INSTITUTE OF PAPER CHEMISTRY
Appleton · Wisconsin

A NEW MEASUREMENT PROCEDURE FOR THE EVALUATION OF SLIME FORMATION IN THE PAPER MILL

Project 3329

Report One
A Progress Report
to
MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

August 1, 1982

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SUMMARY

A new technique to measure slime formation has been evaluated in an extended study under mill conditions. The increased resistance to fluid flow caused by developing slime films was used to monitor growth over time and to appraise the effectiveness of in-mill control programs. A relatively simple apparatus was designed to circulate mill fluids through a section of one-half inch stainless steel tubing and manometrically measure the increase in pressure drop resulting from slime attachment to the inner tubing walls. The apparatus was installed at the saveall [of a paper machine] and operated at that site for approximately six months.

Several mill conditions were followed over the course of the study, including pH, temperature, and nutrient and solids content of the saveall fluid. The microbiological status of the system was characterized by bacterial plate counts and direct tactile testing for the presence of slime at selected sites about the machine wet-end and the saveall. Chlorine residuals were assayed to track biocide treatment. Comparisons were then made between these measurements and the data being provided by the slime-forming apparatus. The latter involved not only the pressure drop changes that occurred with time, but also deposits collected from the test section tubing, which were thoroughly examined as to their microbiological and papermaking material content.

The conditions prevailing in the selected mill system were highly favorable to bacterial growth, with the saveall fluids having an average temperature of 39°C and and a pH of 7.6. The BOD_5 values ranged from 220 to 631 mg/L with TKN and orthophosphate levels, indicating that phosphorus was the limiting nutrient. The dominant

sugars present were glucose and xylose at 68.2 and 24.7%, respectively, and total sugar levels ranged from 57.2 to 126.3 mg/L. These nutrient levels supported bacterial populations that equalled or exceeded 10×10^6/mL over approximately 20% of the plate counts made on saveall fluid.

The overall comparisons showed the expected relationship between pressure drop and slime formation during periods of low bacterial activity that were produced by changes in the biocide treatment program. The agreement between pressure drop measurement and slime development during periods of high bacterial activity was also evident but showed some inconsistencies when flow velocity was seriously disrupted by the developing films. The pressure drop measurement for the assessment of slime conditions was considered to be superior to the other methods of estimating the microbiological status of the system. The plate count technique assays dispersed bacterial cells in the system which do not directly affect the process, whereas pressure drop measured the developing films that do cause process problems. Pressure changes are measured objectively and, therefore, are superior to the subjective opinion estimates obtained by tactile ratings of the amount of slime present on parts of the machine. In addition, pressure drop has the potential to show the rate at which the slime film is growing and to demonstrate that point at which the slime film begins to release, which is especially critical to the papermaking process. The deposits collected from the test section tubing served to establish the composition of the slime matrix, and although all significant deposits collected during this study were typically microbiological, a chemical slime would also be detected by pressure changes.

Changes in the design of the apparatus are suggested to improve the operation and permit the full realization of the potential of the device to follow slime formation. A reduction in size to increase portability and permit location of the unit near the wet-end of a machine is recommended. The addition of automated controls to maintain a constant flow velocity, combined with continuous sensing and recording of pressure data, would be desirable. Although additional mill trials are needed to confirm wide spread application of this technique, the basic concept of using a pressure drop measurement to follow slime formation has been demonstrated.

INTRODUCTION

The major in-mill microbiological problem of the paper industry is "slime." The term is derived from the slippery feel of the film of deposits that collect on the surfaces of tanks, pipes, and machinery in contact with the fluids and slurries used in paper manufacture. Although these deposits can be complex in their make up, the most common cause is the growth of microorganisms that prefer attachment to surfaces. The resulting deposits cause many problems both _in situ_ or after their release as clumps into the process streams. These problems include the following: web breaks; sheet blemishes; plugging of screens, nozzles, wires and felts; poor drainage, and increased corrosion. The cost in product losses, downtime, and microbiological control is estimated in excess of $100 million per year to the U.S. industry, with a minimum of $15 million as a direct outlay for biocides used to restrict organism growth.

To establish an efficient control program it is important to know with reasonable precision what the slime status is within a given machine system. How much slime is present and how fast it is developing are difficult to evaluate, and a definite need for an objective technique to follow these conditions has existed for many years. Probably the only system for in-mill use that will evaluate slime _per se_ involves "slime boards." Buckman Laboratories, a major slimicide supplier, distributed do-it-yourself plans for such a device many years ago (1), and, thereafter, others offered a more sophisticated commercial model (2). The Buckman unit (Appendix I) consists of a wooden board situated in a chamber through which mill white water is circulated. After a period of exposure, usually twenty-four hours, the board is withdrawn from the unit, the free liquid allowed to drain, and any adherent deposit removed for weight checks - wet and/or dry. Control of slime was claimed to be adequate if the wet accumulation proved less than 20 $g/ft^2/day$ (3,4);

however, evidence to support that value is weak. Furthermore, although the slime board reports appeared thirty years ago, we see little evidence of their continued use by the industry.

Currently, bacterial count assays carried out on various mill fluids are the most common test used to evaluate slime status or control program effectiveness. The weakness in this approach is that the dispersed cells measured by these counting methods do not necessarily correlate with the population adherent to surfaces, which is the population of real significance to the process problems. Several studies which combined bacterial count data with a more direct attempt to measure slime have appeared over the years. Hunt (5) constructed a boxlike unit in which a papermaking furnish was circulated. Both bacterial count and deposit formations were observed after treatment with biocides, but only his preliminary work was reported. Stern (6) inserted wooden tongue depressors into small volumes of fiber slurries and weighed the amount of deposit that these accumulated. His method required excessive replication because of the variable amounts of deposit that formed on the controls. A small film-forming device assembled by Leckey (7) was operated both on an artificial laboratory furnish and attached to an operating paper machine. Although the initial results appeared to show some promise, any continuation of these studies was not reported. Nalco Chemical, a large supplier of slime-control agents, reported the use of a laboratory apparatus patterned after the slime board units (8). Again, little information was given that would establish the needed link to mill applications, and these slime units relied on more or less subjective assessment of the extent of slime present.

It was not until the early work by Characklis (9) showed that biological films produced a readily measured change in resistance to fluid flow that the development of a truly objective measure of slime growth became apparent. His work has continued to develop data on the underlying principles of biofilm formation (10-12) under programs supported by the power industry and the U.S. Navy, both of which experience serious biofouling problems in cooling water transmission lines. His studies, therefore, have involved essentially particle-free fluids of low nutrient content, which are markedly different from the slurries common to papermaking.

APPLICATION TO PAPER MILL SYSTEMS

The measurement of the resistance to flow offered a practical yet objective technique to follow the growth of a slime film in either a laboratory or paper mill situation. Initially an apparatus was designed for laboratory use that consisted of a fluid reservoir and an accompanying five-foot section of one-half inch stainless steel pipe fitted with pressure taps at each end. An inoculated nutrient fluid was pumped from the reservoir through the pipe at a set flow rate, and any increase in pressure drop created by film attachment was to be measured via a manometer attached to the pressure taps. Although dispersed bacterial growth in the fluid could be easily achieved, the development of a surface film was somewhat unpredictable. However, when surface films did form, the expected increase in pressure drop was observed.

Obtaining a slime film in a paper mill system is a more reliable event, and therefore a second apparatus, patterned after the laboratory unit, was assembled. Arrangements were made to place the new apparatus in a paper mill where it could be operated on process fluid and used to study slime growth in the mill environment. Initial studies were carried out with the apparatus operating on fluids collected from a common tank fed from several paper machines. Later, after an extensive rebuild the apparatus was moved to a paper machine saveall serving a single machine. This machine was said to have the worst slime problems in the mill, and the major portion of the information presented in this report was obtained at this saveall location.

METHODS AND MATERIALS

APPARATUS DESIGN

The in-mill Slime Former unit consisted of two identical elements, as shown in Fig. 1. Small Eastern centrifugal pumps (7.8 gpm) drew fluid from the mill source and moved it through the apparatus. The flow in each element was controlled by two ball-type valves; one controlled the feed to the test section and the other controlled a by-pass loop. The rate of flow was determined by the pressure difference obtained across an orifice plate. A ten-foot length of 1/2-inch stainless steel pipe with pressure taps at either end provided the area wherein the accumulation of slime was evaluated in the same manner as the laboratory units.

The electrical service for the apparatus pumps was interconnected with the paper machine stock pump; when the machine went down, the unit was automatically turned off. Without the interlock the pumps lost their prime, as when the saveall was emptied during machine down periods. Since the pumps were not self-priming, the flow could not restart without further attention. A delay timer was also added that postponed the restart for thirty minutes after power return, allowing wash water in the saveall to clear before fluid was again circulated through the unit. A time clock indicated the on-time of the stock pump.

Initially, all flexible tubing on the apparatus consisted of either standard plastic garden hose used for feed lines to the pumps or laboratory grade Tygon tubing for circulation and return lines. Neither proved sufficiently durable to withstand the heat and other stresses of the mill environment, and both eventually were replaced with a high-grade vacuum tubing for pump feed lines and a nylon braid pressure tubing for all return lines [Norton Plastics R-3603 and B-44-4x, respectively].

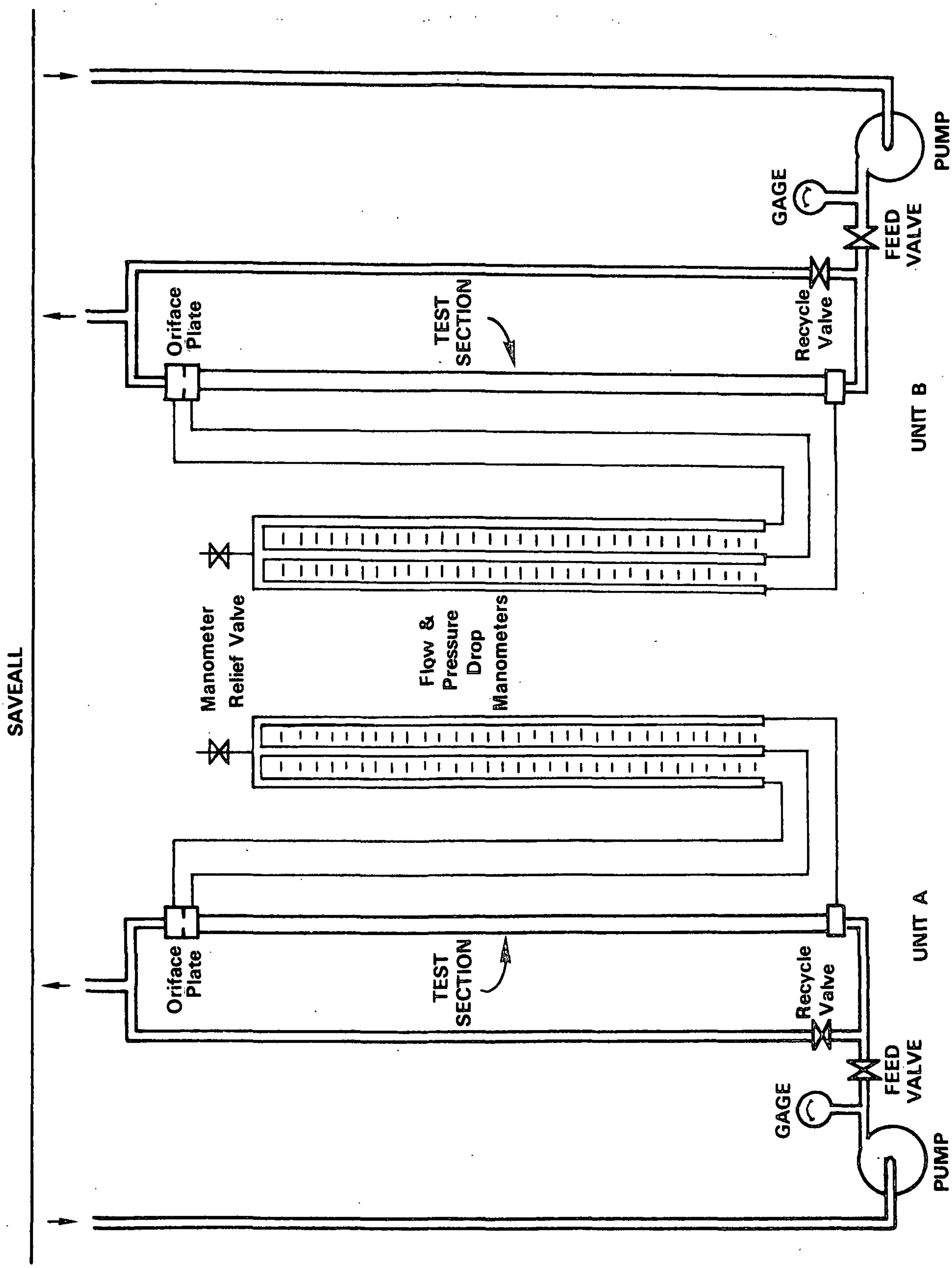


Figure 1. Slime former apparatus.

Occasionally the entire unit required treatment to clear lines and valves of slime. A quart of standard household bleach added to twenty gallons of mill fresh water in a plastic garbage container provided up to 880 mg/L of available chlorine and was used for this purpose. The hypochlorite solution was pumped through the unit for 15 minutes, then acidified to a pH of 5, and circulated another 15 minutes. After such treatment the unit was flushed thoroughly with mill fresh water before returning to the saveall fluid.

FLOW AND PRESSURE CHANGE MEASUREMENT

The flow rate was determined by orifice plate cells constructed in the IPC shop and calibrated via a float type flow meter operating on distilled water at 25°C (Table I). A three-tube manometer measured the pressure difference (ΔP) across both the orifice plate cell and the test section pipe. The center element served as a common leg for both measurements.

When operating on mill fluids, care was taken to free the manometers from settled deposits before any measurements were taken. This was accomplished by venting the manometers, which allowed the manometers to fill and the fluid to cycle for several minutes. An aspirator type air bulb was then used to pump the fluid in the manometer back down to a readable level after each flushing operation. Also, it was commonly necessary to gently backwash each unit before pressure changes were measured by introducing fresh mill water via the outflow line, with the pumps off.

Measurements of the pressure difference occurring across the test section were made at a flow rate of one meter per second. Readings would be taken before and after cleaning of the test section tube. The apparatus was always left operating at 1 m/s when all tests were completed at the mill.

TABLE I

IN-MILL UNIT FLOW CALIBRATION

Orifice Plate ΔP, cm H_2O

	Unit A				Unit B			
m/s[a]	a	b	c	$\overline{x}$	a	b	c	$\overline{x}$
0.5	1.0	1.0	1.0	1.0	1.0	0.75	1.0	1.0
0.75	2.75	2.75	2.5	2.75	2.5	2.25	2.5	2.5
1.0	5.5	5.75	5.75	5.75	4.5	4.5	4.75	4.5
1.25	9.5	9.5	9.5	9.5	8.0	8.0	8.0	8.0
1.5	14.25	14.5	14.25	14.25	12.5	12.25	13.0	12.5
1.75	20.0	20.25	20.25	20.25	17.5	17.25	17.0	17.25
2.0	25.5	26.0	26.0	26.0	23.0	22.0	22.0	22.25

[a]Established by Fischer and Porter flowrator using distilled water at 25°C.

TEST SECTION DEPOSIT COLLECTION

Whenever collection of test section deposits was desired, all attached lines were disconnected from the tubes and the free fluid allowed to drain for several minutes. The tubes were then removed from the apparatus and a small sterile Whirl-pak bag attached to one end. Next, a cylindrical cleaning element fitted with three O-rings was threaded onto a 12-foot, 3/8-inch rod. This tight fitting cylinder was driven through the tube from the end opposite from the bag. Virtually all adhering deposit was effectively cleaned from the tube wall and captured in the attached bag in this manner. The cleaning cylinder was then removed and a small test tube brush attached to the rod which, in combination with a stream of fresh-water, gave a final cleaning to the test section. A cotton-tipped swab was used to clear the pressure taps before reattaching the test section to the apparatus.

DEPOSIT WET WEIGHT AND SPECIFIC GRAVITY

The total wet weight of collected deposit per ten feet of pipe was measured by weighing the Whirl-pak bags and corrected by subtracting an average bag weight of 1.78 g. The accuracy was estimated to be about ± 0.05 g. The specific gravity determinations were limited in number and made use of small 6 x 50-mm test tubes (T) of previously determined dry and water-filled weights. The tubes were loaded with deposit by a positive displacement SMI micropipette. Filling from the base upward avoided bubble entrapment. The procedure was carried out in a constant temperature room, and replicates were found to be within 1% in weight.

$$\text{Sp. Gv.} = \frac{\text{T deposit} - \text{T dry}}{\text{T } H_2O - \text{T dry}}$$

ATP MEASUREMENT

ATP determinations followed the general procedure of SAI Technology Company, which includes an internal standard. The assay was carried out in 6 x 50-mm test tubes with the deposit sample first diluted 1:100 in sterile distilled water. Three measurements were required for each deposit sample.

(1) Blank
  a. 100 µL filtered water
  b. 100 µL 0.05M tris buffer[a]
  c. 100 µL release agent (15-second contact)
  d. 100 µL luciferin - luciferase

(2) Standard
  a. 100 µL filtered water
  b. 100 µL 0.05M tris buffer and 10^{-2} µg ATP

c. 100 µL release agent (15-second contact)

d. 100 µL luciferin - luciferase

(3) Sample

a. 100 µL diluted deposit

b. 100 µL 0.05M tris buffer and 10^{-2} µg ATP

c. 100 µL release agent (15-second contact)

d. 100 µL luciferin - luciferase

Calculation of cell numbers in deposit.

$$\text{I.}\quad K = \frac{\mu g\ \text{ATP}}{(\text{standard} - \text{blank}) - (\text{sample} - \text{blank})}$$

$$\text{II.}\quad \mu g\ \text{ATP/mL} = K\ (\text{sample} - \text{blank}) \times 1{,}000$$

$$\text{III.}\quad \text{Cells/mL} = \frac{\mu g\ \text{ATP/mL}}{0.5 \times 10^{-9}}\ ^{b}$$

[a]Buffer also contains 0.01M $MgSO_4$ and 0.001M EDTA.
[b]Estimated cell ATP content.

MILL SLIME RATINGS

During each mill visit the extent of slime that had developed on the paper machine and on the saveall since the last visit (or wash up) was evaluated. A single site located on the vertical side of a suction box about 12-15 ft from the headbox was checked by hand for the typical slippery feel imparted by slime. A similar check was made at the saveall, which was of a flotation type, at a point where the intermittent flow created by the skimming blades passed into a collection trough. Both a stainless steel and tile surface area were available at this site. All of the film was removed after the rating assessment to provide a fresh start for the next examination. The degree of slime was subjectively ranked on a scale of 0 to 5+.

BACTERIAL COUNTS

The bacterial content of the machine white water, the saveall fluid, and the test section deposits was routinely measured, with all samples collected in the sterile Whirl-pak bags and analyzed promptly after their return to the laboratory. Samples were plated using a loop-streak procedure (13) and tryptone glucose extract agar (Difco) as the nutrient medium. Plates were incubated at 35°C, normally for 18-22 hours, and the developing colonies counted under a dissecting microscope at a magnification of 10X.

SOLIDS MEASUREMENT

Saveall fluid was examined for both total and suspended solids. Machine white water, collected at the point of slime evaluation, was occasionally checked for suspended solids only. Fifty milliliter volumes of each fluid source were used. The test section deposits were also tested for total solids but, because of supply limitations, 2-mL volumes were used if and when the collection was ample. All solids samples were subsequently ashed. The filtration, drying, and ashing procedures described in Standard Methods (14) were used throughout.

CHLORINE RESIDUALS

The total available chlorine residual was measured on saveall fluids and machine white water using a phenylarsine oxide and iodine titration with amperometric detection of the end point. The phenylarsine oxide was added in excess and titrated with iodine as discussed in Standard Methods (14). All reagents and the general procedure were also as described in that reference.

HOLE COUNT

The paper machine had a hole-sensing device that checked the web just before the winder. Read outs were taken on each mill visit and used to estimate the total holes per day.

NUTRIENT ANALYSIS

Several samples of saveall fluid were tested for BOD_5, Kjeldahl nitrogen, and orthophosphate by APHA methods 507, 421, and 425, respectively (15). Some samples were filtered through 0.45 μm membrane filters before these assays. All samples tested for wood sugars were first filtered and then held frozen at -20°C until analysis. The method of Borchardt and Piper (16) was used.

RESULTS AND DISCUSSION

The host mill produces carbonless copy and telephone directory papers from furnishes that contain a mixture of kraft and chemimechanical pulps. The overall sliming potential of this mill is considered to be relatively high and the paper machine with the most serious slime problems was selected for this study.

SLIME CONTROL PROGRAMS

The chemical treatments in use at the start of the study involved the addition of 50 mL/minute of Nalco 7649 (20% 2,2-dibromo-3-nitrilo-propionamide) for a period of one hour to the machine chest three times a day and for a period of 0.5 hour to the white water silo four times a day. Chlorine was being used to treat the mill fresh water and saveall excess effluent when running colored grades at a level sufficient to provide a 0.5-1 mg/L residual. Some additional microbiological control benefit may have been derived from treatments given to the calcium carbonate used in their furnish at a rate of 200 lb/T. Two different $CaCO_3$ sources were used, one treated with 500 ppm of Vancide TH (hexahydro-1,3,5-triethyl sulfone triazine) and the other treated with 1000 ppm of Metasol J (N-[α-(1-nitroethyl) benzyl] ethylene diamine).

Boilouts of the paper machine systems, using hot caustic solutions, were carried out on an infrequent basis. About one or two boilouts per year per machine was considered normal. Wash ups with high pressure hoses and acidified foam spray with occasional brushing were carried out as needed or when the machines went down for various mechanical reasons.

Later in the study the mill changed to chlorine dioxide (ClO_2) as its major chemical control agent while retaining the addition of chlorine to the mill fresh water. This change took place during the study and the effects it produced are discussed later.

INITIAL APPARATUS SETUP

Due to floor space limitations and the size of our test apparatus, it was not possible to place the Slime Former (SF) near the wet-end of the paper machine, and it was initially placed near the [No. 5] saveall on a lower floor. The frequent draining of this saveall during grade changes, cleanups, etc., quickly became a problem with respect to maintaining a continuous flow of fluid through the SF unit. Although this problem was resolved later by the power interlock with the machine stock pump, that change had to be delayed until after a rebuild of the paper machine. It was decided, therefore, that for run-in trials the SF unit would be relocated to draw fluid from a large tank receiving clear water from the paper machine under study, as well as 3 others. This Rich Gathering Tank (RGT) fluid was felt to represent more of a general mill condition with respect to slime-forming potential, and this large volume of fluid was very rarely discharged.

The initial stages of the run-in period were troubled with a variety of equipment failures on the SF unit, including pump burnouts, collapsing intake hoses, tubing ruptures, and foreign objects clogging lines and orifices. Air temperatures in this lower area reached 110°F and eventually led to near total failure of all intake and circuit lines on the apparatus. During the frequent outages little usable information on the microbiological status of the SF unit was obtained.

RICH GATHERING TANK STUDY

Eventually, during the period of operation at the RGT site, two continuous 21-day running periods provided the desired comparisons between pressure changes shown by the apparatus and times of low and high microbiological activity. The first of these periods was one of minimal microbial activity and corresponded to high chlorine residuals and low bacterial counts in the RGT fluid. The SF unit showed little change in pressure drop, and throughout this period test section cleaning was not required. These data are presented graphically in Fig. 2.

The second period occurred several weeks later when chlorine residuals declined sharply and the bacterial count increased markedly. Significant pressure drop changes began to be detected by the SF unit, and cleaning of the test sections was required frequently. The appearance of the deposits obtained from the SF unit was typical of a microbiological slime when viewed under the microscope. The plating of the test section deposits also showed a high bacterial content (8.6-74 x 10^8/mL). Although no direct examination for slime on any of the paper machines was being made during these run-in trials, it was learned that slime buildups had caused an unscheduled cleanup on both two machines. This occurred nine days after the initial indications of significant slime in the SF unit at the RGT site. The data of the second period are shown in Fig. 3.

An increase in pH was also noted during the run-in phase and was a result of mill trials with alkaline sizing. The pH in the RGT fluid moved upward from 6.5 to over 7.5. This shift would be expected to reduce the biological activity of the chlorine being added to the saveall clear water, since the most bioactive form of chlorine is the hypochlorous acid (HOCl) that is formed as chlorine goes into solution [Eq. (1)]. The further dissociation of hypochlorous acid, however, is pH

$$Cl_2 + H_2O \longrightarrow HCl + HOCl \qquad (1)$$

dependent [Eq. (2)] and the bioactivity

$$HOCl \rightleftarrows H^+ + OCl^- \qquad (2)$$

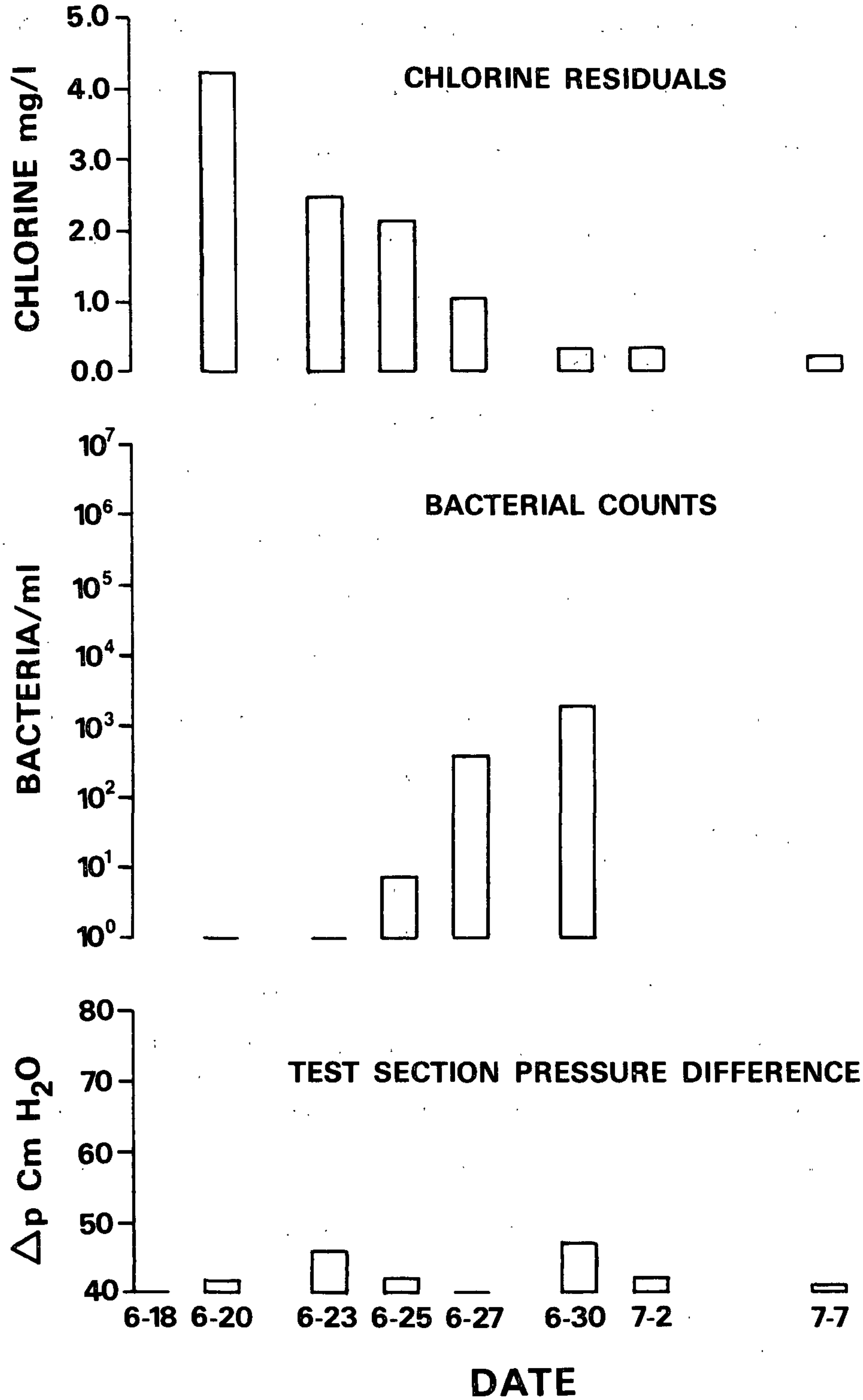


Figure 2. RGT, low slime period.

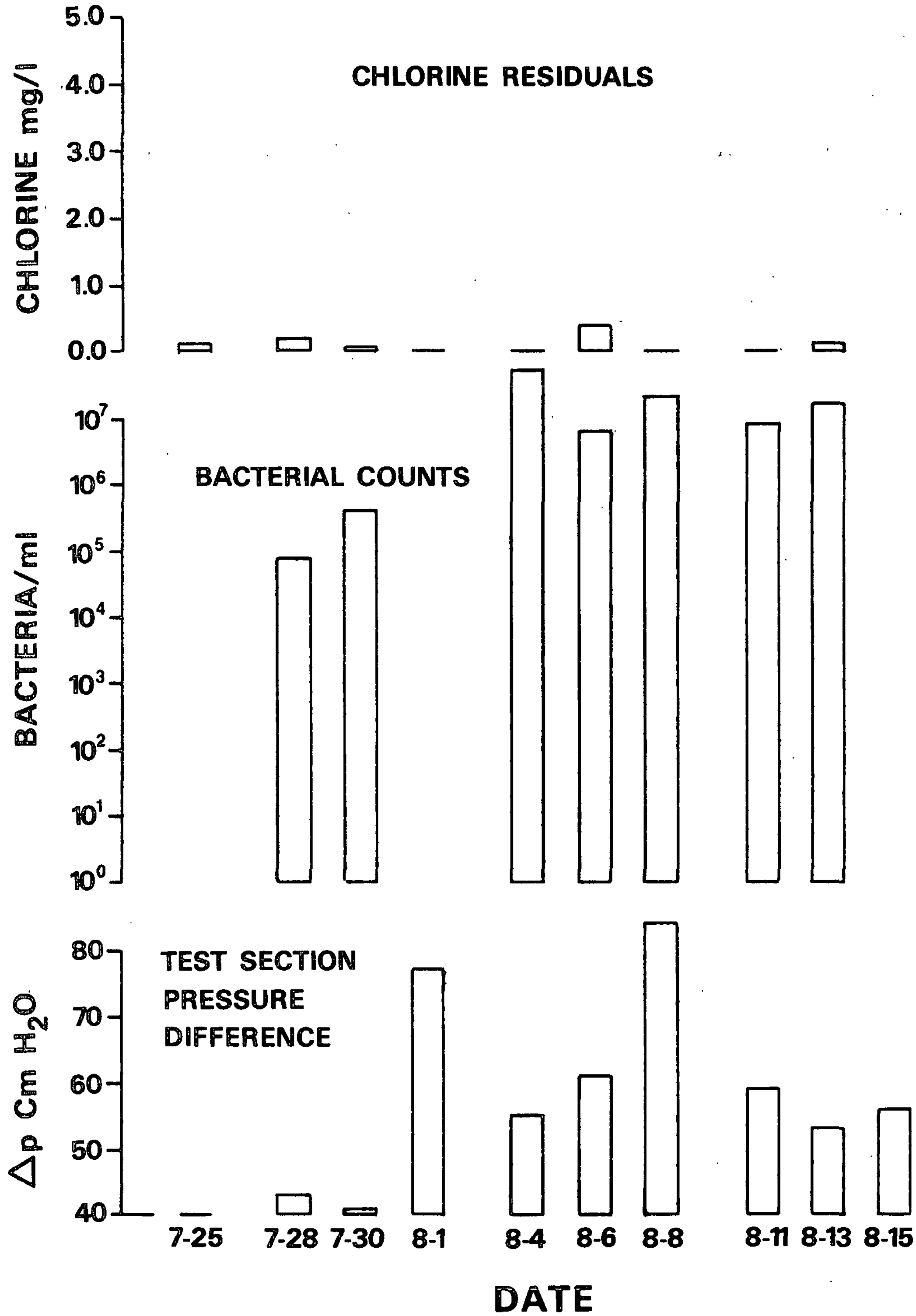


Figure 3. RGT, high slime period.

of the chlorite ion (OCl^-) that is formed at the higher pH values is estimated to be only one-eightieth of that of hypochlorous acid (17). This relationship between pH and the concentrations of HOCl and OCl^- is shown in Fig. 4. It is evident that the reduction in HOCl concentration over the pH range of 6 to 8 is great and would have a significant effect at the RGT site. Additional RGT data are listed in Appendix II.

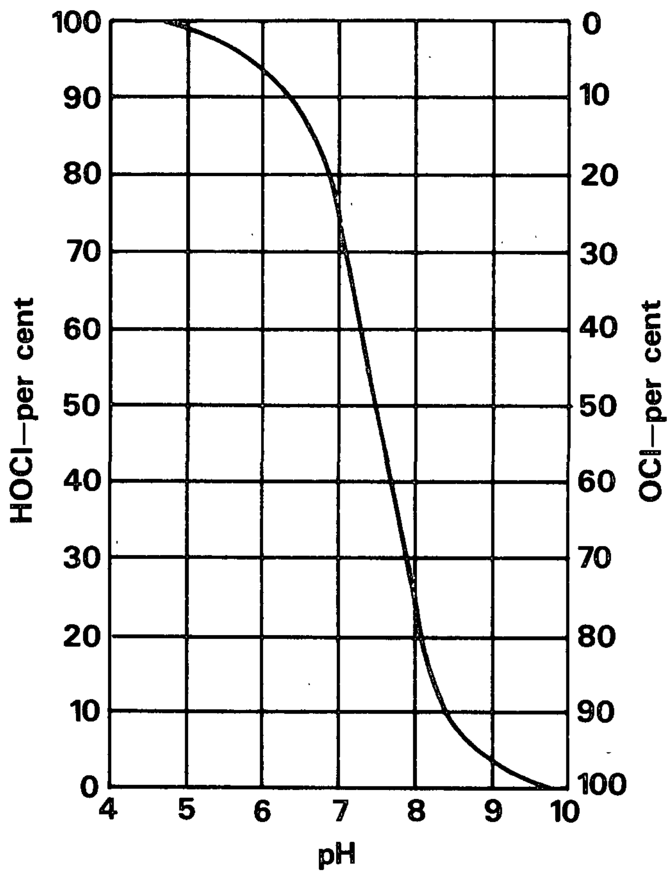


Figure 4. Relationship between HOCl, OCl^-, and pH (18).

At the end of the second period just discussed, the rebuild work on the machine had progressed to a point where the SF unit had to be shifted to an out-of-the-way location. During this period modifications and tubing exchange plans were made for the SF unit in anticipation of expanded trials.

POST REBUILD CHANGES

A return to the machine saveall location was made after the mill had completed the rebuild. The high chlorine levels encountered in the Rich Gathering Tank and the relatively low solids content of those fluids were considered to be less conducive to slime development than would be the case with the saveall fluids. Also, the saveall provided a more direct link to machine operation than did the multisource RGT fluids which are used for purchased pulp makeup and chemimechanical pulp washing.

The problems of the machine having the most difficulty with slime over prior years were probably due in part to alternate acid and alkaline operation. Many color changes were made on the fly, but the changes from a highly colored sheet to a white or light color often required emptying the saveall, a procedure that caused problems for the SF unit. However, after the rebuild the mill provided the power link with the machine stock pump that prevented the apparatus from pumping itself dry. A second priming problem was then uncovered that resulted from simple drainage of the intake lines drawing fluid from the saveall. These lines had a nearly 10-ft drop into the saveall, and the free drainage of fluid from that section of tubing produced a "bubble" sufficient to prevent a return to full flow by the unit pumps on refill of the saveall. A simple upward u-turn at the end of the intake hoses corrected this problem.

The additional changes made on the slime former unit at this time included the entire retubing of the apparatus, the addition of the delay timer, and - after a short period of operation - the installation of an auxiliary power cord that allowed operation of the unit for reading and cleaning purposes during those visits when the paper machine (stock pump) was down.

It was after the paper machine rebuild that the mill changed slime control agents from Nalco 7649 to chlorine dioxide. A small ClO_2 system manufactured by Olin Water Services generates ClO_2 from the on-site reaction of chlorine gas and a solution of sodium chlorite [Eq. (3)]. Chlorine is commonly added

$$2\ NaClO_2 + Cl_2 \longrightarrow 2\ ClO_2 + NaCl \qquad (3)$$

in slight excess of that needed for the reaction. The point of ClO_2 feed was the white water silo and the rate of addition initially was 1.5 mg/L over a two-hour period every eight hours. This was later reduced to 0.5 mg/L over a four-hour period and, eventually, to a continuous feed. As will be discussed later, these changes had a marked effect on the microbiological status of this system.

STUDY MEASUREMENTS

The number of measurements carried out to define the conditions present in the paper machine system, as well as to monitor the performance of the SF unit was expanded considerably in this phase of study. These criteria are outlined in Table II, and about one-fifth have a direct bearing on the microbiological status of the machine and apparatus. The remaining portion of the data defined operating conditions or aspects of fluid makeup which, if not of immediate interest, would serve as a basis for comparison with other systems or to detect changes that might be introduced during the course of the study. Not all measurements were carried out on each visit to the mill. Over the early weeks, visits were made daily but were later cut to three per week (Monday, Wednesday, and Friday).

HOLE COUNTS AND MACHINE DOWNTIME

Early in this second phase of study, it was suggested by mill personnel that the hole-sensing device at the reel was a useful indicator of sliming conditions when they occurred. The hole count data obtained during the study are plotted in Fig. 5. Over the first sixty days the hole counts ran very high, but it was also apparent that the mill was adjusting to a variety of operational problems during this time as a result of the rebuild. By late March these problems were being resolved, and the hole counts began to approach the expected values. However, the hole count data were not related to any of the microbiological shifts observed in the other kinds of measurements. In part the lack of correspondence was affected by the sensitivity setting of the device during a given period. Data as to the sensitivity settings were not available.

The SF unit clock, which operated in conjunction with the machine stock pump through the power link, gave an estimate of machine downtime. These data have been presented in Fig. 5 but showed little correspondence to either the hole count data or to significant microbiological changes observed in other data. Although Nelson (21) was able to make good use of downtime data in his comparison of the before and after periods of ClO_2 introduction to the same paper machine system, his comparisons were extended over relatively long periods. Also, the stock pump was not necessarily shut down during the breaks that formed a significant part of his data. In our study, variability plus the nonbiological influences present in the downtime data precluded the development of significant correlations with the comparatively rapid microbiological shifts encountered. Additional hole count and time clock data are listed in Appendix III.

Machine Web Breaks

Another in-mill parameter that is often considered to be a useful indicator of the extent of slime in the system is the number of web breaks that the machine experiences within a given period. Break data, therefore, were obtained from the mill records, and these were compared with the slime events indicated by the SF apparatus and other test parameters. Like the hole count and downtime data this web break information proved too variable to give significant correlations when compared with the microbiological observations. It was not possible to isolate those breaks due to slime from other mechanical events that produce the same result. The break data are presented in Appendix IV.

TABLE II

OUTLINE OF STUDY CRITERIA

I. Paper Machine
- A. Hole count
- B. Stock pump run time
- C. Slime rating
- D. Bacterial count
  - 1. Total aerobic
- E. Chlorine residual
  - 1. Total available
- F. pH
- G. Suspended solids
  - 1. Organic
  - 2. Inorganic

II. Saveall
- A. Slime rating
- B. Bacterial count
  - 1. Total aerobic
- C. Chlorine residual
  - 1. Total available
- D. Temperature
- E. pH
- F. Total solids
  - 1. Organic
  - 2. Inorganic
- G. Suspended solids
  - 1. Organic
  - 2. Inorganic
- H. Dissolved solids
  - 1. Organic
  - 2. Inorganic
- I. BOD_5
  - 1. As is
  - 2. Filtered

II. Saveall (Continued)
- J. Kjeldahl nitrogen
  - 1. As is
  - 2. Filtered
- K. Orthophosphate
  - 1. Filtered
- L. Sugars
  - 1. Filtered

III. Slime Former Unit
- A. Pressure change
  - 1. Test section
  - 2. Orifice plate
- B. Test section deposits
  - 1. Total wet weight
  - 2. Bacteria count
    - a. Plated
    - b. ATP
  - 3. Macroscopic
    - a. Color
    - b. Odor
    - c. Texture
  - 4. Microscopic
    - a. Unicellular bacteria
    - b. Filamentous bacteria
    - c. Protozoa
    - d. Grit
    - e. Fiber elements
  - 5. Specific gravity
  - 6. Total solids
    - a. Organic
    - b. Inorganic

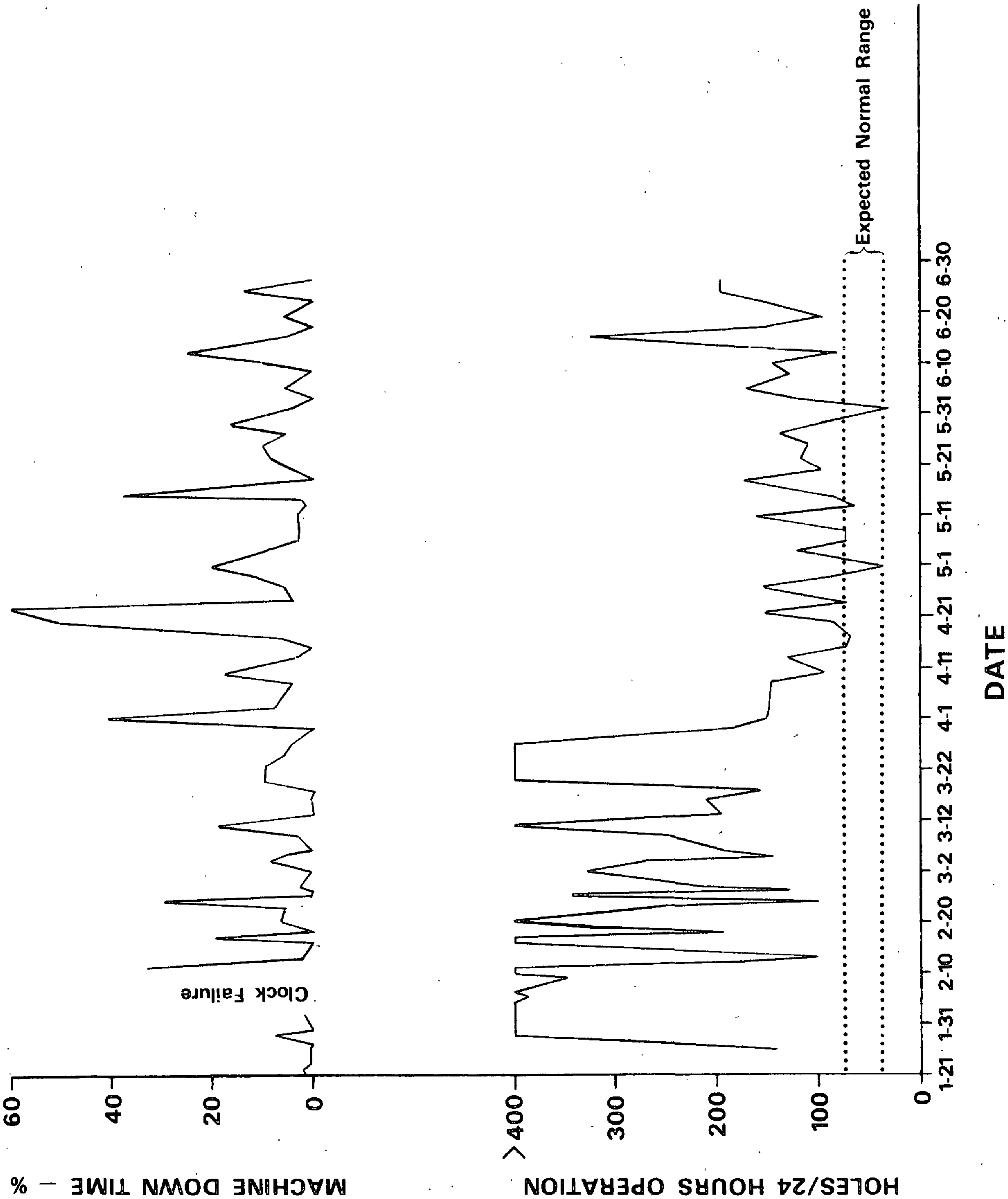


Figure 5. Hole count and machine downtime data.

TEST SECTION PRESSURE RESPONSE

It was the primary intent of the study to determine whether or not this measurement of pressure drop across a length of tubing carrying fluids from a papermaking system would truly indicate the extent of microbiological fouling that was taking place not only within the tubing but, more importantly, within that system. The potential for its doing so had been established in laboratory studies, but the response to mill conditions involving nutrient-rich fluids with high solids content required evaluation. The three major questions posed were (1) would accumulations of deposits become attached to the walls of the tube in sufficient quantity to produce measurable pressure changes, (2) was the makeup of any such accumulation due to microbiological or nonmicrobiological factors, and (3) did the formation of test section deposits, especially those of a microbiological nature, parallel events within the machine system.

The first question was relatively direct and the least difficult to resolve. Over the early weeks of operation at the saveall, the pressure differences were checked frequently and the test section cleaned when the pressure drop (ΔP) exceeded the measurement limit of the manometers. Since slime was being formed relatively rapidly, usually only a few pressure data points were obtained before the manometer limit was exceeded. Later the frequency of cleaning was increased to virtually every mill visit, and this continued until an interval in the last month of the trial resulted in a prolonged period of very scanty slime production. The results of two of the periods when slime formation was fairly rapid plus the scant production period are presented in Fig. 6. It is clear that the test section pressure changes were time-related and certainly of significant magnitude to be easily measured. The wet weight of test section deposits obtained at the end of the first two periods was substantial, as would be expected from the magnitude of the pressure

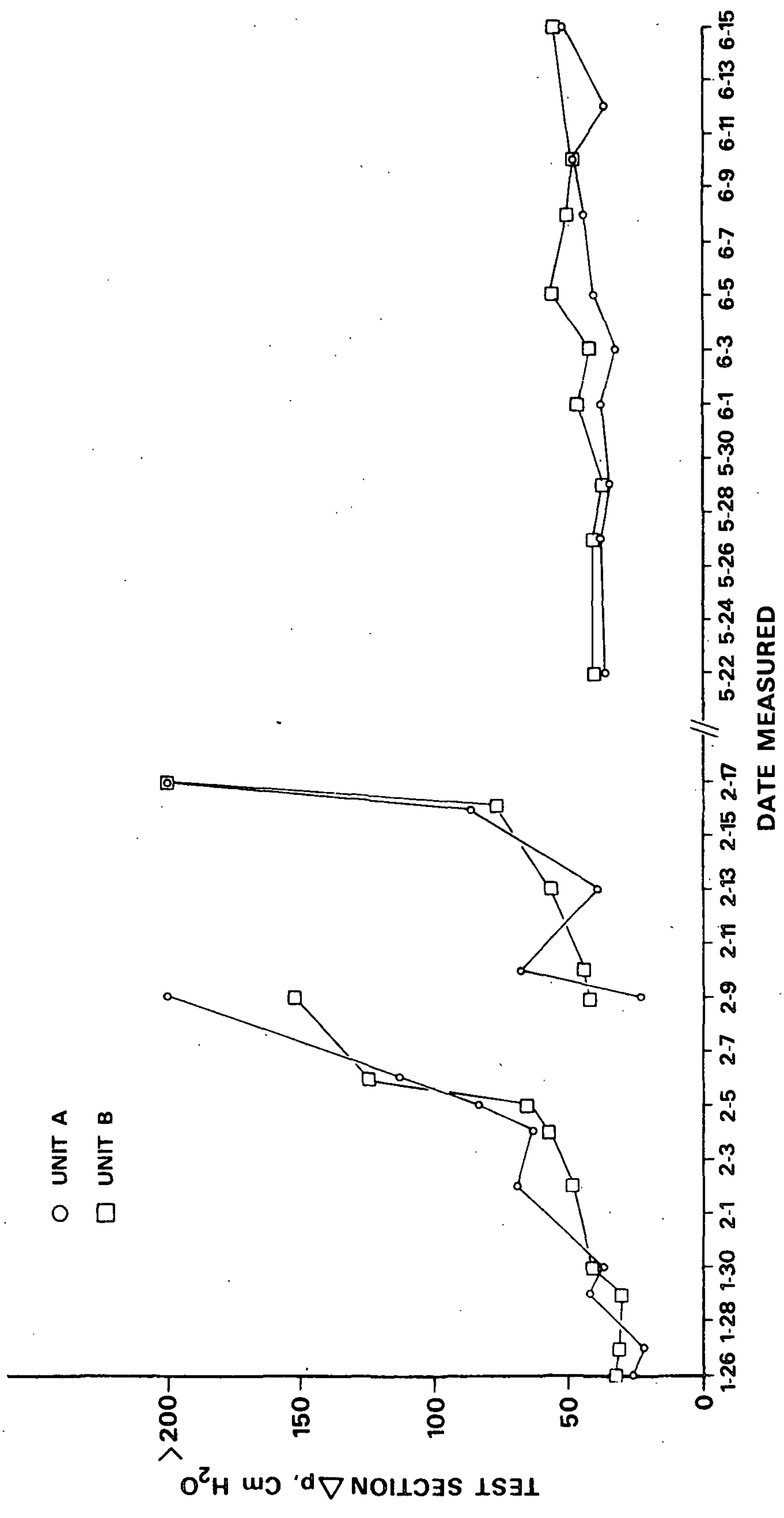


Figure 6. Observed test section pressure differences.

change observed, whereas the third event produced no measurable slime. The value of such test section deposit wet weights to the purposes of the study will be discussed in greater detail later.

Although the data in Fig. 6 show that general agreement existed between the A and B units of the apparatus, it was not possible to obtain smooth curves. Probable causes were the frequent stoppages of the paper machine, plugging of the apparatus by the settling of solids, and a generalized sliming of the entire unit. The addition of an auxiliary tank to provide a continuous flow of fluid in the apparatus during periods when the saveall was drained was considered. However, since fluids do not move continuously within the paper machine system during down periods, the indicated slime release that occurs from nutrient and oxygen starvation during static periods would be part of the real machine condition as well. The settling of solids resulting from reductions in flow velocity as the test section became fouled was strictly an apparatus condition and as flows were adjusted to reestablish the 1.0 m/s condition, undesirable surges occurred as the plugs of solids released. Later, a gentle backwash procedure was instituted using mill fresh water, and thereafter the return to a 1.0 m/s flow became substantially smoother and less likely to disrupt the film. Also, a sanitizing of the apparatus using household bleach corrected the problems that slime buildup throughout the apparatus caused with respect to reduced flow velocity and in manometer reading. The apparatus did not seem unduly sensitive to this extraneous buildup, and sanitizing was required only at about three-week intervals. Additional data on the ΔP values are given in Appendix V.

TEST SECTION DEPOSIT EVALUATION

The cleaning of the test section via the piston device, as described in the methods section, provided a relatively simple means of harvesting the material accumulating on the inner walls of the stainless tubing, an area representing 1.12 square feet. The total wet weight of deposit collected corresponded to the magnitude of the test section ΔP as expected but, of equal importance, the microbiological analysis of those deposits demonstrated that all significant accumulations were typical of a microbiological slime and similiar to that forming on walls and other parts of the saveall. The microbiological analysis involved a microscopic evaluation, a plate count, and - for a number of samples - an adenosine triphosphate (ATP) assay. The bacterial counts were consistently high, with forty-seven of the forty-nine deposit samples that were plated showing bacterial counts in the range of 1-30 x 10^9/mL (Appendix VI). The bacterial numbers estimated by the ATP assay were in general agreement with plate counts, as shown in Table III. The direct microscopic examination of stained and also unstained deposit material confirmed a consistently high level of unicellular bacteria to be present.

TABLE III

COMPARISON OF BACTERIAL CONTENT OF TEST SECTION DEPOSITS
BASED ON PLATING AND ATP ASSAY METHODS

Collection Date	Bacterial Count/mL x 10^9			
	Plate Count		ATP Assay[a]	
	Unit A	Unit B	Unit A	Unit B
3/9	3.8	3.2	9.2	8.0
3/13	4.9	5.6	14	9.7
3/16	18	15	44	16
3/18	8	14	24	24
3/20	12	9.6	24	14
3/25	20	13	17	7
3/30	3.0	1.6	2.3	1.5
4/1	2.2	0.13	5.8	0.88

[a]Based on a 0.5 x 10^{-9} μg ATP/cell content (19).

The microscopic evaluation of the sixteen samples assayed for their ATP content are presented in Table IV. These results are fairly representative of those found for all fifty-eight examinations carried out during the study (Appendix VII). Unicellular bacteria and grit estimates were normally high, whereas the levels of protozoa and filamentous bacteria changed significantly and often rapidly. The reasons for these population shifts were not apparent. Grit in the sample, which appears as small (< 1 µm) optically dense particles, was believed to consist mainly of $CaCO_3$, clay, and silica. Fiber elements observed in the deposits were also small (< 10 µm), generally consisting of ray cell fragments or parenchyma cells with only occasional segments of larger fibers. Overall, these fiber elements were a minor part of the total deposit despite the fact that fiber was a major component of fluid being pumped. This observation is common to most mill slimes; apparently the capture efficiency of large particles by the slime layer is poor.

Several photomicrographs are presented to illustrate the microscopic appearance of the deposits. Figure 7A shows a stained preparation of a glass slide that was submerged for a period in the saveall clear water outflow. It shows the adherent masses of unicellular bacteria plus strands of ensheathed bacteria. The second photomicrograph (Fig. 7B) was taken at low magnification and illustrates the typical cauliflowerlike masses of unicellular bacteria that were observed in test section deposits. Comparisons between saveall and test section deposits formed at the same time were similar with respect to major organism forms. The presence or absence of filamentous bacteria was of particular importance to those comparisons.

The similarity between the bacterial population of the saveall and that in the test section deposits can be seen in the photographs shown in Fig. 8, which are the plate cultures from both saveall fluid and deposit collections made on the same day. Although there has been a shift in dominant type between the saveall fluid and the TS deposits, it is still apparent the same colony forms are present in both samples. Identification of all of the individual types present in the mill system or the deposits was not attempted, since prior experience has conclusively shown the spectrum of organisms having the ability to produce slime is exceedingly broad and problems involving a single type of organism are rare. Therefore, the process of attaching names is seldom productive. The photomicrographs of colony forms presented in Fig. 9 illustrate the diversity in types noted on the plating of test section deposits. The two platings shown were made nearly six weeks apart, and a marked change in organism types between those dates is indicated.

TABLE IV

MICROSCOPIC EXAMINATION OF TEST SECTION DEPOSITS[a]

	Unit A				Unit B			
Date	UB[b]	FB	P	G	UB	FB	P	G
3/9	5+	+	4+	3+	5+	+	4+	3+
3/13	5+	3+	4+	5+	5+	3+	4+	5+
3/16	5+	+	3+	3+	5+	+	3+	3+
3/18	3+	3+	1+	4+	5+	3+	1+	5+
3/20	4+	+	1+	5+	5+	+	1+	5+
3/25	4+	+	4+	5+	3+	+	2+	5+
3/30	3+	+	0	5+	3+	+	2+	5+
4/1	4+	0	0	4+	3+	+	0	4+

[a]Rating scale
0 None
+ Trace
1+ Very few
2+ Few
3+ Moderate
4+ Abundant
5+ Very abundant

[b]Code
UB Unicellular bacteria
FB Filamentous bacteria
P Protozoa
G Grit

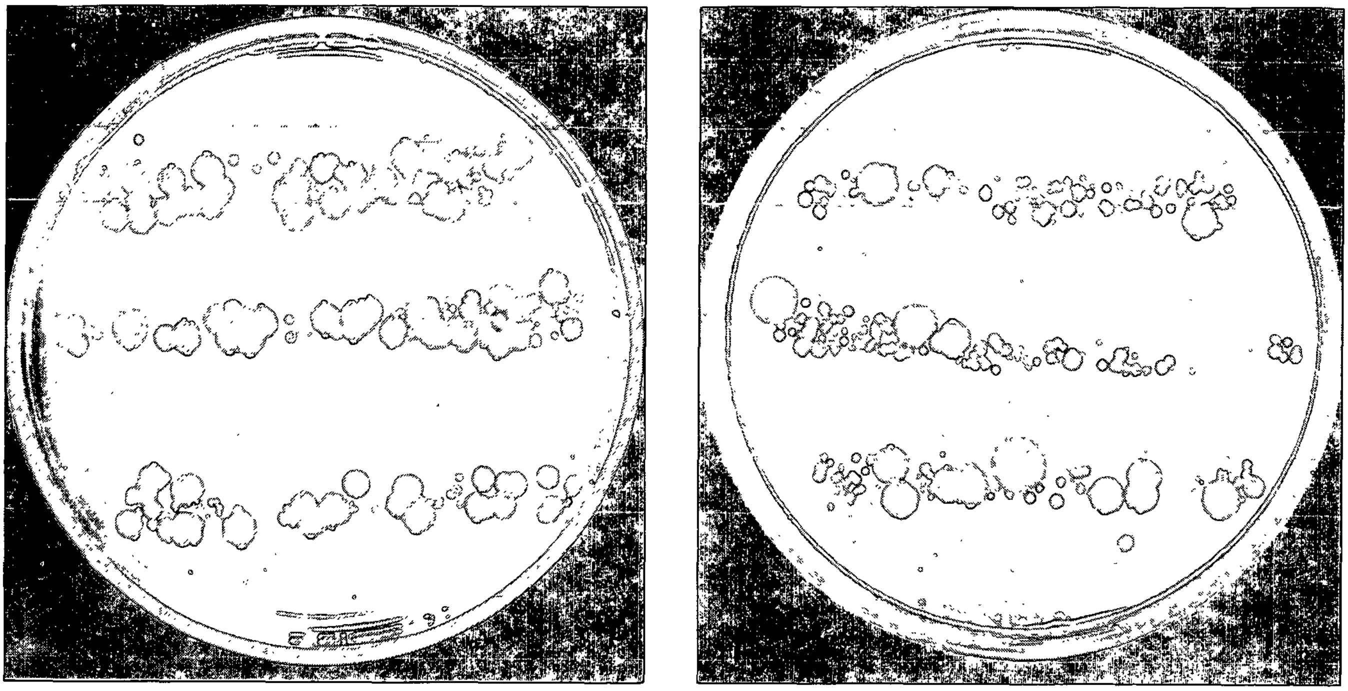
A

B

Figure 7. A - Stained preparation of saveall slime grown in situ. (1000X)
B - Cauliflower appearance of bacterial masses present in test section deposits. (100X)

The solids content of deposits from the test sections was measured when collections were ample. The standard oven dry and ash determinations carried out on the wet deposits provided a general estimate of their organic and inorganic content. Evaluation of these data showed that a high correlation existed between the total solids content of wet slime and its inorganic fraction ($r = 0.98$) but that a similar comparison to its organic component was weak ($r = 0.35$). In effect the organic fraction of all deposits remained relatively constant within a range of 1-5%, whereas the inorganic fraction ranged widely from 0.5 to 16.75%. After observing this correlation between total solids and the inorganic content, several simple checks of the specific gravity of the deposits were made which, as would be expected, also showed a high correlation between inorganic content and specific gravity ($r = 0.96$).

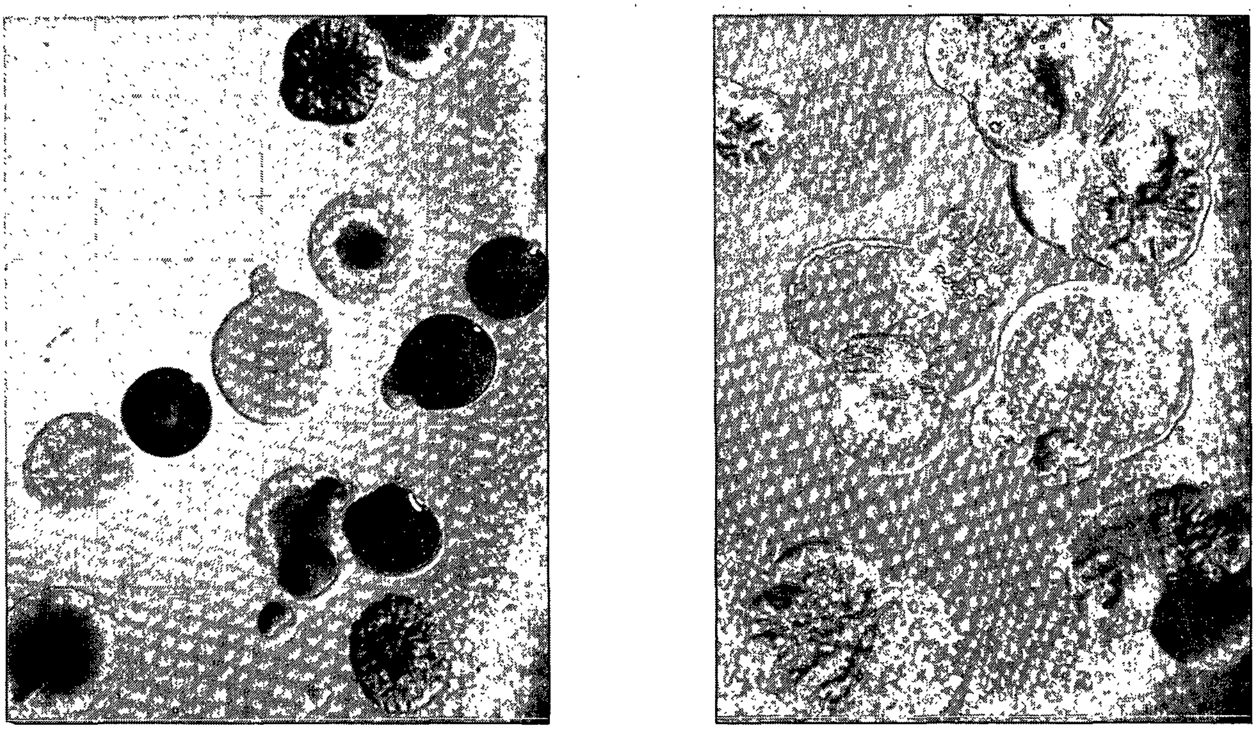
It is apparent that as the deposit became loaded with the more dense inorganic component its specific gravity increased. The specific gravity check gives a quick test for inorganic content, requiring only a few minutes vs. three or four hours for the oven dry-ashing procedure. These data are plotted in Fig. 10 and 11.



A B

Figure 8. Similar colony forms observed in saveall fluid and test section deposits over same time period.

Deposits found to be high in inorganics were long thought to be the result of nonmicrobiological causes. In this mill situation, however, all deposits were found to be typically microbiological, even though the inorganic solids content varied widely. The reasons why some deposits captured greater amounts of grit than others were not apparent, although comparisons via regression analysis were made on such factors as the total quantity of deposit, its rate of formation, the total time over which the deposit formed, or its bacterial content. Also, a relationship could not be found between the inorganic content of the deposit and the relative levels of inorganic material in the fluid being pumped. The effects of changing flow rates on the transport of particles to the tube wall and/or specific properties of the slime film would be high on the list of probable causes.



A B

Figure 9. Colony forms observed is test section deposits formed at differing time periods.

Although values were variable, a typical test section slime deposit would consist of 90-95% water and only 5-10% solids. The solids would be 35% organic and 65% inorganic in makeup, with the bacteria present contributing about 1/5 of the organic material but only 1/100 of the inorganic (Appendix VIII). A similar breakdown of the saveall fluid passing through the unit would show it to be 99.9% water and the solids to be about 50:50 organic-inorganic in makeup. The viable bacteria present would contribute only 1/200 of the organic load and an insignificant 1/2000 of the inorganic. Efforts to establish the relation between the bacterial numbers and either the quantity or rate of deposit buildup were unsuccessful. A difficulty here is that bacterial plate counts detect only viable cells, which represent but a

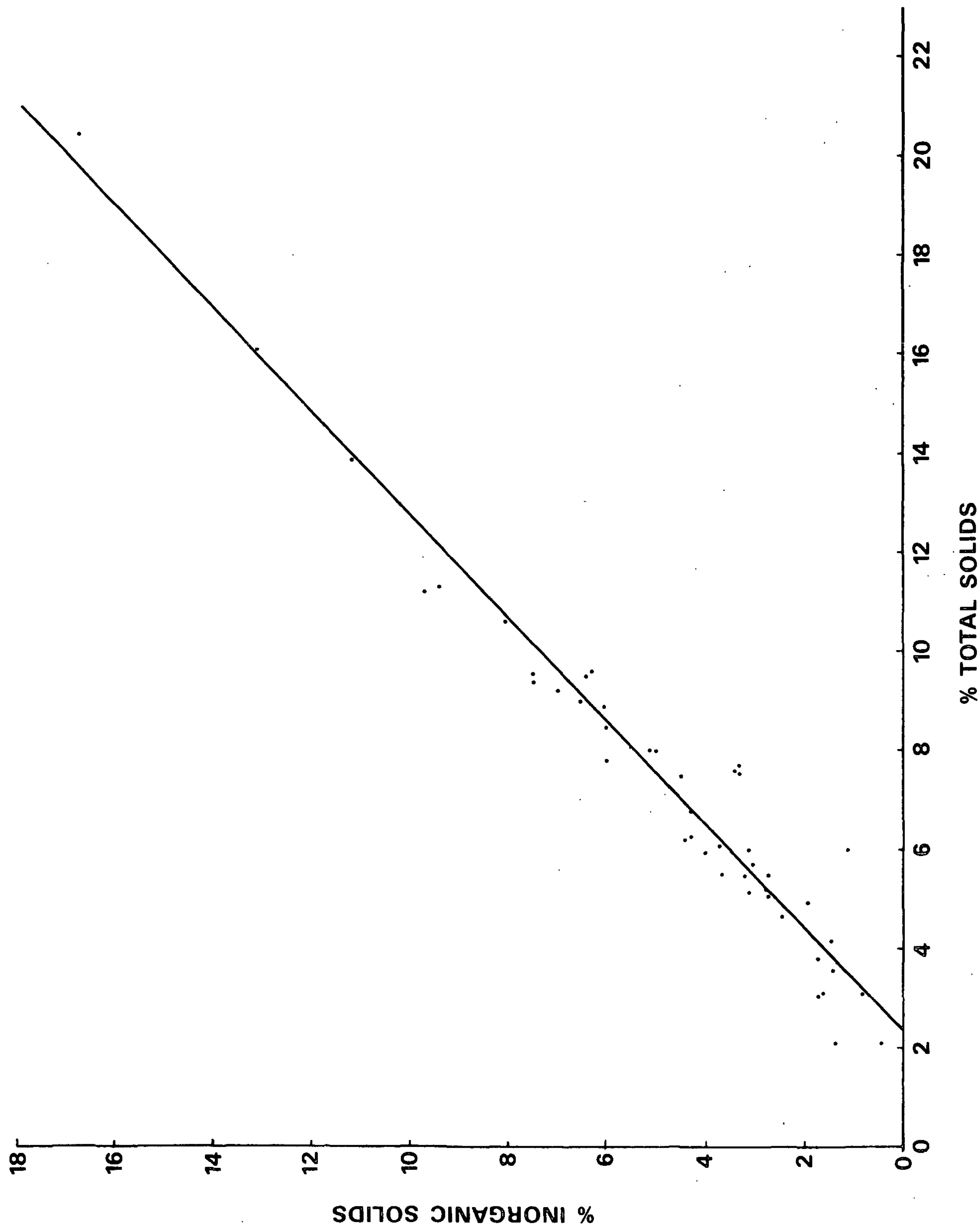


Figure 10. Test section deposit inorganic and total solids relationship [least squares, r = 0.96].

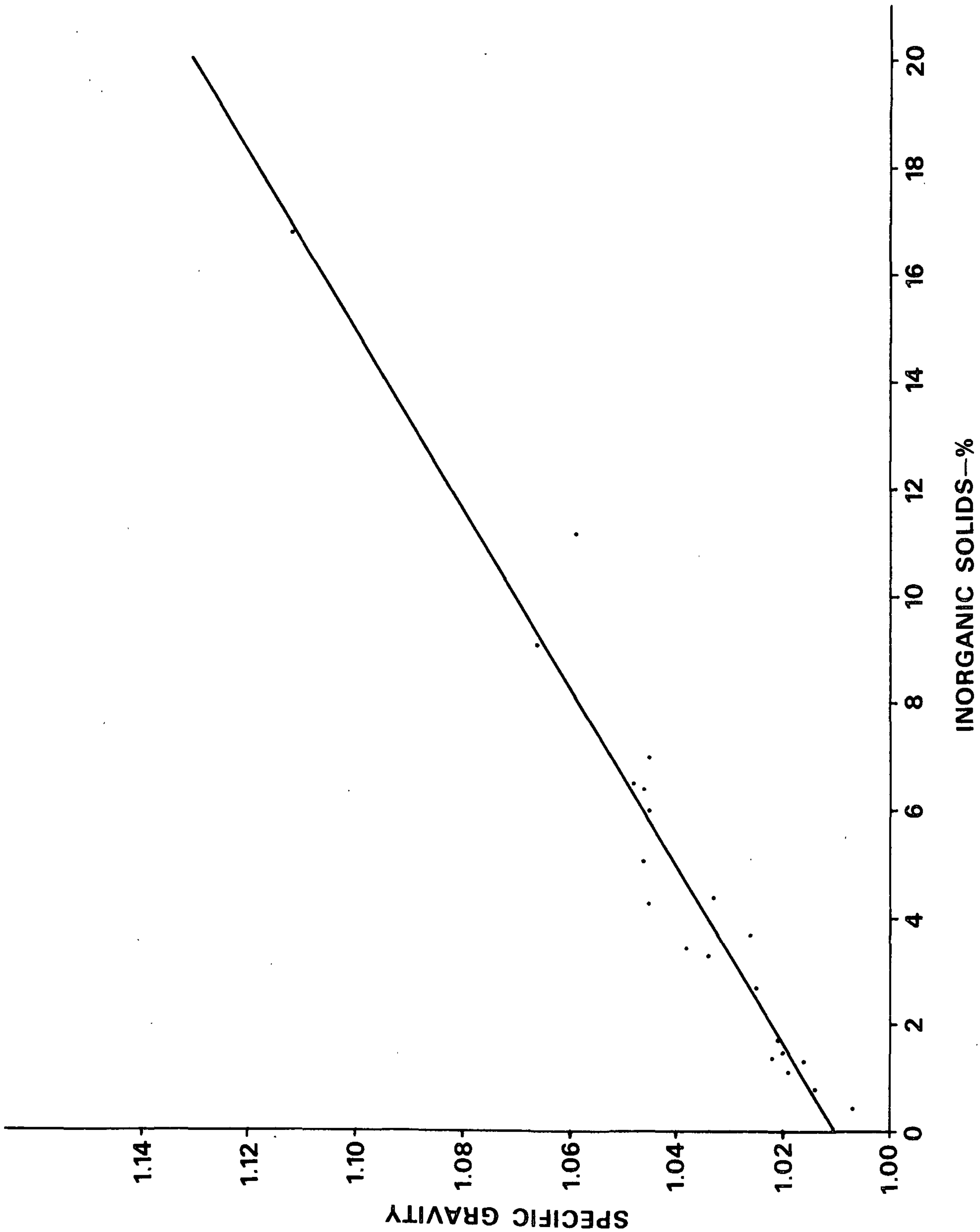


Figure 11. Test section deposit specific gravity and inorganic solids relationship [least squares, r = 0.96].

fraction of the total microbiologically derived material contributing to the deposit. More extensive testing of the deposits would be required to clearly define the relationship between bacterial content and deposit formation.

The relationship between the amount of wet deposit and the increase in pressure drop observed just prior to its collection showed considerable variation but on regression analysis gave an r value of 0.80, which was significant at $P < 0.01\%$ level. If the individual data were grouped according to the weight ranges shown in Table V, a clearer indication of the relationship between Δp and deposit wet weight was obtained. This relationship has been plotted in Fig. 12. The agreement shown by analysis of the grouped data was $r = 0.98$, and the significance was again high ($P < 0.01\%$). The scatter in these data seemed to be a result of the delicate and unstable nature of the deposits. As noted previously, the flow dropped markedly as accumulations increased during the unattended operating periods. Therefore, by the time of collection, the slime film was under considerable stress from low dissolved oxygen and nutrient input. The physical act of draining the test section could cause significant sloughing of the film and resulted in a varying capture of that deposit which had initially produced the manometer reading. Never the less, the observed response was in sufficient agreement to demonstrate that this necessary relationship between slime amount and the pressure drop did indeed exist. Complete wet weight collection data are listed in Appendix IX.

SLIME RATINGS AT PAPER MACHINE AND SAVEALL SITES

After the move of the SF apparatus from the RGT to the machine saveall, it became a routine practice to physically check the amount of slime on the paper machine and the saveall on each mill visit. The use of a number scale to express such opinion data tends to suggest a greater degree of precision than usually exists. A bias/judgment swing of one or even two ranks can easily occur in the absence of any real change. Efforts were made to limit bias in the slime assessment by making all slime ratings before checking the SF unit in order to avoid that potential source of influence. However, the paper machine was examined first, and it is possible that the observation made at the machine site had some effect on the following saveall rating. Also, the form (loose or adherent), texture, and color of the surface deposits changed frequently and affected ratings. Still, despite the subjective limitations, slime ratings over the long-term course of the study proved to be a useful tool.

TABLE V

AVERAGE DEPOSIT WET WEIGHT AND PRESSURE DROP
OVER SELECTED WET WEIGHT RANGES

Wet Weight Range	Wet Weight, g	TS ΔP Increase[a], cmH_2O	n
0-1.25	0.625	3.125	8
1.30-2.5	1.72	6.25	8
2.6-5	3.46	13.8	5
6-10	9.02	43.0	10
11-20	14.4	51.8	10
21-40	32.5	80.8	11
41.80	50.8	151	6

[a]TS ΔP before minus TS ΔP after cleaning and a flow velocity of 1 m/sec.

The pattern shown by the slime ratings indicates that there was general agreement between the two locations. Table VI gives a frequency breakdown of the individual slime rankings (Appendix X) showing the number of ratings that differed between the machine and the saveall. The magnitude of that difference in scale units is also indicated. Seventy-eight percent of all observations were equal or differed by only one scale unit. The frequency with which one site was rated higher than the other or the two were rated equal in slime was very nearly the same. When

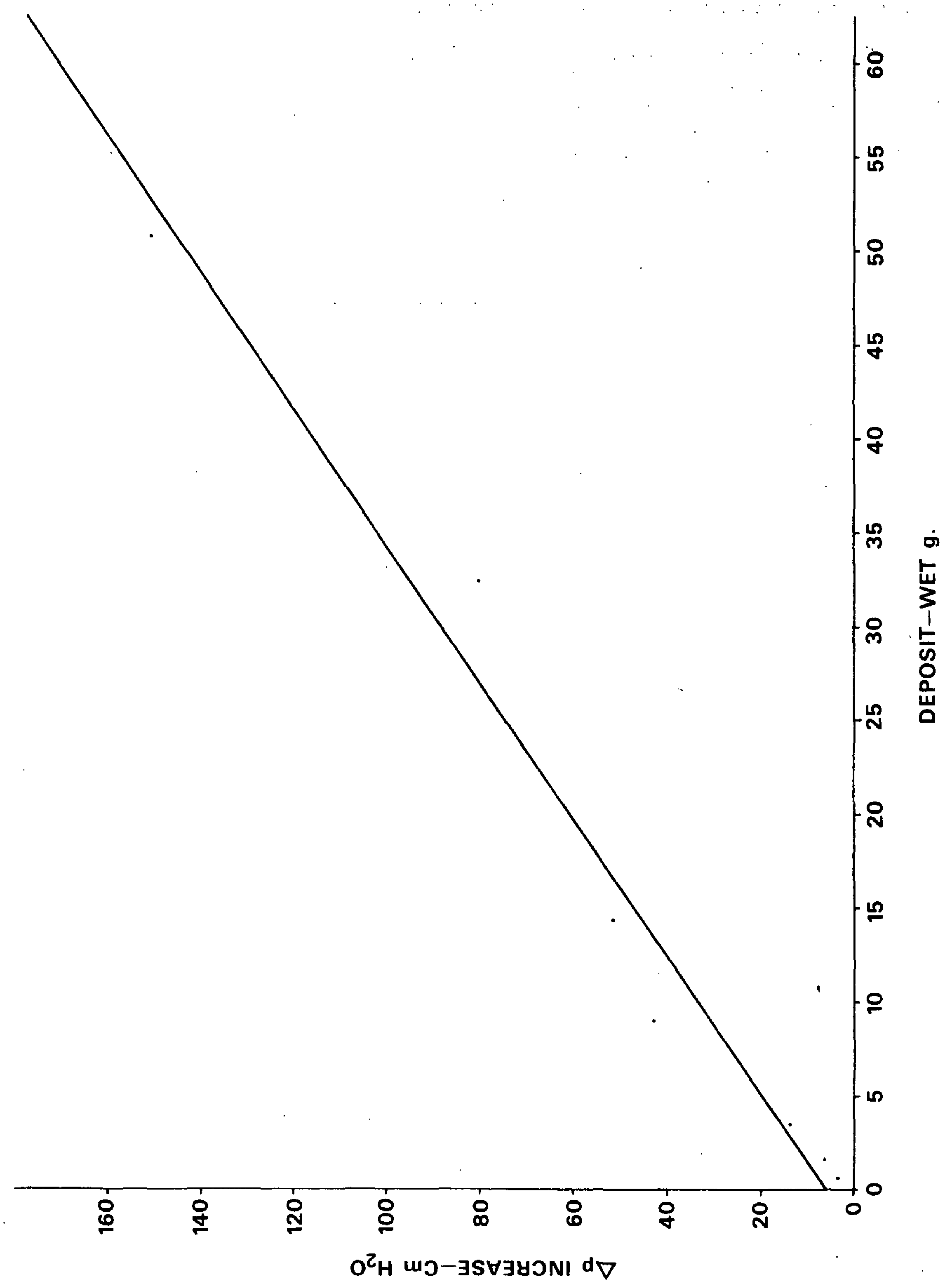


Figure 12. Test section pressure drop and deposite wet weight relationship [least squares, r = 0.98].

large differences between the two sites were noted, i.e., greater than a two-unit spread, it was usually the result of one or the other sites having been hosed down just prior to a visit. This site equivalence is important, since not being able to locate the SF apparatus at the wet end of the paper machine placed the study at some risk of being limited to describing only the saveall condition. Considering that side by side machines, similarly operated, do not always show the same slime-forming tendencies, there is no assurance that all segments of one system must do so.

TABLE VI

DIFFERENCES IN SLIME RATINGS BETWEEN MACHINE AND SAVEALL SITES

Scale Difference	Machine > Saveall	Machine = Saveall	Machine < Saveall
0 unit	--	19	--
1 unit	13	--	16
2 units	5	--	2
3 units	3	--	2
4 units	0	--	1

The relationship of the machine and saveall slime ranking to other measured parameters is considered later.

CHLORINE RESIDUALS

The existence of measurable chlorine residuals in the machine and saveall fluids was not expected initially. The mill consensus was that, considering the small levels of ClO_2 added and the system chlorine demand, it would be unlikely that significant residuals would be carried to the saveall. After observing rather drastic reductions in slime ratings, in bacterial count, and in test section deposits midway in the program, it was learned that a major change had been made in the mill biocide program. These reductions were so marked that checks for available chlorine residuals were instituted at that time and revealed measurable levels did persist into the saveall. Residual tests were subsequently expanded to include the mill freshwater supply and the machine white water. Although the chlorine form applied at the machine was mainly ClO_2, all results of the residual determinations have been computed as Total Available Chlorine.

Similar to slime rankings, the trends shown by chlorine residuals were more revealing than were the individual values found on a given day (Appendix XI). There was general agreement in the residuals found at the saveall and the machine on a given day, with the machine averaging about 15% higher than the saveall. The mill freshwater chlorine residual did not follow the other two values, since it represents a separate chlorine source and dosage. The mill fresh water averaged 0.67 mg/L which was in agreement with their intended residual (0.5-1 mg/L) and less than that being carried in the other fluids. The relationships of the chlorine residual patterns to other measurements are considered later.

BACTERIAL COUNTS

Probably more mills use bacterial numbers as an estimate of their sliming condition than any other assay. The test is relatively easy to perform and does yield an objective number; however, that number does not always correspond to obvious outbreaks of slime or to the production problems that experience has frequently shown to be slime related. Except in the case of a drastic change, the predictive value is poor and often the running of bacterial counts becomes a routine exercise, with little attention given to its output until other events indicate a problem exists. Counts do have real value in following the immediate effects of significant biocide changes.

The total aerobic bacterial content of the saveall fluids was followed throughout the study, with the machine white water also tested over the last 40 days of the study (Appendix XII). The results over this latter period showed no significant difference between the two locations, although the machine count tended to run somewhat lower than that at the saveall. In the main, a high count did not always indicate a high slime-forming condition, but low counts did result when drastic changes in biocide treatment produced a very clean system. These results are presented later,

ADDITIONAL FLUID PROPERTIES AND CONDITIONS

Additional measurements and tests were carried out to define the conditions of the system as opposed to following slime conditions per se. Therefore, on each mill visit measurements were taken of saveall fluid pH, and temperature; color changes also were noted (Appendix XIII). In addition, a substantial number of samples was tested for total solids and suspended solids, and for ash values (Appendix XIV). A comparatively small number of samples was assayed for their nutrient content, which included BOD_5, nitrogen, phosphorus, and sugar levels (Appendix XV). These data have been summarized in Tables VII and VIII.

The data in Table VII show that at an average temperature of 39°C and a pH of 7.6 conditions were nearly ideal for bacterial growth. Furthermore, the range values show these conditions never reached a level that would stress the kinds of microbes common to paper mill systems. The solids data gave a substantial concentration range, with approximately a three fold change from low to high values. Almost one-half of the total solids was made up of dissolved substances, with the majority of these being inorganic. A few suspended solids and pH checks were also made at the machine and differed little from equivalent samples taken at the saveall.

TABLE VII

SUMMARY OF TEMPERATURE, pH, AND SOLIDS AT THE SAVEALL

Criteria	$\bar{x}$	Range
pH	7.6	7.1-8.4
Temperature	39°C	24-45°C
Total solids	1850 mg/L	1025-3350 mg/L
Organic	42%	--
Inorganic	58%	--
Suspended solids	995 mg/L	500-1800 mg/L
Organic	50%	--
Inorganic	50%	--
Dissolved solids	855 mg/L	525-1550 mg/L
Organic	33%	--
Inorganic	67%	--

TABLE VIII

SUMMARY OF NUTRIENT CONTENT OF SAVEALL FLUIDS

Component	Mean, mg/L	Range, mg/L
BOD_5	356	220-631
Filtered[a]	146	57-338
TKN	3.21	2.12-4.15
Filtered[a]	1.81	1.44-2.15
Orthophosphate	0.139	0.014-0.336
Sugars[b]	79.3	57.2-126.3

[a]0.45 μM membrane.

[b]

Sugar type	%
Glucose	68.2
Xylose	24.7
Arabanose	2.4
Galactose	2.2
Mannose	1.3
Rhamnose	1.1
Fucose	0.1

The averaged nutrient values presented in Table VIII show that the BOD_5 was not exceedingly high (356 mg/L); however, it was ample to support substantial bacterial growth. Since the phosphorus and sugar tests were carried out on filtered samples, the same treatment was given to several of the BOD and nitrogen samples. The marked decrease in the BOD_5 and TKN values after filtration (39 and 57%, respectively) suggests that the phosphorus and sugar values, which require filtration, probably are an underestimate of their true levels in the saveall as well. This association between nutrients and solids in mill fluids is in agreement with what has been observed in primary clarifiers in terms of BOD_5 reduction after solids removal (20).

A BOD_5:nitrogen:phosphorus ratio of 100:5:1 is considered to be an effective nutrient balance for effluent treatment processes. The saveall fluid assays indicate a ratio of 100:1.2:0.1, suggesting that the in-mill fluids are first phosphorus and then nitrogen limited. The sugar analysis indicates that this component represents only about one-third of the total BOD_5 found in the saveall fluid. Glucose (68%) was the predominant sugar, followed by xylose (25%). Other sugars were a minor part of the nutrient picture. The sugar pattern found was quite different from that noted in several other mills. A fine paper mill reported levels of 70% mannose and 30% glucose, whereas a kraft mill found 66% xylose, 13% mannose, 12% galactose, and 16% glucuronic acid. The reasons for the high glucose level in this system are not known but, in part, could be due to starch used as internal sizing and in coating that returns to the system via the broke.

Again, although the nutrient content is certainly important to the extent of microbial growth in the wet-end of a paper machine, the main function of these measurements was to help define this particular system. The relationship between nutrient types or levels and slime formation is not sufficiently developed to allow judgments to be made as to the significance of the values found. It is hoped, however, that as this body of information increases it will prove useful to such understanding.

SLIME POTENTIAL COMPARISONS

To provide a common base for comparison, five of the criteria having the greatest bearing on the microbiological status of the system were ranked as to their indication of "slime potential." The selected criteria were (1) pressure drop across the test section, (2) test section wet deposit weight, (3) slime rating at the saveall, (4) bacterial count at the saveall, and (5) chlorine residual at the saveall. A five-point ranking scale was used, with the upper and lower extremes of each data group establishing the high and low slime potential rank. Although the assignment of intermediate rankings was essentially arbitrary, the uppermost and lowest levels, which are the most signficant to these comparisons, were in general agreement with periods when films formed rapidly and abundantly and when slime growth was absolutely nil. A high ranking of slime potential, therefore, is a valid indication that the system is at <u>risk</u> of encountering slime difficulties, even though machine problems are absent, whereas, at a low ranking there would be no significant risk of a microbiological problem.

The test section pressure drop and the wet weight values were considered from two points of view; first, as total pressure change or weight collection on a given reading date and, second, as the amount of pressure change or weight gain per unit time for the interval covered between readings. Since readings were made at substantially differing intervals depending on how rapidly the accumulation formed, the average increase per unit of time plotted over the interval involved gave the best illustration of the level of fouling for these comparisons. The ranges established for each rank are given in Table IX for each of the five selected categories.

Figure 13 shows the data plots; shaded areas represent periods when the slime potential ranking was above the average for that data group.

TABLE IX

SLIME POTENTIAL RANKING VALUES

	Low	Medium Low	Medium	Medium High	High	Values In
Test section ΔP	1-2	3-4	5-6	7-8	>9	cm H_2O/day
Deposit wet weight	0	1	2-3	4-7	>8	g/ft^2/day
Saveall slime	0+	1+	2+	3+	4-5+	Scale rank
Saveall bacterial count	10^3	10^4	10^5	10^6	10^7	Bacteria/mL
Total available chlorine	>1	0.75-1	0.5-0.75	0.25-0.5	0-0.25	mg/L

Rapid changes were observed in all data groups, with much of the roughness in the data caused by machine and/or SF unit outages disrupting the continuity of the readings. However, the general pattern of response by these five groups shows that the overall study period could be broken into five time segments. The first segment ran from the initiation of the study in January to about the middle of March and, in the main, was a time conducive to slime formation. The second period, covering the last week of March and the first week of April, was a period of very low slime growth. The third interval was another potential slime-forming interval and ran from about mid-April through the first week of May. The fourth period began the second week of May and continued until the middle of June, during which the system became exceptionally clean as indicated by all data groups. The fifth interval was a brief high slime potential period during the third week in June; shortly thereafter the unit was disconnected.

Figure 14 gives the clearest representation of these five time intervals and was obtained by averaging the five data groups. The outline of the pressure

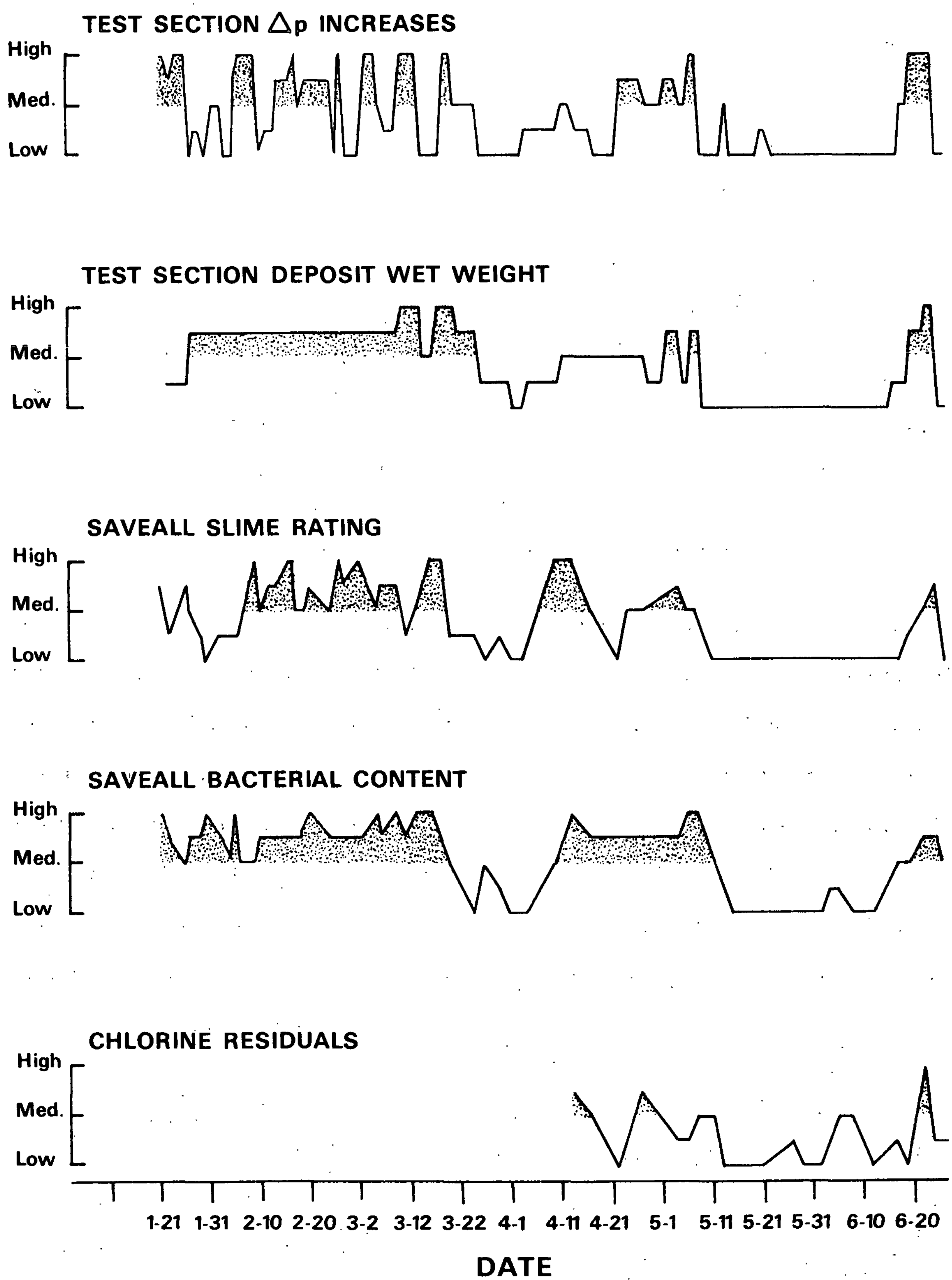


Figure 13. Slime potential comparisons.

drop slime potential curve has been superimposed on the averaged plot. It can be seen that it followed the averaged results quite well and certainly better than its 20-25% contribution to that average would permit.

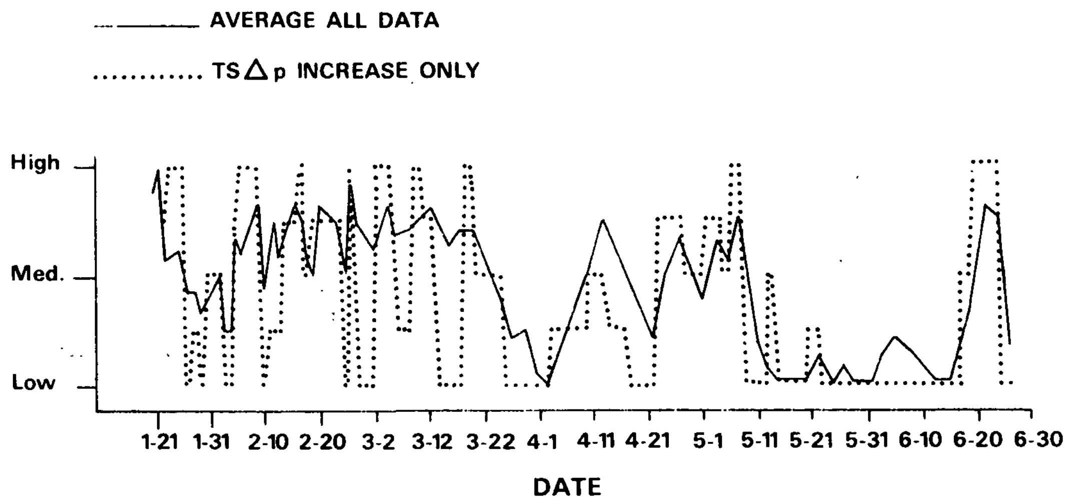


Figure 14. Slime potential average.

Significant to the two low-slime potential periods were changes made in the chlorine dioxide addition program at the mill. On March 27, after noting the first sudden drop in slime formation, the mill was contacted as to possible reasons for this rapid change. We were informed that the ClO_2 program had just been changed from the prior 15-minute addition period every two hours to a 30-minute addition every hour. Although a decrease in the ClO_2 concentration being fed had been made to compensate for the four fold increase in application time, it was not certain at the time what the amount of ClO_2 dosed actually was, since it required some operating time to obtain an accurate estimate of their sodium chlorite consumption.

The second episode of low slime formation that began in May was even more pronounced than the first and persisted much longer. Again, inquiries revealed that another change in the ClO_2 program had been made. The addition of ClO_2 had been put on a continuous basis, and again a reduction in the concentration being fed had been made to compensate for the doubling in feed time and to hold treatment costs level.

Adding high levels for short periods caused problems in color control due to the bleaching effect of the ClO_2. Their prior experience with chlorine indicated that they could achieve good biological control with a lower dosage over a longer period and, in turn, reduce the color problems. Our test results strongly confirmed the mill position that good control would be possible with continuous feeding. The system became so clean that after several weeks it began to seem futile to continue to operate the SF unit at that location. Fortunately, however, a final period of slime was encountered before the SF unit was disconnected.

MILL INFORMATION

It is usually difficult to obtain good corroborative evidence as to the presence of slime from machine performance data unless the slime situation is totally out of hand. During this study machine difficulties that may have been due partly to slime were confounded by the relatively high number of mechanical glitches that resulted from the rebuild. For example, the high hole count data obtained over the early weeks were attributed to openings and small seam burrs in the new headbox, and these required several polishing sessions. However, the fiber hang up problems these burrs caused are known to be accentuated by microbiological growth that prefers a rough site for its attachment.

The calendar of events presented in Table X was provided by the mill technical department and shows the changes made in biocide feeds along with notations of their observations on headbox slime. The marked reductions in the biological slime indicators that occurred after the two changes in the feed program on 3/20/81 and on 5/7/81 have been discussed. The return of slime after the 3/20/81 change resulted from a decrease in ClO_2 concentration caused by a downward drift of the feed pump output. Subsequently the presence of slime in the headbox on 4/15/81 brought about an upward adjustment of the $NaClO_2$ solution feed. Also, the shift to a new intermittent feed program made on 5/4/81 was in response to a slime condition noted in the headbox; however, this change resulted in a substantial reduction in the total amount of $NaClO_2$ solution fed per day from nearly ten gallons to less than three. A high slime indication via the pressure drop measurement was evident during this low feed period. The low feed was sustained only a few days before a pump change was made that marked the initiation of the continuous feed program which ultimately produced a dramatic improvement in slime conditions in late May and early June. All headbox slime observations occurred at points when the overall slime potential rating was above its estimated mid-range.

TABLE X

MILL CALENDAR OF BIOCIDE FEEDS

Date	Program on/off (min)	$NaClO_2$ Feed (cc/min)[a]	$NaClO_2$ (gal/D)	Headbox Slime
2/16/81	15/105	230	10.9	--
3/20/81	30/30	44	8.4	--
4/15/81	30/30	31 —> 57[b]	4.9 —> 10.8	Present
4/28/81	30/30	39 —> 54	7.4 —> 10.3	--
5/4/81	45/315	54	2.6	Present
5/5/81	45/315	62	2.9	--
5/6/81	45/315	120 —> 50	5.7 —> 2.4	--
5/7/81	Continuous	27	10.3	--
5/8/81	Continuous	30 —> 28	11.4 —> 10.6	—
5/15/81	Continuous	29 —> 24	11.0 —> 9.1	--
6/18/81	Continuous	27	10.3	Present[c]
6/23/81	Continuous	50 —> 32	19.0 —> 12.2	--

[a] cc/min x 0.0128 = mg/L ClO_2 concentration estimate.
[b] —> Feed adjusted.
[c] Primarily fiber.

EVALUATION OF MEASUREMENT PROCEDURES

The total results of these six months of intensive in-mill work point to a preference for the use of the pressure drop measurement to follow the status of slime formation in a mill system over all others. Despite the difficulties imposed by the size of the unit, its off-machine location, and the frequent interruptions involved, it still showed that its potential for sensing a developing slime condition promptly and objectively was superior to plate count, chemical residual, or slime ranking procedures. Many of the difficulties encountered could be eliminated by appropriate design changes and would further increase its usefulness, as described later. However, the most important asset of such a unit is that pressure drop can measure those conditions which ultimately cause machine problems and that it does so on a continuous and nonintrusive basis. That statement does not apply to any of the other available measurements.

The collection and measurement of the wet deposits from the test section of the apparatus corresponds most closely with the use of the so-called "slime boards" that have not found great acceptance in the paper industry. Still, some form of deposit collection would be a valuable adjunct to the use of a pressure drop measurement, primarily because the solids permit microscopic verification of the type of deposit present. Furthermore, cleaning is a necessary procedure whenever the pressure drop change exceeds the capacity of the manometer system or should total blockage occur. On a routine basis, however, collecting the deposit is disruptive and introduces a lag period as the film reestablishes itself. It was also time consuming in that considerable disassembly and reconnection of hoses, orifice units, and the test section tubes were required. The drainage of fluid from the test section in some instances caused a significant amount of slime release, and those portions of the film were lost. The rate of film formation, which is certainly of prime importance, was easier and probably more accurately shown by the pressure drop measurement than the deposit wet weight determinations.

Slime rankings derived from the physical examination of both the paper machine and the saveall were certainly the easiest to perform of all the film assessment techniques, but the accessability of the chosen areas meant they were also cleaned during any hose down of these units. This in effect was a zero reset and would take place at unspecified times. Another definite drawback to this evaluation is its subjective nature. Although numbers are used, it is still opinion data and suffers a variety of prejudices, such as the well-recognized tendency to save space at the ends of the scale in the event the next observation should require it. With different individuals carrying out the ranking it becomes even more difficult to achieve consistency. An objective measurement is certain to be preferred.

The determination of bacterial count in various locations about the mill is a widely practiced slime assessment procedure. It is a relatively simple test to perform, but the results are not easy to interpret. The agreement found in this study was quite good, especially during the two periods when the accumulation of slime was exceptionally low. However, it was also found that all significant deposits in this system were typically microbiological in makeup. If a chemical deposit had formed, a low bacterial count would have proved misleading. Without a confirming deposit analysis a high count can also lead to incorrect assessment of conditions, since there is no certainty that the free-flowing bacterial population measured by this test will be directly related to the attached population that is of greatest concern.

The fifth measurement used in this study, chlorine residuals, would not be an option in the many mills that use one of the other chemical agents applied for slime control. The routine analysis of mill fluids for those products is rarely, if ever, practiced due to cost, complexity, or inability to detect the low dosages applied. Furthermore, the acceptance of a chemical residual as a guarantee of the degree of biological control being realized can be totally in error due to the ability of microbial populations to adjust to a given toxic environment. Judging the adequacy of microbe control solely on the basis of a chemical test would be a questionable practice in most paper mill systems.

IMPROVEMENT OF APPARATUS DESIGN

The large size of the current unit was a major disadvantage, not only because size prevented operation near the wet-end of the machine, but also because of the routine operation and maintenance problems that it presented. If such a pressure-sensing device is to gain mill acceptance as a slime control tool, it will be necessary to miniaturize the unit as much as possible. The ten-foot rigid test section tube could be changed to a form of flexible tubing that would be lightweight and could be coiled to reduce overall length. The tubing would be weighed before and after use to measure accumulated solids. These solids would be available for additional analysis if needed, but the tubing would then be discarded rather than cleaned.

A pump change would also be needed. A self-priming type would be preferred over the centrifugal form used. Unfortunately, particulate-containing fluids present problems for most self-priming pump types. If absolutely necessary, a reservoir could be included to avoid priming problems, but this would increase the overall size. The pump should be as small as possible to provide a flow velocity through the test section of at least one meter per second, even with substantial fouling.

Probably one of the most significant changes to improve the data output would be the introduction of a reliable form of continuous automatic flow control.

Under the current design, the established test section flow of one meter per second decreased steadily as the degree of fouling increased. The flow was frequently reduced to a mere trickle by the time of the next mill visit and reading period. Boosting the flow back to 1 m/s for pressure checks could dislodge portions of the biofilm and give erratic results. Occasionally, the flow reduction allowed fiber settling to an extent that produced blockages which could only be removed by back-washing. A continuous sensing and maintenance of flow would certainly improve the consistency of the pressure drop output in this regard.

Another shortcoming of the current model was that the increase in pressure drop could not be followed during relatively long periods when the unit was unattended. In the laboratory, where a closer watch could be maintained over the periods of film development a more complete picture of the change in pressure over time was obtained, as shown in Fig. 15. In the mill system the point of greatest concern in biofilm formation is that at which the film begins to slough and thereby release disruptive clots into the process streams. The addition of a continuous pressure sensing and recording system, along with the appropriate signal feedback to adjust and maintain flow would give a clear indication of the rate at which the deposits were forming and the point at which significant release of the slime film took place. It would also provide a more compact system of measuring pressure changes and thus reduce the size of the unit by eliminating the bulky manometers from the current design.

Finally, attention should be given throughout the design to aid in keeping the unit clean and to provide for occasional sanitizing operations. The use of fittings, orifices, or sharp angles that encourage fiber accumulations and other buildups must be avoided. Since occasional disassembly will still be required, a more simple and rapid method for the disconnection of parts would be required.

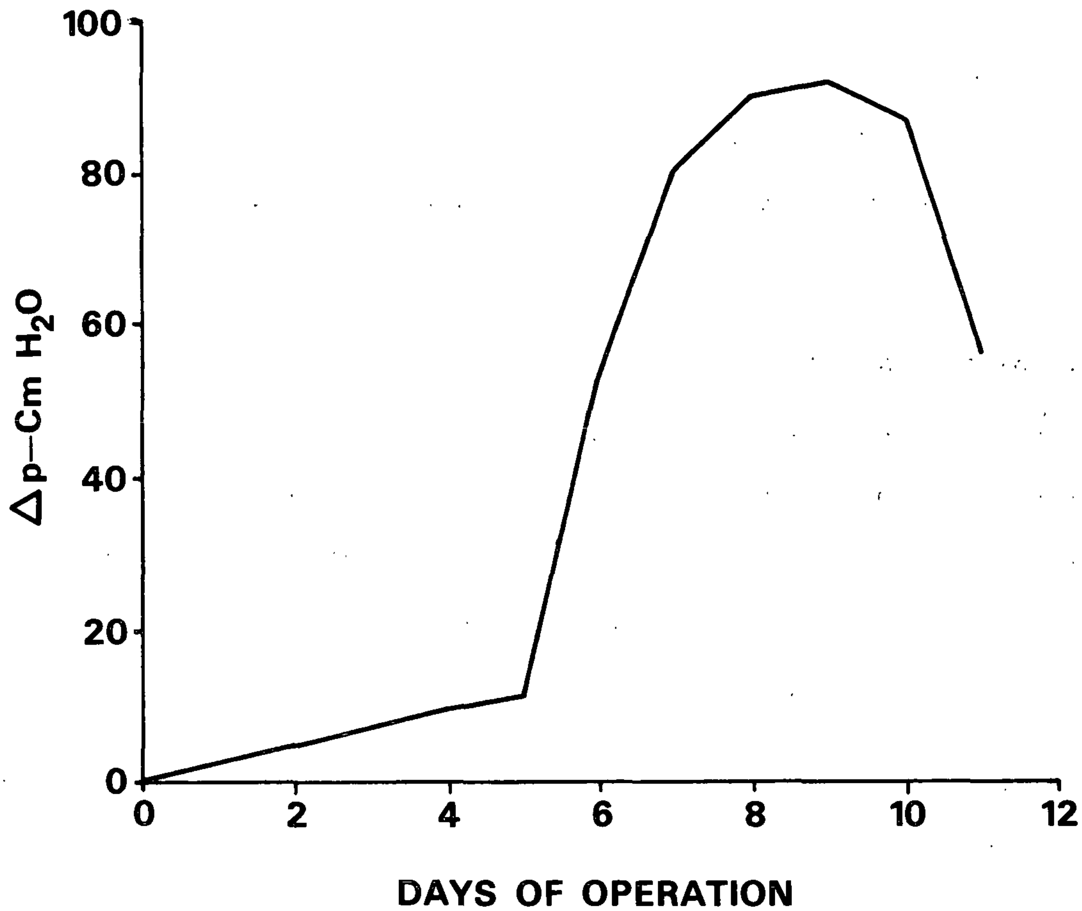


Figure 15. Pressure changes obtained in laboratory unit.

CONCLUSIONS

The measurement of pressure drop across a length of tubing carrying mill fluids is responsive to the extent of microbiological fouling taking place in that tube and, in turn, is indicative of the slime-forming conditions within the machine system.

Agreement between the pressure drop responses shown by the SF unit and periods of low slime formation in the mill system was very good. Agreement between the pressure drop responses shown by the SF unit and those periods when slime formation in the mill system was rapid was acceptable but with appropriate design changes could be improved. Adding automated flow control and continuous pressure drop monitoring capability to the SF unit would be required.

All significant deposit collections observed during the saveall study were typical of microbiological slimes. The amount of small inorganic particles, such as clay or $CaCO_3$, that became entrained in the deposits varied markedly, whereas the organic fraction remained quite constant. A high inorganic content, therefore, did not indicate a nonbiological form of deposit. A specific gravity test was found to give a quick estimate of the amount of entrained inorganic matter in a deposit.

The pH, temperature, and nutrient conditions of the paper machine system studied were highly favorable for microbial growth, and measurements that were related to that activity, such as bacterial counts, did follow the general pattern of slime development in the system. However, the actual measurement of the slime film buildup via the pressure drop technique was equally sensitive and considered fundamentally superior to the other procedures.

FUTURE WORK

The paper industry has been paying a substantial penalty in losses and control costs for in-mill slime problems over many years. Furthermore, in virtually every situation where additional closure of the paper machine system has been instituted, those problems have increased. Although these facts are widely known, there appears to be little movement toward introducing internal procedures that would improve the mills' own capacity to assess and control their slime deposits. Heavy reliance continues to be placed on the biocide suppliers to provide both the monitoring and the control services that the mill requires. It would be to the industry's best interest to accept a greater share of the responsibility in this area.

This study has demonstrated the potential of the pressure drop measurement to detect and monitor slime deposit formation in a paper mill system. Extending that work to other mills would further define how that information can be used to improve control. However, a full realization of the usefulness of a pressure drop sensing unit will require significant changes in the apparatus design. A marked reduction in size is highly desirable, plus the addition of automatic flow control and data recording capability.

In addition to the in-mill needs and goals, there is an equally important role for this type of tool in the laboratory. The mill study has not only confirmed the validity of this type unit for slime studies, but also provided needed information as to the operating parameters that can be used to establish and maintain a slime within the laboratory environment. The high state of flux in the mill situation makes it very difficult to understand the whys and wherefores of observed events. Under laboratory control the effects of particle concentration, presence or absence of surfactants, organism types, etc., can be controlled or observed and related to the amounts of inorganic materials being incorporated into the deposit.

Many similar questions exist that cannot be adequately addressed in the mill system per se. Future work will center on laboratory simulation of in-plant conditions and problems. Solutions to these problems will be sought.

ACKNOWLEDGMENTS

The cooperation of the Appleton Paper Inc. and especially of the following members of Locks Mill Technical Group was essential to the success of the work that was carried out: Jim Beatty, Ted Nelson, Douglas Osterberg, Harry Willemsen, and Wally Morrow. Bruce Andrews of the Institute staff produced much of the original apparatus design, and Eugene Zanella contributed both his administrative support and technical backup at the mill.

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THE INSTITUTE OF PAPER CHEMISTRY

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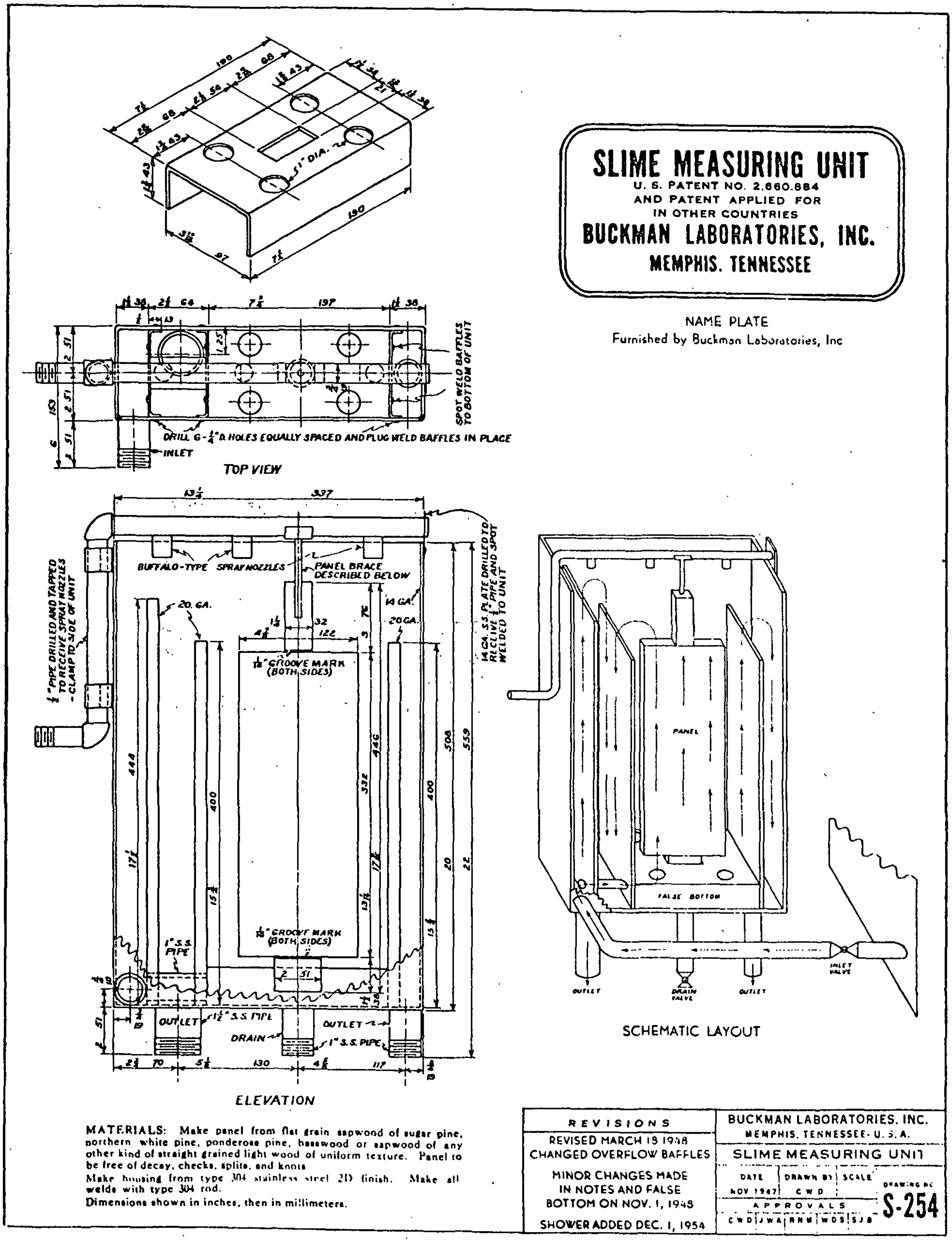
APPENDIX I


SLIME MEASURING UNIT
U. S. PATENT NO. 2,660,884
AND PATENT APPLIED FOR
IN OTHER COUNTRIES
BUCKMAN LABORATORIES, INC.
MEMPHIS, TENNESSEE
NAME PLATE
Furnished by Buckman Laboratories, Inc
SPOT WELD BAFFLES TO BOTTOM OF UNIT
DRILL 6-1/2" D. HOLES EQUALLY SPACED AND PLUG WELD BAFFLES IN PLACE
INLET
TOP VIEW
BUFFALO-TYPE SPRAY NOZZLES
PANEL BRACE DESCRIBED BELOW
20 GA.
14 GA.
1/16" GROOVE MARK (BOTH SIDES)
1/2" PIPE DRILLED AND TAPPED TO RECEIVE SPRAY NOZZLES - CLAMP TO SIDE OF UNIT
14 GA. S.S. PLATE DRILLED TO RECEIVE 1/2" PIPE AND SPOT WELDED TO UNIT
1" S.S. PIPE
OUTLET
1 1/2" S.S. PIPE
DRAIN
1" S.S. PIPE
ELEVATION
PANEL
FALSE BOTTOM
OUTLET
DRAIN VALVE
INLET VALVE
SCHEMATIC LAYOUT
MATERIALS: Make panel from flat grain sapwood of sugar pine, northern white pine, ponderosa pine, basswood or sapwood of any other kind of straight grained light wood of uniform texture. Panel to be free of decay, checks, splits, and knots.
Make housing from type 304 stainless steel 2D finish. Make all welds with type 304 rod.
Dimensions shown in inches, then in millimeters.
REVISIONS
REVISED MARCH 18 1948 CHANGED OVERFLOW BAFFLES
MINOR CHANGES MADE IN NOTES AND FALSE BOTTOM ON NOV. 1, 1948
SHOWER ADDED DEC. 1, 1954
BUCKMAN LABORATORIES, INC.
MEMPHIS, TENNESSEE - U. S. A.
SLIME MEASURING UNIT
DATE NOV 1947
DRAWN BY C W D
SCALE
APPROVALS
DRAWING NO. S-254

APPENDIX II

RICH GATHERING TANK DATA

Date	Temp., °C	pH	Total Solids o.d.	Total Solids Ash	Suspended Solids o.d.	Suspended Solids Ash	Residual Cl_2-mg/L	Bacteria/mL
5/28/80	38	6.0	668	527	40	10	--	< 1000
5/30/80	39	6.8	720	420	140	60	--	< 1000
6/02/80	38	6.8	723	422	180	60	--	57
6/04/80	38	6.7	543	382	30	10	2.10	3
6/06/80	38	6.5	644	402	80	40	1.04	1000
6/09/80	38	6.6	883	783	80	60	0.35	230
6/11/80	38	6.7	644	382	80	40	0.71	76
6/20/80	38	6.8	603	482	60	30	4.25	< 1
6/23/80	38	7.1	673	478	27	20	2.48	< 1
6/25/80	44	6.9	583	382	30	10	2.13	9
6/27/80	41	6.9	845	463	100	40	1.06	440
6/30/80	40	7.0	685	403	100	60	0.35	2100
7/02/80	39	6.9	--	--	--	--	0.35	--
7/07/80	38	7.0	--	--	--	--	0.23	--
7/09/80	42	7.1	--	--	--	--	0.00	--
7/11/80	44	6.9	--	--	--	--	0.00	--
7/14/80	45	6.8	--	--	--	--	0.19	--
7/15/80	44	6.8	--	--	--	--	0.13	--
7/18/80	42	--	--	--	--	--	0.10	--
7/21/80	44	7.1	--	--	--	--	0.00	--
7/23/80	41	--	--	--	--	--	0.10	--
7/25/80	40	7.3	--	--	--	--	0.09	--
7/28/80	36	7.3	--	--	--	--	0.18	74×10^3
7/30/80	37	7.2	--	--	--	--	0.00	39×10^4
8/01/80	40	7.3	--	--	--	--	0.00	--
8/04/80	40	7.1	--	--	--	--	0.00	46×10^6
8/06/80	39	7.1	--	--	--	--	0.38	62×10^5
8/08/80	36	7.5	--	--	--	--	0.00	22×10^6
8/11/80	37	7.5	--	--	--	--	0.00	84×10^5
8/13/80	36	7.7	--	--	--	--	0.12	16×10^6

APPENDIX III

HOLE COUNTER AND RUN CLOCK DATA

Date	Hole Count Register A	Run Clock, hr	Read Time	Date	Hole Count Register A	Run Clock, hr	Read Time
1/23	6042	--	(11:00)	4/1	9028	1118.1	11:05
1/26	6184	--	--	4/3	9121	1163.2	11:05
1/27	6260	--	--	4/8	9348	1274.8	11:00
1/29	9762	190.2	--	4/10	9403	1317.3	10:55
1/30	9918	214.3	--	4/13	9530	1387.1	11:10
2/2	0415	285.0	--	4/15	9575	1432.4	8:40
2/3	0473	Clock failed	--	4/17	9618	1478.2	9:45
2/4	0616	Clock failed	--	4/20	9659	1512.8	8:40
2/5	0746	Clock failed	--	4/22	9701	1532.7	11:30
2/6	0936	Clock failed	--	4/24	9745	1576.1	8:50
2/9	1284	Clock failed	--	4/27	9891	1643.8	8:35
2/10	1505	0.0	--	4/29	9939	1686.7	8:45
2/11	2938	19.1	--	5/1	9958	1725.0	8:50
2/12	2990	38.8	--	5/4	0071	1792.6	11:25
2/13	3024	62.3	--	5/6	0115	1836.3	8:35
2/16	3494	134.3	--	5/8	0162	1883.0	8:40
2/17	4582	153.7	--	5/11	0319	1952.8	8:40
2/18	4646	177.5	10:50	5/13	0360	2000.0	8:35
2/19	4754	201.3	11:05	5/14	--	2024.1	9:15
2/20	4967	223.8	11:05	5/15	0406	2039.8	9:55
2/23	5211	291.8	11:00	5/18	0576	2110.6	8:45
2/24	5234	308.8	11:05	5/20	0638	2156.7	8:50
2/25	5348	333.2	11:25	5/22	0710	2200.5	8:30
2/26	5390	356.7	10:55	5/25	0814	2269.1	12:05
2/27	5460	380.5	11:25	5/27	0894	2310.8	8:30
3/2	5784	451.7	11:10	5/29	0950	2351.1	8:45
3/4	5950	495.3	11:00	6/1	0981	2419.9	8:50
3/5	5995	517.9	11:00	6/3	1064	2467.9	8:50
3/6	6060	542.0	11:00	6/5	1171	2513.1	8:50
3/9	6296	611.9	11:10	6/8	1298	2584.5	8:45
3/11	6513	648.1	8:35	6/10	1385	2627.8	9:10
3/13	6642	696.2	8:45	6/12	1426	2663.4	8:40
3/16	6851	768.0	8:35	6/15	1736	2731.6	8:45
3/18	6958	816.1	8:35	6/17	1837	2779.5	8:40
3/20	7274	861.7	10:50	6/19	1900	2827.1	11:05
3/23	8030	924.9	8:45	6/22	2046	2896.7	8:45
3/25	8481	972.3	10:55	6/24	2158	2938.0	8:35
3/27	8789	1018.6	11:10	6/26	2288	2986.2	8:50
3/30	8970	1090.4	11:05				

APPENDIX IV

WEB BREAKS ON PAPER MACHINE

Day	February	March	April	May	June
1	5	4	0	6	1
2	4	1	1	5	2
3	4	2	4	13	2
4	2	1	2	4	0
5	1	1	3	1	2
6	0	2	0	2	4
7	1	1	0	3	0
8	1	1	0	2	--
9	1	1	1	2	2
10	4	0	3	3	0
11	2	3	--	5	0
12	0	3	7	6	1
13	0	1	2	0	3
14	0	1	5	0	0
15	0	4	2	0	1
16	3	1	3	3	2
17	0	1	--	2	5
18	2	5	--	6	1
19	0	3	--	1	0
20	--	--	0	1	4
21	--	--	6	1	2
22	0	3	3	0	0
23	0	7	--	4	2
24	1	--	--	1	1
25	2	3	--	1	1
26	1	2	--	4	1
27	1	--	0	0	0
28	0	--	0	1	0
29	--	0	0	--	2
30	--	0	0	--	5
31	--	3	--	6	--
Total	35	54	42	83	44
n	26	26	22	29	29
$\bar{x}$	1.35	2.08	1.91	2.86	1.52
Range	0-5	0-7	0-7	0-13	0-5

APPENDIX V

TEST SECTION PRESSURE DIFFERENCES

Total ΔP Readings in Cm H_2O at 1 m/s Flow

Date	Unit A	Unit B	Date	Unit A	Unit B	Date	Unit A	Unit B
1/21	25	23	3/13	61	49	5/8	59	79
1/22	45	39	(3/13)	26	33	(5/8)	34	32
1/23	62	48	3/16	33	40	5/11	38	35
1/26	97	118	(3/16)	32	34	5/13	37	39
(1/26)[a]	26	32	3/18	--	40	5/14	40	48
1/27	22	31	(3/18)	33	32	5/15	32	32
1/29	42	30	3/20	69	99	(5/15)	30	31
1/30	37	40	(3/20)	31	36	5/18	34	37
2/2	69	48	3/25	66	70	5/20	36	38
2/4	63	58	(3/25)	30	36	5/22	40	50
2/5	83	65	3/27	32	46	(5/22)	37	40
2/6	113	124	(3/27)	31	38	5/25	32	30
2/9	> 200	> 200	3/30	32	--	5/27	39	40
(2/9)	23	42	(3/30)	32	38	5/29	35	37
2/10	68	44	4/1	37	41	6/1	38	46
2/13	39	56	(4/1)	30	30	6/3	32	42
2/16	86	77	4/3	34	33	6/5	40	56
2/17	> 200	> 200	(4/3)	32	33	6/8	44	50
(2/17)	34	28	4/10	32	70	6/10	48	48
2/18	38	35	(4/10)	30	32	6/12	36	36
2/20	62	60	4/13	60	35	6/15	52	54
(2/23)	--	--	(4/13)	33	30	(6/15)	29	28
2/24	34	56	4/17	--	48	6/17	29	32
2/25	34	58	(4/17)	34	33	6/19	97	37
2/26	58	73	4/22	31	32	(6/19)	29	30
3/2	62	80	4/27	64	132	6/22	113	92
(3/2)	22	32	(4/27)	30	33	(6/22)	27	30
3/5	75	86	5/1	65	44	6/24	103	97
3/6	82	--	(5/1)	37	39	(6/24)	33	32
3/9	81	112	5/4	89	74	6/26	30	32
(3/9)	26	37	(5/4)	32	32	(6/26)	30	30
3/11	> 200	> 200	5/6	32	62			
(3/11)	23	34	(5/6)	32	31			

[a]( ) = cleaned

APPENDIX VI

TEST SECTION DEPOSITS - BACTERIA AND ATP LEVELS

Bacteria/mL x 10^9

Date	Plate Count Unit A	Plate Count Unit B	ATP Count[a] Unit A	ATP Count[a] Unit B
1/26	10	7.8	--	--
2/9	6.5	15	--	--
2/17	8.8	7.2	--	--
2/23	11	13	--	--
3/2	8.2	12	--	--
3/9	3.8	3.2	9.2	8.0
3/11	15	27	--	--
3/13	4.9	5.6	14	9.7
3/16	18	15	44	16
3/18	8.0	14	24	24
3/20	12	9.6	24	14
3/25	20	13	17	7.0
3/27	--	3.2	--	--
3/30	3.0	1.6	2.3	1.5
4/1	2.2	0.13	5.8	0.88
4/10	0.0027[b]	3.9	--	--
4/13	4.7	2.8	--	--
4/17	9.2	49	--	--
4/27	12	11	--	--
5/1	29	--	--	--
5/4	8.3	8.9	--	--
5/6	--	21	--	--
5/8	6.8	36	--	--
6/19	10	1.2	--	--
6/22	11	14	--	--
6/24	25	36	--	--

[a]Based on an estimated 5 x 10^{-9} μg ATP/cell.
[b]Primarily a water rather than deposit sample.

APPENDIX VII

MICROSCOPIC EVALUATION OF TEST SECTION DEPOSITS[a]

	Unit A				Unit B			
Date	UB[b]	FB	P	G	UB	FB	P	G
1/26	4+	+	4+	4+	4+	+	4+	4+
2/9	4+	4+	4+	4+	4+	4+	4+	4+
2/17	4+	4+	4+	4+	4+	4+	4+	4+
2/23	5+	+	5+	5+	5+	+	5+	5+
3/2	5+	+	4+	3+	5+	+	4+	3+
3/9	5+	+	4+	3+	5+	+	4+	3+
3/11	5+	5+	4+	3+	5+	5+	4+	3+
3/13	5+	3+	4+	5+	5+	3+	4+	5+
3/16	5+	+	3+	3+	5+	+	3+	3+
3/18	3+	3+	+	5+	5+	3+	+	4+
3/20	4+	+	2+	5+	5+	+	2+	5+
3/25	4+	1+	4+	5+	3+	1+	2+	5+
3/27	+	+	3+	4+	5+	+	3+	5+
3/30	3+	+	0	5+	3+	+	2+	5+
4/1	4+	0	0	4+	3+	+	0	4+
4/3	5+	+	2+	4+	5+	+	2+	4+
4/10	2+	+	0	4+	4+	+	0	4+
4/13	4+	1+	1+	4+	4+	1+	1+	4+
4/17	4+	+	+	4+	5+	2+	4+	4+
4/27	5+	+	3+	3+	5+	+	3+	4+
5/1	5+	+	1+	2+	--	--	--	--
5/4	5+	2+	0	3+	4+	2+	0	3+
5/6	4+	+	+	2+	4+	3+	1+	4+
5/8	5+	+	0	2+	5+	+	0	2+
5/15	4+	+	+	2+	3+	+	+	3+
6/19	5+	0	3+	2+	3+	0	0	3+
6/22	3+	0	1+	5+	4+	+	+	4+
6/24	5+	0	0	3+	5+	0	0	3+
6/26	1+	0	0	5+	1+	0	0	5+

[a]Rating Scale

0	None
+	Trace
1+	Very few
2+	Few
3+	Moderate
4+	Abundant
5+	Very abundant

[b]Code

UB	Unicellular bacteria
FB	Filamentous bacteria
P	Protozoa
G	Grit

APPENDIX VIII

TEST SECTION DEPOSITS - SOLIDS CONTENTS

Date	Oven Dry Solids[a], %		Ash Solids[b], %		Bacterial Solids[c], %	
	Unit A	Unit B	Unit A	Unit B	Unit A	Unit B
1/26	5.05	5.46	2.70	3.20	0.482	0.376
2/9	4.65	5.20	2.45	2.75	0.313	0.722
2/17	5.95	6.25	4.00	4.30	0.424	0.347
2/23	7.53	7.98	4.48	5.07	0.530	0.626
3/2	4.15	4.95	1.45	1.90	0.359	0.578
3/9	9.60	8.90	6.30	6.05	0.183	0.154
3/11	5.70	6.00	3.05	3.10	0.723	1.300
3/13	10.60	8.45	8.05	6.00	0.236	0.270
3/16	5.15	3.10	3.11	1.60	0.868	0.723
3/18	9.35	6.05	7.50	3.75	0.386	0.674
3/20	16.10	11.30	13.10	9.40	0.578	0.463
3/25	13.90	20.45	11.15	16.75	0.945	0.579
3/30	--	9.23	--	6.97	--	0.077
4/10	--	6.20	--	4.40	--	0.189
4/13	11.20	5.53	9.07	3.69	0.220	0.136
4/17	7.77	8.04	5.98	5.04	0.440	2.342
4/27	3.55	5.46	1.49	2.71	0.588	0.054
5/1	3.68	--	1.33	--	1.431	--
5/4	3.83	3.05	1.73	1.39	0.407	0.436
5/6	--	6.83	--	4.26	--	1.004
5/8	2.07	5.97	0.45	1.09	0.338	1.766
6/19	3.09	--	0.80	--	0.493	--
6/22	9.04	9.51	6.48	6.36	0.525	0.669
6/24	7.67	7.65	3.31	3.44	1.209	1.734

$$a = \frac{\text{oven dry weight}}{\text{wet weight}} \times 100$$

$$b = \frac{\text{ash weight}}{\text{wet weight}} \times 100$$

$$c = \frac{(\text{total wet weight/specific gravity})\ (\text{bacteria count/mL})\ (5 \times 10^{-13})\ (100)}{\text{total wet weight}}$$

APPENDIX IX

TEST SECTION DEPOSIT WEIGHTS AND SPECIFIC GRAVITY

	Wet Weight-g		Specific Gravity	
Date	Unit A	Unit B	Unit A	Unit B
1/26	9.3	7.0	--	--
2/9	64.0	37.9	--	--
2/17	40.3	43.5	--	--
2/23	34.0	43.2	--	--
3/2	25.3	29.8	--	--
3/9	44.5	38.5	--	--
3/11	47.1	42.8	--	--
3/13	33.2	19.3	--	--
3/16	4.7	7.8	--	--
3/18	22.1	11.6	--	--
3/20	33.0	9.7	--	--
3/25	11.0	34.2	1.059	1.122
3/27	0.5	2.2	--	--
3/30	3.0	--	1.045	--
4/1	1.4	1.6	--	--
4/3	0.8	1.2	--	--
4/10	1.1	13.3	--	1.033
4/13	11.9	7.8	1.066	1.026
4/17	10.0	9.7	1.045	1.046
4/27	16.7	27.6	1.020	1.025
5/1	10.3	0.7	1.013	--
5/4	10.3	11.8	1.021	1.022
5/6	1.4	9.3	--	1.045
5/8	4.2	12.5	1.007	1.019
5/15	2.5	1.5	--	--
5/22	0.0	0.0	--	--
6/15	0.0	0.0	--	--
6/19	7.5	2.7	1.014	--
6/22	16.6	19.4	1.048	1.046
6/24	27.8	29.5	1.034	1.046
6/26	1.8	0.5	--	--

APPENDIX X

IN-MILL SLIME RATINGS AND OPERATION DATA

Date	Slime Rating[a] Mach.[b]	SA[c]	Operation	Date	Mach.	SA	Operation
1/20	--	--	Start of study	3/25	2+	1+	(NaOCl cleaned)
1/21	--	3+	--	3/27	0	0	A-unit flow off
1/22	--	--	Mach. down, SA on wash	3/30	1+	2+	B-unit flow off
1/23	2+	1+	--	4/1	0	0	--
1/26	2+	3+	--	4/3	0	0	--
1/27	2+	2+	Mach. down	4/8	--	--	Mach. and SA down
1/28	--	--	Mach. and SA down	4/10	3+	4+	App. flow off
1/29	2+	1+	(Stock pump circuit in)	4/13	3+	4+	--
1/30	+	+	--	4/15	--	--	Mach. and SA down
2/2	2+	1+	App. flow	4/17	3+	2+	--
2/3	+	1+	Mach. and SA down	4/20	--	--	Mach. and SA down
2/4	+	1+	App. flow off	4/22	2+	0	A-unit flow off
2/5	2+	1+	App. flow off	4/24	3+	2+	Mach. down
2/6	2+	+	--	4/27	4+	2+	Mach. down midvisit
2/9	2+	4+	--	4/29	3+	--	Mach. and SA down
2/10	1+	2+	--	5/1	--	--	Mach. down, SA on wash
2/11	+	--	Mach. down, SA on wash	5/4	3+	3+	--
2/12	--	3+	Mach. down, SA on wash	5/6	2+	2+	--
2/13	2+	3+	(No-drain loops added)	5/8	+	2+	(NaOCl cleaned)
2/16	1+	5+	--	5/11	3+	+	--
2/17	1+	2+	--	5/13	+	0	--
2/18	1+	2+	--	5/14	0	0	--
2/19	--	2+	Mach. down, SA on wash	5/15	0	0	--
2/20	2+	3+	--	5/18	0	0	--
2/23	--	--	Mach. and SA down	5/20	+	0	--
2/24	2+	2+	--	5/22	--	--	Mach. down, SA on wash
2/25	2+	3+	(Unit pump clogged)	5/25	0	0	--
2/26	3+	4+	--	5/27	--	0	Mach. down, SA on wash
2/27	--	3+	Mach. down, SA on wash	5/29	0	0	--
3/2	3+	4+	--	6/1	0	0	--
3/4	--	--	Mach. and SA down	6/3	+	0	--
3/5	2+	2+	--	6/5	1+	0	--
3/6	2+	3+	Mach. down midvisit	6/8	1+	0	--
3/9	3+	3+	--	6/10	--	--	Mach. down
3/11	1+	1+	--	6/12	+	0	App. flow off
3/13	2+	2+	--	6/15	--	0	Mach. down
3/16	2+	5+	App. flow off	6/17	+	0	--
3/18	1+	4+	--	6/19	3+	1+	--
3/20	+	1+	--	6/22	3+	2+	--
3/23	--	--	Mach. down, SA on wash	6/24	3+	3+	--
				6/26	2+	0	Study ended

[a]Slime rating scale: 0 = none; + = very slight; 1+ = slight; 2+ = moderate; 3+ = abundant; 4+ = very abundant; 5+ = super abundant.
[b]Paper machine.
[c]Saveall of machine.

APPENDIX XI

CHLORINE RESIDUAL DATA

Total Available Chlorine - mg/L

Date	Saveall	Machine	Mill Water
4/13	0.25	--	--
4/17	0.40	--	--
4/22	1.32	--	--
4/27	0.20	--	--
5/4	0.78	--	--
5/6	0.67	--	0.48
5/8	0.48	--	0.48
5/11	0.39	--	0.49
5/13	1.34	--	1.05
5/15	1.91	--	1.15
5/18	1.05	1.24	0.67
5/20	1.24	1.15	0.58
5/27	0.74	--	1.11
5/29	1.62	2.03	0.67
6/1	1.24	1.34	0.86
6/3	0.77	1.43	0.67
6/5	0.58	0.67	0.67
6/8	0.59	0.68	0.49
6/12	2.10	2.10	0.77
6/17	0.84	1.11	0.56
6/19	1.02	0.74	0.56
6/22	0.00	0.00	0.72
6/24	0.72	0.95	0.45
6/26	0.71	0.71	0.44

APPENDIX XII

BACTERIAL PLATE COUNT DATA

Date	Bacteria/mL	
	Saveall	Machine
1/20	20×10^6	--
1/21	29×10^6	--
1/23	38×10^5	--
1/27	48×10^5	--
1/29	14×10^5	--
1/30	96×10^5	--
2/2	22×10^5	--
2/4	71×10^4	--
2/5	14×10^6	--
2/6	29×10^4	--
2/9	21×10^4	--
2/10	30×10^5	--
2/13	27×10^5	--
2/16	76×10^5	--
2/17	48×10^5	--
2/18	73×10^5	--
2/20	32×10^6	--
2/24	49×10^5	--
2/25	37×10^5	--
2/26	63×10^5	--
3/2	46×10^5	--
3/5	15×10^6	--
3/6	15×10^5	--
3/9	15×10^6	--
3/11	27×10^5	--
3/13	98×10^5	--
3/16	26×10^6	--
3/18	28×10^5	--
3/20	83×10^4	--
3/25	$<10 \times 10^3$	--
3/27	11×10^4	--
3/30	79×10^3	--
4/1	$<10 \times 10^1$	--
4/3	13×10^2	--
4/10	85×10^4	--
4/13	10×10^6	--
4/17	80×10^5	--
4/22	80×10^5	--
4/27	69×10^5	--
5/4	56×10^5	--
5/6	13×10^6	--
5/8	12×10^6	--
5/13	65×10^3	--
5/15	$<10 \times 10^1$	--
5/18	92×10^2	43×10^2
5/20	50×10^2	$<10 \times 10^2$
5/29	28×10^2	90×10^1
6/1	30×10^1	53×10^0
6/3	22×10^3	15×10^3
6/5	41×10^3	31×10^2
6/8	19×10^2	20×10^1
6/12	54×10^2	10×10^2
6/17	16×10^4	72×10^4
6/19	63×10^4	13×10^5
6/22	17×10^5	18×10^5
6/24	66×10^5	10×10^6
6/26	89×10^4	75×10^4

APPENDIX XIII

SAVEALL FLUIDS pH, TEMPERATURE, AND COLOR DATA

Date	pH	°C	Color	Date	pH	°C	Color
1/20	7.1	--	Yellow	3/20	7.4	36	Yellow
1/21	7.7	42	Orange	3/25	7.3	38	White
1/23	7.8	39	Pink	3/27	7.4	36	White
1/26	8.0	34	White	3/30	7.4	38	White
1/27	7.5	24	White	4/1	7.4	40	Pink
1/29	7.7	44	White	4/3	7.5	38	Pink
1/30	8.3	34	White	4/10	7.3	39	Yellow
2/2	8.2	42	White	4/13	7.3	38	White
2/4	7.6	42	Yellow	4/17	7.5	36	White
2/5	7.8	42	Pink	4/22	7.5	38	White
2/6	7.8	35	White	4/27	7.4	38	Yellow
2/9	7.7	36	White	5/4	7.3	40	Pink
2/10	7.8	25	Yellow	5/6	7.3	40	White
2/13	8.2	35	Cream	5/8	7.0	39	Yellow
2/16	8.0	38	White	5/13	7.5	38	White
2/17	8.4	38	White	5/15	7.4	40	White
2/18	8.4	41	White	5/18	7.3 (7.3)[a]	39	Yellow
2/20	7.6	39	Pink	5/20	7.4	40	White
2/24	7.9	39	White	5/29	7.4	40	Yellow
2/25	7.6	38	White	6/1	7.4	41	White
2/26	7.6	40	White	6/3	7.4	44	White
3/2	7.5	39	White	6/5	7.4	44	White
3/5	7.5	40	White	6/8	7.4	45	Yellow
3/6	7.7	39	White	6/12	7.4 (7.5)	43	White
3/9	7.4	38	White	6/17	8.4 (8.0)	41	Yellow
3/11	7.6	39	White	6/19	8.0 (7.6)	40	White
3/13	7.4	37	White	6/22	8.2 (7.6)	40	White
3/16	7.3	37	White	6/24	8.1 (7.6)	41	White
3/18	7.5	36	White	6/26	7.4 (7.7)	42	Yellow

[a]Paper machine.

APPENDIX XIV

FLUID SOLIDS DATA[a]

	Total Solids, mg/L		Suspended Solids, mg/L			
	Saveall		Saveall		Machine	
Date	Oven Dry	Ash	Oven Dry	Ash	Oven Dry	Ash
1/20	1660	920	680	480	--	--
1/21	1520	800	700	400	--	--
1/23	1325	725	725	425	--	--
1/26	1025	600	500	275	--	--
1/27	1725	925	975	600	--	--
1/29	1875	1200	725	400	--	--
1/30	1875	975	1150	525	--	--
2/2	1650	825	1050	425	--	--
2/4	1525	825	825	425	--	--
2/5	1775	925	975	450	--	--
2/6	1600	1050	850	475	--	--
2/10	2250	1400	1550	950	--	--
2/13	3350	1825	2300	1350	--	--
2/16	2000	1175	1150	650	--	--
2/17	1900	1125	1150	625	--	--
2/18	2225	1375	1400	850	--	--
2/25	2025	1350	1225	800	--	--
3/5	2425	1500	1600	950	--	--
3/11	2975	1925	1650	1050	--	--
3/18	1475	750	850	525	--	--
3/25	1950	1275	1425	925	--	--
3/27	1225	650	675	325	--	--
3/30	1175	625	650	250	--	--
4/1	1250	650	650	275	--	--
4/22	2425	1450	650	300	--	--
5/13	--	--	500	125	--	--
5/15	--	--	850	325	--	--
5/18	--	--	525	200	625	250
5/20	--	--	575	225	600	175
5/29	--	--	1800	875	2825	1550
6/3	--	--	675	200	1075	375
6/5	--	--	925	350	975	475
6/8	--	--	775	250	--	--
6/12	--	--	575	150	800	275
6/17	--	--	1000	325	1025	400
6/19	--	--	900	275	600	175
6/22	--	--	1425	475	1525	550
6/24	--	--	1250	525	1800	575

[a]Paper machine.

APPENDIX XV

NUTRIENT ASSAY DATA

Concentration, mg/L

Date	Untreated		Filtered - 0.45 μM			
	BOD_5	TKN	BOD_5	TKN	Ortho-P	Total Sugars[a]
2/18	329	2.83	--	--	0.336	--
2/25	290	3.64	--	--	0.014	57.2
3/5	405	4.08	93	2.15	0.006	65.8
3/11	631	4.15	338	1.86	0.246	126.3
3/18	260	2.12	94	1.44	0.175	73.1
3/25	220	2.43	57	1.79	0.058	74.2

[a]Individual sugar fraction, %

Date	Rhamnose	Fucose	Arabinose	Xylose	Mannose	Galactose	Glucose
2/25	1.0	0.0	4.4	36.5	1.4	2.8	53.8
3/5	0.6	0.6	2.3	26.7	1.8	2.7	65.2
3/11	1.0	0.0	2.4	21.8	1.6	2.7	70.5
3/18	0.3	0.0	1.5	21.1	0.1	1.8	75.2
3/25	2.4	0.0	1.8	22.2	1.3	1.1	71.2
$\bar{x}$	1.1	0.1	2.4	24.7	1.3	2.2	68.2