Using a Conductivity Level Probe for Thickener Control

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements of the degree of
Master of Engineering

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August, 2001

I dedicate this work to my family and to God.

Abstract

A thickener is a continuous gravity separation device that reduces or removes suspended solid particles from liquor. Clarified liquor is removed from the top and thickened solids are discharged from the bottom. Thickeners are an essential part of plant water management.

A conductivity-based sensor has been developed for use in a thickener and has been successfully tested in industrial applications. Data from at Falconbridge's Kidd Creek operations, Inco's Thompson and, in particular, Inco's Sudbury operations are discussed.

The probe designed for this work is a multi-cell arrangement that exploits the difference in conductivity between the liquor and the slurry. Conductivity measurements are taken as a function of depth to provide a profile of the solids content of the thickener. Conductivity measurements can be converted to solids concentration (percent solids) using a model developed by Maxwell. The resulting solids concentration versus depth profile was used to interrogate the behaviour of the solids and to develop thickener control signals.

The probe design withstood the rigours of an outdoor thickener; the original signals (based on a static view of the solids profile), however, were found to be unreliable when used for extended periods. New signals were designed based on long-term data trending to follow changes in level, inventory (total solids content) and solids concentration. These signals were not affected by deposition on the probe. The new signals were used to diagnose operational difficulties and determine appropriate solutions. The extension to control is discussed.

Despite the ability of the conductivity probe to diagnose thickener problems and provide signals with short response times, the concentrate thickener at Inco's Sudbury

operations could not be optimized due to a lack of control over inputs and outputs. Flocculant addition rates could not be altered and were not automated. The down-stream filtration plant dictated thickener discharge rates and therefore underflow withdrawal control was not available.

The conductivity probe should be installed in a thickener requiring optimization. Signals developed for this thesis could then be incorporated into an automated control strategy. Ultimately, the use of a conductivity probe in thickeners could minimize flocculant consumption and maximize product consistency.

Acknowledgements

This work would not have been possible without the support and love of my family. By family I include my father who translated the abstract into French, delivered the thesis personally and gave me the upbringing enabling me to do complete this task, my mother who was always encouraging and loving, my brother who challenged me by completing a Masters degree himself. I also include my father-in-law (Ian Butler) and mother-in-law (Pam). To finish this thesis by the deadline, they flew from Montreal to Denver to watch over my children and wife so that I could continue working. They also covered all the expenses necessary for me to graduate and Ian even helped correct a rough draft twice. Of course, I would not have been able to do this without my wife who has been my greatest supporter since they day we married; many nights she cared for our children alone... And let me not forget my five little children. Over the past six months, they have been exceedingly patient. Next time they ask, "Can you play Daddy?" I will finally be able to say, "Yes!"

This work would also have not been possible had it not been for my supervisor Prof. Jim Finch. Prof. Finch helped me in every way a supervisor can; he gave excellent advice and was always interested in the research, he arranged for industrial sponsors and an industrial test case, and he helped with all the paper work necessary for me to submit this thesis. Prof. Finch is the ideal supervisor and I am honored to be one of his Masters students. I would also like to thank Norma Procyshyn who helped with the submission as well.

I would like to thank Cesar Gomez (Pato) for his friendship and help with the installation of the probe and all the road trips. Cesar is an excellent researcher and has a unique ability to get the work done while putting people first. I would also like to thank my colleagues at McGill for their friendship and support.

Special thanks go to the people of Inco: The copper cliff crew who I spent the summer with while collecting data, the operators of the thickener who shared their stories, and especially Neville Moores for all his help with the probe.

While writing this thesis, I worked for two wonderful companies, Outokumpu and Dorr-Oliver. I drew from experiences with both companies to write this thesis.

At Outokumpu I learned a lot from David Green, Wes Ulan and Ed Murphy. Their view on thickeners and research showed me the future of thickening technology. I also appreciated the friendship and support of Pierre, Debbie, Heather, and Stan.

At Dorr-Oliver I had a chance to learn from Jim Bowersox who is probably the most knowledgeable person about thickeners on Earth today. I also received great insight from Bill Schwartz who helped me put all the theory into focus. At Dorr-Oliver I became aware of how vast the field of thickening is. It was quite inspiring to work for the company that invented the thickener.

Funding for this work was provided by the Natural Sciences and Engineering Research Council of Canada with industrial sponsorship from Inco Ltd.

Résumé

Un épaississeur (ou agent de liaison) est un dispositif continu de séparation par gravité qui réduit ou retire des particules solides en suspension d'une liqueur. La liqueur clarifiée est enlevée du haut et les solides liés sont déchargés du fond. Les épaississeurs constituent une partie essentielle dans le traitement de l'eau d'une usine.

Dans cadre de notre travail nous avons développé un capteur basé sur la conductivité pour utilisation dans un épaississeur. Nous l'avons testé avec succès dans des applications industrielles et nous présentons des données obtenues dans les installations de Falconbridge à Kidd Creek, et celles d'Inco à Thompson et, tout particulièrement, à Sudbury.

La sonde conçue pour ce travail est un arrangement multicellulaire qui exploite la différence de conductivité entre la liqueur et le schlamm. Des mesures de conductivité ont été prises en fonction de la profondeur pour obtenir un profil du contenu de solides de l'épaississeur. Ces mesures de conductivité peuvent être converties en concentration de solides (pourcentage de solides) en utilisant un modèle développé par Maxwell. La concentration de solides résultante versus le profil de profondeur fût utilisée afin d'étudier le comportement des solides et de développer des signaux de contrôle pour l'épaississeur.

Le dessein de la sonde résista aux rigueurs d'un épaississeur exposé au plein air. Les signaux originaux, basés sur une vue statique du profil des solides, se révélèrent cependant peu fiables lorsque utilisés sur une période étendue. De nouveaux signaux furent conçus, basés sur une tendance à long terme des données pour suivre les changements de niveau, d'inventaire (contenu total en solides) et de concentration des solides. Ces signaux ne furent pas affectés par des dépôts sur la sonde. Les nouveaux signaux furent utilisés pour diagnostiquer des difficultés opérationnelles et déterminer

des solutions appropriées. Leur extension à la fonction de contrôle est également examinée.

Malgré la capacité de la sonde de conductivité de diagnostiquer des problèmes de l'épaississeur et de fournir des signaux avec un temps de réponse plus court, l'agent de liaison du concentré aux installations d'Inco à Sudbury n'a pu être optimisé dû à un manque de contrôle sur les entrées et les sorties. Les taux d'addition de floculant n'ont pas pu être variés et ne furent pas automatisés. L'usine de filtration en aval imposa les taux de déversement de l'épaississeur et pour cette raison le contrôle du retrait du courant dérivé n'était pas disponible.

La sonde de conductivité devrait être installée dans un épaississeur ayant un besoin d'optimisation. Les signaux développés pour cette thèse peuvent ensuite être incorporés dans une stratégie de contrôle automatisée. Finalement, l'utilisation d'une sonde de conductivité dans des épaississeurs pourrait minimiser la consommation de floculant et maximiser la consistance des produits.

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List of Symbols

Symbol	Description	Unit Used
V	Settling Velocity	m/s
C	Mass Fraction of Solid Particles	
g	Acceleration due to gravity (9.81 m/s^2)	m/s^2
d	Particle diameter	mm
ρ_S	Specific gravity of the particle	g/cm^3
ρ_L	Specific gravity of the liquor	g/cm^3
μ	Viscosity of the liquor	cp
G_θ	Solids handling capacity or flux	m/s
u	Zone settling rate	m/s
ΔG	Instantaneous settling flux difference	m/s
ΔC	Instantaneous concentration difference	
Q	Liquor flow	m^3/min
C_o	Discharge coefficient through the slot	
W	Slot width	m
h	Level difference between the feedwell and the rest of the thickener	cm
ε_s	Volume fraction solids	
γ	Ratio of the conductivities of the slurry and the liquid	
K	Conductance	mS/cm^2
κ	Conductivity	mS
T	Operating torque	Nm
D	Diameter of the rake arm	m
k	Empirical factor that describes the force required to displace the solids	
I_{avg}	Average of the readings taken in the interface zone	
L_{avg}	Average of readings taken in the liquor zone	
S_{avg}	Average of the readings taken in the solids zone	
n	Interface point	
S^n	Solids reading at a point n	
L_n	Load at a time n	

Chapter 1

Introduction

1.1 Objectives of the Project

The primary objective was to install a conductivity level probe in a commercial thickener for an extended period of time as a control device. This involved the fabrication, design and programming of the device.

Specific objectives were:

- To determine useful control signals and algorithms for thickeners
- To use operating data to evaluate the success of these control algorithms
- To determine long-term installation requirements for future installations.
- To determine the effectiveness of a conductivity probe as a thickener control instrument

1.2 Methodology

To achieve the thesis objectives, a conductivity-based level probe was designed, fabricated and installed in a thickener at Inco's Copper Cliff facility. The probe was thoroughly lab tested before installation in the thickener, although it was discovered that a sufficiently large body of water could not be found for accurate calibration. Two similar concurrent installations at Inco's Thompson facility and Falconbridge's Kidd Creek facility are also discussed.

Tests were run at the Copper Cliff facility for the ten days immediately following the installation of the probe and a telephone connection was provided allowing subsequent use of PCanywhere (a remote control software package) for data collection. The software package proved invaluable, as it was then possible to reprogram the probe from Montreal.

After a year of remote management, three months were spent at Copper Cliff to evaluate the status of the probe. During the three-month period, several experiments were run to ensure that the results of the probe were an actual representation of the behaviour of the material in the thickener. The experiments revealed some of the limitations of the probe, as it was found that localized anomalies within the thickener would make the thickener product streams behave independently of the area near the probe thereby limiting its effectiveness as a control instrument.

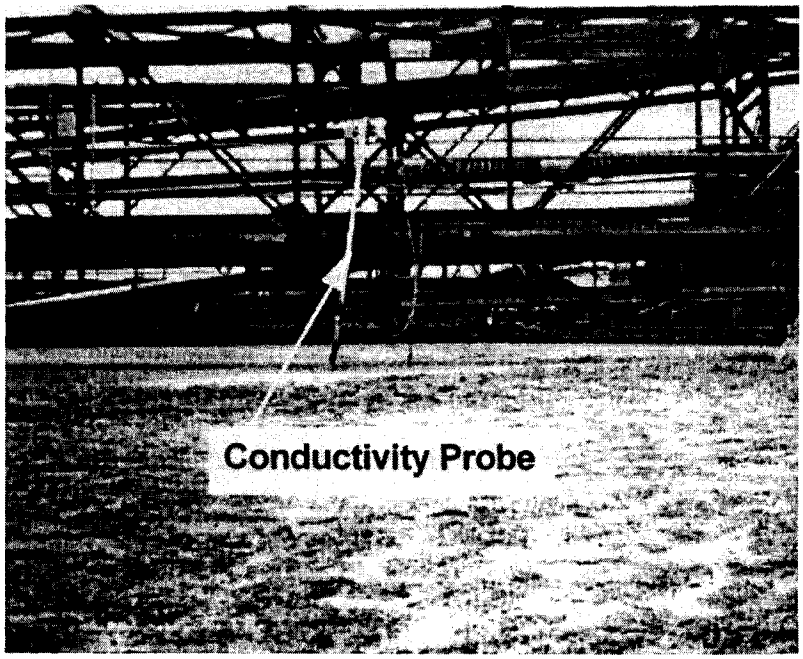

Figure 1.1: Photograph of the Conductivity Probe Installation (author's photograph)

1.3 Outline of Thesis

The present chapter is designed to introduce the topic. Thickeners are extremely important in mineral processing and with an increasing number of water-poor mineral sites, the need for improved thickener control becomes evident.

Chapter 2 focuses on thickeners to better understand both the need for control and the specific requirements for their control. Thickeners are unlike almost all other mineral processing equipment and require a shift in philosophy to understand their operation.

Chapter 3 focuses on the probe itself. The theory behind conductivity based research, the criteria for selecting the number of cells and the criteria for selecting the location of the installation are described. Two other conductivity technologies are also examined.

Chapter 4 looks at the data collected from the industrial installations at Copper Cliff, Thompson, and Kidd Creek. The data collection and analysis routines are also discussed in this chapter.

Chapter 5 examines the control signals developed for use with a conductivity probe. The chapter examines the differences between the signals and possible applications for each of the control signals. The use of the control signals to develop a control algorithm for use in an industrial application is discussed, as well as existing control algorithms.

Chapter 6 concludes the thesis with summaries of the key points of the thesis and gives recommendations for future research.

The appendices at the end of the thesis provide supplementary material used in this project. Appendix A contains the software program written to control the probe. Appendix B contains the formulae used in an Excel spreadsheet designed to process the raw data and Appendix C contains an example of the raw data collected from the probe.

1.4 What is a Thickener?

Based upon the literature, a thickener can best be defined is a continuous device that separates liquid from solids. Thickeners are generally cylindrical in shape and centrally fed to maximize the use of area [1]. The size of a thickener is calculated based on the settling rate of the particles [2]. Sufficient area is required to ensure that all particles will settle against the rising column of liquor. Thickeners generally have

rake mechanisms located close to the bottom and spanning the full diameter. These rake structures have attached angled plates known as scraper blades. The scraper blades move the solids towards a central discharge point. Scraper blades are arrayed on the rake arm to ensure either one or two complete passes of the bottom during every rotation. For a single-pass arrangement, scraper blades are located asymmetrically on the two rake arms in an alternating fashion. A complete 360° pass ensures contact with all solids within the thickener. For a double-pass arrangement, scraper blades are symmetric from the centre and are placed at an interval small enough to ensure contact with a solid particle at any radial distance every 180°.

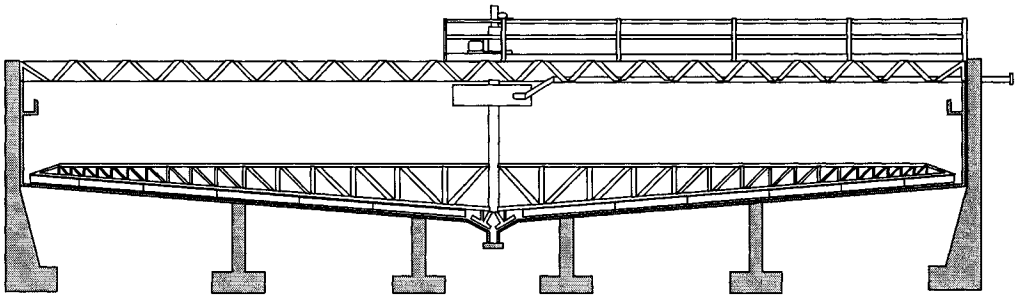

Figure 1.2: Bridge Supported Thickener (adapted from reference [3])

Small thickeners (i.e., diameter up to 25 m) generally have the rake supported by a central shaft, which is in turn supported by a full span bridge. The smaller units use a beam bridge whereas larger units require a truss bridge. Bridge type thickeners have a central discharge cone, normally angled at 45°, for the removal of solids (multiple take-offs are possible from the discharge cone) [4] (Figure 1.2).

Large thickeners require a centre column (either steel or concrete) to prevent any moment caused by uneven loading from damaging the structure. The rakes are attached to a cage, which surrounds and is supported by the centre column [4]. Most of these units have a radial bridge to support the feed pipe and to allow access to the drive head. Solids are removed via an angled discharge trench that surrounds the center column. Unlike the bridge-supported thickeners that use a single gear assembly, most of these units use a large bull-gear and several pinions to supply the

torque [5]. The two principal types of gears used in the industry are worm and planetary [3]. These gears are powered either by electric motors with chain drives or hydraulic power packs with low RPM hydraulic motors [4].

At the periphery of a thickener there is generally an overflow launder with V or U notches for the withdrawal of overflow liquor. Some applications use bustle pipes that remove liquor from several points around the thickener. The launders or bustle pipes are sloped towards take-off points from which the overflow is pumped to its final destination. Launder calculations by Wooh show that multiple take-off points can greatly increase launder capacity [6].

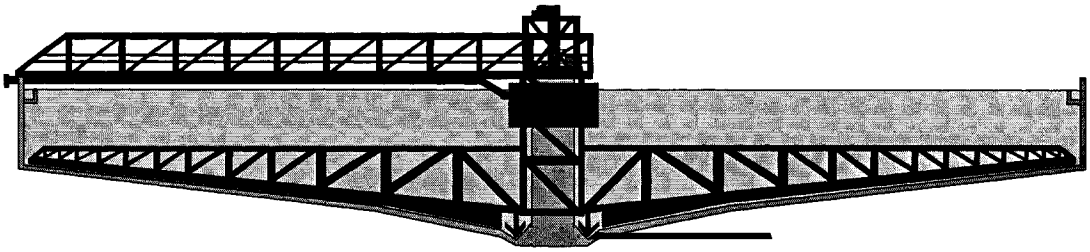

Figure 1.3: Central Column Thickener (adapted from reference [3])

Small thickeners can be installed either in-ground or in elevated steel tanks [7]. Due to the cost of tunnelling, elevated tanks are generally preferred. Large thickeners are almost always installed in-ground. Several options exist, including full concrete tanks, concrete walls and earthen bottoms, steel walls and earthen bottoms, and no walls and earthen bottoms [4]. Earthen bottom tanks require a membrane to prevent process chemicals from entering the ground water[5]. Site conditions dictate the most cost effective choice for a given application.

The term "thickener" implies a separation device for solids concentration. Thickener operation focuses on maximizing solids underflow density with little regard to overflow clarity. A similar device is the clarifier except here the prime product is the overflow with less effort being spent on maximizing underflow density. The term "multi-function sedimentor" [8] better describes the desires of the modern user, who

requires both clarification and thickening in a single step. Thickener research today focuses on both products [8]. The solids concentration of the feed determines whether an application will be considered clarification or thickening [9]. Although the user may want a high underflow density from a feed stream containing only 1% solids, the operation of the device and the calculations used for sizing normally come from clarification experience.

The term "thickener" is sometimes used indiscriminately for both processes, but it is important that the user knows to which of the two general categories a given application applies so that the correct sizing and design parameters will be taken into account.

1.5 The History of the Thickener

Dorr invented the thickener in 1906 for use in the latter part of the Gold Rush [1]. Water recovery prior to the invention was an arduous process and reserved only for concentrates. In fact, water recovery was so difficult that many large deposits in arid climates were not mined until after the invention of the thickener. Notable such deposits are Chuquicamata and El Teniente in Chile (both Codelco). Chuquicamata is the largest copper ore processing operation in the world and El Teniente has the largest underground mine. Both use enormous volumes of water and are located in areas where water is scarce.

Two requirements kept this invention from occurring much earlier. Thickeners require high torque and low RPM motors. This combination was not possible until electricity was widely used, and it was not until the 1960's that high torque units were available [4]. The other requirement, for some thickening applications at least, is high density/high volume pumps. All of the earliest plants were built stepwise on hillsides to allow for gravity flow. High densities were avoided due to the possibility of plugging. In some cases, a stepped plant was not possible due to area topology. Most of these awaited the invention of slurry pumps before being commissioned.

The literature indicates that for the first seventy years, the thickener was a simple separation device that did not use any chemical additives. Because of the slow settling rate of some fine minerals, thickeners grew rapidly in size. By 1916, ten years after its invention, the thickener reached a size of 325' (100 m) in diameter (Figure 1.4). Dorr invented the concept of a "mule" to pull the rake arms of this unit. Unlike the more common centre driven thickeners (either shaft or column), the tank walls have a steel rail that holds a small chain drive "mule". The rakes are attached to the drive on one side and a concrete centre column keeps the rakes from going off-centre. Although this arrangement provided more torque than the centre driven units of the day, the torque was far lower than most modern 325' (100 m) units.

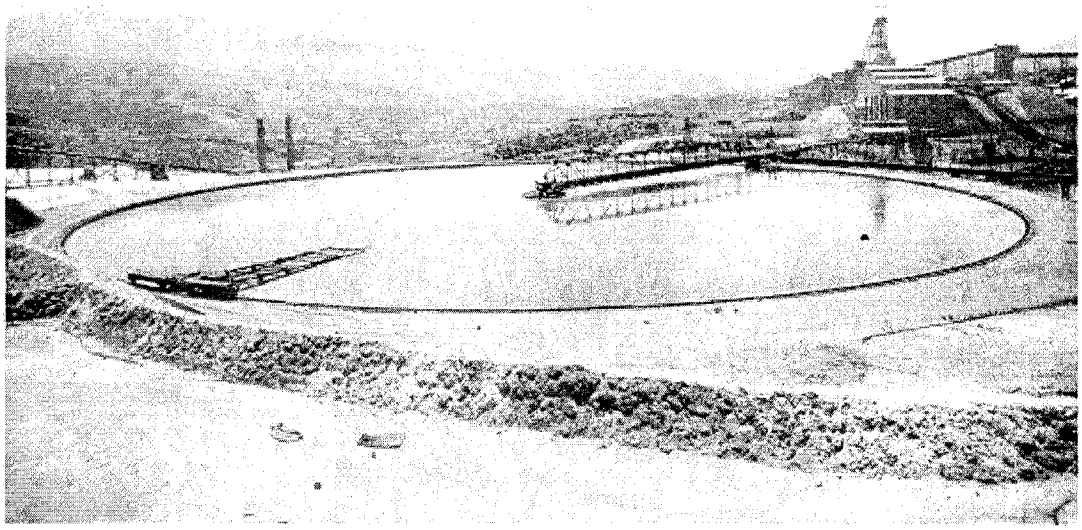

Figure 1.4: 325' (100 m) Single-Mule Traction Thickener (Picture from Bowersox [5])

By 1930, many different driveheads were available and standards were set for all thickener sizes below 25 m in diameter [4]. Above 25 m, thickeners were still tailor-made for each client and low torque was an issue. It was during this time that thickeners for sewage and wastewater treatment plants started appearing. Although torque is an issue for most mineral applications, the components of sewage do not offer much resistance to rake arms.

In 1960, Fitch invented the "Fitch feedwell" [10] (Figure 1.5). The feedwell is in the centre of a thickener and is responsible for transferring feed from the feed pipes or troughs to the thickener. Most early feedwells were shallow rings that did not prevent sudden variations in feed rate from disturbing the operation of the thickener. In many cases, the feed stream had enough momentum to disturb the solids at the bottom or to short circuit the unit. To avoid this situation, thickener manufacturers then sized units considerably larger than required [4]. The Fitch feedwell was invented to improve thickener efficiency and therefore reduce thickener size (or increase thickener throughput). Both were important since high torque was not available for large units and because many operations were expanding and required greater thickener throughput without the real estate available for an additional thickener installation. The Fitch feedwell is fed by a bifurcated pipe that splits the feed stream into two equal streams that are subsequently fed tangentially into a cylinder fitted with shelves. The two streams are fed in opposite tangential directions on different levels to prevent the two streams from colliding. A shear zone is created between the streams that greatly reduces the feed momentum and allows for a uniform downward flow. The Fitch feedwell was a success and although the settling rate of the material was not altered, the efficiency of the thickener was improved yielding higher throughputs per unit area.

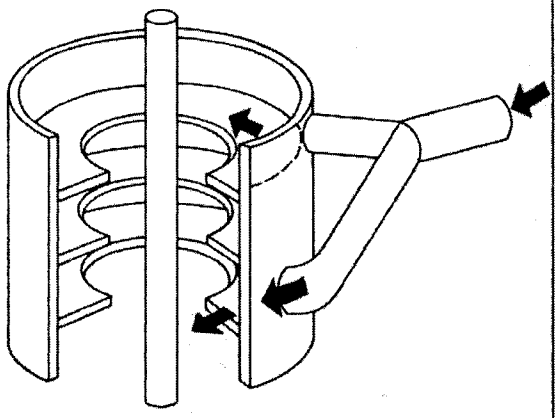

Figure 1.5: The Fitch Feedwell

The first high-torque unit was developed for the Iron Range in the late 1960's [11]. To avoid the limitation of ball bearings on large gears, Dorr-Oliver Inc. devised a hydrostatic bearing [5]. The gear supported by these bearings had a diameter of 5.5 m. The centre column was therefore large enough to house the underflow pumps and

no tunnel was required below the thickener. The maximum torque on these thickeners is between 2,400,000 Nm and 4,800,000 Nm.

The 1970's saw the first use of flocculant in thickeners [12]. Flocculant is a medium-to-long chained organic polymer with several coordination sites for mineral attachment. The resulting "chain" of minerals is significantly heavier than the independent fine particles and therefore settling rates are increased. The widespread use of coagulants also occurred in the 1970's. Unlike flocculant, coagulants act by changing the surface charge of particles such that Van der Waals forces cause the particles to adhere to each other. Both of these chemical additives result in significantly higher throughputs and smaller thickeners.

By the mid-80's, Dorr-Oliver Inc. had sold 50,000 thickeners with their competitors selling another 10,000 to 20,000 units [4]. The majority of the units were in wastewater and clarifier applications for municipalities and electric companies. Most operating mines have several thickeners and/or clarifiers. In many cases, successful operation of the thickener is required for plants to function economically.

In 1985, the high-rate thickener was introduced [4]. Although chemical additives had been used for several years, thickener design had not yet been optimized for their use. Once chemical additives are present, the thickener becomes a chemical reactor. Several companies, such as Supaflo (now Outokumpu) emerged to capitalize on high-rate technology. Brochures for Dorr-Oliver, Eimco, Denver, and Enviroclear all demonstrate their own design to optimize the use of flocculant. The competition for the most efficient design still remains open today.

In the 1980's, it was discovered that dilute suspensions improved flocculation and enabled ultimately higher densification [9]. A level difference is generally noted in an operating thickener between the inside and outside of the feedwell. The use of slots at the top of the feedwell allows liquor to be drawn in based on the density differential between the contents of the feedwell and the liquor outside. Supaflo

invented the concept of dilution flaps [13], so that in the event of dilute feed, the slots close and prevent anything from escaping the feedwell which might possibly short-circuit the thickener.

In the early 1990's several advancements in thickener technology occurred. The continuing quest for "more torque" yielded the dual-mule traction thickener [4]. The highest torque thickener at 19,200,000 Nm operating torque was installed in Indonesia. This 125 m thickener is also the world's largest high-rate unit. Eimco invented the E-duc® feedwell [14] that uses the venturi effect to draw water into the feed stream [15]. Unlike the density differential techniques developed in the 1980's, dilution occurs whenever feedflow is present and is therefore preferred when the specific gravities of the liquor and solids are similar.

The 1990's also saw the emergence of "rakeless" thickeners [14]. Wren technologies (now part of Eimco) invented a unit using a very high height-to-diameter ratio with complex internal components that boasts very high loading rates and requires no moving parts.

The 1990's saw substantial growth in thickener control sensors. The conductivity probe developed at McGill [16] was successfully tested. Outokumpu followed with their own conductivity based sensor [17], using a manufactured sensor head and a lift-and-lower mechanism for a single conductivity cell rather than McGill's multi-cell arrangement. Eimco developed the Pyramid Eye that uses a cluster of ultrasonic probes to give a complete map of the solids bed [14]. Allied Colloids (now CIBA) invented the Clairometer [18]. Dorr-Oliver invented the inductive conductivity probe (*Solids Profile Indicator*) that also uses a single cell raised and lowered through the thickener on one of three patented lift systems [8]. Alcoa developed the thickener mud gauge [19,20] and Oscillation Electrical Engineering developed the "Observer®" [21].

Today, over 6,000 thickener patents exist and thickener technology is a battlefield involving cost effective improved feedwell designs, improved control sensors, and high torque mechanisms.

1.6 The Need for Thickener Control

A poorly operated thickener results in inconsistent operation with either less than optimal underflow densities or an undesirable level of solids in the overflow [8]. This can result in loss of valuable product – mineral particles in a concentrate thickener or metal bearing solution in a gold or uranium counter-current decantation circuits – and disturb downstream operations such as filtering [22]. The water balance of a plant is delicate and consistent thickener operation is thus important. Most thickeners commonly use flocculant so that on top of the operational consequences of poor thickener control, there is the operating expense involved.

A major improvement in thickener operation would occur if stabilizing control were attained. Stabilizing control eliminates or minimizes the oscillations in operation [13]. The user predefines operational set-points and uses several sensors and control parameters to maintain these. Stabilizing control is not currently practiced but, with sensors like the conductivity probe, it is a realistic goal in the next few years.

The ideal situation would be optimizing control [23,8]. This requires a more "intelligent" system than stabilizing control. Whereas a rule-based system is adequate for stabilizing control, optimizing control requires a decision-based system. The optimizing system must be able to evaluate whether the system is at set-point and, if not, must correctly decide which way the system should be moved. With optimizing control, thickeners will provide target products in a cost effective manner.

1.7 The Difficulties in Thickener Operation and Control

Despite their apparent simplicity, thickeners are difficult to control. The first and most obvious reason is their size; thickeners range from 2 to 180 m in diameter. On average, concentrate thickeners are 25 m in diameter and tailings thickeners 75 m [3]. With these large sizes, the residence time ranges up to 30 hours. Large residence times appear beneficial for thickeners as they are able to buffer temporary peak loads or plant upsets. The large residence time, however, reduces the ability of the operator to determine the effectiveness of process modifications if the feed to the thickener is not consistent. For example, an increase in flocculant dosage should improve settling, however, if the increase occurs when the solids content of the feed increases or has poorer settling characteristics, then the change may appear to have a negative effect on the thickener.

The fluid mechanics of the system is complex. Modeling software has been written to map only the feedwell for the case of a single particle size [24]. Despite the simplification, they can only be run on mainframe computers with large memories and still take days to process. On a Pentium II, 233 MHz system, the calculations for a single feedwell with only 1 set of conditions would take 3-5 years. Modeling of a full thickener with the true particle size distribution is currently impossible due to the time (over 150 years). Although mathematical modeling may seem an unnecessary tool to operate a thickener properly, if a computer cannot determine what is happening inside the unit, an operator will find it almost impossible to know what is the proper response to a given set of conditions. With a residence time greater than the 8-12 hour operating shift in a mill, operators cannot observe the cause and effect relationships.

The position of the thickener in a circuit is another handicap. In a mineral processing plant many thickeners are nestled between the flotation circuit and the filters. Production requires that the thickeners feed the filters as fast as the filters can process the slurry. Meanwhile, thickeners have no control over what they receive as feed

from flotation. If the thickener has no control over inputs and outputs, then it is unlikely that flocculant control alone will optimize the unit. Thickener optimization requires control over the discharge rate.

Dealing with large volumes of slurry is a problem. At any given time, plugging or localized sanding is a risk. Thickeners also face material difficulties due to rust or chemical attack and wear. Because of their size, thickeners are normally external and thus face all the rigors of the environment as well. Surface protection and rubber coating in some cases are necessary.

One of the key problems with thickener control and operation is a general lack of knowledge about the devices. A search of the literature reveals a significant lack of information about thickeners and clarifiers. It is for this reason that the AMIRA project P266 [24] has attracted many large companies (including competitive thickener suppliers) for a thorough study of thickeners.

Chapter 2

The Thickener

2.1 Thickening Theory

There are three distinct types of sedimentation: line settling, bulk settling and clarification [25]. Line settling is usually found in homogeneous particle size slurries. As the particles all have the same size and shape, they settle at the same rate given by:

$$V' = V(1 - C)^n \qquad (1)$$

where V' is the hindered settling rate, V is the free settling rate of the particle (e.g., according to Stokes law), C is the mass fraction of particles and n is the particle shape factor. A uniform settling rate and a clear demarcation between the supernatant and the settled solids characterizes this form of sedimentation. Line settling can often be simulated through the addition of coagulants, which tend to homogenize particle size distributions. Bulk settling is more common in dewatering applications and is the result of a broad particle size distribution. In bulk settling, the fastest settling particles settle initially, leaving more room for the slower settling particles, which minimizes the hindered settling effect. Bulk settling is often the result of flocculation that results in a wide range of particle sizes, some of which are very large. Clarification is characterized by very fine particles that settle according to Stokes law:

$$V_t = gd^2(\rho_S - \rho_L)/18\mu \qquad (2)$$

where V_t is the terminal velocity of the particle, g is the acceleration due to gravity (9.81 m/s^2), d is the particle diameter, ρ_S is the specific gravity of the particle, ρ_L is the specific gravity of the liquor and μ is the viscosity of the liquor. It is rare to have all three types of settling in the same slurry, although it is common to have bulk settling with clarification.

There are two basic ways in which the above settling types occur. Figure 2.1 is a paragenesis diagram that shows, depending on the tendency of the particles to cohere, what regimes will take place during the settling of the particles. Slurries that contain particles with no tendency to cohere will go through clarification only with a segregated compact bed building as the particles settle. As the particles increase in cohesiveness, zone settling becomes apparent as well as a compression zone. The compression zone is the result of a settling rate that exceeds the ability of the particles to align within the bed, thus causing the formation of voids that are slowly removed through gravitational forces. In some cases, external action through a rake is required to eliminate voidage. Clearly, the right side of the paragenesis diagram will only occur in fully flocculated slurries.

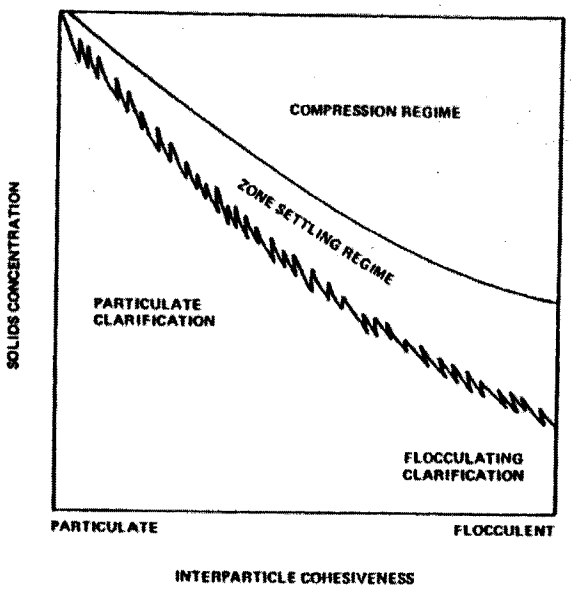

Figure 2.1: Settling Paragenesis Diagram (adapted from reference [35])

Classically, the thickener has been divided into two regimes, free settling and compression. The Coe and Clavenger procedure [26] is to determine a zone settling rate u over a range of concentrations C by observing initial interface subsidence rates in a series of batch tests. They deduce that the solids handling capacity or flux G_θ of any concentration layer existing at steady state must be related to settling rate and pulp consistency by the equation:

$$G_\theta = \frac{u}{(\frac{1}{C} - \frac{1}{C_u})} \qquad (3)$$

where G_θ is the solids handling capacity or flux, u is the zone settling rate, C is the concentration at the particular point and C_u is the concentration at the underflow. The

maximum capacity possible corresponds therefore to the smallest value of G_θ. Overfeeding the thickener will result in a build-up at the layer with the smallest G_θ. The result is a thickener filled with solids of concentration C. This adequately describes both steady-state zone settling and the potential of a sudden intermediate zone (of concentration C) in a thickener.

Kynch [27] deduced three theorems that established quantitative relationships between flux plots and batch settling curves. This made it possible to determine maximum loading rates from a single batch test. His first theorem was that if a concentration discontinuity is propagating in the direction of settling with a velocity δ, then $\delta = \Delta G/\Delta C$, where ΔG is the instantaneous settling flux difference across the discontinuity and ΔC is the instantaneous concentration difference. His second theorem was that if a concentration gradient exists in the neighbourhood of concentration C1, then the locus of this concentration will propagate in the direction of settling with a velocity β such that $\beta = (\delta G/\delta C)_t$. His third and most used theorem states that if a tangent is drawn to a settling curve at some point a, its intercept with the ordinate axis measures $1/C_a$, where C_a is the concentration existing just below the slurry-supernatant interface at point a. Kynch's theorems led to the development of the Talmage and Fitch construction [28] (Figure 2.2), which is still used by most thickener suppliers as a reliable tool for thickener sizing.

While Fitch was able to use Kynch's theories to facilitate the determination of the maximum loading rate, his research into Kynch's and Coe and Clavenger's work revealed two important facts. In his paper entitled "Current Theory and Thickener Design" [10] Fitch states that zone settling cannot be fully applied to flocculated suspensions. He reviews an experiment with flocculant that shows the theorems do not apply as they should for zone settling. In his paper, Fitch also demonstrates that material in the bed operates neither as zone settling nor as compression in some cases.

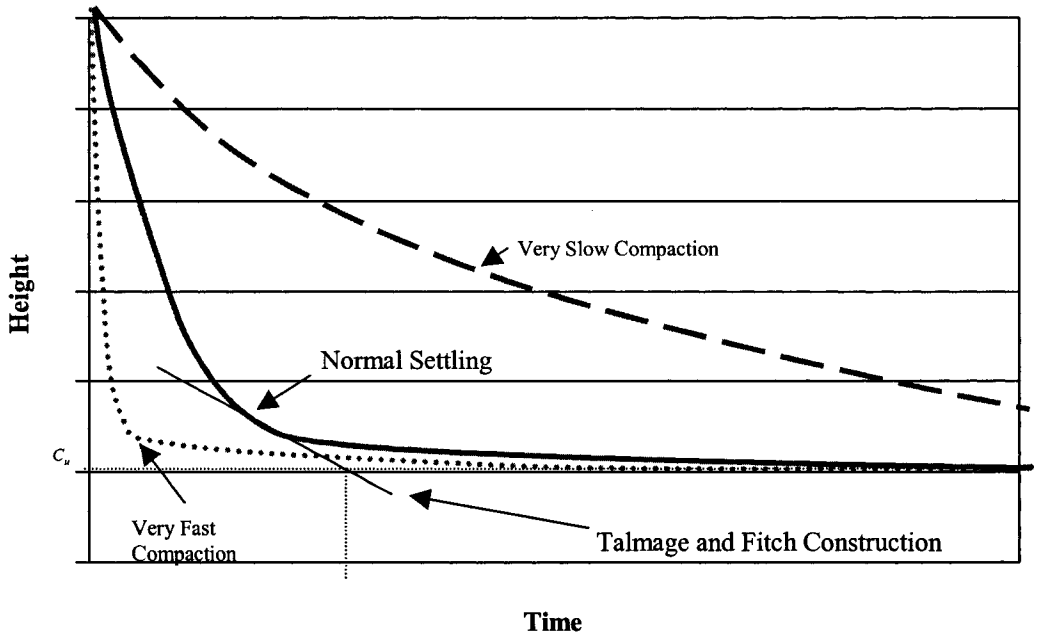

Figure 2.2: The Talmage and Fitch Construction

While these facts suggest the Talmage and Fitch construction is invalid for flocculated suspensions, the error proved to be conservative [8,29]. In other words, applying the Talmage and Fitch construction to a given application results in a thickener, which, in the absence of flocculant, is sized correctly, or, in the cases of flocculated suspensions, greater than required.

In his paper entitled "Fundamentals of Gravity Thickening" [30], Kos continues with Fitch's investigation into the applicability of the Talmage and Fitch construction. He elaborates on the calculations and reveals that the missing parameter is the depth of the unit. Although he is not able to propose a substitute construction, he does recommend pilot tests and proposes that the depth of the thickener is the key variable in improving thickener efficiency. His work resulted in several new technologies in the 1990's based on high height-to-diameter ratios (1.7:1 instead of the more classical 0.3:1).

This work led to the development of the high-rate thickener. The term "high-rate thickener" was coined to describe a thickener that was being fed at rates that met or exceeded the recommendations of the Talmage and Fitch construction. These rates were often determined in laboratory or pilot plant scale equipment and then translated into full-sized thickeners. Supaflo began as a company specializing in high-rate thickeners. To correctly size these units, they adopted the philosophy of empirical testing and designed a laboratory scale unit to test slurries [13]. Most equipment suppliers have these empirical test methods available today.

2.2 Recent Alterations to Thickener Design

Since the use of flocculant has become commonplace, there has been a significant number of thickener design modifications aimed at optimizing thickener design for the settling of a flocculated suspension. These modifications are examined here as they relate to the control of thickeners.

Due to the fragile nature of polymer chains, the way in which flocculant is introduced into slurry has received the greatest amount of attention. All equipment suppliers have devoted some of their research into the optimization of the feedwell. This is one of the major topics for the AMIRA project as well [24]. For flocculation to take place, the flocculant must be gently mixed into the slurry in such a manner that it is fully dispersed but the energy must be carefully controlled to minimize the number of organic chains that are broken. In many cases, some energy is required to unfurl the chains and adhere the particles to them in an efficient manner. The feedwell must therefore supply sufficient but not excessive energy at a specific point. Fitch was the first to design a feedwell to meet these criteria [10]. The Fitch feedwell divides the feed stream into two equal streams that are introduced in opposite tangential directions on different planes. The result is a shear zone between the streams, which is an ideal location for the introduction of flocculant. The Supaflo feedwell (Figure 2.3) is a tapered cone with baffles in some cases. The feed is fed tangentially near the top of the feedwell. The energy of the input stream is converted to a gentle cyclonic

mixing action. A cone is present at the centre-bottom of the feedwell, which prevents the formation of a vortex. The feedwell is dimensioned for a given residence time. Both these concepts use the feed stream energy to mix the flocculant with the slurry.

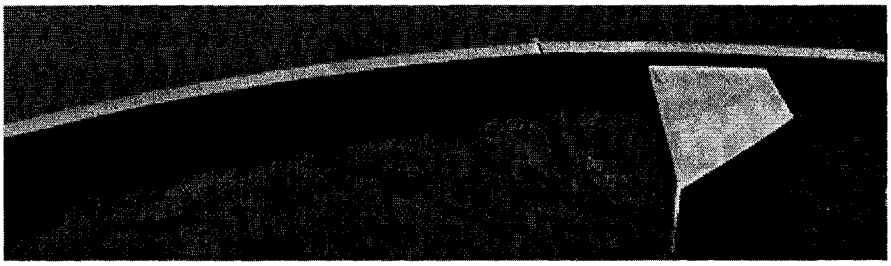

Figure 2.3: Outkumpu Feedwell with Baffle (photograph used with permission)

Flocculation research has shown that dilute suspensions flocculate better than suspensions with high volumetric concentrations [9]. This has prompted the development of dilution technology. There are two types of dilution used in industry today: density differential dilution and venturi based dilution [15]. Density differential dilution was the first used [8]. A significant level difference exists between the liquor and the feed within the feedwell, caused by the higher density of the feed material. One would expect the system to go to equilibrium and resolve this height difference, but due to the mass transport limitations, the height difference exists as long as the thickener receives its regular feed rate. Cutting slots into the top of the feedwell provides a method for liquor to be recycled back into the feedwell. Arbuthnot [15] determined that the dilution rate could be calculated using the following equation:

$$Q = C_o \cdot W \cdot \sqrt{2g} \cdot 2/3 \cdot h^{1.5} \qquad (4)$$

where Q is the liquor flow, C_o is the discharge coefficient through the slot, g is the gravitational constant, W is the slot width, and h is the level difference between the feedwell and the rest of the thickener. Supaflo improved on the concept by adding flaps to the slots that prevent the feed from escaping the feedwell should the level difference disappear (Figure 2.4).

Figure 2.4: Supaflo Dilution Flaps (AutoDil®) (photograph used with permission)

The density differential dilution method proved highly effective, although it was discovered that for some applications it was not well suited [29]. Since the density differential method of dilution relies on the difference between the density of the liquor and the feed slurry, low density materials in concentrated solutions proved to have an insufficient density differential to maintain a height difference. In fact, the friction and mass transport resistance to the flow often resulted in a higher level within the feedwell than outside of it. Several industries are unable to use density differential dilution: Nickel laterites, Alumina red mud, and most high clay deposits.

Eimco developed the Educ® feedwell that uses an eductor in the feed line to draw in liquor based on the venturi effect [15]. Since the liquor is drawn in by the feed flow, even water can be "diluted". The dilution rate cannot be modified after installation, as it is a function of nozzle size. Figure 2.5 shows an Educ® system.

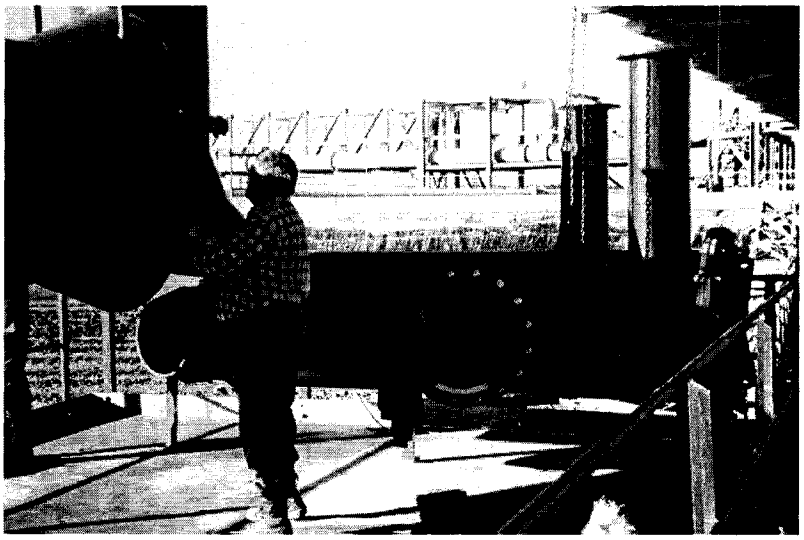

Figure 2.5: Educ® nozzle and funnel prior to installation (phoograph used with permission)

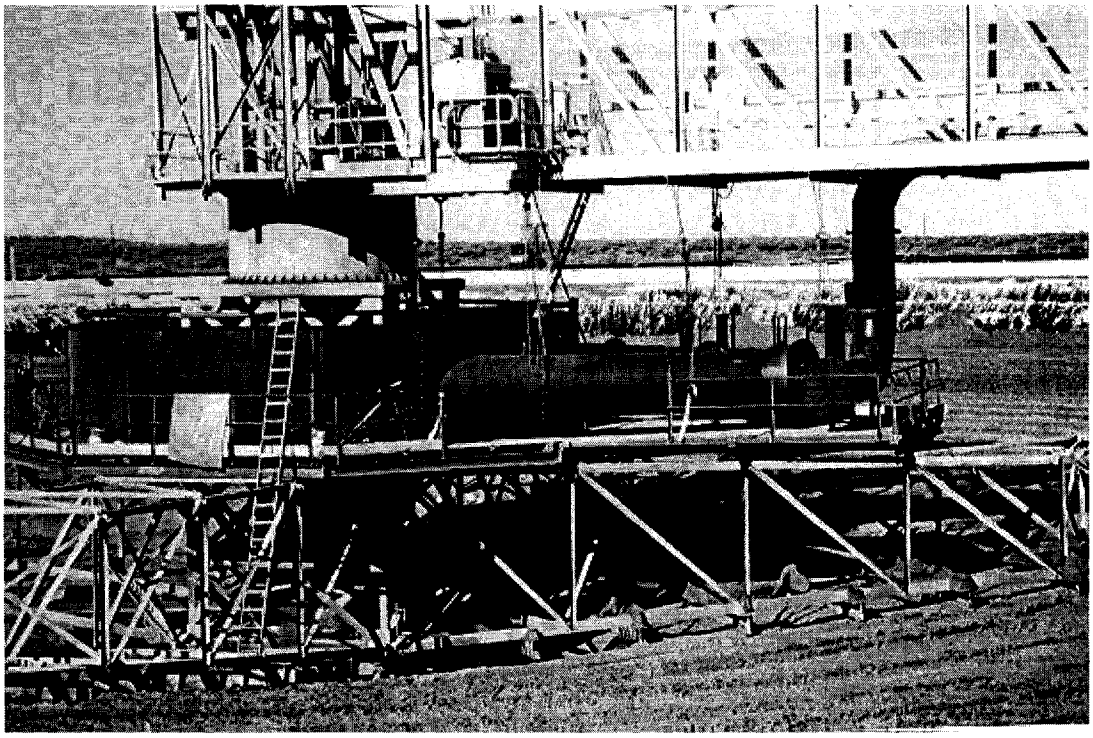

Figure 2.6: Installed Educ® (photograph used with permission)

Dorr-Oliver, realizing the benefits of both venturi and density differential dilution, was the first to offer a "duo-dilution" feedwell [8]. Instead of Eimco's patented in-line eductor, Dorr-Oliver placed venturi slots on the feedwell itself along with the density differential dilution slots (Figure 2.7). Two main advantages were realized by this design; the first is that all the dilution is central in the thickener and therefore the thickener does not become imbalanced as it can with a high dilution flow rate on one side of the thickener. The second advantage is that Dorr-Oliver chose to go with a series of dilution slots that can each be adjusted individually for a carefully controlled dilution rate. An added benefit of these slots is that they can be adjusted without taking the thickener off-line.

Although the majority of thickener development has taken place on the feedwell, there have been some other thickener modifications of note. Supaflo patented the low drag rake arms [13]. Unlike the conventional truss design common to thickeners, Supaflo's design is a solid

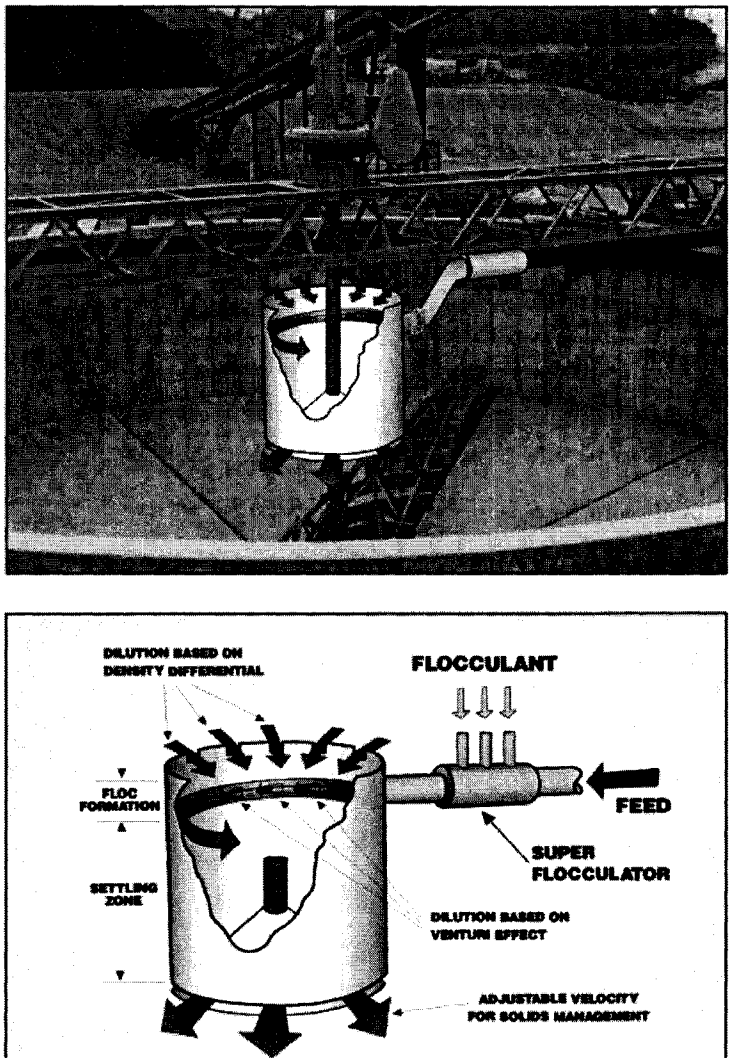

Figure 2.7: Dorr-Oliver duo-dilution feedwell (photograph used with permission)

triangular member that minimizes the deposition of solids on the rake arm surface. This has been found to reduce torque by 5%. As it is only the scraper blades that perform useful work to move solids to the central discharge point, low drag rake arms have recognized benefits. Dorr-Oliver retrofitted a 125m traction unit with tubular members in a truss instead of the more common angle-iron trusses after a large amount of solids deposited on the rake arm and the arms dug into the concrete tank. Tubular members are now part of their offering whenever the solids have a tendency to adhere to structural members [4].

GL&V Inc. addressed the issue of rake design from an optimization point of view. Their research determined that thixotropic solids could not be compacted without depositing on rake surfaces [31]. They found that many rakes are rendered useless by a mass of solids that adheres to the scraper blades and eventually eliminates the inward force vector. Their findings revealed that solids of this nature required pulling instead of compaction. Pulling is achieved by a structural member with a minimal

leading edge that can pass through the slurry with a minimum of frontal resistance (similar to findings in aerodynamic research with vehicles). The solids movement is achieved by the wake of the passing member. They developed a rake blade geometry known as "Gel-cutting" and further advanced this field by designing a special sub-class of thickener known as a Paste Production Storage Machine (PPSM). The PPSM contains several innovations based on paste research and was developed with Inco and Golder Paste technologies [31]. Key features of this design are a discharge pod, a bowl-shaped bottom and an elaborate rake structure that includes a central helix to lift solids and wall-fins that prevent the formation of a dead zone.

Using the research initiated by Kos [30], companies like Wren Technologies (now part of Eimco) and Ultra-sep have determined that the way to improve thickener efficiency is by making them substantially deeper and by working on the feedwell. Due to height limitations, these units are rarely larger than 10m in diameter with a height of 17m. The small diameters make it possible to offer these units without a rake, which has made them financially attractive. In South Africa, these units are replacing thickeners in many plants [8]. The AMIRA project has demonstrated these units to have higher loading rates than an equivalently sized high-rate thickener, although the underflow solids density was more difficult to control [24].

Although raking was originally designed to move solids towards a central discharge point, it has been noticed that the rake serves an equally important role in removing the interstitial water trapped in flocculated suspensions. Suppliers agree that thickener tests must be raked when using flocculant [29]. To increase this beneficial action some suppliers add poles to the rake arm. These poles, known as pickets, have a minimal profile and therefore do not result in a high degree of solids adhesion, but the wake of the poles is substantially larger than is the profile thereby resulting in a large volume of the bed that is subjected to a shearing action. In theory, shearing results in a reorganization of the solid particles thereby releasing interstitial water [24].

2.3 Chemical Additives to Enhance Separation

As discussed in section 2.1, one of the biggest impacts in thickener technology was the widespread use of coagulants and flocculants after 1960. These reagents were known before and used on a limited basis. In India, people have been using crushed nuts or seeds from the Nirmali tree to clear turbid water for centuries [12]. In terms of natural coagulants, many mines have noticed substantially improved settling rates as compared to similar operations elsewhere due to process water chemistry [29].

In general, coagulation is the process of causing particles to cluster through the introduction of charged ions into the electrical double layer of the particle, which eliminates the repulsive charge associated with the surface charge permitting Van der Waals (attractive) forces to dominate. Organic coagulants are short-chained polymers that adhere to the particle surface resulting in an opposite charge to neighbouring particles. The particles are then attracted to each other by the opposing charge. Coagulated particles tend to appear as spherical clumps. In most cases, coagulated particles can undergo intense agitation and reform.

Flocculation is the process of using a bridging agent to group several particles together [12]. Natural forms of flocculant include isinglass, gelatine, alginates and starch (most of these are still used today). Since the 1950's, the most common form of synthetic flocculant is based on polyacrylamide. Polyacrylamide is naturally non-ionic, although ionic character can be induced through controlled hydrolysis. Flocculant suppliers typically boast a wide range of polyacrylamide products ranging both in ionic character and molecular weight. Flocculants are fragile and flocs (flocculated particles) will not reform after agitation.

Both of these reagents have limits at which point they are no longer effective. With coagulants, an inversion point occurs and subsequent addition of reagent will have a dispersant effect and reduce the settling rate. With flocculants, excessive addition can cause a long list of deleterious effects. One of the first signs of over-dosage is

excessive particle cohesiveness; typically, the particles will adhere to structural surfaces. Another sign of over-flocculation is a fluffy bed of solids that will not compact. Excessive flocculation causes channelling as the polymeric chains form relatively robust structures within the bed. This situation often results in water being trapped in the bed. In extreme cases, over-flocculated particles will float on the thickener surface.

One of the biggest misconceptions in the thickener industry is that using flocculant will increase the total water separation. In fact, particles that settle without reagents will always achieve higher densities than do those that receive chemical assistance [12]. The only reason to use chemical additives in thickeners is to increase the settling rate of the particles thereby decreasing the required unit area for separation. Another advantage of flocculated slurries is that they tend to be easier to pump, particularly if the mineral is prone to sanding.

2.4 Maximizing Underflow Density

The purpose of thickener control is to improve the product streams. As a solids-liquid separation device, one of the most important product streams is the underflow. The goal of most operators is to maximize the density of the underflow both to improve filtration and to return as much water as possible to the process. Although filtration should theoretically work better with higher density feed, there are many types of filtration that cannot process pastes or high-density slurries. Disk filters have arm agitators that are not capable of mixing either dilute suspensions or excessively dense slurries. The operators at Inco's Booster station have empirical guidelines for both these limits and have diluted the thickener underflow to achieve better filtration.

The following are limitations that prevent underflow density maximization:

- Inability to discharge thickener due to underflow pump limitations
- Inability to move solids to the discharge due to an underpowered raking mechanism

- Inability to pump the solids to the filters due to long pipelines and slurry rheology
- Insufficient raking capacity leading to a higher volumetric pumping rate than raking rate and the subsequent formation of a hole in the bed near the discharge
- Insufficient thickener depth for compaction
- Insufficient thickener detention time
- A poorly controlled thickener leading to large operating fluctuations
- A poorly designed discharge pipe
- Sanding in the thickener

Some of these limitations can be corrected through proper thickener design (or redesign in some cases) while others are corrected through thickener control. It is not reasonable to assume that thickener control can solve all problems but a survey of approximately 100 thickeners revealed at least 60% could benefit from it [29].

The key to underflow maximization in terms of thickener control is to establish a stable bed at a height that enables complete compaction. For a bed to allow full compaction, the density profile of the bed must be known. This way, if the bed starts showing signs of poor compaction, the reagent doses can be altered to return the shape of the profile to the pre-determined ideal. Having an electronic means of checking this profile allows for a wide variety of control algorithms to be employed. Typically, the control algorithm must recognize the change away from the ideal as early as possible and then make gentle steps to restore the system. Due to the long residence time, the algorithm must be programmed to have a "steady hand". In other words, the thickener will continue to worsen for several hours even after the correct response to the problem has been made.

An example of underflow maximization through improved thickener control is the tailings thickener at Kidd Creek. A 30m diameter Supaflo thickener replaced a 110m diameter Eimco unit. This meant a substantial decrease in detention time. Figure 5.1

shows the underflow density over time. As soon as the smaller, well-controlled thickener came on-line, the large fluctuations were greatly reduced and the average underflow density went up from 58 to 61.5%. Although there are several potential factors, the deleterious fluctuations were eliminated due to improved control and were considered the primary reason for the improvement in underflow density.

2.5 Maximizing Overflow Clarity

In many solid-liquid separation cases, the valuable product is the liquor. While industry has typically treated these thickeners the same way as conventional ones, operators have long known that there are some key differences in control philosophy [32]. When the focus of the unit shifts from underflow to overflow, the way in which the unit operates must be changed. Traditionally, clarifiers or thickeners where the liquor is the valuable product are operated with very low beds. This is particularly true when the solids pose a threat to downstream operations.

While this is the safest course of action, it is rarely the optimizing one. Supaflo designs their feedwells with a depth that ensures that incoming solids will contact the solids in the bed [7]. A transitional zone is created where fresh solids have their momentum absorbed by solids already in the unit. The result is an energy transfer that prevents fine particles from short circuiting the unit. To operate these units with low beds removes this benefit. Excessively high beds in these units often result in the carry-over of fines to the overflow and thus should be avoided as well. Therefore, to properly operate these units, the bed must be kept at a desired height near the bottom of the feedwell. Depending on the mineral and feed rate, it is sometimes beneficial to have the bottom of the feedwell immersed in the bed. In other cases, this promotes carry-over.

An example of an application that has benefited from an immersed bed is a potash mine (proprietary information, details restricted) in Carlsbad, New Mexico [29]. A feed sample was run through a laboratory scale dynamic thickener. The test started

without a bed and the results were fair. As the bed grew, the overflow continuously improved. The bed was beneficial all the way to the top of the unit and no carry-over was detected. Another case of this was a clarification application at Contact Lake, Alberta [29]. Suspended solids were close to the upper limit without a bed in the clarifier. Due the low solids content of the stream, a bed was simulated in the dynamic lab unit from material in the existing clarifier. As soon as the bed was in place, the solids content of the overflow dropped by 300%.

In an alumina (Alcoa, Pocos de Calda, Brazil) application, the reverse was true [29]. As soon as the bed crested the bottom of the feedwell, overflow results deteriorated. The same was true in a hydroxide circuit in Flin Flon [29]. Typically, fluffy light minerals with large surface areas, which do not react well to polymer, are prone to carry-over whereas slightly heavier minerals, even with small particle sizes, which have some affinity for polymer will see advantages to being introduced through a solids bed.

The key to overflow optimization is to control the fluid mechanics of the system. Momentum transfer of the feed stream is one of the most important parts of the system. From a control standpoint, the bed must be monitored to be at height suitable for the given application. Currently, there is not much information in the solids profile that will assist in the control of these units. It is better to tie reagent addition to overflow turbidity meters. One of the new signals developed as part of this thesis (discussed later) shows some promise for overflow clarity maximization. The signal is the change in the clarity of the interface. Typically, the bed will show signs of instability around the interfacial region when the reagent levels fall below a certain threshold. A substantial drop in overflow clarity follows this. If a control device is capable of detecting this interfacial anomaly early enough, the reagent addition can be modified before any deterioration of the overflow takes place. The overflow must be consistently free of solids and not suffer from periodic fluctuations to be truly optimized.

2.6 Maximizing Thickener Throughput

Although most research engineers view the ideal goal of a thickener is to optimize one or both of the product streams, industry normally views production as the goal of any process device. Minimizing capital and operating costs is the key to a good thickener. Maximizing thickener throughput can be the most difficult challenge. In order for the design to be correct, the feed-flow must be maintained with minimum variation. An underfed thickener will not have enough energy to properly mix the flocculant and an overfed thickener will shear the polymer due to excessive energy [10]. The problem is that a thickener has no control over its feed stream. Maximizing throughput also involves a well-designed overflow and underflow system.

In the design, there must be considerable flexibility built in. The feedwell is the most difficult to design for a wide range of flow rates although many thickener suppliers have ways around this. Dorr-Oliver, for example, can alter the size and spacing of the raceways within the feedwell to allow for higher flow rates. The diameter of the feedwell is typically designed for the median flow rate [4]. Dorr-Oliver engineers iterate several flow conditions through a software package and then determine the ideal dimensions both for the median flow and for the maximum and minimum conditions.

For variable feed rates, the ideal underflow system consists of an array of smaller pipes [5]. Some thickeners have as many as eight underflow pipes. This way, each pipe can be pumped at a rate that prevents sanding and the number of pipes being used will vary depending on the pumping rate required. The overflow must be designed for the maximum flow conditions. To reduce the size of the launder, several take-off points are recommended [6].

Once the thickener is installed, throughput maximization is achieved through management of the solids bed [8]. The control device must be able to determine if a

reagent change is required or if a change in the underflow-pumping rate is required. A high solids inventory generally indicates the need for solids withdrawal, whereas a high bed may indicate the need for increased flocculant addition [13]. Conversely, a low bed sometimes indicates the need to slow down the pump rate, but in some cases may indicate an excessive flocculant dose. The ideal control system requires several variables that describe the profile of the solids in the thickener. The system must be able to determine if the thickener is suffering from poor settling or overloading. If the thickener can be maintained to have a bed that is ideal for compaction and clarification despite changes in feed rate and quality, the throughput will be maximized.

2.7 Thickener Economics

A review of the literature indicates that most thickener control systems ignore one key factor: the ideal thickener control system should be able to determine whether the economics of the thickener justify a change in operation. For example, some control systems might indicate the need for more polymer to optimize the products, but the products may be acceptable at a less than optimized state. The change would then cost without providing any economic return. The problem is to determine the economic operation of a thickener.

To this end, the cost associated with drying the underflow (if applicable) must be evaluated for a wide range of densities. The cost associated with treating the overflow or adding more plant water must also be evaluated. For example, in some desert areas, adding water is far more costly than additional polymer. In other areas, water availability is not an issue and the flocculant cost is the over-riding concern. As with the situation at Inco's Booster station, there may be an ideal operating point for the filters. Operating within this range will provide the greatest economy. Anything else will reduce filter throughput and therefore cost more money. There may also be a way to use the filter water as plant water in which case not collecting it

in the thickener is no longer an issue. Due to the wide variety of plants, it is difficult to determine a control platform for every plant that will address economic concerns.

An example of this is at a Dow Chemical plant in Salvador, Brazil where test work [29] has revealed several options for the dewatering circuit. In some of the options, the flocculant dosage was high. When the calculations were completed, it was determined that the operating cost for a slightly smaller thickener exceeded the capital cost of the thickener itself every year. Many plants fall into this trap by steadily increasing their reagent addition without evaluating the overall economics of the dewatering circuit.

Chapter 3

The Conductivity Probe

3.1 Conductivity Theory

Electrical conductivity is the inverse of electrical resistance. In aqueous solutions, current is transferred through ion exchange at the anode and cathode. Due to polarization, the conductivity of a solution is generally measured using alternating current in the 1 kHz range. Maxwell [33] examined the conductivity of dispersions and found that if spherical, non-conducting objects were placed in a field, the length of the ion pathways would be increased and therefore a subsequent drop in conductivity would be measured. His experiments confirmed this fact.

Maxwell's Model for Two Phase Systems

According to Maxwell [33], the following equation applies to a two-phase system in which the dispersed phase is spherical and non-conducting:

$$\varepsilon_s = \frac{1-\gamma}{1+0.5\gamma} \tag{4}$$

where, in the present context, ϵ_s is the volume fraction solids and γ is the ratio of the conductivities of the slurry and the liquid (Figure 3.1). In most cases, Maxwell's model applies since minerals are non-conducting [16]. Experience has shown the model applies up to about 25 % solids by volume (60 % by weight using a specific gravity of 3.5) [34].

If the density of the solids, ρ_s, is known, the following equation can be used to determine the mass fraction solids from the volume fraction:

$$C_s = \frac{\rho_s}{(\rho_s - 1) + \frac{1}{\varepsilon_s}} * 100\% \tag{5}$$

where C_s is the % solids by weight, ρ_s is the specific gravity of the solids and ϵ_s is the volume fraction solids calculated using equation 4.

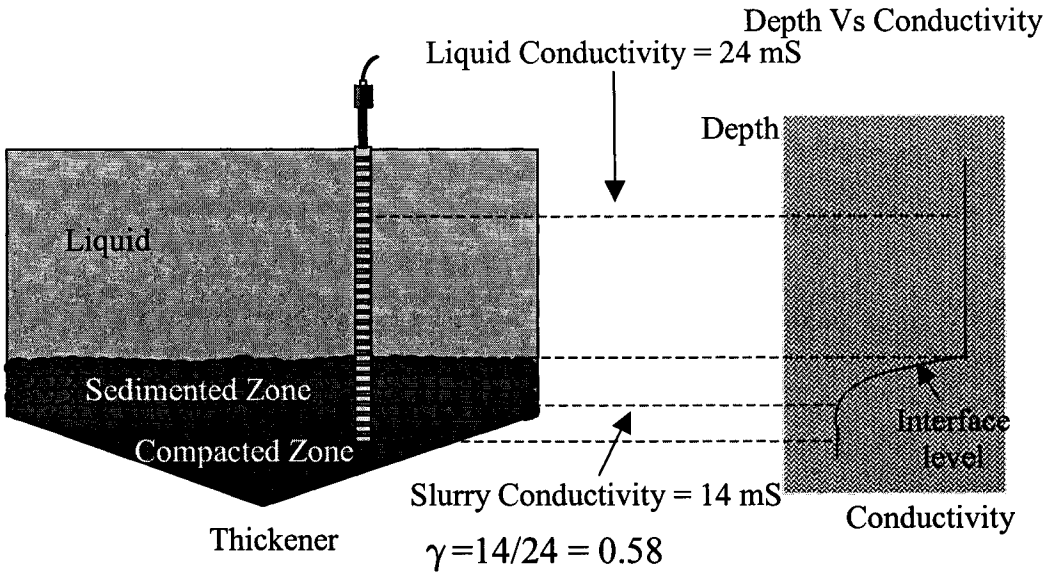

Figure 3.1: Calculation of γ

Since Maxwell's model assumes spherical shapes, some minerals do not fit the model. Banisi [35] has shown that platelets do not fit, whereas many other non-spherical, but non-platelet, shaped particles do. This research has shown that most mineral particles fit the requirements of Maxwell's model.

In general, what is measured using a conductivity meter is conductance (K) and not conductivity (κ). The two are related according to the following equation:

$$K = \kappa C \tag{6}$$

where C is the cell constant (generally A/l where A is the area and l is the length). The cell constant depends on the geometry of the conducting paths, specifically the area through which the electrons travel. Cell constants can be determined for any geometry using an experiment with known conductivities and measured conductances. Unfortunately, the measured cell constants do not always apply in thickeners as it was found in the present research that the thickener itself affects the geometries of the conducting pathways. For this reason, an empirical cell constant is

usually determined on site and can be used to take into account probe anomalies (i.e, depositions, poor connections, etc...). This empirical cell constant leaves the result in terms of conductance since the absolute conductivity cannot be known in the vicinity of the rings; however, when the relative conductances are used – as will be the case here - , the cell constants cancel. Thus, for most purposes of solids determination, it does not matter whether conductance or conductivity is used so long as any differences between the cell geometries is taken into account. It has been found that the cell constant is generally constant over the range of conductivity values found in mineral processing. Over 60% solids by mass, modifications to the cell constant need to be made for accurate % solids measurement. Maxwell's model begins to over estimate the % solids in this range.

The process of empirical cell constant determination is further complicated by the change in the size of the conductive field in the presence of solids. Research conducted by Ingham [34] showed that the geometry of the electrical field was altered by the presence of a dispersed phase. In his tests, the greater the volumetric concentration of spherical glass balls, the smaller the size of the conductive field. This can be seen in thickeners where the empirical cell constants of the rings near the interface would change considerably depending on whether or not they were covered by solids. This can be corrected by determining empirical cell constants only in the liquid phase. In order to correct for the lower cell constants in the bed, a correction factor must be added to the solids model.

3.2 The Origin of the Conductivity Probe

The first reported use of conductivity measurement in mineral processing was for use in slurry-air systems in 1989 [36]. The probe was used to determine froth depth in flotation columns and later the use was expanded to measure gas holdup. In these applications, the dispersed phase (gas bubbles) was always completely non-conductive and mostly spherical. Although laboratory tests showed an applicability

of conductivity measurement for solids dispersions, the cell geometries were not practical until a probe similar to the one used in this thesis was designed.

In this design, the conductive pathways are forced around blocks of non-conductive material so that the probe resembles a segmented rod and has no surfaces where solids can collect. Each cell is comprised of two 1.5cm thick pieces of stainless steel pipe spaced by 10 cm of PVC pipe. A probe of this type was first tested successfully in thickeners in 1991 [37]. It was subsequently modified for permanent installation in 1994.

3.3 *The Design of the Conductivity Probe*

The conductivity probe (Figure 3.2) consists of a series of stainless-steel rings spaced by PVC (10cm wide). Each ring is both positive and negative through connections to two relays allowing for 31 individual measurement cells as opposed to using a common ground with only 16 positive measurement cells. Rubber O-rings between the metal rings and the PVC help prevent leakage. The rings are 1.5cm thick. At the top of the probe is a stainless-steel connecter box with an anphanol connecter for a 32 pin cable. The top and bottom rings are always negative so that when a common

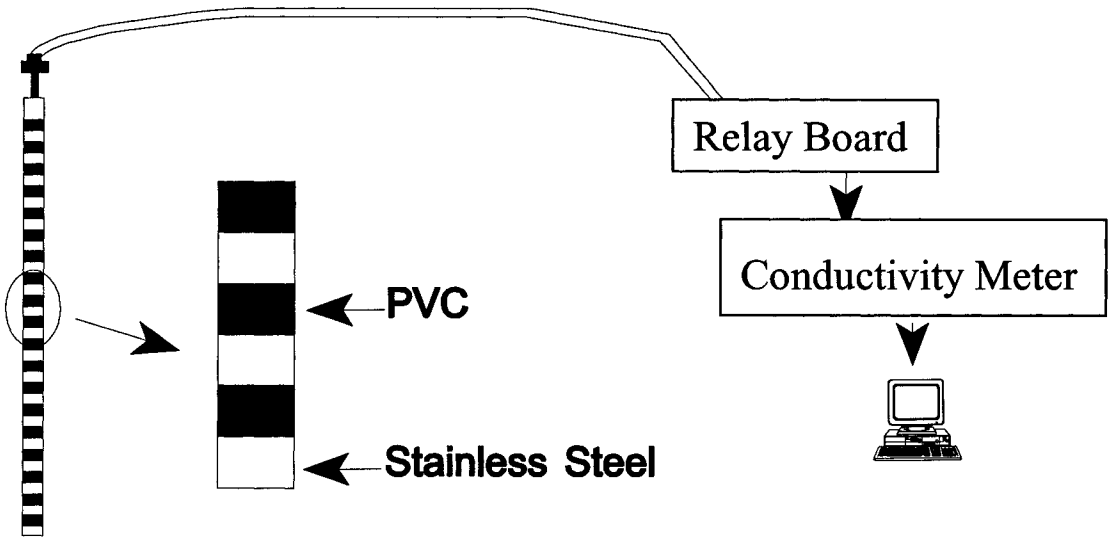

Figure 3.2: Conductivity Probe Schematic.

ground is present a complete conductivity cell may be formed on either side of the positive ring. The diameter of the probe is 5 cm and the useful length (length where rings are present) is 3.3 m. The conductivity probe is filled with epoxy resin to make certain no leakage occurs (leakage is still possible at the connector, as discovered by other test work [37]). The conductivity probe is relatively inexpensive and easy to build and requires no regular maintenance other than cleaning in certain cases.

The data acquisition system (Figure 3.2) consists of a cable from the conductivity probe, a relay board to permit one ring to be read at a time (so that only one conductivity meter is necessary), a conductivity meter, an A/D converter (DAS-8 card) and a computer (PC). A PIO-12 or DDA-06 card is used to control each relay board that have either 16 or 24 relays (the number of relay boards depends on the number of rings). The DAS-8 board must be of the AO variety (analog output), so that it is capable of transmitting signals to the plant computer system.

The software is written in QuickBASIC (Appendix A) to match the subroutines accompanying the DAS 8 card. Many features are included in the program some of which are application specific. The first software designs were for research purposes, not for prolonged use [37]. The software designed for this thesis includes user-friendly options, as well as day and week histograms of the "interface" and inventory (both defined later). The program also starts without prompts so that anyone can run it and restart is automatic after a power failure.

The program includes cell constants, as well as formulae to calculate conductivity and percent solids (an array of 31 cell constants is necessary as there are 31 cells in the probe). Two formulae are necessary to calculate the conductivity: one to take into account the long cable used (it has since been found that the impedance of the cable can be accounted for without the need of a second equation) and the other being the calibration curve for the conductivity meter.

The next feature is graphics. The top right of the screen shows the current profile, the bottom has a histogram which displays the inventory and "interface" over the last seven days with the current day magnified, the top left has the current reading the day average and the week average of the same signals. There are also two screens that make it possible to view an average profile over a day and over a week to determine bed motion around the interface.

One crucial feature is the automatic file naming and saving routine. File names based on the date and a two letter code (e.g, IN0118.dat for a file on January 18 at Inco) are used and closed daily so that they can be retrieved at any future time for data processing. Data are appended into the file so that in case of power failure no data are lost. A year was not included in the file name as it was determined that the data would be retrieved and deleted from the PC before a year had passed.

In each data acquisition routine, there is an averaging so as to reduce hardware noise. In most cases, 25 data points are averaged over a fraction of a second to stabilize the signal.

The plots are designed to ignore defective rings so as not to obscure the profiles (a large jump in a profile caused by a malfunctioning ring could be misinterpreted). For this reason, a series of error codes have been included in the software that enables the operator to clearly define the problem. For example, the error code 16 4095 means that ring number sixteen has short-circuited. Defective rings can, however, increase the standard deviation of the reference liquid (if they occur in this area) thereby increasing the standard deviation of solids estimates. Figure 3.1 indicates the area from which the liquid conductivity values are taken.

The view screens are designed so that it is possible to view any screen without interfering with data acquisition. When the view is returned to the current profile, then plotting on screen recommences live.

When the conductivity probe is in contact with the rake, the top few rings are pushed out of the water and the bottom rings out of the solids bed. For this reason, the program includes a routine that waits for the rake to pass by monitoring the top cell before taking a profile. Two minutes are given for the bed to stabilize before proceeding with data acquisition.

The experimental procedure involved installation of the probe and initiation of the probe software. The probe is installed at r/R = 0.6 or roughly half-way between the centre and the edge of the thickener and is attached to the catwalk. Figure 3.3 shows the pivoting system that allows the rake to pass.

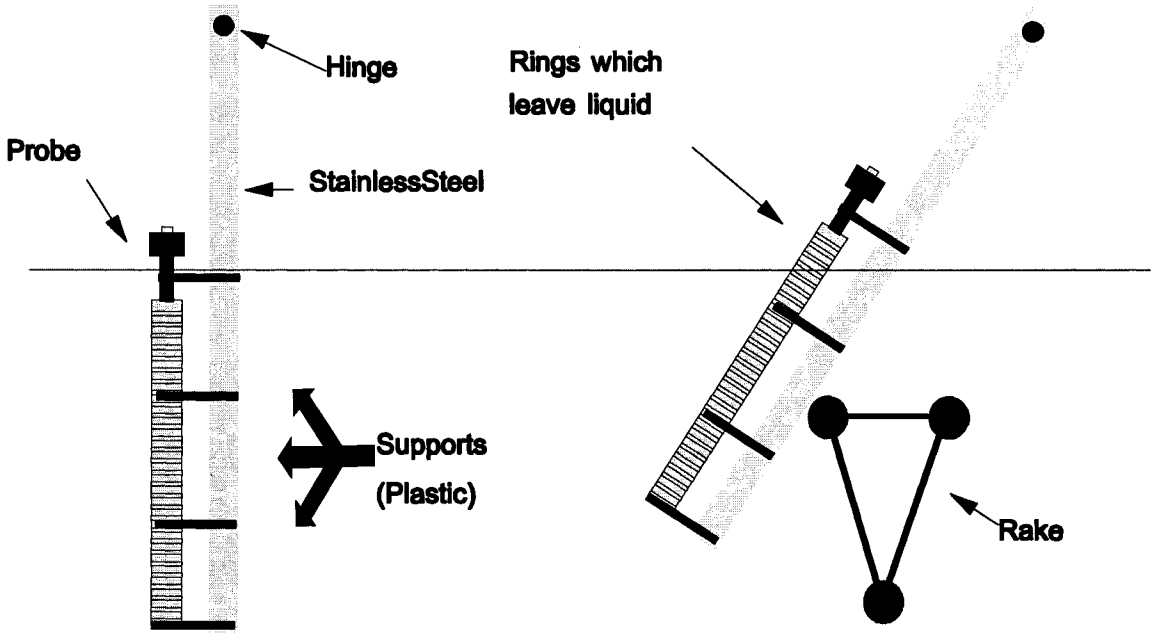

Figure 3.3: Conductivity Probe Pivot System

3.4 *Probe Calibration*

3.4.1 **Standardisation Procedure**

The standardization method involves the use of relative cell constants as corrective measures to make sure that all the rings would read the same value if placed in the

same liquid. In other words, if a ring normally reads a value 10% lower than another, the reading is increased by 10% to compensate. In the case of standardization in the field with an operating probe (assuming you cannot move the probe which is normally the case), the key to the procedure is ensuring that the rings are reading something of equal conductivity. If they are not, the relative cell constant will over compensate and reduce solids readings for that ring until it is recalibrated.

The first step in the procedure is determining which rings should be reading the same value (i.e, which rings are surrounded by liquor as opposed to those surrounded by slurry). This is the most crucial step and should be done with extreme care. Normally, there are several rings that are never surrounded by anything but clear liquid. Assuming that temperature effects are minimal (normally the case) and that the solution is homogeneous, all of these rings can be adjusted by choosing a reference ring (see Figure 3.1) and calculating the ratio of the conductivities over a period of time. The compacted solids at the bottom also yield a zone that has several rings of equal conductivity. The difficulty therefore lies with the rings between the clear liquid and compacted solids. Ironically, these are the most crucial rings for interface measurement. To calibrate these rings an assumption must be made. On a graph of Depth vs % Solids, there are the two linear regions (liquid and compacted solids) that are roughly parallel but offset (the offset reflects the compacted solids density). Assuming that you cannot have a denser region resting on a less dense region, the interfacial rings must represent a transition from the liquid to the compacted solids. Smoothing a solids profile can therefore derive the relative cell constants. In general, few points have to be calibrated this way as different times in the day can be selected to yield either more rings in the liquid or compacted solids so that they can be calibrated with direct ratios with reference rings.

The best way to determine which rings are in the liquid and compacted solids is using linear regression. The independent series should be the reference ring (the 5^{th} ring in the current case is ideal as it is always in the liquor) and the dependent series the ring that you are calibrating. The 5^{th} ring will therefore have a relative cell constant of 1.

The X coefficient represents the relative cell constant and the R^2 value represents how good the coefficient will be at correcting the difference. In general, due to temperature effects and solution non-homogeneity, R^2 values for rings in the liquid should be around 0.8 for 100 data points. A ring that is partly covered by solids even for only a small part of the time selected will show a significantly lower R^2 value. A very clear demarcation can be seen at the interface. The compacted solids are also consistent and have R^2 values around 0.5. The cell constant ratios for the rings in the compacted solids must take into account the % solids around the rings. A good way of doing this is by choosing a reference ring in the compacted solids and comparing all the rings to this one and then using the underflow density to determine the ratio between the reference in the liquid and the ratio in the solids. For example, if the bottom ring is chosen as a reference (a good choice as it is the most compacted) then the ratio between this and the 5^{th} ring must be calculated to yield the underflow density on the solids profile. Then, if the next ring up normally reads 10% higher, the relative cell constant of this ring is the combination of the comparison between the reference rings and the comparison between the bottom two rings.

If an automated version of the standardization procedure is used, it is crucial that the probe does not lose sight of the interface and then recalibrate itself so that it appears as if there were no solids. The probe must also let the user know when cleaning is necessary and use an index to indicate how urgent the cleaning is.

3.4.2 **Curve Fitting**

Curve fitting is the process by which data are collected from a clean probe and used to input the formula of the solids profile. For most well operated thickeners with little variation in feed characteristics, this formula will have only a few coefficients and fit most data sets. The 31 points can then be used to determine the best fit curve and then the relative cell constants can be adjusted so that the readings fall right on the curve. Once a formula is chosen it should not be modified too often as it may misrepresent the actual condition of the thickener.

A curve fitting software must be chosen. Excel has some rudimentary curve fitting options that are sufficient for this application but there are better mathematical packages available. Once data from a clean probe has been collected the profile should be examined to make sure that it is smooth and then a formula should be obtained. Using the same formula, a new set of coefficients should be calculated for a profile several hours later and a profile of this equation should be compared with the actual data. If there is a good fit, keep the equation and then use it to determine relative cell constants on a regular basis by making the readings fit the curve based on the best fit obtained with the formula. The formula should not contain too many coefficients or it will not be very useful.

3.4.3 **Individual Ring Profiling**

The conductivity probe is on a pivot support system so that it can be pushed out of the way by the rakes. This means that every time the rakes come by rings are moved from their normal depth to a higher one. Currently this is being used to determine when the rake is passing. For calibration purposes, this introduces a couple of possibilities. First, there are several rings that will be moved out of the solids and into the clear liquid. With a reading in the clear liquid, the ring can be calibrated with respect to the reference ring. Second, rings that do not rise out of the solids at least change their location. The reading at higher level can be compared to the reading normally taken at that depth (i.e, a few rings up) and since that ring can be calibrated vis-a-vis the liquid ring when it rises into the liquid a two-step calibration can be performed. For example, a ring just below the interface rises and reads a value 10% higher than the reference ring. The relative cell constant for this ring is therefore 0.9 or a 10% reduction to make it read the same in the liquid. Now, if a ring several centimetres down reads 10% higher than this ring when elevated to the same depth, its cell constant would be 0.9 X 0.9 or 0.81. In this manner, all the rings can be recalibrated as they are moved to different heights.

The probe must be reprogrammed to read while the rake goes by. A program was written called "probetes.bas" which does this and saves one file for each ring. In the Inco installation, the ring near the surface gets pushed into the froth, the ring deeper in the liquid stays in the liquid and therefore little change can be seen. The ring in the solids near the interface gets pushed out of the solids into the clear liquid and the ring in the compacted solids gets pushed into the loose solids. For the rings that reach or are in the liquid, the highest conductivity reading represents the liquid conductivity. For the ring in the compacted solids, the highest value can be compared to a higher ring and then calibrated. If the speed of the rake and the angle pivot are known, the ring profiles (particularly those in the solids) can be used to map the bed. For example, if the bottom ring is rising at a known velocity and taking readings on the way up, this gives a solids profile. This profile can be compared to the ones taken from the probe's normal readings and used as a diagnostic.

The difficulty with this approach is that if the probe gets fully or partially immobilized, its velocity through the bed will slow down (maybe stop altogether) and could cause incorrect calibration. As with any automatic calibration, there is a chance of the probe being incorrectly calibrated and misrepresenting the load in the thickener. The algorithm would have to have various precautions to warn users that the calibration should be verified.

3.4.4 **Manual Calibration**

A hand-held, single-cell probe was constructed at McGill and can be used for conductance measurements in thickeners (Figure 3.4). The probe consists of a three-ring conductance cell (1 positive ring, 2 negative) encased in a PVC tube so that the sample is isolated during measurement. By having a single cell and moving it through the thickener, only changes in density and conductivity will affect the results. The single cell can therefore be used to remove any of the differences in the rings of the 32-ring probe that results from uneven deposition (or other factors).

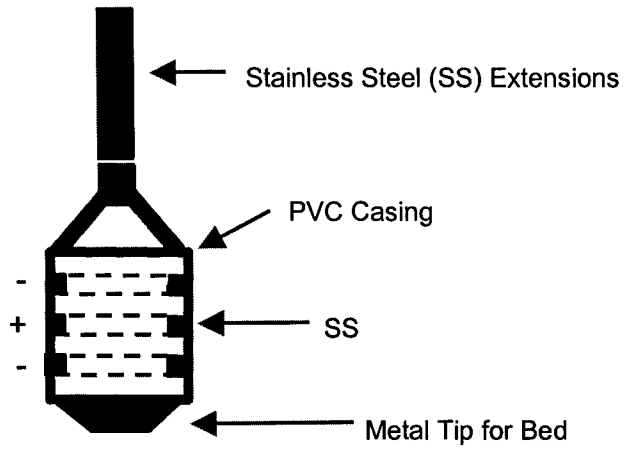

Figure 3.4: Portable Conductivity Probe Design

The probe has frequently had more problems with deposition near the top, as the solids tend to act like a scouring media and keep the probe clean. If the interface level is constant for an extended period of time, there will be a "ghost" interface created by the deposition on the rings that are free of the solids. Fortunately, the deposition reduces conductivity so that a ring that is normally in the solids and is then uncovered will show a particularly high conductivity reading and thus be readily identified. The purpose of calibration is to remove any lack of homogeneity from the different rings. Knowing what each ring is supposed to read by having a second measurement is therefore a good form of calibration.

Comparing the calibration methods, it becomes clear that a combination is ideal. The probe may as well take a ring profile as the rakes push it as this is normally probe downtime. The standardization procedure is the most durable and could be used to verify the ring profiling results regularly. The portable probe is precise and can be used to examine conditions that appear to be related to conductively non-homogeneous solutions. This is also useful as a check on the standardization method. Curve fitting, although it allows for quick and smooth profiles, does not allow for the diversity normally associated with operations. One of the greatest strengths of this probe is its ability to diagnose changes in the solids profile. If you assume a constant formula for the profile, it limits the probe for use as a bed-level sensor only.

3.5 *Other Conductivity Probes*

3.5.1 A Moving, Single -contact Cell

As introduced above, the portable probe constitutes a different form of conductivity probe. Although it was initially designed as a calibration tool for the stationary probe and as a thickener diagnostic tool, Outokumpu has made it into a thickener control tool [17]. Outokumpu redesigned the sensor head into a fiberglass casting with inlaid stainless-steel rings. The improved manufacturing of the head increases the measurement accuracy. Outokumpu also designed a lift and lower mechanism controlled by a proprietary electronics card. The lift system is based on a rotating drum that changes the direction of rotation when an extremity is reached based on a gear change. The system has proven robust and is currently installed in several applications.

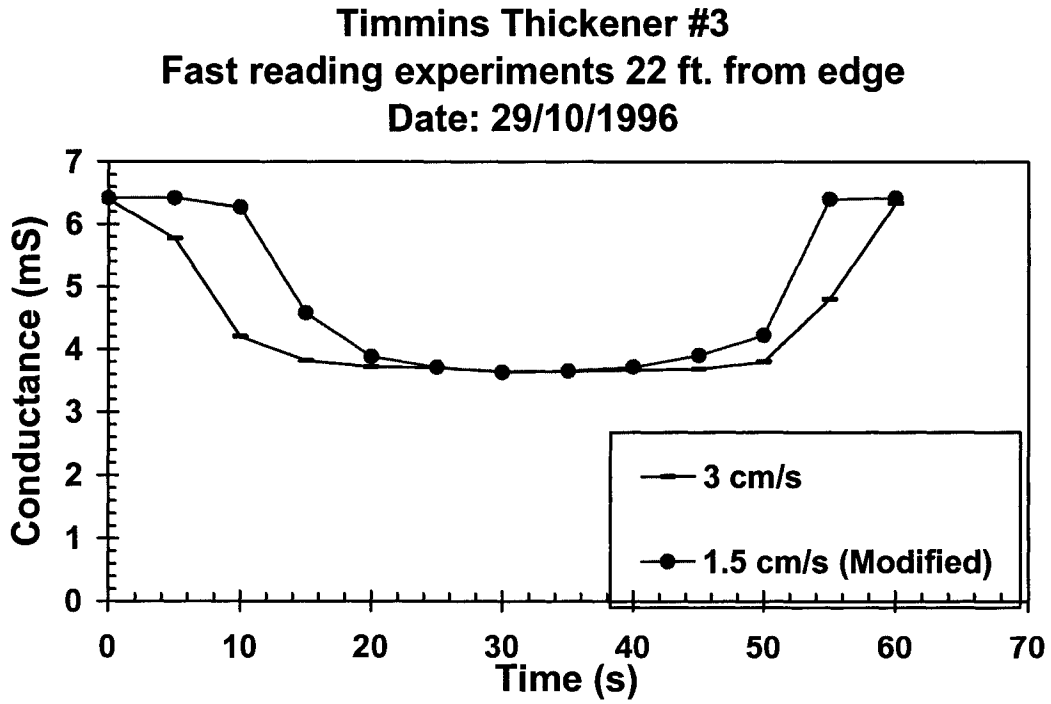

Figure 3.5: Data from a Single-Cell Probe

Data collected from a moving single conductivity cell are presented in Figure 3.5. The figure shows two different insertion speeds. Since the profiles were taken at the same location only a few minutes a part, the difference between the two profiles reflects on the hardware. At 3 cm per second, the conductivity meter did not have time to adjust to the changing conductivity as the probe passed through the interface. At 1.5 cm per second, the profile is a lot better defined (the profile has been modified to fit the same time scale). The figure also shows a lack of symmetry in both profiles (this can be seen by the increased area between the curves on the left side of the figure) despite the fact that the profile undergoes a full lift and lower cycle. Theoretically, the profiles should be symmetric since the bed is the same when the probe goes down as it is when it rises out of the bed. The difference is caused by the fact that the probe carries solids upwards when it rises out of the bed. In both cases, the apparent interface level is higher when the probe is raised out of the thickener. As a result, profiles using a portable probe must be taken during insertion into the bed.

The single contact cell offers the advantage of a single cell constant and therefore a greater facility in the determination of solids content. Solids determination will not be affected by scaling. As the rings are internal, the conductive field is better defined and therefore readings are more accurate. It is also less intrusive than is the larger stationary probe. The disadvantages of this probe design are that it requires a mechanism to raise and lower it that is subject to failure and introduces an increased difficulty in precise depth determination. The internal design also makes it possible to plug the probe.

3.5.2 *A Moving Single Inductive Cell*

The author developed a conductivity probe based on a moving inductive conductivity sensor for Dorr-Oliver Inc. Unlike the contact cells in which a metal surface must be exposed to the slurry, inductive cells work based on the principle that an electric current can be induced at right angles to a toroid. The inductive cell is a toroid in which an electrical current is passed inducing an electric field through the bore of the

sensor head. The conductivity of the field is then measured in the toroid. The inductive cell can be rubber coated or painted since the induced current is independent of the material used to coat the sensor. Likewise, any deposition or scaling will not affect the conductivity unless it significantly restricts the bore of the sensor.

Like the moving contact cell, the inductive cell requires a mechanism to lift and lower it. The author was involved in the development of three systems to move the probe. The simplest is a winch with an actuator so that the probe may be moved to any desired depth. Due to the possibility of the probe getting trapped in the bed, a more robust rod system was invented. The rod is moved by cables and can be positioned at any depth. The third system was a collection of structural members designed to yield a 6:1 vertical movement ratio. This reduces the stroke of the actuators necessary to move the probe through a full profile.

In all three designs, the probe can be moved to a desired location for calibration or test purposes. Although the full profile yields the most information about the thickener, there is additional information possible. For example, monitoring the top of the bed while the rake goes by can help determine the raking efficiency of the unit.

This probe has several advantages over the prior contact electrode technology. The sensor is more resistant to all forms of corrosion, scaling and other forms of chemical attack. The sensor head is approximately 40% of the size of the contact sensor head and therefore will be less intrusive in unstable beds. Its only disadvantage is the movement mechanism. Most thickener operators are leery about added moving parts in a plant as they increase maintenance requirements.

3.6 *Competitive Technologies*

3.6.1 Ultrasonic-level Measurement Devices

One of the first automated techniques for measuring thickener interface levels was an ultrasonic probe [3]. Adapted from the concept of a commercial "fish finder", ultrasonic probes function based on an ultrasonic signal that is emitted from the sensor head and tuned to deflect off a denser medium. The sensor must be in the liquor to emit the signal and the tuning must be done carefully or the sensor will not read the solids-liquid interface. In many installations, ultrasonic probes that are incorrectly tuned actually read the beginning of the compaction zone. Generally, ultrasonic probes are set to read only one specific interface. Many operators tune the sensor to read approximately 2% solids.

Eimco developed a sensor array based on ultrasonics called the Pyramid Eye [14]. The array makes it possible to scan the bed for multiple densities thereby giving a full profile. The array also gives a full radial view such that the operator gets a full two-dimensional radial cut of the thickener. A problem with the pyramid eye output is that a two-dimensional picture of a thickener provides more information than an operator knows what to do with. Operators are not experts in solids-liquid separation and prefer useful control signals to a full picture of the bed. Many thickeners are unmanned and require the control signals to be directly connected to control logic hardware which directly manages flocculant and/or underflow discharge rates. The Pyramid Eye does not always control flocculant well since the algorithms that interpret the thickener image are still being developed.

3.6.2 Optical and Infrared Sensors

Optical sensors are generally mounted as an array on a rod or channel. The channel has emitters on one side and receivers on the other. As the solids prevent the light from reaching the receiver, the interface is determined as the point at which the

receiver reads below a certain threshold. The Markham probe [31] is a light-based version of this. These probes do not give profiles, nor do they give an indication of the solids density. They are well suited to clarifier applications where the solids are light and fluffy and will block light at very low densities.

3.6.3 Amdel's Thickener Interface Gauge

Amdel [20] has developed a probe that scans slurry for naturally occurring radioactive materials. The liquor rarely contains any radioactive elements unless fine suspended solids are present. From the level of radioactivity detected by the sensor, the concentration of solids can be determined. As with the conductivity probe installed as part of this thesis, Amdel's probe is either installed above the rakes or a tilt mechanism is included. Amdel's installation list includes many difficult applications including alumina red mud settlers. Although the technology makes a full profile possible, Amdel has focused on interface determination and this is the only output signal (4-20 mA) provided. The screen provided with the sensor shows both the solids-liquid interface and the beginning of the compaction zone.

3.6.4 Settling-rate Measurement

Control texts are replete with the advantages of feed forward control, particularly when residence time is a concern as it is with thickeners [32]. Allied Colloids (now Ciba) has designed an on-line settling cylinder called the Clarometer [18]. The instrument takes a slipstream of feed, flocculates it and then monitors the time to settle beneath a certain point. Based on the result, the flocculant addition to the thickener is immediately changed so that the feed receives the flocculant it requires. The cylinder is then flushed with water and prepared for the next test. Many plants have developed their proprietary version of this device, frequently using an optical sensor to determine where the settled solids interface is (it is also possible to use conductivity to deduce settling rates in a cylinder [51]). Thickeners with a feed

forward control system are at a significant advantage but still require controls to regulate underflow withdrawal rates.

3.6.5 Allied Colloid's Sentry Process Management System

The Sentry Process Management System [18] is not a single competitive technology but rather, a complete control system. It includes Allied Colloids Clarometer, an ultrasonic level indicator, an overflow turbidity meter and both feed and underflow density measurements. It is one of the premiere thickener control packages available. Comparing this to the conductivity probe is done to show the versatility of the probe. The probe will yield a better interface signal than does the ultrasonic probe provided as part of this package. The probe cannot provide feed forward control, but there are signals that it provides which will give the user almost immediate information about a possible thickener upset. The probe can give underflow solids with an equal precision to the sensor provided as part of the package. While the probe cannot determine the feed solids concentration, the sentry system cannot evaluate the way in which the material is compacting. To optimize flocculant, the probe can evaluate the entire profile and determine reagent requirements based both on settling and compaction requirements. The probe can also be made to evaluate raking efficiency and the presence of froth on the surface of the thickener. It can be argued that a better control of the thickener can be achieved using a conductivity probe to control the full solids profile than through a control system even as complete as the Sentry system.

Chapter 4

Conductivity Probe Installations

4.1 Kidd Creek Conventional Tails Thickener

Kidd Creek (a division of Falconbridge, Ltd.) operations in Timmins, Ontario was the first industrial installation of the conductivity probe. The plant had an existing probe that was designed for a flotation column. During a plant shut down, the tailings thickener was emptied and a plate was added on the rake truss where the probe was installed to eliminate the possibility of the probe getting wedged in the truss structure. The probe was installed a few metres past the end of the short rake arms so that plates were installed only on the two long rake arms. A pivot was installed on the bridge and an aluminum pipe was used to secure the probe. The location was approximately 25 m from the centre.

The data were collected Aug. 17, 1994 since this was the first full day of operation with a program that saved data files. The probe was repositioned on Aug. 18 that

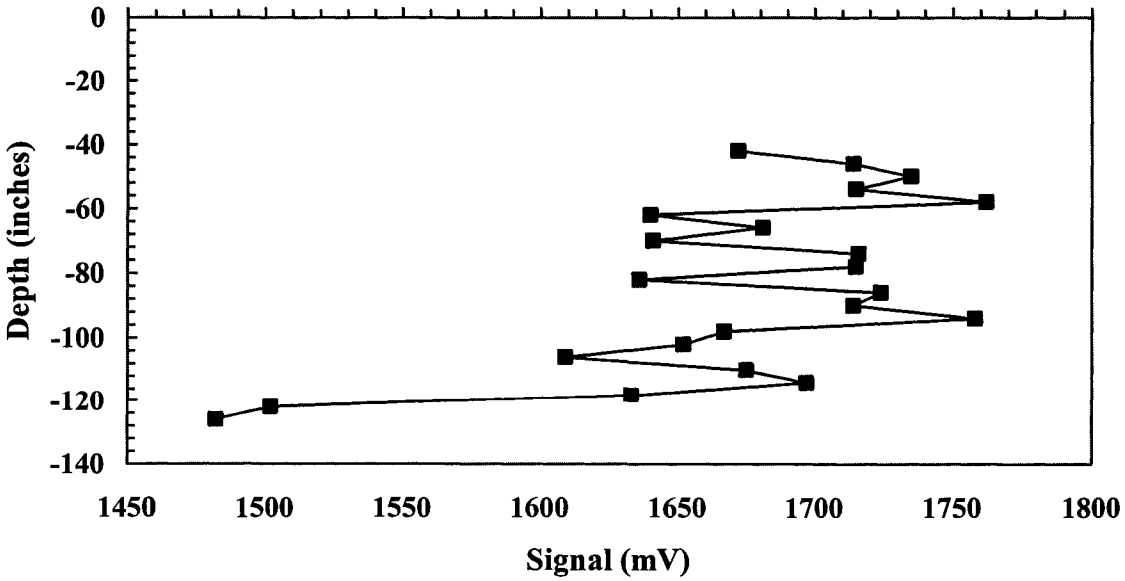

Figure 4.1: Typical Profile at Kidd Creek

resulted in the submerging of the anphanol connector (and subsequent leakage). The probe was removed and dried after the leak and then reinserted. Figure 4.1 shows a typical conductivity profile; the solids only contact the bottom most rings, which is why the decision was made to reposition the probe. There is a large degree of noise in the profile but this is mostly due to the fact that cell constants were not calculated for the system. Cell constants were calculated in the laboratory but could not be applied once the probe had been attached to the supporting bar as the bar altered the cell geometries. The situation can be seen on the profile as the large decreases in conductivity at rings 1, 6, 11, and 17. Each decrease represents the location of one of the fasteners used to connect the probe to the aluminum support bar and all decreases are present on all profiles. The reason for the decrease in conductivity is the fact that the cell is partially filled with the non-conducting supporting plastic, which acts to impede the passage of electrons, much the same way solids would. Despite the noise, the last two rings are clearly in the solids as can be seen by their significantly lower conductivities. An attempt was made to lower the probe; however, not only was the anphanol connector submerged but the probe hit the scrapers and was severely thrown about each time the rake passed. This is because the solids bed is quite low in the thickener. The only way to remedy this is to either alter the operation (i.e, slow the underflow pumps) or to reposition the probe closer to the centre where the scrapers are lower and there are more solids. This thickener was eventually replaced by a 30m diameter Supaflo unit, since the torque was insufficient to build a bed capable of compacting the material to the desired underflow density.

Figure 4.2 shows how the conductivity of different rings varies with time. The top and 6^{th} cells mirror each other quite closely and the 12th and 18th cells are quite similar, but there are significant differences between the two pairs despite the fact that they are all in the liquid. The bottom cell is in the solids until 860 minutes at which point a sharp rise is noted after which the bottom cell mirrors the others. Surprisingly, the conductivity of the bottom and top rings are quite similar at the start even though the bottom ring is in the bed and the top ring is not. This is most likely due to temperature differences and perhaps some liquid miscibility. This in no way

hampers the ability of the software to read the interface, however, as the algorithm looks for a change towards higher percent solids and not lower. An interesting point is that the bottom ring left the bed shortly (approximately 20 minutes) after a division was shut down.

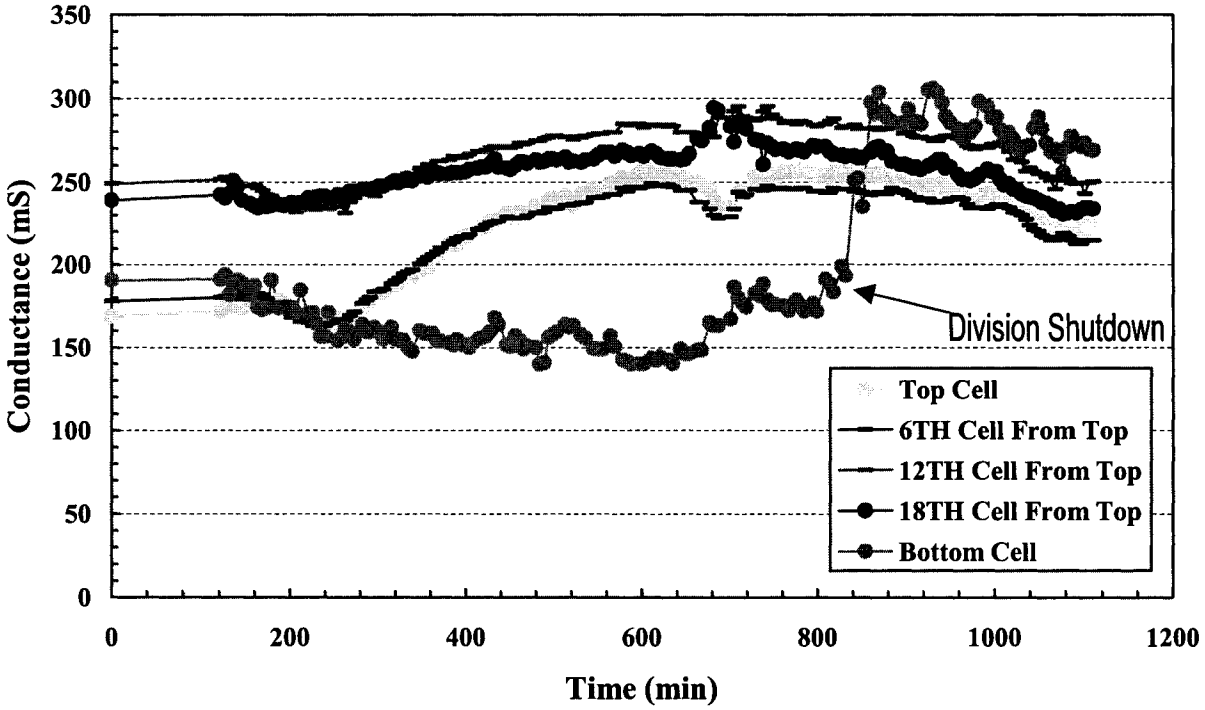

Figure 4.2: Comparison of Conductivity Changes (Kidd Creek)

Figure 4.3 shows the conductivity of the bottom ring as it leaves the solids bed. Note that at this time it was the only ring in the bed and most likely only partially covered. The dip that can be seen shortly before the large rise to the conductivity of the liquid is due to the solids that are carried in front of the rake (there may also be some densification due to the rake). As the rake approaches the probe, a mound of solids appears to precede it that temporarily raised the level of solids around the bottom ring before the probe was removed from the bed. It is interesting to note that the probe never comes closer than 1 metre from the rake due to the supporting bar which means that the mound is considerable in size. Since the scrapers are angled blades, a calculation based on the size of the mound and the angle of the plate could yield the mass transport towards the centre. This data could allow units with variable speed

rake drives to have another control variable as the rake speed could be altered to keep the rake rate even with the underflow withdrawal rate.

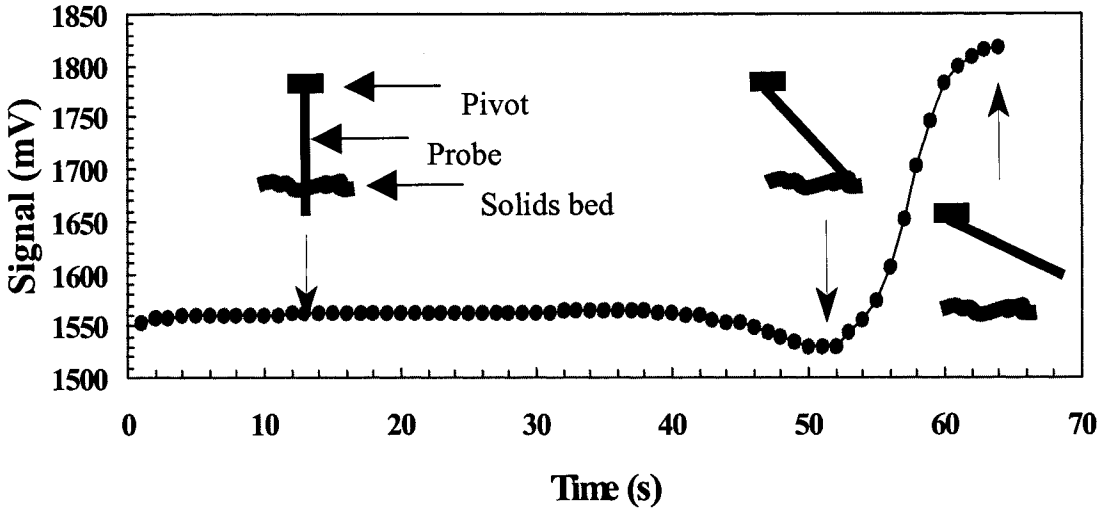

Figure 4.3: Conductivity of the Bottom Ring When Removed From Solids

Figure 4.4 shows the bottom ring as it re-enters the solids bed. The change is clear and shows that the ring was near the top of the solids bed. Using Maxwell's model, the density of the region to where the ring returns is only around 25% solids by weight. Compared to the work done on tailings applications with a portable probe

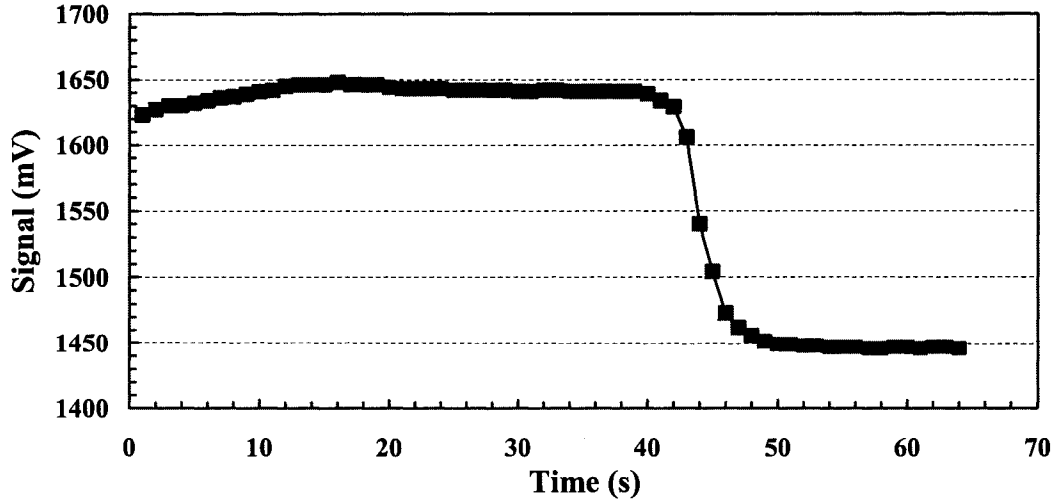

Figure 4.4: Conductivity of the Bottom Ring When Lowered Back Into the Solids

[17], this corresponds to the top of a bed for a tailings application.

The probe was poorly positioned (too high) and with only one or two rings in the bed that made the trend algorithm give erroneous interface levels occasionally (two points is not enough to detect a trend accurately). Figure 4.2 shows a cyclic pattern, starting low, raising to a maximum and then falling again. Considering the fact that the time scale is one day, this could be the effect of daily temperature fluctuations. The ability of the plot to detect a division shut-down is quite promising especially since the 20-minute time lag can be related to the solids retention time of the mill.

After a few weeks of operation, the bottom of the support bar and the bottom two rings of the probe were ground off by the plate on the rake arms. The plate was mild steel and corroded to the point where it was abrasive enough to damage the probe on each pass. By the time the problem was detected, the probe was already damaged beyond repair. Due to the problems with the plate in this installation, the Inco probe was installed without a plate and fared much better. The Kidd Creek probe yielded important data prior to the commissioning of Inco's probe. It was also helpful to Kidd Creek in determining that the tailings thickener could not be operated with a high enough bed due to torque considerations. If the probe had not been destroyed, it could have been used in one of their other thickeners.

Kidd Creek's tailings thickener was the only installation to feature a side-by-side comparison between an ultrasonic level detector and the conductivity probe. The conductivity probe was installed relatively close to the location of the ultrasonic sensor. As soon as the probe was on-line, it was discovered that the ultrasonic sensor was not reading the interface. It was re-tuned according to standard procedure and then agreed quite closely with the conductivity probe. The signal from the ultrasonic level indicator appeared to fluctuate around the interface point. The fluctuations were not detected with the conductivity probe nor are they normally present that far from the centre of such a thickener. The fluctuations were more than likely the result of sensor noise.

4.2 Inco's Booster Station Bulk Concentrate Thickener

The main focus of this thesis is the conductivity probe installed at Inco's Booster station (Copper Cliff, Ontario). Figure 4.5 shows the flow sheet. Inco's Booster station contains five thickeners of which two are normally used for thickening the flotation concentrate from Inco's Clarabelle Mill. The thickener discharge normally gets pumped to a holding tank where it gravity flows to a bank of disk filters. If the thickener requires a discharge rate that exceeds the capacity of the disc filter bank, the underflow can be diverted to a series of storage tanks. The material sent to the storage tanks is eventually fed back to the thickeners. Due to the intense agitation that occurs in the storage tanks and during pumping, the material returns with all the flocculant chains sheared. Since the sheared chains still take up surface area, recycled particles tend to flocculate poorly.

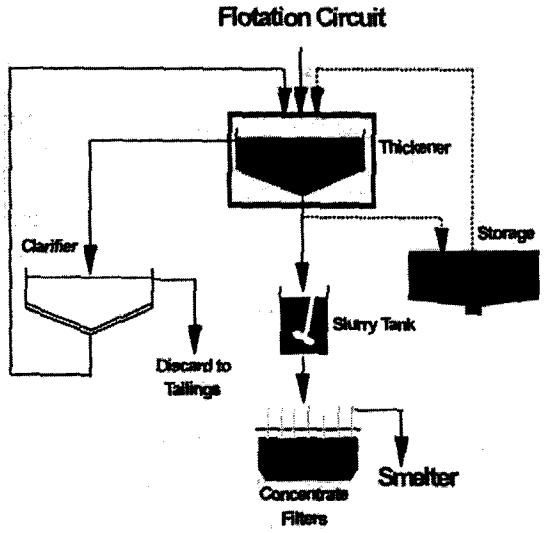

Figure 4.5: Booster Station Flow Sheet

The probe was installed at an r/R of 0.6 and had 32, 1.5cm thick stainless-steel rings spaced by 10 cm of PVC. The probe was filled with epoxy resin to prevent leakage. The probe was attached to a stainless-steel support bar on a pivot so that the rakes could move the probe out of the way. Stainless steel was employed instead of the aluminum used at Kidd Creek to prevent the damage that occurred at that installation. Each ring was connected to two relays so that they could be positive or negative thus allowing the conductive field to be uniform around each of the rings. It also made it possible for each ring to be positive. In earlier probe models, only every second ring could be positive which would have limited this installation to 16 active cells instead of 32. Having 32 measurement points improved the definition of the profiles.

The probe was installed on Oct. 7, 1994 and readings were collected starting on Oct. 8, 1994. Figure 4.6 shows a profile taken on the first day. The two lines represent the calculations of the interface and mud line (discussed later). These calculations were included in the original software as it was intended for this probe to send two 4-20 mA signals to Inco's control system.

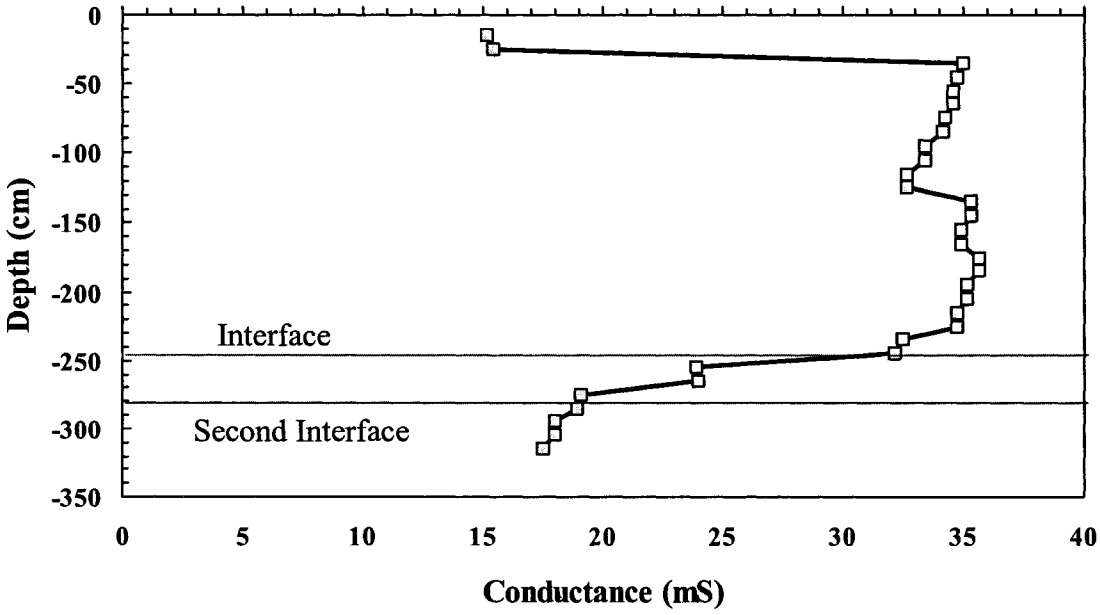

Figure 4.6: Typical Profile at Inco

It was noticed that the thick froth on the surface of the thickener prevented the probe from returning to a fully vertical position in some cases. A water hose was attached to the catwalk and the area around the probe was continuously sprayed with water to keep the area free of excessively thick froth.

The rakes in these thickeners rotate 4.4 revolutions per hour. This means approximately 13.6 minutes for a full rotation, which leaves approximately 6.8 minutes between rake passes. The duration of the rake pass is approximately 1.8 minutes leaving 5 minutes available for measurement. Due to the possibility of a change in rake velocity, the probe was programmed to use 3.5 minutes with 1 minute of dead time before the reading to allow for bed stabilization and 0.5 minutes after the profile as additional dead time.

The original idea was to use the full solids (or conductivity) profile such as Figure 4.6. An experienced person can identify much useful information from even a single profile. From Figure 4.6, an operator can see that the solids-liquid interface is at a depth of 240 cm. An operator can also see that there is only a small bed in the thickener that is fully compacted. In such a situation, an operator would feel comfortable allowing the thickener to fill with solids and the sharpness in the change in the profile indicates that additional flocculant is not required. Upon further investigation, however, it was found that most operators could not determine what an ideal profile should look like. With thickeners, the unit can be gradually filling and approaching an alarm condition without operators being able to detect it since the change is so gradual.

The key is to show the data over a longer time span so that the operator can discern what is happening in the thickener. An example is Figure 4.7 where several profiles are plotted, each at an even time interval so that changes in the profile over time become apparent. Figure 4.7 shows three profiles taken 12 hours apart. As is

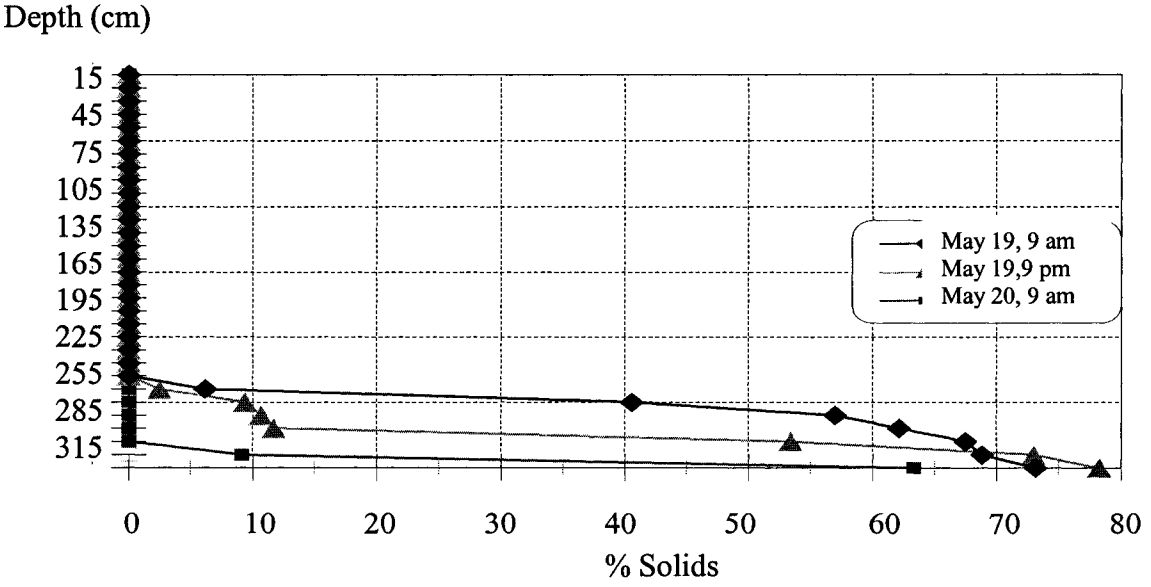

Figure 4.7: Overlapping Profiles (May 19-20, 1995)

evident, the first profile at 9 am on May 19 shows a low bed that reaches a density of 73%. Twelve hours later the bed is lower but a higher density (78.5%) is attained.

This higher density resulted in a higher torque on the rake despite the fact the total solids content of the thickener was essentially constant. The result was that the operators discharged the thickener and 12 hours later, at 9 am on May 20, the bed had practically been eliminated. This is one of many examples in which a change in the density of the bed led the operators to believe there was a change in the total solids content of the thickener. The deception is mostly due to the reliance on torque measurement. The problem with profile analysis is that it is time consuming and requires experience. Furthermore, even someone with experience cannot always tell which features of the curve are due to deposition on the rings and which are true data.

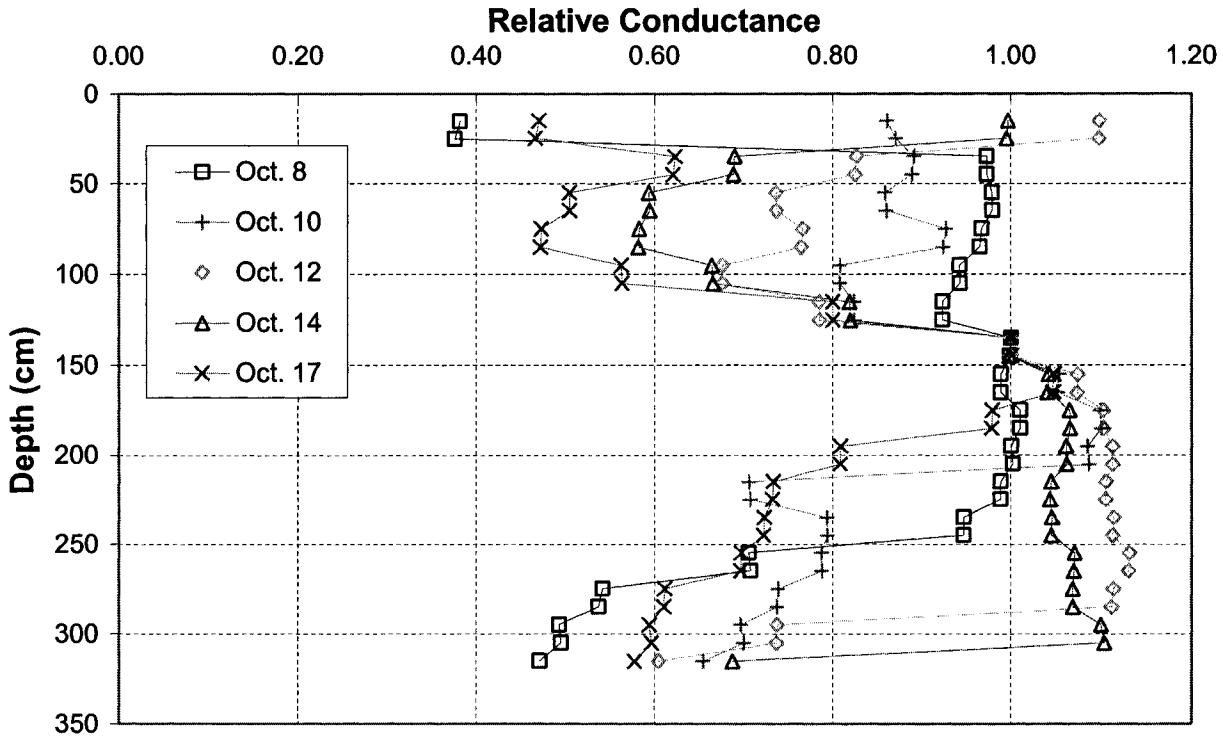

Figure 4.8: Bump Formation Due to Deposition, Oct. 8 - 17, 1994

Figure 4.8 shows several profiles taken over the first week. The bottom half of the chart shows considerable changes in the bed over this period. The top half of the chart, however, should be the same for all profiles since those rings are in the liquid. The "bump" on the profile appears to grow with time. The probe was removed at the end of the first week and a deposition was noticed on the rings near the top (Figure 4.9). The deposition was originally black in color but changed at different times of

the year. The deposition was not present near the bottom of the probe, presumably because the abrasive solids scoured the probe clean as the deposition formed. The deposition on the probe has been one of the most intriguing problems. Although it can be taken into account through the cell constant, its inconsistent rate of growth and seasonal characteristics make it difficult to account for long term. The deposition seems to have the greatest effect in the fall and the least effect in the spring. Its colour has changed from black to gold to dark red. Analysis showed the deposition to have roughly the same chemical composition as pyrite. The deposition is non-conductive so as the film on a ring increases the resulting conductivity value decreases. After a while a profile of the deposition is obtained with the top rings being less conductive than the bottom ones (i.e, a profile in water alone would show a curve based on the different deposition growth rates which would look like an inverted solids profile). The result is a smaller difference in conductivity between rings covered by solids and those that are not. Eventually, there would be no difference and the probe would cease to yield a useful signal. It may ultimately be possible to account for the deposition and correct its effect on the conductivity of the affected cells or it may be possible to substitute a probe material resistant to such depositions. For the time being, someone must periodically (once a week) update the cell constants and a monthly cleaning of the probe is recommended. Figure 4.10 shows the effect of cleaning a ring on the probe. The probe was removed from the thickener and a ring was sanded clean. The effect is an increase of 66% in the reading of the ring.

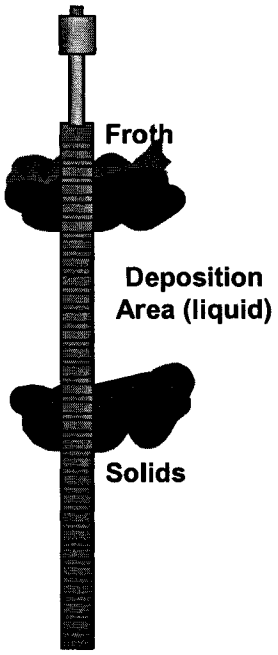

Figure 4.9: Deposition Formation

In order for the probe to deliver reliable control signals, the deposition must be accounted for as soon as it forms. It was discovered that a deposition on the surface of the conductive cell has the same effect as any alteration of the cell constant. By changing the cell constant the deposition can be accounted for. Figure 4.11 shows a

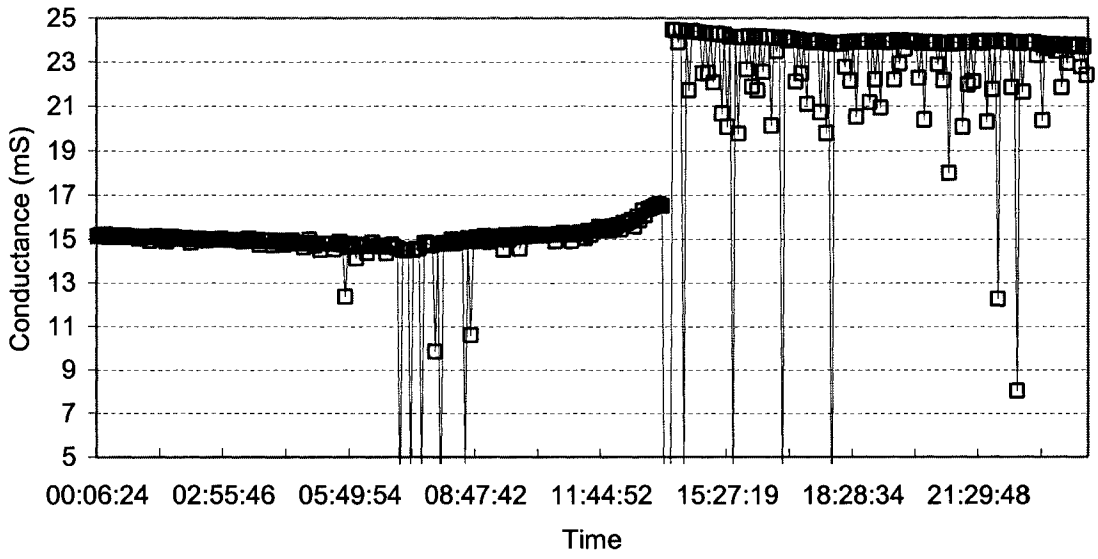

Figure 4.10: Probe is Removed and a Ring is Cleaned, Jan 30, 1995

profile before and after correction of the cell constants. This profile was chosen because the thickener was running without flocculant and the solids-liquid interface was not very clear. The correction of the cell constants must not start correcting for

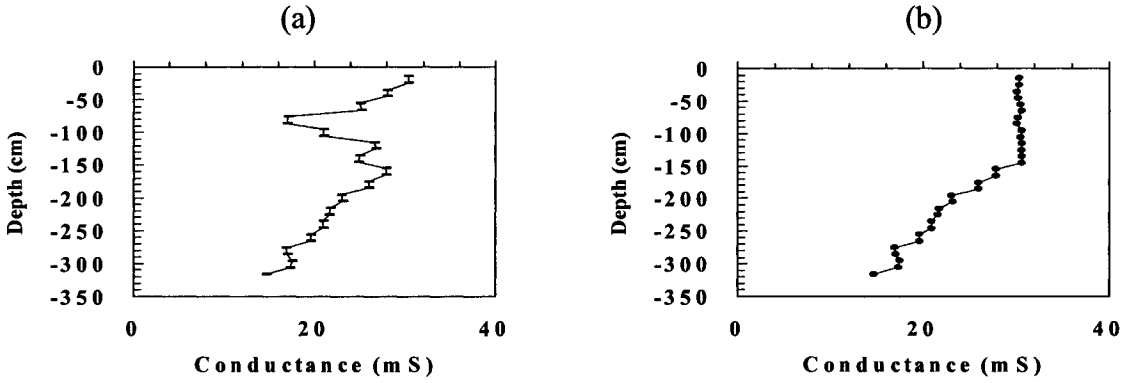

Figure 4.11: Typical Profiles: (a) Uncorrected, (b) Corrected

solids and therefore a technique was developed to ensure that only rings in the liquid were corrected. Figure 4.12 shows the profile with the standard deviation of the readings of each of the rings over a day superimposed. As the reading of a particular ring will only change as a result of the presence of solids, the rings that never encounter solids will show small standard deviations. The chart shows that all rings above a depth of 90 cm are clearly in the liquid. The greatest standard deviation is between a depth of 90 and 200 cm. This is the range over which the solids-liquid

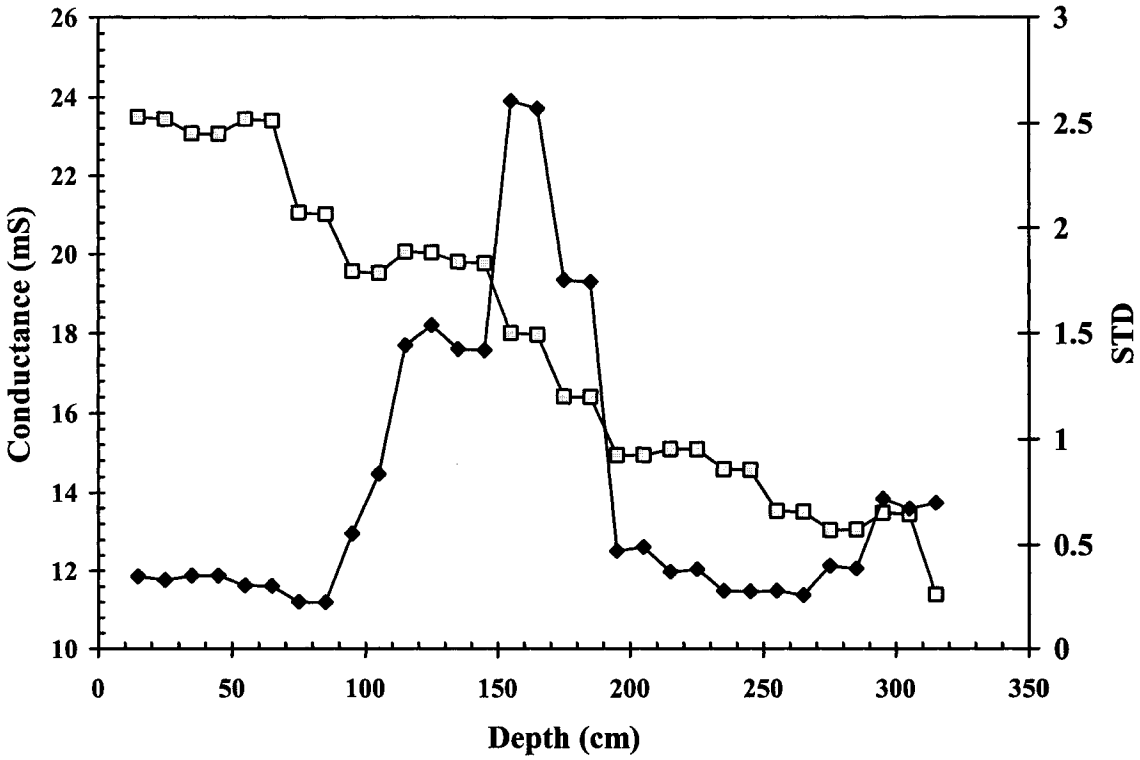

Figure 4.12: Standard Deviation of Readings Vs Depth

interface varied during that day (i.e., about 110 cm). The drop in standard deviation below 200 cm is due to the fact that rings that are constantly surrounded by solids will also show a small standard deviation. It is interesting to note that the standard deviation increases near the bottom of the probe, which indicates that the underflow density varied considerably over the day. Although the standard deviation method was developed to ensure the location of the solids bed for the purposes of probe calibration, the technique is also useful for solids bed detection in general. It also shows the effect of poor thickener control on the underflow density. The result of a 110-cm range for the solids-liquid interface is an inconsistent underflow density that has deleterious down stream effects.

The original control signals were the interface level and the mud level (discussed in Chapter 5). An algorithm that detects the greatest change in the profile determines the thickener interface. The mud level is subsequently determined by another algorithm that looks for the minimization of change in the readings below the interface. Both algorithms were designed based on concentrate thickener profiles

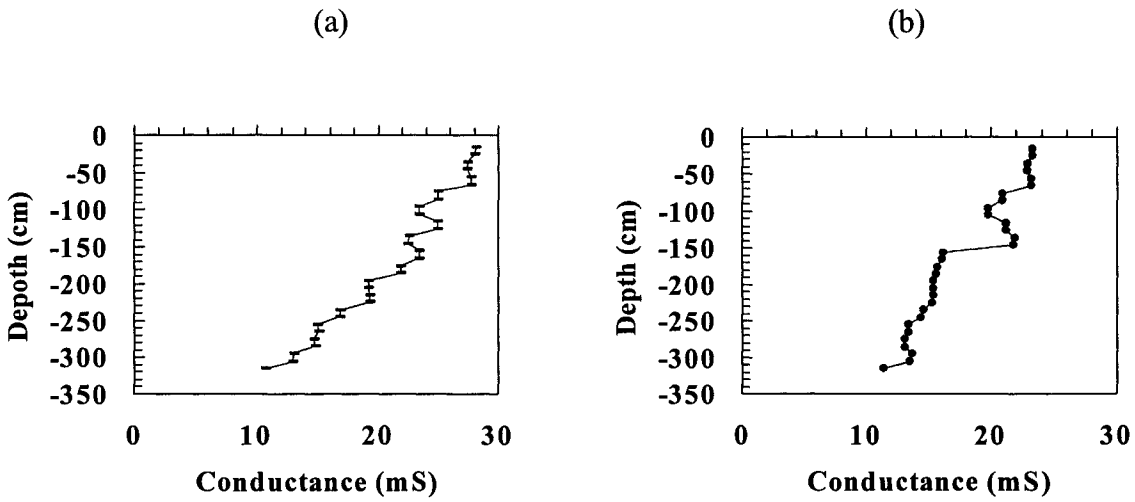

Figure 4.13: Typical Profiles: (a) Disturbed , (b) Clear

collected at Kidd Creek using a mobile conductivity probe [13]. Because of the possibility that Inco's bulk concentrate thickener would have substantially different profiles than those collected at Kidd Creek, the ability to change the tolerance of both algorithms was made flexible. From October to January, the interface signal proved acceptable, but the mud line signal frequently failed. In early February, several profiles were recorded which prevented either algorithm from yielding a usable control signal. Figure 4.13 shows two profiles taken in early February 1995. On February 2, the profile is almost linear with no clear interface. Both signals failed and despite the obvious presence of solids, the signals showed the thickener to be empty. The profile taken on February 6 shows a detectable interface, but the mud line could not be discerned. Due to several days of operation with profiles of this nature, the data collected from the probe were reviewed for improved methods of signal generation. Figure 4.14 shows several rings plotted vs. time on February 6. At 800 minutes, a clear change can be seen as the bed drops, uncovering a ring and then builds again. The ring is uncovered over 5 readings or 30 minutes. This method of representing the data makes the location of the interface very clear as soon as a ring is uncovered. It also makes it possible to determine the rate at which the bed is rising or dropping.

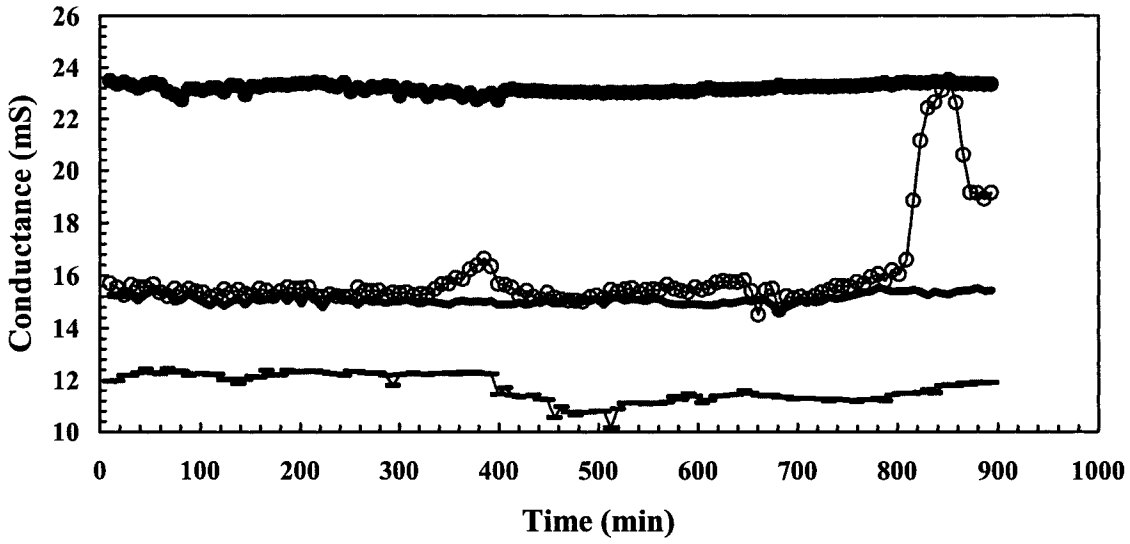

Figure 4.14: Four Rings Over a Day, Feb 6, 1995

Based on the success of this data representation method, a more detailed analysis was made when a series of known changes were made to the operation of the thickener in May, 1995. Figure 4.15 shows the bottom 7 rings of the probe and a ring in the liquid over time. From 2:30 to 8 pm, the already light load in the thickener (only 1 ring is covered by compacted solids) seemed to be getting lighter. The torque reading also suggested this so the operator decided that the solids must be settling poorly and added flocculant to increase settling rates. The operator felt that his adjustment was successful as the density quickly rose and resulted in a corresponding rise in torque. As can be seen in Figure 4.15, however, only two rings (#1 fully and #2 partly) are in the solids despite the increase in floc dosage. At 11:30 pm, underflow discharge was suspended since the bins at the dryer were full. This resulted in the bed rising to cover another ring. Underflow discharge resumed at a slightly increased rate 45 minutes later as the operators were told that an increase in feed rate was expected. Steady state was maintained until 2:30 am, at which point the feed rate did increase as expected. The increase in feed rate resulted in the filling of the thickener as can be seen from the increasing number of rings that get covered by solids. This type of analysis can be quite complex since up to 31 rings, in principle, could be tracked. In

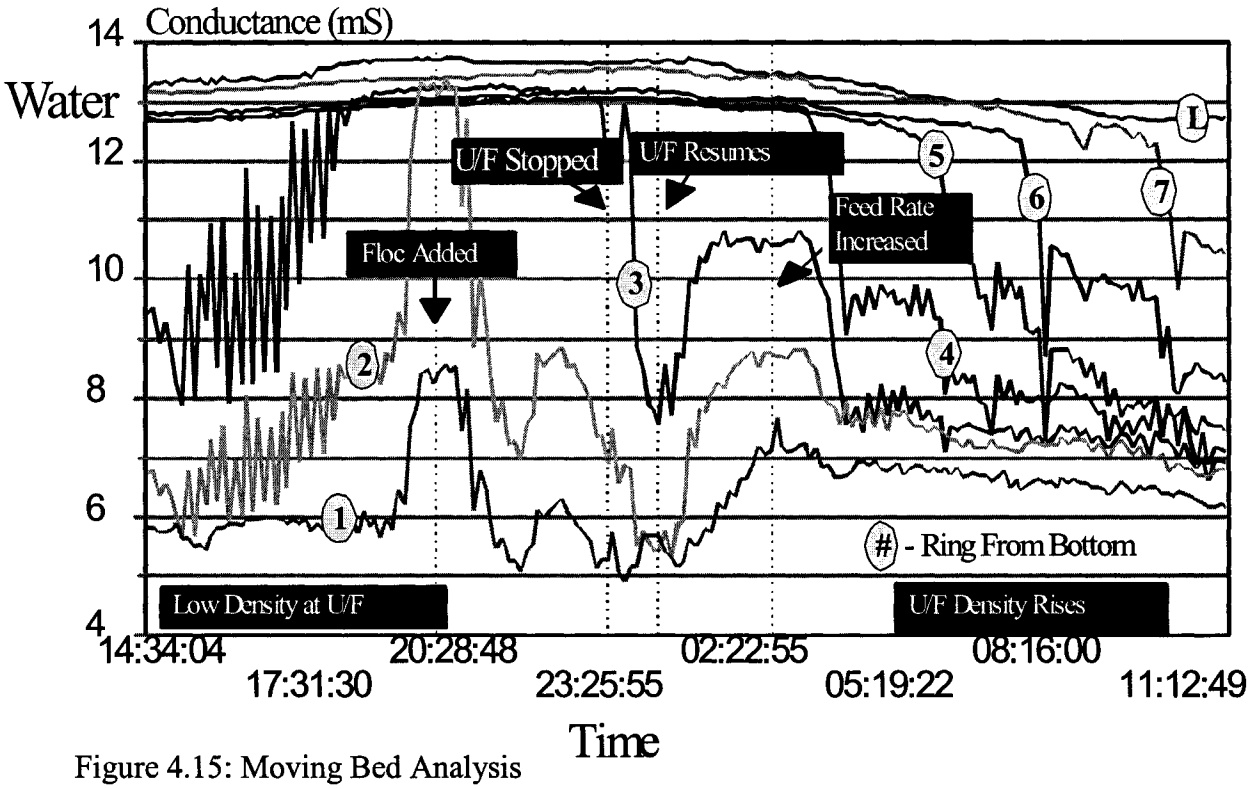

Figure 4.15: Moving Bed Analysis

fact, only a few rings need be tracked, provided they are carefully selected to represent all the zones of the thickener with an emphasis on the interface region.

While Figure 4.15 yields much information, it is not intuitive as conductivity is inversely related to the presence of solids and thus a rise in value actually represents a drop in solids content. Figure 4.16 shows the same rings in terms of % solids vs. time instead of conductivity. This representation clearly shows the increasing %solids as the thickener fills on the right-hand side of the chart. Unfortunately, the confusing feature of this chart is the fact that the liquor % solids seems to range up to 14%. This is the result of the deposition that caused several rings to read "ghost" solids. When plotting rings vs. time, the rings that are in the liquid are best determined by the shape of the profile in comparison to a ring that is known to be in the liquor. Figure 4.15 shows that the rings that are uncovered clearly mirror the pattern represented by the ring that is known to be in the liquor. This pattern recognition clearly demonstrates that the strength of the conductivity probe lies in the use of relative

signals as opposed to absolute values. Since control devices require absolute signals, algorithms that convert good relative values into absolute control values are required.

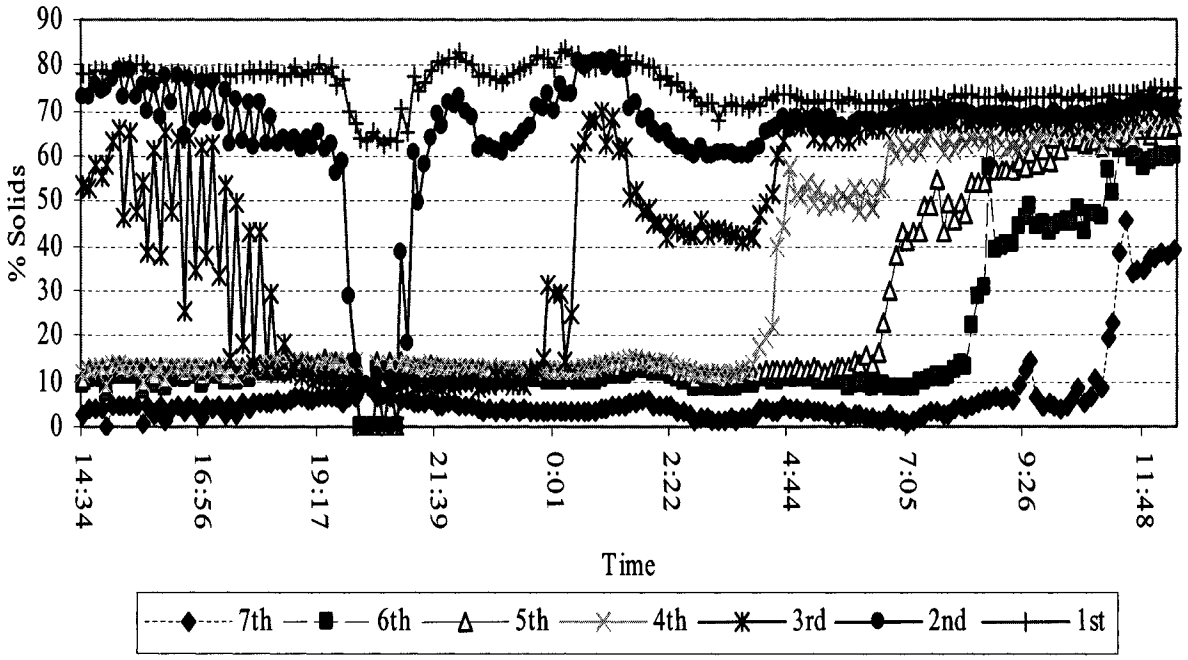

Figure 4.16: Moving Bed Analysis (% Solids)

Figure 4.17 shows a signal that was developed for thickener control as part of this thesis and is discussed in detail in Chapter 5. While a true interface measurement signal has been extensively used in industry, results from the use of this signal are varied. In some plants, the profile below the interface is consistent and therefore the actual interface height is a very powerful control signal. In other cases, however, the solids profile beneath the interface can vary significantly and therefore the interface height is not as important as a method of characterizing the nature of the bed. The "interface" signal (the quotations are used to differentiate this signal from an actual interface depth measurement) is a relative calculation based on the readings in three zones of a thickener (Figure 4.17). For signal calculation, the thickener must be divided, based on historical data, into a region that almost never contains solid and a region where solids are almost always present. The region between these two is the

interfacial region where solids may or may not be present based on operating conditions. The calculation is the difference between the average solids content of the interfacial region and the liquor region divided by the difference between the

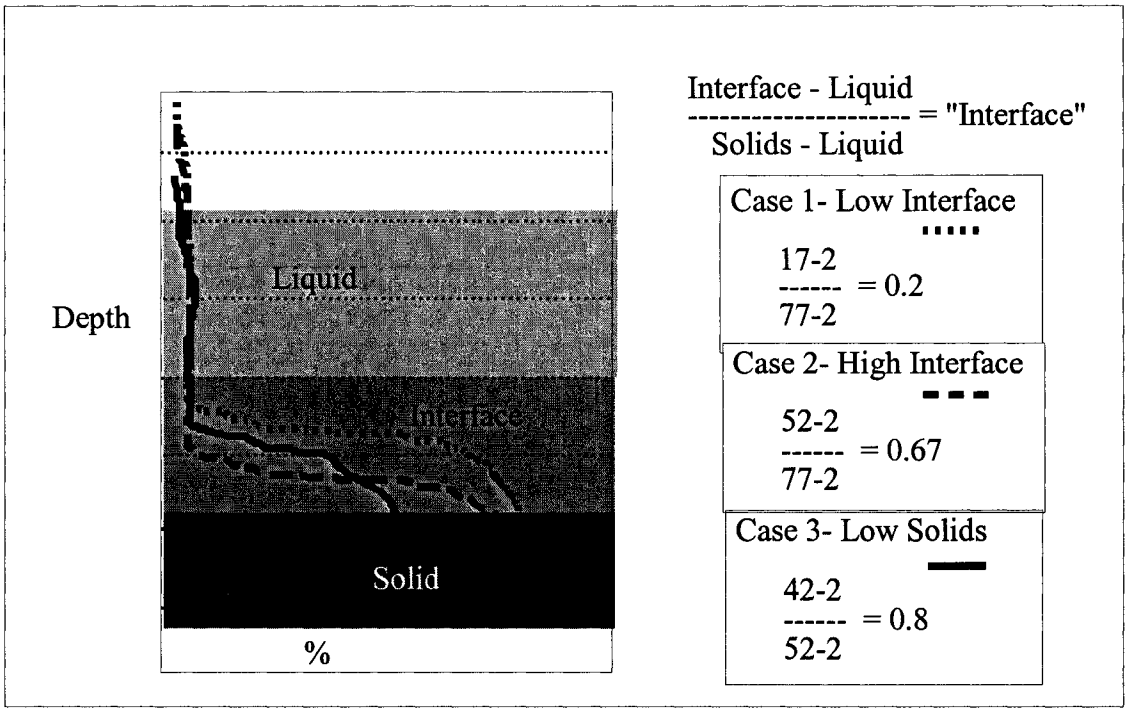

Figure 4.17: "Interface" Calculation

average solids content of the solids region and the solids content of the liquor. The denominator represents the full span of solids readings detected in the thickener whereas the numerator is the normalized solids content of the interfacial region. As can be shown by case 1 of Figure 4.17, a low bed will yield a low "interface" signal. Likewise, case 2 shows that a high bed will yield a high "interface" value. Case 3 is designed to demonstrate that the signal is not infallible and therefore should be used in conjunction with another signal. When the solids content of the solids zone is low, the "interface" signal can be made artificially high. Case 3 is, however, a very unlikely scenario.

Figure 4.18 show the "interface" signal plotted versus time from June 20-23, 1995. The signal responds well to changes in thickener operation. The drop at 9:00 am on

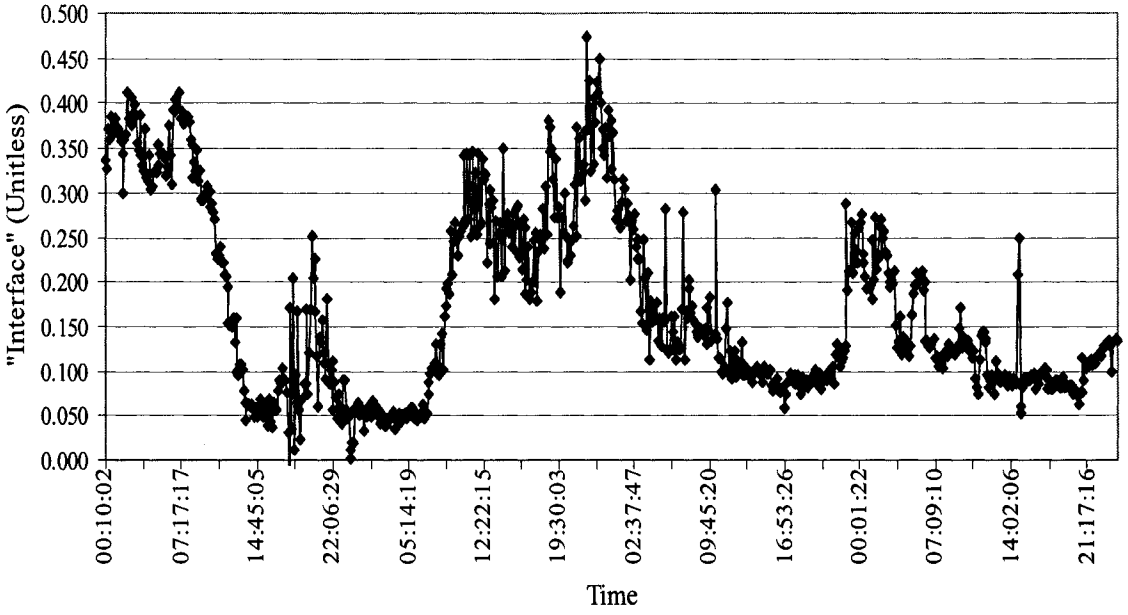

Figure 4.18: "Interface" Vs Time

June 20 was due to a shut down of the Clarabelle mill. The subsequent rise at 12:00 on June 21 was when the plant started back up. The drop on June 22 at midnight was because the flocculant pump broke and was not repaired for 76 hours. Figure 4.19 compares the "interface" signal to the interface calculation provided with the original

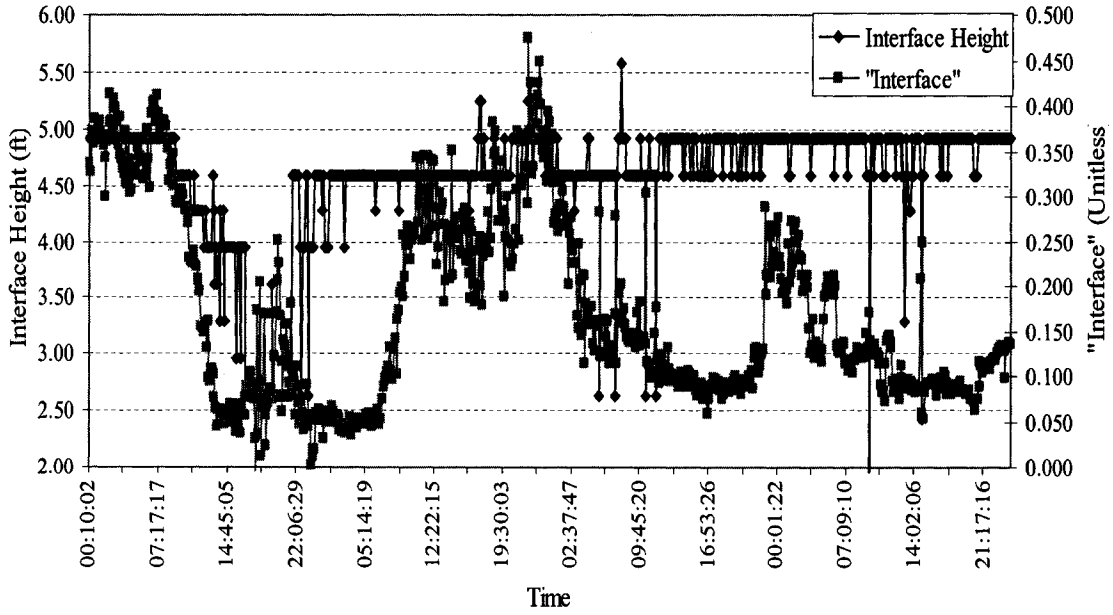

Figure 4.19: Interface compared to "interface"

software. The interface calculation did show the drop in bed height when Clarabelle went down, but the bed reverts back faster than does the "interface" signal. The reason for this was the fact that the flocculant pump was not started when the plant went back into operation and a very light bed rapidly formed in the thickener. The interface signal only reports the top of the bed so the thickener appears to be at the same operating condition as it was before the shut down. In fact, the feed pipe could not handle the volume of feed required to increase the bed by 1-m in such a short time span. This can be seen again on June 22-23 as the "interface" signal drops but the interface height even rises by a little. The broken flocculant pump caused this. While the interface height signal in no way indicates the low solids content of the thickener, the "interface" signal shows a drop in solids content for the interfacial region. Another difficulty with the interface height signal is that when the thickener load was low, the interface height calculation either became erratic or did not show any bed at all. By making the detection algorithm too strict, a gently increasing bed does not show a severe enough interface for detection while making the algorithm too flexible results in reading ghost interfaces and wildly changing readings due to small abnormalities in the probe signal. There are many parallels that can be drawn between a simple interface signal calculation and the results achieved using an ultrasonic probe.

The "interface" signal demonstrated several advantages over the interface height signal. In many cases, particularly when the probe was not properly calibrated, the interface signal indicated that the thickener was empty when it wasn't. It was only successful in determining the interface height approximately 75% of the time. In contrast, the "interface" signal never failed to indicate correctly changes in thickener operation. The "interface" values could not, however, be compared with historical "interface" readings as the scale constantly changed when the probe was recalibrated or the deposition changed in size. The "interface" values were consistent over a 3 day span (i.e., the operator could operate based on numerical set points) and therefore operators could develop responses for given absolute values of the signal. The difficulty was that the set points could not be made into a written procedure since

they slowly drifted. The fact that the "interface" signal yields information about the quality of the bed through the solids content of the interfacial region as opposed to a simple interface height, indicates that this signal is the only one that theoretically can be used as a solitary control signal.

Since "interface" is a unit-less, relative calculation, either the conductivity or the % solids can be used. Another value that can be used is the "corrected" % solids. Due to the deposition and subsequent shift in percent solids readings in the upper readings, a correction was performed on a spreadsheet before cell constants were determined. The correction involved the zeroing of rings known to be in the liquor through a standard deviation analysis. Signal noise is amplified by the conversion of conductivity to % solids and is not removed by the "correction". For this reason, the "interface" signal calculation was programmed using the raw conductivities as part of the thesis.

Figure 4.19 clearly shows that a simple interface height calculation does not yield any information regarding the nature of the bed. One way of determining the character of the bed is to determine the interface height and then determine the total solids content of the bed. Outokumpu's control strategy [13] involves the use of a simple level detection probe and a bed mass transducer to give a relative reading regarding the total solids content of the thickener (Figure 4.20). Their control system has proven very effective using these two signals in tandem.

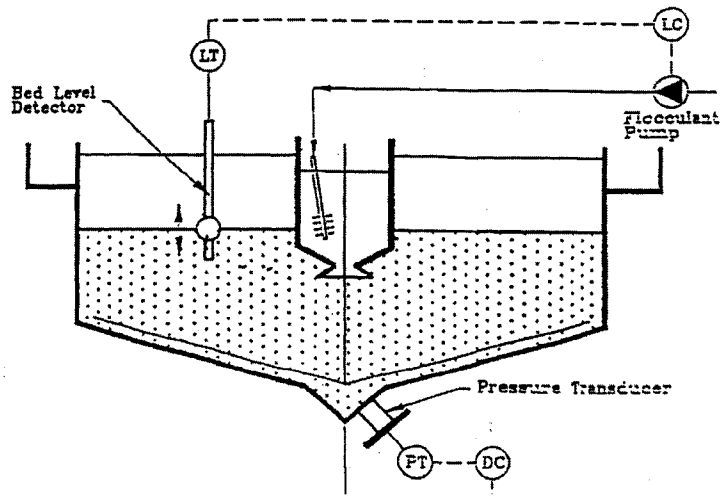

Figure 4.20: Outokumpu's Control Strategy [13]

With the conductivity probe, it is possible to get a measure of the solids content of the

thickener by examining the solids content of each measurement point. In essence, the thickener can be divided up into 32 cylinders, each having the same area as the thickener and a height of 10 cm. Using the % solids reading for each region, the solids content can be determined. The total solids content of the thickener is the summation of the solids content of all the regions. Due to the drift in values near the top of the probe, using the corrected solids value determined by the standard deviation method proved more reliable. The total solids content of a thickener is called the thickener load or inventory. Figure 4.21 shows the load over the same 4 day period (June 20-23). The drop in thickener load can be seen when the Clarabelle mill shut down. Interestingly, on June 22 and 23, the load does not drop as suggested by the "interface" signal, instead the load signal seems to agree more with the

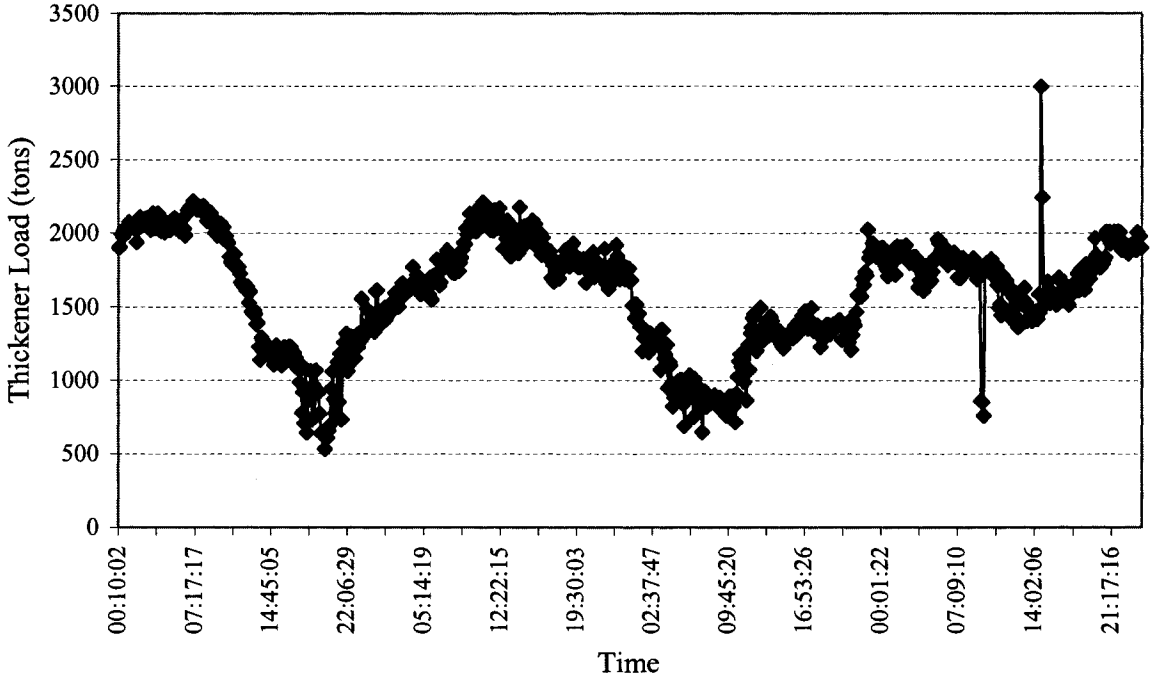

Figure 4.21: Thickener Load Vs. Time

calculated interface height. An analysis of the thickener bed when the flocculant pump ceased operating reveals the fact that the unflocculated pulp split into a low % solids portion and a highly compacted bottom portion. This is predicted by settling theory in the absence of flocculant and was confirmed by high operating torque values on June 22 and 23. The "interface" signal, by showing a drop, was actually

demonstrating the fact that the majority of the solids were below the predetermined interfacial region whereas the interface height was correct in indicating a consistent bed height. If the operator were to use the interface height and the load, they would be forced to assume that the bed was homogeneous. This is unlikely in the absence of flocculant. If the operator were using the "interface" signal and the load signal to control the unit, the drop in "interface" coupled with a steady load value would

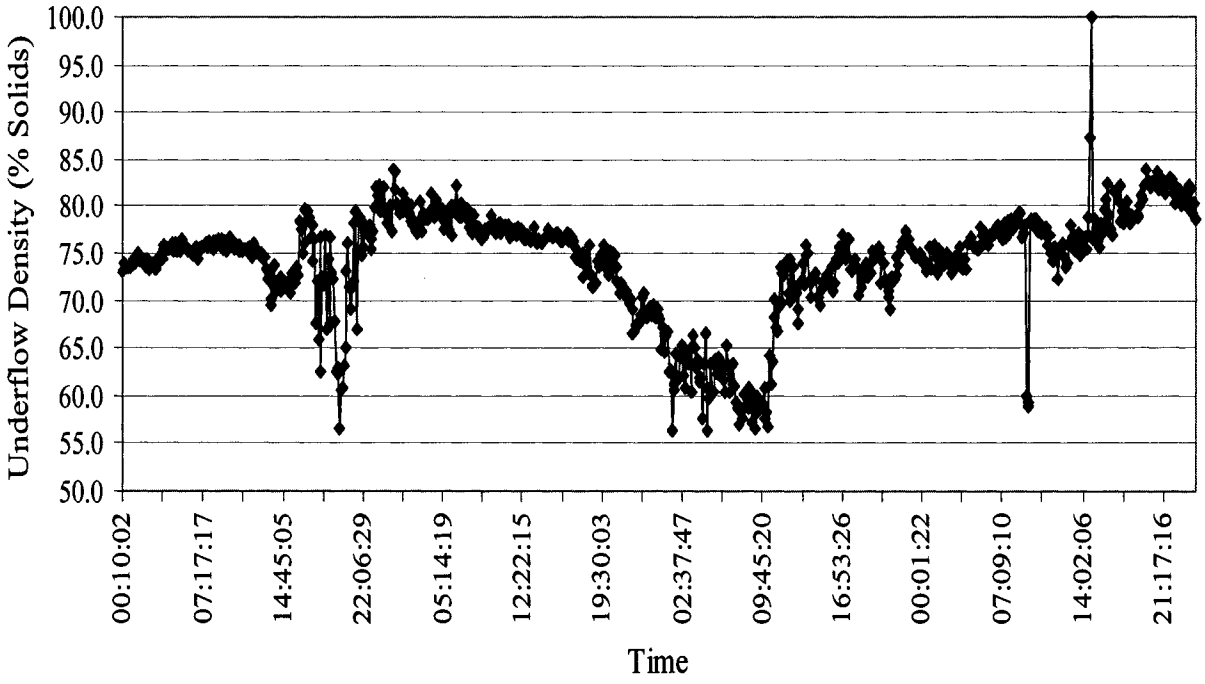

Figure 4.22: Thickener Underflow Density Vs. Time

indicate a high density in the rake area of the thickener and near the discharge. This would help the operator take measures to avoid plugging the thickener or stalling the rakes. Clearly, the "interface" signal offers more information to a well-trained operator in this example.

Along with load and "interface", the probe can also deliver a signal indicating the % solids around the bottom ring (i.e., an indication of underflow density, Figure 4.22). Figure 4.23 shows these three operating signals corresponding to the time analysis of the rings in Figure 4.15 discussed earlier. Correlation between the three signals and the torque on the rake as well as other information such as overflow clarity and filter-

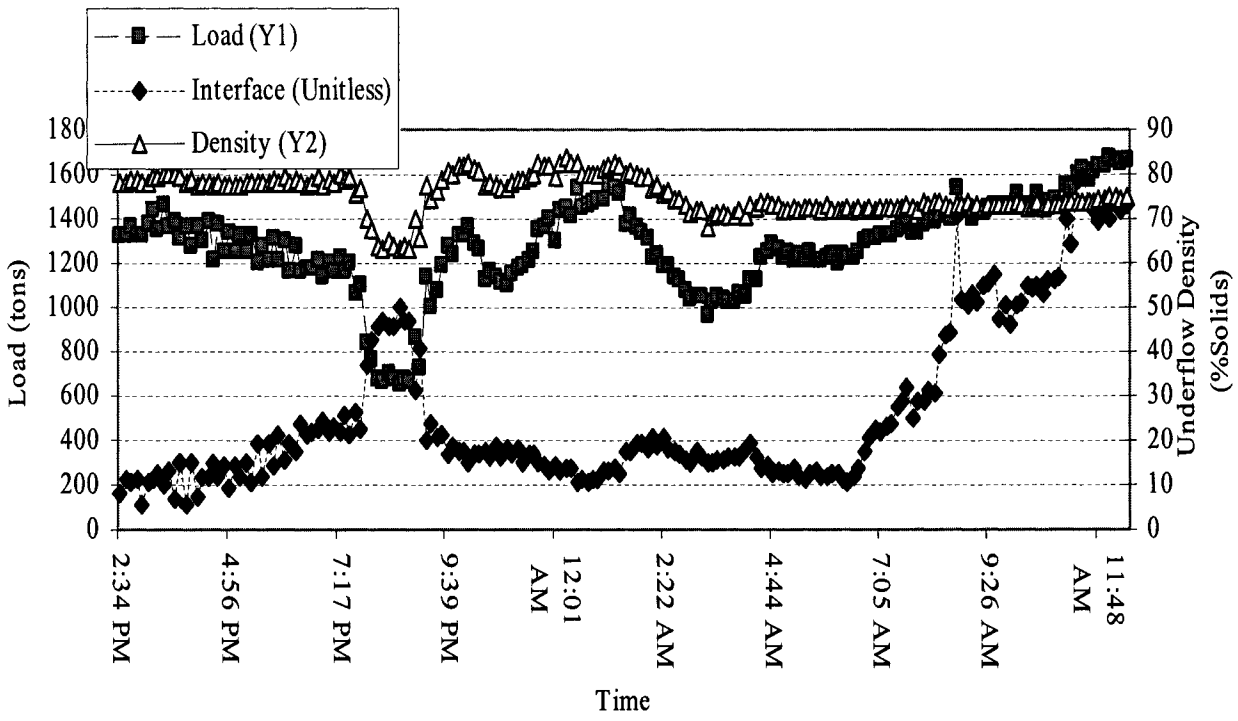

Figure 4.23: Final Operating Signals

cake quality yields a powerful set of signals on which to design a control strategy. The torque can be used to confirm the presence of compacted solids in cases where the probe shows a high load with a low "interface". Conversely even with a moderate load, if the "interface" is very high a low torque is expected since the solids are not near the rake. The load tells the operator how much solids are in the thickener, the "interface" tells him where they are in the thickener. Consider the right-hand side of Figure 4.23: the underflow density is constant and the load is rising so therefore the "interface" must be rising which is indeed the case. The fact that the "interface" and the load are rising shows that the solids are filling the thickener rather than there being a change in settling characteristics. By repeating Figure 4.15 in terms of the operating signals instead of individual rings, the advantages to a control system are clear. Rather than numerous lines, a single curve showing an upward trend reflecting the increasing level of solids is seen. By inspection of Figures 4.15, it becomes evident that only through close scrutiny can the beginning of the rise in the interface be detected, whereas Figure 4.23 clearly shows that the change begins at 6:40 am. The final operating signals do not lose any of the information contained in the

detailed analysis of the bottom rings yet they are far better suited for integration into a PLC or other control system.

The rings on the conductivity probe can be accessed in different ways and at different times. The signals discussed above are all derived from the typical probe profile. Even the ring analyses discussed above involve the plotting of the profile readings versus time instead of depth. In order to explore some control options using non-conventional probe reading methods, the calibration program probetes.bas was used. The program takes readings from a single ring without stopping for the passage of the rake. Figure 4.24 shows readings from two rings near the top of the probe. The ring at a depth of 15 cm is lifted out of the thickener when the rake passes and a conductivity reading of 0 is attained. This value can be used to determine probe verticality. If the probe is frozen at an angle, the software can use the value of the top ring to warn operators. The second profile in Figure 4.24 shows a ring that is lifted

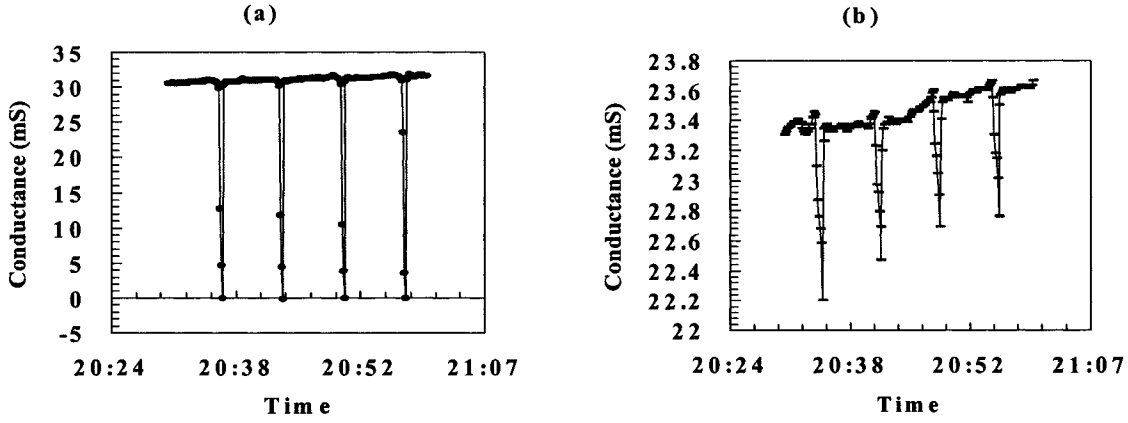

Figure 4.24: Rings Near Surface Plotted Vs. Time: (a) 15 cm, (b) 65 cm

near the froth on the surface of the thickener. The drop in conductivity is a result of the solids and air content of the froth.

Figure 4.25 shows one ring at a depth of 115 cm and a second at a depth of 165 cm. One is near the top of the bed and is therefore covered by loose solids. When the rake passes, the ring is moved into liquid. The flat top of the curve over the time the rake

passes is an indication that the ring is in the liquor for most of the rake passage. This is in contrast to the second profile on Figure 4.25 that shows a ring deeper in the bed. Since the ring must first rise through the solids that are covering it, it is only in the liquor for a brief time as indicated by the sharp point of the curve.

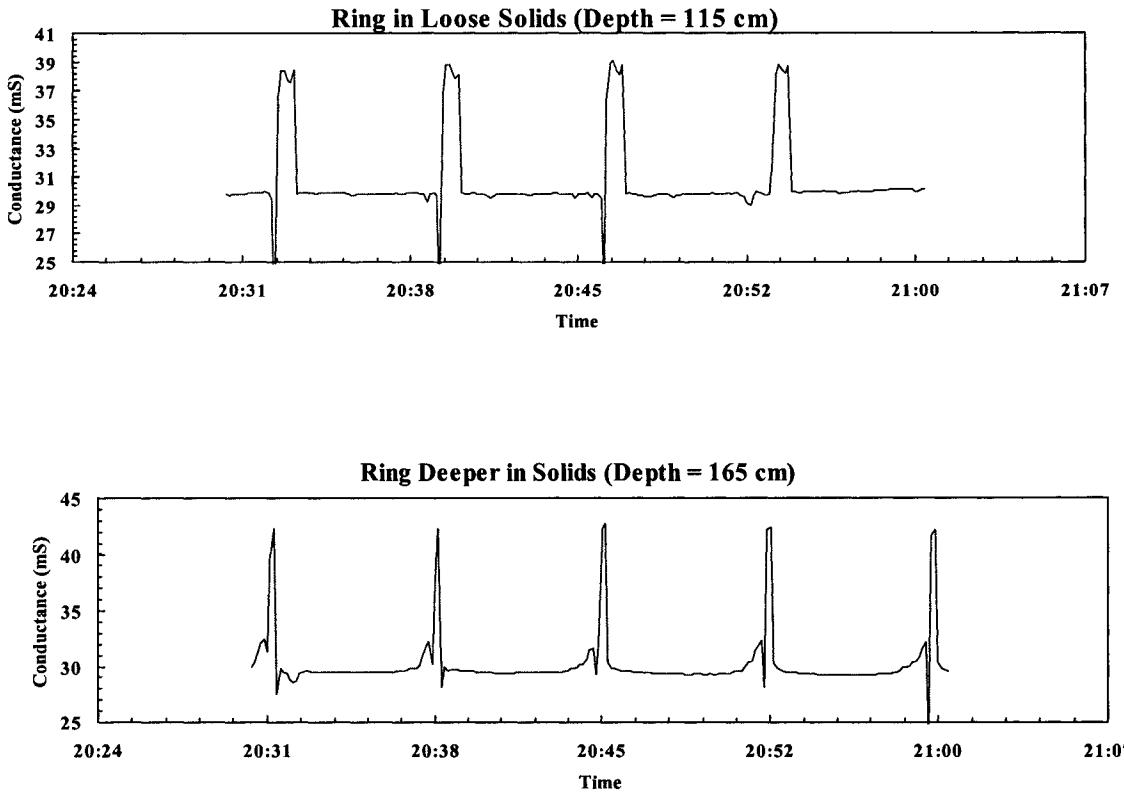

Figure 4.25: Rings in the Loose Solids Plotted Over Time: (a) 115 cm, (b) 165 cm

Figure 4.26 shows two rings in the compacted part of the bed. The ring is closer to the top of the compacted bed as indicated by the narrower base of the curves. The profile of the ring at 265 cm shows a substantially broader base as the ring is lifted through compacted solids for a considerable part of the rake passage. The ring at 215 cm also shows slightly higher conductivity values, which indicate less dense solids. Neither of these profiles indicate that the rings are lifted clear of the solids into the liquor. Figure 4.27 shows the bottom ring of the probe in a reduced time scale so that the curve shape can be examined. Both rake passages produce an indentation near the peak. This is caused by the fact that the front member of the rake structure lifts the

support bar until the probe support bar clears the front member. The probe falls back into the thickener until it rests on the top structural member of the rake at which point the lift is continued until the probe clears this member and falls back into its vertical position. If the compacted bed were homogeneous, one would expect a pseudo-square function. Instead, the profile seems to suggest a gradient even in the compacted part of the bed.

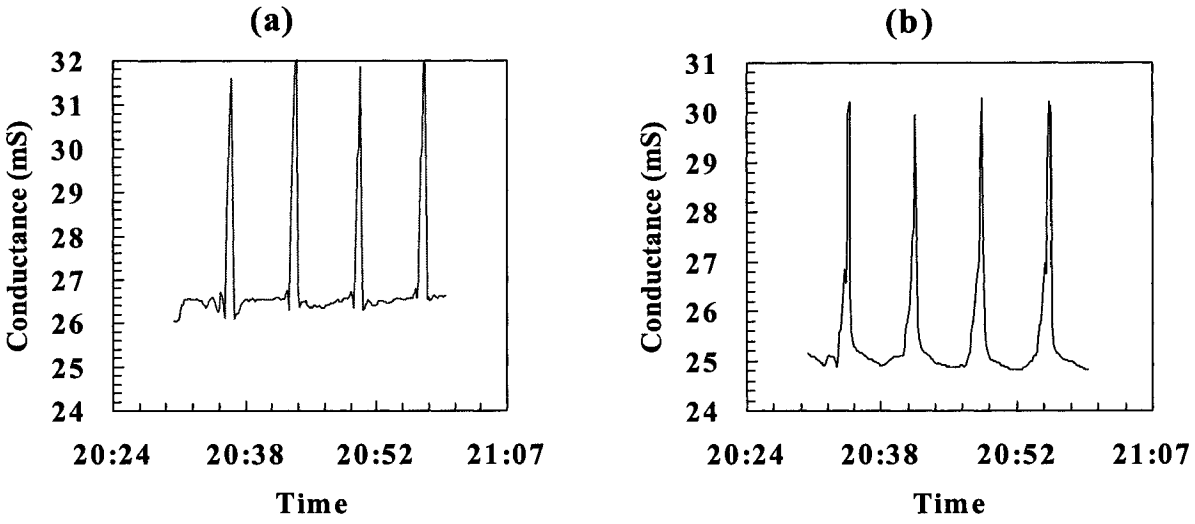

Figure 4.26: Rings in the Compacted Solids Plotted Over Time, Depth (a) 215 cm, (b) 265 cm

While these signals seem to indicate no more than the passage of the rake, the shape of the curve indicates the rings relative position in the thickener. Rings that are pushed out of the thickener will yield zero conductivity. Rings that are pushed into the froth zone will show a drop in conductivity, whereas a ring in the solids will show a rise in conductivity. A ring in the liquor that is not pushed into the froth will show no change as the rake passes. A ring near the top of the bed will yield a pseudo-square plot with a rise in conductivity. As the ring is deeper in the bed, the shape of the plot becomes more peaked. A ring that is covered by compacted solids will be moved into the interfacial region and show a rise in conductivity. The broader the base of the compacted ring plots, the deeper the ring is in the compacted bed. These observations are clear and completely independent of the absolute value of the

readings. The probe could be programmed to measure a profile and determine the key rings to examine in this fashion. Dead time would then be used to enhance the information obtained through conventional profile analysis. Eventually, it may be determined that this method for examining the location of solids in the thickener is more precise due to its complete independence from absolute values.

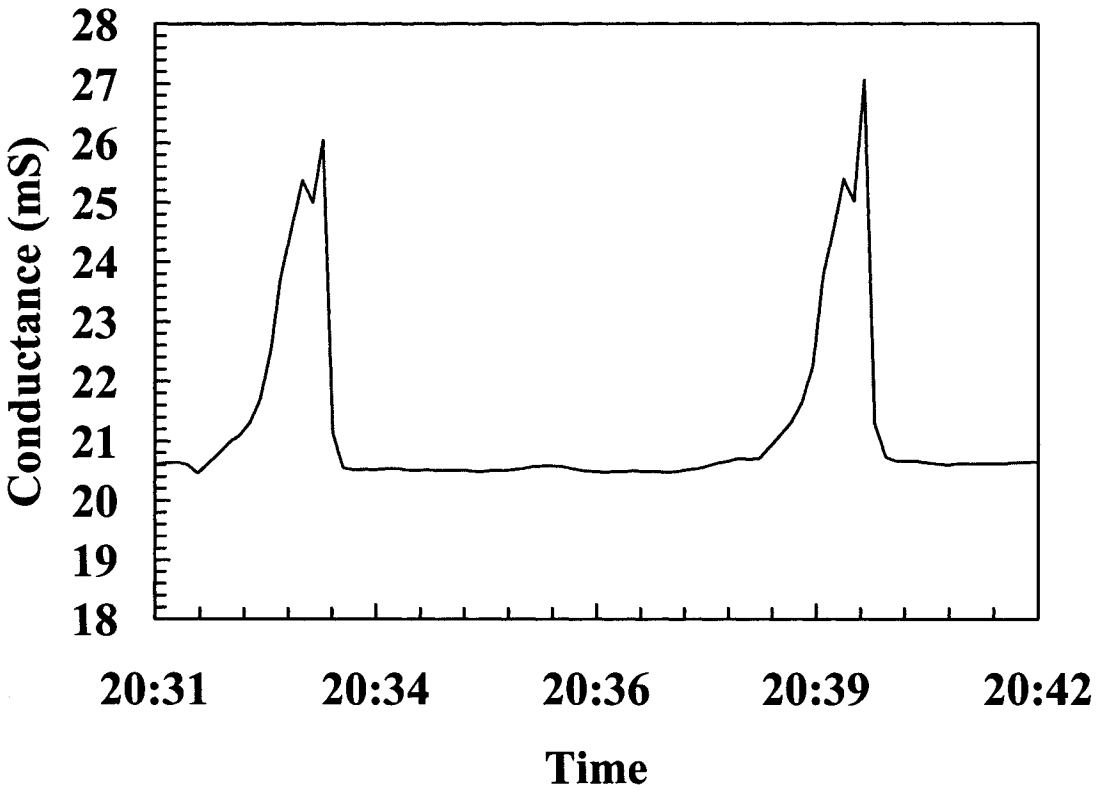

Figure 4.27: The Bottom Ring (Depth 315 cm) Plotted Over Time

Although the primary reason for a probe installation is for control, it is a very useful tool for studying thickeners. Since chemicals can affect conductivity, the conductivity of rings in the liquid could be used to detect changes in process chemistry at Clarabelle mill. Insight into the dynamic and steady-state effects of flocculants and coagulants (e.g., lime addition) could be gained. The probe provides a window into a thickener. This window can be used for a variety of research and operational investigations.

The Inco probe was in service for over 3 years in an outdoor thickener. There were some problems with the hardware and difficulties with the froth. Initially, it was discovered that instead of 32 independent readings, the probe was providing 16 pairs of readings. Figure 4.28 shows a paired profile compared to an unpaired profile. The pairing was the result of poor grounding in the plant. To resolve this problem, the probe was isolated from the plant ground.

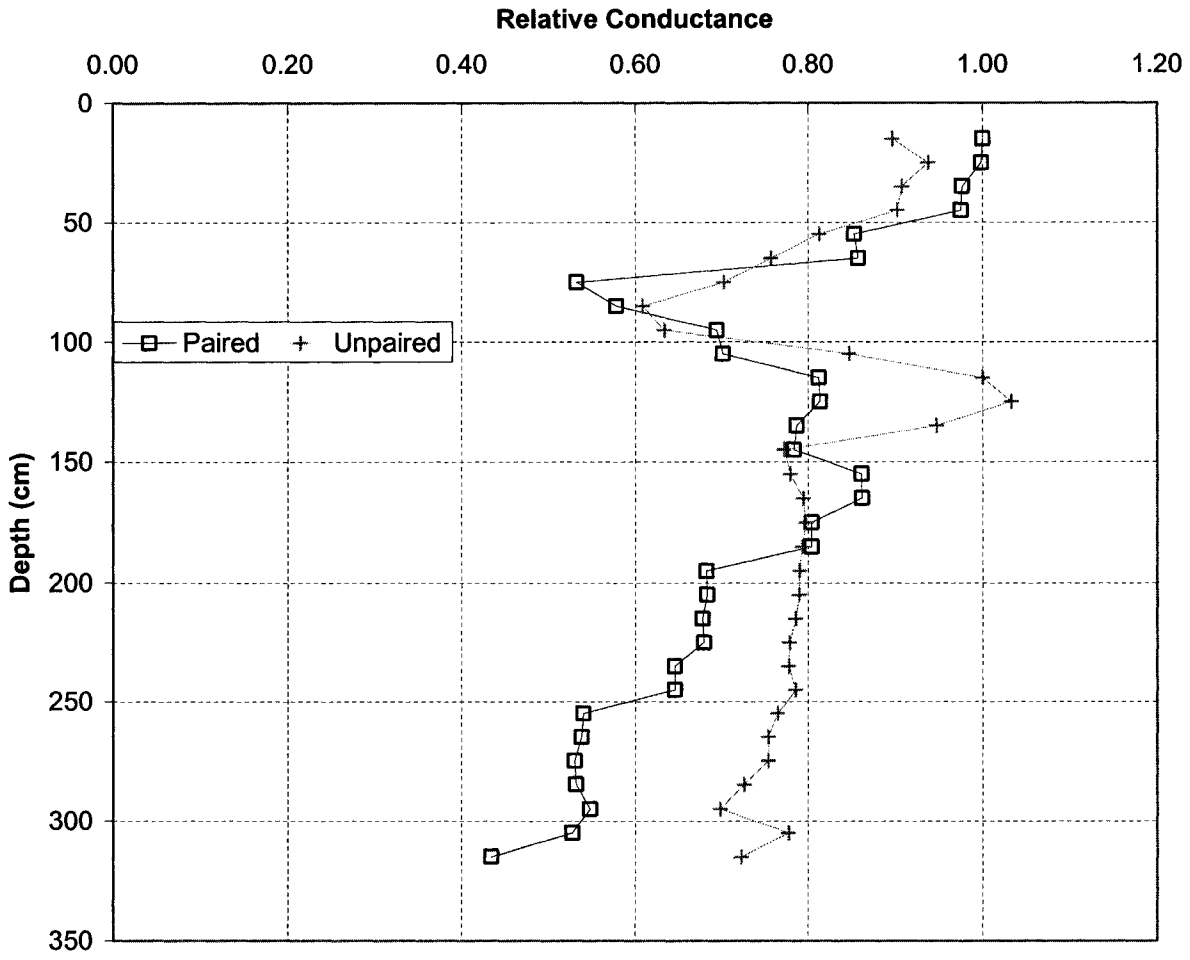

Figure 4.28: The Effect of Ring Pairing February 1995

Most of the hardware survived for the full time but, in late July 1995, it was discovered that the DAS 8 card (responsible for converting the conductivity signal from analog to digital for the computer) was malfunctioning. It cannot be ascertained exactly when the malfunction first occurred, but a diagnostic program has been

created to test for such failures in the future. The card was replaced and no further hardware problems have been detected. The computer worked well although the hard disk became worn and the computer used is not a good long-term solution. The computer hardware was not designed for an industrial environment although it surpassed expectations in terms of longevity.

The physical location of the probe provided the greatest challenge. A surface froth freezes in the winter impairing the motion of the probe and even hampers movement in warm weather. The addition of a water stream breaks up the froth in the summer and prevents it from freezing in the winter. Figure 4.29 shows a profile taken with the probe frozen at an angle. The operators were unable to free the probe so the profile was corrected for the angle of measurement until it could be thawed out. An effort has been made to minimize the turbulence caused by the stream of water but,

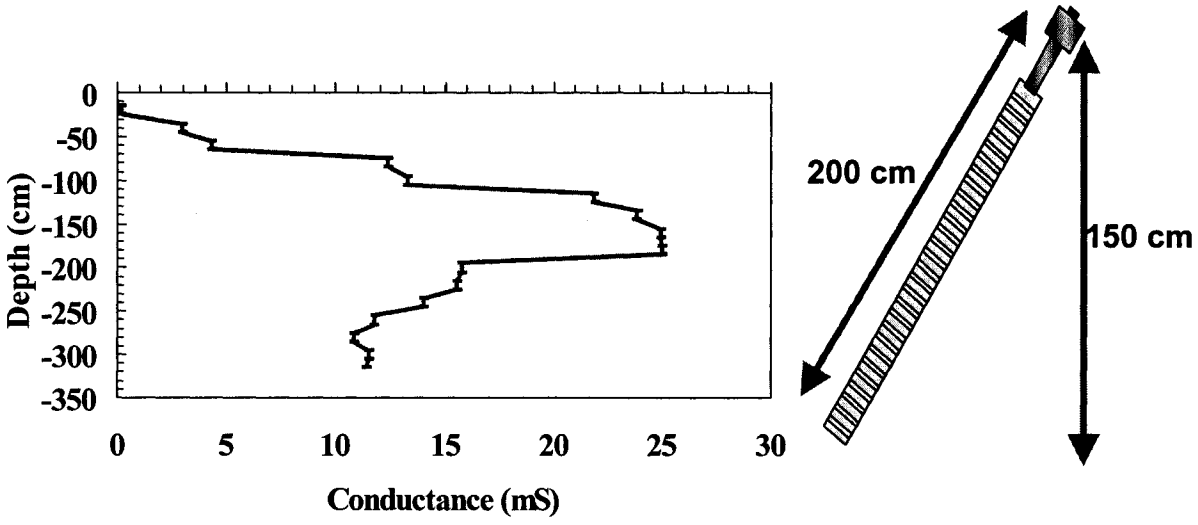

Figure 4.29: Immobilized Probe, December 20, 1994

on numerous occasions, the flow rate has been too low to allow for proper probe movement so a minimum rate must be maintained. The water flow-rate must be kept higher in the winter or it actually promotes freezing and risks rupturing the hose. A stainless-steel bar replaced the PVC support bar originally shipped with the probe. It

was thought that a PVC support bar would minimize the effect on the conductive field of the probe, but the weight proved insufficient to allow the probe to sink back into the solids bed. The weight of the stainless-steel bar assisted the return of the probe to a vertical position following a rake pass. The bed of solids impeded the probe's return to its vertical position - on days where the thickener was particularly full this was clearly evident. Vergouw [38] installed a rubber spring to pull the probe to its vertical position.

One small, but significant, problem was in interfacing the probe with Inco's Provox control system. Although it should be easy to send milliamp signals, there were numerous problems. The first problem was isolation. Since the probe's computer must be grounded separately from Inco's common ground, when a signal is sent from one system to the other, the connection acts as a conduit for the difference between the two grounds. Two current isolators were installed and this resolved the problem. Soon after, however, the DAS 8 card became unstable and was replaced. The replacement card took two months to arrive and then, unfortunately, the settings were not correct resulting in a zero signal being sent to the Provox system. This means that despite the large amount of useful data the probe had produced, very little of it succeeded in reaching the operators. For this instrument to be an operational success it must be proven reliable to the operators and the signals must be clear and well understood.

The Inco Booster station set-up has provided much useful information about the probe and its abilities. It can now be concluded that the probe can function as anticipated but that it requires some attention particularly to local conditions (i.e., the froth at the Inco installation).

Since the operators have no control over feed or discharge rates and they have no control over the flocculant addition rate, there is little the operator can do to control the thickener. The probe was proven to provide the necessary signals, but the operators were frequently unable to use them to improve thickener operation. Inco's

Booster station thickeners either need improved underflow and flocculant control or the probe would be better used in a different application.

4.3 *Thompson Concentrate Thickener*

A few months after the commissioning of the probe at Inco's Sudbury operations, another one was set up in their Thompson, Manitoba division. The probe was constructed in March, 1995 and shipped in the summer for installation in a metallurgical thickener at an r/R of 0.6. McGill personnel did not commission this probe, but data from this installation were shared with McGill. The probe hardware arrived in Thompson damaged. Most of the connections to the relays had shaken free during shipment. The personnel at Thompson called for assistance to rewire the probe in June and were successful in repairing the hardware. Figure 4.30 shows the earliest data received by McGill on October 3, 1995. The profile shows the same pairing phenomenon found at Copper Cliff. It is likely that since the conductivity probe was designed by McGill for use with a vendor's conductivity meter in the place

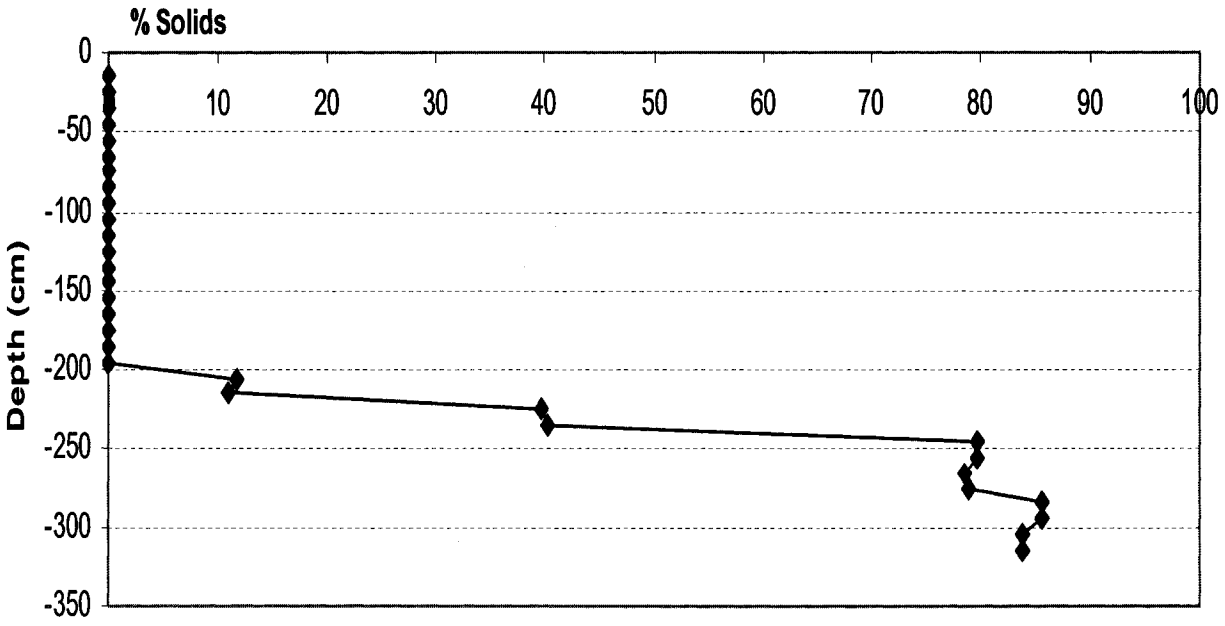

Figure 4.30: Typical Thompson Profile, October, 1995

of a vendor-designed sensor, this and other related compatibility issues will appear regularly. Conductivity cell construction is dependent on conductivity meter technology. As conductivity meter vendors endeavour to design better conductivity cells, McGill will have to re-engineer the internal connections of the probe hardware. One idea that is being explored by McGill is to replace the vendor supplied conductivity meter by a chip that contains a special high-speed conductivity meter designed by McGill. This chip would permit the probe to be used both in its conventional fashion and in the alternative methods discussed in section 4.2, due to the decrease in the time necessary to collect a profile. With a conventional conductivity meter, between 5 and 10 seconds are required to stabilize the signal, with McGill's high-speed conductivity meter, less than 1 second is required.

Figure 4.30 shows a clear interface at a depth of 200 cm. The interface is very similar to profiles taken at Inco's Booster Station. The underflow density is slightly higher but this may be due to the fact that the cell constants were not calibrated for this installation. The profile shows the presence of a compacted bed at a depth of 250 cm. Figure 4.31 shows the load and "interface" signal for the full day. Both signals mirror each other almost exactly, except for a period of time between 3:00 and 7:30 am. For this timeframe, the interface is rising while the load is steady. The similarity of the two signals is due to the fact that the nature of the bed is consistent over the day. Between 3 and 7:30 am, the feed rate is increased but the underflow is increased to keep the unit at steady state. The flocculant rate, however, is not increased to keep up with the increased solids and therefore the bed starts rising. At 7:30 am, the flocculant rate is increased as the bed returns to its usual state. The "interface" signal shows a very rapid response to the change in flocculant, which indicates that flocculant is a very strong control variable for this application.

Although data were collected through the end of January 1996, the only data set that showed a thickener profile was that collected on October 3, 1995. The data collected after this date does show some changes, but the values are not conductivity readings. It is possible that the personnel at Thompson reprogrammed the probe to send better

signals to their control systems. They may not have considered the effect on the historical data saved to the data files.

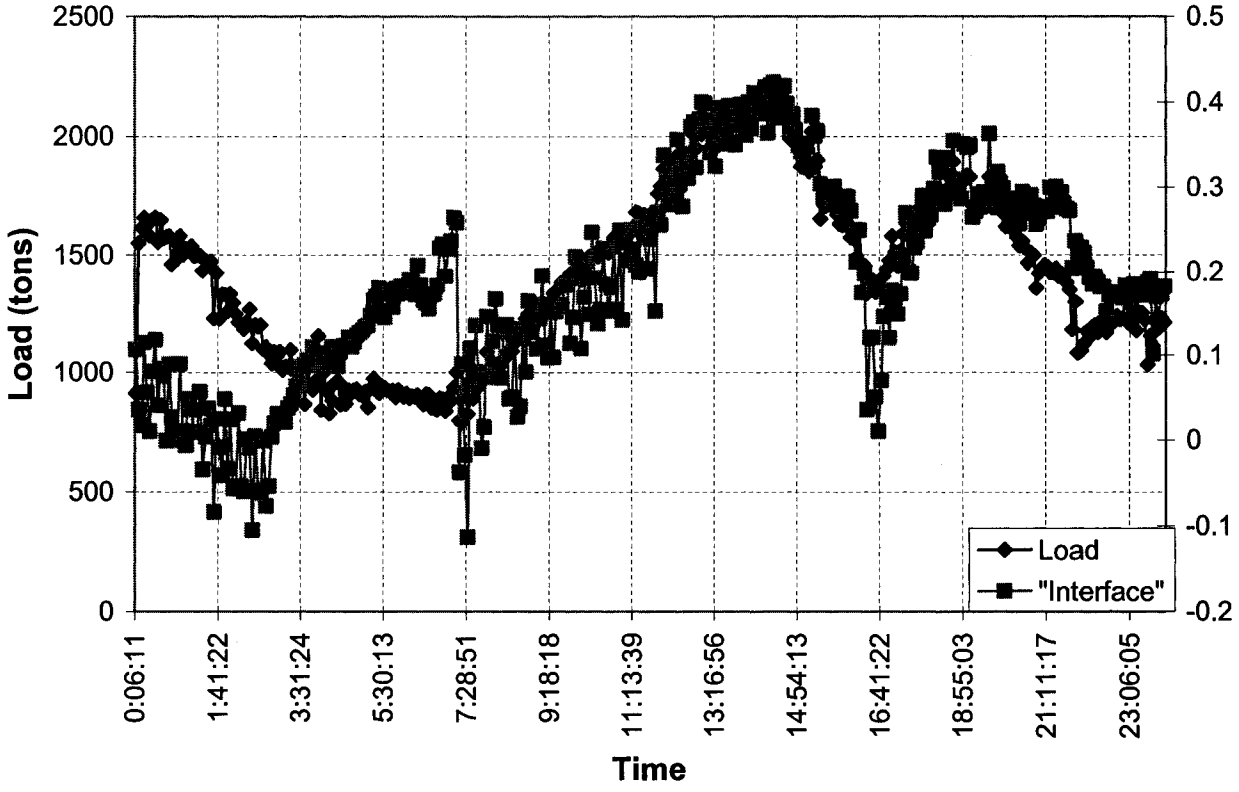

Figure 4.31: "Interface" and Load (Thompson)

This installation demonstrates another successful application of the conductivity probe. Unlike the Inco case, the bed seems more stable and responsive to flocculant. The "interface" signal may not be ideal for this application if it consistently mirrors the load signal. The "interface" signal is better suited to describe changes in the quality of the bed. Applications where the bed is generally constant are better suited to other control signals. The installation does show the same ring "pairing" found at Inco. Even without being present for the commissioning or analysis of the behaviour of the thickener, the profiles taken using the conductivity probe yield enough information to diagnose the thickener. A good control sensor should allow the operator to discern enough information about the thickener to be able to react with the

proper responses without having to be anywhere near the thickener. Part of the Thompson probe experiment was to use its signals to look at thickener behaviour without predisposing the data analyst to any knowledge of the thickener. This experiment proved fruitful as the load and "interface" signals were able to give enough information about the thickener to control it.

Chapter 5

Developing Useful Control Signals

5.1 Existing Operator Signals

5.1.1 Underflow Density

The earliest control signal was underflow density [1]. The method involves collecting a slurry sample, weighing it, then drying and weighing the dried solids. The percent solids is the weight of dry solids over the total slurry weight. This a time-consuming method so operations substituted use of the Marcy scale [1]. This device is based on a spring scale and density charts to convert from slurry density to percentage solids by weight. Paper overlays are made for most mineral densities. To limit the number of paper overlays, each overlay has five mineral densities on it. Another version of this technique, used in industry, is to measure the slurry weight using an electronic scale and then calculate the dry percentage solids using an approximate mineral solids density. All these manual techniques have the disadvantage of being offline and operator dependent. Operators monitor some thickeners well while others are practically abandoned.

To overcome the above difficulties, on-line automatic density measurement systems were developed. Now, over 50% of thickeners have automatic underflow measurement systems based on a personal survey by the author conducted of over 120 thickeners in Canada, the United States, Mexico, Chile, Peru, South Africa, Finland and Brazil. In this survey, the occurrence of automatic measurement systems is much higher in developed nations where labor is expensive. Figure 5.1 shows a plot of thickener underflow density (measured using a radiation based sensor on the discharge pipe) over time.

Irrespective of the manner in which underflow density measurements are performed, the signal gives operators a valuable tool. In most cases, the underflow is the primary product for a thickening application. The idea behind the underflow signal is to treat the thickener as a "black box" and to alter the control parameters in such a way as to maximize underflow density (without plugging the thickener). Most operations will vary flocculant and underflow pumping rates until a correlation is found with the underflow density measurement. Control algorithms are discussed later in this chapter.

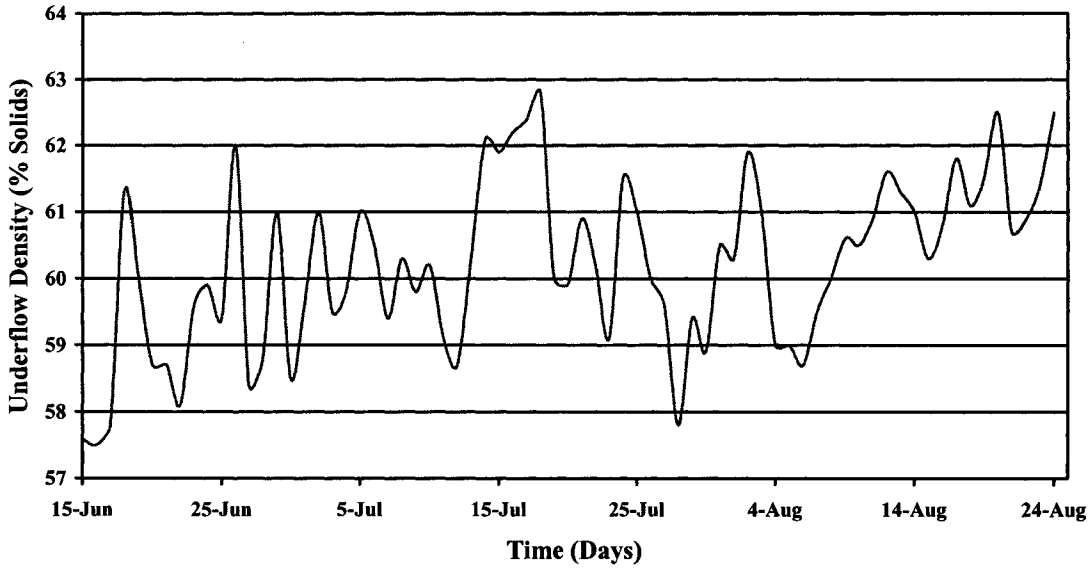

Figure 5.1: Thickener Underflow Density Vs Time, Kidd Creek Tailings 1996

5.1.2 Torque Measurement

With large thickeners and high underflow densities, mechanical limitations necessitate torque measurement to protect the thickener mechanism. In many operations, the lack of torque measurement resulted in mechanical failure of a thickener mechanism. As a result of the lost production and expense caused by the failure, operators tend to operate the units conservatively. Torque measurement

enabled the detection of mechanical problems before costly failures, allowing operations to use thickeners more efficiently.

Torque is a measurement of the lever arm stress applied on the central shaft. The greater the distance an applied stress is from the center of the thickener, the greater the effect of the stress is on the central shaft. For this reason, it is very important that the solids not build up at the extremities of a thickener. A common equation used for total torque determination is:

$$T = kD^2 \qquad (7)$$

where T is the operating torque, D is the diameter of the rake arm, and k is an empirical factor that describes the force required to displace the solids. For light solids, a k factor of 10 or less is used, while values over 20 are reserved for extra heavy solids applications. The highest torque output on a thickener is currently 19 million Nm peak (Freeport, Indonesia) and the highest k factor is over 100 in a Red Mud application in Jamaica.

Obtaining a direct measurement of torque is very difficult due to the high stresses involved. The earliest forms of torque measurement were based on the amperage of the motors. While not a direct measurement, the current used by the motor does give a good indication of torque. Torque measurement was improved through the invention of a bellows system. The bellows is located on top of the shaft and when a stress is applied, the shaft gets pushed up increasing the oil pressure, which deforms the bellows. A strain gauge on the bellows then yields a reliable indication of the torque. The problem with the bellows system is that, over time, the bellows permanently deform and therefore the torque slowly trends to higher values. The bellows system was subsequently replaced by a thrust system in which the strain gauge is directly mounted on the shaft and the gear casing so that the movement of the shaft is more accurately measured. This system required very careful machining

of the gear casing and therefore increased the price of the gear system despite its simple design.

A more recent method of torque measurement has arisen due to the increased use of hydraulic power for gear systems. Although thickeners are not large power consumers, as compared to most mineral processing equipment, they are amenable to the advantages of hydraulic power. Unlike electro-mechanical motors, hydraulic motors always provide soft starts and are not susceptible to power fluctuations. Hydraulic systems also have the advantage that the hydraulic oil pressure can be directly related to the torque. Torque measurement therefore requires only addition of a pressure sensor as opposed to a more costly, full torque measurement system.

The torque signal in a thickener is generally used as a warning sign for impending mechanical failure. It is usually wired to automatic shut-offs and to a rake-lift system when one is present. As a control signal, high torque is often misunderstood to represent a full thickener, while low torque values are misunderstood to represent thickeners with low solid contents. High torque values actually represent a dense solids zone near the end of the rake arms in the bottom 30 cm of the thickener. An empty thickener fed with enough gravel to fill the bottom 30 cm would show a high torque and cause the rake arms to cease operating. A thickener filled with low-density solids that do not compact well would actually yield a very low torque even though solids may be overflowing the unit. The problem is further accentuated by the fact that most torque measurement systems are relative to the size of the gear and the requirements of the system. The torque signal in an over-designed thickener may not yield any useful information about the operation of the unit. In a hydroxide thickener application (further details restricted) at Dow Chemical's Aratu operations (Salvador, Brazil), the thickener was designed with excess torque since it was not known what the k factor for the material would be. The torque measurements for this application consistently yield an unchanging value and are unresponsive to changes in thickener operation. The torque value shown is based entirely on the internal resistance of the system.

5.2 The Full Solids Profile

With an increasing number of sensors capable of measuring the localized density at any point within the thickener, the solids profile has become a common control signal. As a profile is comprised of around a minimum of 12 to more than 25 measurement points, the profile is the result of a compilation of a set of readings taken at different depths at the same point within a short period of time. The profile provides a great deal of information and is the basis for the development for most of the signals discussed in this chapter.

By itself, the profile can indicate underflow density, the interface (liquor-slurry) depth, the second interface depth (sedimenting slurry and compacted slurry) and give a general indication of thickener load. Figure 5.2 indicates the determination of both interfaces and the underflow density. Not all applications have two interfaces, however it is a common attribute of thickened flocculated mineral slurries. Thickener load is derived from the area beneath the curve and therefore can be visually discerned from the curve by experienced operators.

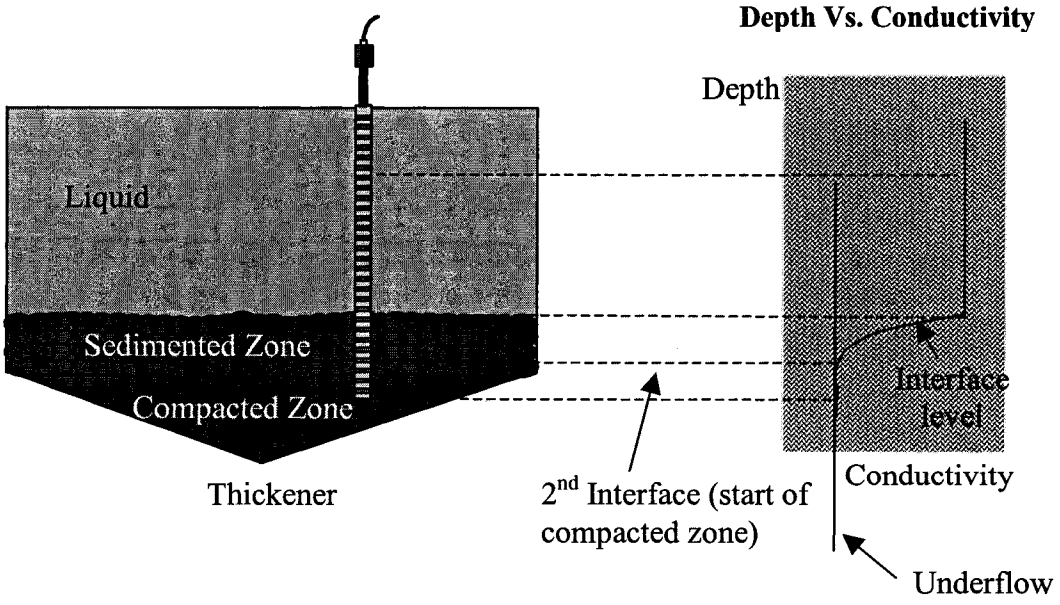

Figure 5.2: Interface Determination Using the Solids Profile

These values represent a momentary look within a thickener. As with most diagnoses, a history is required for proper analysis. These values are therefore most effective for thickener control when registered over time.

Figure 5.2 is a typical profile in a concentrate or tailings application. In many situations, atypical profiles may be registered. Some applications never register a profile as neat as Figure 5.2. Figure 5.3 shows a profile where none of the signals can be determined. There is no indication that the bottom of the probe is in the compacted solids nor can any point be truly said to be an interface between two zones. Algorithms used to determine these signals (discussed later in this chapter) would either register arbitrary values are no value at all.

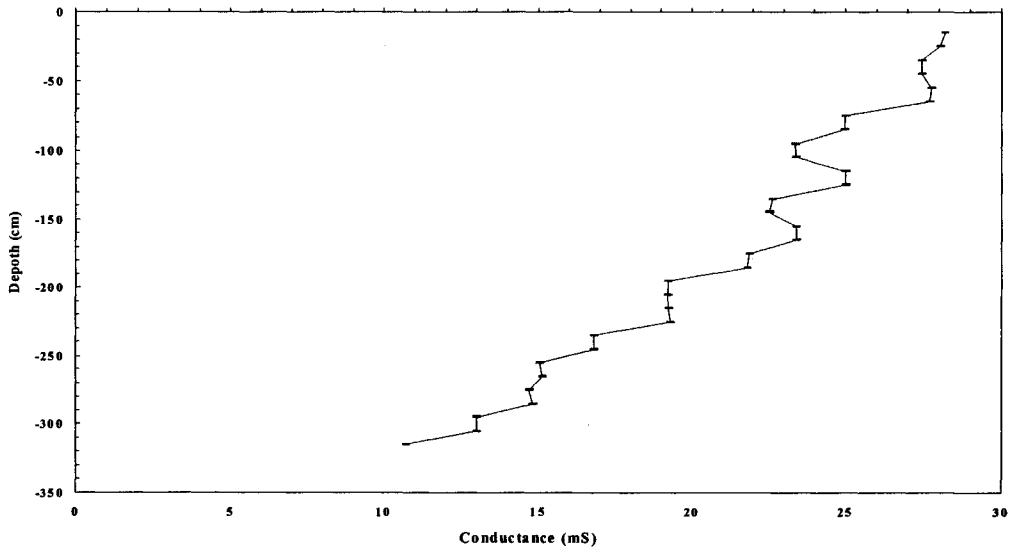

Figure 5.3: Disturbed Profile, Inco, February 1995

The solids profile itself, as opposed to the signals that may be derived from it, is not an ideal control signal. The profile cannot be directly used to control ancillary equipment, as it requires a trained operator to interpret it. It also lends itself to operator bias. At Inco, given identical profiles, operator responses varied considerably. Some would augment underflow pumping rates while others would cease underflow pumping altogether. In many ways, the profile may be more of a hindrance to operations, as it may encourage seasoned operators to bypass automatic controls inappropriately.

5.3 Interface Determination

In thickener terminology [3], the interface is the transition point between the zone containing liquor and that containing "loose" solids. Interface determination, using Figure 5.2 as an example, is the search for a drop in conductivity (or increase in percentage solids) that is greater than the normal variance in the readings. The original software for the conductivity probe used a laboratory-determined variance of 0.02 mS. Starting from the top of the profile, any change greater than the variance is determined to be the interface.

The variance in an industrial application was expected to be considerably higher due to fluctuations in the conductance of the liquor caused by changes in reagents or temperature. The software was modified to calculate the variance of the readings taken in the liquor and use this to detect the interface. This proved satisfactory as long as the thickener profile was clear. In an upset condition, interface determination was impossible. The variance of the readings rose considerably and with no clear demarcation point, the interface was calculated to be at the bottom of the thickener.

The second interface in a thickener is known by many terms [3]. Some call it the mud level while others term it the terminal density region. Despite the fact that thickener theory [10] predicts that this layer will exist and is crucial to determining thickener efficiency, most sensors do not detect this interface [19,18,20]. The conductivity probe was programmed with an algorithm to calculate this second interface. This interface is located by starting at the first interface and looking for the point at which readings no longer change more than the normal variance of the system. Clearly, the determination of the second interface relies on both the determination of the first interface and the presence of a zone containing fully compacted solids at the bottom of the thickener.

A precise interface depth is a useful control signal and can be used to control ancillary equipment without the need for operators. The signal is not always reliable,

however, and is most likely to fail when it is most required. During an upset, the algorithm used to determine either interface would frequently default to the bottom of the thickener. If the underflow density is low, the operator may determine that the ideal course of action in the above scenario is to lower the underflow pumping rate which may exacerbate the situation.

5.4 The "Interface" Signal

The "interface" signal was designed by the author for the conductivity probe to ensure a reliable interfacial control signal. All the algorithms designed to determine an exact interface based on the solids profile (as discussed in section 5.3 and Chapter 4) proved unreliable over time. The cause for algorithm failure was the fact that no unique interfacial point existed. Fitch [10] hypothesized that the solids in a thickener should be arrayed as a series of concentrations versus depth with each concentration feeding the others so that at steady state the mass transport across the concentrations is equal. In the normal profile, the concentrations are only changing in the vicinity of the two interfaces discussed in section 5.3 (Figure 5.4). In the case of an unflocculated suspension, the theory predicts that a thickener will have a profile that is a continuous solids gradient or a straight line when plotted versus depth. Figure 5.3 is very close to a straight line and occurred when flocculant addition to the thickener was suspended.

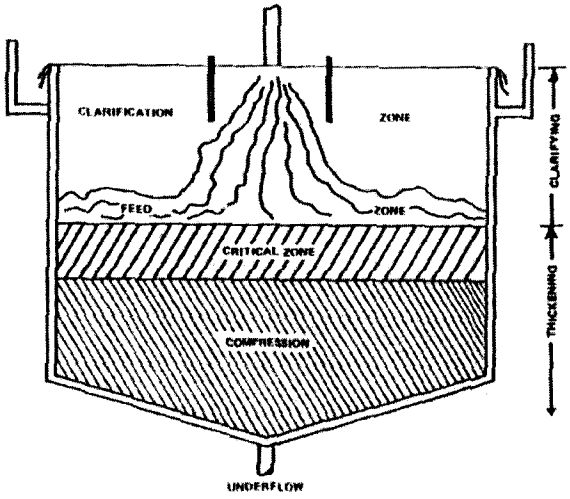

Figure 5.4: Thickener Zones [25]

With the possibility of solids profiles devoid of inflection points, interface algorithms designed to detect inflection points are ineffective. The "interface" algorithm is

therefore an attempt to characterize the solids profile with respect to solids level as opposed to searching for an inflection point.

To determine "interface", the solids profile is divided into three regions based on profiles taken during normal operation. The bottom of the thickener, where compacted solids normally reside, is termed the solids zone. The top of the thickener, which normally contains liquor, is termed the liquor zone. The area between these zones is termed the interfacial zone. The division of the profile into zones does not imply that these regions are sacrosanct. In many cases, solids will be found in the liquor zone and loosely packed solids will be found in the solids zone. The "interface" is calculated by averaging all the readings of the solids profile in each of the three zones and then using the following equation:

$$"Interface" = \frac{I_{avg} - L_{avg}}{S_{avg} - L_{avg}} \qquad (8)$$

where I_{avg} is the average of the readings taken in the interface zone, L_{avg} is the average of readings taken in the liquor zone and S_{avg} is the average of the readings taken in the solids zone. $S_{avg} - L_{avg}$ represents the range and $I_{avg} - L_{avg}$ represents the solids content of the interface zone relative to overflow liquor. By dividing by the range, the signal becomes a unitless relative signal applicable to any thickener.

The "interface" signal is reliable, but must be used in conjunction with another signal since a given "interface" value can be achieved several different ways. For example, for the case depicted in Figure 5.3, the "interface" reading would be approximately 0.3 depending on the determination of the three zones. The same "interface" reading can be achieved with a low solids content in the thickener with a profile that looks like Figure 5.2. To differentiate these two scenarios, the underflow density or torque could be used to determine the nature of the solids near the bottom of the unit. The situation represented by Figure 5.2 would yield a higher underflow density and torque than the situation represented by Figure 5.3.

Given the fact that any control system would use all the available control signals, the value of the "interface" signal lies in its ability to represent any conceivable profile as opposed to the interface measurement techniques discussed in section 5.3, which presuppose the presence of an inflection point in the curve.

5.5 Thickener Load

With a solids profile, it is possible to measure the total solids content of a thickener. Each reading in the profile represents the density at a given depth. The thickener can be divided into a series of stacked cylinders, each with a height equal to the spacing between readings. The diameter of the cylinders is the diameter of the thickener unless the bottom is tapered, in which case the diameter is reduced towards the bottom of the thickener. With the volume of the cylinders and the solids content, it is possible to calculate the weight of solids in each cylinder. The summation of all cylinders results in the total solids content of the thickener.

Thickener load is a very useful control signal since it can be used to control ancillary equipment and like "interface" does not presuppose any particular profile shape. Where "interface" is used to determine the location of solids within the thickener, load is used to determine and quantify the presence of solids within the thickener. Given the scenario discussed in section 5.4, the load relative to Figure 5.3 may be higher than the load relative to Figure 5.2 since the bed would have to be quite deep to simulate an "interface" of 0.3. Figure 5.3 has solids at every depth and even though the underflow density is lower, the quantity of solids suspended would be substantially higher. This is predicted by Kynch's theorems [27], which indicate that instantaneous sedimentation precludes the presence of solids at any location other than the discharge point. As sedimentation rates drop from this ideal, the amount of suspended solids necessarily increases.

Thickener load measurement is also useful for metallurgical inventory and as a back-up for the torque monitoring system. Outokumpu's control algorithm (discussed later

in this chapter) relies heavily on the measurement of thickener load although they use a pressure sensor in the discharge cone to approximate the load rather than measuring it more precisely.

5.6 Interface Clarity

Interface clarity requires interface measurement (as discussed in section 5.3) and therefore presupposes the presence of an inflection point in the solids profile. Interface clarity is calculated using the equation below:

$$Interface \quad Clarity = \frac{S^{n-3} + S^{n-2} + S^{n-1}}{S^{n+3} + S^{n+2} + S^{n+1}} \tag{9}$$

where n is the interface point and S^n is the solids reading at a ring n. Figure 5.5 shows interface clarity plotted versus time for the same data discussed in chapter 4 (Figures 4.15 and 4.16). A lower value represents a sharper change at the interface. The corrective measures discussed in chapter 4 ultimately result in a well-defined

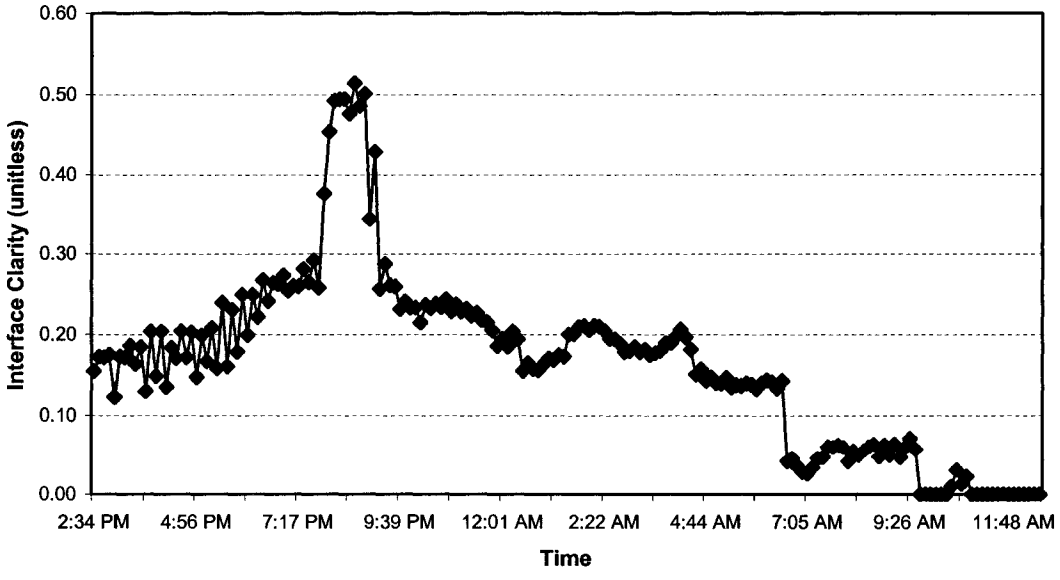

Figure 5.5: Interface Clarity Vs. Time.

interface (as demonstrated by the low interface clarity).

The interface clarity signal focuses on the area that both field work [29] and Kynch's theorems [27] indicate will respond first to a sudden change in the system. Unlike other signals that take an aggregate view of the thickener, the interface clarity signal is designed to be an early warning signal. Only a short time after a change in the settling nature of the feed material occurs, the interface clarity will mirror this change.

Responding quickly to changes in settling behavior is the key to thickener optimization since it is very difficult to regain control of a thickener that has lost the inflection points in the solids profile. Work done with miniature thickeners [29] indicates that 5 minutes of lost control results in up to an hour of subsequent operational difficulties.

5.7 Delta-Interface and Delta-Load

To reduce the propensity of operators to respond to set points in unpredictable ways, delta signals are designed to indicate the change in the signals versus time to give a better indication of the proper responsive action. All delta signals are calculated by taking the instantaneous rate of change of the signal versus time. Given the periodic nature of the measurements, a differential is not necessary. The equation below is an example of how the rate of change can be determined:

$$\Delta Load = \frac{(L_n + L_{n-1} + L_{n-2})/3 - \sum_{n=1-10} L_{10-n}/10}{reading \quad Interval} \qquad (10)$$

where L_n is the load at a time n and the interval is the time between readings (typically 5 to 10 minutes). Three readings are taken to establish the current value to reduce signal noise and ten values are used to form a current baseline to ensure that the change is real.

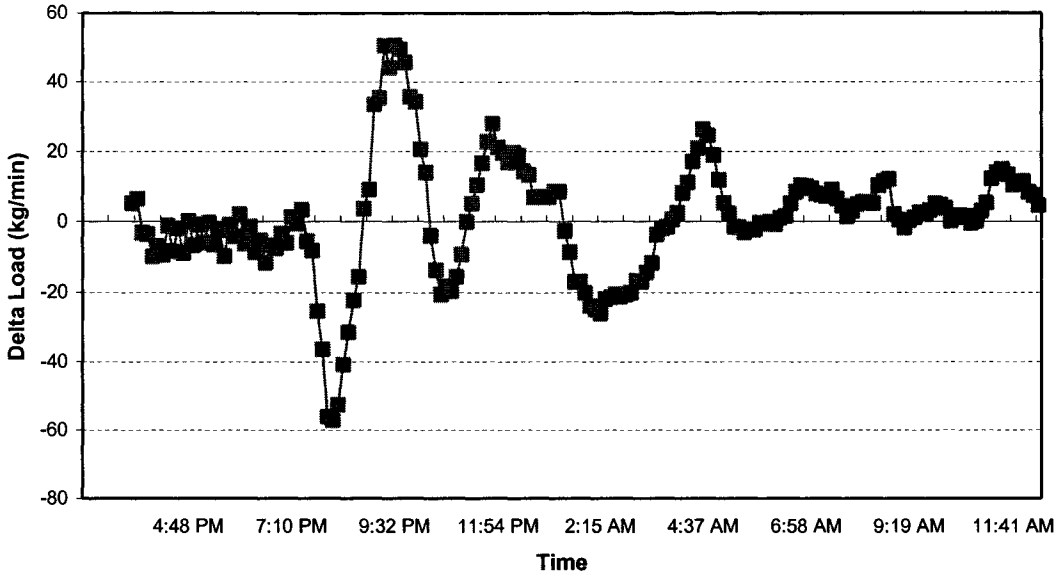

Figure 5.6: Delta Load Vs. Time

Figure 5.6 shows Delta Load versus time for the same data as Figure 5.5. The larger deviations coincide with the corrective actions discussed in chapter 4.

This signal makes it possible to determine the rate at which the load is increasing. The rate of change allows the operator or automatic control system to determine the severity of a change in the operation of a thickener and makes it possible to see the systems responsiveness to any corrective action. A typical problem with thickener control is excessive corrective actions to small upsets.

Delta signals are particularly useful once optimized steady-state conditions have been achieved. Any change away from the ideal state will be detected and can be prevented through corrective action. With the large residence time of thickeners, the earlier a corrective action can be used without over compensating, the more likely the thickener products will remain unchanged. Delta signals reduce the occurrence of over compensation by detecting the over compensation immediately through an inversion in the instantaneous rate of change.

5.8 *The Use of Liquor Conductivity as a Control Signal*

Figure 5.7 shows the conductivity of a single ring over time. The ring is 40 cm from the surface and well clear of any solids yet the curve is not linear. The changes are the result of changes in the conductivity of the liquor due to either chemistry or temperature effects. With the volume of liquor in a thickener, the heat capacity would dictate that changes in temperature must occur slowly and it is therefore unlikely that the shape of the curve is the result of temperature changes. As the process prior to this thickening step is froth flotation, changes in chemistry can have significant process implications. While the flotation circuit at Inco is well monitored, it is always a good idea to have a secondary method for verifying slurry characteristics.

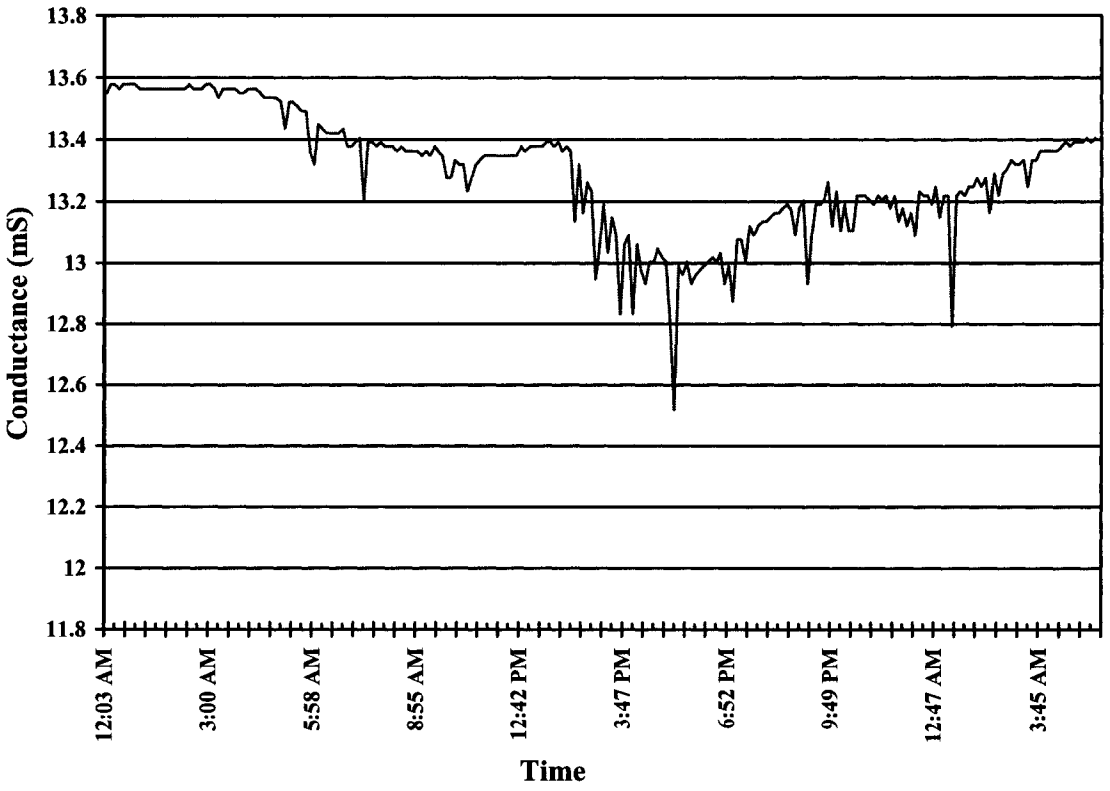

Figure 5.7: Liquor Conductivity Vs Time, Inco, May 18-19, 1995

There are several applications for conductivity-based control of the systems. The probe is far more robust than most other analytic equipment. Inco required a probe for a highly corrosive application [39] and had a probe fabricated out of Teflon and titanium. Escondida [40] ordered an in-line conductivity probe built by McGill to control lime addition in a lime dilution stage. Compared to previous sensors, the conductivity probe required the least maintenance and provided the highest reliability. As research is continued in slurry chemistry, correlations will be made between slurry conductivity and optimized recovery.

5.9 Control Algorithms

The Inco conductivity probe demonstrated the potential benefits of new control signals but did not result in improved control since the project did not include the development of control algorithms. Knowledge of the system determines required actions. The actions must be both appropriate and timely. Inco's Booster Station did not have the equipment to monitor or control flocculant addition and underflow rates were controlled by downstream processes.

Because of the size of a thickener, small disturbances in operation are insignificant to thickener operation. Known as "buffering" [41], this minimizes operational fluctuations but also increases the amount of change necessary to induce a positive reaction in the system. Most thickeners respond slowly to corrective measures and then continue responding after the corrective measure is no longer beneficial resulting in an over-compensated situation. Knowing when to stop the corrective action is the art of thickener control

5.9.1 Conventional Control Algorithms

Conventional control algorithms predate most modern sensors [42,26]. These algorithms rely on control through product analysis otherwise known as "black box" control. The primary method for altering product quality was through increasing or

decreasing the underflow withdrawal rate. A low underflow density would indicate the need to slow the underflow withdrawal rate and a high underflow density would indicate the need to increase the underflow withdrawal. Overflow quality was not regularly monitored although if visual inspection indicated the presence of a substantial quantity of solids near the surface, underflow rate would be increased regardless of the underflow density. Torque measurement was used primarily for mechanism protection. Operators would override process considerations in the face of impending mechanical problems.

With flocculant, operators have another control parameter. Conventional control algorithms are slightly more complex with flocculant and frequently require another parameter such as bed level or torque. In "black box" thickener control with flocculant, high density still results in an increase in underflow withdrawal rates, although some operators will choose to add flocculant if the torque is high and the solids in the underflow do not appear heavily flocculated. Low underflow density is treated by decreasing the underflow withdrawal rate unless a visual inspection indicates the presence of solids near the surface. With low underflow solids, most operators will add more flocculant unless the torque is high which may indicate a solids movement problem typically caused by excessive flocculant. Due to the variety of flocculants and their reactions with different minerals, there is no consistent reaction to a given situation. There are, however, industry specific norms.

5.9.2 Outokumpu's High Rate Control Algorithm

Outokumpu designs and fabricates smaller thickeners with improved control to handle the same feed rates as larger thickeners. To accomplish this, they devised a control algorithm dubbed "High Rate Thickener Control" [13](Figure 4.20). This control system relies on two sensors and two control variables. An ultrasonic sensor measures the interface between loose solids and liquor while a pressure sensor in the discharge cone gives an approximation of thickener load. The load signal is linked to the underflow withdrawal pump so that the load can be maintained constant. The

interface signal is tied into the flocculant control pump. If the bed is high (given a constant load), more flocculant is required to lower the bed. If the bed is low, the thickener is over flocculated and the flocculant rate is decreased to avoid operational problems associated with excessive flocculant and to reduce reagent cost.

Outokumpu's control system has proven effective in several applications. Adaptations to the control algorithm include the use of the torque signal to automatically over-ride the underflow pump and a maximum interface set-point at which the underflow rate is increased. Both of these adaptations were put in due to the maintenance requirement on the pressure sensor in the underflow cone and the possibility of interruptions in the load signal.

5.9.3 Conductivity Probe Control Algorithm

With all the available signals, the number of control algorithms possible with a conductivity probe is considerable. The ideal is to determine industry and even site-specific algorithms based on a short trial period. The added benefit to this is the ability to utilize fully all the control variables rather than specifying a smaller subset of required control variables common to several thickeners.

The work done at Inco suggests that given proper flocculant and underflow rate control a control algorithm would be very effective. The requirements of this installation are unique in that the filters subsequent to the thickener are not optimized at higher underflow densities. Local practice is to dilute the thickener underflow prior to filtration. Based on this requirement, the algorithm for Inco's Booster Station would control the flocculant pump to use the minimum quantity of flocculant while ensuring a clear overflow. Solids in the overflow represent lost concentrate and there is, therefore, economic justification to use reagents to minimize these losses. The probe signals best suited for this are the "interface" and interface clarity signals. The ideal operating state may not be the clear profile depicted in Figure 5.2. Instead, the profile will more likely resemble Figure 5.3. Given this control strategy, the type of

flocculant should be revisited, as a coagulant may be more effective in promoting overflow clarity.

This example is not unique in that as a unified control strategy is designed for a given application, all the parameters must be revisited. What is unique about the probe is its ability to offer signals for any control strategy. If the goal of this application had been maximum underflow density, the probe could have delivered load and the compaction level. The probe can be used with either conventional control algorithms or high rate control algorithms, but the key to thickener optimization may lie in more sophisticated algorithms specific to a given application similar to the theory of "smart" control systems [3].

Chapter 6

Conclusions and Recommendations for Future Work

6.1 Conclusions

The results of this thesis work will now be presented in point form. Following this, some recommendations for future work will be made.

6.1.1 Conductivity as a Control Property

- A new conductivity probe has yielded a reliable signal over its life span despite a wide range of environmental and process changes indicating the suitability of conductivity as a control property.
- The conductivity probe reliably gave % solids readings in the range expected for the application.
- The conductivity probe successfully detected changes in the operation of the thickener.
- Profiles taken using the conductivity probe could be directly related to thickener operation.
- Two companies have successfully developed thickener sensors based on conductivity measurement subsequent to this work.
- The reliability of the signal engendered trust among the operators.

6.1.2 The Conductivity Probe as a Control Device

- The conductivity probe physically endured the industrial test well.
- The electronics, although not intended for prolonged industrial use, survived for a full year before requiring maintenance.

- The 31 readings of the probe were more than sufficient to provide good profile definition.
- None of the rings failed although some rings developed a coating which affected readings.
- The probe was immobilized for two weeks due to the low temperature in the winter and the presence of froth on the surface of the thickener.
- The location of the probe proved ideal as readings near the bottom of the probe mirrored the underflow well, while the turbulence associated with the centre of the thickener did not affect the readings
- The probe was more reliable and robust than competitive technologies according to Inco operators (personal communication to the author).

6.1.3 Control Signals and Algorithms

- The probe is capable of reproducing industry recognized control signals as well as several new signals.
- The probe can detect the interface more accurately than does ultrasonic technology.
- In those cases in which a thickener does not have an interface, the "interface" signal is a more reliable control signal.
- Plotting signals over time is essential for their use in control.
- Thickener load has been used in high-rate control algorithms with a large degree of success.
- Interface clarity is a proposed new signal for optimizing flocculant control.
- Providing the full solids profile is only useful to thickener operators who have considerable knowledge about solids-liquid separation. The profile is frequently used incorrectly to justify preconceptions.
- The conductivity probe is capable of many possible control signals that can be used to optimize thickening. Control algorithms using the conductivity probe can, therefore, be specially designed for any application.

6.1.4 Summary of Results from the Trial Installations

Falconbridge, Kidd Creek

- The support system for the probe interfered with the conductivity measurements.
- The probe was located too far from the centre of the thickener and was frequently above the thickener solids level.
- The plates put on the rake to prevent the probe from being caught in the truss structure of the rake arms, destroyed the probe.
- A plant shutdown was clearly detected by the probe through a sudden drop in solids level.
- Few data were collected prior to the demise of the probe.

Inco, Booster Station

- The pivot support system for the probe did not return the probe to a vertical position consistently after the rake passed.
- The probe successfully monitored the thickener for over a year.
- Operators began trusting the signal from the probe (personal communication with the author).
- Using the conductivity probe, it was possible to monitor thickener operations from a remote location.
- The Booster Station was not an ideal location for the probe since the thickener did not have sufficient controls to remedy problems detected by the probe.
- Despite the difficulties, the probe yielded a reliable signal.
- A large amount of data was collected (100 MB) yielding new information about the internal fluid mechanics of a thickener. The data generally supported thickener theory.

Inco, Thompson

- The probe data were analyzed successfully off-site by transferring the data to McGill via PC Anywhere.
- The thickener showed a greater responsiveness to flocculant than did the Booster Station thickener.
- The load signal mirrored the "interface" signal very closely and therefore should be replaced by another signal for this application.
- The company operators reprogrammed the probe and the subsequent data could not be successfully analyzed.
- Only a small amount of data was collected prior to the reprogramming.

6.2 Recommendations for Future Work

i. The conductivity probe should be relocated to a thickener with more controls. A thickener in which quality control is essential would be an ideal way to test the effectiveness of the probe.

ii. Control algorithms should be written and tested to control the underflow and flocculant pumps directly.

iii. The data acquisition program should be rewritten to incorporate a database so that the probe becomes "intelligent". With the flexibility of the probe, an intelligent system may be able to self-engineer new control signals for any given application.

iv. Several probes should be installed simultaneously in identical applications at different plants. Analyzing probe data with the operational log files for each installation would make it possible to determine solutions to operational problems and their effectiveness.

v. The probe should be installed in a thickener equipped with other technologies for a thorough comparison.

vi. The probe should be rake mounted for a full radial profile. This would make it possible to detect non-concentricity in thickening applications and its cause.

vii. Other conductivity probe geometries should be tested.

viii. The probe should be used to identify an ideal flocculant (or combination of flocculants) for a specific application. The research would indicate the effects of a non-ideal reagent on the thickener profile.

ix. Several probes should be installed at different radial locations in a single thickener to identify the ideal radial location. The research would also indicate radial solids distribution in thickeners.

x. A smaller probe should be designed for use in a pilot scale thickener. A smaller thickener would facilitate changes in operating parameters for correlation with thickener optimization and require smaller volumes of slurry.

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Appendix A

Programs similar to this were written for the Thompson and Kidd Creek probes. Only one program has been presented due to the size.

Inco's Data Acquisition Software written in QuickBasic:

```
Dim d%(10), LT%(10), x%(8)
Dim cond(35), cellconst(35), corrsolids(35), solids(35), solidsv(35), flgbr(35), x(8)
Dim histday(500), histday2(500), histweek2(2500), histweek(2500)
Dim profweek(35), profday(35)
Dim nochange(35)

COMMON SHARED d%(), LT%(), S
DECLARE SUB das8 (md%, BYVAL num%, fl%)
DECLARE SUB delay (ti)

On Key(1) GoSub 399
KEY(1) ON
For q = 0 To 3
    OUT (&H100 + q), 0
Next q
For j = 1 To 8
    x(j) = 0
Next j
daytot = 0
tot = 0
flgsp = 0
flgsav = 0
For j = 0 To 30
    flgbr(j) = 0
Next j
Cls
Screen 9
Color 3, 8
flgbr = 0
md% = 0
BADR% = &H300
fl% = 0
Call das8(md%, VarPtr(BADR%), fl%)
md% = 19
d% = 9
fl% = 0
Call das8(md%, VarPtr(d%), fl%)
md% = 1
LT%(0) = 0
LT%(1) = 0
fl% = 0
Call das8(md%, VarPtr(LT%(0)), fl%)
x(7) = 0
```

```
Height = 12.47
Depth = 15 / 30.48
ti = 6
ring = 30
density = 4.2
densityw = 1
1
For i = 0 To 30
    READ cellconst(i)
Next i
Data 0.885, 0.877, 0.889, 1.12, 1, 0.997, 1.03, 0.752, 0.772, 0.798, 0.835, 1.275, 1.143, 0.73,
0.96, 0.97, 0.89, 0.71, 0.85, 0.9, 0.96
Data 0.96, 0.96, 0.96, 1.01, 1.1, 0.93, 0.75, 0.71, 0.75, 0.85

Line (360, 10)-(620, 270), 6, BF
Line (392, 265)-(392, 275), 3
LINE (425, 10)-(425, 275), 3, , &HF0F0
Line (457, 265)-(457, 275), 3
LINE (490, 10)-(490, 275), 3, , &HF0F0
Line (522, 265)-(522, 275), 3
LINE (555, 10)-(555, 275), 3, , &HF0F0
Line (587, 265)-(587, 275), 3
Line (355, 32)-(365, 32), 3
LINE (355, 75)-(620, 75), 3, , &HF0F0
Line (355, 107)-(365, 107), 3
LINE (355, 140)-(620, 140), 3, , &HF0F0
Line (355, 172)-(365, 172), 3
LINE (355, 205)-(620, 205), 3, , &HF0F0
Line (355, 237)-(365, 237), 3
Line (360, (1 - Height / 16) * 260 + 10)-(620, (1 - Height / 16) * 260 + 10), 12

LOCATE 23, 57
Print "% Solids"
LOCATE 3, 40
Print "H"
LOCATE 4, 40
Print "E"
LOCATE 5, 40
Print "I"
LOCATE 6, 40
Print "G"
LOCATE 7, 40
Print "H"
LOCATE 8, 40
Print "T"
LOCATE 21, 46
Print "0    20    40    60    80"
LOCATE 1, 43
Print "16"
LOCATE 6, 43
Print "12"
```

```
LOCATE 11, 44
Print "8"
LOCATE 15, 44
Print "4"
LOCATE 20, 44
Print "0"
LOCATE 1, 10
Print "LOAD"
LOCATE 1, 27
Print "INTERFACE"
LOCATE 2, 1
Print "Press W-eek"
LOCATE 3, 1
Print "Week Avg:"
LOCATE 5, 1
Print "Press D-ay"
LOCATE 6, 1
Print "Day Avg: "
LOCATE 8, 1
Print "Press C-urrent"
LOCATE 9, 1
Print "Current:"
LOCATE 16, 1
Print "L"
LOCATE 17, 1
Print "O"
LOCATE 18, 1
Print "A"
LOCATE 19, 1
Print "D"
LOCATE 13, 6
Print "Time (Days  Hrs)"
Line (110, 95)-(110, 102), 1
LOCATE 14, 2
Print "2500"
LOCATE 18, 2
Print "1250"
LOCATE 22, 4
Print "0"
LOCATE 14, 42
Print "1"
LOCATE 18, 42
Print ".5"
LOCATE 22, 42
Print "0"
LOCATE 23, 6
Print " 1  2  3  4  5  6  7 0  6  12  18  24"
Line (45, 187)-(325, 302), 8, BF
LINE (61, 187)-(61, 302), 3, , &HF0F0
LINE (86, 187)-(86, 302), 3, , &HF0F0
LINE (111, 187)-(111, 302), 3, , &HF0F0
```

```
LINE (136, 187)-(136, 302), 3, , &HF0F0
LINE (161, 187)-(161, 302), 3, , &HF0F0
LINE (186, 187)-(186, 302), 3, , &HF0F0
Line (211, 187)-(211, 302), 15
LINE (235, 187)-(235, 302), 3, , &HF0F0
LINE (263, 187)-(263, 302), 3, , &HF0F0
LINE (295, 187)-(295, 302), 3, , &HF0F0
flg = 1
9
ON ERROR GOTO 9.5
Data$ = "c:\inco\in" + Left$(Date$, 2) + Mid$(Date$, 4, 2) + ".dat"
Open Data$ For Append As #1
Print #1, "Date: ", Date$
Print #1, "Time: ", Time$
Print #1, " "
Close #1
NT$ = Mid$(Date$, 4, 2)
ringspace = 10 / 30.48
GoTo 10
9.5
errorcode$ = "99"
If flgsav = 0 Then
    GoSub 999
    flgsav = 1
End If
10
total = 0
water = 0
For S = 10 To 12
        y = S + 1

        If (S < 8) Then
            OUT (&H100), (2 ^ S)
        End If

        If (S > 7) And (S < 16) Then
            OUT (&H101), (2 ^ (S - 8))
        End If

        If (S > 15) And (S < 24) Then
            OUT (&H102), (2 ^ (S - 16))
        End If

        If (S > 23) And (S < 32) Then
            OUT (&H103), (2 ^ (S - 24))
        End If
        If (y < 8) Then
            If S > 8 Then
                OUT (&H100), (2 ^ (y))
            Else
                OUT (&H100), (2 ^ (y) + 2 ^ (S))
```

```
            End If
        End If
        If (y > 7) And (y < 16) Then
            If (S < 8) Or (S > 15) Then
                OUT (&H101), (2 ^ (y - 8))
              Else
                OUT (&H101), (2 ^ (y - 8) + (2 ^ (S - 8)))
              End If
        End If
        If (y > 15) And (y < 24) Then
            If (S < 16) Or (S > 23) Then
                OUT (&H102), (2 ^ (y - 16))
            Else
                OUT (&H102), (2 ^ (y - 16) + 2 ^ (S - 16))
            End If
        End If
        If (y > 23) And (y < 32) Then
            If (S < 24) Or (S > 31) Then
               OUT (&H103), (2 ^ (y - 24))
            Else
                OUT (&H103), (2 ^ (y - 24) + 2 ^ (S - 24))
            End If
        End If
    Call delay(ti)
    sig = 0
    For z = 1 To 25
        md% = 4
        d% = 0
        fl% = 0
        Call das8(md%, VarPtr(d%), fl%)
        sig = sig + d%
    Next z
    d% = sig / 25
    K = (d% ^ 3) * 0.000000000060636 + (d% ^ 2) * 0.0000000842806 + d% * 0.012095 -
9.675
    K = 1000 / K
    K = K - 3.927
    K = 1000 / K
    cond(S) = K
20   cond(S) = cond(S) / cellconst(S)
        K$ = INKEY$
        If K$ = "c" Or K$ = "C" Then
            GoSub 500
        End If
        If K$ = "D" Or K$ = "d" Then
            GoSub 600
        End If
        If K$ = "W" Or K$ = "w" Then
            GoSub 700
        End If
        If K$ = "X" Or K$ = "x" Then
```

```
                GoTo 399
            End If
        If (d% > 10) And (d% < 4095) Then
            total = total + cond(S)
            water = water + 1
        End If
        For q = 0 To 3
            OUT (&H100 + q), 0
        Next q
Next S
numer = 0
If water = 0 Or water = 1 Then
    water = 2
End If
averl = total / water
For j = a To b
    numer = numer + (averl - cond(j)) ^ 2
Next j
Lstd = (numer / (water - 1)) ^ 0.5
Sstd = Lstd
K$ = ""
For g = 0 To 30
            S = g
            y = S + 1
            If (S < 8) Then
                OUT (&H100), (2 ^ S)
            End If

            If (S > 7) And (S < 16) Then
                OUT (&H101), (2 ^ (S - 8))
            End If
            If (S > 15) And (S < 24) Then
                OUT (&H102), (2 ^ (S - 16))
            End If
            If (S > 23) And (S < 32) Then
                OUT (&H103), (2 ^ (S - 24))
            End If
            If (y < 8) Then
                If S > 8 Then
                    OUT (&H100), (2 ^ (y))
                Else
                    OUT (&H100), (2 ^ (y) + 2 ^ (S))
                End If
            End If
            If (y > 7) And (y < 16) Then
                If (S < 8) Or (S > 15) Then
                    OUT (&H101), (2 ^ (y - 8))
                Else
                    OUT (&H101), (2 ^ (y - 8) + (2 ^ (S - 8)))
                End If
            End If
```

```
        If (y > 15) And (y < 24) Then
            If (S < 16) Or (S > 23) Then
                OUT (&H102), (2 ^ (y - 16))
            Else
                OUT (&H102), (2 ^ (y - 16) + 2 ^ (S - 16))
            End If
        End If
        If (y > 23) And (y < 32) Then
            If (S < 24) Or (S > 31) Then
                OUT (&H103), (2 ^ (y - 24))
            Else
                OUT (&H103), (2 ^ (y - 24) + 2 ^ (S - 24))
            End If
        End If
        Call delay(ti)
        sig = 0
        For z = 1 To 25
            md% = 4
            d% = 0
            fl% = 0
            Call das8(md%, VarPtr(d%), fl%)
            sig = sig + d%
        Next z
        d% = sig / 25
        LOCATE 2, 55
        Print "                ";
        LOCATE 2, 55
        Print USING; "Cell ##: DIG: ####"; y, d%
        If (d% < 20) Or (d% > 4094) Then
            cond(S) = averl
            errorcode$ = "Bad Ring" + Str$(S) + " " + Str$(d%)
            If flgbr(S) = 0 Then
                GoSub 999
                flgbr(S) = 1
            End If
        End If
        K = d% ^ 3 * 0.000000000060636 + d% ^ 2 * 0.0000000842806 + d% * 0.012095
- 9.675
        K = 1000 / K
        K = K - 3.927
        K = 1000 / K
        cond(S) = K
        nochange(S) = K
30       cond(S) = cond(S) / cellconst(S)

        LOCATE 3, 55
        Print "            ";
        LOCATE 3, 55
        Print USING; "Cond.: ##.##"; cond(S)
        If averl = 0 Then
            averl = cond(10)
```

```
            End If
            If g > 9 Then
                averl2 = (cond(10) + cond(11) + cond(12)) / 3
                If (Abs(averl - averl2) > 0.3) Then
                    averl = averl2
                End If
            End If
            solidsv(S) = (1 - cond(S) / averl) / (1 + 0.5 * cond(S) / averl)
            solids(S) = solidsv(S) * density / (solidsv(S) * density + densityw * (1 -
solidsv(S)))
            If solids(S) < 0 Then
                solids(S) = 0
            End If
            If solids(S) > 0.8 Then
                solids(S) = 0.8
            End If
            solids(S) = solids(S) * 100
            LOCATE 4, 55
            Print "                ";
            LOCATE 4, 55
            Print USING; "Solids (%): ###.##"; solids(S)
            profweek(S) = profweek(S) + solids(S)
            profday(S) = profday(S) + solids(S)
            K$ = INKEY$
            If K$ = "c" Or K$ = "C" Then
                GoSub 500
            End If
            If K$ = "D" Or K$ = "d" Then
                GoSub 600
            End If
            If K$ = "W" Or K$ = "w" Then
                GoSub 700
            End If
            If K$ = "X" Or K$ = "x" Then
                GoTo 399
            End If
            For q = 0 To 3
                OUT (&H100 + q), 0
            Next q
Next g
If flg = 1 Then
Line (360, 10)-(620, 270), 6, BF
Line (392, 265)-(392, 275), 3
LINE (425, 10)-(425, 275), 3, , &HF0F0
Line (457, 265)-(457, 275), 3
LINE (490, 10)-(490, 275), 3, , &HF0F0
Line (522, 265)-(522, 275), 3
LINE (555, 10)-(555, 275), 3, , &HF0F0
Line (587, 265)-(587, 275), 3
Line (355, 32)-(365, 32), 3
LINE (355, 75)-(620, 75), 3, , &HF0F0
```

```
Line (355, 107)-(365, 107), 3
LINE (355, 140)-(620, 140), 3, , &HF0F0
Line (355, 172)-(365, 172), 3
LINE (355, 205)-(620, 205), 3, , &HF0F0
Line (355, 237)-(365, 237), 3
Line (360, (1 - Height / 16) * 260 + 10)-(620, (1 - Height / 16) * 260 + 10), 12
End If
For j = 0 To 29
    If solids(j) < 0 Then solids(j) = 0
    If solidsv(j) < 0 Then solidsv(j) = 0
    corrsolids(j) = solids(j)
    For K = j To 30
        If solids(j) > solids(K) And solids(K) < 10 Then
            corrsolids(j) = 0
            solidsv(j) = 0
        End If
    Next K
Next j
corrsolids(30) = solids(30)
For S = 0 To 30
        If flg = 1 Then
            y = S + 1
            If S = 0 Then
                X1 = (corrsolids(S) / 80 * 260 + 360)
                Y1 = (1 - Height / 16) * 260 + 10
            End If
            X2 = (corrsolids(S) / 80 * 260 + 360)
            Y2 = ((16 - Height) + Depth + ringspace * y) / 16 * 260 + 10
            Line (X1, Y1)-(X2, Y2), 14
            X1 = X2
            Y1 = Y2
        End If
Next S
50
LSinterface = Height
SSinterface = Height
ring = 27
cond(31) = 0
cond(32) = 0
cond(33) = 0
For j = 2 To 30
    x = 30 - j
    If (solids(x) < 10) And (solids(x - 1) < 10) And (solids(x - 2) < 10) Then
        LSinterface = (x + 0.5) * ringspace + Depth
        ring = x
        GoTo 100
    End If
Next j
100
For j = (ring + 1) To 30
    Sstd = 0.2
```

```
    If (Abs(cond(j) - cond(j + 1)) < (2 * Sstd)) And (Abs(cond(j) - cond(j + 2)) < 2 * Sstd)
And (Abs(cond(j) - cond(j + 3)) < 2 * Sstd) Then
        SSinterface = (j + 0.5) * ringspace + Depth
        GoTo 200
    End If
Next j
200
Load = 0
For j = 0 To 29
    Load = Load + solidsv(j) * 88.289 * 4.2 / 0.9072
Next j
Load = Load + solidsv(30) * 484.47 * 4.2 / 0.9072
INTERFACE = 0
LIQ = 0
SOL = 0
MUD = 0
For j = 10 To 17
    LIQ = LIQ + cond(j)
Next j
LIQ = LIQ / 8
For j = 18 To 27
    SOL = SOL + cond(j)
Next j
SOL = SOL / 10
For j = 28 To 30
    MUD = MUD + cond(j)
Next j
MUD = MUD / 3
INTERFACE = (LIQ - SOL) / (LIQ - MUD)
LOCATE 9, 10
LSinterface = Height - LSinterface
SSinterface = Height - SSinterface
Print USING; "####"; Load
LOCATE 9, 27
Print USING; ".###"; INTERFACE
x(7) = x(7) + 1
daytot = daytot + Load
daytot2 = daytot2 + INTERFACE
dayavg = daytot / x(7)
dayavg2 = daytot2 / x(7)

histweek(tot + x(7)) = Load
histweek2(tot + x(7)) = INTERFACE
weektot = 0
weektot2 = 0
For j = 1 To (tot + x(7))
    weektot = weektot + histweek(j)
    weektot2 = weektot2 + histweek2(j)
Next j
weekavg = weektot / (tot + x(7))
weekavg2 = weektot2 / (tot + x(7))
```

```
LOCATE 3, 10
Print USING; "####"; weekavg
LOCATE 3, 27
Print USING; ".###"; weekavg2
LOCATE 6, 10
Print USING; "####"; dayavg
LOCATE 6, 27
Print USING; ".###"; dayavg2
MUDLINE = SSinterface
sedimentline = LSinterface
Line (360, (1 - SSinterface / 16) * 260 + 10)-(620, (1 - SSinterface / 16) * 260 + 10), 14
LINE (360, (1 - LSinterface / 16) * 260 + 10)-(620, (1 - LSinterface / 16) * 260 + 10), 14, ,
&HF0F0

Open Data$ For Append As #1
Print #1, Time$,
For S = 0 To 30
  Print #1, nochange(S),
Next S
Print #1, LSinterface, SSinterface, Load, INTERFACE
Close #1
If Load < 0 Then
      Load = 0
End If
If Load > 2500 Then
      Load = 2500
End If
If INTERFACE < 0 Then
      INTERFACE = 0
End If
If INTERFACE > 1 Then
      INTERFACE = 1
End If

If Val(Left$(Time$, 2)) = 0 Then GoTo 209
If x(7) = 1 Then
209     star = Val(Left$(Time$, 2)) * 60 + Val(Mid$(Time$, 4, 2))
      x3 = star / 1440 * 114 + 211
      y3 = (2500 - Load) / 2500 * 115 + 187
      Line (x3, y3)-(x3, y3), 15
Else
      cont = Val(Left$(Time$, 2)) * 60 + Val(Mid$(Time$, 4, 2))
      x4 = cont / 1440 * 114 + 211
      y4 = (2500 - Load) / 2500 * 115 + 187
      Line (x3, y3)-(x4, y4), 15
      x3 = x4
      y3 = y4
End If
IF VAL(LEFT$(TIME$, 2)) = 0 THEN GOTO 209.5
If x(7) = 1 Then
209.5     star = VAL(LEFT$(TIME$, 2)) * 60 + VAL(MID$(TIME$, 4, 2))
```

```
        x3 = star / 1440 * 114 + 211
        y3 = (1 - INTERFACE) * 115 + 187
        Line (x3, y3)-(x3, y3), 13
Else
        cont = Val(Left$(Time$, 2)) * 60 + Val(Mid$(Time$, 4, 2))
        x4 = cont / 1440 * 114 + 211
        y4 = (1 - INTERFACE) * 115 + 187
        Line (x3, y3)-(x4, y4), 13
        x3 = x4
        y3 = y4
End If
If Load > 2500 Then LOADOUT = 4095
If INTERFACE > 1 Then INTOUT = 4095
LOADOUT = Int(Load / 2500 * 4095)
INTOUT = Int(INTERFACE * 4095)
md% = 23
d%(0) = 0
d%(1) = LOADOUT
fl% = 0
Call das8(md%, VarPtr(d%(0)), fl%)
md% = 23
d%(0) = 1
d%(1) = INTOUT
fl% = 0
Call das8(md%, VarPtr(d%(0)), fl%)
210
S = 1: y = 2
OUT (&H100), (2 ^ (y) + 2 ^ (S))
Call delay(ti)
sig = 0
For z = 1 To 25
        md% = 4
        d% = 0
        fl% = 0
        Call das8(md%, VarPtr(d%), fl%)
        sig = sig + d%
Next z
d% = sig / 25
oldad1 = d%
newad1 = d%
S = 4: y = 5
OUT (&H100), (2 ^ (y) + 2 ^ (S))
Call delay(ti)
sig = 0
For z = 1 To 25
        md% = 4
        d% = 0
        fl% = 0
        Call das8(md%, VarPtr(d%), fl%)
        sig = sig + d%
Next z
```

```
d% = sig / 25
oldad2 = d%
newad2 = d%
Counter = 0
newad3 = 1000
newad4 = 1000
While (oldad1 / newad1 < 1.15) Or (oldad2 / newad2 < 1.15)
      S = 1: y = 2
      OUT (&H100), (2 ^ (y) + 2 ^ (S))
      Call delay(ti)
      sig = 0
      For z = 1 To 25
            md% = 4
            d% = 0
            fl% = 0
            Call das8(md%, VarPtr(d%), fl%)
            sig = sig + d%
      Next z
     d% = sig / 25
     newad1 = d%
     S = 4: y = 5
     OUT (&H100), (2 ^ (y) + 2 ^ (S))
     Call delay(ti)
     sig = 0
     For z = 1 To 25
           md% = 4
           d% = 0
           fl% = 0
           Call das8(md%, VarPtr(d%), fl%)
           sig = sig + d%
    Next z
     d% = sig / 25
     newad2 = d%
     OUT (&H100), (2 ^ 6 + 2 ^ 7)
    Call delay(ti)
   md% = 4
  d% = 0
    fl% = 0
    Call das8(md%, VarPtr(d%), fl%)
    newad3 = d%
     OUT (&H100), (2 ^ 3 + 2 ^ 4)
     Call delay(ti)
     md% = 4
     d% = 0
     fl% = 0
     Call das8(md%, VarPtr(d%), fl%)
     newad4 = d%
     K$ = INKEY$
    If K$ = "c" Or K$ = "C" Then
          S = 31
          GoSub 500
```

```
    End If
    If K$ = "D" Or K$ = "d" Then
        GoSub 600
    End If
    If K$ = "W" Or K$ = "w" Then
        GoSub 700
    End If
    If K$ = "x" Or K$ = "X" Then
        GoTo 399
    End If
    Counter = Counter + 1
    If Counter > 100 Then
            GoTo 220
    End If
Wend
Call delay(60)
220
If NT$ = Mid$(Date$, 4, 2) Then GoTo 10
300
tot = x(1) + x(2) + x(3) + x(4) + x(5) + x(6) + x(7)
GoSub 400
For j = 1 To tot
    histweek(j) = histweek(j + x(1))
    histweek2(j) = histweek2(j + x(1))
Next j
For j = 1 To 22
    profweek(j) = profweek(j) - x(1) * profweek(j) / tot
    profday(j) = 0
Next j
weektot = weektot - x(1) * weekavg
weektot2 = weektot2 - x(1) * weekavg2
daytot = 0
daytot2 = 0
x(1) = x(2)
x(2) = x(3)
x(3) = x(4)
x(4) = x(5)
x(5) = x(6)
x(6) = x(7)
x(7) = 0
tot = x(1) + x(2) + x(3) + x(4) + x(5) + x(6) + x(7)
GoTo 9
399
End
400
Line (45, 187)-(325, 302), 8, BF
LINE (61, 187)-(61, 302), 3, , &HF0F0
LINE (86, 187)-(86, 302), 3, , &HF0F0
LINE (111, 187)-(111, 302), 3, , &HF0F0
LINE (136, 187)-(136, 302), 3, , &HF0F0
LINE (161, 187)-(161, 302), 3, , &HF0F0
```

```
LINE (186, 187)-(186, 302), 3, , &HF0F0
Line (211, 187)-(211, 302), 15
LINE (235, 187)-(235, 302), 3, , &HF0F0
LINE (263, 187)-(263, 302), 3, , &HF0F0
LINE (295, 187)-(295, 302), 3, , &HF0F0
st = 211
For j = 1 To 7
    If x(j) > 0 Then
        st = st - 166 / 7
    End If
Next j
For j = 1 To tot
    range = 211 - st
    If histweek(j) < 2.5 Then
        histweek(j) = 2.5
    End If
    If histweek(j) > 12.5 Then
        histweek(j) = 12.5
    End If
    If j = 1 Then
        x5 = st
        y5 = (12.5 - histweek(j)) / 10 * 115 + 187
        Line (x5, y5)-(x5, y5), 15
    Else
        x6 = j * range / tot + st
        y6 = (12.5 - histweek(j)) / 10 * 115 + 187
        Line (x5, y5)-(x6, y6), 15
        x5 = x6
        y5 = y6
    End If
Next j
For j = 1 To tot
    range = 211 - st
    If histweek2(j) < 2.5 Then
        histweek2(j) = 2.5
    End If
    If histweek2(j) > 12.5 Then
        histweek2(j) = 12.5
    End If
    If j = 1 Then
        x5 = st
        y5 = (12.5 - histweek2(j)) / 10 * 115 + 187
        Line (x5, y5)-(x5, y5), 7
    Else
        x6 = j * range / tot + st
        y6 = (12.5 - histweek2(j)) / 10 * 115 + 187
        Line (x5, y5)-(x6, y6), 7
        x5 = x6
        y5 = y6
    End If
Next j
```

```
Return
500
Line (360, 10)-(620, 270), 6, BF
Line (392, 265)-(392, 275), 3
LINE (425, 10)-(425, 275), 3, , &HF0F0
Line (457, 265)-(457, 275), 3
LINE (490, 10)-(490, 275), 3, , &HF0F0
Line (522, 265)-(522, 275), 3
LINE (555, 10)-(555, 275), 3, , &HF0F0
Line (587, 265)-(587, 275), 3
Line (355, 32)-(365, 32), 3
LINE (355, 75)-(620, 75), 3, , &HF0F0
Line (355, 107)-(365, 107), 3
LINE (355, 140)-(620, 140), 3, , &HF0F0
Line (355, 172)-(365, 172), 3
LINE (355, 205)-(620, 205), 3, , &HF0F0
Line (355, 237)-(365, 237), 3
Line (360, (1 - Height / 16) * 260 + 10)-(620, (1 - Height / 16) * 260 + 10), 12
For K = 0 To S
    j = K + 1
    If K = 0 Then
        X1 = 360
        Y1 = 10 + (1 - Height / 16) * 260
    End If
        X2 = (solids(S) / 12 * 260 + 360)
        Y2 = ((16 - Height) + Depth + ringspace * j) / 16 * 260 + 10
        Line (X1, Y1)-(X2, Y2), 14
        X1 = X2
        Y1 = Y2
Next K
flg = 1
K$ = " "
Return
600
Line (360, 10)-(620, 270), 6, BF
Line (392, 265)-(392, 275), 3
LINE (425, 10)-(425, 275), 3, , &HF0F0
Line (457, 265)-(457, 275), 3
LINE (490, 10)-(490, 275), 3, , &HF0F0
Line (522, 265)-(522, 275), 3
LINE (555, 10)-(555, 275), 3, , &HF0F0
Line (587, 265)-(587, 275), 3
Line (355, 32)-(365, 32), 3
LINE (355, 75)-(620, 75), 3, , &HF0F0
Line (355, 107)-(365, 107), 3
LINE (355, 140)-(620, 140), 3, , &HF0F0
Line (355, 172)-(365, 172), 3
LINE (355, 205)-(620, 205), 3, , &HF0F0
Line (355, 237)-(365, 237), 3
Line (360, (1 - Height / 16) * 260 + 10)-(620, (1 - Height / 16) * 260 + 10), 12
For j = 0 To 30
```

```
        If j < S Then
            pt = x(7) + 1
        Else
            pt = x(7)
        End If
        j = K + 1
        If K = 1 Then
            X1 = 360
            Y1 = 10 + (1 - Height / 16) * 260
        End If
            X2 = (profday(j) / pt / 80 * 260 + 360)
            Y2 = ((16 - Height) + Depth + ringspace * j) / 16 * 260 + 10
            Line (X1, Y1)-(X2, Y2), 14
            X1 = X2
            Y1 = Y2
Next j
flg = 0
K$ = " "
Return
700
Line (360, 10)-(620, 270), 6, BF
Line (392, 265)-(392, 275), 3
LINE (425, 10)-(425, 275), 3, , &HF0F0
Line (457, 265)-(457, 275), 3
LINE (490, 10)-(490, 275), 3, , &HF0F0
Line (522, 265)-(522, 275), 3
LINE (555, 10)-(555, 275), 3, , &HF0F0
Line (587, 265)-(587, 275), 3
Line (355, 32)-(365, 32), 3
LINE (355, 75)-(620, 75), 3, , &HF0F0
Line (355, 107)-(365, 107), 3
LINE (355, 140)-(620, 140), 3, , &HF0F0
Line (355, 172)-(365, 172), 3
LINE (355, 205)-(620, 205), 3, , &HF0F0
Line (355, 237)-(365, 237), 3
Line (360, (1 - Height / 16) * 260 + 10)-(620, (1 - Height / 16) * 260 + 10), 12
For j = 0 To 30
        If j < S Then
            pt = tot + 1
        Else
            pt = tot
        End If
        If j = 1 Then
            X1 = (profweek(j) / pt / 80 * 260 + 360)
            Y1 = Depth / Height * 260 + 10
            Line (X1, Y1)-(X1, Y1), 14
        Else
            X2 = (profweek(j) / pt / 80 * 260 + 360)
            Y2 = ((16 - Height) + Depth + ringspace * (j + 1)) / 16 * 260 + 10
            Line (X1, Y1)-(X2, Y2), 14
            X1 = X2
```

```
            Y1 = Y2
        End If
Next j
flg = 0
K$ = " "
Return
999
md% = 23
d%(0) = 0
d%(1) = 4095
fl% = 0
Call das8(md%, VarPtr(d%(2)), fl%)

md% = 23
d%(0) = 1
d%(1) = 4095
fl% = 0
Call das8(md%, VarPtr(d%(2)), fl%)

LOCATE 13, 47
Print "Error "; errorcode$
LOCATE 14, 47
Print "Please call McGill!"
LOCATE 15, 47
Print "Press 'A' to continue"
LOCATE 16, 47
Print "Err ="; Err
999.2
IF INKEY$ = "a" OR INKEY$ = "A" THEN GOTO 999.5
GOTO 999.2
999.5
md% = 23
d%(0) = 0
d%(1) = slout
fl% = 0
Call das8(md%, VarPtr(d%(2)), fl%)
md% = 23
d%(0) = 1
d%(1) = mlout
fl% = 0
Call das8(md%, VarPtr(d%(2)), fl%)
Return
Sub delay(ti)
    t1 = Timer + ti
    If t1 > 86400 Then
        t1 = t1 - 86400
999.9       IF TIMER < 80000 THEN
              GoTo 1000
            Else
              GOTO 999.9
            End If
```

```
    End If

1000      Do
           If t1 - Timer > 120 Then GoTo 1001
          Loop Until Timer >= t1

1001
End Sub
```

Appendix B

A spreadsheet was developed to analyze the data files. The first sheet was designed to hold the raw data (Appendix C). The second sheet contains the corrected conductivity measurement; these are calculated by applying the cell constant to each ring. The third sheet calculates the % solids by volume using Maxwell's model. The fourth sheet contains the % solids by weight calculated from the % solids by volume and a solids specific gravity of 4.2 (provided by Inco). The fifth sheet contains the corrected % solids by weight; the presence of froth at the surface appears to the probe as solids and therefore must be corrected for. This sheet removes the froth effect. The sixth sheet is the thickener load, calculated from the corrected solids sheet. The formulas (copied from Excel) are listed below:

Sheet 1: No formula

Sheet 2: =Data!D8/Data!D$2

Sheet 3: =(1-(Cond!D46/((Cond!$D46+Cond!$E46+Cond!$F46)/3))) /
(1+0.5*(Cond!D46/((Cond!$D46+Cond!$E46+Cond!$F46)/3)))

Sheet 4: =('Solids vol'!D17*4.2)/(1+3.2*'Solids vol'!D17)*100

Sheet 5: =IF(Solids!T15<0,0,IF(AND(Solids!T15>MIN($U15:AF15)
,Solids!T15<10), 0,IF(MIN($U15:AF15)<=0,0,Solids!T15)))

Sheet 6: =88.289*'Corr Solids'!T17/100*3.2/(4.2-('Corr Solids'!T17/100*3.2))

This spreadsheet was used to generate all the charts generated for this thesis.

Appendix C

Over 500 days of data have been collected. Each day the data below is collected.

The data are presented as a series of readings at the following depths (in cm) followed by the interface and mud line. Readings are taken every 7 minutes. Only 1 hour of data is presented for the sake of brevity. Over 100 MB of data have been collected (3,000,000 data points).

Depths:

-15.0 -25.0 -35.0 -45.0 -55.0 -65.0 -75.0 -85.0 -95.0 -105.0 -115.0 -125.0 -135.0 -145.0 -155.0 -165.0 -175.0 -185.0 -195.0 -205.0 -215.0 -225.0 -235.0 -245.0 -255.0 -265.0 -275.0 -285.0 -295.0 -305.0 -315.0

Date: 02-05-1995

Time: 00:04:52

00:08:36	24.4	24.4	23.9	23.9	24.1	24.1	21.6	21.6	20.3
20.3	21.6	21.6	15.1	15.1	16.5	16.4	16.0	16.2	15.6
15.6	15.8	15.8	15.3	15.3	14.0	14.1	13.0	13.1	13.3
13.3	11.8	9.5	8.9						
00:15:34	24.4	24.4	23.9	23.9	24.1	24.1	21.6	21.6	20.3
20.3	21.6	21.6	15.1	14.9	15.9	16.1	15.9	16.0	15.5
15.6	15.8	15.9	15.3	15.4	14.1	14.0	13.0	13.1	13.3
13.3	11.7	10.2	9.5						
00:22:42	24.4	24.4	23.9	23.9	24.1	24.0	21.5	21.5	20.3
20.3	21.6	21.6	15.3	15.2	16.0	15.9	15.9	16.0	15.6
15.6	15.9	15.9	15.4	15.4	14.0	14.1	13.0	13.2	13.3
13.3	11.7	11.2	9.2						
00:29:22	24.4	24.4	23.9	23.9	24.1	24.1	21.5	21.5	20.3
20.3	21.7	21.7	15.2	15.1	15.8	15.8	15.9	15.9	15.7

15.6	15.7	15.7	15.4	15.4	14.0	13.9	13.0	12.9	13.4
13.3	11.7	11.5	10.8						
00:36:31	24.4	24.4	23.9	23.9	24.1	24.1	21.5	21.6	20.3
20.3	21.7	21.7	15.2	15.3	16.1	16.2	15.9	15.9	15.7
15.6	15.8	15.8	15.4	15.4	14.1	14.0	13.0	13.0	13.4
13.4	11.6	11.5	0.0						
00:43:28	24.4	24.4	23.9	23.9	24.1	24.1	21.6	21.6	20.3
20.4	21.7	21.7	15.3	15.3	16.0	15.7	15.9	15.9	15.6
15.7	15.8	15.8	15.4	15.4	14.0	13.9	12.9	13.0	13.1
13.2	11.7	11.5	4.9						
00:50:37	24.4	24.4	23.9	23.9	24.1	24.1	21.6	21.6	20.3
20.4	21.8	21.8	15.3	15.2	15.9	16.0	15.9	16.0	15.5
15.5	15.8	15.8	15.4	15.4	13.9	13.9	13.0	12.9	13.4
13.3	11.7	11.5	4.9						
00:57:35	24.5	24.5	23.9	23.9	24.1	24.1	21.7	21.6	20.3
20.4	21.7	21.8	15.2	15.2	15.9	15.9	16.0	16.0	15.8
15.8	15.8	15.8	15.4	15.4	14.0	14.0	13.1	13.1	13.3
13.2	11.7	11.5	4.9						
01:04:43	24.5	24.4	23.9	23.9	24.2	24.1	21.6	21.6	20.3
20.4	21.8	21.8	15.3	15.3	15.9	15.9	16.0	16.0	15.4
15.5	15.9	15.9	15.4	15.5	14.0	13.9	13.1	13.0	13.2
13.3	11.7	11.5	0.0						
01:09:41	24.0	24.4	23.6	23.9	24.2	24.1	21.7	21.6	20.4
20.4	21.8	21.8	15.5	15.3	15.9	15.8	15.8	15.9	15.6
15.6	15.9	15.9	15.5	15.5	14.0	14.0	13.3	13.3	13.3
13.4	11.6	0.0	0.0						
01:19:15	24.4	24.4	23.9	23.9	24.1	24.1	21.7	21.7	20.3
20.3	21.6	21.7	15.2	15.2	15.9	15.9	15.9	15.9	15.6
15.6	16.1	16.1	15.7	15.8	14.0	14.0	13.3	13.4	13.2
13.2	11.5	9.5	8.9						