Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

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TEST PROCEDURES FOR THE SELECTION AND PROCUREMENT OF POLYMERS FOR CENTRIFUGAL DEWATERING OF ANAEROBICALLY DIGESTED SLUDGE

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TEST PROCEDURES FOR THE SELECTION AND PROCUREMENT OF POLYMERS FOR CENTRIFUGAL DEWATERING OF ANAEROBICALLY DIGESTED SLUDGE

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DISCLAIMER

INTRODUCTION

Appropriate and economical sludge treatment technologies as well as relevant management techniques have become increasingly important in recent years as a result of both public concern for environmental quality and safety and the need of municipal water reclamation plants (WRPs) to comply with the United States Environmental Protection Agency's (USEPA) regulations for the utilization and disposal of sludge and biosolids. One of the important facets of sludge treatment is the conditioning of raw and/or digested sludge with organic polymers for thickening and dewatering.

Application of organic polymers as sludge conditioners has accelerated the development of a variety of polymer products by different manufacturers. Different polymer products are effective to varying degrees as sludge conditioners. The availability of a vast array of products makes the selection of the most appropriate sludge conditioner at the lowest cost for a particular sludge and a given application (e.g., thickening or dewatering) very difficult.

Empirical test procedures are of immense value to select the most efficient and economical polymer for a given sludge dewatering application. Such test procedures must account for both sludge and polymer characteristics because of the interactive influences of both these characteristics on the performance of any dewatering equipment.

Any such developed empirical test procedures will typically involve either a full-scale, pilot-scale, or laboratory bench scale test for a particular dewatering application, e.g., centrifugal dewatering. Full-scale tests, of course, are the most reliable but they are cumbersome, expensive, time-consuming, and resource-intensive. Conversely, pilot-scale and laboratory bench scale tests are more convenient than full-scale tests, but they may not be able to entirely simulate the performance of full-scale devices and, hence, they are less reliable. Obviously, pilot-scale and laboratory bench tests allow for more controlled conditions than full-scale tests, but ultimately because of greater reliability of full-scale tests, they become the prime choice to select a polymer for optimum performance at the least cost.

Although full-scale tests are quite reliable for polymer selection, the importance of pilot-scale or laboratory bench scale tests should not be underestimated because they lay down a solid foundation for full-scale tests by providing useful experience and information which help to reduce the workload and time involvement associated with full-scale tests.

The research staff at the Metropolitan Water Reclamation District of Greater Chicago (District) faced a challenge in 1980 to develop protocols for screening different polymer products for the selection of the best polymer at the lowest cost for centrifugal dewatering application. The essential requirement of the protocols was that the protocols must support a competitive bidding environment and be acceptable to all vendors participating in the bidding process. The development of test protocols became necessary because of the addition of low-performance rotating bowl centrifuges for sludge dewatering at the District's three major WRPs; viz., Stickney, Calumet, and John E. Egan, in order to yield a centrifuge cake of about 15 percent solids content.

Even before the full-scale centrifuges were installed, an empirical test procedure for polymer selection was developed by using laboratory bench scale tests and a pilot-scale centrifuge machine. Based on the pilot-scale test results, polymers were selected and subsequently used for optimal centrifugal dewatering of anaerobically digested sludge at the District's centrifuge complexes. However, due to poor reliability in predicting full-scale centrifuge cake solids performance based solely on bench and pilot-scale tests, full-scale polymer test procedures for polymer selection were developed.

The full-scale test procedures, first developed for low-performance rotating bowl centrifuges, were satisfactorily used until 1989. At that time, the District replaced the low-performance centrifuges with high-performance rotating bowl centrifuges at each of its three major WRPs with the intent of doubling the centrifuge cake solids content from about 15 to about 30 percent. The greater complexity of these new machines, along with the additional variables required for process control, necessitated the development of a more sophisticated full-scale test procedure for polymer selection. The test procedure for the high-performance machines also required the development of new performance models and optimization techniques for the selection of the best polymer at the least cost.

This report presents and discusses the relevant details of the polymer testing protocols developed for the high-performance rotating bowl centrifuges. These protocols include the performance models, optimization techniques used with the performance models, and commentary on algorithms developed for the high-performance machines. Suggestions are also made for alternatives or possible modifications of the protocols. This report also presents the software code used to implement the model parameter estimation and the optimization procedure in Appendices AII and AIII, respectively.

The authors believe that the test protocols and bidding procedures, described in this report, for the selection of polymers with the best performance are a novel contribution to the field of centrifugal dewatering. It is hoped that the proven test procedure developed and presented in this report will help WRP operators to purchase polymer products for optimum centrifuge dewatering performance at the lowest cost in a competitive bidding environment.

OVERVIEW OF POLYMER SELECTION PROCEDURES AND PROTOCOLS FOR THE PURCHASE OF POLYMERS

A competitive bidding environment which ensures a fair and unbiased treatment of submittals by all polymer vendors is very essential for the selection of the best polymer at the least cost. Major critical steps which typically take place in a sequential fashion in implementing the polymer selection procedure at the District are shown as indicated below along with an estimated time duration for each of these steps:

1. Preparation of advertisement and contract documents (2 weeks).
2. Advertisements containing details of the bidding process and centrifuge dewatering test protocols sent to polymer manufacturers (2 to 3 weeks).
3. Laboratory tests (1 week).
4. Full-scale tests (3 weeks).
5. Data analysis (2 weeks).
6. Preparation of contract and its award (2 to 6 weeks).

A bid document (Appendix AI) is sent to various polymer manufacturers and their authorized agents for the submittal of polymer products. The advertisements may state that participants send samples (of approximately one pint size) of their polymer products to the Wastewater Treatment Research Laboratory at Stickney for screening and/or polymer dosage estimation, if they wish to have them tested on full-scale centrifuge machines.

By conducting laboratory tests (see the section on Laboratory Test: Significance and Test Procedure), dosage is estimated for each polymer submitted. Estimated polymer dosage is that which corresponds to the minimum capillary suction time (CST). This is obtained from a CST vs. polymer dose curve developed from laboratory test results. Optionally, all the polymers then may be ranked based on the minimum CST values and/or floc-strength values. Polymers which exhibit high minimum CST values and/or low floc strength may be deleted from further consideration for full-scale tests.

The estimated dosages of the promising polymers provide important guidance for calculating the number of required 55-gallon drums of polymer for the test and for preparing the appropriate polymer concentration during the full-scale test. Usually 1 to 9, 55-gallon drums of raw polymer will be used to conduct a full-scale test on one centrifuge for at least three to four hours. During this time, a sufficient number of samples for the determination of percent cake and centrate solids can be collected.

Usually, only one or two polymers can realistically be tested during an eight-hour workday. Therefore, it is prudent to restrict the number of polymer submittals to one or two per vendor for evaluation. The current practice at the District prohibits vendors from submitting more than two polymer products for full-scale evaluation.

During the full-scale test runs, a sufficient number of cake, centrate, and feed samples are collected at various settings of pinion speed and polymer dosage, over a practical operating range of torque. The model parameter estimation is enhanced by ideally using a factorial or fractional factorial sampling design. The samples must be taken after at least 15 minutes of centrifuge operation when settings are changed to allow for the cake in the bowl to be replaced from the previous settings. The feed sludge flow rate must be held constant for the duration of the tests, whereas the polymer flow rate and pinion speed are varied.

The bowl speed is the number of revolutions per minute of the outer centrifuge bowl, and the pinion speed is the number of revolutions per minute of the scroll inside the bowl which is revolving in the opposite direction to that of the bowl's rotation. The pinion speed is always less than the bowl speed. Bowl speed remains constant during test runs and normal operation.

The safest sampling order of centrifuge feed, cake, and centrate is to start at high pinion speeds (high torque, low capture, high cake) and to go to low pinion speeds in equal spaced increments (low torque, high capture, low cake). If sampling begins at low pinion speeds, there is a greater risk of the cake being liquefied, causing downtime for cleanup, along with ill feelings among plant personnel. Detailed test procedures for the full-scale tests are presented in the section, "Full Scale Test: General Principles, Sampling Strategy, and Test Procedure."

Upon completion of sampling, all samples are analyzed for percent total solids. Then the pinion speeds and polymer doses used, along with the percent capture and cake solids achieved, are tabulated. These data are then used in the model parameter estimation and optimization procedures. By using the estimated values of parameters in the models, optimum dose, optimum percent cake solids, and optimum pinion speed are obtained as explained in the section, "Data Analysis and Discussion."

Parameters of selected models are estimated by using a commercially available computer program called "Scientist" (6) while the pinion speed, cake solids, and dose are optimized by using a computer program called "TK Solver" (7). Both programs are installed in the District's computer work stations. The necessary information on software is provided in the section, "Data Analysis and Discussion," while the computer codes developed in both programs are presented in Appendices AII and AIII.

The optimum dosages of all polymers are then communicated through a memorandum to the Chief of the Maintenance and Operations (M&O) Department by the Director of the Research and Development (R&D) Department. A sample memorandum with test results is presented in Appendix AI. The respective vendors are then contacted by the Chief of the M&O Department to submit their price quotation based on the dosage requirements of their respective polymers and the quantity of solids to be conditioned during the contract period.

The bid price quoted by vendors for each of the polymers submitted which successfully met the criterion specified is individually substituted into an equation developed by District staff (Equation 10 and also refers to Sample Bid documents in Appendix AI), and the total processing cost for each of the polymers is calculated. The polymers are then ranked according to the total processing cost. The polymer with the lowest processing cost is finally selected.

A contract for the selected polymer is awarded to the vendor by the Purchasing Department of the District.

The entire procedure described in this section is summarized in Figure 1.

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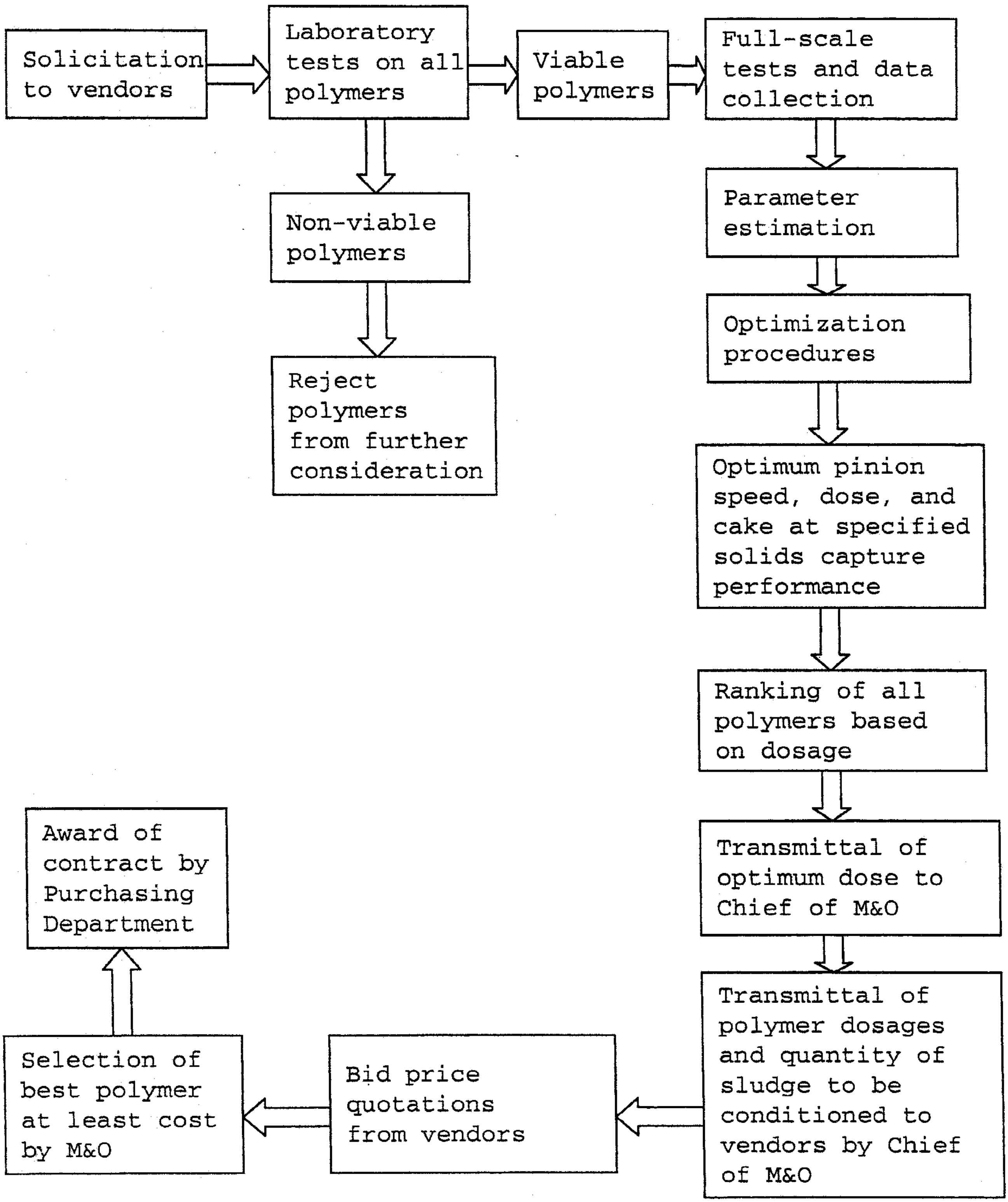
FIGURE 1

FLOW DIAGRAM SHOWING POLYMER TESTING AND PROCUREMENT PROCESS AT THE DISTRICT



LABORATORY TESTS: SIGNIFICANCE AND TEST PROCEDURES

Significance of Laboratory Tests

Prior to undertaking full-scale tests, consideration may be given to screening out unpromising polymers and estimating optimum polymer dosages of all promising polymers by a standardized laboratory procedure so that the number of polymer drums and appropriate polymer concentration required for the full-scale tests can be estimated.

In addition to estimation of quantity of polymer and its concentration for full-scale tests, laboratory tests also provide important guidance regarding the control of machine variables. Proper control of the machine and other variables (polymer flow, pinion speed) at the start of full-scale testing can potentially avert emergency situations such as liquefaction of cake in the centrifuge bowl or plugging up the bowl with cake.

In either case, the emergency centrifuge alarm sounds. In the worst case, the centrifuge may possibly shut down. Such emergency occurrences will not endear the test personnel to the plant operators and may cause hours of downtime. Depending upon the situation, either the floor may need to be hosed down or the cake may need to be softened by inputting water (instead of sludge) into the centrifuge bowl during downtime.

CST Test

INTRODUCTION TO CST TEST

In the laboratory test for estimating polymer dosage for centrifuge dewatering applications, the capillary suction time (CST) apparatus manufactured by Triton Electronics, England (Figure 2), is used. This instrument consists of a hollow well which serves as a sludge reservoir resting on filter paper. When sludge is poured into the reservoir, filtrate is drawn out of the sludge and moves outward as it saturates the filter paper. When the filtrate reaches the first electrode touching the paper, a timer starts, and when the filtrate reaches the second electrode touching the paper, the timer stops. The time interval taken by the filtrate to travel the distance between the two electrodes is called CST.

While interpreting CST results, it must be kept in mind that the absolute minimum achievable CST is 5 seconds, the CST of water. With increase in coagulant dose, more bound water is released from the sludge matrix and as a result, the CST approaches absolute minimum. The closer the minimum CST is to 5 seconds, the better is the effectiveness of a polymer.

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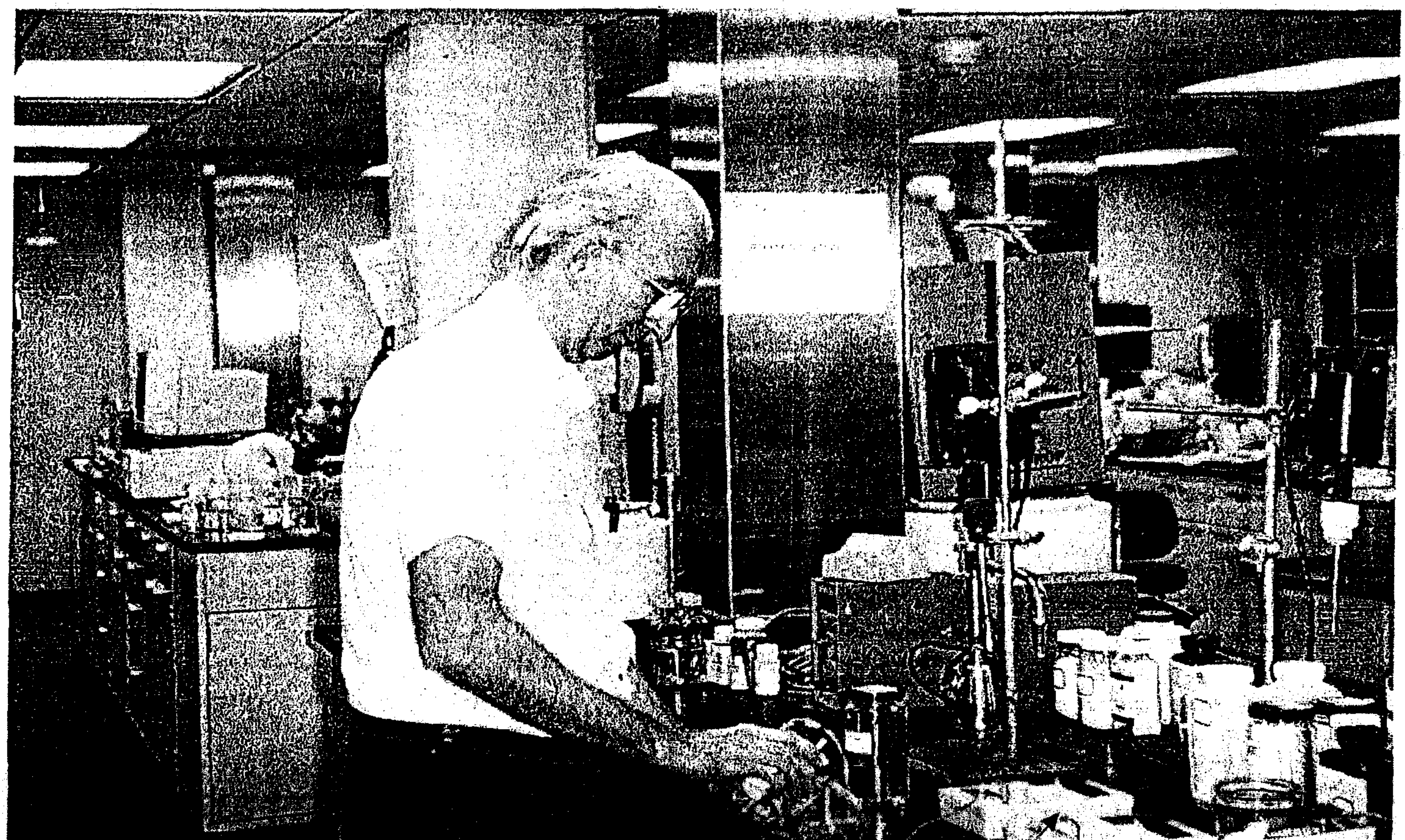
FIGURE 2

CST APPARATUS



CST Apparatus

General experience in this type of work indicates that the minimum CST should be approximately 10 seconds for effective dewatering performance (relevant mixing/stirring protocols are discussed later in this section).

APPLICABILITY OF CST TEST RESULTS FOR DEWATERABILITY EVALUATION

Both theoretical and historical perspectives in the technical literature focus on the filtration aspect of CST. Viewing CST as a measure of unbound water in highly flocculated sludge leads to the consideration of the filter paper as a collection vessel for the water, rather than as a filtration medium for the sludge. This realization leads to the implication that CST can be used for dewatering applications in a more general context than filtration.

Extensive laboratory and full-scale experimental work conducted at the District (10) has conclusively demonstrated that enlarging the scope of CST as a tool in dewatering applications is feasible and has practical applications. The development of CST test protocols and laboratory test methodology as described in this section is an example of the work carried out at the District.

FACTORS AFFECTING CST TEST RESULTS AND DEVELOPMENT OF CST TEST PROTOCOLS

Among the most important factors affecting CST are the quality of filter paper, geometry of mixing containers, preparation of polymer solution, dilution of sludge by addition of polymer, and mixing/stirring protocols (intensity of shear stress forces and their duration when applied to sludge flocs).

Homogenous fiber density allows for less variation in CST readings, so that making a standard practice of using quality filter paper in the test, the variations in sorption of water by the type of paper used can be potentially minimized. Therefore, in this test, Whatman #17 chromatography grade filter paper cut into strips 2 cm. wide and 7 cm. long (Figure 3) is used as a standard protocol at the District, since it is produced to have a constant fiber density from batch to batch.

Shear stress on the sludge flocs varies depending on the dewatering device used. In laboratory tests, although it cannot be exactly simulated, one should attempt to approximate the shear stress conditions in laboratory containers using mechanical mixers. The geometry of the containers used with respect to the mixing device for sludge/polymer mixing is also important. At the District laboratory, the containers used

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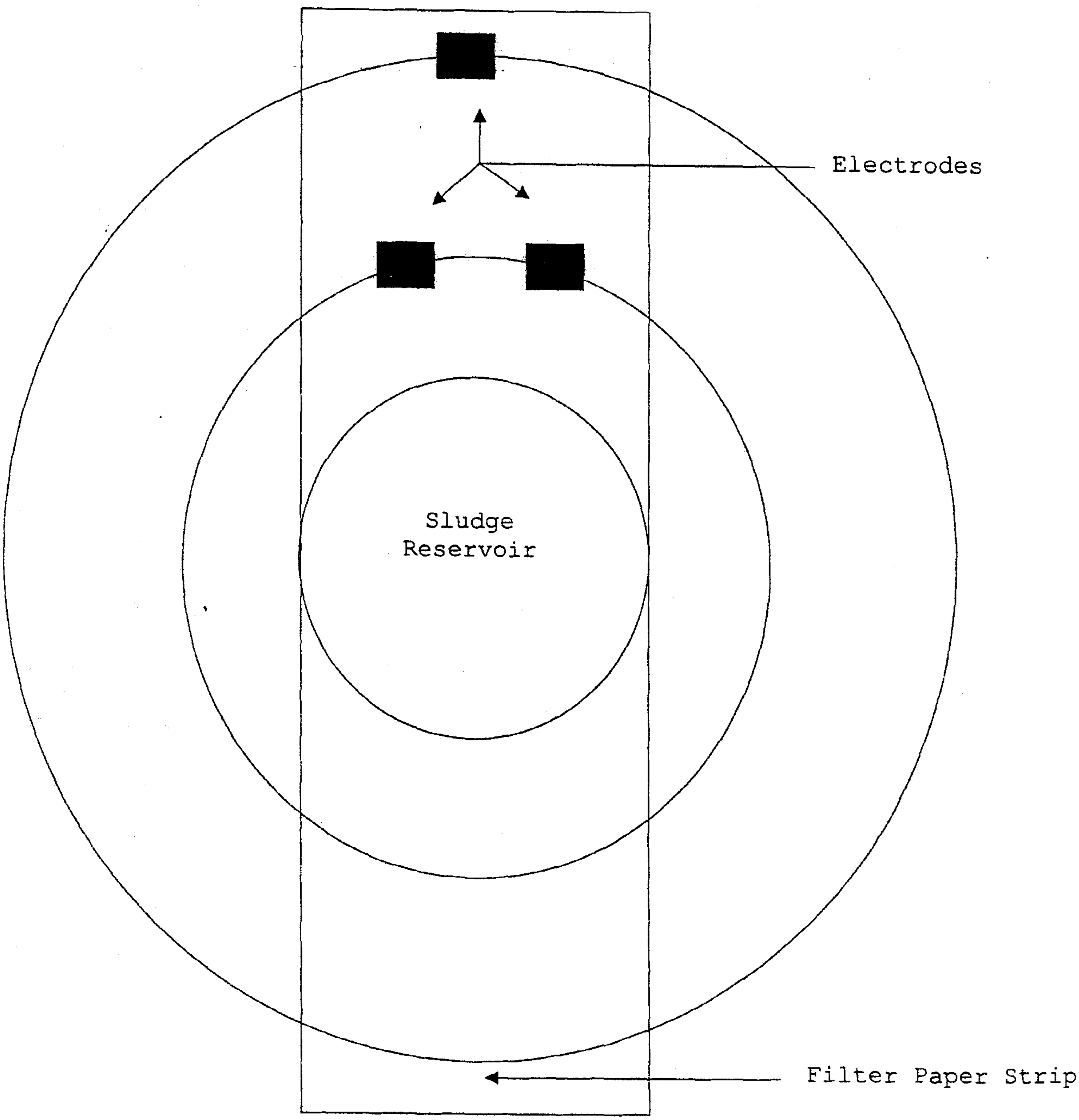
FIGURE 3

FILTER PAPER ARRANGEMENT FOR CST TEST



for polymer/sludge mixing are 600 mL beakers. In addition to that, a fixed quantity of 200 wet grams of sludge is used in all cases to keep constant the effect of geometry on shear destruction of floc. This is because mixing intensity is affected by the volume of sludge being mixed, and the intent is to standardize mixing intensity.

Polymer solution preparation is also an important consideration. Polymer solutions must be prepared daily to minimize the effect of polymer deterioration (the loss of active percent solids) with time. The deterioration in polymer performance over a time span of several hours is substantial. However, the extent of deterioration differs with the polymer structure and other characteristics, such as type of polymer. For example, mannich-type polymers deteriorate most rapidly since they are subject to hydrolysis with subsequent reduction of coagulation activity.

The mixing time involved in polymer solution preparation must also be standardized because the time and rigor of mixing affects and deteriorates polymer flocculation performance. The extent of the deterioration depends on polymer structure and other characteristics, such as the type of polymer. Mannich-type polymers, for example, are the most affected polymers.

These considerations are important when conducting a laboratory CST procedure, because different conclusions regarding the effectiveness of the same polymer can be reached depending on the procedure used for polymer solution preparation, other experimental conditions being equal. For example, tests conducted with a freshly prepared polymer solution using a specific laboratory preparation protocol can yield results different from those obtained with a polymer solution that has been "aging" for several hours to days or a week and is prepared with a different protocol.

The mixing time to prepare a polymer solution varies with the type of polymer, and is further elaborated upon in a section entitled "Polymer Solution Preparation."

No more than 40 mL of polymer solution should be added to 200 wet grams of sludge in order to keep the dilution with sludge preferably at 10 percent (by volume), but definitely below 20 percent, in order to keep the dilution ratio of polymer to sludge (by volume) similar to what is observed in the centrifuges. At the District, an attempt is made to prepare the polymer solution concentration so that the minimum CST is attained at a dosage of around 20 mL of polymer solution per 200 mL of sludge. This effort is made to center the dosage curve minimum CST (Figure 4) at midrange (0 to 40 mL) and to

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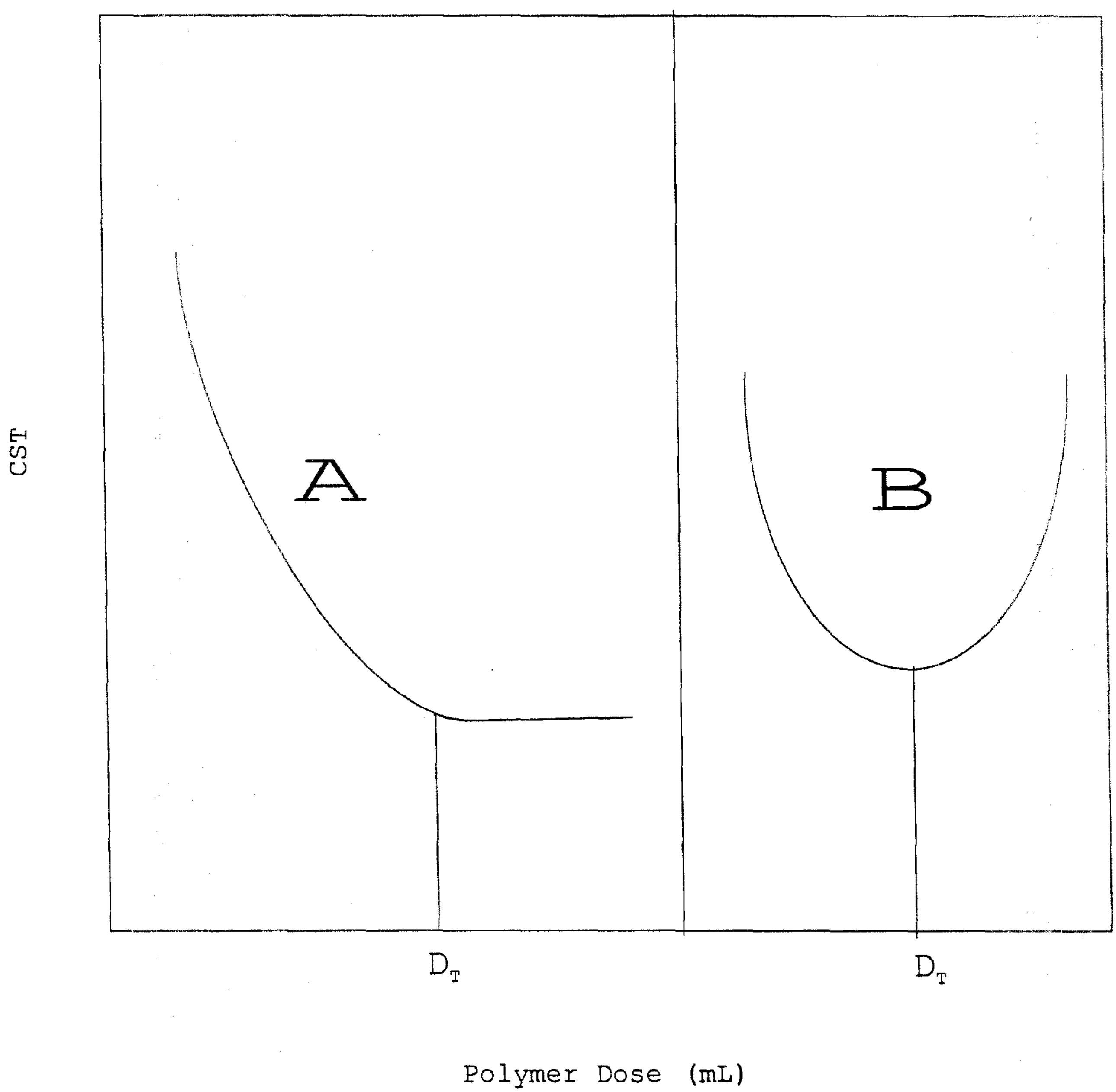
FIGURE 4

TYPICAL DOSAGE CURVES



keep the dilution with sludge constant at approximately 10 percent in almost all cases. When the optimum polymer dose is obtained from the dosage curve in terms of polymer volume (D_T in Figure 4), it can then be expressed in terms of a wet, dry, or active polymer basis in any units desired.

In addition to the standardization of important components of the CST test as discussed above, the mixing/stirring protocol (mixing time and mixing speed RPM) of the polymer/sludge mixture must also be appropriate to the dewatering application in order for polymer performance evaluation to be viable. To adjust the mixing time and mixing speed variables, a digital timer is used in conjunction with a variable speed mixer (Figure 5).

It is important to distinguish between mixing and stirring. Mixing, which is more gentle and at lower revolutions per minute (RPM) than stirring, promotes floc formation due to polymer distribution, while stirring, which is associated with higher RPMs, promotes floc deterioration due to shearing of the flocs already formed. As such, both mixing and stirring of the polymer/sludge mixture exert shear stress on the flocs. Therefore, the amount of energy transferred as shear stress to the polymer/sludge mixture must be adequately simulated to represent the shear stress that affects the flocs in a

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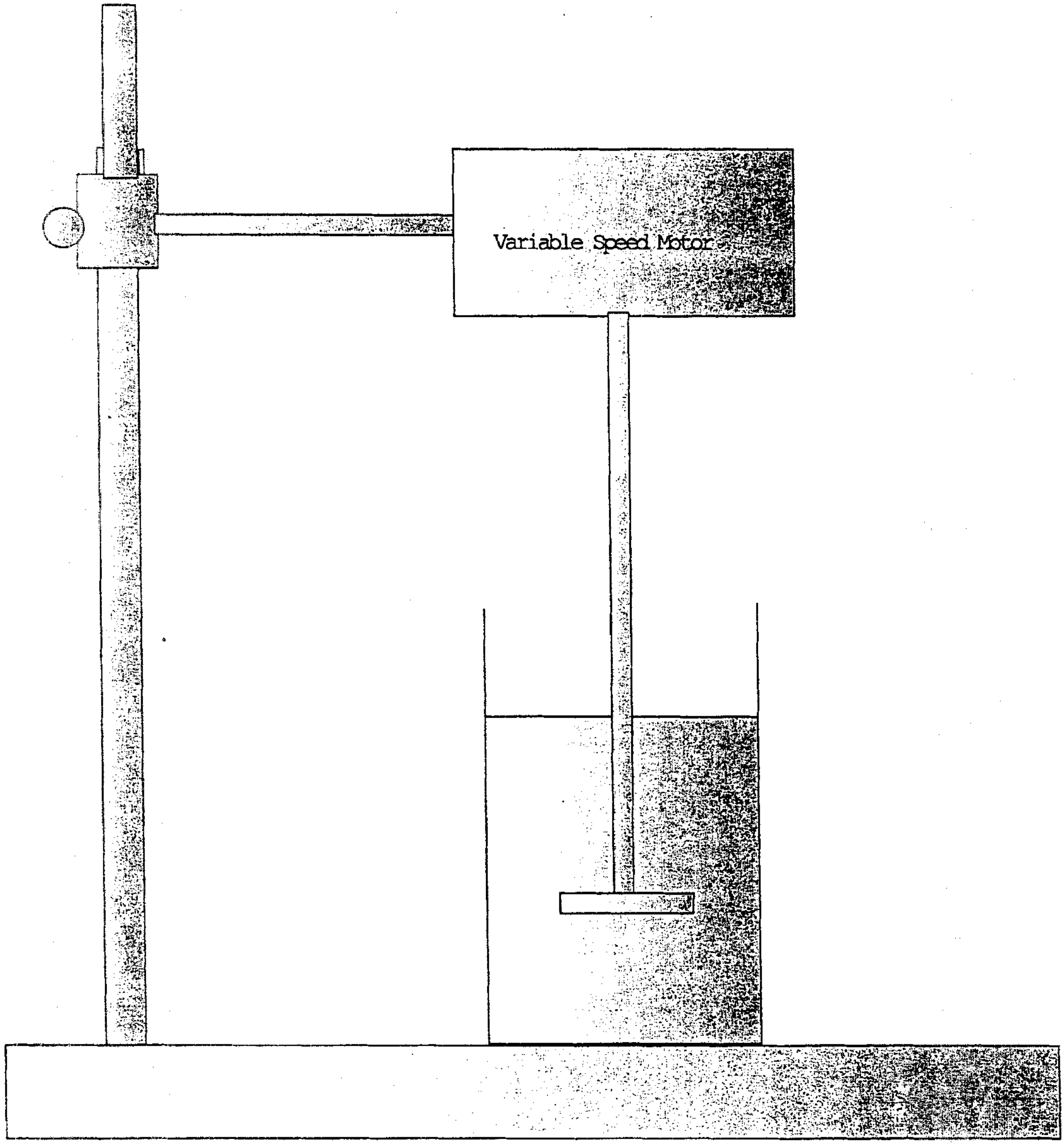
FIGURE 5

MIXER/STIRRER ARRANGEMENT



dewatering device by translating into an appropriate combination of mixing time and mixing speed in a mechanical laboratory mixer in order to obtain CST test values that are related to full-scale dewatering devices.

The CST mixing/stirring protocol for the laboratory tests is related to the sludge matrix and the degree of floc destruction from agitation and turbulence during a specific dewatering application. Therefore, simulation must account for shear stresses expected to be experienced by the coagulated flocs during full-scale dewatering application. Due to shear forces imposed upon the flocs in the flocculation chamber, piping network, and the pumping equipment through which the conditioned sludge passes, floc deterioration occurs. Such deterioration is in addition to what occurs in the centrifuge bowl or any full-scale dewatering application.

Failure to simulate the actual shear stress imparted to polymer-flocculated sludge by a plant process may result in a laboratory dosage determination for an inappropriate floc shearing condition of a dewatering application. As a result, the laboratory and full-scale doses may not correspond to each other.

Simulation of shear stress conditions may range in impact from simple swirling of a polymer and sludge mixture contained in a beaker by hand, to violent stirring of the same for several minutes at as much as 1000 RPM using a mechanical mixer. Vesilind (1979) showed that the mechanical shear experienced by sludge in a centrifuge could be simulated by stirring 100 mL of sludge in a 250-mL beaker at 1000 RPM for a mixing time of between 5 and 20 minutes (9). This finding illustrated the violent shear destruction that occurs in a centrifuge.

The shear stress in any dewatering application may be determined empirically by matching the deterioration of flocs that occurs in a full-scale device during dewatering, with the deterioration in CST using a laboratory mixing/stirring protocol that produces the same floc deterioration (an increase in CST value).

In extensive work conducted at the District (using 200 grams of wet sludge in a 600 mL beaker), it was observed that using a mixing/stirring protocol of 120 seconds at 500 RPM correlated minimum CST polymer dosages well, with polymer dosages determined separately from both pilot-scale and full-scale centrifuges (10). In other words, the shear stresses that the flocs were exposed to in District centrifuges corresponded to the shear stresses using the mixing/stirring protocol just described.

In this context, CST is a measure of free water (unbound from the sludge matrix by polymer flocculation) under specific shear stress conditions defined by a particular dewatering application in terms of laboratory mixing/stirring protocol. Evaluation of CST results from this perspective is critical, because as flocs deteriorate, the free water released by the polymer flocculation is reabsorbed into a bound condition in the sludge matrix (although not necessarily as strongly as in the initial condition). Such reabsorbance of the released bound water impairs the dewatering performance of any device. This behavior of sludge flocs is related to the floc strength of the conditioned sludge, which may be crucial to proper dewatering performance, such as in the case of a centrifugation application.

In summary, it is critical to apply CST dosage curves with a mixing/stirring protocol comparable in floc shearing destruction that occurs in a centrifuge, if the polymer dosages obtained from them are to correlate with corresponding full-scale centrifuge performance. This applies as well to any other dewatering device.

CST Test Procedures

By using the above mentioned protocols, the CST test can be applied for screening less efficient polymers from a pool of polymers submitted by various vendors and for estimating the concentration, dosage and quantity of polymer in full-scale centrifuge tests. Since the CST test is so useful in this respect, the procedure for obtaining a CST vs. dosage curve of a polymer is presented in detail. Prior to that, however, important related issues like polymer preparation and equipment and labware needed for the test are presented. Also presented is the procedure for estimating the concentration, dosage and quantity of promising polymers for full-scale tests followed by protocols used for screening out less efficient polymers from further consideration.

POLYMER PREPARATION

Fresh stock solutions of liquid (mannich and emulsion) and solid polymers (dry powder or granules, etc.) are prepared on a percent wet basis as needed. As a guideline, mannich polymer solutions in the range of 7 to 12 percent, emulsion polymers in the range of 0.5 to 1.5 percent, and solid polymers in the range of 0.25 to 0.5 percent are prepared. All solutions should be mixed by similar kinds of mixers, and used soon after preparation. As a guideline, mannich polymers, emulsion polymers, and solid polymers are mixed for about 30, 15, and 60 minutes, respectively. These may change with the degree of energy transferred by a given mixer type and, therefore, guidelines presented herein should be used with discretion. Polymer vendors may be requested to offer their recommendations as well.

EQUIPMENT AND LABWARE NEEDED

1. CST apparatus.
2. Whatman #17 chromatography grade filter paper cut into strips 2 cm. wide by 7 cm. long.
3. 500 RPM, multibladed, 2-inch diameter propeller-type stirrer.
4. 600-mL glass beakers.
5. Digital timer (1-second increments).

CST TEST PROCEDURE

1. Measure 200 grams (wet basis) of digested sludge into a 600-mL beaker.
2. Pipette an aliquot of polymer solution into the sludge (maximum aliquot is 40 mL to avoid dilution effects).

3. Mix the contents by hand, swirling until coagulation has visibly occurred.
4. Stir the contents for 120 seconds at 500 RPM.
5. Determine the CST of the stirred contents in duplicate (if wide divergence is observed, make a third CST reading).
6. Add different aliquots of polymers and repeat steps 1-5 until enough points are available to draw the CST vs. polymer dosage curve with an obvious absolute minimum or asymptotic minimum observed.
7. Plot the average CST vs. polymer volume points on a graph paper as shown in Figure 6 (CST is on the Y-axis and polymer volume is on the X-axis). It may be helpful to plot on semilog graph paper, where CST is on the log scale (Y-axis) and the polymer volume is on the linear scale (X-axis).

PROTOCOLS FOR SCREENING OUT POLYMERS THAT PERFORM POORLY

The first and simplest way of screening polymers is to perform the CST test for each polymer as described and to draw the CST vs. polymer dosage curve. All the polymers tested are

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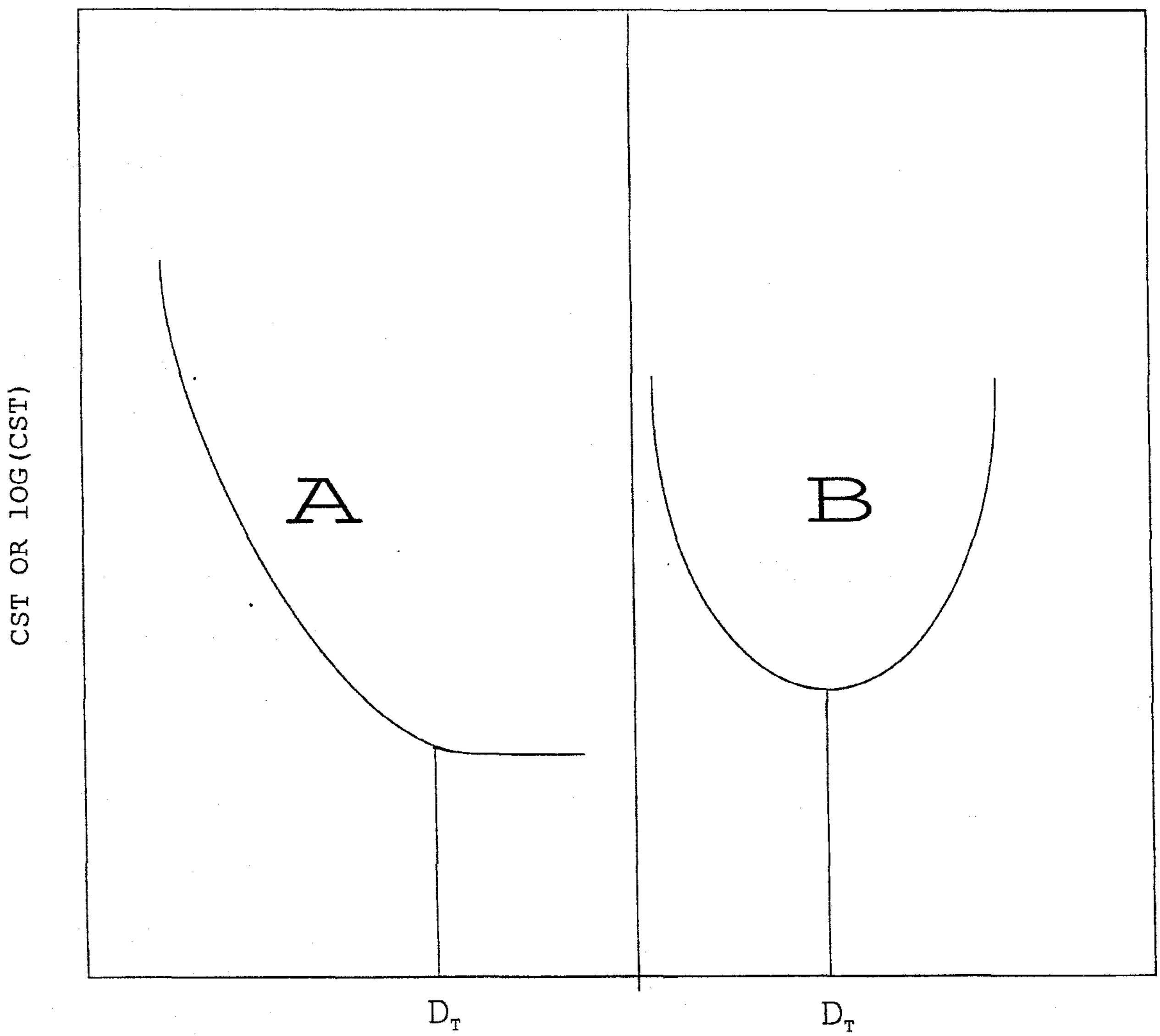
FIGURE 6

TYPICAL CST VS. POLYMER VOLUME CURVES
A: ASYMPTOTIC MINIMUM CST
B: ABSOLUTE MINIMUM CST



Polymer Volume (mL/200 grams of wet sludge) ranked on the basis of their minimum CST values. Depending upon the number of polymer samples received, they may be screened out with reference to an absolute CST value of ten seconds (i.e., reject polymers whose minimum CST values are greater than ten seconds). Alternatively, rank the polymers from the lowest to highest minimum CST values and choose the top ten or any other appropriate subset of polymers from a pool of all polymers. Thus, the polymers selected from laboratory test results can be further evaluated on full-scale tests.

A second way of screening polymers is on the basis of their floc strength test results. The details on the application of floc strength test results are described elsewhere (10). Basically, in this test, 200 grams (wet basis) of digested sludge conditioned at the optimum polymer dosage (as determined from a CST vs. dosage curve) are mixed at 500 RPM for 100 seconds and a CST value is determined. The same sludge is mixed for an additional 100 seconds at the same speed. Once again, a CST value is determined. By doing this repeatedly, several values of cumulative mixing times and corresponding CST values are obtained. Essentially, additional CST measurements are obtained by subjecting the previously stirred sludges to additional stirring at 100-second increments. The purpose of this test is to determine how well the flocs (coagulated at the optimum dosage) withstand different energy levels transferred by varying mixing durations at the same speed. With cumulative mixing time on the X axis and CST on the Y axis, a graph is prepared and the slope value determined for each polymer. The data may need to be transformed to obtain a straight line graph. The polymer with the maximum floc strength has the lowest slope value and vice versa (Figure 7). The polymers with the highest floc strengths should be selected for further consideration.

Because of the restriction that each vendor cannot submit more than two polymer samples, the polymers are not presently screened at the District. However, it is felt appropriate to include the basis on which the polymers can be screened out, since the two-polymer limit restriction was not enforced in the early District tests and the screening protocols were used at those times. A combination of both screening approaches presented in the preceding paragraphs is superior to applying either one alone.

OPTIMUM POLYMER DOSAGE ESTIMATION FOR FULL-SCALE TESTS

The optimum dosage is determined by using the dosage curve which is a plot of CST vs. volume of polymer solution.

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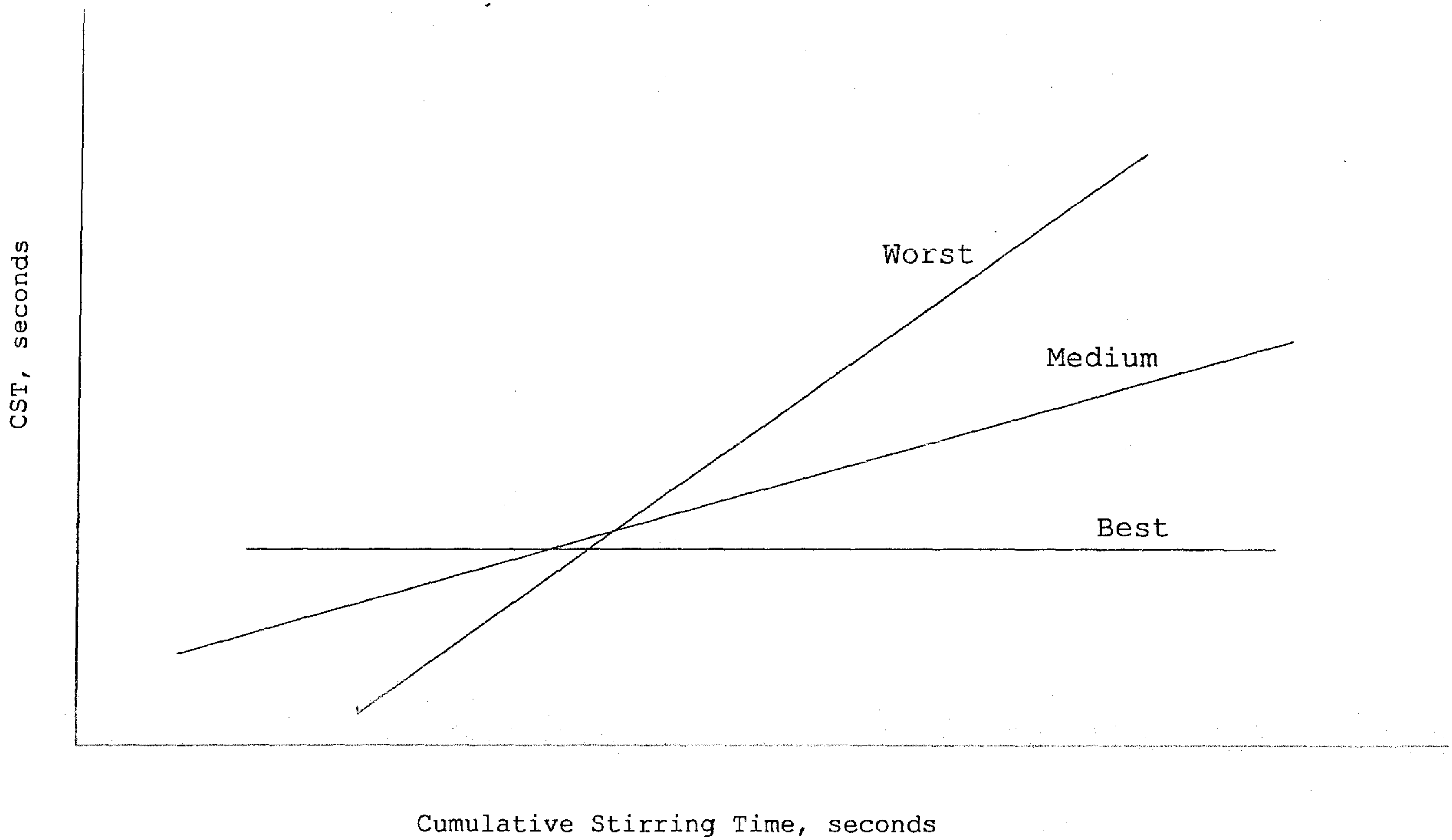
FIGURE 7

TYPICAL FLOC STRENGTH CURVES



As the polymer dose is increased, the CST value becomes smaller and smaller due to increased floc formation and release of bound water. Based on this characteristic of the CST vs. polymer dose curve, the optimum dose is defined as the dose at which the minimum CST point occurs, beyond which further polymer addition does not lower the CST. This minimum point determination may be done by eye or by curve-fitting techniques.

The optimum polymer dose in pounds of polymer per dry ton of sludge solids is calculated as follows after obtaining the polymer solution volume (for 200 grams of wet sludge) at the minimum CST from the dosage curve (Figure 6).

$$\text{OPTIMUM POLYDOSE}_{\text{LBS / TON}} = \frac{V_{POLY} C_{POLY}}{V_{SLG} C_{SLG}} (2000)$$

Where,

V_{POLY} = polymer volume at minimum CST (in mL)

C_{POLY} = polymer solution concentration (in percent on a wet basis)

V_{SLG} = sludge volume (in mL) (200 mL)

C_{SLG} = sludge concentration (in percent) (total solids)

ESTIMATED POLYMER DOSAGE FOR FULL-SCALE TESTS AT THE DISTRICT'S CENTRIFUGE COMPLEXES

Polymer dosage is a function of centrifuge bowl speed; therefore, the laboratory polymer dosage may be adjusted to estimate the full-scale polymer dosage more effectively by accounting for this variable. For the District centrifuges installed at the three centrifuge complexes (i.e., Stickney, Calumet and John E. Egan WRPs), the following correlation has been obtained using District sludge:

$$[\text{POLYDOSE}]_{\substack{\text{FULL}\\\text{SCALE}}} = [\text{POLYDOSE}]_{\substack{\text{LAB}\\\text{TEST}}}(F)$$

Where,

$$F = a + b(\text{RPMB})$$

$$\text{RPMB} = \text{bowl speed in RPM}$$

$$(2000 \le \text{RPMB} \le 2900)$$

$$a = -1.3668$$

$$b = 8.0957 \times 10^{-4}$$

$$F = \text{correlation factor}$$

$$(0 \le F \le 1)$$

The estimated polymer dosage is used as a guide to determine the quantity of the polymer, and the concentration of the polymer solution needed to perform full-scale tests for obtaining the bid dosages of the polymers submitted by various vendors. The vendors are permitted to observe the testing if they wish.

ESTIMATION OF CONCENTRATION AND QUANTITY OF POLYMER NEEDED FOR FULL-SCALE TESTS

The optimum polymer dosage as determined from a CST test is used to estimate both the number of 55-gallon drums of polymer required (that the manufacturer must bring) and the polymer concentration to be prepared for the full-scale tests. A computer program called "TK Solver" is used for readily computing estimates of the concentration of the polymer and number of drums needed to perform the test. Necessary details of "TK Solver" are presented in the section, "Data Analysis and Discussion," and the computer code used for estimating the needed quantities, along with a sample output sheet, is presented in Appendix AIII under the title of "POLYDRUM."

The input variables to "POLYDRUM," a computer file, are:

1. Optimum polymer dose from a laboratory bench test.
2. Percent total solids of the feed sludge.
3. Sludge flow into the centrifuge.
4. Average polymer solution flow into the centrifuge.
5. The volume of polymer solution prepared.

In addition to both the number of 55-gallon polymer drums and the polymer concentration required for full-scale tests, an additional output of "POLYDRUM" is the number of hours available to complete the test with the prepared amount of polymer volume and the concentration of polymer. Since the test samples are taken every 15 minutes, multiplying the number of hours available for the test by four gives the maximum number of sample runs that can be conducted. For example, during three hours, a maximum of 12 sample runs can be conducted. However, practical consideration should always allow for the possibility of unexpected problems that may surface resulting in the loss of both time and the limited quantity of polymer available for testing.

The example in the Appendix AIII "TK Solver" file illustrates the following:

Polymer Dose, lbs/ton:	415
Percent Total Solids in Sludge Conditioned:	3.5
Sludge Flow Rate, gpm:	200
Average Polymer Flow Rate, gpm:	10
Polymer Solution Concentration, percent (wet basis):	14.5
Volume of Polymer Solution Needed, gallons:	2000
Number of 55-gallon Drums of Raw Polymer Needed:	5.85 (say 6)

This file also shows that the test time available for sampling is 3.3 hours, so that about 12 sample runs can be made with the amount of polymer solution prepared allowing for the fact that the two 1000-gallon tanks of polymer available cannot be fully drained.

It takes a great discipline of purpose, an organized scheme of sampling, and good cooperation from WRP operations personnel to complete 12 sample runs in three hours. With experience, this number of samples can be completed. However, inexperienced staff might not be able to do as much in three hours, and this must be factored into the testing schedule.

FULL-SCALE TESTS: GENERAL PRINCIPLES, SAMPLING STRATEGY, AND TEST PROCEDURE

General Principles

Basically, the test protocols consist of ranking the polymer products with respect to a dosage requirement in order to achieve a specified performance criterion. The performance criterion indicates the overall combined efficiency of sludge conditioning and centrifugal dewatering operation. The performance criterion for centrifugal dewatering may be specified in terms of either percent solids capture, or percent cake solids. Any reasonable value may be specified for either criterion as long as it satisfies the overall objective.

For example, in order to maximize the cake solids objective at the District, the selected criterion is a percent solids capture with a specified value of 95. Specifying a solids capture criterion lower than 95 percent increases the number of polymers qualifying for the bidding process, whereas selecting a solids capture criterion higher than 95 percent reduces the number of polymers qualifying for the bidding process.

At the District, a 95 percent solids capture criterion was found to be quite adequate to minimize the adverse effect of recycling excessive centrate solids on plant performance.

Hence, as a first step in ranking all the polymers, the dosage of each polymer required to achieve the selected criterion of 95 percent solids capture is determined. The dosage for each of the polymers tested is obtained from characteristic performance models. The characteristic performance models are determined for all polymers by using the data collected from the full-scale tests.

Due to the complex nature of the characteristic performance models, nonlinear algorithms are used for estimating the model parameters. The performance data obtained for each of the polymers tested with the full-scale centrifuge are used for parameter estimation. As a result, each polymer product tested would have its own performance models that characterize its influence on the centrifuge output (percent capture and percent cake solids).

The characteristic performance models have three input variables (bowl speed, pinion speed, and polymer dosage) that influence the percent cake solids and percent solids capture. The bowl speed is the number of revolutions per minute of the outer centrifuge bowl, and the pinion speed is the number of revolutions per minute of the scroll inside the bowl which is revolving in the opposite direction to that of the bowl rotation. The pinion speed is always less than the bowl speed.

Bowl speed remains constant during normal operation and, hence, during test runs.

A complex and nonlinear mathematical relationship exists between polymer dose and pinion speed, and it must be taken into account before optimum dose can be determined for each polymer product. The optimum pinion speed at which the optimum dose occurs varies from polymer to polymer at the specified performance criterion of 95 percent solids capture. Hence, pinion speed cannot be arbitrarily set to a specific constant value for all the polymers to be tested. On the other hand, a pinion speed variable cannot be ignored to simplify the situation because it is the single most significant factor (even more significant than polymer dosage) influencing the efficiency of the high-performance centrifuge, i.e., a specified percent solids capture and/or percent cake solids.

Because the optimum pinion speed is unknown for a given polymer, centrifuge performance data are collected at different pinion speed settings to estimate it from the performance models whose parameter value estimates are derived from the full-scale test runs. The performance models, in essence, define a family of characteristic performance curves (polymer dosage vs. percent cake solids and percent capture) for each polymer, each curve corresponding to various settings of the pinion speed. In order to obtain the optimum dose of a polymer, an optimization technique is used to obtain the optimum pinion speed from the particular family of curves associated with a polymer.

For centrifuges that operate at a set pinion speed, such as the low-performance centrifuge machines which were previously used at District facilities, the entire testing and data analysis procedure is simplified because it is impossible to conduct the full-scale test at various pinion speed settings. Needless to say, the performance models and optimization procedure are correspondingly simplified as well.

The polymer dosage that meets the 95 percent solids capture criterion is determined from the performance characteristic curve (percent capture vs. polymer dosage) corresponding to the optimized pinion speed. Corresponding to that dosage and performance criterion of 95 percent of solids capture, the percent cake solids performance is determined from the performance characteristic curve (percent cake solids vs. polymer dosage) at the same optimized pinion speed.

All polymer products that do not achieve the specified 95 percent solids capture at any pinion speed used in the full-scale tests are eliminated from further consideration. Of those remaining, the polymers are ranked according to polymer dosage at 95 percent solids capture.

The District has further chosen to develop a cost function (details are presented in the section, "Data Analysis and Discussion") that not only considers polymer cost, but also other relevant issues such as transportation cost of the cake and agitation drying (air-drying) cost for the cake to obtain a specific percentage of dry solids in the final air-dried product. In this way, the polymer products that produce higher cake performance are given an advantage during bidding, while polymer products with low cost but poorer cake performance are given a corresponding disadvantage. In any event, the District has chosen not to consider any polymers which do not conform to 95 percent solids capture, in order to minimize the adverse effect of recycling excessive centrate solids on plant performance.

A sub-criterion with a specified value of percent cake solids may also be added (if desired) to eliminate the polymer products with poor cake solids performance. A polymer may then be selected for purchase which is the least expensive among those that meet the chosen performance criteria.

ALTERNATIVES OR MODIFICATIONS TO THE PERFORMANCE SPECIFICATION CRITERION

An alternative optimization strategy is to choose a percent cake solids performance criterion instead of percent solids capture. All polymer products that do not achieve this cake solids criterion are then eliminated from further consideration. Of those remaining, the polymers may be ranked according to percent solids capture at the percent cake solids criterion. A minimum percent solids capture specification may then be set (if desired) to eliminate those polymer products with poor percent solids capture performance. The least expensive polymer is then selected from those remaining.

Sampling Design Strategy for Optimum Test Runs and Data Collection

Cake, centrate, and feed samples must be taken at various settings of pinion speed and polymer dosage, ideally using a factorial or fractional factorial sampling design over the operating range of minimum and maximum torque. Using such a systematic sampling design approach helps avoid data spacing problems with the performance model parameter value estimation using nonlinear algorithms that apply iterative methods.

For example, in the case of the District's full-scale tests, two major variables (pinion speed and polymer flow rate into centrifuge) may be set at different operating levels during full-scale testing, and samples of centrifuge feed, cake and centrate can be collected at various combinations of variable settings. The application of full factorial sampling is shown in an example to be presented later in this section, while one variant of the application of fractional factorial sampling is depicted in Figure 8.

In general, a reasonable starting pinion speed for the District's centrifuges is 150 rpm less than the bowl speed, and the starting polymer flow is at mid-range of the flow meter. These must be adjusted so that the torque is between 1000 and 1200 inch-lbs. The centrifuge is run for 15 minutes, and then samples are taken. This is the first run (Figure 8, step ①). For the second run (Figure 8, step ②), the pinion speed is reduced by 25 rpm, and the polymer flow and the sludge flow rate remain the same. After making this adjustment, the centrifuge is run for 15 minutes, and then samples are taken that represent this new machine setting. For the third run (Figure 8, step ③), the pinion speed and the sludge flow rate remain the same, but the polymer flow is increased. After this adjustment, the centrifuge is run for 15 minutes, and then samples are taken that represent this machine setting. The sampling continues in this way with the pinion

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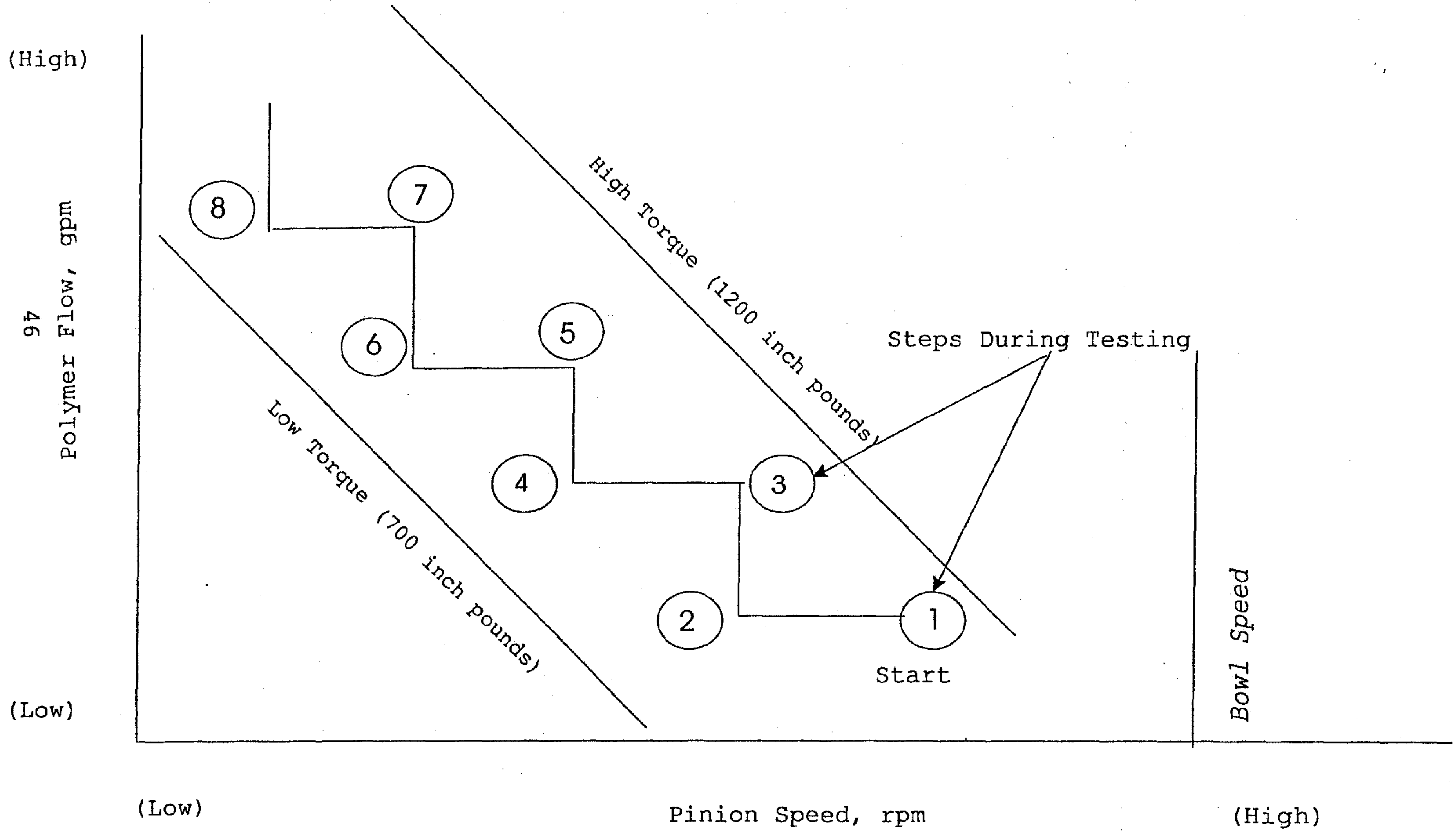
FIGURE 8

FULL-SCALE FRACTIONAL FACTORIAL SAMPLING DESIGN SCHEME



speed being reduced by 25 rpm each time it is changed. The increase in polymer flow partially compensates for torque reduction as the pinion speed is lowered, step by step, until the torque cannot be lowered any further without liquefying the cake. This is a terse description of the sampling order schematic. Such a sampling order may be used when time and polymer quantity are insufficient for full factorial sampling. In practice, actual runs will deviate somewhat from what is shown in Figure 8 because of the constraint on the torque to be within a particular range (so as not to plug up the machine or liquefy the cake). Limited machine controls make such symmetric sampling difficult with the torque constraint enforced. Figure 8 is an idealization which may require compromise or alteration to another variant of fractional sampling under specific circumstances.

Using the sampling scheme depicted in Figure 8, a typical and recommended sampling protocol, currently being used at the District, is presented in Figure 9 and Table 1. It provides a template for sampling that can be expanded or reduced as needed. Each run corresponds to a different setting of polymer flow and/or pinion speed. For each run, polymer dose and percent capture must be calculated. Since two 1000-gallon tanks of polymer solution are prepared, the polymer solution

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FIGURE 9

FULL-SCALE SAMPLING SCHEME

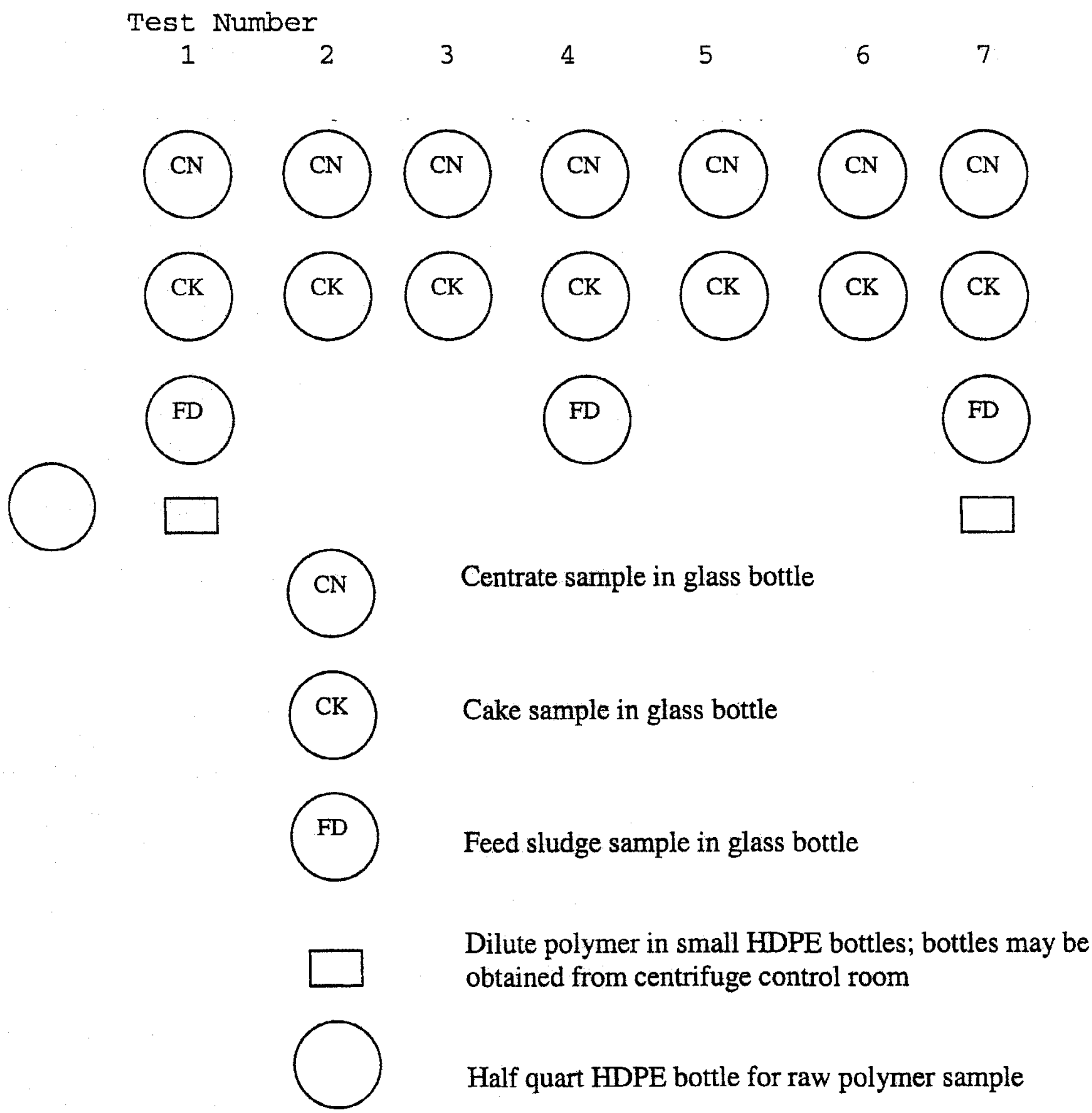

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TABLE 1

SUGGESTED SAMPLING PROTOCOL DURING FULL-SCALE TEST

Sample Type	Run Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Raw Polymer	X											
Dilute Polymer	X			X			X			X		
Feed	X			X			X			X		
Centrate	X	X	X	X	X	X	X	X	X	X	X	X
Cake	X	X	X	X	X	X	X	X	X	X	X	X
Sample Time	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00	12:15	12:30	12:45

Note: An "X" represents taking a sample.

concentration can be calculated for each tank or averaged to obtain one value that is used for all the sampling runs.

The example data set in Table 2 or Table AIV-1 shows an extended three-level factorial sampling for two variables.

The safest sampling order is to start at high pinion speeds (high torque, low capture, high cake) and to go to low pinion speeds in equal spaced increments (low torque, high capture, low cake) (Figure 8). If sampling begins at low pinion speeds, there is a high risk of the cake being liquefied, causing downtime for cleanup along with ill feelings between plant personnel and staff conducting the tests.

As indicated earlier, the feed sludge flow rate must be held constant for the entire duration of the tests. Bowl speed, as mentioned previously, remains constant during a given test run (i.e., at any particular polymer dose and pinion speed) of the full-scale test.

Ordinarily, 2000 gallons of polymer solution are prepared for a full-scale test. The polymer flow rate value should be set at half of the maximum polymer solution flow possible in the beginning of the test, so as to allow for adequate "room" for adjusting polymer flow rate settings at higher and lower values during the test. Flow rates in the extremely low and high settings of the flow meter used should be avoided since

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TABLE 2

RECORD SHEET FOR FULL-SCALE POLYMER EVALUATION

Date : ________ Bowl Speed : 2800

Raw Polymer : ____________
Dilute Polymer : 14.5 %
Product Designation : ____________
Product Type : MANNICH
Polymer Manufacturer : ____________
Manufacturer Representative : ____________
MWRDGC Representative : ____________

Run #	Time of Sampling	Sludge Flow, gpm	Dilute Poly Flow, gpm	Post Dilution H_2O, gpm	Feed Sludge, % TS	Cake % TS	Centrate % TS	% Capture	Dilute Poly % TS	Polymer, Dose, lb/DT	Δ	Torque	Pinion Speed, rpm
1	10:00	200	8.80		3.5	24.1	0.956	75.7	14.5	365			2550
2	10:15	200	9.10		3.5	26.4	0.714	81.8	14.5	376			2550
3	10:30	200	9.40		3.5	27.7	0.592	84.9	14.5	389			2550
4	10:45	200	9.40		3.5	27.8	0.352	91.1	14.5	389			2525
5	11:00	200	9.70		3.5	28.1	0.301	92.4	14.5	402			2525
6	11:15	200	10.00		3.5	28.3	0.273	93.1	14.5	415			2525
7	11:30	200	9.40		3.5	26.7	0.232	94.2	14.5	389			2500
8	11:45	200	9.70		3.5	27.3	0.179	***95.5***	14.5	***402***			***2500***
9	12:00	200	10.00		3.5	27.6	0.151	96.2	14.5	415			2500
10	12:15	200	9.40		3.5	24.4	0.158	96.1	14.5	389			2475
11	12:30	200	9.70		3.5	25.1	0.125	96.9	14.5	402			2475
12	12:45	200	10.00		3.5	25.6	0.105	97.4	14.5	415			2475

the built-in flow meter may not be very accurate and reliable in the extreme flow ranges. Flow meter readings are frequently known to exhibit nonlinear patterns in the upper and lower 25 percent ranges of the flow meter. As a guide, the initial polymer flow rate value of 10 gpm should be selected if a maximum polymer flow range happens to be 20 gpm.

Centrifuge cake samples must be taken at least 15 minutes after the beginning of the centrifuge operation and whenever settings are changed in order to allow enough time for the cake in the bowl from the previous settings to be replaced. Thus, after an interval of equilibration to the new settings of machine variables, cake, centrate and feed sludge samples should be taken simultaneously so that all the samples will represent current operating conditions. Dilute and raw polymer samples should also be collected a few times over the entire sampling duration. Average results of many polymer solution samples are representative of the concentration of polymer used during the test.

Test Procedure

Keeping the sampling design strategy in mind, the following procedure, currently being used at the District, may be followed.

1. As far as possible, all the polymers should be tested in the shortest duration on the same centrifuge machine to minimize variations.
2. Observe machine performance in automatic mode and record the average pinion speed, average polymer flow, average sludge flow, and average torque.
3. Switch the centrifuge machine from automatic mode to manual mode for the duration of the test. (Independent pinion speed settings are not possible in automatic mode.)
4. Gradually raise pinion speed by approximately 150 to 200 rpm. The increase in pinion speed is with respect to the average pinion speed observed. Watch for gradual darkness in centrate.
5. Observe the torque at this new pinion speed for about five minutes. If torque appears to be going beyond 1200 rpm, lower the polymer flow slightly or lower the pinion speed by 25 rpm, or do both if neither works alone. Once torque is stabilized at approximately 1050, wait for about 15 minutes and take the first set of samples

(Figure 9). Note that centrate should be dark in the first set of samples.

6. Continue sampling every 15 minutes with changed pinion speed and/or changed polymer flow as shown in Figure 8 or in the example of Table 2. Reduce pinion speed from high to low in decrements of 25 rpm. Keep torque between 700 and 1200. Continue sampling until centrate becomes clear. The upper and lower torque limits will vary with sludge type, centrifuge model, and various internal machine settings. As a point of reference, the following centrifuges are in use at the three District centrifuge complexes:

   Stickney: Sharples model PM-76000

   Calumet: Sharples model PM-706

   Egan: Sharples model PM-76000

DATA ANALYSIS AND DISCUSSION

Tabulation of Full-Scale Test Results for Data Analysis

Upon completion of sampling in a full-scale test conducted with various polymers, the samples taken are analyzed for percent total solids. Based on the percent solid results, percent capture and polymer dose are calculated for model parameter estimates. The actual polymer solution concentration prepared at the plant must also be calculated from these results since polymer solution prepared at full-scale can be imprecise. Because of the difficulty in measuring large volumes of polymer and dilution water accurately, the polymer solution concentration is obtained much more precisely from laboratory sample analysis and subsequent calculation.

The percent solids capture (%CP) is calculated as follows:

1. $$\%CP = \left[\frac{FD - CN}{FD}\right]\left[\frac{CK}{CK - CN}\right]100$$

or

2. $$\%CP = \left[\frac{FD - CN}{FD - TDS}\right]\left[\frac{CK - TDS}{CK - CN}\right]100$$

Where,

FD = percent total solids of the feed sludge

CN = percent total solids of the centrate

CK = percent total solids of the cake

TDS = percent total dissolved solids of the feed sludge

%CP = percent solids capture

Two formulas are presented above for the computation of %CP. The second formula corrects the percent solids capture calculation for dissolved solids in the feed sludge. Some plant operators use the first formula, whereas others use the second. Either formula will work for the purposes of the test procedure presented here.

The polymer dose in pounds of polymer per dry ton of sludge solids is calculated as follows:

$$POLYDOSE_{LBS/TON} = \frac{(\%\ POLYMER)(GPM_{PLY})}{(\%\ SLUDGE)(GPM_{SLG})}(2000)$$

where,

% POLYMER = polymer solution concentration (in percent wet basis by weight)

% SLUDGE = sludge concentration (in percent by weight) (total solids)

GPM_{PLY} = polymer flow (in gpm)

GPM_{SLG} = sludge flow (in gpm)

$POLYDOSE_{LBS/TON}$ = polymer dose (in lbs/ton)

The polymer solution concentration is calculated as follows:

$$\% \text{ POLYMER} = \left[\frac{TS_{DILPLY} - TS_{DILH_2O}}{TS_{RAWPLY}}\right]100$$

where,

TS_{DILPLY} = percent total solids of the dilute polymer solution

TS_{DILH_2O} = percent total solids of the dilution water used to prepare the polymer solution

TS_{RAWPLY} = percent total solids of the raw polymer (from the 55-gallon drum)

% POLYMER = polymer solution concentration (in percent wet basis by weight)

Based on percent solids test results of the polymer samples, the dilute polymer solution concentration used during the test is determined. The flow rate values of the dilute polymer fed to the centrifuge during the full-scale tests are corrected, if needed, and then recorded on the data sheet. Also, the pinion speeds and polymer dosages applied during the test runs are recorded. The calculated values for percent capture and cake solids are also tabulated as shown in Table 2.

These tabulated data are then subjected to the model parameter estimation and optimization procedures. The parameter estimation and optimization procedures use algorithms which are coded in software programs. The software programs are installed in the District's computer workstations. The procedures for parameter estimation and optimization of pinion speed, dose, and cake are followed by comments on the use of algorithms and information about proprietary software.

Use of Algorithms and Proprietary Software - "Scientist" and "TK Solver" in Data Analysis

COMMENTS ON ALGORITHMS AND SOFTWARE

It is strongly recommended that the model parameter estimation be done with a combination of the Nelder/Mead simplex algorithm (2) and the Golub/Pereyra algorithm (3). A Fortran IV coding of the Nelder/Mead simplex algorithm and the Golub/Pereyra algorithm is provided by Olsson (4), and Ottoy and Vansteenkiste (5), respectively.

A strongly recommended commercial software package called "Scientist" (6) is used at the District for model parameter estimation. This software implements a variation of both of these algorithms and also provides an exceptional graphics capability. Many difficulties with convergence can be avoided simply by using these robust algorithms for parameter estimation.

Another commercial software package called "TK Solver" (7) is strongly recommended for the optimization procedure. This software is also used at the District. This program is an equation solver that allows for automated and convenient solutions to nonlinear equations without the need for sophisticated programming skills.

It is necessary to become familiar with the "Scientist" and "TK Solver" software manuals to effectively use the application programs. It is redundant, and simply not possible, to reproduce all the relevant details in this report. However, a brief introduction for both the programs is presented here while the developed codes for both the programs are presented as various computer files in <u>Appendices AII</u> and <u>AIII</u>.

INTRODUCTION TO "SCIENTIST" SOFTWARE

"Scientist" was designed by MicroMath Scientific Software Inc., Salt Lake City, Utah, to obtain the comprehensive solution to the problem of fitting experimental data by using the Microsoft Windows on MS-DOS based computer. This software is widely used in many teaching and research areas. Its capabilities include solution to a set of equations including, but not limited to, nonlinear, ordinary differential, and Laplace transform equations. Because of its interactive nature, optimal parameter values can be determined with very little effort, unlike other programs. It facilitates model entry, model manipulation, data management, and allows for control of initial estimates and constraints on parameter values. It also produces useful statistics and graphics output.

The computer files in DOS and Windows versions are identical and work exactly the same way. Details on the use of this software may be found elsewhere (6). Necessary details for using specific files relevant to the estimation of parameters for models used in the polymer evaluation protocols are provided towards the end of this section.

GENERAL DIRECTIONS FOR WINDOWS VERSION

Run the "Scientist" program and choose the "New" command from the "File" menu, then select the "Model" command from the submenu that is displayed. Enter the model equations by modifying a standard template and define dependent and independent variables, and parameters. Save the model entered. The saved model file has a default extension "EQN."

Compile the saved model. Both commands for saving and compiling can be selected from main "File" menu. By compiling the model, derivatives are computed and the software checks for formatting errors and any other errors which, if found, are pointed out through a message window. Without successfully compiling the model, the model cannot be run for estimation of parameters.

From the main menu, open a spreadsheet and enter the experimental data. These data are automatically selected for the model fitting. Save this file and it automatically obtains an extension of "MMD."

For simulating, fitting by least-squares, or for initial parameter value refinement by using the simplex algorithm, the initial parameter values need to be loaded in the program. From the "Calculate" menu, choose "Least Squares Fit" command to fit the model. The final parameter values from the fit are displayed in the file which has an extension of "PAR."

By choosing the "Plot" options, the data can be plotted, and the plots subsequently can be edited and printed. Goodness of fit statistics are also available with the "Statistics" command from the "Calculate" menu.

INTRODUCTION TO "TK SOLVER" SOFTWARE

The "Tools Kit Solver" program, abbreviated as "TK Solver," was designed by Universal Technical Systems, Inc., Rockford, Illinois. This program is offered in many operating systems such as DOS, Windows, VAX/VMS, Macintosh, UNIX, etc.

"TK Solver" is a declarative, rule-based programming language. Because of that, equations can be entered in any order; additional equations may be added, or existing equations may be deleted any time; the unknowns of the equations need not be separated out on one side as in other equation solving programs. This provides unlimited freedom in building and manipulating models according to the needs and constraints of a specific problem.

In the Windows version, various worksheets (known as TK sheets) neatly and modularly organize all the information. Upon opening the program, two out of ten TK sheets appear as open windows, whereas the remaining eight sheets appear as eight icons. Each sheet has a specific role, and is furnished with specific tools to accomplish specific functions.

The rule sheet contains the relationships among variables while the variable sheet contains the input or output values of each variable. Other sheets contain unit conversions, definitions of plots, tables, lists of values, user-defined functions, comments, and formatting directions. The sheet called "MathLook" (available only in the Windows version as the tenth sheet) contains a collection of information from all sheets, and can be viewed along with the original equations/models in formal mathematical notation. This feature is very useful to track, document, or verify models.

All of the "TK Solver" optimization model files work essentially the same way, so only general directions that apply to all of them are provided for both Windows and DOS versions. Necessary details on the use of computer files created in the "TK Solver" program are presented towards the end of this Section. Additional in-depth information may be found elsewhere (7).

GENERAL DIRECTIONS FOR WINDOWS AND DOS VERSIONS

Run the "TK Solver" program. Enter the equations to be solved in the rule sheet. The variables from each equation are automatically placed into the variable sheet. Define functions to be used in the function sheet. These functions can be used in the rule sheet as needed.

The input variables in the variable sheet are assigned specific values, and the equations are solved to obtain specific values for the output variables by pressing F9. All variables may be categorized very simply as either input or output types which allows great flexibility in equation solving. If direct solving is not possible, the program automatically applies the multivariable Newton root solving algorithm in order to obtain a solution by iteration from starting values provided by the user. Plots and tables may be generated from the equations as required.

Mathematical Models

The models describing the percent solids capture (Equation 1) and the percent cake solids (Equation 2) are developed from experience gained in numerous tests conducted at the District's three centrifuge facilities.

$$[\%\ \text{capture}] = K_1 + K_2 e^{M(RPM-RPMB)} + K_3(\text{Dose})^N + K_4(\text{Dose})^N e^{P(RPM-RPMB)} \qquad \text{(Equation 1)}$$

$$[\%\ \text{cake}] = K_1' + K_2'(RPMB - RPM)^R + K_3'(RPMB - RPM)^{2R} + K_4'(\text{Dose})^S \qquad \text{(Equation 2)}$$

Where:

[% capture] = percent solids capture

[% cake] = percent cake solids

Dose = polymer dose in pounds per dry ton of sludge solids

RPMB = bowl speed in revolutions per minute

RPM = pinion speed in revolutions per minute

K_1, K_2, K_3, K_4, M, N, P, K_1', K_2', K_3', K_4', R, S are the curve fitting parameters determined by the method of least squares.

The parameter P may be set equal to M with little or no loss in generality (P = M). This simplification allows for a closed form solution for the RPM variable.

Reparameterization of Mathematical Models

The capture and cake models (Equations 1 and 2) are reparameterized for purposes of effective and convenient estimation of parameter values, using a nonlinear least squares algorithm. If the data set has enough points (about 11 or more test run results) and no data spacing problems, then the parameters may be estimated directly from the original models (i.e., Equations 1 and 2 without reparameterization) by using the "Scientist" program. However, a reparameterization step in the data analysis procedure can enhance parameter estimation and often forces convergence of the algorithm regardless of data spacing problems. Therefore, as a standard practice of data analysis, it is recommended that the reparameterization step not be avoided.

Reparameterization is helpful in satisfying model boundary conditions, in minimizing algorithm convergence difficulties, and in providing geometrical interpretations for some of the parameters such as DOSEZ, RPMZ1, and RPMZ2 (Figure 10). Reparameterization is also used to constrain the parameter

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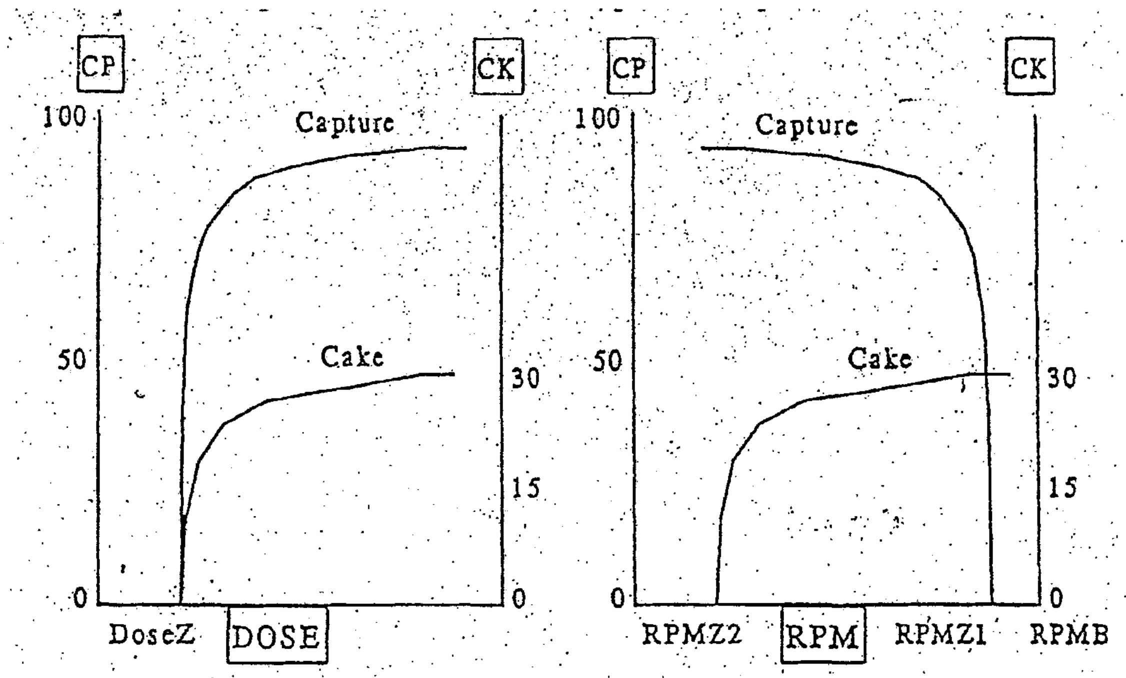
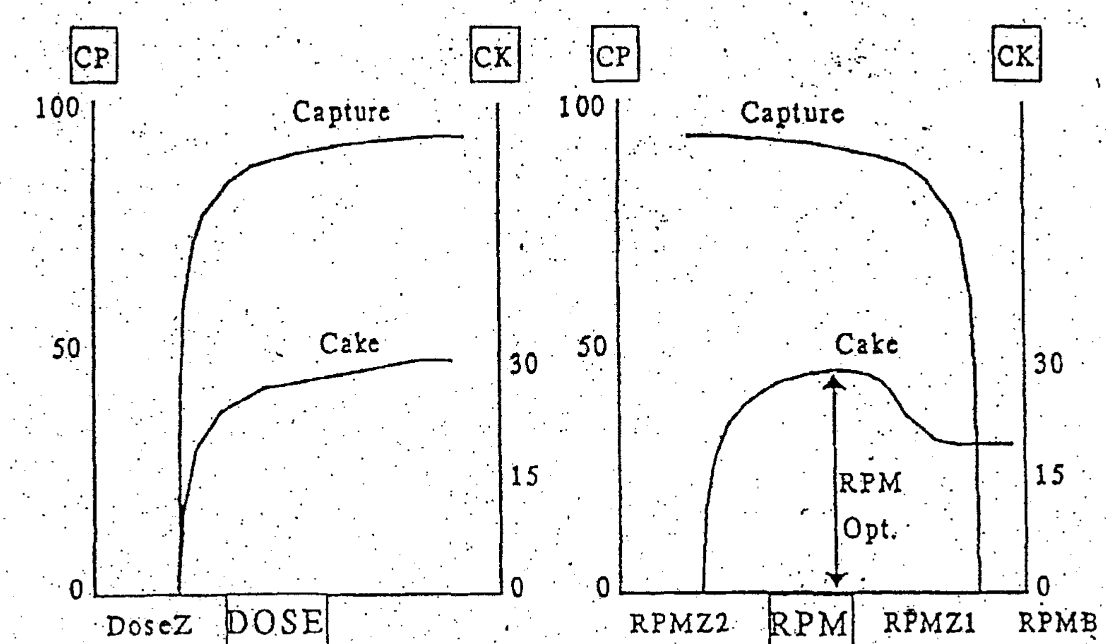
FIGURE 10

RELATIONSHIP BETWEEN POLYMER DOSE AND PINION SPEED AND PERCENT SOLIDS CAPTURE AND CAKE SOLIDS - TYPE 1 ASYMPTOTIC CASE



Relationship Between Polymer Dose and Pinion Speed and Percent Solids Capture and Cake Solids - Type 2 Quadratic Case



values so that they remain within physically realistic boundaries, and to reduce the number of data points required to fit the models. These are all important and practical reasons for implementing reparameterization.

The data spacing from experimental runs can often produce algorithm difficulty in a nonlinear parameter estimation process. In some cases, the algorithm does not converge to specific parameter values and in other cases the algorithm converges to unrealistic (out of range) parameter values. Such artificial difficulties (artifacts of data sampling) can often be alleviated by appropriate reparameterization which effectively constrains the new parameters so that the algorithm does not have estimation problems.

Thus, an important component of the rationale behind reparameterization comes from the fact that nonlinear algorithms estimate parameter values by iterative methods that start with initial assumed values, which are sequentially improved upon until no more improvement is possible. Due to poor data spacing of experimental runs, it can happen that either the algorithm does not converge to a single value of some parameters (fluctuating wildly or going to infinity), or the algorithm converges to nonsense conditions (out of range parameter values). In some of these cases, internal calculation errors occur in the computer which result in the necessity for rebooting the computer because error messages force the software program execution to stop, or "freeze up" the computer. The point being emphasized is that reparameterization can avoid such serious problems and, therefore, is worth implementing for this reason alone.

Geometrical parameter interpretations provide guidance for initial assumed values of the parameters. If they are chosen poorly, convergence problems of the sort discussed above may occur. As experience is gained by working with the full-scale data in this test procedure, the occurrence of such problems is greatly minimized. After least squares fitting, the reparameterized models are transformed back into their initial forms since optimization takes place on the models in their initial forms.

Equations 1 and 2 when reparameterized take the following form:

$$CP = 100\left[1 - K\left(e^{M(RPM-RPMZ1)} + \left(\frac{DOSE}{DOSEZ}\right)^{N}\right)\right] \quad \text{(Equation 3)}$$

$$CK = CKMX\left[1 - CC1(RDEL)^{R} - CC2(RDEL)^{2R} - \left(\frac{DOSE}{DOSEZ}\right)^{S}\right] \quad \text{(Equation 4)}$$

$$\text{where } (RDEL) = \frac{RPMB - RPM}{RPMB - RPMZ2}.$$

CP = percent solids capture

CK = percent cake solids

Dose = polymer dose in pounds per dry ton of sludge solids

RPM = pinion speed in revolutions per minute

RPMB = bowl speed in revolutions per minute

K, M, N, R, S are curve fitting parameters to be determined by the method of least squares, along with the following:

CKMX = maximum percent cake solids

RPMZ1 = pinion speed at which percent capture drops to zero

RPMZ2 = pinion speed at which cake solids start to form

DOSEZ = polymer dose at which both cake solids start to form and solids capture begins to occur

Both of these models must be fit simultaneously due to the common parameter "DOSEZ," which appears in both models. The CC1 and CC2 parameters are not for purposes of estimation, but they are used as dummy variables, therefore, they must be set in a specific manner in order to obtain the asymptotic or maximum quadratic type of curve. The settings are as follows:

Type	CC1	CC2
(Type II) Maximum Quadratic	-1	+1
(Type I) Asymptotic Quadratic	+1	+1
(Type I) Asymptotic Linear	+1	0

These two types of curves (I and II) correspond to three model parameter estimation cases. The Type II quadratic case as well as both Type I asymptotic cases are illustrated in Figure 10. Both Type I asymptotic cases (quadratic and linear) look alike on a graph, but the models representing them are different. One case is represented by a modified quadratic model while the other case is represented by a modified linear model, but both models represent an asymptotic situation which plots as the same kind of curve in either case.

In the asymptotic case (Type I), CKMX is the maximum cake possible under any dose or pinion speed. In the quadratic maximum case (Type II), this interpretation no longer holds true. In the capture model (Equation 1), the term with the parameter K_4 only improves the fit when sample values are below 80 percent capture. By excluding all samples below 80 percent capture, K_4 may be set equal to zero, thus providing a simplification in the reparameterization of the capture model without obscuring the region of interest (approximately 95 percent capture). In order for the geometrical interpretation of RPMZ2 to be maintained in the quadratic maximum case, a further constraint must be imposed on the cake model which is shown in the software files. The quadratic maximum case (Type II) is extremely rare while the asymptotic case (Type I) is the most typical.

In order to obtain a robust convergence that ensures the best fit in the range of greatest interest (80 to 100 percent capture), the percent capture model is constrained so as to pass exactly through the sample point associated with the highest pinion speed in which the percent capture performance specification is exceeded (RPMH, in Equation 7). This produces a percent capture model that best approximates the performance response surface, in the area where optimization is to occur, in the same way as expanding a Taylor series around a particular point produces an approximation to a function that is the most accurate around that point. This constraint is also shown in the software files. The forced point is: (PDOSE,PRPM,PCP).

The file "CPCK1FQ2" shows all the constraints on both percent capture and percent cake models. The parameters M, N, R, and S all correspond to the degree of curvature in the performance response surfaces of the percent capture and percent cake models. The parameters N and M are transformed into the parameter P so as to remap from an infinite range $(0,-\infty)$ to a finite range (0,1). The typical value of P is 0.95. The parameter K must be set equal to one, in order to maintain the geometric interpretation of RPMZ1 and DOSEZ. It should be kept constant during the curve-fitting process and is included only for the sake of generality.

The file "CPCK1FQ5" shows the same constraints on both capture and cake models, but also imposes several more constraints in order to remap RPMZ1, RPMZ2, DOSEZ from infinite ranges to finite ranges (from zero to one). This remapping makes fitting easier since the new parameters have relatively constant typical values:

$0 < KRZ1 < 1$	Typical Value = 0.93
$0 < KRZ2 < 1$	Typical Value = 0.97
$0 < KDZ < 1$	Typical Value = 0.85

File "CPCK2FQ5" is included in case some difficulty occurs with the cake fit. This file is similar to "CPCK1FQ5," but it uses two forced points: one through the percent capture model (as in "CPCK1FQ5") and another through the percent cake model. The second forced point is: (PDOSE,PRPM,PCK). The percent cake model is constrained so as to pass exactly through the sample point associated with the highest pinion speed in which the capture specification is exceeded (RPMH in Equation 7). The constraint is shown in the file.

Many other computer files with minor improvements over the above mentioned files have been developed over a long time period to represent a variety of situations. However, it is not under the scope of this report to discuss these numerous (but infrequent) scenarios with their corresponding computer files, therefore, only three select files ("CPCK1FQ2," "CPCK1FQ5," and "CPCK2FQ5") which are the most commonly used, are presented in sequence along with their corresponding parameter files.

The parameter files provide upper and lower estimation limits for each parameter in the model (as well as suggested initial starting values). Some parameters are placed in the parameter file for convenience, and not because their values are to be estimated. These include the dummy variables (CC1 and CC2), the bowl speed (RPMB), and the fixed points (PDOSE,PRPM,PCP,PCK). They must be kept constant during the estimation of the other parameters by clicking their corresponding locations in the software "fix" column.

It is recommended that file "CPCK1FQ5" be used for routine purposes. In general, these files need the input of full-scale test data points to fit the models. The output from these files is the model parameter estimates that specify the best model fit for the data set.

Optimization of Pinion Speed, Dose, and Cake

The optimum dose, optimum cake, and optimum pinion speed, at a particular percent capture (typically 95 percent) can be determined by using the following equations.

OPTIMUM PINION SPEED

1. If K_2' is greater than zero, the constrained solution for the optimum pinion speed (RPM_{opt}) is obtained by setting the derivative of the following function equal to zero and solving for the variable RPM_{opt}:

$$[\%\ \text{cake}] = K_1' + K_2'(RPMB - RPM_{opt})^R + K_3'(RPMB - RPM_{opt})^{2R} + K_4'\left(\frac{95 - K_1 - K_2 e^{M(RPM_{opt} - RPMB)}}{K_3 + K_4 e^{P(RPM_{opt} - RPMB)}}\right)^{\frac{S}{N}} \quad \text{(Equation 5)}$$

2. In the event that the constrained solution does not exist, the unconstrained solution for the optimum pinion speed (RPM_{opt}) is obtained from the following equation:

$$RPM_{opt} = RPMB - \left[\frac{-K_2'}{2K_3'}\right]^{\frac{1}{R}} \quad \text{(Equation 6)}$$

3. If K_2' is less than zero, the optimum pinion speed is obtained from the following equation:

$$RPM_{opt} = \left[(RPMB - RPMH) - \frac{1}{M} \ln\left(\frac{K_2}{95 - K_1} \right) \right] \phi + RPMH \qquad \text{(Equation 7)}$$

Where $\phi = 0.25$

RPMH = highest pinion speed in which a sample exceeds 95 percent capture.

4. RPM_{opt} is rounded to units place.

OPTIMUM DOSE

1. The optimum dose ($Dose_{opt}$) is obtained from the following equation rounded to three significant digits:

$$Dose_{opt} = \left[\frac{95 - K_1 - K_2 e^{M(RPM_{opt} - RPMB)}}{K_3 + K_4 e^{P(RPM_{opt} - RPMB)}} \right]^{\frac{1}{N}} \qquad \text{(Equation 8)}$$

OPTIMUM CAKE SOLIDS

1. The optimum cake solids (% $cake_{opt}$) is obtained from the following equation rounded to three significant digits:

$$\% \, cake_{opt} = K_1' + K_2' (RPMB - RPM_{opt})^{R^{2R}} + K_3' (RPMB - RPM_{opt}) + K_4' (Dose_{opt})^S \qquad \text{(Equation 9)}$$

The equations are coded in three "TK Solver" files. Since the input to the "TK Solver" files depends upon the output of the "Scientist" files, three "TK Solver" optimization files must be used in tandem with the three "Scientist" performance model files. The correspondence between the two kinds of files is as follows:

	Model Scientist Files	Optimization TK Solver Files
(1)	CPCK1FQ2	OPTFP1Q2
(2)	CPCK1FQ5	OPTFP1Q5
(3)	CPCK2FQ5	OPTFP2Q5

In general, to use the "TK Solver" files it is necessary to set the correct optimization case and input the model parameter estimates obtained from the "Scientist" files. Then, solve the equations and obtain the output from the "TK Solver" files as optimum dose, optimum cake, and optimum pinion speed at a particular percent capture (typically 95 percent).

The optimization case is set according to the model type which is specified by the dummy variables CC1 and CC2 (previously described in the section on the "Scientist" files). Table 3 shows the relationships used to set the proper optimization cases. It is cautioned that the relationships as shown in Table 3 are not the same as those previously discussed for model parameter estimation cases in the "Scientist" files.

In the "TK Solver" files, the optimization case is set by setting the appropriate case variable equal to 1, while blanking out the other two case variables. The three case variables are: CASE1, CASE2, and CASE3. Optimization Case 3 is

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TABLE 3

TABLE OF RELATIONSHIPS USED TO SET THE PROPER OPTIMIZATION CASE IN THE TK SOLVER OPTIMIZATION FILES

Model Type	Dummy Variable Settings		Optimization Case	RPM_{opt} Equation
	CC1	CC2		
I Linear Asymptote	+1	0	Case 1 (Asymptotic)	7
I Quadratic Asymptote	+1	+1	Case 1 (Asymptotic)	7
II Quadratic Maximum	-1	+1	Case 2 (Unconstrained Maximum)	6
II Quadratic Maximum	-1	+1	Case 3 (Constrained Maximum)	5

an iterative procedure which is sensitive to starting values of RPM_{opt}. Optimization Case 3 corresponds to Equation 5; optimization Case 2 corresponds to Equation 6; and optimization Case 1 corresponds to Equation 7 in the optimization section of the test procedure.

The "TK Solver" optimization files also allow for options such as model plotting and model function evaluation. The three files are presented in sequence with the file "OPTFP1Q5" containing additional sections that also apply to the other two files. The main sections of all three files consist of a rule sheet containing the equations used in optimization and a variable sheet containing the variables and parameters used in those equations. The input and output appear in the variable sheet.

Directions for Using Specific "Scientist" Files

DIRECTIONS FOR WINDOWS VERSION FILES, "CPCK1FQ2," "CPCK1FQ5," AND "CPCK2FQ5"

1. Run the "Scientist" program and open the model file (e.g., "CPCK1FQ5.EQN"), its corresponding parameter file (e.g., "CPCK1FQ5.PAR"), and a spreadsheet file. Compile the model.
2. Key in the data in the spreadsheet file (pinion speed, dose, capture, and cake).

3. In the parameter file, key in the fixed point, the bowl speed, the values of the two dummy variables (CC1 and CC2), and starting values for all the other variables. Click on the variables that are to remain fixed (constant) in the "fix" column.

4. Do a simplex fit several times in order to refine the parameter starting values (press Shift-F7).

5. Do a least squares fit to optimize the parameter values (press F7).

6. Obtain the goodness of fit statistics report (from the "Calculate" menu).

7. Print out the parameter file, the statistics report, and the regression residuals in the spreadsheet file.

Directions for Using Specific "TK Solver" Files

DIRECTIONS FOR WINDOWS VERSION FILE "POLYDRUM"

The "TK Solver" file ("POLYDRUM") consists of a rule sheet containing the relevant equations and a variable sheet containing the variables used by the equations. The software is simple to use: Enter the five input values in the input column, press F9, and read the output values in the output column. A graph of polymer concentration vs. average polymer flow during the test can be obtained by pressing F10 to calculate the graph values and then pressing F7 to display the graph. This shows the estimated polymer concentration which needs to be prepared if other values of average polymer solution flow were used in the input rather than the mid-range recommended value.

DIRECTIONS FOR USING WINDOWS VERSION FILES "OPTFP1Q2", "OPTFP1Q5", AND "OPTFP2Q5"

1. Run the "TK Solver" program and open the existing file by name (e.g., "OPTFP1Q5"). When the model for optimization appears on the screen, set the optimization case. Case 1 is the asymptotic cake case while Case 2 and Case 3 are the quadratic cake cases, which are very rare. This is done by setting the appropriate case variable equal to 1, while blanking out the other two case variables.
2. After setting the optimization case, enter the appropriate parameter values on the variable sheet. Then press F9 to solve for optimum cake, optimum dose, and optimum pinion speed at 95

percent capture. The capture specification value, if desired, can be changed from 95 percent to another value. At this point, you are done. Everything else in steps 3 to 7 is optional.

3. An optimization summary table appears as a result of pressing the F9 key. The summary table values only appear if Case 1 (the asymptotic cake case) is used.
4. At this point, evaluation of the capture and cake performance at various values of dose and pinion speed is possible. For that, just key in the variable values of dose and pinion speed and press F9 to solve for capture and cake after the optimization components have been deactivated by blanking out the "OPTFIND" and case dummy variables.
5. You can also choose to plot the capture and cake performance as a function of dose or pinion speed (RPM). First set the plot variable equal to 1; then begin data entry (to set up the two plots that are possible) for the following plotting variables:

a. XVAR: This is either "DOSE" or "RPM." ("X" axis variable.)

b. FROM: Minimum X-axis value for plot.

c. TO: Maximum X-axis value for plot.

d. N: Number of intervals (just leave it at 50).

e. $DOSE_{CON}$: The optimum dosage (or another value you want to make constant in the plot).

f. RPM_{CON}: The optimum pinion speed (or another value you want to make constant in the plot).

6. After inputting the values for variables a through f in step 5, you get the plot for the "X" variable you picked ("DOSE" or "RPM") by clicking on it in the plot sheet and pressing F7. To get the plot for the second variable, repeat the data entry process. When you get to "XVAR," put in the name of the other "X" variable. After completion of data entry, you will get the other plot by clicking on it in the plot sheet and pressing F7.

7. You can also display one of three possible tables (summary table, dose plot table, and RPM plot table) by clicking on them in the table sheet.

DIRECTIONS FOR USING DOS VERSION FILES "OPTFP1Q2," "OPTFP1Q5," AND "OPTFP2Q5"

1. Run "TK Solver" program and open the existing file by name (e.g., "OPTFP1Q5"). When the model for optimization appears on the screen, a message on available macros appears. Press enter to continue.
2. Now, the general menu appears with a list of options. The first thing to do is to set the optimization case. Case 1 is the asymptotic cake case while Case 2 and Case 3 are the quadratic cake cases which are very rare. Just follow the menu and the case will be set automatically.
3. After setting the optimization case, enter the appropriate parameter values on the variable sheet. Then press F9 to solve for optimum cake, optimum dose, and optimum pinion speed at 95 percent capture. You can change the capture

specification value from 95 percent to another value, if desired. At this point you are done. Everything else in steps 4 to 10 is optional.

4. Now you can press ALT-F1 to get back to the menu or press F8 to see an optimization summary table. The summary table only appears if you are in Case 1 (the asymptotic cake case).

5. If you are in the menu, you can choose to evaluate the capture and cake performance at various values of dose and pinion speed. This is item #2 on the menu. Key in the variable values of dose and pinion speed and press F9 to solve for capture and cake. The optimization components are automatically deactivated when item #2 on the menu is chosen.

6. You can also choose to plot the capture and cake performance as a function of dose or pinion speed (RPM). This is item #3 on the menu. When you pick this item, the cursor guides you in data entry (to set up the two plots that are possible) for the following plotting variables:

   a. XVAR: This is either "DOSE" or "RPM." (X-axis variable.)

b. FROM: Minimum "X" axis value for plot.

c. TO: Maximum "X" axis value for plot.

d. N: Number of intervals (just leave it at 50).

e. $DOSE_{CON}$: The optimum dosage (or another value you want to make constant in the plot).

f. RPM_{CON}: The optimum pinion speed (or another value you want to make constant in the plot).

7. After you input the values for variables a through f in step 6, you get the plot for the "X" variable you picked ("DOSE" or "RPM"). To get the plot for the second variable, return to the menu and repeat the process. When you get to "XVAR," put in the name of the other "X" variable. After completion of data entry, you will get the other plot.

8. You can see both plots simultaneously in the presentation view by pressing "\" (backslash). To get out of presentation view, press ESC.

9. Once both plots are created, you can choose to see a full-screen version of either one by picking item #4 in the menu.

10. You can also pick item #5 in the menu to display one of three possible tables: summary table, dose plot table, and RPM plot table.

Development of a Model for Total Processing Cost

The optimum dose for each of the polymers tested is determined by using the specific files for estimating parameters and optimizing pinion speed, dose, and cake. Since the District has chosen to consider other important sludge processing cost components such as sludge transportation and sludge drying, these components are added to polymer cost. In order to calculate the total processing cost, a mathematical model was developed (Equation 10). The total processing cost for a given polymer is calculated according to the cost function given below:

$$\text{Cost} = (A)(B) + C_1 + C_2\left(\frac{1}{D}\right) \qquad \text{(Equation 10)}$$

Where:

Cost = total processing cost ($/ton)

A = optimum polymer dose (lbs/ton)

B = polymer cost ($/lb)

D = optimum cake solids

C_1 and C_2 are site-specific constants that are a function of cake transportation cost and cake agitation drying cost. (Drying achieved by agitation is a function of weather conditions, evaporation rates, etc. These are considered in deriving the site specific coefficients.)

The polymer product with the lowest total processing cost is selected for purchase.

The values of C_1 and C_2 for the District's Stickney centrifuge operations are $C_1 = -7.1771$ and $C_2 = 906.39$. The transportation cost and agitation drying cost are as follows:

$$\text{Transportation Cost} = 475.75\left(\frac{1}{\%\ \text{cake solids}}\right)$$

$$\text{Agitation Drying Cost} = -7.1771 + 430.64\left(\frac{1}{\%\ \text{cake solids}}\right)$$

Both costs are expressed in dollars per dry ton of sludge solids. If both equations are added together, the values of C_1 and C_2 will be obtained as shown above. Other municipal agencies can obtain such values from their own specific historical data just as they were obtained at the District.

These cost functions are obtained by plotting historical transportation cost against reciprocal percent cake solids and historical agitation drying cost against reciprocal percent cake solids. The resulting curves are transformed into algebraic functions using linear or polynomial regression with reciprocal percent cake solids as the independent variable. Details of how cost functions for transportation and agitation drying are derived are given in Appendix AVII.

A Detailed Example

Before the actual data set is used to exemplify data analysis, general guidelines are presented as an overview for an understanding of the overall flow of the analysis. The detailed example is presented with necessary calculations and explanations. A sample data set, calculations, software outputs, and charts are included in Appendix AIV. A description of all coefficients and parameters used in the various equations are presented and combined in Appendix AV for easy reference.

GENERAL DATA ANALYSIS PROTOCOL

1. Collect necessary data from full-scale test runs. Obtain percent solids data from laboratory and calculate percent capture and polymer dose in lbs/ton. Now, tabulate all the data as shown in Table 2.

2. Use the "Scientist" program to estimate the parameters in the reparameterized capture and cake models, using equation file "CPCK1FQ5" (or "CPCK2FQ5").

3. Key in data (CP, CK, DOSE, RPM) in the data window.

4. Set the fixed point (PCP, PRPM, PDOSE) in the parameter window to the sample point associated with the highest pinion speed in which the capture performance specification is exceeded. Set K = 1 and set the bowl speed to a constant value. Finally, set the dummy variables CC1 and CC2 appropriately and solve to obtain the model parameter estimates and residual sum of squares (RSS) for three cases:

   a. First, set CC1 = 1 and CC2 = 0. (Get the parameter estimates and RSS for the asymptotic linear case.)

   b. Next, set CC1 = 1 and CC2 = 1. (Get the parameter estimates and RSS for the asymptotic quadratic case.)

c. Finally, set CC1 = -1 and CC2 = 1. (Get the parameter estimates and RSS for the maximum quadratic case.)

5. Pick the model with the lowest RSS. If the RSS from the asymptotic linear model and the asymptotic quadratic model are close in value, pick the simpler model (linear).

6. Use the "TK Solver" program to obtain the optimization values (from the model picked above), using equation file "OPTFP1Q5" (or "OPTFP2Q5"). Key in the required data on the variable sheet after setting the appropriate case for optimization. RPM_{run} is equal to PRPM (the pinion speed of the fixed point). Solve the system of equations (by pressing F9) and read the output values under the section called "model variables" on the variable sheet.

In the example, the data set presented in Table AIV-1 consists of 12 points. The data shown in line 1 of Table AIV-1 are deleted because the percent capture is below 80 percent. The model "CPCK1FQ5" is used for data fitting. The optimization calculations are shown in this example for all three categories/cases as shown in step 4 of "general data analysis protocol." It is obviously not necessary to do all three optimization cases, but all three cases are illustrated for the benefit of the reader.

The asymptotic linear model has a RSS of 0.4609 while the asymptotic quadratic model has an RSS of 0.4641. Both have about the same goodness of fit. However, the linear case is preferred since it has a slightly smaller RSS and is the simpler model (one less term). The maximum quadratic case has an RSS of 17.0899. This model is obviously rejected for this data set since the RSS is 37 times higher than those of the asymptotic cases.

In the example, the "OPTFP1Q5" optimization model is used with "CPCK1FQ5."

The example is partitioned into three categories, and the fixed point used is: PRPM = 2500, PDOSE = 402, and PCP = 95.5.

MODEL TYPE: (I) LINEAR ASYMPTOTE; OPTIMIZATION: CASE #1 (ASYMPTOTIC) (SOFTWARE FILES ARE IN APPENDIX AIV)

In this category, CC1 = 1 and CC2 = 0 (in the "Scientist" file). This file consists of four sections: parameter estimations, statistics, residuals, and data. In the first section, the parameter estimations appear in the middle column named "Value." The dummy variables CC1 and CC2 are kept constant, as are K, RPMB, PDOSE, PRPM, and PCP. RPMB is the bowl speed, and the last three parameters correspond to the fixed point. The second section contains the RSS and other statistics for the capture model, the cake model, and the combined models. The residual sum of squares (RSS) is called "sum of squared deviations" in this section and is equal to 0.4609 for both models combined. The third section contains the residuals (the differences from the model predictions and the actual data) and the actual model calculated predictions. The fourth section contains the actual data used in the curve fitting process.

The "TK Solver" file that follows consists of two sections: the variable sheet and the optimization summary table. The variable sheet contains the input and output variables necessary for the optimization while the table summarizes the optimum dose, optimum cake, and optimum pinion speed under the column heading "OPT." In the variable sheet, the Case 1 variable is set equal to 1 (CASE1 = 1); the parameter estimates from the "Scientist" file are keyed into the input column, and the optimization results appear in the output column (in the model variable section) after pressing F9. The optimized values (at 95 percent capture) are:

$$DOSE_{opt} = 400 \text{ lbs/ton}$$

CK_{opt} = 27.5%

RPM_{opt} = 2504 RPM

These are the same as they would appear in the optimization summary table. The output also consists of the model parameters in the original form prior to reparameterization in the "Scientist" file.

MODEL TYPE: (I) QUADRATIC ASYMPTOTE; OPTIMIZATION: CASE #1 (ASYMPTOTIC) (SOFTWARE FILES ARE IN APPENDIX AIV)

In this category, CC1 = 1 and CC2 = 1 (in the "Scientist" file). As before, this file consists of four sections. The RSS for the combined models is equal to 0.4641, as found in the second section.

Again, the "TK Solver" file that follows consists of two sections. In the variable sheet, the Case 1 variable is set equal to 1 (CASE1 = 1) and the optimized values (at 95 percent capture) are:

$DOSE_{opt}$ = 400 lbs/ton

CK_{opt} = 27.5%

RPM_{opt} = 2504 RPM

There is no difference in these optimized values from those obtained in the previous category (as would be suspected from the similar values of RSS). As a result, there is no statistical justification to prefer the models of category one over the models of category two. However, the linear case (category one) is chosen over the quadratic case (category two) based on the fact that it is a simpler model (one less term).

MODEL TYPE: (II) QUADRATIC MAXIMUM; OPTIMIZATION: CASE #2 (UNCONSTRAINED MAXIMUM) AND CASE #3 (CONSTRAINED MAXIMUM) (SOFTWARE FILES ARE IN APPENDIX AIV)

In this category, CC1 = -1 and CC2 = 1 (in the "Scientist" file). This file consists of four sections. The RSS for the combined models is equal to 17.0899, as found in the second section. The cake model fit is much worse, as can be seen by the residuals (in the third section) and the cake model RSS (in the second section). The algorithm has difficulty with convergence in estimating the parameters R and KRZ2 (R approaches infinity and KRZ2 approaches zero). Therefore, to obtain algorithm convergence, R is set equal to 50 (a reasonable upper limit), and KRZ2 is set equal to 0.97 (a typical value). The RSS for this model is 37 times higher than the RSS for the asymptotic models in categories one and two. This model is obviously rejected for this data set since the RSS needs to be <u>less than or equal to</u> that of the asymptotic models in order to be considered as a viable model alternative. Ordinarily this model would be given no further consideration, but for the purposes of this example, it will be used for optimization with the "TK Solver" file applying both Case 2 (the unconstrained maximum criteria) and Case 3 (the constrained maximum criteria) just to show how it is done.

The "TK Solver" files that follow the four sections of the "Scientist" file consist of two different variable sheets. There is no summary optimization table in this situation. In the first variable sheet the Case 2 variable is set equal to 1 (CASE2 = 1) while in the second variable sheet the Case 3 variable is set equal to 1 (CASE3 = 1). For Case 2, the optimized values (at 95 percent capture) are:

$$DOSE_{opt} = 379 \text{ lbs/ton}$$

$$CK_{opt} = 33.2\%$$

$$RPM_{opt} = 2434 \text{ RPM}$$

In Case 3, the optimized values are obtained by an iterative technique. After 36 iterations, the equation solver converges to the exact same optimized values as obtained from Case 2 above. This may not always happen. If the solutions from the two cases are not equal, the constrained solution from Case 3 should be used. Sometimes there may be no solution from Case 3. If so, the solution from Case 2 must be used (as the only solution available).

It should be noted that the CK_{opt} and RPM_{opt} values are way out of range for the data which also shows the inappropriateness of the model. The optimized values are normally in the vicinity of the values for the fixed point.

In summary, the optimized values for this example data set (at 95 percent capture) are as follows:

$DOSE_{opt}$ = 400 lbs/ton

CK_{opt} = 27.5%

RPM_{opt} = 2504 RPM

Because there are sufficient data points and no data spacing problems with this data set, these optimized values could also be obtained by fitting the data directly into the original model forms (Equations 1 and 2, without reparameterization) and then solving the optimization equations (see Appendix AIV, "Original Model Parameter Estimation and Optimization").

GRAPHS OF CAPTURE AND CAKE MODELS FOR EXAMPLE DATA

Graphs are included in Appendix AIV with the example. These are graphs of the capture and cake models along with the data points used to fit the linear asymptote model form. Where dose is the x-axis, the various curves correspond to different values of RPM. Where RPM is the x-axis, the various curves correspond to different values of dose.

SUMMARY OF SELECTION AND PROCUREMENT OF POLYMER FOR FULL-SCALE SLUDGE DEWATERING APPLICATION

The entire procedure, at a conceptual level, is succinctly presented in a paper entitled "A Cost Effective Procedure for the Selection and Procurement of Polymers for Centrifugal Dewatering of Anaerobically Digested Sludge" in Appendix AVI. This paper was presented at the annual WEFTEC conference held in Dallas, Texas, October 1996.

DISCUSSION

The polymer testing procedure described in this report has been applied yearly, over a period of ten years, at all three District centrifuge facilities. More than 300 polymers have been tested to date. Replicated experimental runs with the same mannich polymer at the District's Stickney centrifuge location have shown the polymer dose precision for this procedure to be ±6 lbs/ton (for an average polymer dose of 389 lbs/ton). This precision estimate is in the form of a 95 percent confidence interval (8). Precision is defined in terms of variation with respect to the mean of individual values. It is related to repeatability as well as to the shape of the underlying sampling distribution of successive polymer dose determinations. It is not possible to address accuracy issues since there is no way to determine the standard or "correct" polymer dosage for a given polymer at a given centrifuge facility and then to compare the test obtained dosage with it. The polymer dosage is a function of operation and particularly of how much attention is given to maintaining the operation in a state of optimization. If little or no attention is given to this matter in day-to-day operations (for whatever reasons: time constraints, personnel limitations, etc.), the day-to-day polymer dosage will obviously be inflated over the values obtained by the test procedure.

Over the years, the procedure has been refined to make it more effective for selecting polymers that meet District performance criteria at the lowest cost. It is an example of process optimization using response surface methodology, an experimental discipline in use throughout science, engineering, and industry, which exemplifies current experimental practice in all technical professions (11, 12). This experimental technique is also in use as a <u>continuous</u> program of optimization in various process-oriented technological organizations due to its value in providing ongoing process improvement under conditions of high variability. In this context, response surface optimization is known as evolutionary operation, or EVOP (13). Although other technical fields have applied response surface methodology to their disciplines, the municipal wastewater technology profession has been slow to recognize the value of response surface optimization in its involvement with process improvement and operations research. It is hoped that this example will serve to generate greater interest in applying response surface optimization to other areas in the water and wastewater-related professions.

The essence of the surface response optimization procedure consists of the performance models and the optimization specifics (Equations 1 through 10). Everything else is commentary. This commentary attempts to fill in the gaps inherent in a practical implementation of these equations. As such, there is room for doing things differently by way of tailoring test activities to specific experience, environment, and in the case of centrifuges machine characteristics. The CST laboratory polymer dose estimation procedures provided herein are not intrinsically necessary to do the surface response optimization on full-scale centrifuges. One may use other laboratory procedures for polymer dose estimation or not use any laboratory procedure whatsoever, relying instead on personal experience or manufacturer advice. Likewise, there is great latitude in how sampling is to be done during the test. The sampling schemes provided are simply suggestions for what has worked well at the District. Certainly, other sampling schemes may be instituted, as appropriate. Of course, the computational details do not need to be done with the "Scientist" and "TK Solver" software. One may use other appropriate nonlinear algorithms for model parameter estimation (or use the ones suggested in the references). There is much room for creativity in applying Equations 1 through 10 in the specific and unique circumstances that are likely to be found in the field. The point is that this procedure does not lend itself to be expressed as a standard method of the sort to be found in technical cookbook-style manuals for chemical analysis. It is a template for research under difficult and stressful field conditions while working with large quantities of nonhomogenous material under severe time constraints, material quantity limitations, and error consequences. It is not and never will be the leisurely and highly controlled laboratory experience assumed in executing a standard method for chemical analysis. In fact, full-scale process experimentation requires a substantially different set of skills than does laboratory experimentation. Moreover, these skills are not taught in academic institutions (14, 15, 16, 17, 18, 19). Instead, they are taught in industrial training seminars and workshops which cater to professionals desiring to expand their skills in this area (15, 20). Of course, appropriate work experience and self-study can also contribute to the development of these skills. Regardless of how they may be attained, some mastery of these skills is a requirement for consistent success in orchestrating this type of test procedure effectively.

Apart from issues on commentary, it may be asked when the performance models (Equations 1 and 2) are applicable. These models have been developed to describe the behavior of high-performance counter-current rotating bowl centrifuges which have variable pinion speed capability. They have been found appropriate to describe such machines from two manufacturers: Sharples and Humbolt. Concurrent rotating bowl centrifuges may exhibit behavior that is not adequately described by those models. If questions of applicability arise, it is suggested that experiments be performed to characterize machine performance and that a comparison be made with the behavior shown in Figure 10. If the machine behavior is the same, the performance models (Equations 1 and 2) will apply, and the test procedure presented may be used for optimization.

If the test machines are low-performance rotating bowl centrifuges without variable pinion speed capability (pinion speed is constant and set by the manufacturer), the corresponding performance models are greatly simplified in form. In this case, $K_2 = K_4 = 0$ (in Equation 1) and $K'_2 = K'_3 = 0$ (in Equation 2), and as a result the models appear as follows:

$$[\%\ \text{CAPTURE}] = K_1 + K_3(\text{DOSE})^N$$

$$[\%\ \text{CAKE}] = K'_1 + K'_4(\text{DOSE})^S\ .$$

Thus, the three-dimensional response surfaces defined by the performance models become two-dimensional response curves. Reparameterization is not required in this simpler situation, but quadratic terms may be added for improved data fit if necessary:

$$[\%\ \text{CAPTURE}] = K_1 + K_3(\text{DOSE})^N + K_5(\text{DOSE})^{2N}$$

$$[\%\ \text{CAKE}] = K_1' + K_4'(\text{DOSE})^S + K_5'(\text{DOSE})^{2S}$$

The corresponding optimization is also greatly simplified since there is no pinion speed to optimize. In this case, the percent capture specification (95 percent) is substituted into the capture performance model, and the equation is solved for dose. This is the optimum dose at 95 percent capture. The optimum dose is then substituted into the cake performance model, and the equation is solved for percent cake. This is the optimum percent cake at 95 percent capture. In formal notation, the optimization takes place as follows:

$$[\%\ \text{CAPTURE}] = F_1(\text{DOSE})$$

$$[\%\ \text{CAKE}] = F_2(\text{DOSE})$$

$$95 = F_1(\text{DOSE})$$

$$\text{DOSE}_{\text{OPT}} = F_1^{-1}(95)$$

$$[\%\ \text{CAKE}]_{\text{OPT}} = F_2(\text{DOSE}_{\text{OPT}})$$

where F_1 and F_2 are the mathematical functions that correspond to the capture and cake models, respectively, just described. F_1^{-1} is the inverse function of F_1.

If any questions of model applicability arise, it is suggested that experiments be performed to characterize machine performance and that a comparison be made with the behavior shown on the left (DOSE) side of Figure 10. If the machine behavior is the same, the simplified performance models will apply, and the simplified optimization procedure can be used. Since the pinion speed is fixed, the previous commentary in this report concerning variable pinion speed is not relevant in this case. These simplified performance models (and simplified optimization procedure) were used effectively at the District for many years on the low-performance, constant pinion speed centrifuges prior to replacement with the high-performance, variable pinion speed centrifuges.

Some final comments on the impact of sludge matrix nonhomogeneity are of importance. Sludges can have the same gross characteristics (such as pH, total solids, volatile solids, and alkalinity) and yet have completely different sludge matrices composed of complex interparticle arrangements and other interconnecting structures which have great impact on a variety of important issues. Some examples of such issues are how strongly the water is bound, how much polymer it takes to release that water through the process of floc formation, and how resistant the flocs are to destructive shear forces that cause reabsorption of the released water. It is clear that such issues vitally affect polymer dose estimates in any kind of test procedure where the sludge matrix can vary substantially. In fact, if such sludge matrix variability is sufficiently large, it can compromise the effectiveness of the entire test polymer dosage comparison and/or prevent the test obtained polymer dose estimates from accurately predicting annual polymer usage and annual polymer costs for budgetary considerations.

When large sludge matrix variability occurs during the testing of a group of polymers, the comparison of polymer dosages may become invalid without adjustment for the sludge matrix variability. If the sludge matrix variability is such that it varies from day to day, this adjustment can be made by testing the same control polymer each day in addition to the actual test polymer. Thus, the specific day-to-day variation in the control polymer dosages allows for an adjustment of the corresponding test polymer dosages. This adjustment provides a comparison of the polymers tested, as if they were all tested with the same sludge matrix. Indeed, such an adjustment has been necessary several times during District centrifuge polymer tests over a two-decade period.

Of course, such test adjustments cannot be made if the sludge matrix variability is hour to hour, month to month, or seasonal. Under such circumstances, the sludge matrix variability becomes part of the test variability, and the polymer dose estimate precision is inflated as a result. If this inflation becomes large enough, the test comparison becomes ineffective since all the polymer dose estimates then fall within each others' error limits and thus are not distinguishable from each other in any significant way. If this happens, the test is reduced to nothing better than a random choice between polymers.

It cannot be emphasized enough that sludge matrix nonhomogeneity can subvert this or any polymer test procedure. This problem is most likely to be aggravated in locations where the sludge feed to the centrifuge comes from many different digesters (the situation at the District). A serious nonhomogeneous sludge matrix situation at a centrifuge facility means that the polymer dose changes constantly as the sludge matrix changes and that no one-day test procedure can hope to describe this complex situation with its polymer dose estimation for a given day. It is to be anticipated that this type of situation will not allow for accurate annual predictions of either polymer dosage or polymer costs and that in order to provide such predictions, historical plant experience must be applied to develop appropriate factors which must be used with the test obtained polymer dose estimates for appropriate adjustment.

Although it cannot be guaranteed that the precise polymer dosage determined on the testing day will remain constant throughout the year, the test procedure described in this report does in fact provide for the selection of the polymer, from those tested, that would give the best performance at the lowest cost of the polymers submitted for evaluation.

CONCLUSION

This report describes a polymer testing procedure which has been developed and used at the District's three centrifuge facilities for screening and selecting polymers, in a competitive bidding process, which are best suited to the District's operation. The District has used this procedure for over ten years, during which time more than 300 polymers have been tested. Based upon replicated experimental runs using the same mannich polymer at the District's Stickney centrifuge complex, the test procedure has been shown to have a polymer dose precision of ±6 lbs/ton of solids at an average polymer dose of 389 lbs/ton of solids.

The performance models and optimization procedures which have been developed for the high-performance counter-current rotating bowl centrifuges with variable speed pinion speed capability used at the District could be adapted to other facilities, depending upon their experience and the information available regarding machine performance.

The technique in a simplified form may also be applicable to low-performance rotating bowl centrifuges without variable pinion speed capability.

While the test procedure provides for the selection of the polymer which gives the best performance at the lowest cost, the actual annual polymer usage will vary depending upon a number of variables, including sludge characteristics, machine characteristics, and operator control.

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APPENDIX AI

SAMPLE BID DOCUMENTS

AND

SAMPLE LETTER WITH TEST RESULTS

SAMPLE BID DOCUMENTS

SUBMITTAL OF POLYMERS FOR TESTING AT THE STICKNEY WATER RECLAMATION PLANT

The Metropolitan Water Reclamation District of Greater Chicago (District) will conduct tests at the Stickney Water Reclamation Plant Centrifuge Complex during **February and March,** 1999 to select suitable polymers for dewatering anaerobically digested winter sludge.

Bids will be invited on all successful products. The only products eligible for bidding will be those which have successfully completed all of the specified procedures at the scheduled times. Any polymer for which each section of the procedure is not followed promptly and exactly will be rejected from consideration.

The following procedures shall be strictly adhered to:

1. Each interested manufacturer shall furnish the following items to **Stanley Soszynski**, R & D Laboratory, Metropolitan Water Reclamation District of Greater Chicago, 6001 West Pershing Road, Stickney, Illinois 60650:

    a) One completed polymer data form for each polymer that the manufacturer wishes to be tested.

    b) One polymer sample with a volume of 1 pint for each polymer.

    c) One material data safety sheet for each polymer.

Each manufacturer may submit no more than 2 polymers for testing. Each copy of these documents includes 2 blank data forms.

The completed data forms and polymer samples shall be delivered by mail or by hand, and must reach **Stanley Soszynski** not later than 3:00 p.m. on **February 19, 1998**. The District's storage tanks and unloading facilities may be inspected at the Stickney Water Reclamation Plant during normal business hours by contacting **Mr. Omar Zayyad** at the Stickney Water Reclamation Plant, 6001 West Pershing Road, Stickney, Illinois 60650, telephone **(708) 222-4158**.

Only manufacturers may submit polymers for testing. A prospective supplier who is not the manufacturer should contact the manufacturer to request that the manufacturer participate in the testing program. Manufacturer authorized suppliers, as well as the manufacturers themselves, may participate in bidding.

2. Polymers must have the following physical/chemical characteristics:

A. Liquid polymers (emulsions or gels) must have an absolute viscosity less than 60,000 centipoises (23 degrees C) when measured with the Brookfield viscometer, Model LV, with the appropriate spindles (usually spindles 4 or 5) at 30 R.P.M.

B. Solid polymers shall not be submitted.

C. The polymer must be safe to handle with protective equipment limited to face mask and gloves.

D. The liquid polymers must be available for delivery by the successful bidder in tank trucks with a nominal capacity of 5,000 gallons.

E. Polymers which cause operating problems related to foaming, scale, or struvite formation will not be accepted by the District.

F. All polymers must be compatible with the District's polymer feed equipment at the Stickney Water Reclamation Plant Centrifuge Complex.

3. The District will determine a testing schedule and notify each manufacturer of the test date for each of his polymers. On a scheduled date, prior to the date of the test, the manufacturer shall deliver to Mr. Omar Zayyad, free of charge, a properly labeled sample of each polymer for which the manufacturer submitted information in item 1 above.

The concentration and composition of the polymer sample shall be identical to concentration and composition of polymer which the manufacturer will furnish in the event that such polymer is, as the ultimate result of the bidding, the successful product. The required amount of polymer is that which is sufficient for one complete, full scale, 8 hour test. This amount is impossible to accurately determine in advance, but the following dosage ranges may be of use as guidelines:

For emulsions: 20 - 80 lbs per dry ton of sludge
For gels: 200 - 600 lbs per dry ton of sludge

The District estimates that 12 to 14 dry tons of sludge will be processed during the 8 hour test. The District will notify each manufacturer of the proper amount of polymer to deliver for the test.

The manufacturer must supply his own drum pump to transfer the polymer from the manufacturer's drums into the District's mixing tank, which is approximately 6 feet high. The drum pump must be powered either by air or by standard 115 Volt AC electricity. The pump must be supplied with a discharge hose, and a 3-wire power supply cord. The manufacturer will be responsible for transfer of his polymer into the District's mixing tank. Immediately after this transfer, the manufacturer must remove his drums from the site.

4. The polymers which successfully pass the initial elimination procedure, as set forth in step II below, will be eligible for bidding. The optimum dosage of each polymer required per dry ton of sludge will be determined in accordance with step III of the testing procedure.

5. The District will determine the number of dry tons of sludge it wishes to condition, and will calculate the number of pounds of each polymer required to condition such quantity of sludge.

6. When the District advertises for bids, the prospective supplier of each polymer will be required to bid upon the quantity of polymer calculated by the District. The total processing cost for each eligible polymer is based on the bid price, intrafacility transportation cost, and agitation drying processing cost; it is calculated in accordance with the following formula:

$$\text{Processing Cost}(\$) = (A)(B) + C_1 + C_2(1/D)$$

where:

A = pounds of polymer per dry ton of sludge determined in section III below.

B = Cost (dollars) of polymer per pound of polymer.

C_1 = -7.17712423

C_2 = 906.39397333

D = Percent total solids of centrifuge cake (at the optimum dosage), as determined in section II-E below.

Cost($) = Total dollars per dry ton of sludge.

LARGE SCALE CENTRIFUGE EVALUATION TEST

I. Field Test Procedure

A. Cake solids, centrate, and feed samples will be taken at various dosages for each polymer. The samples will be taken after at least 15 minutes of centrifuge operation at a given dosage. These samples will be analyzed for percent total solids.

B. Samples will be taken at different pinion speeds (RPM) at various dosages for each polymer. These samples will be analyzed to determine how the polymer performs over the entire range of torques.

C. The performance of the polymer, **Secodyne No. LE-891**, which is currently in use at the Stickney Centrifuge Complex, will be concurrently evaluated with each polymer sample. If the sludge feed solids concentrations fluctuate widely during the test, then the test results for **Secodyne No. LE-891** will be used to adjust the test results of the polymers sample.

D. The sludge flow rate will be kept constant during the test. The sludge flow rate will be chosen to allow for seasonal performance variations.

E. All tests will be conducted with a Sharples Model PM-76000 centrifuge located at the Stickney Centrifuge Complex.

II. Polymer Performance Evaluation

A. Performance Characteristic Curves

The method of least squares will be used to fit the data gathered from Step I to the following equations:

$$[\%\ \text{capture}] = K_1 + K_2 e^{M(RPM-RPMB)} + K_3(\text{Dose})^N + K_4(\text{Dose})^N e^{P(RPM-RPMB)}$$

$$[\%\ \text{cake}] = K'_1 + K'_2(RPMB-RPM)^R + K'_3(RPMB-RPM)^{2R} + K'_4(\text{Dose})^S$$

Where:

[% capture] = percent solids capture defined in general note 3 below

[% cake] = percent cake solids

Dose = polymer dose in pounds per dry ton of sludge solids

RPMB = bowl speed in revolutions per minute

RPM = pinion speed in revolutions per minute

K_1, K_2, K_3, K_4, M, N, P, K_1', K_2', K_3', K_4', R, S are the curve fitting parameters to be determined by the method of least squares.

B. Initial Elimination Procedure

Polymers which do not produce a percent capture value greater than 95% at some point on the curve described in II-A (above) will be eliminated from further evaluation. All polymers which meet this criterion are eligible for further evaluation.

C. Optimum Pinion Speed

1. If K_2' is greater than zero, the constrained solution for the optimum pinion speed (RPM_{opt}) is obtained by setting the derivative of the following function equal to zero and solving for the variable of RPM_{opt}:

$$[\%\ \text{cake}] = K_1' + K_2'(RPMB - RPM_{opt})^R + K_3'(RPMB - RPM_{opt})^{2R} + K_4'\left[\frac{95 - K_1 - K_2 e^{M(RPM_{opt} - RPMB)}}{K_3 + K_4 e^{P(RPM_{opt} - RPMB)}}\right]^{\frac{S}{N}}$$

2. In the event that the constrained solution does not exist, the unconstrained solution for the optimum pinion speed (RPMopt) is obtained from the following expression:

$$RPM_{opt} = RPMB - \left[\frac{-K_2'}{2K_3'}\right]^{\frac{1}{R}}$$

3. If K_2' is less than zero, the optimum pinion speed is obtained from the following expression:

$$RPM_{opt} = \left[RPMB - RPMH - \frac{1}{M}\ln\left(\frac{K_2}{95 - K_1}\right)\right]\phi + RPMH$$

where:

$\phi = .25$

RPMH = highest pinion speed in which a sample exceeds 95% capture

4. RPM_{opt} is rounded to the units place.

D. Optimum Dose

The optimum dose, $Dose_{opt}$, is obtained from the following expression rounded to 3 significant digits:

$$Dose_{opt} = \left[\frac{95 - K_1 - K_2 e^{M(RPM_{opt} - RPMB)}}{K_3 + K_4 e^{P(RPM_{opt} - RPMB)}}\right]^{\frac{1}{N}}$$

E. Optimum cake solids

The optimum cake solids, $\%cake_{opt}$, is obtained from the following expression rounded to 3 significant digits:

$$\%cake_{opt} = K'_1 + K'_2(RPMB - RPM_{opt})^R + K'_3(RPMB - RPM_{opt})^{2R} + K'_4(Dose_{opt})^S$$

This optimum cake solids value is represented as the variable "D" in the equation on page T-3 for total cost per dry ton of sludge.

III. Bidding Dosage

The bidding dosage is $Dose_{opt}$ which was obtained in II-D.

This optimum dose value is represented as the variable "A" in the equation on page T-3 for total cost per dry ton of sludge.

IV. Polymer Selection

The polymers which provide the lowest cost per dry ton of sludge from the February and March, 1999 tests according to the equation on page T-3, will be the polymers of choice.

General Notes

1. Equipment

   A. 1,000 gal mixing tank
   B. 0-20 gpm polymer feed pump

2. All machine adjustments will be made solely by the District

3. %capture = [(F-H)/F][G/(G-H)] X 100

   where:

   F = % TS in feed
   G = % TS in cake
   H = % TS in centrate

SAMPLE LETTER WITH TEST RESULTS

INTER OFFICE MEMORANDUM

Metropolitan Water Reclamation District of Greater Chicago

DEPARTMENT: Research and Development **DATE:** April 1, 1999

TO: Thomas K. O'Connor
Chief of Maintenance and Operations

FROM: Cecil Lue-Hing

SUBJECT: Polymer Tests - Stickney Water Reclamation Plant (WRP) Centrifuge Complex, March 1999

The winter polymer testing program for the Stickney WRP centrifuge complex has been completed according to the contract documents entitled, "Submittal of Polymers for Testing at the Stickney Water Reclamation Plant."

A total of eight polymers from four manufacturers was submitted for full-scale testing. Attached in Table 1 is a listing of the polymer products qualified for bidding, along with the sludge cake solids and dosages determined from the testing program. One of the polymer products (PMX 5040) from Polymex did not meet the 95 percent capture specification. Therefore, it does not appear on the bidding list.

Cecil Lue-Hing
Director
Research and Development

CLH:DTL:lmf
Attachment
cc: Tata
Sawyer
Lordi
Soszynski

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE 1

POLYMER TEST RESULTS AT STICKNEY WRP CENTRIFUGE COMPLEX - MARCH 1999

Polymer Manufacturer	Polymer Identification	Sludge Cake Solids (%)	Polymer Dose (Lbs/Dry Ton)
Polydyne	NW108	25.5	427
Polydyne	NW109	24.3	406
Polymex	PMX 5035	21.7	499
Ciba	7953WR	22.4	641
Ciba	7552QY	22.9	578
Stockhausen*	K260 FL	26.1	60.6
Stockhausen*	K275 FLX	24.8	73.8

*These are emulsion polymer products.

APPENDIX AII

COMPUTER FILES IN "SCIENTIST" SOFTWARE

PERFORMANCE MODEL FILE:
CPCK1FQ5

PERFORMANCE MODEL FILE:
CPCK2FQ5

PERFORMANCE MODEL FILE:
CPCK1FQ2

CODE FOR
SCIENTIST
PERFORMANCE MODEL FILE:
CPCK1FQ5

```
IndVars:  DOSE RPM
DepVars:  CP CK
Params:  P K KRZ1 KDZ CKMX CC1 CC2 R S KRZ2 RPMB PDOSE PRPM PCP
RPMZ1 := KRZ1*RPMB
M := 1/P*LN(1/K*(1-PCP/100))/(PRPM-RPMZ1)
Q := 1/K*(1-PCP/100)-EXP(M*(PRPM-RPMZ1))
DOSEZ := KDZ*PDOSE
N := LN(SQRT(Q*Q))/(LN(PDOSE/DOSEZ))
CP := 100*(1-K*(EXP(M*(RPM-RPMZ1))+(DOSE/DOSEZ)^N))
RPMZ2 := KRZ2*PRPM
PHIMAX := ((1+SQRT(5))/2)^(1/R)
PHIASY := ((-1+SQRT(5))/2)^(1/R)
PHI := PHIMAX*(1-CC1)/2+PHIASY*(1+CC1)/2
RPMZ2MX := (RPMZ2+(PHI-1)*RPMB)/PHI
RPMZ2G :=RPMZ2*(1-CC2)+RPMZ2MX*CC2
RDEL := (RPMB-RPM)/(RPMB-RPMZ2G)
CK := CKMX*(1-CC1*RDEL^R-CC2*RDEL^(2*R)-(DOSE/DOSEZ)^S)
***
```

ParamName	Lower Limit	Value	UpperLimit
P	0.000000000	0.950000000	1.00000000
K	0.000000000	1.00000000	Infinity
KRZ1	0.000000000	0.930000000	1.00000000
KDZ	0.000000000	0.850000000	1.00000000
CKMX	0.000000000	30.0000000	50.0000000
CC1	-Infinity	1.00000000	Infinity
CC2	-Infinity	0.000000000	Infinity
R	0.000000000	15.0000000	75.0000000
S	-75.0000000	-15.0000000	-1.00000000
KRZ2	0.000000000	0.970000000	1.00000000
RPMB	-Infinity	2725.00000	Infinity
PDOSE	-Infinity	94.0000000	Infinity
PRPM	-Infinity	2385.00000	Infinity
PCP	-Infinity	96.0000000	Infinity

CODE FOR
SCIENTIST
PERFORMANCE MODEL FILE:
CPCK2FQ5

```
IndVars: DOSE RPM
DepVars: CP CK
Params: P K KRZ1 KDZ CC1 CC2 R S KRZ2 RPMB PDOSE PRPM PCP PCK
RPMZ1 := KRZ1*RPMB
M := 1/P*LN(1/K*(1-PCP/100))/(PRPM-RPMZ1)
Q := 1/K*(1-PCP/100)-EXP(M*(PRPM-RPMZ1))
DOSEZ := KDZ*PDOSE
N := LN(SQRT(Q*Q))/(LN(PDOSE/DOSEZ))
CP := 100*(1-K*(EXP(M*(RPM-RPMZ1))+(DOSE/DOSEZ)^N))
RPMZ2 := KRZ2*PRPM
PHIMAX := ((1+SQRT(5))/2)^(1/R)
PHIASY := ((-1+SQRT(5))/2)^(1/R)
PHI := PHIMAX*(1-CC1)/2+PHIASY*(1+CC1)/2
RPMZ2MX := (RPMZ2+(PHI-1)*RPMB)/PHI
RPMZ2G :=RPMZ2*(1-CC2)+RPMZ2MX*CC2
RDEL := (RPMB-RPM)/(RPMB-RPMZ2G)
RDELP := (RPMB-PRPM)/(RPMB-RPMZ2G)
CKMX := PCK/(1-CC1*RDELP^R-CC2*RDELP^(2*R)-(PDOSE/DOSEZ)^S)
CK := CKMX*(1-CC1*RDEL^R-CC2*RDEL^(2*R)-(DOSE/DOSEZ)^S)
***
```

SUGGESTED PARAMETER VALUES TO BE
USED IN FILE CPCK2FQ5

ParamName	Lower Limit	Value	UpperLimit
P	0.000000000	0.950000000	1.00000000
K	0.000000000	1.00000000	Infinity
KRZ1	0.000000000	0.930000000	1.00000000
KDZ	0.000000000	0.850000000	1.00000000
CC1	-Infinity	1.00000000	Infinity
CC2	-Infinity	0.000000000	Infinity
R	0.000000000	15.0000000	75.0000000
S	-75.0000000	-15.0000000	-1.00000000
KRZ2	0.000000000	0.970000000	1.00000000
RPMB	-Infinity	2725.00000	Infinity
PDOSE	-Infinity	158.000000	Infinity
PRPM	-Infinity	2375.00000	Infinity
PCP	-Infinity	96.0000000	Infinity
PCK	-Infinity	25.1000000	Infinity

```
IndVars: DOSE RPM
DepVars: CP CK
Params: P K RPMZ1 DOSEZ CKMX CC1 CC2 R S RPMZ2 RPMB PDOSE PRPM PCP
M := 1/P*LN(1/K*(1-PCP/100))/(PRPM-RPMZ1)
Q := 1/K*(1-PCP/100)-EXP(M*(PRPM-RPMZ1))
N := LN(SQRT(Q*Q))/(LN(PDOSE/DOSEZ))
CP := 100*(1-K*(EXP(M*(RPM-RPMZ1))+(DOSE/DOSEZ)^N))
PHIMAX := ((1+SQRT(5))/2)^(1/R)
PHIASY := ((-1+SQRT(5))/2)^(1/R)
PHI := PHIMAX*(1-CC1)/2+PHIASY*(1+CC1)/2
RPMZ2MX := (RPMZ2+(PHI-1)*RPMB)/PHI
RPMZ2G := RPMZ2*(1-CC2)+RPMZ2MX*CC2
RDEL := (RPMB-RPM)/(RPMB-RPMZ2G)
CK := CKMX*(1-CC1*RDEL^R-CC2*RDEL^(2*R)-(DOSE/DOSEZ)^S)
***
```

SUGGESTED PARAMETER VALUES TO BE
USED IN FILE CPCK1FQ2

ParamName	Lower Limit	Value	UpperLimit
P	0.000000000	0.950000000	1.00000000
K	0.000000000	1.00000000	Infinity
RPMZ1	2500.00000	2600.00000	2833.00000
DOSEZ	0.000000000	325.000000	750.000000
CKMX	0.000000000	30.0000000	50.0000000
CC1	-Infinity	1.00000000	Infinity
CC2	-Infinity	0.000000000	Infinity
R	0.000000000	15.0000000	50.0000000
S	-50.0000000	-15.0000000	0.000000000
RPMZ2	2300.00000	2425.00000	2500.00000
RPMB	-Infinity	2833.00000	Infinity
PDOSE	-Infinity	402.000000	Infinity
PRPM	-Infinity	2500.00000	Infinity
PCP	-Infinity	95.5000000	Infinity

APPENDIX AIII

COMPUTER FILES IN "TK SOLVER" SOFTWARE

POLYMER DRUM AND POLYMER CONCENTRATION
MODEL FILE: POLYDRUM

OPTIMIZATION FILE: OPTFP1Q5

OPTIMIZATION FILE: OPTFP2Q5

OPTIMIZATION FILE: OPTFP1Q2

CODE FOR "TK SOLVER" FILE:
POLYDRUM

NOTE: POLYDRUM FILE CODE CONSISTS OF EQUATION (RULE) SHEET AND INPUT/OUTPUT VARIABLE SHEET

EQUATION (RULE) SHEET OF POLYDRUM FILE

S Rule

TONSLG=GPMSLG*(HOURS/24)*(%TS/100)*1440*8.34/2000

LBSPLY=TONSLG*DOSE

DRUMS=LBSPLY/(50*8.34)

VOLUME=GPMPLY*HOURS*60

VOLPLY=VOLUME*%PLY/100

DOSE=(%PLY/%TS)*(GPMPLY/GPMSLG)*2000

C DRUMS=VOLPLY/50

INPUT/OUTPUT VARIABLE SHEET OF POLYDRUM FILE

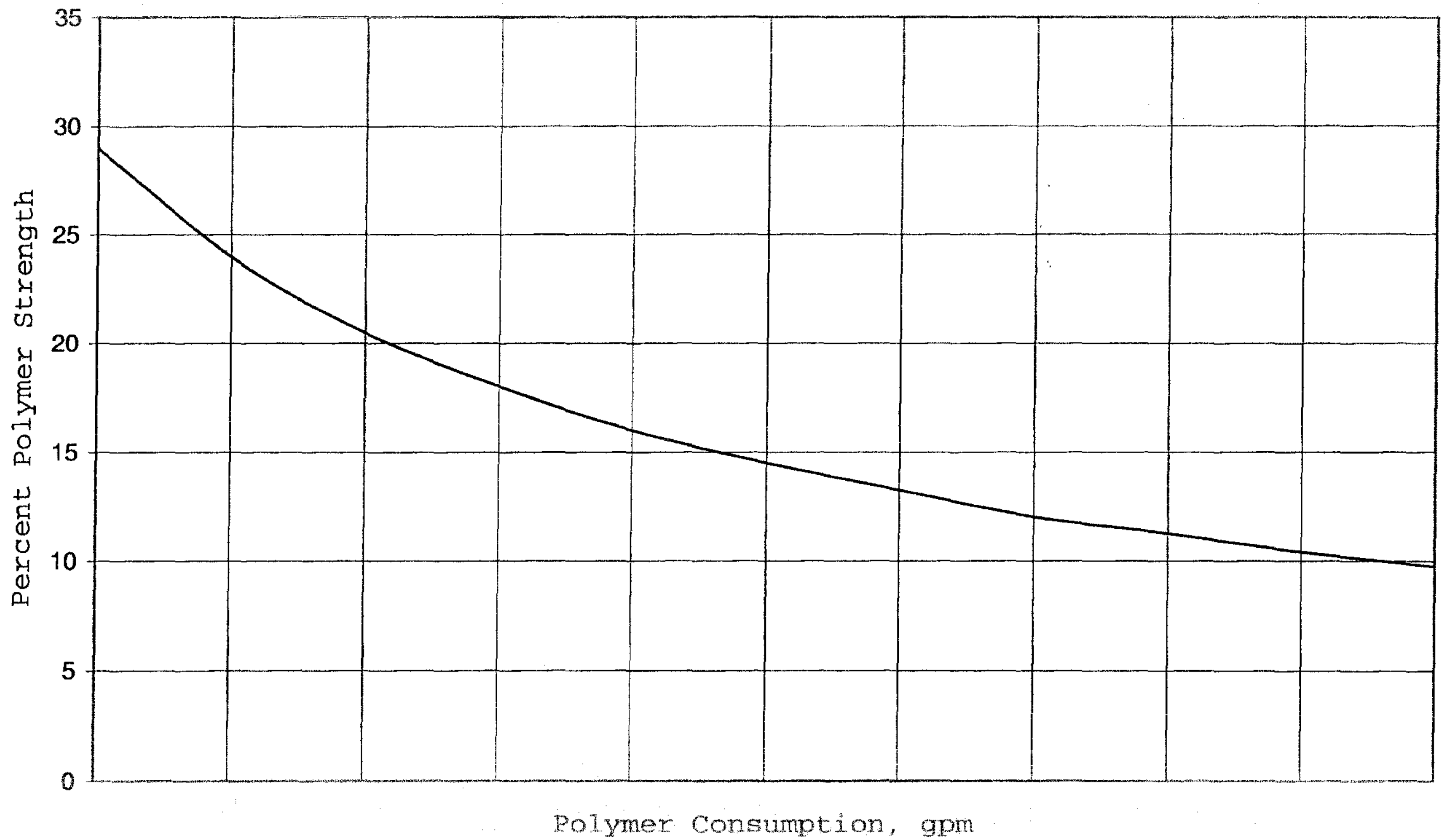
St	Input	Name	Output	Unit	Comment
		HOURS	3.3333333	HR	TIME FOR TEST IN HOURS
	415	DOSE		LBS/TON	POLY DOSE IN LBS PER DRY TON
	3.5	%TS		%	PERCENT TS OF FEED SLUDGE
	200	GPMSLG		GAL/MIN	FLOW OF SLUDGE IN GPM
L	10	GPMPLY		GAL/MIN	FLOW OF POLYMER IN GPM
		TONSLG	5.838	TONS	TONS OF DRY SLUDGE USED
		LBSPLY	2422.77	LBS	LBS OF POLY USED
		DRUMS	5.81		DRUMS OF POLY NEEDED (55 GAL)
L		%PLY	14.525	%	POLY SOLUTION CONCENTRATION
	2000	VOLUME		GAL	POLY SOLUTION VOLUME NEEDED

GRAPH OF
POLYMER CONSUMPTION (FLOW RATE) VS. PERCENT POLYMER STRENGTH
(POLYMER CONCENTRATION)
FROM THE INPUT/OUTPUT VARIABLE SHEET
OF POLYDRUM FILE

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE AIII-1

RELATIONSHIP BETWEEN PERCENT POLYMER STRENGTH AND CONSUMPTION OF POLYMER



CODE FOR "TK SOLVER" OPTIMIZATION
FILE: OPTFP1Q5

NOTE: OPTFP1Q5 FILE CODE CONSISTS OF EQUATION (RULE) SHEET, INPUT/OUTPUT VARIABLE SHEET, FUNCTION DEFINITION SHEETS, AND SUBROUTINES FOR COMPILING SUMMARY TABLES AND CHARTS

EQUATION (RULE) SHEET OF FILE OPTFP1Q5

```
                    ;CAPTURE AND CAKE MODELS;
  CP=CPF(RPM,DOSE)
  CK=CKF(RPM,DOSE)
  DOSE=DOSEF(CP,RPM)

                   ;OPTIMIZATION EQUATIONS (C2<0);
  CASE1*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE1
  CASE1*RPMopt=((RPMmax-RPMrun)*ALPHA+RPMrun)*CASE1

             ;OPTIMIZATION EQUATIONS (C2>0) : UNCONSTRAINED CASE;
* CASE2*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE2
* IF CASE2<>1 THEN DEN=1 ELSE DEN=2*C3
* IF C3<>0 THEN CASE2*RPM2=(RPMB-((-C2)/(DEN))^(1/R))*CASE2
* IF C3<>0 THEN CASE2*RPM1=((RPMmax-RPMrun)*ALPHA+RPMrun)*CASE2
* IF RPM2>RPMmax THEN CASE2*RPMopt=RPM1 ELSE CASE2*RPMopt=RPM2
* IF RPM2>RPMmax THEN CALL TSUMMARY1()

             ;OPTIMIZATION EQUATIONS (C2>0) : CONSTRAINED CASE;
* CASE3*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE3
* CASE3*A=(CKF(RPMopt+KK*RPMopt,DOSEF(CP,RPMopt+KK*RPMopt)))*CASE3
* CASE3*B=(CKF(RPMopt-KK*RPMopt,DOSEF(CP,RPMopt-KK*RPMopt)))*CASE3
* CASE3*0=((A-B)/(2*KK*RPMopt))*CASE3

                   ;GENERAL OPTIMIZATION EQUATIONS;
  OPTFIND*RPM=ROUND(RPMopt)*OPTFIND

                   ;MAKE SUMMARY TABLE FOR CASE1;
  CALL BLANK('RUN)
  CALL BLANK('OPT)
  CALL BLANK('MAX)
  IF CASE1=1 THEN CALL TSUMMARY1()

                   ;CALCULATE PARAMETER VALUES;
  K1=100
```

S Rule

```
K2=-100*K*EXP(M*(RPMB-RPMZ1))
K3=-100*K*(DOSEZ)^(-N)
K4=0
RPMZ1=KRZ1*RPMB
DOSEZ=KDZ*PDOSE
M=(1/P)*LN((1/K)*(1-PCP/100))/(PRPM-RPMZ1)
Q=(1/K)*(1-PCP/100)-EXP(M*(PRPM-RPMZ1))
N=LN(SQRT(Q*Q))/LN(PDOSE/DOSEZ)
C=1.5

C1=CKMX
C2=-CKMX*CC1*(RPMB-RPMZ2G)^(-R)
C3=-CKMX*CC2*(RPMB-RPMZ2G)^(-2*R)
C4=-CKMX*(DOSEZ)^(-S)
RPMZ2=KRZ2*PRPM
PHIMAX=((1+SQRT(5))/2)^(1/R)
PHIASY=((-1+SQRT(5))/2)^(1/R)
PHI=PHIMAX*(1-CC1)/2+PHIASY*(1+CC1)/2
RPMZ2MX=(RPMZ2+(PHI-1)*RPMB)/PHI
RPMZ2G=RPMZ2*(1-CC2)+RPMZ2MX*CC2

                    ;MISCELLANEOUS EQUATIONS;
RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))
IF PLOT=1 THEN CALL qplot()
```

INPUT/OUTPUT VARIABLE SHEET OF FILE OPTFP1Q5

St	Input	Name	Output	Unit	Comment
					*DUMMY VARIABLES TO SET CASE
	1	OPTFIND			SET OPTIMIZATION ALGORITHIM
	1	CASE1			C2<0 : ASYMPTOTE
		CASE2			C2>0 : UNCONSTRAINED MAX
		CASE3			C2>0 : CONSTRAINED MAX
					MODEL VARIABLES
	95	CP			
		CK	25.7		
		RPM	2432		
		DOSE	97.69		
					OPTIMIZATION VARIABLES
		RPMmax	2454		
		RPMopt	2432.25		
	2425	RPMrun			
					PARAMETERS FOR CP & CK
	2730	RPMB			
					PARAMETERS FOR CAPTURE
		K1	100		(FROM CALCULATION)
		K2	-3296.185		(FROM CALCULATION)
		K3	-1.121E65		(FROM CALCULATION)
		K4	0		(FROM CALCULATION)
		M	.02356218		(FROM CALCULATION)
		N	-32.53295		(FROM CALCULATION)
		C	1.5		(FROM CALCULATION)
	.85	KDZ			*DOCUMENTATION
	.94566087	KRZ1			*DOCUMENTATION
	1	K			
	.95	P			*DOCUMENTATION

St	Input	Name	Output	Unit	Comment
		C1	31.2		(FROM CALCULATION)
		C2	-1.15E-30		(FROM CALCULATION)
		C3	0		(FROM CALCULATION)
		C4	-9.59E35		(FROM CALCULATION)
	12.196281	R			
	-17.79531	S			
	.97	KRZ2			*DOCUMENTATION
	1	CC1			*DOCUMENTATION (CC1 : 1 OR -1)
	0	CC2			*DOCUMENTATION (CC2 : 1 OR 0)
	31.2	CKMX			
					FIXED POINT
	102	PDOSE			
	2425	PRPM			
	97	PCP			
					PARAMETERS FOR OPTIMIZATION
	.0001	KK			
	.25	ALPHA			
					VARIABLES FOR PLOTTING
	'DOSE	xvar			function "x" variable (DOSE or RPM)
	1	from			MIN
	125	to			MAX
	50	n			number of intervals
	97.7	DOSEcon			DOSE constant (xvar=RPM)
	2432	RPMcon			RPM constant (xvar=DOSE)
		PLOT			SET PLOTTING ALGORITHIM

FUNCTION DEFINITION SHEETS OF FILE OPTFP1Q5

Comment: CP(RPM,DOSE)

Parameter Variables: K1,K2,K3,K4,M,N,C,RPMB,K,DOSEZ,RPMZ1

Argument Variables: RPM,DOSE

Result Variables: CP

S Rule

```
    ; ORIGINAL FORM
C   CP=K1+K2*EXP(M*(RPM-RPMB))+K3*DOSE^N+K4EQN
C   K4EQN=K4*DOSE^N*EXP(C*M*(RPM-RPMB))

    ; ALTERNATE FORM
    CP=100*(1-K*(EXP(M*(RPM-RPMZ1))+(DOSE/DOSEZ)^N))
```

Comment: CK(RPM,DOSE)

Parameter Variables: C1,C2,C3,C4,R,S,RPMB,CKMX,CC1,CC2,DOSE

Argument Variables: RPM,DOSE

Result Variables: CK

S Rule

```
; ORIGINAL FORM
C CK=C1+C2*(RPMB-RPM)^R+C3*(RPMB-RPM)^(2*R)+C4*DOSE^S

; ALTERNATE FORM
RDEL=(RPMB-RPM)/(RPMB-RPMZ2G)
CK=CKMX*(1-CC1*(RDEL)^R-CC2*(RDEL)^(2*R)-(DOSE/DOSEZ)^S)
```

Comment: DOSE(CP,RPM)

Parameter Variables: K1,K2,K3,K4,M,N,C,RPMB,K,DOSEZ,RPMZ1

Argument Variables: CP,RPM

Result Variables: DOSE

<u>S</u> <u>Rule</u>

```
  ; ORIGINAL FORM
C DOSE=((CP-K1-K2*EXP(M*(RPM-RPMB)))/DEN)^(1/N)
C DEN=K3+K4*EXP(C*M*(RPM-RPMB))

  ; ALTERNATE FORM
  DOSE=DOSEZ*(((1-CP/100)/K)-EXP(M*(RPM-RPMZ1)))^(1/N)
```

A PORTION OF "OPTFP1Q5" FILE CODE WHICH COMPILES AND ORGANIZES THE SUMMARY TABLE

Comment: SUMMARY TABLE FOR CASE 1

Parameter Variables: RPMrun,RPM,RPMmax,CP

Input Variables:

Output Variables:

S Statement

```
'RUN[1]=RPMrun
'RUN[2]=DOSEF(CP,RPMrun)
'RUN[3]=CKF(RPMrun,'RUN[2])
'RUN[4]=CP
'OPT[1]=RPM
'OPT[2]=DOSEF(CP,RPM)
'OPT[3]=CKF(RPM,'OPT[2])
'OPT[4]=CP
'MAX[1]=RPMmax
'MAX[2]=DOSEF(CP,RPMmax)
'MAX[3]=CKF(RPMmax,'MAX[2])
'MAX[4]=CP
'NAME[1]='RPM
'NAME[2]='DOSE
'NAME[3]='CK
'NAME[4]='CP
```

PLOT SUBROUTINE CODE OF FILE OPTFP1Q5

Comment: PLOTTING SUBROUTINE

Parameter Variables: xvar,from,to,n

Input Variables:

Output Variables:

<u>S</u> <u>Statement</u>

```
CALL STATMSG('WORKING)
IF xvar='DOSE THEN GOTO SPOT1
IF xvar='RPM THEN GOTO SPOT2
CALL ERRMSG('xvar,'value,'must,'be,'DOSE,'or,'RPM)
SPOT1:
    name='CPFD
    name2='CKFD
    GOTO SPOT3
SPOT2:
    name='CPFR
    name2='CKFR
    GOTO SPOT4
SPOT3:
call blank('xxx)
call blank('yyy)
call blank('yyy2)
dp:= (to-from)/n
p:= from
for i=1 to n+1
  ('xxx[i],'yyy[i]):= (p,apply(name,p))
  ('xxx[i],'yyy2[i]):= (p,apply(name2,p))
  p:= p + dp
next i
CALL BEEP()
RETURN
SPOT4:
call blank('xxx2)
call blank('zzz)
call blank('zzz2)
dp:= (to-from)/n
```

S Statement

```
p:= from
for i=1 to n+1
  ('xxx2[i],'zzz[i]):= (p,apply(name,p))
  ('xxx2[i],'zzz2[i]):= (p,apply(name2,p))
  p:= p + dp
next i
CALL BEEP()
RETURN
```

CODE FOR "TK SOLVER" OPTIMIZATION
FILE: OPTFP2Q5

NOTE: OPTFP2Q5 FILE CODE CONSISTS OF EQUATION (RULE) SHEET, INPUT/OUTPUT VARIABLE SHEET, FUNCTION DEFINITION SHEETS, AND SUBROUTINES FOR COMPILING SUMMARY TABLES AND CHARTS

EQUATION (RULE) SHEET OF FILE OPTFP2Q5

```
S  Rule
                    ;CAPTURE AND CAKE MODELS;
   CP=CPF(RPM,DOSE)
   CK=CKF(RPM,DOSE)
   DOSE=DOSEF(CP,RPM)

                    ;OPTIMIZATION EQUATIONS (C2<0);
   CASE1*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE1
   CASE1*RPMopt=((RPMmax-RPMrun)*ALPHA+RPMrun)*CASE1

          ;OPTIMIZATION EQUATIONS (C2>0) : UNCONSTRAINED CASE;
*  CASE2*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE2
*  IF CASE2<>1 THEN DEN=1 ELSE DEN=2*C3
*  IF C3<>0 THEN CASE2*RPM2=(RPMB-((-C2)/(DEN))^(1/R))*CASE2
*  IF C3<>0 THEN CASE2*RPM1=((RPMmax-RPMrun)*ALPHA+RPMrun)*CASE2
*  IF RPM2>RPMmax THEN CASE2*RPMopt=RPM1 ELSE CASE2*RPMopt=RPM2
*  IF RPM2>RPMmax THEN CALL TSUMMARY1()

          ;OPTIMIZATION EQUATIONS (C2>0) : CONSTRAINED CASE;
*  CASE3*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE3
*  CASE3*A=(CKF(RPMopt+KK*RPMopt,DOSEF(CP,RPMopt+KK*RPMopt)))*CASE3
*  CASE3*B=(CKF(RPMopt-KK*RPMopt,DOSEF(CP,RPMopt-KK*RPMopt)))*CASE3
*  CASE3*0=((A-B)/(2*KK*RPMopt))*CASE3

                    ;GENERAL OPTIMIZATION EQUATIONS;
   OPTFIND*RPM=ROUND(RPMopt)*OPTFIND

                    ;MAKE SUMMARY TABLE FOR CASE1;
   CALL BLANK('RUN)
   CALL BLANK('OPT)
   CALL BLANK('MAX)
   IF CASE1=1 THEN CALL TSUMMARY1()

                    ;CALCULATE PARAMETER VALUES;
   K1=100
```

S Rule

```
K2=-100*K*EXP(M*(RPMB-RPMZ1))
K3=-100*K*(DOSEZ)^(-N)
K4=0
RPMZ1=KRZ1*RPMB
DOSEZ=KDZ*PDOSE
M=(1/P)*LN((1/K)*(1-PCP/100))/(PRPM-RPMZ1)
Q=(1/K)*(1-PCP/100)-EXP(M*(PRPM-RPMZ1))
N=LN(SQRT(Q*Q))/LN(PDOSE/DOSEZ)
C=1.5

C1=CKMX
C2=-CKMX*CC1*(RPMB-RPMZ2G)^(-R)
C3=-CKMX*CC2*(RPMB-RPMZ2G)^(-2*R)
C4=-CKMX*(DOSEZ)^(-S)
RPMZ2=KRZ2*PRPM
PHIMAX=((1+SQRT(5))/2)^(1/R)
PHIASY=((-1+SQRT(5))/2)^(1/R)
PHI=PHIMAX*(1-CC1)/2+PHIASY*(1+CC1)/2
RPMZ2MX=(RPMZ2+(PHI-1)*RPMB)/PHI
RPMZ2G=RPMZ2*(1-CC2)+RPMZ2MX*CC2
RDELP=(RPMB-PRPM)/(RPMB-RPMZ2G)
CKMX=PCK/(1-CC1*RDELP^R-CC2*RDELP^(2*R)-(PDOSE/DOSEZ)^S)

                  ;MISCELLANEOUS EQUATIONS;
RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))
* IF PLOT=1 THEN CALL qplot()
```

INPUT/OUTPUT VARIABLE SHEET OF FILE OPTFP2Q5

St	Input	Name	Output	Unit	Comment
					*DUMMY VARIABLES TO SET CASE
	1	OPTFIND			SET OPTIMIZATION ALGORITHIM
	1	CASE1			C2<0 : ASYMPTOTE
		CASE2			C2>0 : UNCONSTRAINED MAX
		CASE3			C2>0 : CONSTRAINED MAX
					MODEL VARIABLES
	95	CP			
		CK	24.5		
		RPM	2380		
		DOSE	154.36		
					OPTIMIZATION VARIABLES
		RPMmax	2395		
		RPMopt	2380		
	2375	RPMrun			
					PARAMETERS FOR CP & CK
	2725	RPMB			
					PARAMETERS FOR CAPTURE
		K1	100		(FROM CALCULATION)
		K2	-2424.855		(FROM CALCULATION)
		K3	-3.092E68		(FROM CALCULATION)
		K4	0		(FROM CALCULATION)
		M	.01879042		(FROM CALCULATION)
		N	-31.24433		(FROM CALCULATION)
		C	1.5		(FROM CALCULATION)
	.85	KDZ			*DOCUMENTATION
	.93773214	KRZ1			*DOCUMENTATION
	1	K			
	.95	P			*DOCUMENTATION

St	Input	Name	Output	Unit	Comment
		C1	26.448957		(FROM CALCULATION)
		C2	-1.22E-74		(FROM CALCULATION)
		C3	0		(FROM CALCULATION)
		C4	-5.15E41		(FROM CALCULATION)
	28.705016	R			
	-18.93231	S			
	.97	KRZ2			*DOCUMENTATION
	1	CC1			*DOCUMENTATION (CC1 : 1 OR -1)
	0	CC2			*DOCUMENTATION (CC2 : 1 OR 0)
		CKMX	26.448957		
					FIXED POINT
	158	PDOSE			
	2375	PRPM			
	96	PCP			
	25.1	PCK			
					PARAMETERS FOR OPTIMIZATION
	.0001	KK			
	.25	ALPHA			
					VARIABLES FOR PLOT TING
	'DOSE	xvar			function "x" variable (DOSE or RPM)
	1	from			MIN
	200	to			MAX
	50	n			number of intervals
	154	DOSEcon			DOSE constant (xvar=RPM)
	2380	RPMcon			RPM constant (xvar=DOSE)
		PLOT			SET PLOTTING ALGORITHM

CODE FOR "TK SOLVER" OPTIMIZATION
FILE: OPTFP1Q2

NOTE: OPTFP1Q2 FILE CODE CONSISTS OF EQUATION (RULE) SHEET, INPUT/OUTPUT VARIABLE SHEET, FUNCTION DEFINITION SHEETS, AND SUBROUTINES FOR COMPILING SUMMARY TABLES AND CHARTS

EQUATION (RULE) SHEET OF FILE OPTFP1Q2

S Rule

```
                    ;CAPTURE AND CAKE MODELS;
  CP=CPF(RPM,DOSE)
  CK=CKF(RPM,DOSE)
  DOSE=DOSEF(CP,RPM)

                    ;OPTIMIZATION EQUATIONS (C2<0);
  CASE1*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE1
  CASE1*RPMopt=((RPMmax-RPMrun)*ALPHA+RPMrun)*CASE1

              ;OPTIMIZATION EQUATIONS (C2>0) : UNCONSTRAINED CASE;
* CASE2*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE2
* IF CASE2<>1 THEN DEN=1 ELSE DEN=2*C3
* IF C3<>0 THEN CASE2*RPM2=(RPMB-((-C2)/(DEN))^(1/R))*CASE2
* IF C3<>0 THEN CASE2*RPM1=((RPMmax-RPMrun)*ALPHA+RPMrun)*CASE2
* IF RPM2>RPMmax THEN CASE2*RPMopt=RPM1 ELSE CASE2*RPMopt=RPM2
* IF RPM2>RPMmax THEN CALL TSUMMARY1()

              ;OPTIMIZATION EQUATIONS (C2>0) : CONSTRAINED CASE;
* CASE3*RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))*CASE3
* CASE3*A=(CKF(RPMopt+KK*RPMopt,DOSEF(CP,RPMopt+KK*RPMopt)))*CASE3
* CASE3*B=(CKF(RPMopt-KK*RPMopt,DOSEF(CP,RPMopt-KK*RPMopt)))*CASE3
* CASE3*0=((A-B)/(2*KK*RPMopt))*CASE3

                    ;GENERAL OPTIMIZATION EQUATIONS;
  OPTFIND*RPM=ROUND(RPMopt)*OPTFIND

                    ;MAKE SUMMARY TABLE FOR CASE1;
  CALL BLANK('RUN)
  CALL BLANK('OPT)
  CALL BLANK('MAX)
  IF CASE1=1 THEN CALL TSUMMARY1()

                    ;CALCULATE PARAMETER VALUES;
  K1=100
```

S Rule

```
K2=-100*K*EXP(M*(RPMB-RPMZ1))
K3=-100*K*(DOSEZ)^(-N)
K4=0
M=(1/P)*LN((1/K)*(1-PCP/100))/(PRPM-RPMZ1)
Q=(1/K)*(1-PCP/100)-EXP(M*(PRPM-RPMZ1))
N=LN(SQRT(Q*Q))/LN(PDOSE/DOSEZ)
C=1.5

C1=CKMX
C2=-CKMX*CC1*(RPMB-RPMZ2G)^(-R)
C3=-CKMX*CC2*(RPMB-RPMZ2G)^(-2*R)
C4=-CKMX*(DOSEZ)^(-S)
PHIMAX=((1+SQRT(5))/2)^(1/R)
PHIASY=((-1+SQRT(5))/2)^(1/R)
PHI=PHIMAX*(1-CC1)/2+PHIASY*(1+CC1)/2
RPMZ2MX=(RPMZ2+(PHI-1)*RPMB)/PHI
RPMZ2G=RPMZ2*(1-CC2)+RPMZ2MX*CC2

                ;MISCELLANEOUS EQUATIONS;
RPMmax=INT(((1/M)*LN((CP-K1)/K2)+RPMB))
* IF PLOT=1 THEN CALL qplot()
```

INPUT/OUTPUT VARIABLE SHEET OF FILE OPTFP1Q2

St	Input	Name	Output	Unit	Comment
					*DUMMY VARIABLES TO SET CASE
	1	OPTFIND			SET OPTIMIZATION ALGORITHIM
	1	CASE1			C2<0 : ASYMPTOTE
		CASE2			C2>0 : UNCONSTRAINED MAX
		CASE3			C2>0 : CONSTRAINED MAX
					MODEL VARIABLES
	95	CP			
		CK	26.8		
		RPM	2502		
		DOSE	396.08		
					OPTIMIZATION VARIABLES
		RPMmax	2509		
		RPMopt	2502.25		
	2500	RPMrun			
					PARAMETERS FOR CP & CK
	2833	RPMB			
					PARAMETERS FOR CAPTURE
		K1	100		(FROM CALCULATION)
		K2	-38586.73		(FROM CALCULATION)
		K3	-1.001E61		(FROM CALCULATION)
		K4	0		(FROM CALCULATION)
		M	.02768709		(FROM CALCULATION)
		N	-23.48844		(FROM CALCULATION)
		C	1.5		(FROM CALCULATION)
	325	DOSEZ			
	2617.9	RPMZ1			
	1	K			
	.95	P			*DOCUMENTATION

St	Input	Name	Output	Unit	Comment
		C1	29.8		(FROM CALCULATION)
		C2	-6.97E-23		(FROM CALCULATION)
		C3	0		(FROM CALCULATION)
		C4	-8.973E42		(FROM CALCULATION)
	8.8968	R			
	-16.513	S			
	2380	RPMZ2			
	1	CC1			*DOCUMENTATION (CC1 : 1 OR -1)
	0	CC2			*DOCUMENTATION (CC2 : 1 OR 0)
	29.8	CKMX			
					FIXED POINT
	402	PDOSE			
	2500	PRPM			
	95.5	PCP			
					PARAMETERS FOR OPTIMIZATION
	.0001	KK			
	.25	ALPHA			
					VARIABLES FOR PLOTTING
	'DOSE	xvar			function "x" variable (DOSE or RPM)
	1	from			MIN
	450	to			MAX
	50	n			number of intervals
	396	DOSEcon			DOSE constant (xvar=RPM)
	2502	RPMcon			RPM constant (xvar=DOSE)
		PLOT			SET PLOTTING ALGORITHIM

EXAMPLE DATA SHEET
(TABLE AIV-1)

APPENDIX AIV

A DETAILED EXAMPLE

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AIV-1

RECORD SHEET FOR FULL-SCALE POLYMER EVALUATION

Date : ________ Bowl Speed : 2800

Raw Polymer : ________
Dilute Polymer : 14.5 %
Product Designation : ________
Product Type : MANNICH
Polymer Manufacturer : ________
Manufacturer Representative : ________
MWRDGC Representative : ________

Run #	Time of Sampling	Sludge Flow, gpm	Dilute Poly Flow, gpm	Post Dilution H_2O, gpm	Feed Sludge, % TS	Cake % TS	Centrate % TS	% Capture	Dilute Poly % TS	Polymer, Dose, lb/DT	Δ	Torque	Pinion Speed, rpm
1	10:00	200	8.80		3.5	24.1	0.956	75.7	14.5	365			2550
2	10:15	200	9.10		3.5	26.4	0.714	81.8	14.5	376			2550
3	10:30	200	9.40		3.5	27.7	0.592	84.9	14.5	389			2550
4	10:45	200	9.40		3.5	27.8	0.352	91.1	14.5	389			2525
5	11:00	200	9.70		3.5	28.1	0.301	92.4	14.5	402			2525
6	11:15	200	10.00		3.5	28.3	0.273	93.1	14.5	415			2525
7	11:30	200	9.40		3.5	26.7	0.232	94.2	14.5	389			2500
8	11:45	200	9.70		3.5	27.3	0.179	***95.5***	14.5	***402***			***2500***
9	12:00	200	10.00		3.5	27.6	0.151	96.2	14.5	415			2500
10	12:15	200	9.40		3.5	24.4	0.158	96.1	14.5	389			2475
11	12:30	200	9.70		3.5	25.1	0.125	96.9	14.5	402			2475
12	12:45	200	10.00		3.5	25.6	0.105	97.4	14.5	415			2475

"SCIENTIST" FILE
FOR LINEAR ASYMPTOTE

LEAST SQUARES PARAMETER VALUE ESTIMATIONS

ParamName	Lower Limit	Value	UpperLimit
P	0.000000000	0.918176003	1.00000000
K	0.000000000	1.00000000	Infinity
KRZ1	0.000000000	0.938882016	1.00000000
KDZ	0.000000000	0.829538551	1.00000000
CKMX	0.000000000	29.1181538	50.0000000
CC1	-Infinity	1.00000000	Infinity
CC2	-Infinity	0.000000000	Infinity
R	0.000000000	13.5144032	75.0000000
S	-75.0000000	-20.2733126	-1.00000000
KRZ2	0.000000000	0.967364142	1.00000000
RPMB	-Infinity	2800.00000	Infinity
PDOSE	-Infinity	402.000000	Infinity
PRPM	-Infinity	2500.00000	Infinity
PCP	-Infinity	95.5000000	Infinity

GOODNESS OF FIT STATISTICS

*** MicroMath Scientist Statistics Report ***

Model File Name : c:\modfitw\cpck1fq5.eqn
Data File Name : c:\modfitw\example.mmd
Param File Name : c:\modfitw\cpck1fq5.par

Goodness-of-fit statistics for data set: c:\modfitw\example.mmd

Data Column Name: CP

	Weighted	Unweighted
Sum of squared observations :	94763.7400	94763.7400
Sum of squared deviations :	0.301768710	0.301768710
Standard deviation of data :	0.274667394	0.274667394
R-squared :	0.999996816	0.999996816
Coefficient of determination :	0.998821626	0.998821626
Correlation :	0.999413498	0.999413498

Data Column Name: CK

	Weighted	Unweighted
Sum of squared observations :	7928.26000	7928.26000
Sum of squared deviations :	0.159113529	0.159113529
Standard deviation of data :	0.199445186	0.199445186
R-squared :	0.999979931	0.999979931
Coefficient of determination :	0.990582972	0.990582972
Correlation :	0.995281293	0.995281293

Data Set Name: c:\modfitw\example.mmd

	Weighted	Unweighted
Sum of squared observations :	102692.0000	102692.0000
Sum of squared deviations :	0.460882239	0.460882239
Standard deviation of data :	0.175286858	0.175286858
R-squared :	0.999995512	0.999995512
Coefficient of determination :	0.999980907	0.999980907
Correlation :	0.999990460	0.999990460
Model Selection Criterion :	10.2298197	10.2298197

MODEL RESIDUALS AND CALCULATED MODEL PREDICTIONS

	CP_CALC	CK_CALC	CP_RESIDUALS	CK_RESIDUALS
1	81.8649414	26.4670496	-0.0649414400	-0.0670495569
2	91.0201121	27.4874216	0.0798878971	0.312578381
3	95.5000000	27.3315902	0.000000000	-0.0315902184
4	97.7242496	25.4457823	-0.324249625	0.154217723
5	84.9367976	27.7394258	-0.0367976238	-0.0394257603
6	92.3407230	28.1114380	0.0592769553	-0.0114379597
7	92.9242502	28.4246390	0.175749820	-0.124639033
8	96.0835271	27.6447913	0.116472865	-0.0447912920
9	94.1793891	26.7075739	0.0206109417	-0.00757387742
10	97.1407225	25.1325812	-0.240722490	-0.0325812037
11	95.8201115	24.5085649	0.279888452	-0.108564863

DATA USED IN MODEL FITTING AND PARAMETER ESTIMATION

	RPM	DOSE	CP	CK
1	2550.00000	376.000000	81.8000000	26.4000000
2	2525.00000	389.000000	91.1000000	27.8000000
3	2500.00000	402.000000	95.5000000	27.3000000
4	2475.00000	415.000000	97.4000000	25.6000000
5	2550.00000	389.000000	84.9000000	27.7000000
6	2525.00000	402.000000	92.4000000	28.1000000
7	2525.00000	415.000000	93.1000000	28.3000000
8	2500.00000	415.000000	96.2000000	27.6000000
9	2500.00000	389.000000	94.2000000	26.7000000
10	2475.00000	402.000000	96.9000000	25.1000000
11	2475.00000	389.000000	96.1000000	24.4000000

"TK SOLVER" FILE FOR LINEAR ASYMPTOTE

INPUT/OUTPUT VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					*DUMMY VARIABLES TO SET CASE
	1	OPTFIND			SET OPTIMIZATION ALGORITHIM
	1	CASE1			C2<0 : ASYMPTOTE
		CASE2			C2>0 : UNCONSTRAINED MAX
		CASE3			C2>0 : CONSTRAINED MAX
					MODEL VARIABLES
	95	CP			
		CK	27.5		
		RPM	2504		
		DOSE	400.23		
					OPTIMIZATION VARIABLES
		RPMmax	2514		
		RPMopt	2503.5		
	2500	RPMrun			
					PARAMETERS FOR CP & CK
	2800	RPMB			
					PARAMETERS FOR CAPTURE
		K1	100		(FROM CALCULATION)
		K2	-8867.951		(FROM CALCULATION)
		K3	-1.126E63		(FROM CALCULATION)
		K4	0		(FROM CALCULATION)
		M	.02620826		(FROM CALCULATION)
		N	-24.19744		(FROM CALCULATION)
		C	1.5		(FROM CALCULATION)
	.82953855	KDZ			*DOCUMENTATION
	.93888202	KRZ1			*DOCUMENTATION
	1	K			
	.918176	P			*DOCUMENTATION

St	Input	Name	Output	Unit	Comment
		C1	29.118154		(FROM CALCULATION)
		C2	-3.76E-34		(FROM CALCULATION)
		C3	0		(FROM CALCULATION)
		C4	-4.121E52		(FROM CALCULATION)
	13.514403	R			
	-20.27331	S			
	.96736414	KRZ2			*DOCUMENTATION
	1	CC1			*DOCUMENTATION (CC1 : 1 OR -1)
	0	CC2			*DOCUMENTATION (CC2 : 1 OR 0)
	29.118154	CKMX			
					FIXED POINT
	402	PDOSE			
	2500	PRPM			
	95.5	PCP			
					PARAMETERS FOR OPTIMIZATION
	.0001	KK			
	.25	ALPHA			
					VARIABLES FOR PLOT TING
	'RPM	xvar			function "x" variable (DOSE or RPM)
	2300	from			MIN
	2600	to			MAX
	50	n			number of intervals
	56.3	DOSEcon			DOSE constant (xvar=RPM)
	2405	RPMcon			RPM constant (xvar=DOSE)

OPTIMIZATION SUMMARY TABLE

Title: OPTIMIZATION SUMMARY

	VARIABLE	RUN	OPT	MAX
1	'RPM	2500	2504	2514
2	'DOSE	395.8	400.2	449.3
3	'CK	27.1	27.5	28.5
4	'CP	95	95	95

"SCIENTIST" FILE FOR QUADRATIC ASYMPTOTE

LEAST SQUARES PARAMETER VALUE ESTIMATIONS

ParamName	Lower Limit	Value	UpperLimit
P	0.000000000	0.918249926	1.00000000
K	0.000000000	1.00000000	Infinity
KRZ1	0.000000000	0.938887054	1.00000000
KDZ	0.000000000	0.829595767	1.00000000
CKMX	0.000000000	29.1420530	50.0000000
CC1	-Infinity	1.00000000	Infinity
CC2	-Infinity	1.00000000	Infinity
R	0.000000000	12.6120332	75.0000000
S	-75.0000000	-20.2677225	-1.00000000
KRZ2	0.000000000	0.970276890	1.00000000
RPMB	-Infinity	2800.00000	Infinity
PDOSE	-Infinity	402.000000	Infinity
PRPM	-Infinity	2500.00000	Infinity
PCP	-Infinity	95.5000000	Infinity

GOODNESS OF FIT STATISTICS

*** MicroMath Scientist Statistics Report ***

Model File Name : c:\modfitw\cpck1fq5.eqn
Data File Name : c:\modfitw\example.mmd
Param File Name : c:\modfitw\cpck1fq5.par

Goodness-of-fit statistics for data set: c:\modfitw\example.mmd

Data Column Name: CP

	Weighted	Unweighted
Sum of squared observations :	94763.7400	94763.7400
Sum of squared deviations :	0.301839451	0.301839451
Standard deviation of data :	0.274699586	0.274699586
R-squared :	0.999996815	0.999996815
Coefficient of determination :	0.998821350	0.998821350
Correlation :	0.999413370	0.999413370

Data Column Name: CK

	Weighted	Unweighted
Sum of squared observations :	7928.26000	7928.26000
Sum of squared deviations :	0.162226598	0.162226598
Standard deviation of data :	0.201386816	0.201386816
R-squared :	0.999979538	0.999979538
Coefficient of determination :	0.990398727	0.990398727
Correlation :	0.995188877	0.995188877

Data Set Name: c:\modfitw\example.mmd

	Weighted	Unweighted
Sum of squared observations :	102692.0000	102692.0000
Sum of squared deviations :	0.464066049	0.464066049
Standard deviation of data :	0.175891264	0.175891264
R-squared :	0.999995481	0.999995481
Coefficient of determination :	0.999980775	0.999980775
Correlation :	0.999990394	0.999990394
Model Selection Criterion :	10.2229353	10.2229353

MODEL RESIDUALS AND CALCULATED MODEL PREDICTIONS

	CP_CALC	CK_CALC	CP_RESIDUALS	CK_RESIDUALS
1	81.8643842	26.4682459	-0.0643842278	-0.0682459322
2	91.0201310	27.4818422	0.0798689574	0.318157825
3	95.5000000	27.3341046	0.000000000	-0.0341046303
4	97.7241926	25.4469255	-0.324192647	0.153074498
5	84.9374946	27.7440592	-0.0374946095	-0.0440592192
6	92.3406820	28.1076616	0.0593179614	-0.00766155938
7	92.9239267	28.4218246	0.176073297	-0.121824607
8	96.0832447	27.6482677	0.116755335	-0.0482676776
9	94.1794490	26.7082852	0.0205509960	-0.00828524634
10	97.1409480	25.1327625	-0.240947982	-0.0327624544
11	95.8203970	24.5069431	0.279603014	-0.106943070

DATA USED IN MODEL FITTING
AND PARAMETER ESTIMATION

	RPM	DOSE	CP	CK
1	2550.00000	376.000000	81.8000000	26.4000000
2	2525.00000	389.000000	91.1000000	27.8000000
3	2500.00000	402.000000	95.5000000	27.3000000
4	2475.00000	415.000000	97.4000000	25.6000000
5	2550.00000	389.000000	84.9000000	27.7000000
6	2525.00000	402.000000	92.4000000	28.1000000
7	2525.00000	415.000000	93.1000000	28.3000000
8	2500.00000	415.000000	96.2000000	27.6000000
9	2500.00000	389.000000	94.2000000	26.7000000
10	2475.00000	402.000000	96.9000000	25.1000000
11	2475.00000	389.000000	96.1000000	24.4000000

"TK SOLVER" FILE FOR QUADRATIC ASYMPTOTE

INPUT/OUTPUT VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					*DUMMY VARIABLES TO SET CASE
	1	OPTFIND			SET OPTIMIZATION ALGORITHIM
	1	CASE1			C2<0 : ASYMPTOTE
		CASE2			C2>0 : UNCONSTRAINED MAX
		CASE3			C2>0 : CONSTRAINED MAX
					MODEL VARIABLES
	95	CP			
		CK	27.5		
		RPM	2504		
		DOSE	400.23		
					OPTIMIZATION VARIABLES
		RPMmax	2514		
		RPMopt	2503.5		
	2500	RPMrun			
					PARAMETERS FOR CP & CK
	2800	RPMB			
					PARAMETERS FOR CAPTURE
		K1	100		(FROM CALCULATION)
		K2	-8857.125		(FROM CALCULATION)
		K3	-1.22E63		(FROM CALCULATION)
		K4	0		(FROM CALCULATION)
		M	.02620328		(FROM CALCULATION)
		N	-24.21094		(FROM CALCULATION)
		C	1.5		(FROM CALCULATION)
	.82959577	KDZ			*DOCUMENTATION
	.93888705	KRZ1			*DOCUMENTATION
	1	K			
	.91824993	P			*DOCUMENTATION

St	Input	Name	Output	Unit	Comment
		C1	29.142053		(FROM CALCULATION)
		C2	-6.34E-32		(FROM CALCULATION)
		C3	-1.38E-64		(FROM CALCULATION)
		C4	-3.998E52		(FROM CALCULATION)
	12.612033	R			
	-20.26772	S			
	.97027689	KRZ2			*DOCUMENTATION
	1	CC1			*DOCUMENTATION (CC1 : 1 OR -1)
	1	CC2			*DOCUMENTATION (CC2 : 1 OR 0)
	29.142053	CKMX			
					FIXED POINT
	402	PDOSE			
	2500	PRPM			
	95.5	PCP			
					PARAMETERS FOR OPTIMIZATION
	.0001	KK			
	.25	ALPHA			
					VARIABLES FOR PLOT TING
	'RPM	xvar			function "x" variable (DOSE or RPM)
	2300	from			MIN
	2600	to			MAX
	50	n			number of intervals
	56.3	DOSEcon			DOSE constant (xvar=RPM)
	2405	RPMcon			RPM constant (xvar=DOSE)

OPTIMIZATION SUMMARY TABLE

Title: OPTIMIZATION SUMMARY

	VARIABLE	RUN	OPT	MAX
1	'RPM	2500	2504	2514
2	'DOSE	395.8	400.2	449.6
3	'CK	27.1	27.5	28.5
4	'CP	95	95	95

"SCIENTIST" FILE FOR QUADRATIC MAXIMUM

LEAST SQUARES PARAMETER VALUE ESTIMATIONS

ParamName	Lower Limit	Value	UpperLimit
P	0.000000000	0.909304892	1.00000000
K	0.000000000	1.00000000	Infinity
KRZ1	0.000000000	0.938279715	1.00000000
KDZ	0.000000000	0.822607867	1.00000000
CKMX	0.000000000	27.0630191	50.0000000
CC1	-Infinity	-1.00000000	Infinity
CC2	-Infinity	1.00000000	Infinity
R	0.000000000	50.0000000	75.0000000
S	-75.0000000	-26.9578257	-1.00000000
KRZ2	0.000000000	0.970000000	1.00000000
RPMB	-Infinity	2800.00000	Infinity
PDOSE	-Infinity	402.000000	Infinity
PRPM	-Infinity	2500.00000	Infinity
PCP	-Infinity	95.5000000	Infinity

GOODNESS OF FIT STATISTICS

*** MicroMath Scientist Statistics Report ***

Model File Name :	c:\modfitw\cpck1fq5.eqn
Data File Name :	c:\modfitw\example.mmd
Param File Name :	c:\modfitw\cpck1fq5.par

Goodness-of-fit statistics for data set: c:\modfitw\example.mmd

Data Column Name: CP

	Weighted	Unweighted
Sum of squared observations :	94763.7400	94763.7400
Sum of squared deviations :	0.305161602	0.305161602
Standard deviation of data :	0.225522209	0.225522209
R-squared :	0.999996780	0.999996780
Coefficient of determination :	0.998808377	0.998808377
Correlation :	0.999405840	0.999405840

Data Column Name: CK

	Weighted	Unweighted
Sum of squared observations :	7928.26000	7928.26000
Sum of squared deviations :	16.7846966	16.7846966
Standard deviation of data :	1.67255775	1.67255775
R-squared :	0.997882928	0.997882928
Coefficient of determination :	0.00660893709	0.00660893709
Correlation :	0.108811315	0.108811315

Data Set Name: c:\modfitw\example.mmd

	Weighted	Unweighted
Sum of squared observations :	102692.0000	102692.0000
Sum of squared deviations :	17.0898582	17.0898582
Standard deviation of data :	1.00263941	1.00263941
R-squared :	0.999833581	0.999833581
Coefficient of determination :	0.999292013	0.999292013
Correlation :	0.999645950	0.999645950
Model Selection Criterion :	6.79853993	6.79853993

MODEL RESIDUALS AND CALCULATED MODEL PREDICTIONS

	CP_CALC	CK_CALC	CP_RESIDUALS	CK_RESIDUALS
1	81.9294552	26.2139031	-0.129455224	0.186096905
2	91.0214755	26.7233845	0.0785244579	1.07661548
3	95.5000000	26.9236337	0.000000000	0.376366286
4	97.7285306	27.0378040	-0.328530613	-1.43780397
5	84.8554167	26.7233765	0.0445833277	0.976623476
6	92.3459464	26.9230168	0.0540535547	1.17698319
7	92.9611201	27.0036598	0.138879875	1.29634022
8	96.1151737	27.0042767	0.0848263200	0.595723325
9	94.1755291	26.7240014	0.0244709032	-0.0240014170
10	97.1133569	26.9571610	-0.213356933	-1.85716101
11	95.7888860	26.7575287	0.311113970	-2.35752872

DATA USED IN MODEL FITTING AND PARAMETER ESTIMATION

"TK SOLVER" FILE
FOR UNCONSTRAINED MAXIMUM
(CASE2 = 1)

INPUT/OUTPUT VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					*DUMMY VARIABLES TO SET CASE
	1	OPTFIND			SET OPTIMIZATION ALGORITHIM
		CASE1			C2<0 : ASYMPTOTE
	1	CASE2			C2>0 : UNCONSTRAINED MAX
		CASE3			C2>0 : CONSTRAINED MAX
					MODEL VARIABLES
	95	CP			
		CK	33.2		
		RPM	2434		
		DOSE	379.42		
					OPTIMIZATION VARIABLES
		RPMmax	2515		
		RPMopt	2433.7051		
	2500	RPMrun			
					PARAMETERS FOR CP & CK
	2800	RPMB			
					PARAMETERS FOR CAPTURE
		K1	100		(FROM CALCULATION)
		K2	-10293.09		(FROM CALCULATION)
		K3	-1.239E59		(FROM CALCULATION)
		K4	0		(FROM CALCULATION)
		M	.02681486		(FROM CALCULATION)
		N	-22.66122		(FROM CALCULATION)
		C	1.5		(FROM CALCULATION)
	.82260787	KDZ			*DOCUMENTATION
	.93827972	KRZ1			*DOCUMENTATION
	1	K			
	.90930489	P			*DOCUMENTATION

St	Input	Name	Output	Unit	Comment
		C1	27.063019		(FROM CALCULATION)
		C2	8.71E-128		(FROM CALCULATION)
		C3	-2.8E-256		(FROM CALCULATION)
		C4	-2.241E69		(FROM CALCULATION)
	50	R			
	-26.95783	S			
	.97	KRZ2			*DOCUMENTATION
	-1	CC1			*DOCUMENTATION (CC1 : 1 OR -1)
	1	CC2			*DOCUMENTATION (CC2 : 1 OR 0)
	27.063019	CKMX			
					FIXED POINT
	402	PDOSE			
	2500	PRPM			
	95.5	PCP			
					PARAMETERS FOR OPTIMIZATION
	.0001	KK			
	.25	ALPHA			
					VARIABLES FOR PLOT TING
	'RPM	xvar			function "x" variable (DOSE or RPM)
	2300	from			MIN
	2600	to			MAX
	50	n			number of intervals
	56.3	DOSEcon			DOSE constant (xvar=RPM)
	2405	RPMcon			RPM constant (xvar=DOSE)

"TK SOLVER" FILE
FOR CONSTRAINED MAXIMUM
(CASE3 = 1)

INPUT/OUTPUT VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					*DUMMY VARIABLES TO SET CASE
	1	OPTFIND			SET OPTIMIZATION ALGORITHIM
		CASE1			C2<0 : ASYMPTOTE
		CASE2			C2>0 : UNCONSTRAINED MAX
	1	CASE3			C2>0 : CONSTRAINED MAX
					MODEL VARIABLES
	95	CP			
		CK	33.2		
		RPM	2434		
		DOSE	379.42		
					OPTIMIZATION VARIABLES
		RPMmax	2515		
		RPMopt	2433.7196		
	2500	RPMrun			
					PARAMETERS FOR CP & CK
	2800	RPMB			
					PARAMETERS FOR CAPTURE
		K1	100		(FROM CALCULATION)
		K2	-10293.09		(FROM CALCULATION)
		K3	-1.239E59		(FROM CALCULATION)
		K4	0		(FROM CALCULATION)
		M	.02681486		(FROM CALCULATION)
		N	-22.66122		(FROM CALCULATION)
		C	1.5		(FROM CALCULATION)
	.82260787	KDZ			*DOCUMENTATION
	.93827972	KRZ1			*DOCUMENTATION
	1	K			
	.90930489	P			*DOCUMENTATION

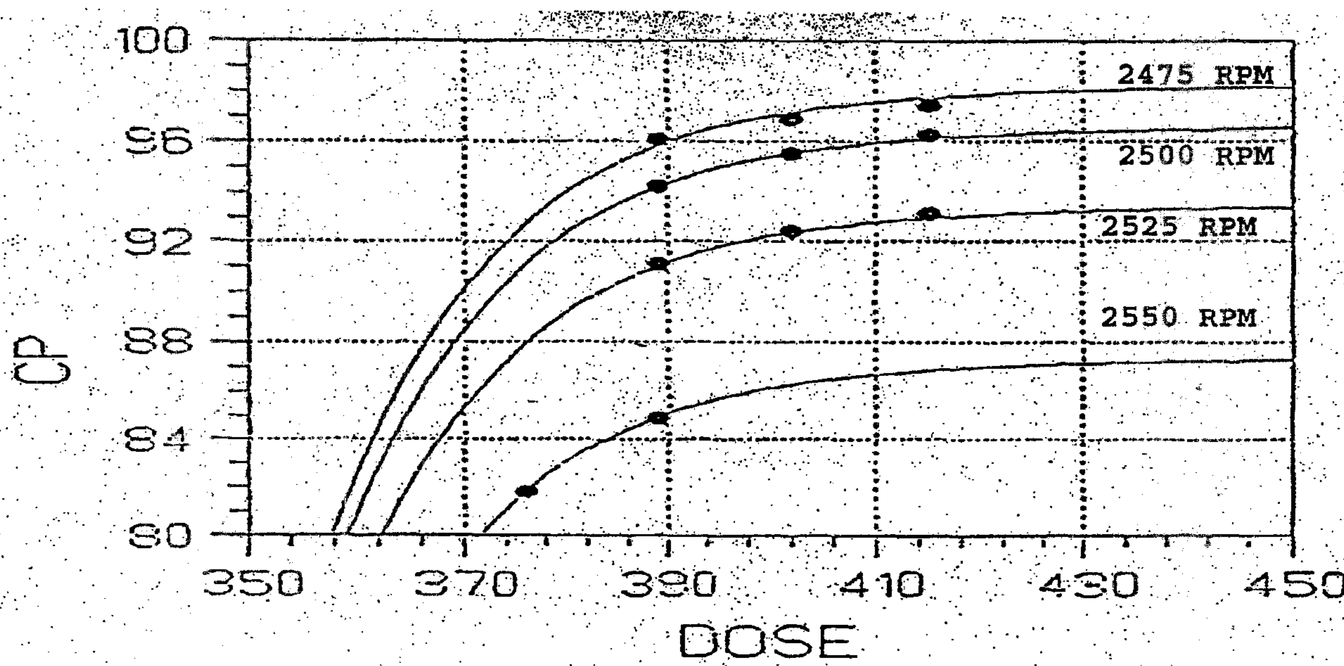
St	Input	Name	Output	Unit	Comment
		C1	27.063019		(FROM CALCULATION)
		C2	8.71E-128		(FROM CALCULATION)
		C3	-2.8E-256		(FROM CALCULATION)
		C4	-2.241E69		(FROM CALCULATION)
	50	R			
	-26.95783	S			
	.97	KRZ2			*DOCUMENTATION
	-1	CC1			*DOCUMENTATION (CC1 : 1 OR -1)
	1	CC2			*DOCUMENTATION (CC2 : 1 OR 0)
	27.063019	CKMX			
					FIXED POINT
	402	PDOSE			
	2500	PRPM			
	95.5	PCP			
					PARAMETERS FOR OPTIMIZATION
	.0001	KK			
	.25	ALPHA			
					VARIABLES FOR PLOT TING
	'RPM	xvar			function "x" variable (DOSE or RPM)
	2300	from			MIN
	2600	to			MAX
	50	n			number of intervals
	56.3	DOSEcon			DOSE constant (xvar=RPM)
	2405	RPMcon			RPM constant (xvar=DOSE)

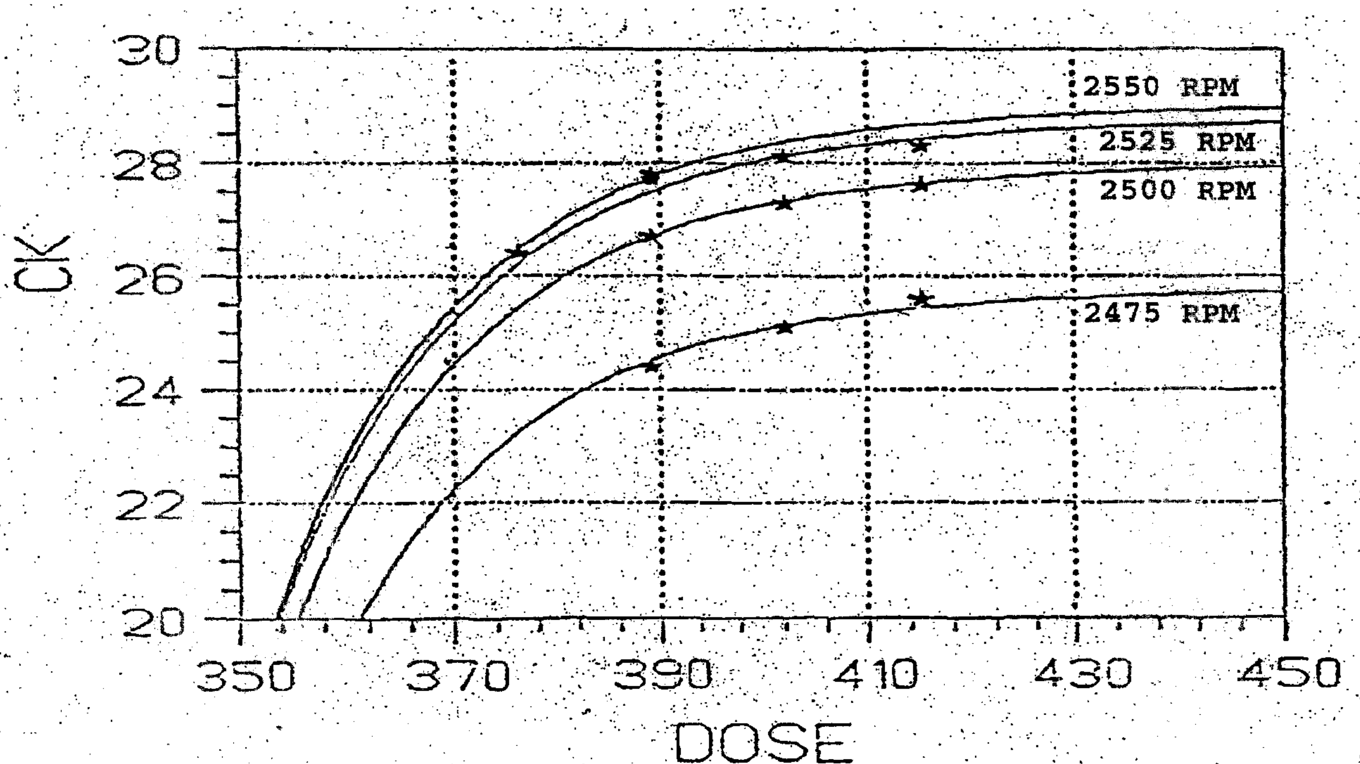
GRAPHS OF THE PERCENT SOLIDS CAPTURE AND
PERCENT CAKE SOLIDS
FOR THE LINEAR ASYMPTOTE MODEL
ALONG WITH THE DATA USED TO
FIT THE MODEL AND ESTIMATE PARAMETERS

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE AIV-1

RELATIONSHIP BETWEEN POLYMER DOSE AND
PERCENT SOLIDS CAPTURE AND CAKE SOLIDS

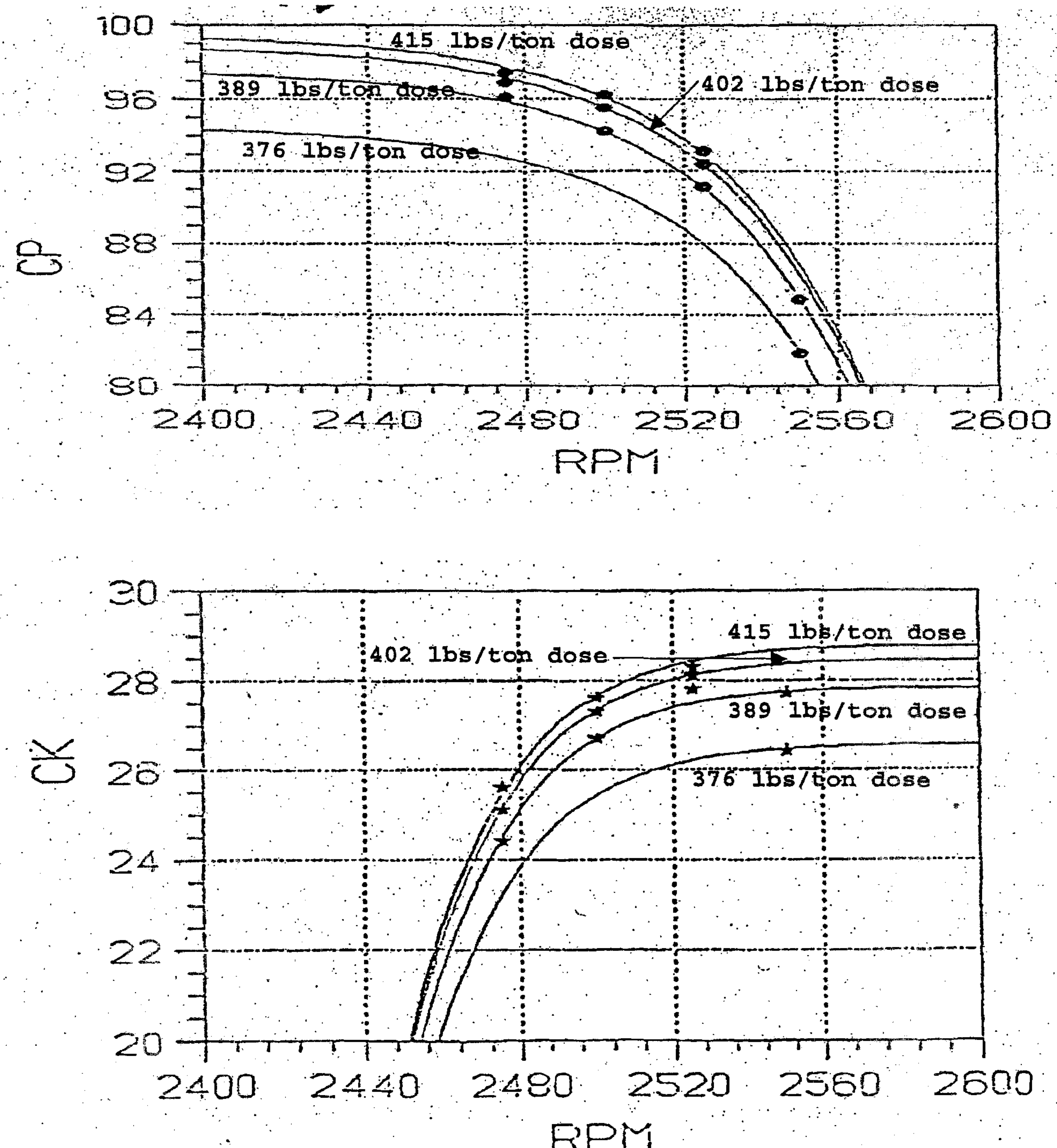




METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE AIV-2

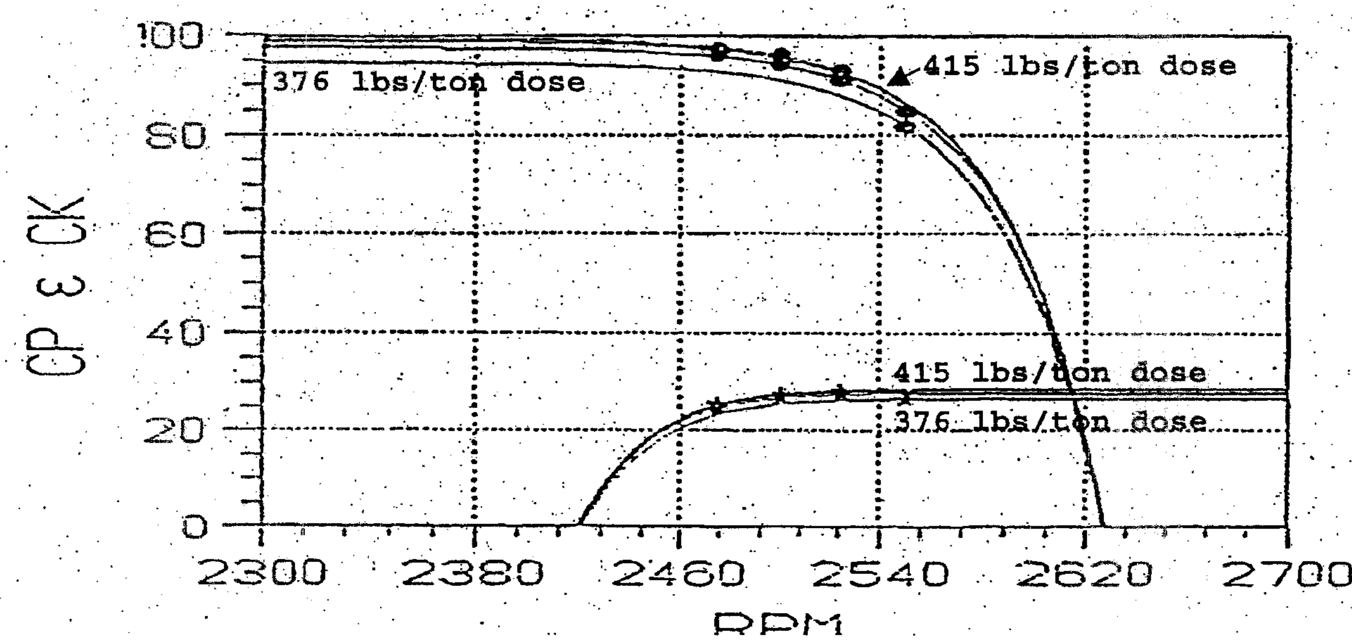
RELATIONSHIP BETWEEN PINION SPEED AND PERCENT SOLIDS CAPTURE AND CAKE SOLIDS

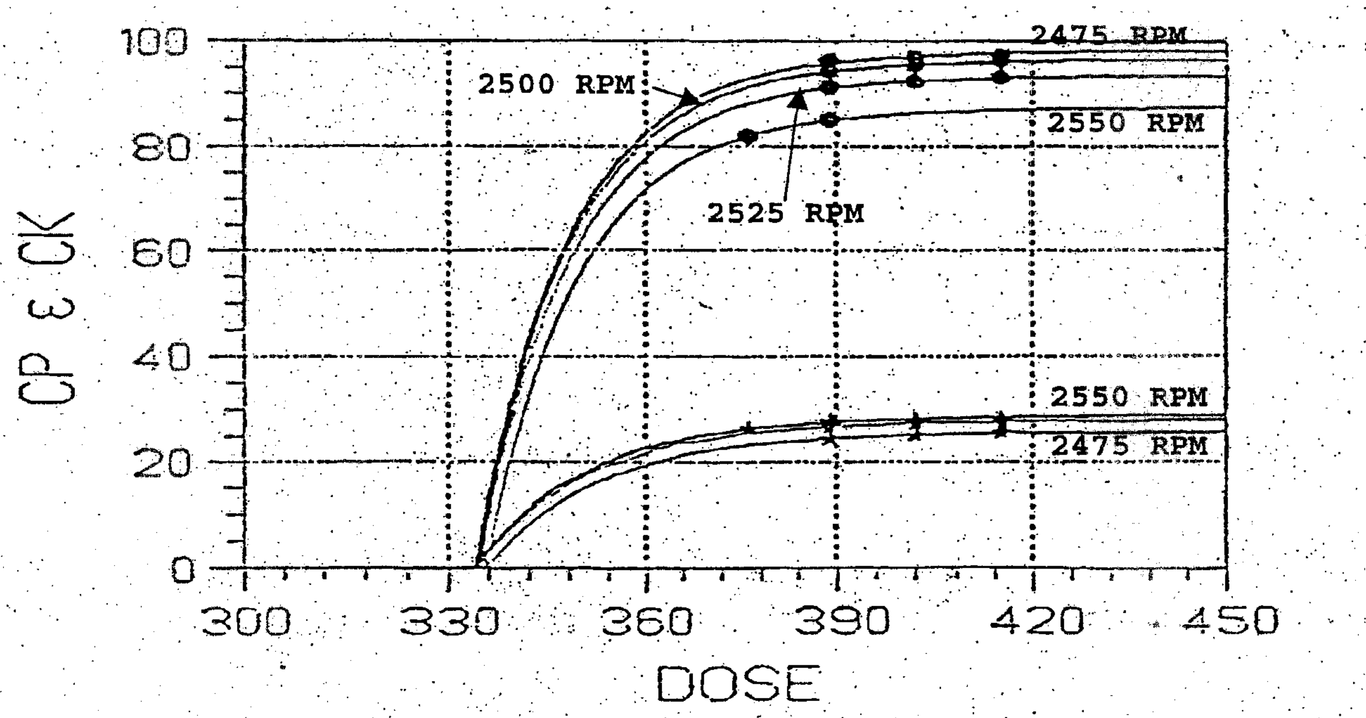


METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE AIV-3

RELATIONSHIP BETWEEN PINION SPEED AND POLYMER DOSE AND PERCENT SOLIDS CAPTURE AND CAKE SOLIDS





ORIGINAL MODEL PARAMETER ESTIMATION AND OPTIMIZATION

"SCIENTIST" FILE
FOR ORIGINAL MODEL PARAMETER ESTIMATION

```
IndVars: DOSE RPM
DepVars: CP CK
Params: K1,K2,K3,K4,M,N,C1,C2,C3,C4,R,S,RPMB

P := M

CP := K1+K2*EXP(M*(RPM-RPMB))+K3*DOSE^N+K4*DOSE^N*EXP(P*(RPM-RPMB))

CK := C1+C2*(RPMB-RPM)^R+C3*(RPMB-RPM)^(2*R)+C4*DOSE^S
***
```

LEAST SQUARES PARAMETER VALUE ESTIMATIONS

ParamName	Lower Limit	Value	UpperLimit
K1	-Infinity	99.5286585	Infinity
K2	-Infinity	-10362.9436	Infinity
K3	-Infinity	-3.00167916E+59	Infinity
K4	-Infinity	-1.13854806E+62	Infinity
M	0.000000000	0.0271351201	0.500000000
N	-75.0000000	-22.8510107	-1.00000000
C1	-Infinity	28.8304878	Infinity
C2	-Infinity	-3.87564249E-62	Infinity
C3	-Infinity	1.1437287E-124	Infinity
C4	-Infinity	-2.45364045E+58	Infinity
R	0.000000000	24.8048235	75.0000000
S	-75.0000000	-22.5252162	-1.00000000
RPMB	-Infinity	2800.00000	Infinity

GOODNESS OF FIT STATISTICS

*** MicroMath Scientist Statistics Report ***

Model File Name : c:\modfitw\cpckorg.eqn
Data File Name : c:\modfitw\example2.mmd
Param File Name : c:\modfitw\cpckorg.par

Goodness-of-fit statistics for data set: c:\modfitw\example2.mmd

Data Column Name: CP

	Weighted	Unweighted
Sum of squared observations :	100494.2300	100494.2300
Sum of squared deviations :	0.149449758	0.149449758
Standard deviation of data :	Infinity	Infinity
R-squared :	0.999998513	0.999998513
Coefficient of determination :	0.999712995	0.999712995
Correlation :	0.999856487	0.999856487

Data Column Name: CK

	Weighted	Unweighted
Sum of squared observations :	8509.07000	8509.07000
Sum of squared deviations :	0.133184607	0.133184607
Standard deviation of data :	Infinity	Infinity
R-squared :	0.999984348	0.999984348
Coefficient of determination :	0.994373076	0.994373076
Correlation :	0.997182569	0.997182569

Data Set Name: c:\modfitw\example2.mmd

	Weighted	Unweighted
Sum of squared observations :	109003.3000	109003.3000
Sum of squared deviations :	0.282634365	0.282634365
Standard deviation of data :	0.153469423	0.153469423
R-squared :	0.999997407	0.999997407
Coefficient of determination :	0.999988980	0.999988980
Correlation :	0.999994490	0.999994490
Model Selection Criterion :	10.4158218	10.4158218

MODEL RESIDUALS AND CALCULATED
MODEL PREDICTIONS

	CP_CALC	CK_CALC	CP_RESIDUALS	CK_RESIDUALS
1	81.6763578	26.4024969	0.123642151	-0.00249692448
2	91.1771820	27.5833945	-0.0771819916	0.216605519
3	95.4759889	27.3045254	0.0240110599	-0.00452539946
4	97.5216174	25.4120801	-0.121617359	0.187919880
5	84.9825194	27.6951176	-0.0825194250	0.00488235665
6	92.4442234	28.1711921	-0.0442234207	-0.0711920661
7	93.0291069	28.4454135	0.0708930616	-0.145413453
8	96.0093332	27.5787468	0.190666826	0.0212532135
9	94.3205978	26.7167278	-0.120597790	-0.0167278141
10	97.0144262	25.1378587	-0.114426188	-0.0378587328
11	95.9156908	24.5500611	0.184309213	-0.150061147
12	75.7329561	24.1023854	-0.0329561370	-0.00238543218

DATA USED IN MODEL FITTING AND PARAMETER ESTIMATION

	RPM	DOSE	CP	CK
1	2550.00000	376.000000	81.8000000	26.4000000
2	2525.00000	389.000000	91.1000000	27.8000000
3	2500.00000	402.000000	95.5000000	27.3000000
4	2475.00000	415.000000	97.4000000	25.6000000
5	2550.00000	389.000000	84.9000000	27.7000000
6	2525.00000	402.000000	92.4000000	28.1000000
7	2525.00000	415.000000	93.1000000	28.3000000
8	2500.00000	415.000000	96.2000000	27.6000000
9	2500.00000	389.000000	94.2000000	26.7000000
10	2475.00000	402.000000	96.9000000	25.1000000
11	2475.00000	389.000000	96.1000000	24.4000000
12	2550.00000	365.000000	75.7000000	24.1000000

"TK SOLVER" FILE FOR ORIGINAL MODEL OPTIMIZATION

St	Input	Name	Output	Unit	Comment
		CKopt	27.478954	%	OPTIMUM CAKE
		RPMopt	2503.731	rpm	OPTIMUM RPM
		DOSEopt	399.7429	lbs/ton	OPTIMUM DOSE
	95	CPopt		%	OPTIMUM CAPTURE SPECIFICATION
		CP		%	CAPTURE
		CK		%	CAKE
		RPM		rpm	PINION SPEED
		DOSE		lbs/ton	POLYMER DOSE
	99.528656	K1			CP MODEL PARAMETERS
	-10362.99	K2			
	-3.002E59	K3			
	-1.139E62	K4			
	.02713514	M			
	-22.85104	N			
		P	.02713514		
	28.830488	C1			CK MODEL PARAMETERS
	-3.88E-62	C2			
	1.14E-124	C3			
	-2.454E58	C4			
	24.804824	R			
	-22.52522	S			
	2800	RPMB		rpm	BOWL SPEED
	2500	RPMH		rpm	OPTIMIZATION PARAMETERS
	.25	PHI			

```
S  Rule
*  CP=K1+K2*EXP(M*(RPM-RPMB))+K3*DOSE^N+K4*DOSE^N*EXP(P*(RPM-RPMB))
*  CK=C1+C2*(RPMB-RPM)^R+C3*(RPMB-RPM)^(2*R)+C4*DOSE^S
   P=M

   IF C2<0 THEN RPMopt=((RPMB-RPMH)-(1/M)*(LN(K2/(CPopt-K1))))*PHI+RPMH
*  IF C2>0 THEN RPMopt=RPMB-(-C2/(2*C3))^(1/R)

   ZZ=(M*(RPMopt-RPMB))
   CPopt=K1+K2*EXP(ZZ)+(K3+K4*EXP(ZZ))*DOSEopt^N
   CKopt=C1+C2*(RPMB-RPMopt)^R+C3*(RPMB-RPMopt)^(2*R)+C4*DOSEopt^S
```

APPENDIX AV

SYMBOL DEFINITIONS

SYMBOL DEFINITIONS

The symbols and notations used in this report are largely grouped into five categories for the convenience of quick reference while studying. All symbols/notations in each category are arranged in alphabetic order.

CATEGORY - I: ORIGINAL MODELS

SYMBOLS/NOTATIONS	DEFINITION
% Cake	Percent Cake Solids
% Capture	Percent Solids Capture
Dose	Polymer Dose Expressed as Pounds of Polymer Per Dry Ton of Sludge
K_1	Model Fitting Parameter
K_1'	Model Fitting Parameter
K_2	Model Fitting Parameter
K_2'	Model Fitting Parameter
K_3	Model Fitting Parameter
K_3'	Model Fitting Parameter
K_4	Model Fitting Parameter
K_4'	Model Fitting Parameter
M	Model Fitting Parameter
N	Model Fitting Parameter
P	Model Fitting Parameter

R	Model Fitting Parameter
RPM	Pinion Speed, rpm
RPMB	Bowl Speed, rpm
S	Model Fitting Parameter

CATEGORY - II: REPARAMETERIZED FORM OF THE ORIGINAL MODELS

SYMBOLS/NOTATIONS	DEFINITION
CC1	Dummy Variable
CC2	Dummy Variable
CK	Percent Cake Solids
CKMX	Maximum Percent Cake Solids
CP (PCP)	Percent Solids Capture (same at forced point)
DOSE (PDOSE)	Polymer Dose Expressed as Pounds of Polymer Per Dry Ton of Sludge (same at forced point)
DOSEZ	Polymer Dose at Which Both Cake Solids Start to Form and Solids Capture Begins to Occur, Pounds of Polymer Per Dry Ton of Sludge
K	Model Fitting Parameter
M	Model Fitting Parameter
N	Model Fitting Parameter
R	Model Fitting Parameter

RDEL	Intermediate Variable
RPM (PRPM)	Pinion Speed, rpm (same as forced point)
RPMB	Bowl Speed of Centrifuge During Full-Scale Testing, rpm
RPMZ1*	Pinion Speed at Which Percent Capture Drops to Zero, rpm in "CPCK1FQ2" file
RPMZ2*	Pinion Speed at Which Cake Solids Begin to Form, rpm in "CPCK1FQ2" file
S	Model Fitting Parameter
RPMZ2MX	Intermediate Variable
RPMZ2G	Intermediate Variable
KRZ1*	Model Fitting Parameter in "CPCK1FQ5" file
KRZ2*	Model Fitting Parameter in "CPCK1FQ5" file
KDZ*	Model Fitting Parameter in "CPCK1FQ5" file
PHIMAX	Intermediate Variable
PHIASY	Intermediate Variable
PHI	Intermediate Variable

*The symbols/notations with asterisk appear in only specified "Scientist" file(s), whereas the rest of symbols/notations appear in all "Scientist" files.

CATEGORY - III: OPTIMIZATION PROCEDURE	
SYMBOLS/NOTATIONS	DEFINITION
% $Cake_{opt}$, CK_{opt}	Optimum Percent Cake Solids
$Dose_{opt}$	Optimum Polymer Dose Expressed as Pounds of Polymer Per Dry Ton of Sludge
RPMH	Highest Pinion Speed at Which a Sample Exceeds 95% Capture, rpm
RPM_{opt}	Optimum Pinion Speed, rpm
CASE1 CASE2 CASE3	Case Variable(s)

CATEGORY - IV: POLYMER PROCESSING COST EQUATION	
SYMBOLS/NOTATIONS	DEFINITION
A	Optimum Polymer Dose, Pounds of Polymer Per Dry Ton of Sludge
B	Polymer Cost, Dollars per Pound
C_1	Site-specific Constant that is a function of Cake Transportation and Cake Agitation Drying Cost
C_2	Site-specific Constant that is a Function of Cake Transportation and Cake Agitation Drying Cost

Cost	Total Processing Cost, Dollars per Dry Ton of Sludge
D	Optimum Cake Solids, %

CATEGORY - V: SYMBOLS/NOTATIONS USED ELSEWHERE IN THE REPORT

SYMBOLS/NOTATIONS	DEFINITION
CST	Capillary Suction Time
V_{poly}	Polymer Dose at Minimum CST, mL
V_{slg}	Sludge Volume, mL
C_{poly}	Polymer Solution Concentration, %
C_{slg}	Feed Sludge Concentration, %
F	Correlation Factor

APPENDIX AVI

SUMMARY PAPER ON TEST PROCEDURE
(PAPER PRESENTED AT ANNUAL WEFTEC CONFERENCE HELD
IN DALLAS, TEXAS, 1996)

A COST EFFECTIVE PROCEDURE FOR THE SELECTION AND PROCUREMENT OF POLYMERS FOR CENTRIFUGAL DEWATERING OF ANAEROBICALLY DIGESTED SLUDGE

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ABSTRACT

The Metropolitan Water Reclamation District of Greater Chicago (District) spends over three million dollars annually to purchase polymers to condition anaerobically digested sludge for centrifugal dewatering at three of its water reclamation plants (WRPs). Due to the large sums of money involved, it is important to the District to procure effective polymers for the least cost for use at its centrifuge facilities. Hence, the District has developed a procedure, which includes a testing protocol, for the selection and procurement of polymers. This procedure has been in use for the last seven years to the satisfaction of the District's Purchasing and Maintenance and Operations Departments, as well as the vendors who compete in the District's polymer bidding process.

Key Words: Polymers, selection, procurement, centrifuges, dewatering.

INTRODUCTION

Appropriate and economical sludge management techniques have become increasingly important in recent years as a result of environmental awareness, financial responsibility and accountability of municipal agencies, public concerns, and sludge regulations promulgated by the United States Environmental Protection Agency. Sludge thickening and dewatering are two important aspects of sludge management. These components have spawned an industry that provides a variety of organic polymer products which can be used for the thickening and dewatering of sludges. This availability of a wide array of polymer products makes selection of a polymer for optimum performance with a given dewatering process and a particular sludge very difficult. Polymer physical characteristics alone are not adequate to allow for such a selection. As a result, empirical test procedures involving bench-, pilot-, or full-scale tests must be used to determine which polymer works best for a given dewatering device and sludge. Bench- and pilot- scale tests although convenient are less reliable than full-scale tests. However, full-scale tests are cumbersome, time consuming and resource intensive. Obviously, the bench- and pilot-scale tests allow for more controlled conditions than full-scale tests. But, ultimately, the greater reliability of full-scale tests offers the best opportunity for providing guidance in the determination of the best polymer for the least cost. If full-scale tests are chosen for the selection of the most suitable polymer for dewatering from the standpoint of cost and performance, bench- or pilot-scale tests may still be used for selection of polymers prior to the full-scale tests to reduce the workload and need for extensive resources.

In 1980, the District purchased rotating bowl centrifuges for the dewatering of anaerobically digested sludge at three of its WRPs. Prior to the installation of these centrifuges, empirical polymer test procedures were developed using a pilot-scale centrifuge to select a polymer for use with the full-scale machines. However, the pilot-scale tests are not very reliable in predicting full-scale centrifuge performance, and test protocols using full-scale centrifuges were ultimately developed for polymer selection.

In 1989, the District purchased new high performance rotating bowl centrifuges as replacements for the centrifuges purchased in 1980 at all three of its centrifuge complexes with the intention of doubling the average cake solids content from 15 to 30 percent. These machines required the development of a more sophisticated full-scale test procedure for the selection of polymers because of greater complexity of the control variables. The polymer selection procedure for the high performance centrifuges required the determination of performance models, and the development of optimizing techniques that can be used for selection of the best performing polymer at the least cost. This paper describes the polymer selection procedures that are currently used by the District. The performance models developed, the optimization techniques used, details of the polymer testing protocol, suggestions for alternatives or modifications to the testing protocol, and commentary on the algorithms developed for the high performance centrifuges are also discussed. The computer software code used to implement the testing protocol and to determine the polymer dosage rate is contained in this paper. It is hoped that the testing protocol developed by the District will aid treatment plant operators and managers to purchase polymer products for optimum centrifugal dewatering at the lowest cost.

UNDERLYING PRINCIPLES AND RATIONALE OF THE POLYMER SELECTION PROCEDURE

The objective of the polymer testing procedure is to rank polymers according to the dosages required to achieve a specified performance criterion. Such a performance criterion can be the percent capture solids, and/or percent cake solids. In the polymer testing protocol, performance characteristics curves describing polymer dosage vs., percent cake solids and polymer dosage vs. percent solids capture have to be developed for each of the polymers to be ranked in the test procedure. From these curves, the actual dosage required to achieve the performance specification is determined using optimization techniques.

The polymer performance characteristics curves are basically obtained from two mathematical models. For a given sludge, these models include three input variables, which have the most influence on the percent cake solids and percent solids capture. These variables are the centrifuge bowl speed, pinion speed, and polymer dosage. The inclusion of sludge characteristics as inputs into these models is not necessary. It is assumed that sludge characteristics in tests conducted within a short span of time, usually a week to ten days, will not change significantly.

Nonlinear algorithms describing the relationships between percent solids capture, cake solids, bowl and pinion speed of the centrifuge, are developed and used to estimate model parameters from the data collected during the polymer evaluation tests. In these tests, one polymer is tested per day at different dosage rates and at different pinion speeds. From the data, optimization techniques are used to determine the optimum pinion speed, because the optimum polymer dosage rate occurs at this pinion speed. Unlike the bowl speed, which is held constant (a constant machine parameter), the optimum pinion speed varies with the polymer tested. Hence, optimization procedures are used to estimate the optimum pinion speed from test data, which can then be used to obtain the optimum polymer dosage rate that corresponds to the optimum pinion speed. Optimization criteria are provided, to optimally determine and set the pinion speed needed to condition the sludge at an optimal polymer dosage. Since the optimum pinion speeds vary for different polymers, they cannot be arbitrarily set to a constant value to determine the optimum polymer dosage for all the polymers tested. It should be noted, that with some polymers the performance criteria specified (i.e., percent solids capture and/or percent cake solids desired) may not be achievable no matter where the pinion speed is set on the centrifuge. Such polymers are excluded from the competitive bidding procedure.

The polymer dose and pinion speed have a complex nonlinear interaction which must be accounted for if optimum performance is to be obtained with a given polymer. As indicated earlier, it is necessary to run polymer tests at various dosages, and at various pinions speeds to estimate the optimum pinion speed. Thus, for each polymer, a family of characteristics performance curves (polymer dose vs. percent cake solids and percent solids capture) corresponding to various pinion speed settings are developed. Using optimization techniques with these family of curves, the optimum pinion speed, and the corresponding polymer dosage is determined that satisfies the performance criteria specified.

In the District's polymer testing protocol, the performance specification is chosen to be 95 percent solids capture. All polymers that produce this specified percent solids capture will be considered for competitive bidding and others are rejected. Polymers are then ranked according to the optimum dosage rates determined. Polymers may also be ranked according to a minimum percent cake solids desired at 95 percent solids capture to eliminate those polymers with poor cake solids performance. A polymer which meets all the specified performance criteria and has the lowest cost, can then be purchased in the quantity needed to condition a specified number of dry tons of sludge at the optimum polymer dosage (lbs per dry ton) which is determined in the test protocol. The District has further chosen to develop a cost function that not only considers polymer cost, but also other relevant costs such as transportation cost of the cake to a given location and agitation drying cost for the centrifuge cake.

For centrifuges that do not have variable pinion speed control the rationale for polymer selection is the same. The testing procedure is simplified since optimization of the pinion speed is not required. The performance models are correspondingly simplified as well.

MODELS AND DETERMINATION OF OPTIMUM PINION SPEED, POLYMER DOSAGE RATE, OPTIMUM CAKE SOLIDS, AND TOTAL PROCESSING COST

Models

Based on the results obtained from the actual tests conducted for polymer evaluation and selection, the resulting performance characteristics curves have shapes that can be typically characterized as Type 1 and Type 2, respectively (Figures 1 and 2). Type 1 describes an asymptotic linear or quadratic relationship, whereas Type 2 describes a maximum quadratic rela-

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

Figure 1
Relationship Between Polymer Dose and Pinion Speed and Percent Solids Capture and Cake Solids - Type 1 Example

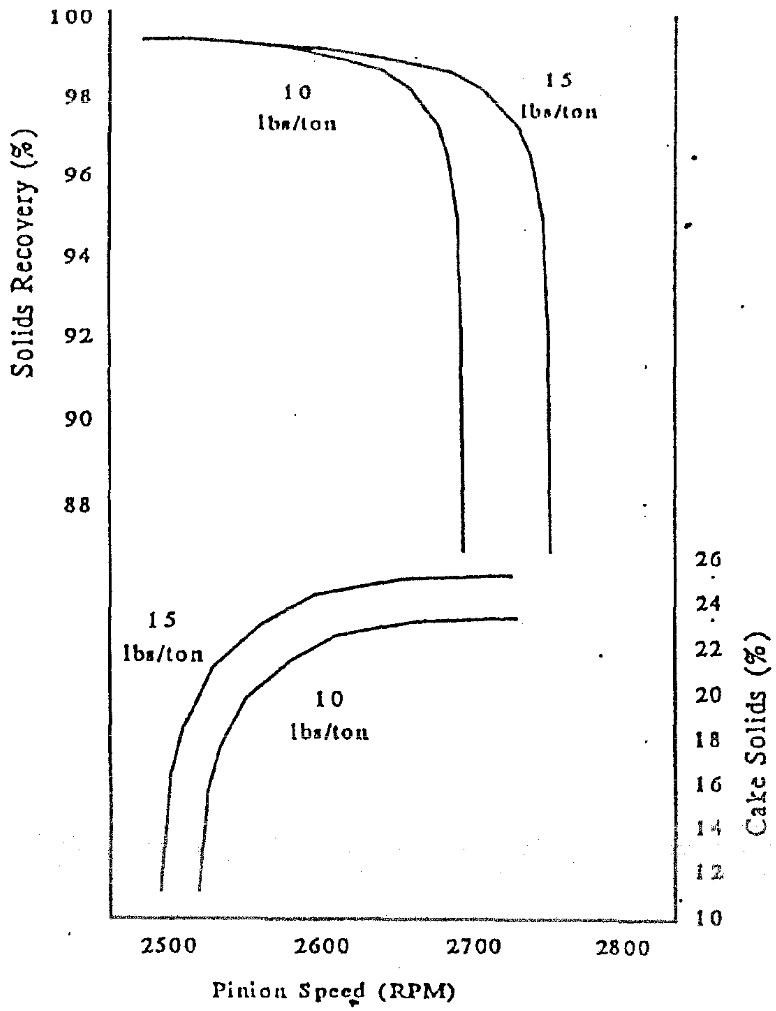
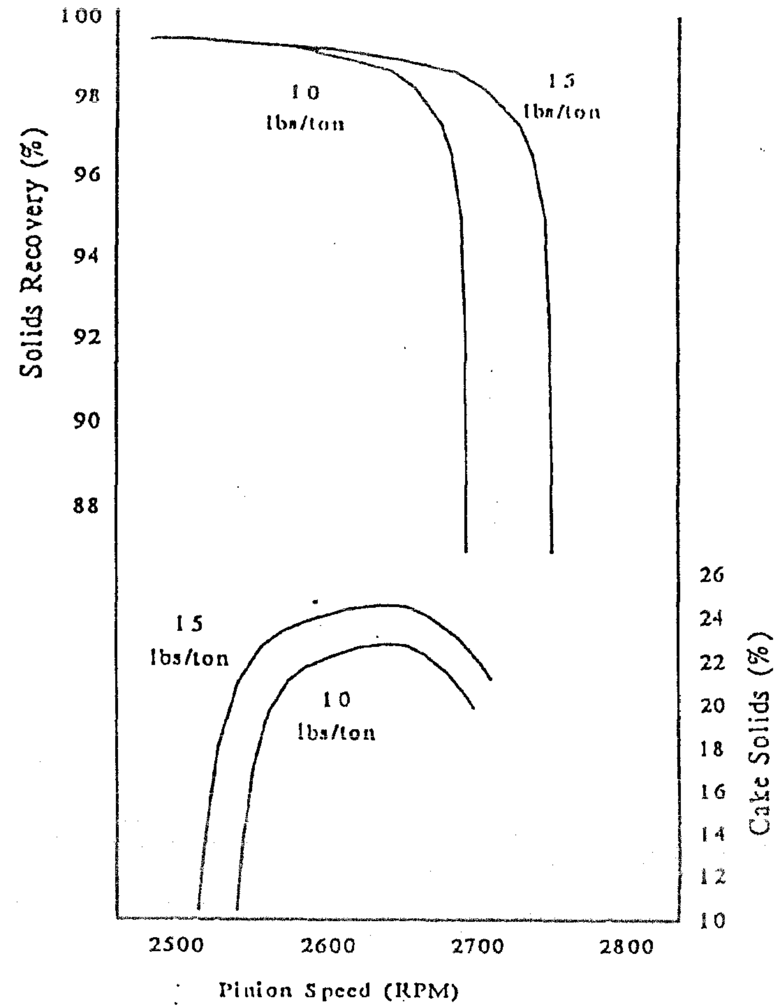


Figure 2
Relationship Between Polymer Dose and Pinion Speed and Percent Solids Capture and Cake Solids - Type 2 Example



tionship. In Type 1 cases (performance characteristic curves which are asymptotic linear and asymptotic quadratic forms), the percent cake solids reaches a maximum and stays constant (CK [Max]) with any combination of polymer dose and pinion speed. In the Type 2 cases (quadratic maximum), however, the percent cake solids drops off after the maximum is achieved as the polymer dose is increased beyond the optimum polymer dosage. These curves can be fitted to the following equations (Equations 1 and 2) using the method of least squares.

$$[\%\ Capture] = K_1 + K_2\, e^{M(RPM-RPMB)} + K_3\,(Dose)^N + K_4\,(Dose)^N e^{P(RPM-RPMB)} \tag{1}$$

$$[\%\ Cake] = K_1' + K_2'\,(RPMB-RPM)^R + K_3'\,(RPMB-RPM)^{2R} + K_4'\,(Dose)^S \tag{2}$$

Where:

[% Capture] = percent solids capture.

[% Cake] = percent cake solids.

Dose = polymer dose in pounds per dry ton of sludge solids.

RPMB = bowl speed in revolutions per minute.

RPM = pinion speed in revolutions per minute.

K_1, K_2, K_3, K_4, M, N, P, K_1', K_2', K_3', K_4', R, S are the curve fitting parameters to be determined by the method of least squares.

In most polymer test cases, the performance characteristics curves fall under the category of Type 1 (asymptotic linear or quadratic), and the Type 2 cases (quadratic maximum) are very rare. In the case of Type 1 cases the K_2' value is less than zero, whereas it is greater than zero for Type 2 cases.

The models are reparameterized for each polymer evaluation event for effective and convenient estimation of parameter values by a nonlinear least squares algorithm. This is required in order to constrain the parameter values so that they remain within physically realistic boundaries. The reparameterizations are also helpful in minimizing convergence difficulties and provide geometrical interpretations for some of the parameters. For example, the DoseZ, RPMZ1, and RPMZ2 points on the performance characteristic curves given in Figures 3 and 4 are obtained by the reparameterization process. These points represent the boundary conditions defined by the reparameterized models. The reparameterized models are as follows:

$$CP = 100\,\{1-K(e^{M(RPM-RPMZ1)} + (Dose/DoseZ)^N)\} \tag{3}$$

$$CK = CK(Max)\,\{1-CC1\,(RDel)^R - CC2\,(RDel)^{2R} - (Dose/DoseZ)^S\} \tag{4}$$

where,

RDel = (RPMB - RPM)/(RPMB-RPMZ2).

CP and CK = capture and cake solids in percent.

CK(Max) = the maximum percent cake solids possible.

CC1 and CC2 = dummy variables to specify the asymptotic (Type 1) and quadratic (Type 2) cases.

RPMZ1 = pinion speed at which percent capture drops to zero.

RPMZ2 = pinion speed at which cake solids start to form

DoseZ = polymer dose at which both cake and solids capture begin to occur.

K, M, N, R, S are curve fitting parameters.

Both of these models must be fitted simultaneously due to the common parameter DoseZ, which appears in both models. The values for CC1 and CC2 are given as follows to satisfy the Type 1 and Type 2 cases:

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

Figure 3

Relationship Between Polymer Dose and Pinion Speed and Percent Solids Capture and Cake Solids - Type 1 Asymptotic Case

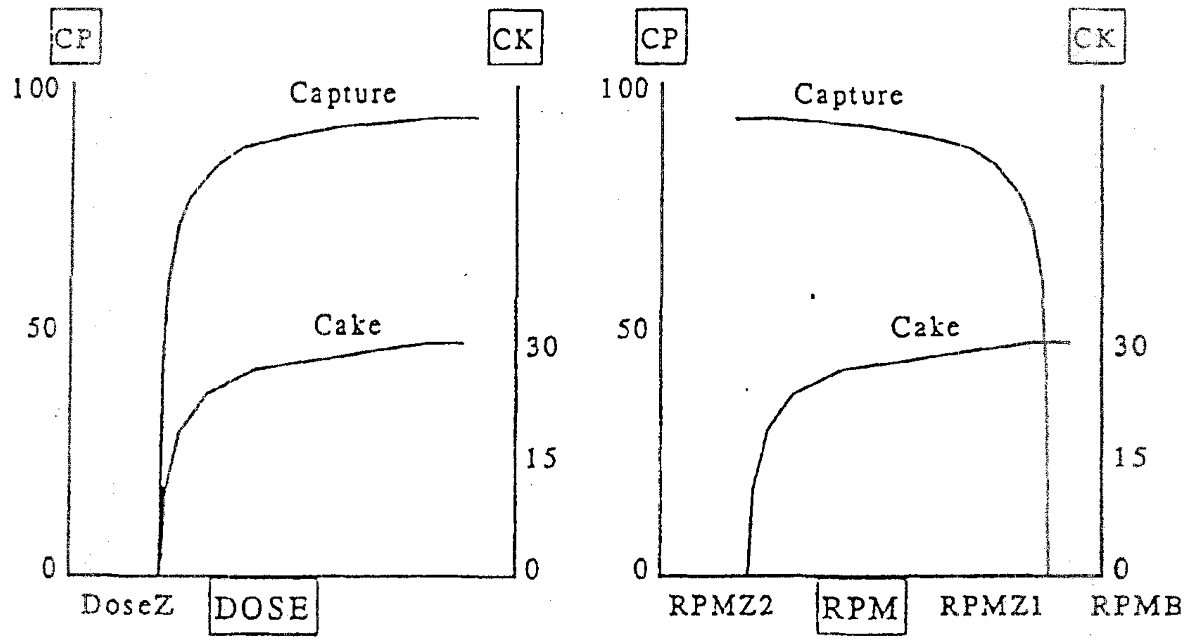
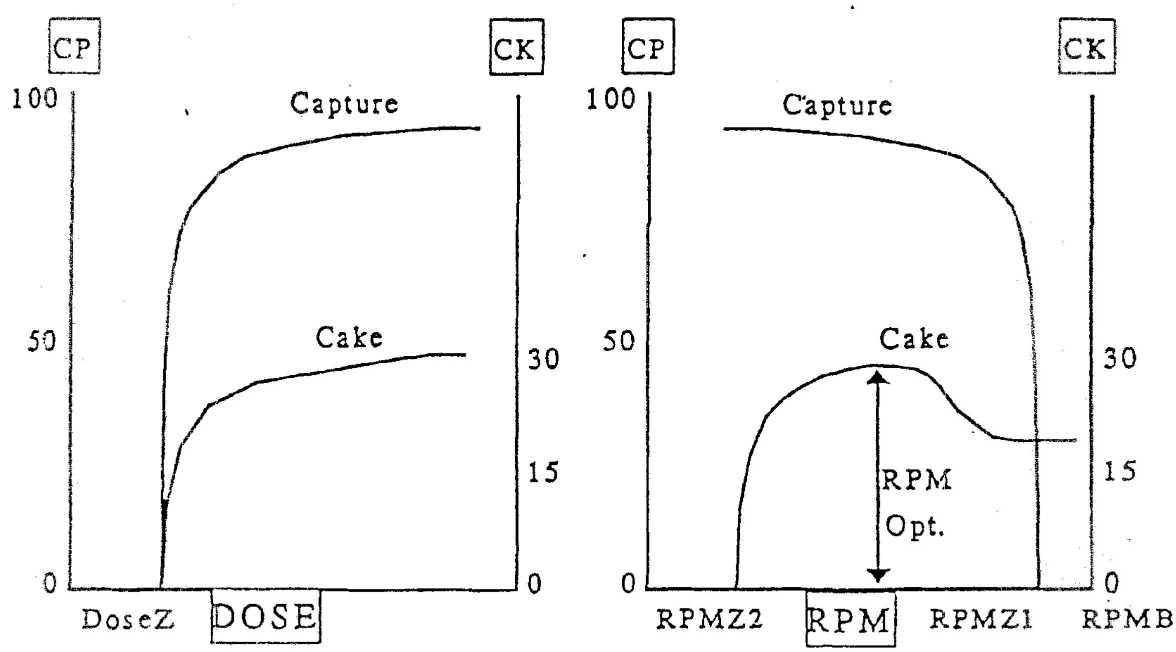


Figure 4

Relationship Between Polymer Dose and Pinion Speed and Percent Solids Capture and Cake Solids - Type 2 Quadratic Case



	Type	CC1	CC2
1A	(Asymptotic Linear)	+1	0
1B	(Asymptotic Quadratic)	+1	+1
2	(Maximum Quadratic)	-1	+1

In the asymptotic case (Type 1), as indicated earlier, CK(Max) is the maximum cake solids concentration possible under any dose or pinion speed beyond the optimum polymer dose/pinion speed. In the quadratic maximum (Type 2) case this is not true as the cake solids fall at the optimum pinion speed as the polymer dose is increased. In the model representing solids capture (Equation 1), the term with the parameter K_4 only improves the fit when capture values are below 80 percent. By excluding all samples below 80 percent capture, K_4 may be set equal to zero. This enables the simplification of the reparameterization of the solids capture model for situations where the percent capture values are close to 95 percent. In order for the geometrical interpretation of RPMZ2 to be maintained in the asymptotic quadratic case, a further constraint must be imposed on the model representing percent cake solids. This is done in the software files (not presented here). As indicated earlier, Type 2 (quadratic maximum) cases are extremely rare and are not discussed further here.

In order to obtain a robust convergence that ensures the best fit in the range of greatest interest, the percent solids capture is constrained so as to pass exactly through the sample point associated with the highest pinion speed at which the capture performance specification is exceeded (this pinion speed is shown as RPMH in Equation 7). This constraint produces a percent solids capture model that best approximates the performance response surface in the area where optimization is to occur. This constraint is shown in the software files developed (not presented here). The point through which the model is forced is: (P_{dose}, P_{RPM}, and P_{Cp}). As indicated previously, the parameters, M, N, R, and S all correspond to the degree of curvature in the performance response surfaces of the capture and cake models. The parameter, K, must be set equal to one and held constant during the model fitting process in order to maintain the geometric interpretation of RPMZ1 and DoseZ. After least squares fitting, the reparameterized models are transformed back into their initial forms (i.e., in terms of K_1, K_2, K_3, K_4, K_1', K_2', K_3', K_4'), since optimization for dose, cake, and pinion speed takes place on the models in their initial forms.

Algorithms and Software Used for Parameter Estimation

The estimation of model parameters is done with a combination of the Nelder-Mead Simplex algorithm (1965), and the Golub-Pereyra algorithm (1973). A Fortran IV coding of the Nelder-Mead Simplex algorithm is provided by Olsson (1974), and a Fortran IV coding of the Golub-Pereyra algorithm is provided by Ottoy and vanSteenkiste (1980). Commercial software packages, such as SCIENTIST can implement a variation of both of these algorithms, and also provide an exceptional graphics capability. Many difficulties with convergence can be avoided by using these algorithms for parameter estimation.

It is also desirable to implement the optimization procedure on a commercially available software package. One such package is called "TK SOLVER," which is an equation solver that allows for automated and convenient solutions to nonlinear equations without the need for sophisticated programming skills. At the District, the optimization procedure is carried out using both the "SCIENTIST" and "TK SOLVER" packages.

Determination of Optimum Pinion Speed

As indicated previously, the optimum polymer dosage to condition a sludge for dewatering occurs at the optimum pinion speed for a specified performance criterion. Optimization of pinion speed is necessary with the District's existing centrifuges to obtain optimum performance as it can be different with different polymers and sludges.

In Type 1 performance characteristics curves, as indicated previously, the value of K_2' is less than zero, whereas it is greater than zero in the case of Type 2 curves. If K_2' is greater than zero, the constrained solution for the optimum pinion speed (RPM_{opt}) is obtained by setting the derivative of the following function (Equation 5) equal to zero and solving for the variable of RPM_{opt}:

$$[\% \text{ Cake}] = K_1' + K_2'(RPMB - RPM_{opt})^R + K_3'(RPMB - RPM_{opt})^{2R} + K_4'\left[\frac{95 - K_1 - K_2 e^{M(RPM_{opt} - RPMB)}}{K_3 + K_4 e^{P(RPM_{opt} - RPMB)}}\right]^{\frac{S}{N}} \quad (5)$$

In the event that the constrained solution does not exist, the unconstrained solution for the optimum pinion speed (RPM_{opt}) is obtained from the following expression:

$$RPM_{opt} = RPMB - \left[\frac{-K_2'}{2K_3'}\right]^{\frac{1}{R}} \quad (6)$$

In Type 1 performance characteristics curves, where K_2' is less than zero, the optimum pinion speed is obtained from the following expression:

$$RPM_{opt} = \left[(RPMB - RPMH) - \frac{1}{M}\ln\left(\frac{K_2}{95 - K_1}\right)\right]\phi + RPMH \quad (7)$$

where:

$\phi = 0.25$

RPMH = highest pinion speed in which a sample exceeds 95 percent capture.

RPM_{opt} is rounded to the units place.

Determination of Optimum Dose

The optimum dose, $Dose_{opt}$, is obtained from the following expression rounded to three significant digits:

$$Dose_{opt} = \left[\frac{95 - K_1 - K_2 e^{M(RPM_{opt} - RPMB)}}{K_3 + K_4 e^{P(RPM_{opt} - RPMB)}}\right]^{\frac{1}{N}} \quad (8)$$

Determination of Optimum Percent Cake Solids

The optimum cake solids, $\%Cake_{opt}$, is obtained from the following expression rounded to three significant digits:

$$\% \text{ Cake}_{opt} = K_1' + K_2'(RPMB - RPM_{opt})^R + K_3'(RPMB - RPM_{opt})^{2R} + K_4'(Dose_{opt})^S \quad (9)$$

Total Processing Cost

The total processing cost with a polymer is calculated according to the relationships given below:

Processing Cost (\$) = (A) (B) + C1 + C2 (1/D) (10)

where:

Processing Cost (\$) = Dollars per dry ton of sludge.

A = Pounds of polymer per dry ton of sludge ($Dose_{opt}$) as determined in the polymer evaluation test.

B = Cost ($) of polymer per pound of polymer.

C_1 = A value specific to a processing site and reflects interfacility transportation cost.

C_2 = A value to reflect agitation drying costs specific to a particular drying site.

D = Percent cake solids at optimum polymer dose ($\%Cake_{opt}$).

The polymer with the lowest total processing cost is selected for purchase.

ADMINISTRATIVE PROTOCOL

A typical polymer testing and selection protocol consists of the following steps:

1. Sending advertisements to polymer manufacturers and receipt of responses from manufacturers (four weeks).
2. Laboratory tests, if needed (one week).
3. Field tests (three weeks).
4. Data analysis (two weeks).
5. Bidding process and contract award.

The Purchasing Department issues bid documents to various polymer vendors, and also advertises for the procurement of polymers. After the responses are received within a specified time (usually four weeks from the date of advertisement), full-scale testing of the polymers submitted by vendors (a maximum of two per vendor) is scheduled and the vendors are informed with the dates on which their respective polymers will be tested. Sometimes, it may be necessary to conduct laboratory tests to determine the acceptability of the polymers submitted by manufacturers prior to full-scale testing. Usually, a full-scale field test takes at least one full day to test one polymer.

FIELD TEST PROCEDURE

The sludge flow rate to the centrifuge is kept constant during the test. The same centrifuge is used with all polymer tests. Cake solids, centrate, and centrifuge feed samples are taken at various dosages (lbs/dry ton of solids) and pinion speeds using a factorial or fractional factorial sampling design over the operating range of minimum and maximum torque, for each polymer to be tested. The testing and sampling order is to start at high pinion speeds (high torque, low capture, high cake condition) and to follow with progressively lower pinion speeds (low torque, high capture, low cake condition) in equally spaced intervals. If sampling begins at significantly lower pinion speeds, there is a high risk of the cake liquefying and spilling over from the conveyor belts of the centrifuges, thereby causing downtime for cleanup. All samples are taken after at least 15 minutes of centrifuge operation at a given polymer dose. These samples are then analyzed for percent total solids. The percent solids capture is calculated according to the following equation:

$$\%CP = \left[\frac{FD-CN}{FD}\right] \times \left[\frac{CK}{CK-CN}\right] 100 \qquad (11)$$

where:

%CP = percent capture of solids.

FD = feed solids (%).

CN = centrate solids (%).

CK = cake solids (%).

Polymers which do not produce a percent capture value greater than 95 percent at some point on the performance characteristics curve (polymer dose vs. percent capture) are eliminated.

DATA EVALUATION PROCEDURE

After the full-scale scale tests are conducted, the pinion speeds and polymer doses used, and percent capture and cake solids achieved is tabulated. The data are then subjected to the model selection and optimization procedures. Software programs are used for the model selection and optimization. The following are the steps in the evaluation, selection, and optimization of models:

1. Initially, the data on pinion speeds, polymer percent capture, percent cake solids is tabulated: the "SCIENTIST" software program is used with these data to estimate the parameters in the reparameterized capture and cake models (Equations 3 and 4) by using equation file CPCK1FQ5 (or CPCK1FQ2).

2. The data on percent cake solids, polymer dose, percent capture, and RPM are keyed in the data window (CP, CK, Dose, and RPM) of this program.

3. Then, the fixed point (PCP, PRPM, PDose) is set in the parameter window to the sample point associated with the highest pinion speed at which the percent solids capture specification (95 percent) is exceeded. Also, the coefficient K (Equation 3) is set at the value of 1. Appropriate values of CC1 and CC2 are chosen as given above for the two cases under Type 1 (asymptotic linear, asymptotic quadratic) and under Type 2 (maximum quadratic), and the model parameters and their corresponding residual sum of squares (RSS) are estimated for each case. The model with the lowest RSS is picked for optimization. If the RSS from the asymptotic linear model and the asymptotic quadratic model are close in value, the simpler asymptotic linear model is chosen for optimization.

4. The "TK SOLVER" program is then used to obtain the optimization values from the model obtained above by using Equation file OPTFP1Q5 (or OPTFP1Q2). The required data are then keyed into the "VARIABLE SHEET" after following the menu directives to set the appropriate case for optimization. RPMrun on this sheet is equal to PRPM (the pinion speed for the fixed point). The system of equations are then solved, and the output values are read under the section called "MODEL VARIABLES". The optimum dose and optimum percent cake solids values at a solids capture rate of 95 percent for all the polymers tested, are read from the "VARIABLE SHEET" generated for each of the polymers and are used to select the polymer to be purchased.

POLYMER SELECTION PROCEDURE

The optimum dose, percent optimum cake solids, and the total processing cost are obtained according to the equations presented above. The polymers are then ranked according to the cost of processing per dry ton of sludge (Equation 10), and the polymer that has the lowest processing cost is selected.

RESULTS

The following is an example of a data set to illustrate the optimization procedure. In real life polymer evaluations, however, the selection of pinion speeds and polymer dosages are selected and adjusted appropriately during the test, based on the percent solids capture and cake solids content observed, in order to predict the optimum dosage in the evaluation of one polymer. (Table 1). These data are subjected to the above model selection and optimization procedure using the "SCIENTIST" and "TK SOLVER" programs. The model chosen was Type 1 asymptotic linear model as it yielded the lowest RSS. Subjecting this model for optimization with the "TK SOLVER," the optimum polymer dose was found to be 400 lbs/ton, and the optimum percent cake solids was found to be 27.5 percent, at an optimum pinion speed of 2504 RPM for the specified criterion of 95 percent solids capture. Similarly, all polymers submitted by different vendors are tested and the polymer doses determined. Using the polymer selection procedure described above, all polymers tested are ranked according to Equation 10.

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TABLE 1

POLYMER TEST DATA

Pinion Speed (RPM)	Polymer Dose (lbs/ton)	Solids Capture (%)	Cake Solids (%)
2550	365	75.7	24.1
	376	81.8	26.4
	389	84.9	27.7
2525	389	91.1	27.8
	402	92.4	28.1
	415	93.1	28.3
2500	389	94.2	26.7
	402	95.5	27.3
	415	96.2	27.6
2475	389	96.1	24.4
	402	96.9	25.1
	415	97.4	25.6

*Wet basis: Multiply by percent dry solids content of the polymer (usually the dry solid content is five to six percent) to obtain dry polymer dosage.

CONCLUSIONS

A method has been developed for the selection of polymers in a competitive bidding procedure adopted by the District. This procedure has been in use for the last seven years to the satisfaction of the District, as well as the manufacturers of polymers who participate in a competitive bidding procedure.

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6. Micromath Scientific Software, P. O. Box 21550, Salt Lake City, Utah, 84121. (801) 943-0290.

7. Universal Technical Systems, Inc., 1220 Rock Street, Rockford, Illinois, 61101. (815) 963-2220.

APPENDIX AVII

TOTAL PROCESSING COST FUNCTION DERIVATION

GENERAL COMMENTS

The cost functions included in the polymer contract documents are derived from historical data shown in Table AVII-1. The agitation, drying, and transportation costs per dry ton of sludge solids is inversely related to the percent cake solids. Figure AVII-1 shows sludge transportation cost (TCOST), and sludge agitation drying cost (ADCOST) as a function of percent cake solids. If these costs are plotted against the reciprocal of percent cake solids, the curves will be linearized as shown in Figure AVII-2. Thus, these curves can be transformed into algebraic functions using linear regression with the reciprocal of percent cake solids as the independent variable:

$$\text{COST} = K_1 + K_2\left(\frac{1}{\text{CK}}\right).$$

If some curvature remains after the attempted linearization, additional quadratic or cubic terms may be added to the linearized model as follows:

$$\text{COST} = K_1 + K_2\left(\frac{1}{\text{CK}}\right) + K_3\left(\frac{1}{\text{CK}}\right)^2$$

$$\text{COST} = K_1 + K_2\left(\frac{1}{\text{CK}}\right) + K_3\left(\frac{1}{\text{CK}}\right)^2 + K_4\left(\frac{1}{\text{CK}}\right)^3$$

etc.

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TABLE AVII-1

HISTORICAL TRANSPORTATION COST AND AGITATION DRYING COST RELATED TO SLUDGE PERCENT CAKE SOLIDS

Percent Cake Solids	Reciprocal of Percent Cake Solids	Transportation Cost ($/dry ton)	Agitation Drying Cost ($/dry ton)
10	0.1000	47.58	35.89
12	0.0833	39.65	28.71
14	0.0714	33.98	23.58
16	0.0625	29.73	19.74
18	0.0556	26.43	16.75
20	0.0500	23.79	14.35
22	0.0455	21.63	12.40
24	0.0417	19.82	10.77
26	0.0385	18.30	09.39
28	0.0357	16.99	08.20
30	0.0333	15.86	07.18
32	0.0312	14.87	06.28
34	0.0294	13.99	05.49

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE AVII - 1

TRANSPORTATION COST (TCOST) AND AGITATION DRYING COST (ADCOST) vs. PERCENT CAKE SOLIDS

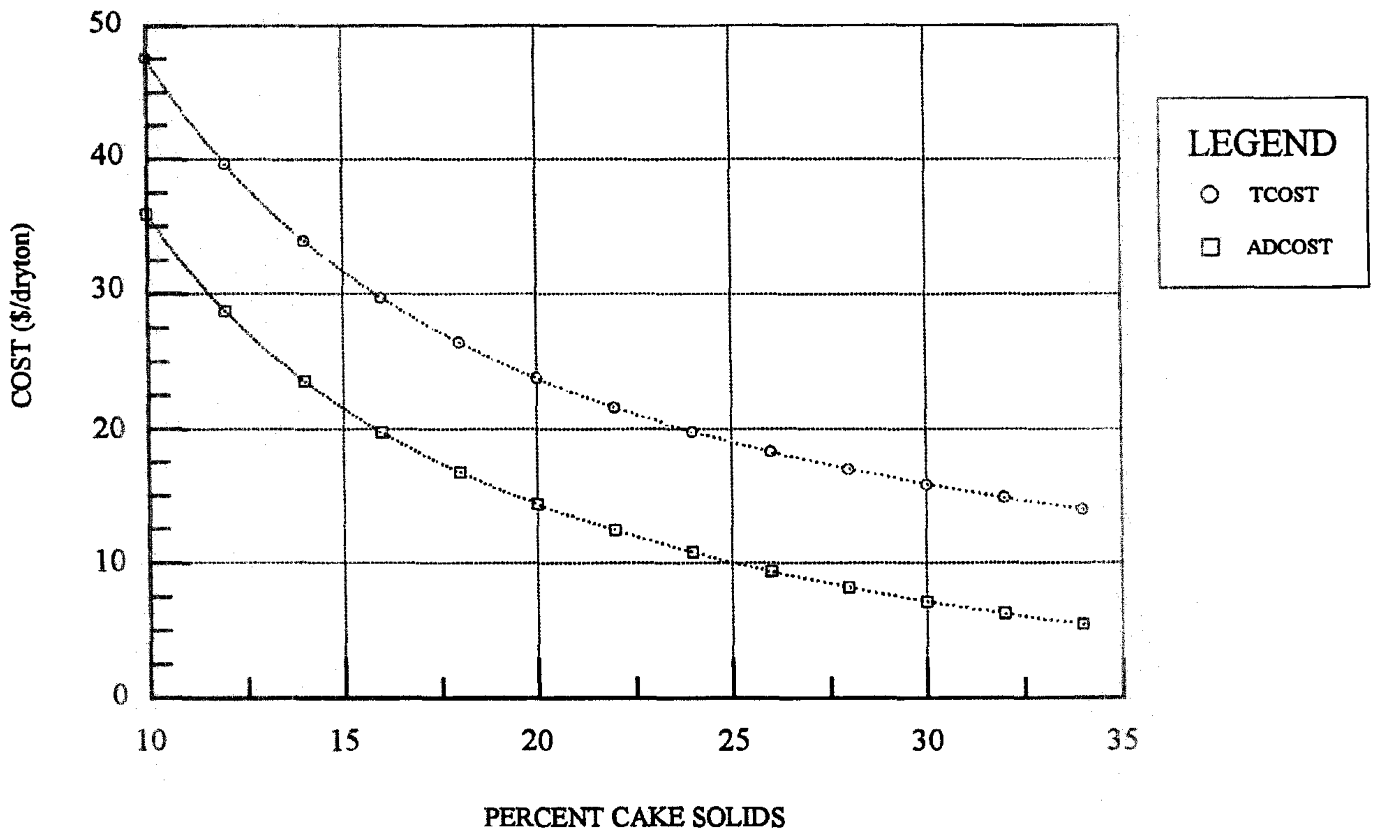

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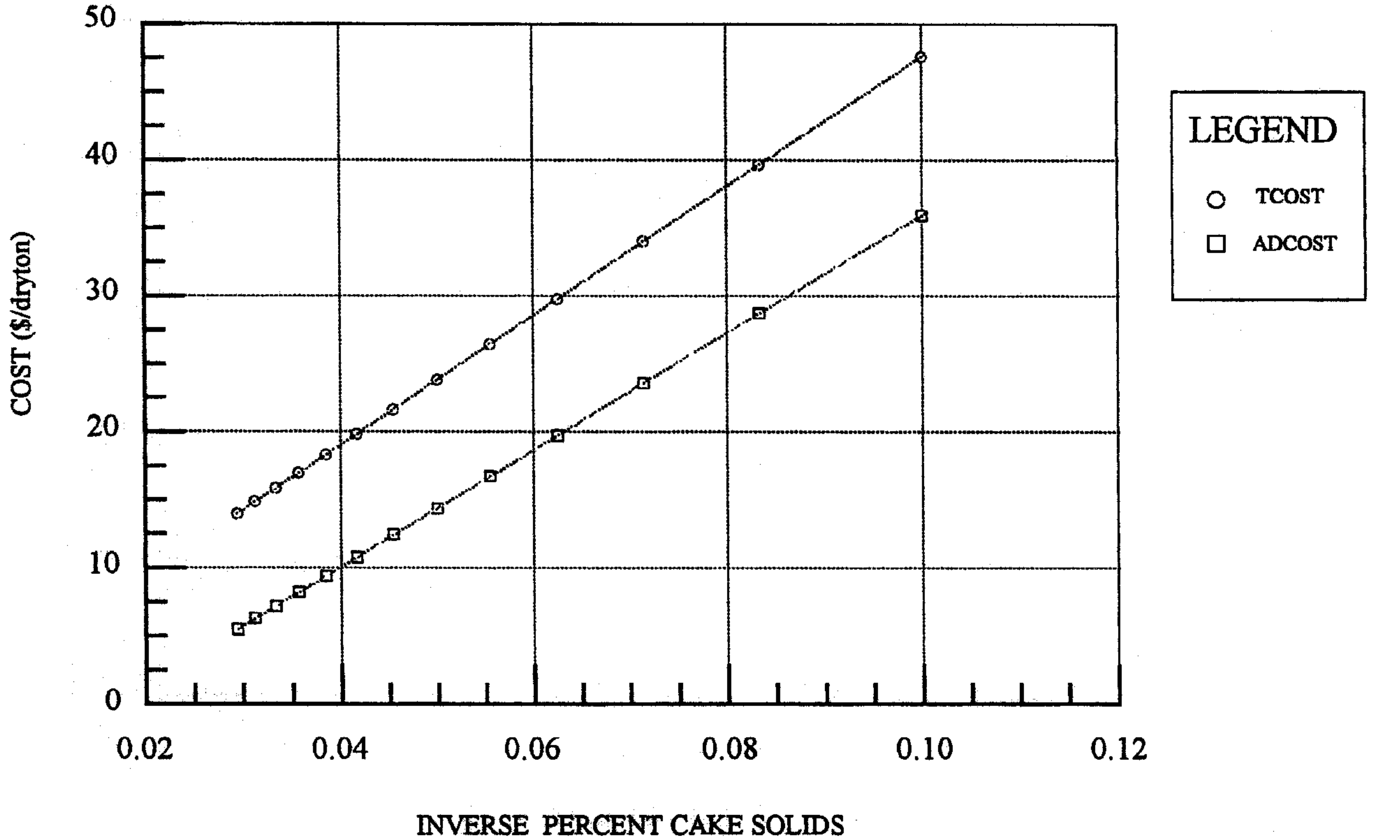
FIGURE AVII - 2

TRANSPORTATION COST (TCOST) AND AGITATION DRYING COST (ADCOST) vs. INVERSE CAKE SOLIDS



Thus, polynomial regression may be applied to these more complex functional forms, if necessary, in order to transform the historical data into algebraic functions.

Derivation of Agitation Drying Cost Function

If linear regression is applied to the agitation drying cost and cake solid data in Table AVII-1, using the functional form $COST = K_1 + K_2\left(\frac{1}{CK}\right)$, the following parameter estimates are obtained:

$$K_1 = -7.1771$$
$$K_2 = 430.64$$

Derivation of Transportation Cost Function

If linear regression is applied to the transportation cost and cake solids data in Table AVII-1, using the same functional form $COST = K_1 + K_2\left(\frac{1}{CK}\right)$, the following parameter estimates are obtained:

$$K_1 = -0.0014267$$
$$K_2 = 475.79$$

It turns out that K_1 is not significantly different from zero at a 95 percent confidence level, so the regression form may be truncated to the following:

$$COST = K_2\left(\frac{1}{CK}\right)$$

By applying linear regression to this truncated form, with the same data, the following parameter estimate is obtained:

$$K_2 = 475.75$$