineral recovery when slimes were present, increasing media recovery, improving plant control, and extending the lower limit of ore particle sizes that can be effectively separated. Klassen et al (18) found that additions of sodium hexametaphosphate or sodium silicate in concentrations of 0.5 to 2.0 grams per liter decreased medium viscosity 25 to 50 percent and resulted not only in better separation efficiency but improved cleaning of the media.

Batch Tests

The batch tests were of limited scope made preliminary to the pilot plant tests to study the effects of consistency and stability of the medium on yield and quality of product. The consistency and stability were varied by successive additions of clay to the same medium. The specific gravity of the starting medium was 2.34, and it was measured again after each addition of clay; thus the tests were made at successively lower specific gravities. A specific gravity of 2.34 was selected for the original medium on the basis of previous experience with the cone vessel. It had been noted that the upward movement of the medium imparted by pumping resulted in a higher effective specific gravity of separation than would be realized with a medium of the same specific gravity in full-size plant cones. The specific gravity compositions of the sink and float products were not determined in these tests because of the large amount of time and extra expense required. Thus, the specific gravity of separation and the sharpness of separation achieved in the tests could not be determined.

Evaluations of performance are made on the basis of yield and quality of product, which are the criteria of immediate interest in actual plant operations, and also on the basis of an expression of efficiency which reflects the recovery of sound gravels and elimination of deleterious gravels. Such an expression of efficiency is:

$$\text{Efficiency, \%} = 100-(\text{weight \% total deleterious gravels in sink} + \text{weight \% sound gravels in float})$$

where the amounts of deleterious and sound gravels are percentages of the feed. An efficiency of 100 percent would be found only with perfect separation of a feed in which all of the deleterious gravels are of lower specific gravity than the sound gravels. Since this expression of efficiency includes effects of the specific gravity composition of the feed gravels, it cannot be compared with the Fraser-Yancey separation efficiency.

Cumulative percent weight distributions by specific gravity of the sound, total deleterious, and soft nondurable gravels (as percentages of the feed weight) are shown in Figure 23 for sample no. 1 and in Figure 24 for sample no. 4. In attempting to make a product that would meet specifications for 6A class aggregate from feed gravels typical of these two samples, it is apparent that the specific gravity of separation should be at least 2.40 to reject enough of the soft nondurable type to meet the specification and at the same time realize a high recovery of the sound gravels. With the operating characteristics of the small cone vessel as previously described, a starting medium specific gravity of 2.34 was selected to give the desired effective gravity of separation.

The batch test data are listed in Table 9, and graphs of the yield of the sink product, the percent weights of total deleterious and of soft nondurable gravels in the sink product, the percent weight of sound gravels in the float product, and the efficiency versus additions of clay are shown in Figures 25 and 26 for samples 1 and 4, respectively.

Interpretations of the batch test results are clouded by the hydrodynamics of the small cone vessel and an apparent interaction of the decreasing specific gravity of the medium and the increasing consistency and stability. Turbulent flow conditions were noted with the uncontaminated medium, but as clay was added the flow became laminar; with 10 percent clay the medium had the appearance of a plastic gel. Both the turbulent and the plastic laminar conditions could cause the elutriation of sound gravels as indicated by the graphs with the mediums containing no clay and 10 percent clay.

It can be inferred that the results would have been better if the specific gravity of the medium had been maintained constant at 2.34 by additions of media along with the clay. After the initial test, the specific gravity was too low to accomplish efficient rejection of the deleterious gravels, as indicated by the coincidence of maximum yield and deleterious content. Moreover, the clay

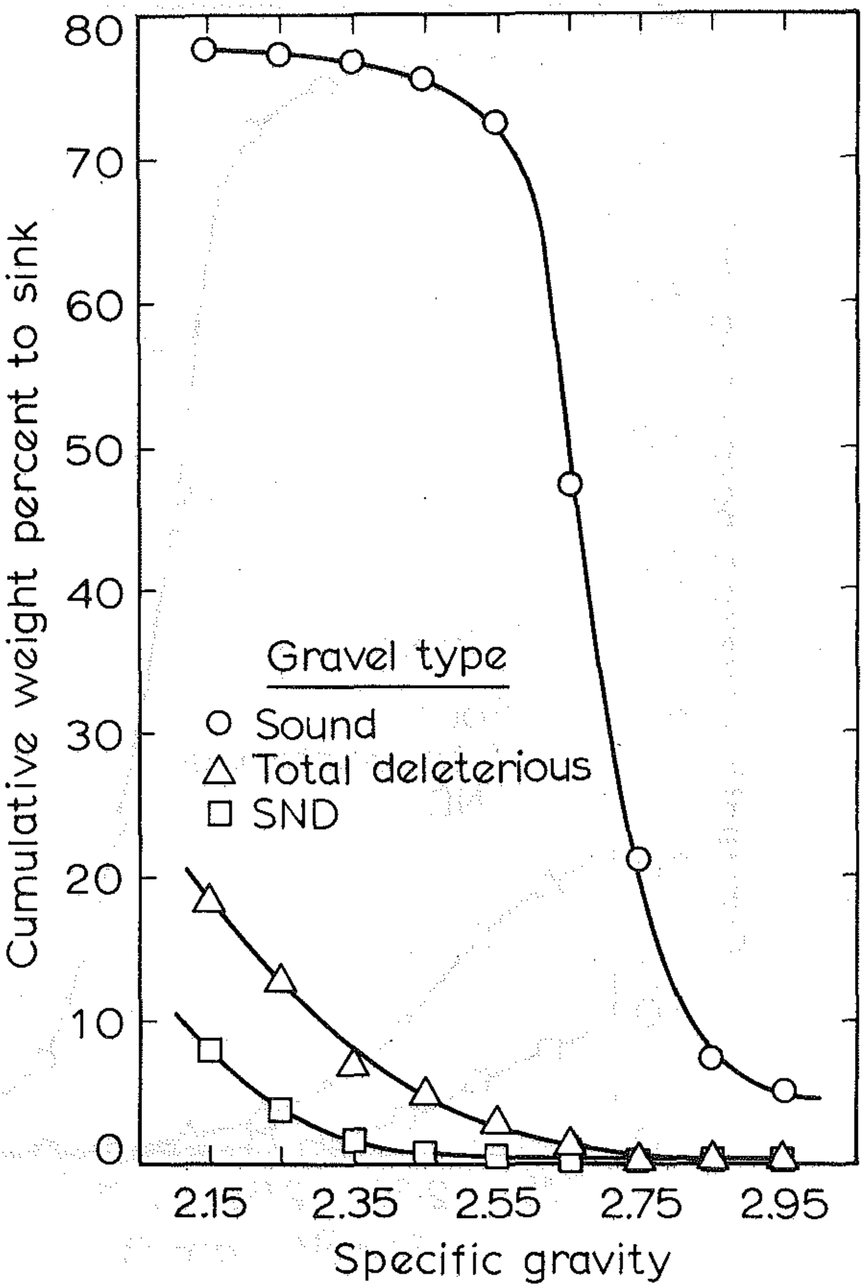


Figure 23. Cumulative weight percent to sink by specific gravity of gravel types in sample no. 1.

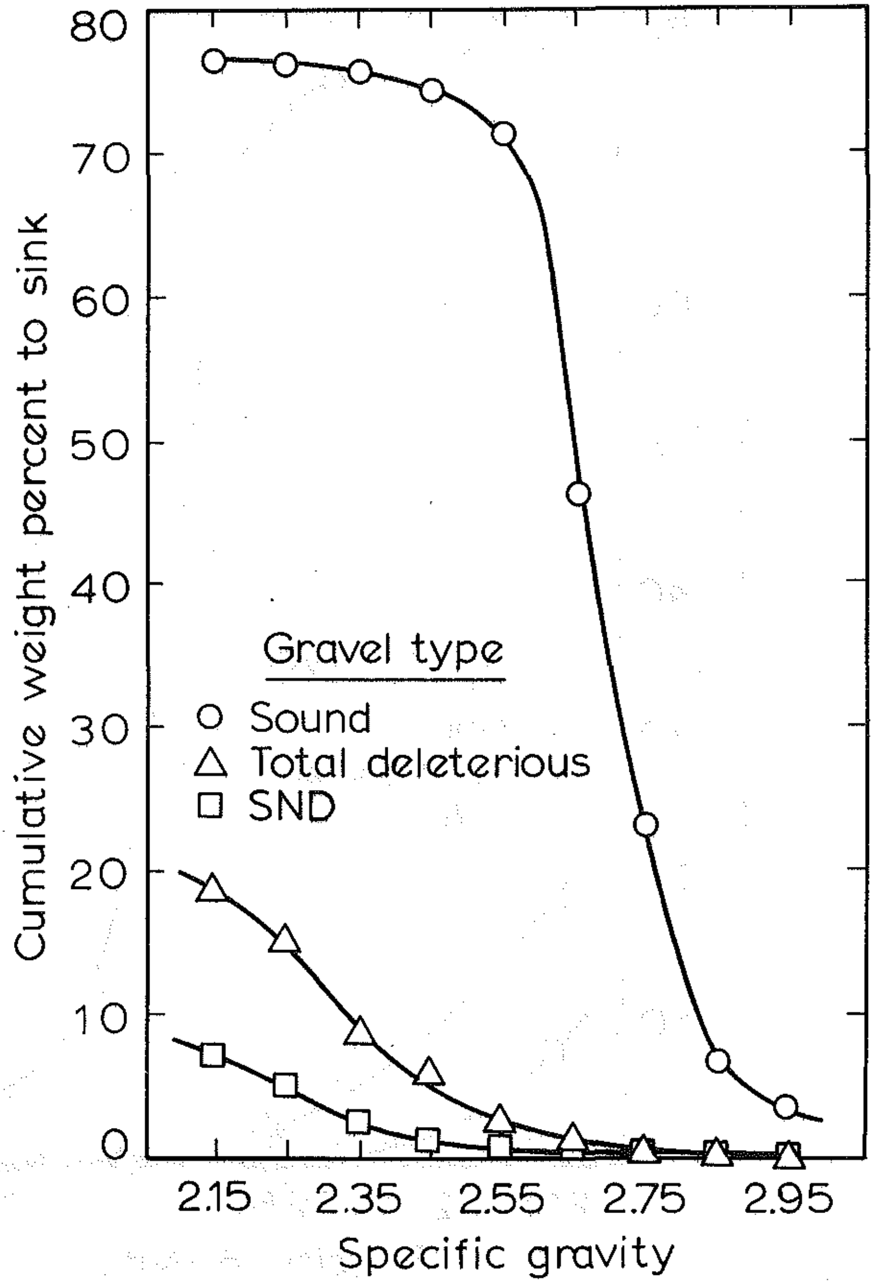


Figure 24. Cumulative weight percent to sink by specific gravity of gravel types in sample no. 4.

Table 9

Evaluation of Batch Tests

	Sample no. 1					Sample no. 4				
Clay, wt. %	0	2.50	5.00	7.50	10.00	0	2.50	5.00	7.50	10.00
Sp. grav. medium	2.34	2.31	2.28	2.22	2.19	2.34	2.31	2.28	2.22	2.19
Sp. grav. diff.	0.27	0.17	0.13	0.05	0.03	0.27	0.17	0.13	0.05	0.03
Consistency, cP	2.74	2.76	3.62	4.47	4.78	2.74	2.76	3.62	4.47	4.78
Stability, %	0	13.0	22.8	26.5	42.4	0	13.0	22.8	26.5	42.4
Yield of sink, wt. %	73.3	86.5	87.2	85.1	79.3	78.9	90.9	84.2	84.6	72.2
Total delet. in sink, wt. %	8.7	13.0	11.8	9.5	7.7	11.6	16.7	10.9	10.8	5.9
SND in sink, wt. %	2.7	4.9	3.8	2.7	2.2	3.1	5.7	3.0	2.8	1.1
Sound gravel in float, wt. %	11.4	3.1	1.5	1.5	5.2	6.9	0.9	1.6	1.2	8.6
Efficiency, %	82.2	85.6	88.1	90.5	88.6	84.0	83.9	89.2	89.6	87.2

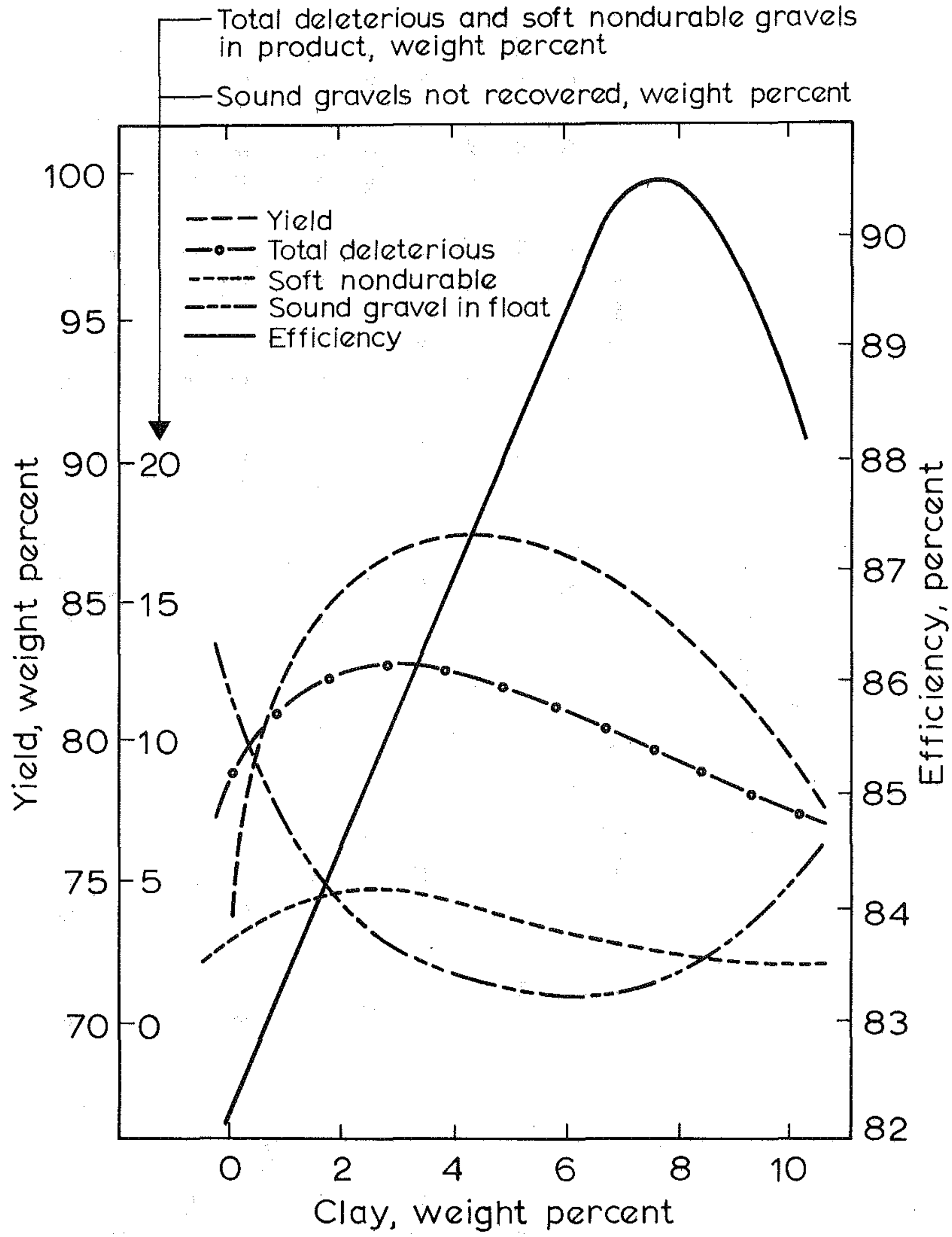


Figure 25. Yield of sink product, weight percent of total deleterious and soft nondurable in sink product, weight percent of sound gravel in float product and efficiency versus clay additions for sample no. 1.

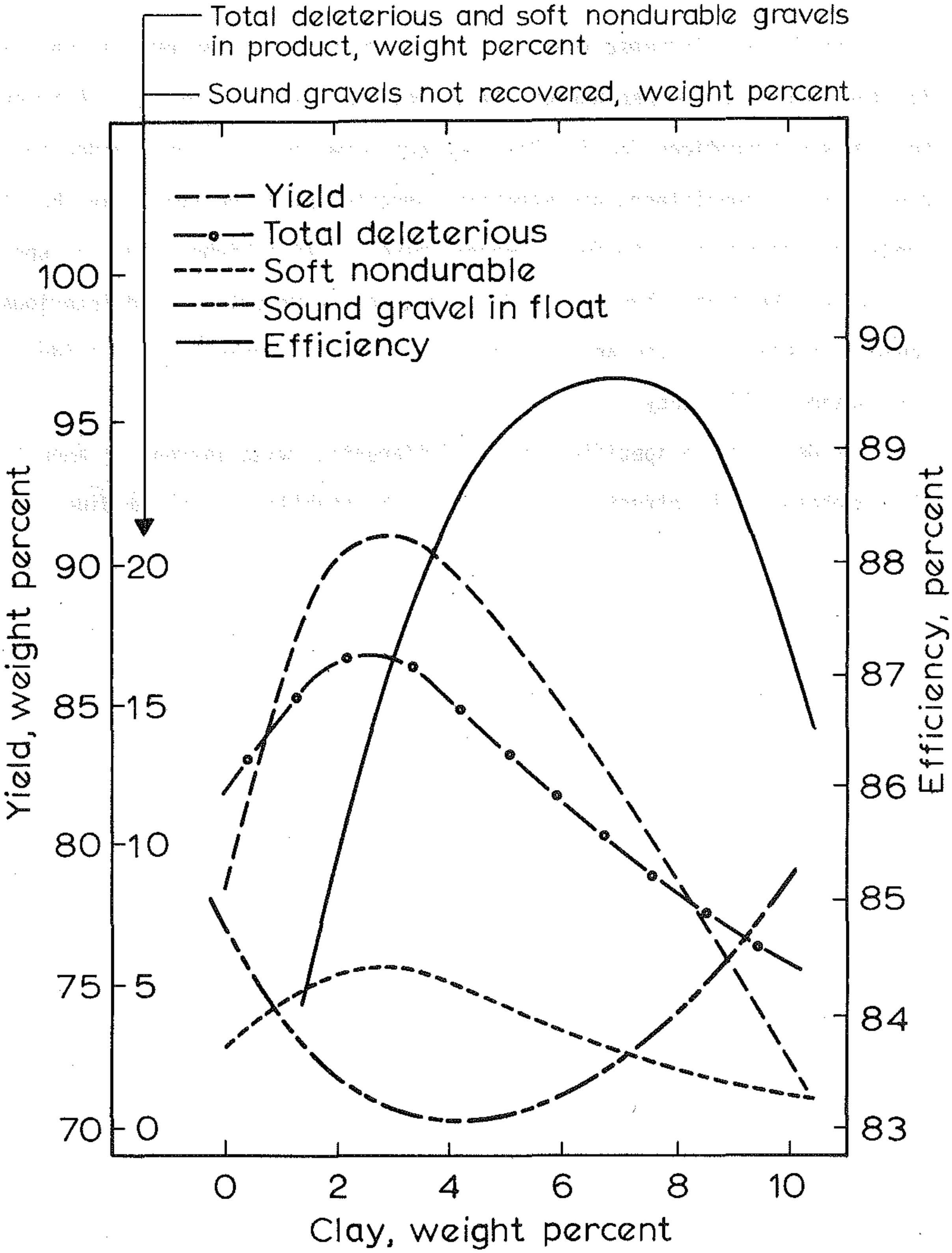


Figure 26. Yield of sink product, weight percent of total deleterious and soft nondurable in sink product, weight percent of sound gravel in float product and efficiency versus clay additions for sample no. 4.

additions did not increase the consistency and stability as much as was expected for the amounts added because of the decreasing specific gravity. A product meeting specifications for 6A class aggregate was realized only under the conditions of consistency and stability imparted by 10 percent clay, but these conditions caused elutriation of sound gravels. If a higher level of specific gravity of the medium had been maintained, better rejection of deleterious gravels would have been realized and optimum yield would probably have coincided better with maximum efficiency.

The decrease in specific gravity differential with increasing amounts of clay emphasizes the effect of the clay on the stability of the medium.

Pilot Plant Tests

Of the thirty tests planned in Phases I and II to investigate three levels of feed rate and five levels of specific gravity with uncontaminated media and with the media containing 5 percent clay, only 15 tests were completed. During the tests it became apparent that satisfactory control of the consistency and stability could not be maintained by periodic sampling of the medium because of time lapses and variations in the measurements. Furthermore, it was found not practicable to adjust the medium in the successive tests to the exact specific gravity required for fixed incremental increases of this variable.

The amounts of sound and deleterious gravels in the feed sample and their specific gravity compositions are shown in the cumulative distributions of Figure 27. It is apparent that this was not a typical gravel feed sample; it contained only half the normal amount of deleterious gravels, about a third of the soft gravels, and disproportionate amounts of heavy deleterious gravels.

The separation results and medium conditions at four levels of specific gravity are listed in Table 10 along with predicted results taken from the specific gravity distributions of Figure 27 (the results at specific gravity 2.30 are omitted). The criteria used to evaluate plant performance could not be applied to the pilot plant tests because it was not practicable to make heavy liquid separations of the test products.

The measurements of consistency and stability of the uncontaminated mediums cannot be reconciled with those predicted from Figure 18. The only explanation that can be offered is that the measurements were made by different persons, and operator errors are a significant source of variation. The influence of the clay contaminant on the specific gravity differential, consistency, and stability of the medium is apparent, and the inverse relationship between specific gravity differential and medium consistency and stability supports the plant practice of taking the differential as an indication of medium conditions. The actual

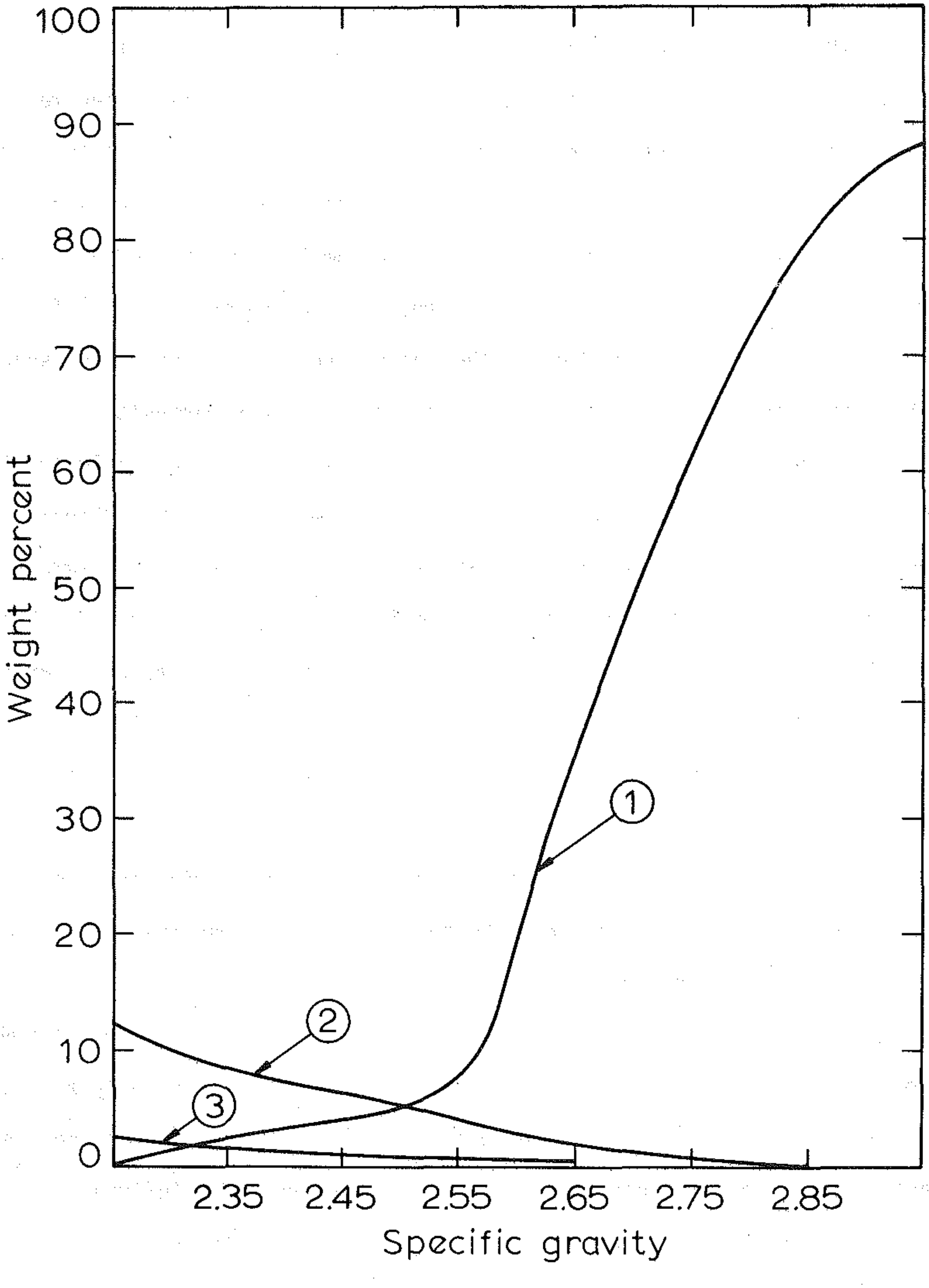


Figure 27. Cumulative distributions of weight percent by specific gravity of gravels in feed sample for pilot plant tests, phases I and II: sound (1) gravels less than specific gravity, total deleterious (2) and soft (3) gravels greater than specific gravity.

Table 10

Pilot Plant Test Conditions and Separation Results in Phase I and II

	Specific gravity of circulating medium							
	2.38		2.48		2.63		2.69	
	U	C	U	C	U	C	U	C
Spec. grav. differential	0.30	0.11	0.24	0.09	0.17	0.06	0.14	0.05
Consistency, cP	7.1	7.4	7.5	7.9	9.1	11.8	10.9	14.9
Stability, %	5	43	7	57	12	84	20	91
Yield, percent(a)	95.4	91.8	85.0	87.1	68.7	74.3	42.2	48.6
Yield, percent(b)	93.1		89.4		60.8		44.3	
Total deleterious in sink, percent(a)	8.1	6.6	5.9	4.8	3.3	3.1	2.7	2.3
Total deleterious in sink, percent(b)	8.6		6.5		32.8		2.7	
Soft in sink, percent(a)	1.0	0.8	0.6	0.5	0.5	0.4	0.4	0.3
Soft in sink, percent(b)	1.3		0.8		0.7		0.7	
Sound loss, percent(a) (c)	0.5	2.4	8.1	5.2	21.7	16.1	47.0	40.6
Sound loss, percent(b) (c)	3		4.5		29.		45.	

Note: U - uncontaminated medium
C - medium contaminated with 5 percent clay
(a) - actual separation
(b) - theoretical from heavy liquid separations
(c) - percent of sound gravel in feed

and predicted separation results are shown in the graphs of Figure 28. As would be expected, the yield and the amounts of total deleterious and soft gravels in the sink product decreased with increasing specific gravity, while the loss of sound gravel in the float product increased. It is noteworthy that the presence of the clay contaminant improved separation results over those predicted on the basis of specific gravity alone; greater yields were realized through decreased loss of sound gravels at the higher gravities and better product quality was realized through increased rejection of the deleterious gravels at the lower gravities. To what extent these results were due to misplacement of the types of gravels cannot be positively ascertained from the data because heavy liquid separations of the test products were not made. However, it is apparent that factors other than specific gravity entered into the separations.

The pilot plant tests were made at feed rates of one and two tons per hour. Somewhat better yields and product quality were realized at the higher rate, and thus the optimum rate for this feed sample probably was not reached. Since these tests did not furnish much information about the effect of feed rate on HMS separations, it is worthwhile to include a brief discussion of the importance of this operational variable. Effective separation requires sufficient time for the gravels to stratify, and thus it is essential that the feed rate be such that the zone of separation does not become congested. The proper feed rate depends upon the character of the gravels and the specific gravity of separation. At the higher gravities where more of the sound gravels are near the sgs, and for gravels predominantly of the smaller sizes, lower feed rates are required for optimum separation efficiency.

There is a lack of information about the settling rates of particles in dense mediums under the flow conditions existing in HMS vessels, and quantitative information was not found about the effect of feed rate on the efficiency of separation by the HMS process. In a study of the performance of dense

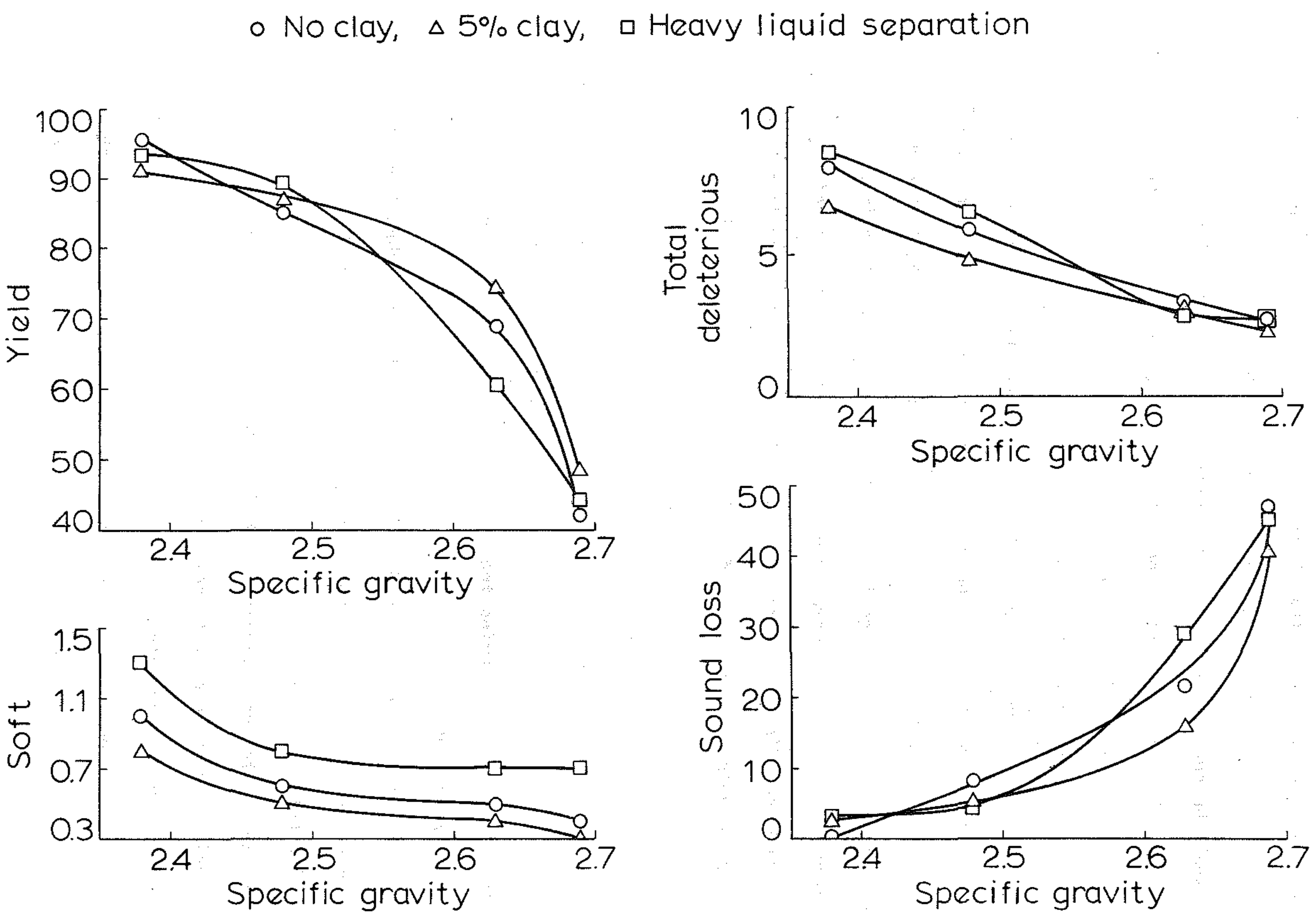


Figure 28. Results of pilot plant tests, in phases I and II, with clean and contaminated mediums compared with theoretical separations; yield, percentages total deleterious and soft gravels in sink product, and loss of sound gravel versus specific gravity.

medium baths with magnetite, shale, and clay individually forming the media, Valentik and Whitmore (14) noted that large mats formed at high throughputs and entrapped particles in spite of their densities, and they concluded that the feed rate should be such as to ensure free movement of all particles and eliminate "rafting". They also observed a decline in the sgs with increasing feed rate provided the media is flocculated, a condition which normally exists. They pointed out that the feed should be spread smoothly on the surface of the bath so as to avoid an excessive drop which would cause the lighter particles to sink to a point where they would be carried into the sink product by mass flow.

A factor related to the feed rate is the rate of circulation of the medium, which must be adjusted for the specific gravity and amount of contaminant so as to have a properly functioning teeter zone and minimize misplacement of gravels because of streaming effects. In these pilot plant tests, the circulation rate with the uncontaminated medium varied from 268 to 288 gallons per minute for the specific gravity range of 2.30 to 2.69 and with the contaminated medium from 280 to 305 gallons per minute for the same range of specific gravity.

The pilot plant tests of Phases I and II, in spite of imperfection, provided useful information for locating the conditions of optimum separation and for planning the final tests. Assuming that a sample more representative of plant feeds and of more favorable specific gravity composition would have yielded products of about the same quality under these test conditions, then from the point of view of optimizing yield and minimizing loss of sound gravel, the medium specific gravity should be in the range of 2.48-2.63. For the production of a 6A class aggregate, satisfactory product yield and quality should be realized with a medium specific gravity near the lower end of the range and with controlled conditions of consistency and stability. For production of 6AA class aggregate, the medium specific gravity should approach the higher end of the range. The specific gravity referred to is that of the medium as returned to the bath.

The pilot plant tests in Phase III were designed on the basis of the results in Phase I and II to demonstrate that continuous measurement of the specific gravity and consistency of the circulating medium will provide operational control for maximizing product yield and quality; the tests were designed also to indicate the possibilities of process inspection.

The feed sample of approximately 1000 pounds was made up from gravels collected in the second plant survey combined with gravels from the feed used in the preliminary pilot plant tests. A sample of this size was necessary so that each test would be of sufficient duration to establish equilibrium and collect representative samples of the sink and float products. The feed sample contained 30 percent by weight deleterious gravels, all less than 2.52 in specific gravity and marked so that they could be quickly picked after each test. The sound gravels all exceeded 2.53 in specific gravity. With this artificial specific gravity composition by type of gravels, the efficiency of separation could be determined by picking and weighing the marked (deleterious) gravels in the sink product and the unmarked (sound) gravels in the float product, thus eliminating time consuming heavy liquid separations. A size analysis of the feed sample was not made.

Six tests were made with the same feed sample and each test was replicated to assess reproducibility. All tests were made at the feed rate of two tons per hour, a medium circulation rate of 295-300 gallons per minute, and the specific gravity of the float screen underflow medium maintained at 2.52. The sgs could not be accurately determined because specific gravity compositions of the products were not measured but it was considered to be relatively constant and near the specific gravity of the float screen underflow. The test conditions and results are listed in Table 11.

Table 11. Final Pilot Plant Test Conditions and Results

	Test Number											
	1		2		3		4		5		6	
Spec. grav. (1)	2.52		2.52		2.52		2.52		2.52		2.52	
Spec. grav. (2)	2.62		2.60		2.58		2.55		2.54		2.53	
Spec. grav. (3)	2.71		2.66		2.62		2.58		2.55		2.53	
Differential (4)	0.19		0.14		0.10		0.06		0.03		0.01	
Consistency, cP (5)	26		38		45		64		88		118	
Consistency, cP (6)	8.5		9.1		10.4		13.8		18.0		22.7	
Stability, % (7)	51		59		70		82		89		94	
Clay, wt. % (8)	4.3		5.2		6.1		7.0		8.2		9.1	
Yield, wt. % (9)	73.6	72.2	67.6	69.0	61.6	65.0	55.5	63.0	64.5	63.0	70.5	66.5
Delet. in sink, wt. % (10)	6.2	5.8	3.4	4.8	6.1	7.3	13.0	11.1	13.4	14.3	15.0	17.0
Sound loss, wt. % (11)	1.6	2.8	6.7	6.0	17.4	14.0	31.0	19.8	20.4	23.0	14.5	21.0
Efficiency, %	94.3	93.8	93.0	92.5	84.0	85.5	71.1	79.1	77.1	74.9	79.2	74.0

(1) Medium samples from float screen underflow, measured by pulp density balance.
(2) Circulating medium measured by automatic density gauge.
(3) Medium samples from sink screen underflow, measured by pulp density balance.
(4) Specific gravity differential, (3)-(1).
(5) Circulating medium measured by automatic consistometer.
(6) Samples of circulating medium measured by DeVaney-Shelton consistometer.
(7) Samples of circulating medium measured by Geer instrument.
(8) Weight percent of media solids determined by Davis tube magnetic separation.
(9) Sink product, weight percent of feed.
(10) Deleterious gravels as weight percent of sink product.
(11) Sound gravels in float product as weight percent of sound in feed.

The measurements characterizing the rheology of the medium will be examined first, and then the relationships between these measurements and the separation results will be analyzed. It must be pointed out that a number of factors which were held constant in these tests influenced the results; these included the specific gravity and size composition of the feed; the type, composition, and size structure of the media; the type and size structure of the clay contaminant; the specific gravity of separation; and the type and size of the separatory vessel.

The measurements of consistency by the automatic consistometer and the DeVaney-Shelton capillary flow device are compared in the graph of Figure 29; a good linear relationship is indicated.

The relationships of amount of clay to specific gravity of the circulating medium, specific gravity differential, gauge consistency as measured by the automatic consistometer, and stability are shown in the graphs of Figure 30. The general relationships of decreasing specific gravity and gravity differential and increasing consistency and stability of the medium with increasing amounts of clay are evident.

The relationships of specific gravity, consistency, and stability of the circulating medium to specific gravity differential are shown in the graphs of Figure 31. In holding the specific gravity of the medium at the surface of the bath constant while substituting clay for heavy media, the specific gravity of the medium decreased nearly linearly with the specific gravity differential. The inverse relationships between specific gravity differential and consistency and stability are about what would be predicted from the graphs of Figure 30. However, since the clay concentration in the medium generally is not accurately known and the specific gravity differential can be readily measured, the graphs of Figure 31 are of greater interest for the purposes of plant control. It is noteworthy that the inverse relationship between the specific gravity differential and stability was nearly linear in these tests.

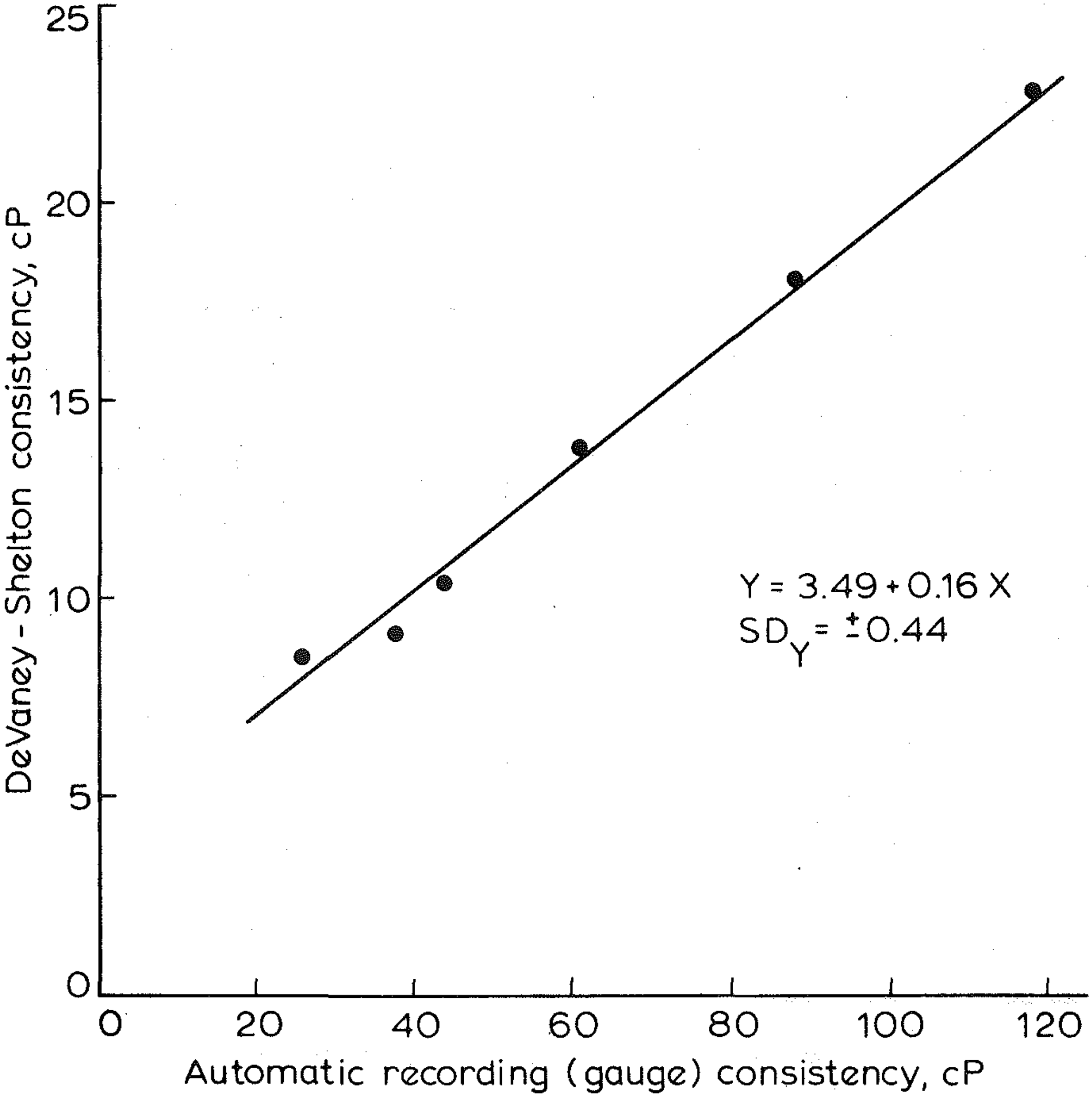


Figure 29. Consistencies as measured by De Vaney - Shelton and automatic recording consistometers.

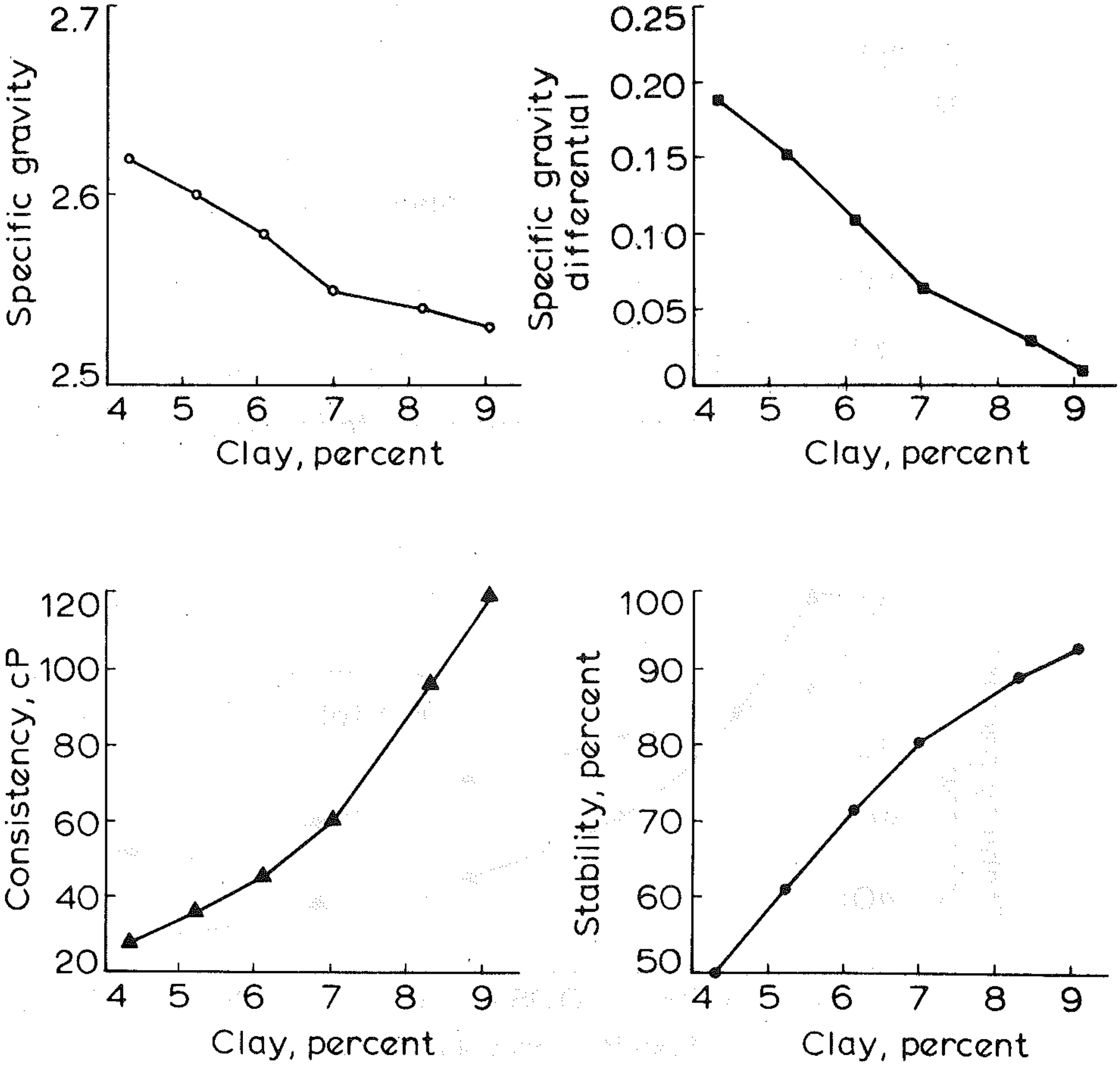
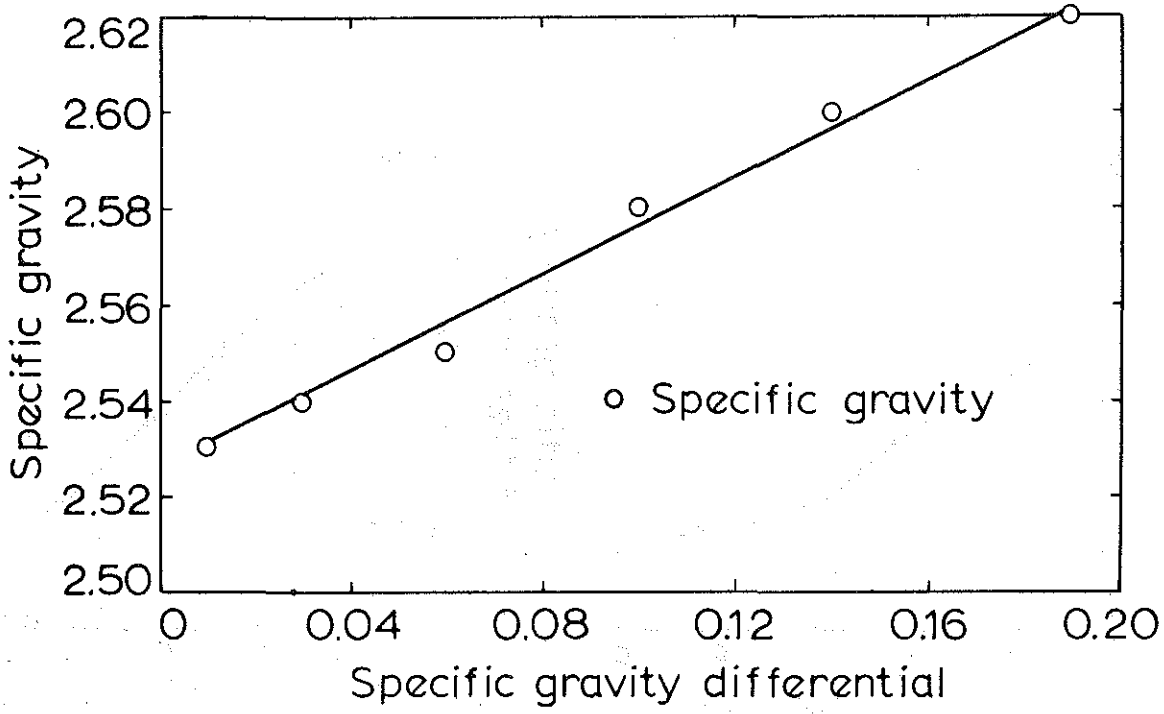


Figure 30. Clay concentration versus specific gravity, specific gravity differential, consistency and stability.



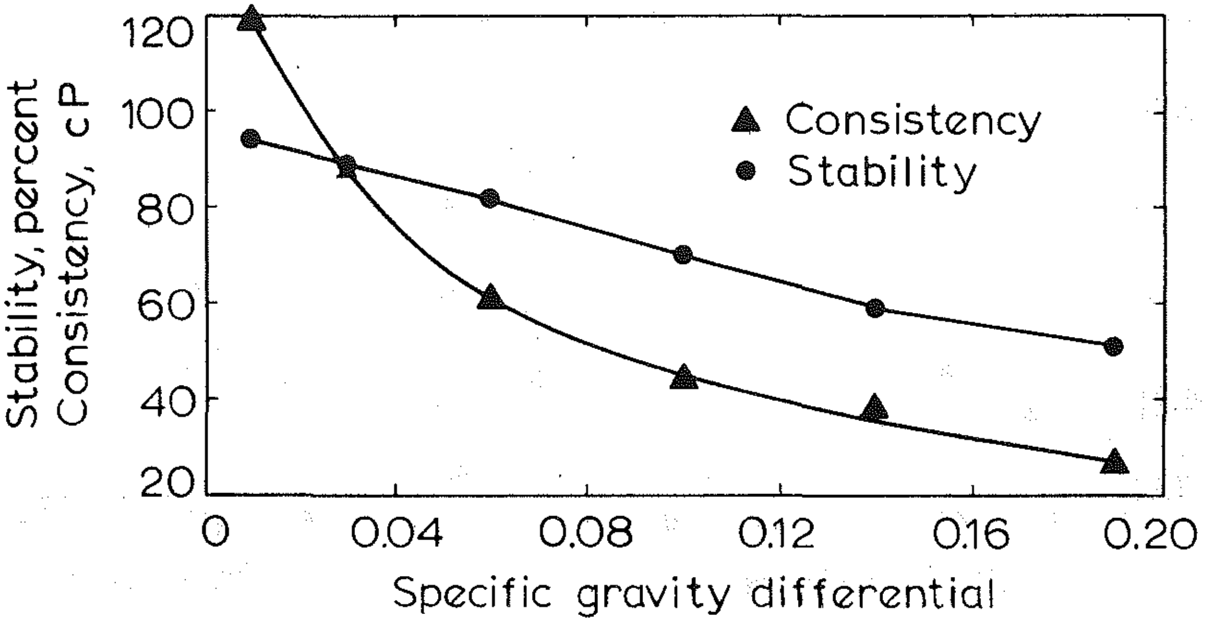


Figure 31. Specific gravity, consistency and stability of circulating medium vs. specific gravity differential.

The relationships between the amount of clay contaminant and product yield, quality as defined by the percentage of total deleterious gravels in the sink product, loss of sound gravels, and efficiency are shown in the graphs of Figure 32; the averages of the replicated test results are connected by straight lines and the differences by vertical lines. Reversals in the trends of yield, sound loss, and efficiency are indicated, and the largest variation occurred at a clay concentration of about 7 percent. It is concluded that this amount of clay in the media solids increased the consistency to the extent that stratification of the gravels became severely restricted and separations resulted largely from division of the medium flow, or streaming effects, rather than from specific gravity differences. The results indicate that clay contaminant not exceeding 5 percent imparted stability to the medium without increasing the consistency enough to seriously impair separations.

Since the specific gravity differential and consistency are more readily measured than clay concentration, it is of interest for the purpose of plant control to know the relationships of these medium characteristics to yield and quality of product, loss of sound gravels, and efficiency. These relationships are shown in the graphs of Figures 33 and 34. With medium conditions and contaminant such as existed in these tests, the critical lower limit of specific gravity differential was about 0.15; this was higher than would be maintained for the same medium conditions in the large cone vessels used in plants. The best range of medium stability as defined by Geer measurement was 50-70 percent. The critical level of gauge consistency was about 40 centipoises, or 10 centipoises by DeVaney-Shelton measurement, and at consistencies exceeding 60 centipoises, the separations were influenced largely by mass flow effects rather than specific gravity.

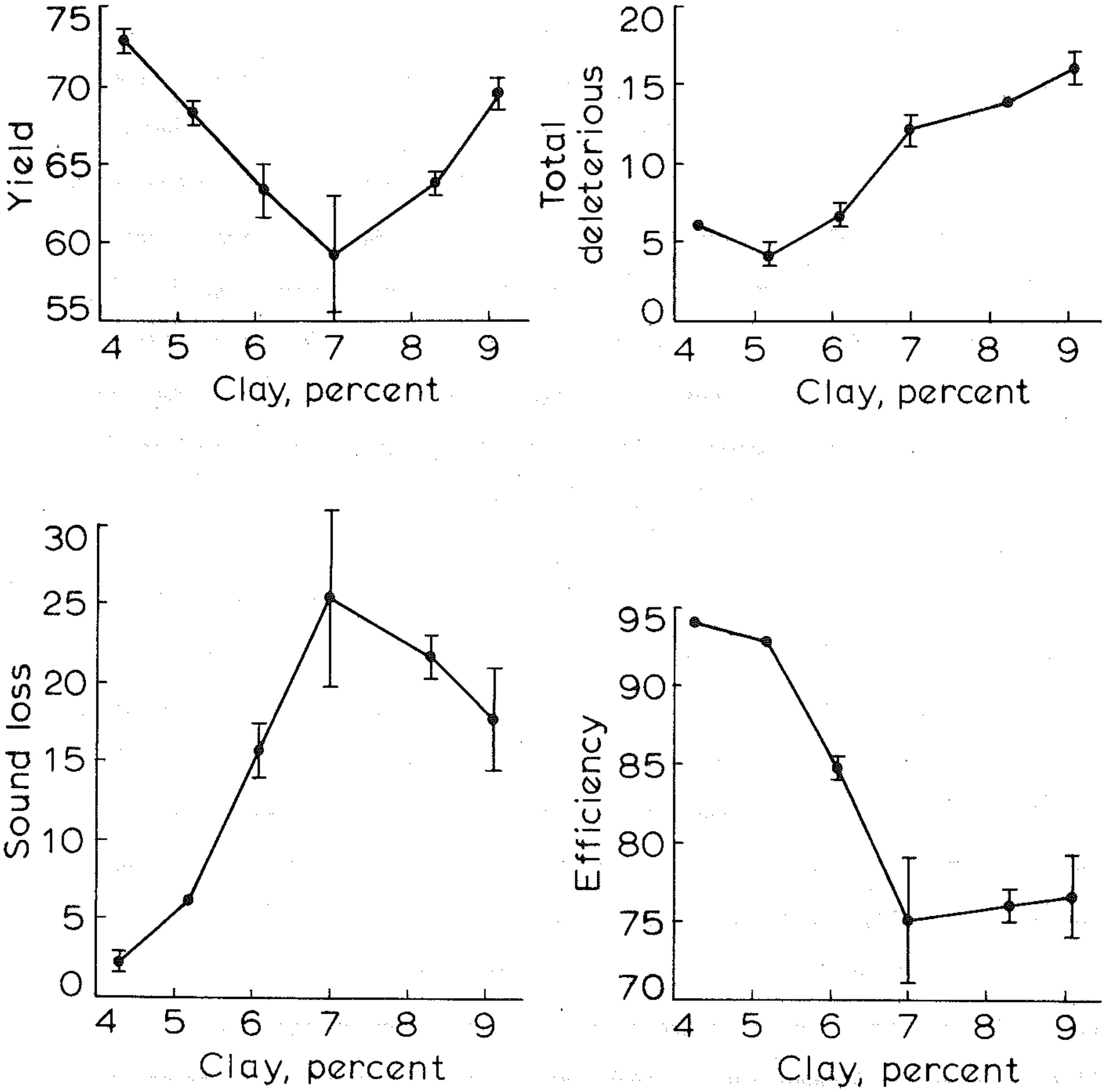


Figure 32. Clay concentration versus yield, deleterious gravels in sink product, loss of sound gravels and efficiency.

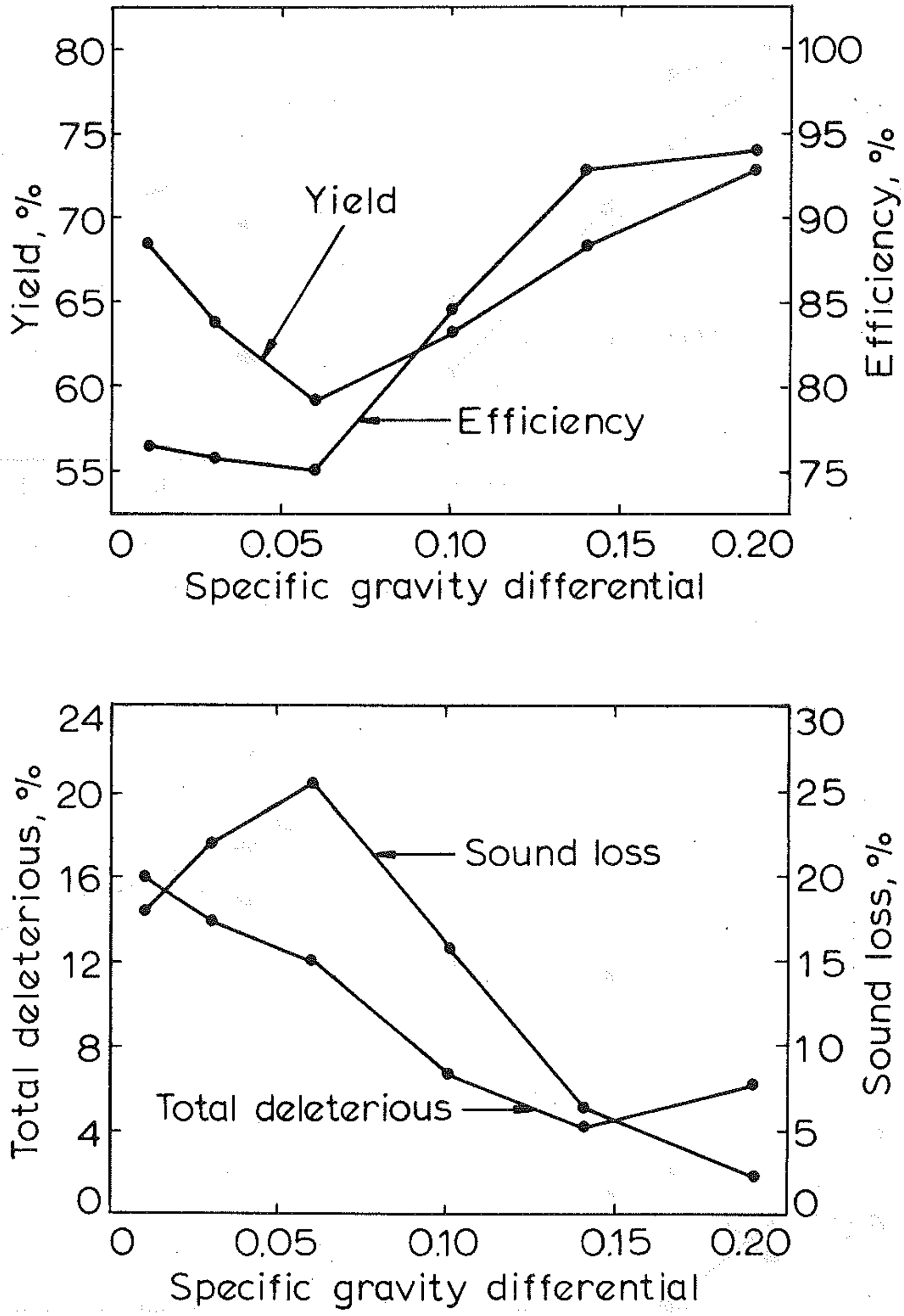


Figure 33. Specific gravity differential vs. yield, efficiency, deleterious gravels in sink product and loss of sound gravels.

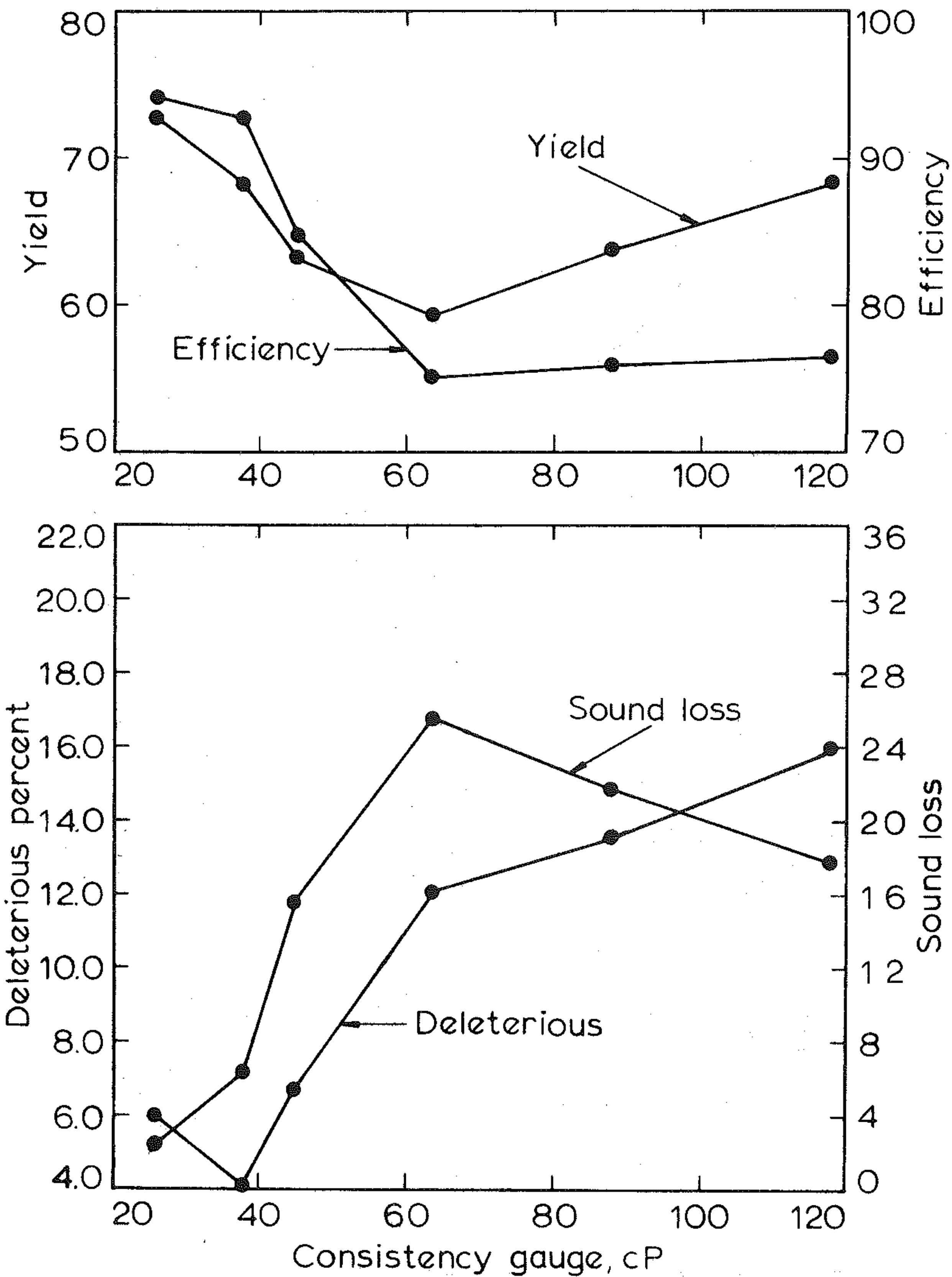


Figure 34. Consistency of medium versus yield, efficiency, percent deleterious gravels in sink product, and loss of sound gravels.

On the basis of the graphs, there is not much to choose between specific gravity differential and consistency for plant control. However, consistency is the rheological property of the medium which directly affects separations while the specific gravity differential is more directly related to medium stability, and the relationship of stability to consistency varies with the character of the medium. Small changes in consistency are not as critical as small changes in gravity differential, and thus the continuous recording of consistency provides a warning of changes in the medium that enables corrective action to be taken before separations become impaired.

The pilot plant results indicate that automatic monitoring of both the specific gravity and the consistency of the medium would provide sufficient control for optimizing product yield for a designated quality of product with feeds of relatively uniform composition by specific gravity, size, and types of gravels, and with media of fixed type and composition, and of relatively constant size structure. Although monitoring of medium specific gravity has been advocated as sufficient for automatic control of HMS coal cleaning plants (19) through the known relationship between the specific gravity and consistency of clean magnetite suspensions, the relationship does not include the effects of contaminants which are so important in the heavy media separation of gravels. It is concluded that measurement of specific gravity alone is not sufficient for plant control in the HMS beneficiation of gravels.

Measurements of medium specific gravity and consistency by the automatic density gauge and automatic consistometer are more accurate and reliable than measurements of samples periodically withdrawn from the medium circuit; moreover, operator errors are eliminated. Continuous monitoring of the medium offers the means of automatic plant control through feedback to servomechanisms which would adjust the cleaning circuit, feed rate, additions of media, and other operational variables.

Automatic monitoring and recording of the specific gravity and consistency of the medium along with surveillance of the feed rate and medium circulation rate and relatively constant additions of media of fixed type, composition, and size structure should provide all of the conditions for process inspection that would assure a designated quality of product in treating relatively uniform feeds. Plant operations now are conducted with the medium specific gravity at high enough levels to provide a margin of protection in product quality, but this policy results in significant losses of sound gravels and lower product yields. A comfortable margin is readily attained in producing 6A class aggregate but only a narrow margin can be maintained in producing the 6AA class. With process inspection substituted for sampling inspection, high efficiencies in terms of product yield yet with assured product quality could be realized through proper plant control.

The use of chemical dispersants to control medium consistency while maintaining stability at workable levels has been noted. During the final pilot plant tests, preliminary trials of sodium hexametaphosphate were made as a means of correcting consistency when it approached a critical level, and the response from small additions of the chemical was very rapid. This indicates that dispersants can be used in conjunction with automatic monitoring of the consistency to prevent impairment of separation until the excessive contaminant can be eliminated in the cleaning circuit. Very small amounts of the chemical would be needed in this kind of use as compared to regular additions advocated by others.(17,18)

Types of Separatory Vessels

As the pilot plant tests were carried out in a cone type separator, in which under ordinary working conditions and with the media used an appreciable difference in specific gravity exists between the top and the bottom of the separating vessel, it is of interest to compare and relate the results with those to be expected in the drum type of separatory vessel used in HMS gravel plants.

It has already been mentioned in the section dealing with the pilot plant circuit and equipment that instead of the conventional air-lift system, a pump was used to elevate the underflow from the cone to the sink screen. Thus the controls available for adjusting the vertical and horizontal components of the fluid motion in the separator were the pumping rate of the underflow and that of medium circulation. The horizontal component is reinforced by the gently revolving paddle. The inflow from medium recirculation gives the upper part of the bath a strong streaming force, while down toward the apex of the cone there is an increasingly heavy pull exerted by the underflow pump. These flow effects are intensified by the relative instability of the media which results in the increase in specific gravity from top to bottom of the cone and which decreases the settling rate of the gravels the further they descend. This teeter bed used as a controlling factor in the operation of a cone indicates a higher efficiency for this type of separatory vessel. The specific gravity differential between the top and bottom of a cone (0.15) is higher than that maintained in a drum (0.04-0.12) but effectively less at any point in the separation zone since the depth of the bath in the cone is 10-15 feet while that in the drum is only 4 feet. More agitation of the medium is imparted by the lifters in the drum as compared to the slowly revolving paddle in the cone, and the horizontal component imparted by the flow of the medium is greater in the drum. Thus the bath in the cone is less subject to turbulence which adversely affects the sharpness of separation. This suggests that the beneficial effects of medium adjustments may be more readily attained in the cone than in the drum and that accurate control to achieve the sharpest separation can be achieved better in the cone. However, the results obtained in the pilot plant tests are equally valid for drum and other types of separators provided the characteristics of the separators are taken into consideration.

CONCLUSIONS

Michigan HMS gravel plants are controlled largely by pulp density balance measurements of medium samples periodically taken from the bath or other places in the circulation system, along with visual surveillance based on operating experience. The specific gravity differential is measured in some plants. Quality control is based largely upon the results of sampling inspection. The plant feed and products are not routinely weighed and analyzed as is normally done in other mineral beneficiation operations.

HMS plant performance depends primarily upon three factors: the specific gravity composition of the feed, the gravity of separation, and the sharpness with which separations are made. Samples from a number of Michigan plants contained about 20 percent deleterious gravels, 75 percent of which were less than 2.45 in specific gravity, while about 88 percent of the sound gravels exceeded 2.55 in specific gravity. Within this range of gravity, separations near the lower limit result in higher yields but higher content of deleterious gravels while separations near the upper limit result in higher quality but greater losses of sound gravel. The average specific gravity of the sound gravel was about 2.62 and thus separations at gravities greater than 2.55 result in significant losses of sound gravel. It is important that the specific gravity composition of the feed by types of gravels be relatively uniform, or that the plant operator have a knowledge of variations in the feed composition.

Ideal separations according to specific gravity differences are not realized in the HMS process. Misplacement results from characteristics of the feed, characteristics of the medium, and the way the separatory system is operated. The amount of misplacement is a measure of the sharpness of separation. Misplacement occurs more among the gravels of specific gravity near the gravity of separation (sgs). With the specific gravity compositions inherent in plant feeds, it is evident that higher gravities of separation bring increasing amounts of the sound gravels near the sgs. Thus separation should be made at the lowest gravity which yields the quality of product desired, and sharper separations are required at the higher gravities. At an sgs of 2.55, the probable error should not exceed 0.03 nor the error area exceed 20.

A limited analysis of plant separations showed that the larger gravels are separated at lower gravities and more sharply than the smaller sizes. This suggests consideration of separate treatment of the minus 1/2 inch gravels, particularly with feeds in which this size is predominant. Heavy media cyclones might be found most economical in beneficiation of the minus 1/2 inch gravels.

Limited measurements of an index of shape and surface roughness indicated that the gravels are quite uniformly rounded and smooth, but the effects of geometric irregularity and surface roughness on separations were not determined. Increasing angularity and surface roughness result in more misplacement of gravels in the float product, which would be fortunate with respect to rejection of deleterious gravels but not with respect to recovery of sound gravels. Measurements of geometric and surface characteristics are not readily made, but significant changes should be readily detected by visual observation.

The gravity of separation is determined primarily by the specific gravity of the medium. However, the usefulness of the medium is profoundly affected by its apparent viscosity, or consistency, and its stability. In HMS beneficiation of gravels, clay and fine rock particles enter the circuit to contaminate the ferrosilicon-magnetite suspensions and increase their consistency and stability. A degree of medium stability is desirable, but consistencies above a critical level impair the separations. A proper balance of consistency and stability is accomplished by controlling the amount of contaminant. The tests with ferrosilicon-magnetite mediums and clay contaminants indicated that in the specific gravity range within which gravel separations are made, 3.5-5 weight percent clay in the media solids imparts desirable stability but does not increase the consistency enough to seriously impair gravel separations. The pilot plant tests in Phase I and II showed that the presence of clay contaminant not exceeding 5 percent improved separations.

The Phase III pilot plant tests in which the feed character, feed rate, and media composition and size structure were constant, confirmed preliminary results and demonstrated that automatic monitoring of the medium specific gravity and consistency provided satisfactory plant control for maximizing product yield and quality. The tests defined the critical levels of contaminant concentration, consistency, and specific gravity differential with respect to product yield and quality, loss of sound gravel, and separation efficiency. While the test results indicated that measurement of specific gravity differential can be used for plant control, application of the measurement depends upon the empirical relationship between stability and consistency. Measurement of consistency, which is the rheological property of the medium directly affecting gravel separations, seems preferable for plant control purposes.

The final pilot plant tests demonstrated that automatic monitoring and recording of the specific gravity and consistency of the medium along with use of a media of fixed type, composition and size structure and surveillance of the feed rate and medium circulation rate, should provide all the conditions for process inspection that would assure a designated quality of product in treating relatively uniform feeds. Process inspection substituted for sampling inspection would have distinct advantages for the producer in terms of higher yields along with assured product quality, and process inspection would eliminate the necessity for operating conditions intended to provide enough margin in product quality to minimize the risk of rejection of the product.

The final pilot plant tests indicated that continuous monitoring of the medium specific gravity and consistency offers a means of automatic plant control through appropriate feed back mechanisms. The tests indicated that chemical dispersants can be used in conjunction with automatic monitoring of the consistency to immediately correct medium conditions and prevent impairment of separations.

The feed rate and manner of feeding the separatory vessel are important, and a uniform feed rate should be maintained. Lower feed rates are required to maintain sharp separations under conditions which impede the stratification of gravels and congest the separation zone.

The data and interpretations presented in this report provide the basis for projections of operating results to be expected under various conditions. However, in making such projections, due consideration must be given to differences in important variables such as the specific gravity composition and other characteristics of the feed, the specific gravity and other conditions of the medium, the feed rate, the type of separatory vessel and method of introducing the feed, and the other operating conditions which may be different than the experimental conditions.

RECOMMENDATIONS

For the purposes of accurate process control, the instrumentation developed in this project should be installed and tested in one or more of the operating HMS plants. After determining the character of the average feed, the medium and other operating conditions for producing the desired product quality could be set on the basis of the known information. Then periodic checks of gravel quality should be carried out during a relatively short period to define the control limits for producing gravel acceptable by Michigan Department of State Highway specifications. After that the gravel producer would have only to monitor the operating conditions and particularly the specific gravity and consistency of the medium so as to stay within control limits. The advantages of operating with maximum plant control so as to have a high quality of product along with optimum yield should appeal to the producer.

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APPENDIX

Table A1

Heavy Liquid Separation Data, Sample No. 1: Weights of Specific Gravity Fractions By Aggregate Types in Sink and Float Products

	Sink Product				Float Product			
	Weight of Sink Fraction, Grams				Weight of Sink Fraction, Grams			
Specific Gravity	Sound	SND*	HA**	Chert	Sound	SND*	HA**	Chert
> 2.96	816	3		4	52			
2.85	1259	3		10	74			
2.75	3693	20		13	382			2
2.65	8453	50	7	22	729	3		6
2.55	13211	89	57	243	1151	16		32
2.45	13794	128	101	658	1183	16	4	78
2.35	13986	252	167	865	1203	35	6	144
2.25	14059	293	197	898	1267	571	165	484
2.15	14061	293	197	898	1299	1299	277	670
< 2.15	14061	293	197	898	1343	1581	290	1011

* SND - soft nondurable

** HA - hard absorbent

Table A2

Heavy Liquid Separation Data, Sample No. 2: Weights of Specific Gravity Fractions by Aggregate Types in Sink and Float Products

	Sink Product				Float Product			
	Weight of Sink Fraction, Grams				Weight of Sink Fraction, Grams			
Specific Gravity	Sound	SND*	HA**	Chert	Sound	SND*	HA**	Chert
> 2.96	238	1			38			
2.85	403	5			53			
2.75	1614	15		16	286	1		23
2.65	3476	44		39	657	8		49
2.55	6230	59	9	143	1143	10		151
2.45	6535	107	41	317	1205	18	10	214
2.35	6649	164	59	508	1219	24	17	305
2.25	6684	228	102	610	1232	57	53	388
2.15	6684	229	108	618	1241	141	105	422
< 2.15	6684	229	108	618	1249	330	105	725

* SND - soft nondurable

** HA - hard absorbent

Table A3

Heavy Liquid Separation Data, Sample No. 3: Weights of Specific Gravity Fractions By Aggregate Types in Sink and Float Products

Specific Gravity	Sink Product				Float Product			
	Weight of Sink Fraction, Grams				Weight of Sink Fraction, Grams			
	Sound	SND*	HA**	Chert	Sound	SND*	HA**	Chert
> 2.96	760	29			2			
2.85	1322	29			9			
2.75	4608	39	5	4	36			2
2.65	9512	76	11	20	95	7		2
2.55	15128	98	12	190	178	7		11
2.45	15661	133	42	404	234	7		50
2.35	15720	140	51	457	409	224	157	549
2.25	15720	165	70	457	550	754	406	956
2.15	15720	171	70	457	572	1259	517	1109
< 2.15	15720	171	70	457	599	1571	554	1266

* SND - soft nondurable

** HA - hard absorbent

Table A4

Heavy Liquid Separation Data, Sample No. 4: Weights of Specific Gravity Fractions By Aggregate Types in Sink and Float Products

Specific Gravity	Sink Product				Float Product			
	Weight of Sink Fraction, Grams				Weight of Sink Fraction, Grams			
	Sound	SND*	HA**	Chert	Sound	SND*	HA**	Chert
> 2.96	682	13			9			
2.85	1216	17			16			
2.75	4586	43		16	59			
2.65	9220	66	3	71	154			5
2.55	14344	98	50	285	278			7
2.45	14897	164	104	702	301	6	4	84
2.35	14988	205	147	768	382	115	77	358
2.25	14990	208	147	773	534	785	428	723
2.15	14990	208	147	773	549	1286	521	919
< 2.15	14990	208	147	773	601	1726	541	1339

* SND - soft nondurable

** HA - hard absorbent

Table A5

Heavy Liquid Separation Data, Sample No. 5: Weights of Specific Gravity Fractions By Aggregate Types in Sink and Float Products

	Sink Product				Float Product			
	Weight of Sink Fraction, Grams				Weight of Sink Fraction, Grams			
Specific Gravity	Sound	SND*	HA**	Chert	Sound	SND*	HA**	Chert
> 2.96	329	20		2	4			
2.85	580	39		2	4			
2.75	2858	39		5	33			
2.65	6633	46		13	107			3
2.55	10298	71	2	214	468	1		54
2.45	10468	84	13	327	1118	139	114	1118
2.35	10468	84	13	327	1501	509	203	1813
2.25	10468	84	13	327	1559	948	334	1991
2.15	10468	84	13	327	1570	1252	394	2037
< 2.15	10468	84	13	327	1583	1310	394	2084

* SND - soft nondurable

** HA - hard absorbent

Table A6

Sample No. 6: Heavy Liquid Separation Data by Aggregate Types, Total Deleterious and Total Aggregate

Specific Gravity	Weight of Sink Fraction, Grams					
	Sound	SND*	HA**	Chert	Total Deleterious	Total Aggregate
> 2.85	18711	326	91	180	597	19308
2.75	66771	427	140	1172	1739	68510
2.65	123102	702	427	2407	3536	126638
2.55	189873	1157	1128	6866	9151	199024
2.45	197585	1698	2162	11142	15002	212587
2.35	200570	3152	3544	13438	20134	220704
< 2.35	206964	5965	4872	17271	28108	235072

*SND - soft nondurable
**HA - hard absorbent

Table A7

Sample No. 4: Weights of Heavy Liquid Sink Fractions by Size Classes and Aggregate Types in Sink and Float Products

-1 1/2"+1"

Specific Gravity	Sink Product, Grams				Float Product, Grams			
	Good	SND	HA	Chert	Good	SND	HA	Chert
>2.96	73							
2.85	146							
2.75	372							
2.65	1145							
2.55	2237							
2.45	2267	32		32				
2.35	2267	32		32		43	103	
2.25	2267	32		32		97	103	34
2.15	2267	32		32		97	103	34
<2.15	2267	32		32		97	103	34

-1"+1/2"

Specific Gravity	Sink Product, Grams				Float Product, Grams			
	Good	SND	HA	Chert	Good	SND	HA	Chert
>2.96	431	7						
2.85	1300	18						
2.75	4562	50		14				
2.65	10676	101		62	58			
2.55	20362	176	41	248	146			
2.45	20653	200	91	521	150			42
2.35	20691	224	133	547	187	40	56	145
2.25	20691	224	133	547	283	472	261	316
2.15	20691	224	133	547	286	785	319	383
<2.15	20691	224	133	547	311	1079	334	569

-1/2"+3/8"

Specific Gravity	Sink Product, Grams				Float Product, Grams			
	Good	SND	HA	Chert	Good	SND	HA	Chert
>2.96	178	6			9			
2.85	452	12			25			
2.75	1550	23		2	75			
2.65	3883	38	3	25	180			5
2.55	7449	61	12	124	370			12
2.45	7681	71	16	236	389	6	4	47
2.35	7734	88	17	276	433	75	21	218
2.25	7736	91	17	281	489	270	64	412
2.15	7736	91	17	281	501	404	99	507
<2.15	7736	91	17	281	528	551	104	741

Table A8

Sample No. 5: Weights of Heavy Liquid Sink Fractions by Size Classes and Aggregate Types in Sink and Float Products

-1 1/2"+1"

Specific Gravity	Sink Product, Grams				Float Product, Grams			
	Good	SND	HA	Chert	Good	SND	HA	Chert
>2.96	36							
2.85	91							
2.75	350							
2.65	569							
2.55	604							
2.45	604							29
2.35	604							29
2.25	604					24		29
2.15	604					24	23	29
<2.15	604					24	23	29

-1"+1/2"

Specific Gravity	Sink Product, Grams				Float Product, Grams			
	Good	SND	HA	Chert	Good	SND	HA	Chert
>2.96	251	20						
2.85	630	49						
2.75	2063	49			12			
2.65	4440	56		8	40			
2.55	6826	69		145	200			16
2.45	6913	73	10	227	587	80	102	614
2.35	6913	73	10	227	827	350	179	999
2.25	6913	73	10	227	853	666	298	1072
2.15	6913	73	10	227	855	877	327	1093
<2.15	6913	73	10	227	855	877	327	1093

-1/2"+3/8"

Specific Gravity	Sink Product, Grams				Float Product, Grams			
	Good	SND	HA	Chert	Good	SND	HA	Chert
>2.96	78			2	4			
2.85	243			4	8			
2.75	1033			7	25			
2.65	2172			7	71			3
2.55	3232	12	2	71	272	1		38
2.45	3280	21	3	102	535	59	12	475
2.35	3280	21	3	102	678	159	24	785
2.25	3280	21	3	102	710	258	36	890
2.15	3280	21	3	102	719	351	44	915
<2.15	3280	21	3	102	719	351	44	915

Table A9

Consistency and Stability of Mediums Made Up to Various Specific Gravities with Ferrosilicon and Magnetite and Additions of Clay

	Specific Gravity 2.40								
Clay, Wt. %	0	2	4	5	6	8	10	11	12
Consistency, cP	5.95	6.21	7.12	7.87	9.12	13.58	517.1	538.1	739.8
Stability, %	2.5	4.8	14.5	42.9	62.2	68.5	81.4	85.4	72.2

	Specific Gravity 2.45									
Clay, Wt. %	0	0*	1.5	3	3.8	4.1	4.4	5.8	8.5	11.0
Consistency, cP	3.68	4.32	3.95	3.96	4.80	4.97	5.22	6.05	7.82	105.5
Stability, %	2.9	2.0	2.5	7.0	12.2	34.8	75.6	80.7	92.4	91.4

	Specific Gravity 2.50							
Clay, Wt. %	0	2	3	4	5	6	7	8
Consistency, cP	6.74	7.28	8.25	8.50	10.40	11.40	13.80	219.7
Stability, %	1.8	5.0	11.4	33.4	76.0	76.4	100.00	94.6

	Specific Gravity 2.55							
Clay, Wt. %	0	0*	2	3	4	6	8	10
Consistency, cP	4.54	4.57	4.66	5.78	6.14	8.47	15.64	521.0
Stability, %	0.6	0.6	6.5	18.1	71.2	87.6	87.8	84.0

	Specific Gravity 2.60								
Clay, Wt. %	0	2	3	4	6	8	8*	9	10
Consistency, cP	4.71	7.72	7.86	12.11	14.28	43.90	43.55	113.3	808.4
Stability, %	1.9	10.9	35.0	56.5	85.3	94.3	93.1	92.7	85.0

	Specific Gravity 2.65										
Clay, Wt. %	0	0*	1	2	3	4	4*	5	6	7	8
Consistency, cP	6.53	6.29	7.09	5.91	6.15	7.69	7.72	9.84	12.63	23.23	44.53
Stability, %	3.3	3.8	8.2	14.9	36.7	74.3	76.3	88.1	89.6	94.0	90.6

*Tests repeated

Note: Clay addition is weight percent of total media solids

Table A10

Measurements of Consistency and Stability of Mediums Made Up with Media of Various Size Structures

Mean Size, Microns*	Consistency, cP	Stability, %
172	5.64	0
172	5.93	0
Mean	5.78	
96	5.88	1.83
96	6.04	1.87
96	5.81	1.89
Mean	5.91	1.86
74	6.42	20.27
74	6.76	10.48
74	6.56	13.33
Mean	6.58	14.69
44	7.54	78.12
44	7.34	83.68
44	7.32	80.55
Mean	7.40	80.78

* Midpoint of cumulative distribution (Figure 20)

Note: All tests were made at 2.35 specific gravity.

Table A10-1

Measurements of Consistency and Stability
With Media of Various Size Structures

Mesh Size	Weight %							
	Medium A		Medium B		Medium C		Medium D	
	1	2	1	2	1	2	1	2
+100	10.0	10.0	8.0	7.7	6.0	6.2	4.0	4.2
+150	14.0	13.6	14.0	12.8	12.0	11.0	8.0	7.1
+200	16.0	14.8	14.0	13.2	12.0	11.8	10.0	9.5
+270	14.0	11.7	13.0	10.3	11.0	10.6	11.0	9.0
+325	11.0	10.2	9.0	8.2	7.0	7.0	5.0	6.3
+500	20.0	26.7	17.0	30.9	15.0	27.3	12.0	34.5
-500	15.0	13.0	25.0	16.9	37.0	26.1	50.0	29.4
Consistency, cP	7.85	7.18	6.40	6.16	7.84	6.82	8.27	8.63
Stability, %	7.0	7.4	45.4	23.1	34.7	67.5	87.5	85.6

Note: media 2:1 weight percent ferrosilicon to magnetite.

1 - original media made up to 2.55 specific gravity

2 - filtered, screened and repulped media.

Table A10-2

Measurements of Consistency and Stability With Media of the Same Size Structure and Varying Amounts of Clay and Rock Sand Added

Mesh Size	Weight %							
	Medium A		Medium B		Medium C		Medium D	
	1	2	1	2	1	2	1	2
+100	13.47	13.33	12.95	12.73	12.35	12.14	11.76	11.68
+150	12.93	12.92	12.78	12.75	12.63	12.86	12.49	12.57
+200	15.70	16.01	15.73	15.86	15.46	15.58	15.34	15.32
+270	16.60	14.97	16.48	15.30	16.39	16.09	16.29	16.43
+325	8.76	9.50	8.71	8.58	8.66	7.91	8.62	7.64
+500	27.72	26.48	27.69	25.85	27.69	26.00	27.70	25.97
-500	4.82	6.79	5.81	8.92	6.81	9.43	7.81	10.39
Clay, Wt. %	1.0		2.0		3.0		4.0	
Rock Sand, Wt. %	3.5		2.5		1.5		0.5	
Stability, %	13.1	24.3	22.7	42.0	29.5	24.9	40.9	42.0
Consistency, cP	6.89	6.91	6.72	6.78	9.58	7.63	7.76	7.49

1 - original media mixture

2 - filtered, screened and repulped media mixture

Note: media mixture 2:1 weight percent ferrosilicon to magnetite with 4.5 weight percent clay and rock sand added in proportions shown; medium made up to 2.55 specific gravity.

Table A 11

Heavy Media Batch Test Conditions and Separation Results by Aggregate Types

Test No.	Test Conditions				
	1	2	3	4	5
Clay, Wt. %*	0	2.50	5.00	7.50	10.00
Spec. Grav. Mid.	2.34	2.31	2.31	2.22	2.19
Spec. Grav. Dif.	0.17	0.27	0.13	0.05	0.03
Consistency, cP	2.74	2.76	3.62	4.47	4.78
Stability, %	0	13.0	22.8	26.5	42.4

Sample No. 1

	Sink Product				Float Product			
	Aggregate Type, Wt Gms.				Aggregate Type, Wt Gms.			
Test No.	Sound	SND	HA	Chert	Sound	SND	HA	Chert
1	13100	386	177	687	2221	1439	304	1253
2	14705	833	272	1103	611	984	207	837
3	15012	642	247	1130	300	1163	234	810
4	15041	447	200	925	261	1352	280	1015
5	14284	345	149	701	1014	1445	332	1246

Sample No. 4

	Sink Product				Float Product			
	Aggregate Type, Wt Gms.				Aggregate Type, Wt Gms.			
Test No.	Sound	SND	HA	Chert	Sound	SND	HA	Chert
1	14097	489	406	957	1405	1410	275	1181
2	15293	1047	558	1461	191	852	122	677
3	15155	510	377	964	335	1377	303	1169
4	15189	477	399	978	245	1415	278	1172
5	13698	160	212	491	1743	1740	465	1651

* Weight percent of media solids

Table A12

Conditions for Pilot Plant Tests, Phases I and II

Test No.	Feed Rate tons/hr	Clay wt. pct. (1)	Medium Circulation Rate(2)	Medium Specific Gravity		Medium Consistency, centipoise(5)	Stability, pct.(6)
				Gauge(3)	Dif.(4)		
1	1	0	277	2.30	0.20	6.8	27.6
2	1	0	268	2.38	0.19	8.1	34.3
3	1	0	278	2.48	0.18	9.7	42.1
4	1	0	285	2.63	0.15	11.8	46.0
5	1	0	270	2.69	0.14	12.4	49.7
6	2	0	278	2.30	0.35	7.4	34.8
7	2	0	278	2.38	0.30	7.9	39.0
8	2	0	278	2.48	0.24	9.1	42.6
9	2	0	278	2.63	0.17	10.9	53.0
10	2	0	288	2.69	0.14	13.3	54.2
11	2	3.4	280	2.30	0.08	12.6	77.6
12	2	3.8	280	2.38	0.07	13.1	84.4
13	2	5.0	290	2.48	0.06	30.3	91.4
14	2	3.7	305	2.63	0.06	32.5	89.4
15	2	1.9	297	2.69	0.07	26.7	82.9

1. Weight percent of media solids.

2. Gallons per minute measured by Venturi flow meter.

3. Specific gravity of circulating medium recorded by density gauge.

4. Specific gravity differential determined by pulp density balance measurements of samples from sink and float drain screen underflows.

5. Mean consistency of samples from sink and float drain screen underflows averaged with consistency of sample from circulation sump.

6. Mean stability of samples from sink and float drain screen underflows averaged with stability of sample from circulation sump.

Table A13

Weight Percent Distributions of Aggregates by Types in Sink and Float Products from HMS Pilot Plant Tests

		Sink Product					Float Product				
		Aggregate Type, Wt. Gm.					Aggregate Type, Wt. Gm.				
Test No.	Spec. Grav.	Sound	SND*	HA**	Chert	Total	Sound	SND*	HA**	Chert	Total
1	2.30	71732	2126	1976	6056	81890	88	897	68	649	1702
2	2.38	66284	565	686	3650	71185	162	2118	885	2058	5223
3	2.48	100788	515	663	3735	105701	2665	3675	1854	5078	13272
4	2.63	88984	365	279	1815	91443	13414	3874	2343	6819	26450
5	2.69	39498	155	72	580	40305	40092	2772	1815	6103	50782
6	2.30	76429	1033	775	5638	83875	304	594	186	629	1713
7	2.38	86915	924	1088	5682	94609	409	1721	561	1613	4304
8	2.48	77755	497	627	3746	82625	550	2058	1174	3003	6785
9	2.63	65480	367	182	1569	67598	6003	2125	1164	4921	14219
10	2.69	42070	194	161	830	43255	28984	2145	1397	5344	37870
11	2.30	82985	863	1032	5080	89960	654	1220	704	1857	4435
12	2.38	81810	711	1054	3988	87563	2040	1803	1229	3094	8166
13	2.48	59598	319	399	2306	62622	22219	1630	1324	4252	29425
14	2.63	80755	333	291	2210	83589	22285	2544	1895	6278	33002
15	2.69	47303	165	205	737	48410	41478	1970	1505	6792	51745

Note: Tests Nos. 1-5 at feed rate 1 ton/hour, no clay added
Tests Nos. 6-10 at feed rate 2 tons/hour, no clay added
Tests Nos. 11-15 at feed rate 2 tons/hour, clay added
* Soft nondurable
** Hard absorbent

Table A14

Heavy Liquid Separation Data of Samples Taken from Nine Michigan Plants

Specific Gravity	No. 1		No. 2		No. 3		No. 4	
	Sink Wt. %	Float %	Sink Wt. %	Float %	Sink Wt. %	Float %	Sink Wt. %	Float %
> 2.96	4.26	0.15	5.19	-----	8.31	0.08	1.71	0.01
2.75	19.60	1.20	16.02	0.14	15.37	1.86	15.53	1.06
2.65	28.60	3.40	33.05	0.83	33.64	1.47	31.81	3.01
2.55	37.70	6.00	23.11	4.63	25.01	4.83	25.87	9.47
2.35	16.00	6.63	1.00	11.50	1.45	7.09	0.54	8.94
2.15	-----	0.75	-----	4.06	-----	0.79	-----	1.62
< 2.15	-----	0.10	-----	0.47	-----	0.10	-----	0.42
	81.76	18.23	78.37	21.63	83.78	16.22	75.46	24.54

Specific Gravity	No. 5		No. 6		No. 7		No. 8		No. 9	
	Sink Wt. %	Float %	Sink Wt. %	Float %	Sink Wt. %	Float %	Sink Wt. %	Float %	Sink Wt. %	Float %
> 2.96	5.27	-----	6.31	0.15	3.40	0.01	1.93	-----	1.74	-----
2.75	11.46	0.35	18.36	0.53	6.62	0.28	12.86	0.34	4.65	0.02
2.65	35.72	1.38	36.57	1.91	45.63	5.12	24.09	1.79	34.83	1.48
2.55	28.25	5.12	19.14	4.17	22.38	3.36	34.94	5.70	37.43	6.45
2.35	3.34	6.17	2.38	9.30	3.35	6.23	2.76	12.89	3.41	9.39
2.15	-----	2.41	-----	1.17	0.08	3.11	-----	1.46	-----	-----
< 2.15	-----	0.53	-----	0.01	-----	0.43	-----	1.24	-----	-----
	84.04	15.96	82.76	17.24	81.46	18.54	76.58	23.42	82.06	17.94