FINAL REPORT

Project Title: Acoustic Separation Technology

Covering Period: March 1, 2000 through August 30, 2001

Date of Report: February 22, 2002

Recipient: Institute of Paper Science and Technology (IPST)
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Acknowledgement: This material is based upon work supported by the U.S. Department of Energy under Award no. DE-FC07-97ID13553.

Award Number: DE-FC07-97ID13553

Subcontractors: None

Other Partners: IPST member companies, SP Newsprint

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Project Objective: The overall objectives are:

- To perform a mill demonstration of ultrasonic whitewater clarification using Acoustic Separation Technology (AST)
- To evaluate the economics and commercialization potential of AST-based whitewater clarification

Executive Summary:

Today's restrictive environmental regulations encourage paper mills to close their water systems. Closed water systems increase the level of contaminants significantly. Accumulations of solid suspensions are detrimental to both the papermaking process and the final products. To remove these solids, technologies such as flotation using dissolved air (DAF), centrifuging, and screening have been developed. Dissolved Air Flotation systems are commonly used to clarify whitewater. These passive systems use high pressure to dissolve air into whitewater. When the pressure is released, air micro-bubbles form and attach themselves

to fibers and particles, which then float to the surface where they are mechanically skimmed off. There is an economic incentive to explore alternatives to the DAF technology to drive down the cost of whitewater processing and minimize the use of chemicals. The installed capital cost for a DAF system is significant and a typical DAF system takes up considerable space. An alternative approach, which is the subject of this project, involves a dual method combining the advantages of chemical flocculation and in-line ultrasonic clarification to efficiently remove flocculated contaminants from a water stream.

With the assistance of DOE funding, the Institute of Paper Science and Technology has been engaged in the development of a new separation technology relying on ultrasonic principles. The technology (AST) is aimed at the processing of large quantities of liquids and/or pulp stocks. More precisely, a traveling (unidirectional) ultrasonic wave field is used to redistribute water-suspended particles in such a way as to separate them according to particle size and to a lesser extent particle density. As a possible industrial application, the separation technology could be used to clarify whitewater in a paper mill. Since whitewater solids are relatively small (<100 μm), chemical flocculation was proposed as a simple means to increase particle size in preparation for subsequent ultrasonic clarification. The desired goal is to process a whitewater stream in a continuous mode and obtain two output streams: a clean stream and a stream of concentrated solids. In some ways, the dual flocculation/ultrasonic clarification method can be described as an active sedimentation method into which a weak gravitational force acting on small particles is replaced by a strong acoustic force acting on large flocculated particles. The original project resulted in a laboratory-scale (15 gpm) AST whitewater clarification process. The completed one-year project focused on a mill pilot-scale demonstration of whitewater clarification at SP Newsprint in Dublin, GA.

Based on an economic analysis of earlier results produced using our lab scale system, we anticipated a more than 50% capital cost reduction and annual operating cost savings of about 33% compared to conventional technology. We have obtained whitewater clarification results from the mill pilot setup. However these were limited, due to transducer performance degradation problems. The mill setup uses a horizontal flow channel, which tended to enhance the AST separation process due to the effect of the gravity force. This could potentially be used to reduce energy operating costs. We also needed a higher proportion of chemicals than used in the lab system. This would increase the cost of chemicals.

Actual project results achieved in FY01:

There were seven stated goals/milestones listed in the Milestone log. In this section, a summary of each goal and what was accomplished to fulfill the goal will be discussed.

Goal one was to search for a commercialization partner. Due to substandard transducers and degradation problems with the transducers, commercialization partners, who had shown interest, are waiting for the development of more reliable second-generation, large-scale, high power transducers before any decisions are made. We did visit Voith Paper in Appleton, WI, in October 2000 and presented an overview of the AST work.

Goal two was the design and construction of a 100 GPM pilot clarifier. This work was completed in September 2000. Figure 1 shows part of the completed pilot clarifier dealing with the acoustic section and the "Y" divider section.

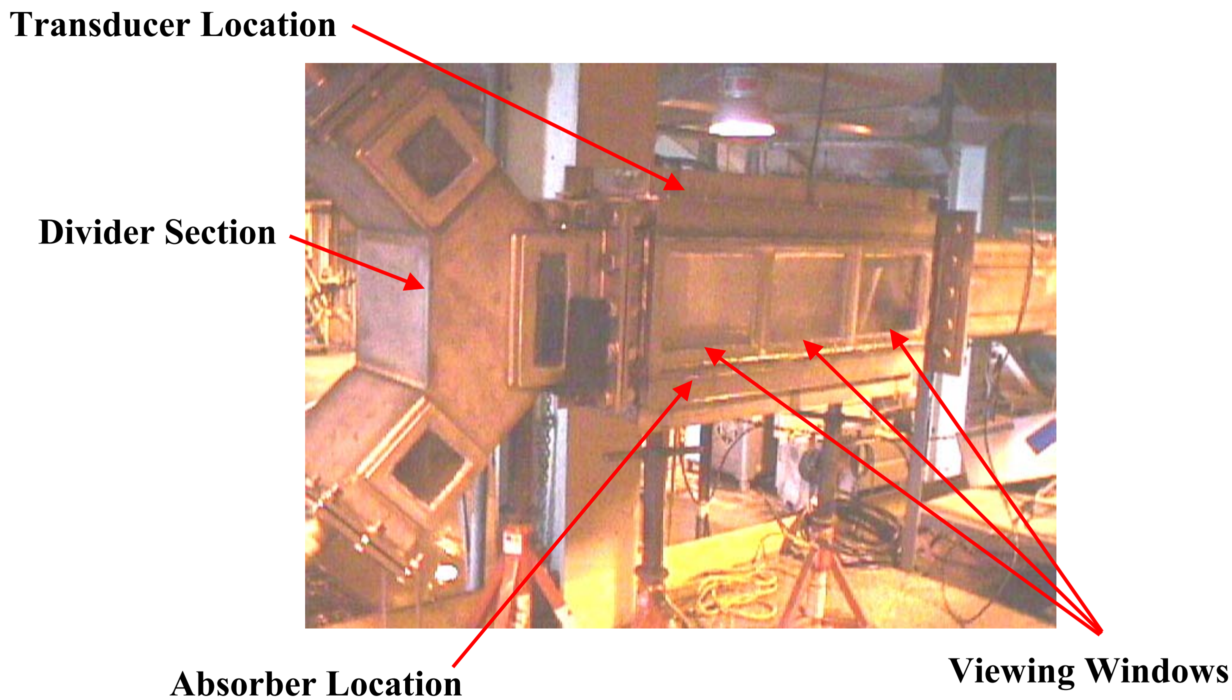

Figure 1: The Acoustic section and the "Y" Divider section of the pilot clarifier in the mill.

Goal three was completion of lab experiments using dissolved air. One of the variables that had been identified in the previous laboratory work as important for AST performance is the air content of the water (e.g., tap water nearly saturated with air vs. degassed water). It had appeared that the cavitation resulting from dissolved air provides an additional driving force for separation, although it also increases attenuation of the ultrasound intensity. During the lab evaluation of the Sonic Concepts transducer, some data were obtained on the effect of dissolved air that seemed inconsistent with our expectations. Since time did not permit the investigation of this low priority goal, we did not investigate the situation further to better clarify the role of dissolved air in AST performance.

Goal four was the design and construction of custom ultrasonic equipment. Two companies were chosen to design the ultrasonic equipment. The original supplier of transducers for the project is Sonic Concepts (Woodenville, WA). This company has supplied transducers to this project and the associated internal IPST project for the last 8 years. The company is a small one, specializing in acoustic transducers for research purposes. They have specifically said that they are not interested in mass production, though they were willing to license their technology. Sonic Concepts used solid blocks of PZT to construct the transducers. Sonic Concepts delivered the large transducer (see Figure 2) to be used in the first phase of the mill trial at SP Newsprint in the Fall of 2000.

MSI (Material Systems Inc., Littleton, MA) began working with IPST on transducer construction at the beginning of 2000. Initially, there were a few problems because our operating requirements were significantly different from what they had dealt with in the past. Specifically, we required significantly more power output. MSI builds the transducers using a casting and sintering process. This process is more amenable to mass production than the process used by Sonic Concepts. We had previously (Summer 2000) completed the testing of four small-scale transducers (design variants) produced by MSI. Based on that testing, we had ordered a large transducer, based on the best design, for use in the mill trial. MSI was supposed to deliver the large transducer in Nov. 2000, but some delays (including temporary unavailability of the needed piezoelectric material) occurred. We also requested a thorough testing of the transducer at full power, with monitoring of its temperature, to be done at MSI prior to shipment. The transducer was delivered in February 2001, and tested in the IPST laboratory prior to installation at the mill.

25 x 37.5 cm Transducer (front view)

Back side of Transducer

Matching network

Figure 2: Picture of the Sonic Concepts transducer used in the pilot clarifier.

Goal five was to conduct mill trials at SP Newsprint. SP Newsprint has been extremely supportive of the work to set up a pilot clarifier system at their mill in Dublin, GA. The pilot clarifier has a nominal 100 gpm capacity. Whitewater streams from various mill sources can be diverted to a holding (feed) tank that is connected to the flow loop. The flow loop included a feed tank, a clean stream collection tank, provision for adding flocculant (flocs make the separation process more efficient) to the stream prior to reaching the acoustic section, and instrumentation for pressure, flow, and consistency measurements. The acoustic section consisted of a flow straightening section, a transducer section, and a “Y” divider section (see Figure 1). The “Y” is used to direct the clean and floc-concentrated streams to the respective collection tanks.

The mill pilot trials were then initiated, but a matching network problem for the Sonic Concepts transducer caused an early interruption/delay. The matching network had to be sent back to Sonic Concepts for redesign and rebuilding. Also in November, some leakage problems were encountered at the viewing windows in the acoustic section; these were resolved in December.

In Jan. 2001, the Sonic Concepts transducer and redesigned matching network were reinstalled and runs at full power were initiated. Qualitative data on separation were obtained during the brief period before the next set of transducer problems was encountered (see Project Activities section for details). Both the Sonic Concepts and the MSI transducers were installed and tested in the pilot unit in early April. Again, qualitative separation data (video images) were obtained, but transducer problems and off-optimum flocculant input precluded the attainment of useful quantitative data.

Following the assessment of the MSI and Sonic Concepts transducers in May/early June, and the repair of the MSI transducer, the mill pilot trial work was continued in June/early July. Although the experimental ranges were somewhat limited (particularly the transducer power levels (acoustic intensity)), the throughflow velocity, intensity, flow (divider) split between clean and concentrated streams, flocculant concentration and input consistency were varied during the runs. The consistencies of the clean and concentrated streams, and the deflection angle of the acoustically deflected flocs were measured.

Analysis of the experimental results is complete. In view of the reduced transducer performance during the trials, it was necessary to use a combination of pilot and laboratory data to project/estimate the pilot performance at full functionality.

Goal six is commercialization. The original commercialization partner envisioned for the Acoustic Separation Technology (AST) was Beloit. The group within the former Beloit that was responsible for Beloit's participation in the project is now part of GL&V. Unfortunately, GL&V is not interested in pursuing AST at this time. We have, therefore, been continuing to identify other potential commercialization partners (both major papermaking equipment suppliers and suppliers of separation equipment). We had felt it would be best to wait until the mill demonstration unit is fully functional before pursuing these leads vigorously, but with the early demise of the two transducers, that task may have to wait for a new generation of more reliable transducers. Fortunately, the State of Georgia is funding an additional year of AST work (focussed on the pilot system at SP Newsprint) that will allow new transducers to be designed and evaluated. This work is in progress.

Goal seven is project management. We are scheduled to submit the final report before the end of February of 2002.

Project Activities:

Background:
The Acoustic Separation Technology (AST) uses a high-power ultrasonic force to push particles suspended in water away from the ultrasonic source (transducer). When the particles are exposed to an ultrasonic wave field, they migrate in the direction of wave propagation due to acoustic radiation pressure. For nonspherical particles such as pulp fibers, they can reorient due to the presence of an acoustic radiation torque. In addition to acoustic radiation pressure, acoustic streaming and acoustic cavitation can contribute to the total acoustic force. All together, these acoustic effects are important because they enable the noncontact mechanical manipulation of fibers and other particles. To separate fines that are small in size, chemical flocculant is added to flocculate the fines in the whitewater to optimal sizes that are better affected by ultrasonics. By adding a divider blade after the transducers, two output streams can be obtained; a clean water stream and a floc concentrated stream. A number of whitewater clarification runs were performed in the mill and they will be discussed in detail. Some results from lab tests that were used to determine the effect of air on clarification will also be discussed.

Mill System Description:
The development of a 100 GPM pressurized ultrasonic clarifier was initiated in September 1999 under another project. There are four basic parts (see Figure 3): (1) chemical injection and mixing, (2) flow development section, (3) acoustic section, (4) collection section which consists of a separator to separate clean water and concentrated solids. The acoustic section, shown in

Figure 3, is capable of accommodating two 37.5 x 25 cm transducers mounted in series. Only one transducer is necessary to process flocculated whitewater.

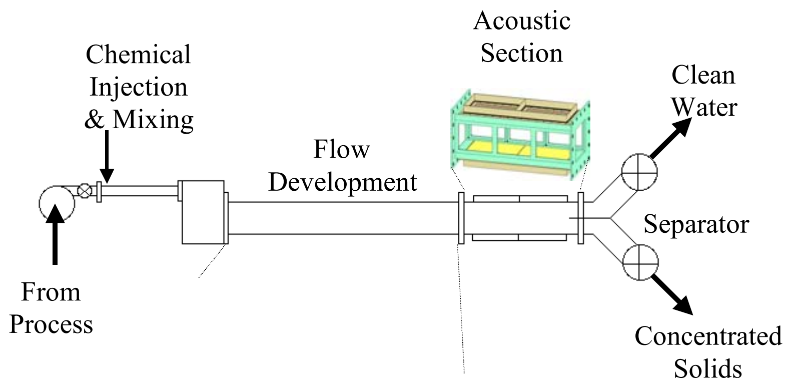

Figure 3: Schematic diagram of the 100 GPM pressurized acoustic clarifier

The input variables of interest for the pilot trials were:

- Acoustic Intensity
- Throughput (Flow Velocity)
- Divider Blade Location (flow split)
- Input Consistency
- Type of Chemical Flocculant
- Amount of Flocculant Required

The key responses are the two output stream consistencies and the deflection angle of the concentrated stream. The trial results can be used to estimate how many stages would be required to obtain a stream as clean as the one currently available through DAF.

Problems Encountered:

The primary obstacle encountered was a lack of reliable transducers. The Sonic Concepts transducer was initially tested in the laboratory. After the test, it was installed in the mill pilot system (in November 2000). Unfortunately, during the initial operation in November, the transformers in the impedance matching networks, which transfer power to the transducer elements, catastrophically overheated. The networks were redesigned, fabricated and tested at Sonic Concepts, with a dramatic improvement in thermal performance. These new networks were received in December, allowing the mill trials to proceed. Unfortunately, during operation at the mill, there was evidence of excessive transducer heating, and the amplifiers overloaded (possibly due to the absorber reflecting a significant amount of acoustic power back into and through the transducer). The transducer-overheating problem was found to be correctable by use of active air cooling of the backside of the transducer. The reflection problem was investigated in the laboratory, and a modified absorber was selected that could reduce the reflection effect. However, in the early April 2001 mill trial, it was found that the power input to the transducer still had to be severely limited, in order to avoid overloading the amplifier. Impedance measurements in early June 2001 showed that the transducer itself had degraded. Examination at the manufacturer's facility showed that the matching layer had separated from the piezoelectric material. This was likely due to a thermal expansion mismatch or to an epoxy failure. The Sonic Concepts transducer was not used in the pilot trials conducted in June and early July.

In March 2001, the mill clarifier was operated briefly with the MSI transducer, but it was found that the water-contacting surface had a leakage path, so actual experiments were not feasible until repairs were made. In early April, the MSI transducer was operated in the mill clarifier. The middle of the three elements ran well at high power for a few days, but operation of the first and third elements was greatly impaired by overheating problems. In May/early June, the transducer was returned to MSI for inspection and repair. It was found that the matching layer and electrodes had partially separated from the piezoelectric material. After rebuilding, using a different matching layer and epoxy, the middle element was nearly back to full function, element 1 was minimally functional, and element 3 was essentially non-functional. The transducer was used in this condition (thus limiting the range of experimental conditions available) for trials at the mill in June and early July, after which it basically stopped functioning.

There were also problems with the amplifier overloading due to ultrasonic waves being reflected back from the absorber. Therefore, the absorber surface was cut to produce an irregular surface and hence reduce reflection. The irregular surface caught the fibers and created lumps of fibers on the bottom of the flow channel. These lumps would occasionally be released into the concentrated flow stream and affect the solids mass flow rate of the dirty stream. Precautions were taken to avoid collecting concentrated stream samples during such intervals.

All runs were done using manual control of the system. The turbidity meters did not work well because they could not read flocculated fiber bundles, so post-test consistency analysis had to be done. The valves in the clean and concentrated streams had to be controlled manually to get flows proportional to areas determined by divider blade setting, but this was not an exact technique and that could have affected clarification.

Results Obtained:
Several variables were considered in the design of clarification experiments. Only one transducer was run at any particular time. Each transducer was made up of three elements in series. Element 3 was closest to the divider blade. Only results obtained with the MSI transducer will be shown. Element 3 of the MSI transducer was not functional. The ranges for the variables are:

- Flow Velocity
  0.050 m/s, 0.073 m/s, 0.100 m/s, 0.130 m/s
- Acoustic Intensity
  Zero
  Low – Element 1 @ 0.5W/cm^2, Element 2 @ 1 W/cm^2
  High – Element 1 @ 0.5W/cm^2, Element 2 @ 2 W/cm^2
- Divider Split
  50:50, 30:70 (% Clean Stream flow area: % Concentrated Stream flow area)
- Flocculant
  Phenol Formaldehyde Resin (PFR) - 15 ppm
  PolyEthylene Oxide (PEO) - 2, 5, 9, 12 ppm
- Input Consistency
  0.022 – 0.059%

Selected results are presented in two formats for the clarification runs. The first format is visually through images (Figs. 4, 5). The second format is graphical (Figs. 6 to 9). The graphs present two different types of data. The first type of data is deflection angle (see Figs. 6,9). The second type is based on results of consistency measurements (see Figs. 7,8).

Figure 4 and 5 shows images of acoustic clarification. The black and white images are average images from a video clip five seconds long. The color image is a five-color thresholded image of the same five seconds. Each color is based on the amount of background light going through the flow cell as recorded by the camera. The more light going through the flow cell, the better the clarification (yellow and blue show the cleanest water). The color image is used in conjunction with the black and white image to locate the deflection angle. At zero power, some clarification is seen. Element 1 (right side of image), which ran at 0.5 W/cm^2, showed no separation effect. The deflection angle is therefore based on element 2 (see white lines showing angle on color image). The deflection angle is measured at the intersection of the blue and green areas of the color average thresholded image. The key difference between Figure 4 and Figure 5 was the flow velocity. A lower velocity produces a higher deflection angle.

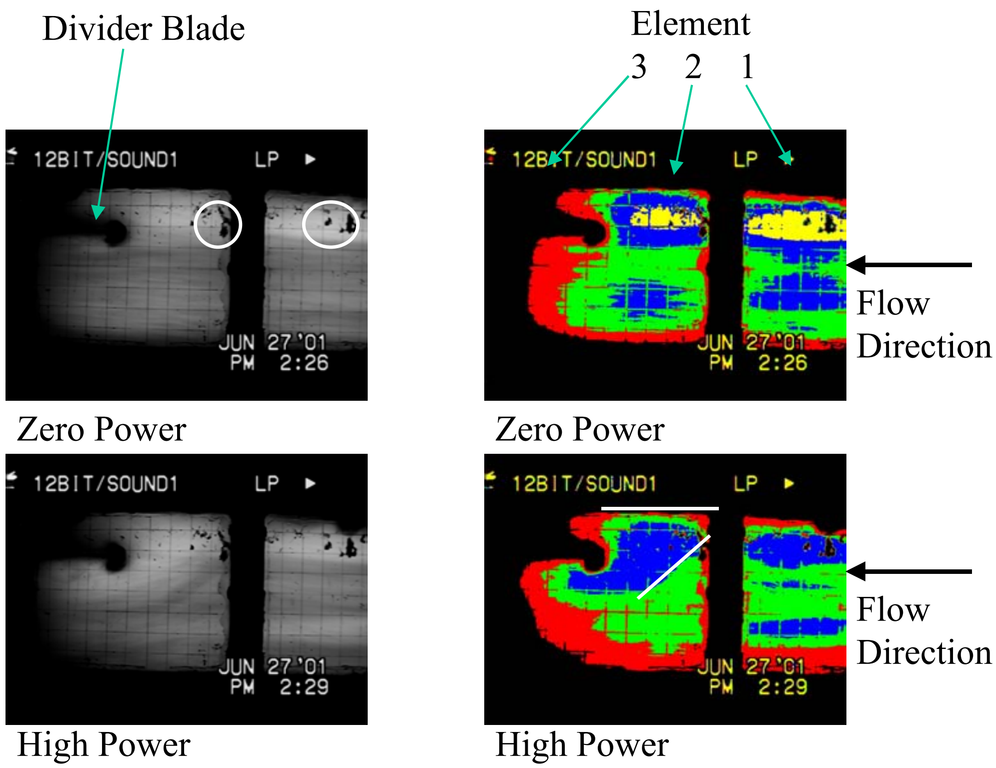

Figure 4: Flow velocity is 0.102 m/s, Consistency is 0.024%, and Divider position is 30:70. Material Systems Inc transducer was used. The circled areas show some of the flocculated fibers sticking to the surface of the flow loop.

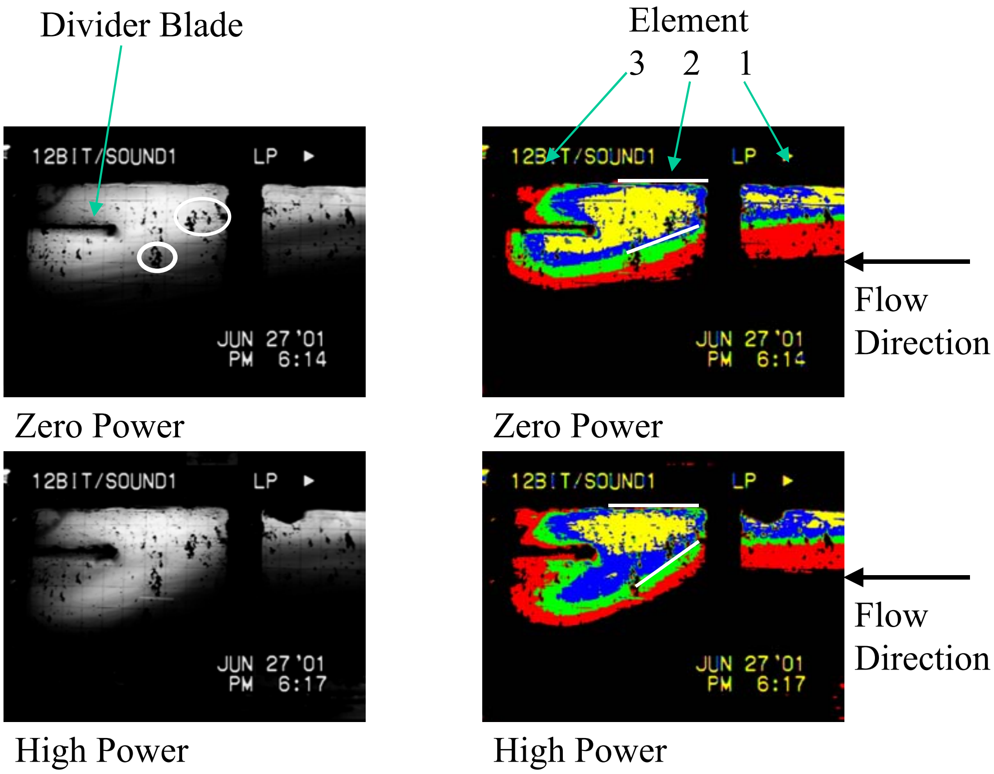

Figure 5: Flow velocity is 0.051 m/s, Consistency is 0.039%, and Divider position is 30:70. Material Systems Inc transducer was used. The circled areas show some of the flocculated fibers sticking to the surface of the flow loop.

In Figure 6, the deflection angles at different flow velocities (primary variable) and different consistencies (secondary variable) are plotted. Three five second average color images were used to find the average deflection angle. In general, as one increases the power, the deflection angle increases. The non-zero deflection angle at zero power and low velocity is apparently due to the gravity effect. Due to limitations of the transducer, runs above 2 W/cm^2 were not feasible, but based on our earlier lab experiments, the deflection angle increases a substantial amount up to 3 W/cm^2, after which the increases are minimal.

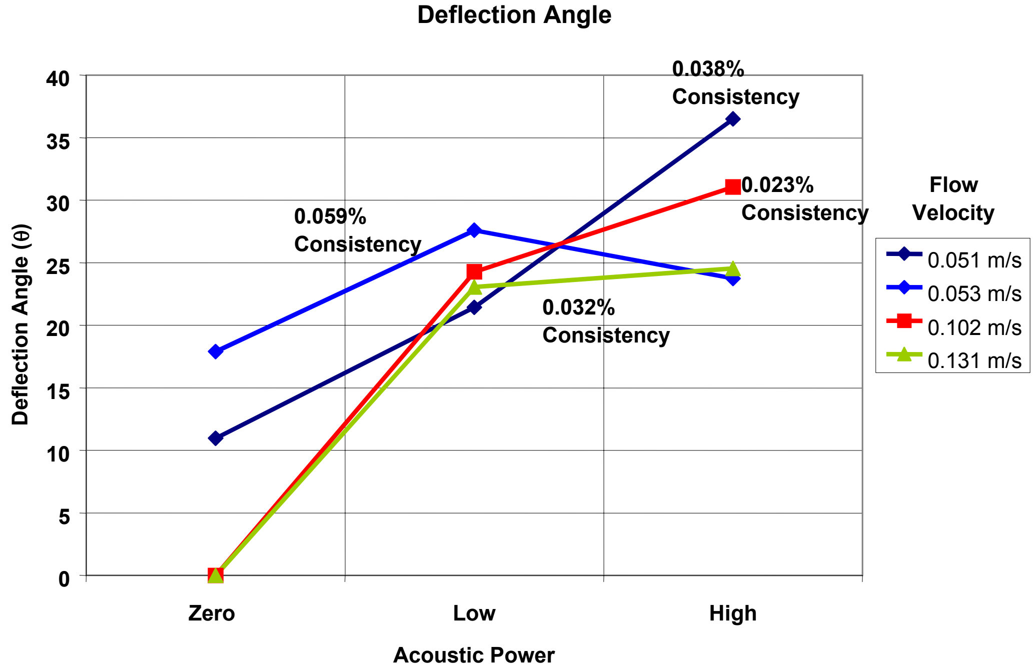

Figure 6: Deflection angle measurements done for MSI element 2 at different flow velocities and different consistencies. Divider position is at both 30:70 and 50:50.

For Figures 7 and 8 the y-axis is shown as mass flow rate of solids. Mass flow rate of solids is the total solids of fibers and chemicals. This number is derived from the consistency values. The consistency measurements were done in accordance with TAPPI T-240 (Consistency (concentration) of pulp suspensions) test method. Three consistencies were taken for each point and the average value was used to calculate the mass flow rate of solids. For Figures 7 and 8, we see that there was a greater mass flow rate of solids for the concentrated stream regardless of the flow velocity. At "zero" power there was also a greater mass flow rate of solids for the concentrated stream than the clean water stream. This was due to the effect of gravity. In Figure 7, as more power was applied, the concentrated stream mass flow rate increased and the clean stream values were steady. Applying power did not seem to clarify the clean water stream further at low flow velocities. Therefore, the increase in concentrated stream mass flow rates was probably due to lumps of fiber being released that were stuck to the surface of the absorber. The second possibility is that any unevenness of power from the transducer allowed for particles to bounce back from the absorber and flow through the clean stream. At times, flocculated fibers were also seen clumping at the surface of the transducer elements at zero power. These fibers did on occasion dislodge and flow through the clean stream. At higher flow velocities (Figure 8), the clean stream mass flow rate was higher at zero power. This was because gravity force is not sufficient enough for the particles to settle. At the higher flow velocities, more acoustic power is needed to clarify the whitewater, but the acoustic power available from the transducer was insufficient.

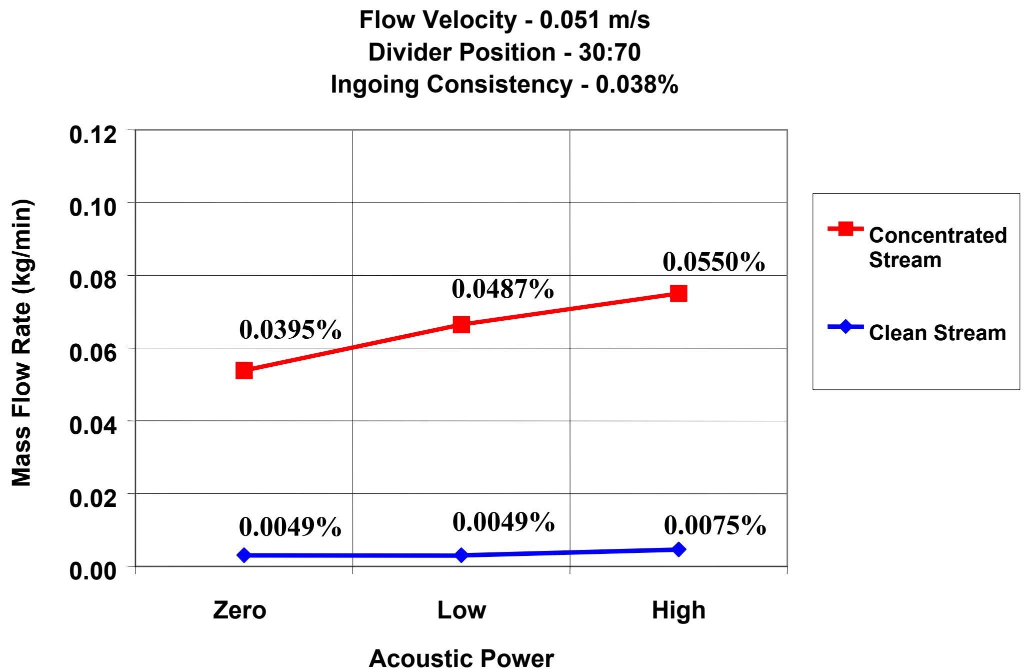

Figure 7: Mass flow rate of solids at low velocity for clean and concentrated streams. Divider blade at 30:70. The consistency reading is shown above the points.

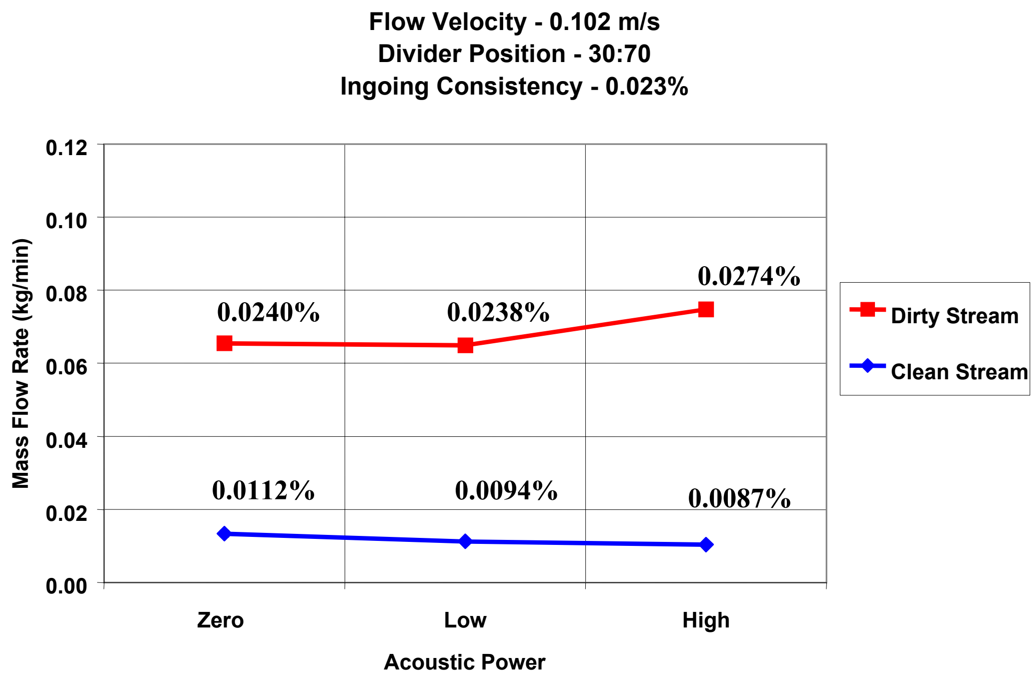

Figure 8: Mass flow rate of solids at mid-velocity for clean and concentrated streams. Divider blade at 30:70. The consistency reading is shown above the points.

In Figure 9, the y-axis is the tangent of the deflection angle. U represents the flow velocity of the whitewater stream and v represents the flow migration velocity of the flocs that are deflected towards the absorber as they interact with the ultrasonic field. Since the mill pilot scale transducer did not function above 2 W/cm^2, a projection was made as to what would be the deflection angle at higher intensities and a flow speed of 0.1 m/s. This projection is based on results from the vertical lab scale trials. Based on Figure 9, we see that the deflection angle should increase if more power were applied. Consequently this would indicate an increase in clarification.

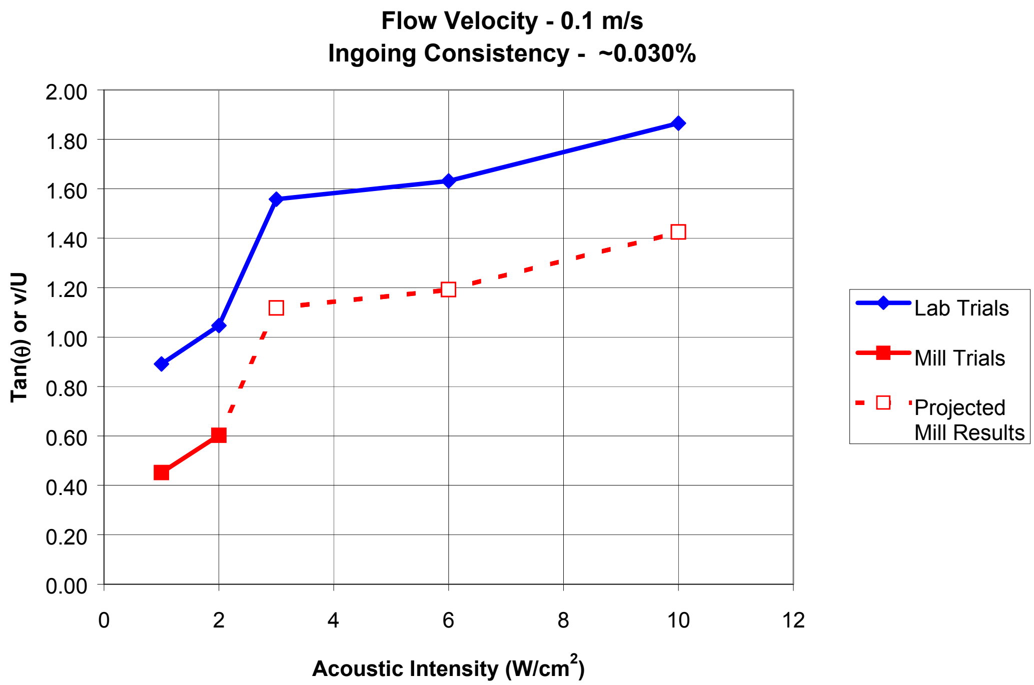

Figure 9: Graph comparing deflection angle of vertical flow lab trials with horizontal flow mill trials. The dotted lines are projections of mill trials if the mill pilot scale transducer worked at full potential.

A force balance method, as shown in Figure 10, was used to determine if dissolved air in the acoustic clarifier system would be useful in increasing clarification of whitewater. An oversized absorber was hung underwater from a balance. A 150-kHz transducer was rigidly supported above the absorber on the surface of the water. When power was applied to the transducer, the radiation pressure was transmitted to the absorber and read on the balance. Water at approximately 9-ppm oxygen content (saturated tap water) and water at approximately 1.5-ppm oxygen content (degassed water) were used. An optional anti-streaming membrane (Saran wrap) can be inserted between the transducer and absorber to eliminate acoustic streaming effects. The balance readings obtained with degassed water were higher than those obtained with saturated water. Therefore, it was decided not to saturate the whitewater with air during the mill trials.

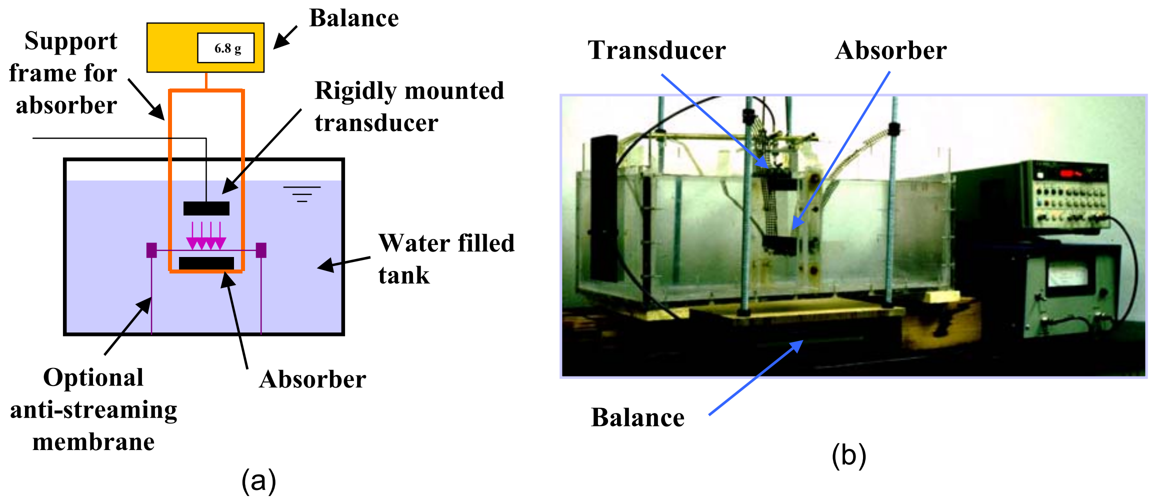

Figure 10: Force balance method for determining transducer efficiency. (a) Conceptual schematic showing transducer, absorber, balance and water tank. (b) Picture of actual setup.

Potential application for industry:

Our former industry partner, Beloit, estimated that the new technology, when compared to current dissolved air flotation technology, would reduce electricity consumption from 761,000 kWh to 408,000 kWh, i.e., a decrease of nearly 46% (based upon a 3000 GPM flow). Furthermore, the new clarification process eliminates airborne emissions of particulates and hydrocarbons, which would be improvements that the pulp and paper industry can expect. These numbers are based on vertical flow lab trials. In the mill trials, the effect of gravity enhanced the clarification of whitewater. Therefore, it is anticipated that there will be a further decrease in power consumption.

A preliminary economic assessment of the clarification method was conducted using mill data. The mill data suggest that more chemicals are needed. This could be because, in the lab, cloudy whitewater was used, whereas, in the mill, we used water from the 2nd stage effluent that was diluted down to the consistency of cloudy whitewater. Chemical costs for PEO and PFR are approximately \$5/kg (\$5000/ton) and \$1/kg (\$1000/ton), respectively. Most runs were done at 5 mg/L: 15 mg/L and for this the cost would be \$0.04/1000 L (\$0.152/1000gal). Good flocculation was also observed at 3 mg/L: 15 mg/L and the cost for this would be \$0.03/1000 L (\$0.114/1000 gal). A complete study on the lower limit of the flocculants needed has not been done.

Lab deflection angle measurements were used to predict the operating cost of a hypothetical whitewater ultrasonic clarification system aimed at increasing the feed stream consistency by a factor of 10. The basis for comparison is a 22,750 L-per-min (6000-gpm) commercial DAF system. Table I shows capital (including installation cost in the mill) and operation costs for the DAF system and ultrasonic clarifier based on laboratory and mill data. It is assumed that the ultrasonic clarifier operates under the following conditions: frequency of 150 kHz, flow velocity of 0.3 m/s, and acoustic intensity of 3 W/cm^2. Also, the PEO/PFR flocculant dosage is 3 mg/L: 15 mg/L. For this scenario, a unit-annualized cost of \$0.041/1000 L (\$0.156/1000 gal.) is estimated for the ultrasonic clarifier (including chemical costs). Reductions in capital and operating costs are expected in the future due to improved efficiency and lower part costs. Installed capital is based upon FY00 part costs and includes installation.

It is imperative that the economic data be updated, as additional pilot data become available, to reflect more realistic conditions at the mill. With better operating transducers, the need for chemicals would be reduced. Also, in a mill system, where turbulence can be minimized, less chemicals would be sufficient to flocculate the fines.

TABLE I. Estimated cost for a 22,750 l-per-min (6000-gpm) hypothetical ultrasonic clarification system and commercial DAF system (* based on initial mill data)

Item	**Ultrasonic Clarifier ($1000)**	**DAF System ($1000)**
Capital and Installation Cost	352	1073
Annual Energy Cost for Ultrasonic Equipment	*45*	*0*
Annual Energy Cost for Pumping	*8*	*103*
*Annual Chemicals Cost**	*360*	*250*
Total Annual Operating Cost	413	353

Journal Publication:

A paper was published (based on the lab results):
Brodeur, P.H., Deng, Y., Gerhardstein, J.P., Yan, Z., Bose, F., Jong, J.H., and Choi, M.H. "Whitewater Clarification Using a Dual Flocculation/Ultrasonic Method", *JPPS* 27(4): 130-138 (April 2001).