Feasibility of Recycling Post-Consumer Diapers

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ABSTRACT

Disposable diapers constitute about 2% of all U.S. municipal solid waste. Recycling discarded diapers depends on reducing the level of contaminants in the pulp. This report describes how conventional separation equipment was used to reduce the level of vegetable hulls, absorbent gel material, and synthetic fiber in pulp recovered from discarded diapers reclaimed in a demonstration study at the Rabanco Recycling Company in Seattle, WA. Under specific operating conditions, forward and throughflow cleaners were shown to be effective in removing the gel and synthetic fiber contaminants. The results indicated the need for developing a process to improve the removal of vegetable hulls. About 35% of feedstock was recovered after processing. Using standard industry recovery loops, the cleaning process has the potential to increase final pulp yield from 35% to 85%, assuming a process is developed for improved hull separation. Although a commercial operation for reclaiming diaper pulp is technically possible, the economic feasibility of such an operation is undermined by the high costs associated with the collection and processing of discarded diapers.

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KEYWORDS

Diapers, Disposables, Impurities, Pulping, Reclaimed fibers, Recycling.

INTRODUCTION

Disposable diapers make up about 2% of all U.S. municipal solid waste (1); about 18 billion single-use diapers were purchased in 1988 (2). Disposable diapers consist of about two-thirds bleached softwood pulp and one-third plastic material. Other types of pulp, such as bleached hardwood kraft, mechanical, and alpha pulps, are sometimes used in diapers, but not in a significant amount.

A disposable-diaper recycling pilot program, sponsored by Procter and Gamble, the Seattle Solid Waste Utility, and Rabanco Recycling Company, demonstrated that bleached softwood fiber can be recovered from discarded diapers. In assessing the technical and economic aspects of this program, Arthur D. Little Inc. (3) identified three contaminants in the recovered pulp: (a) undigested vegetable hulls from infant feces, (b) absorbent gel material, and (c) synthetic fiber from the nonwoven top sheet of the diaper, These contaminants must be removed before the recovered diaper fiber can be used in products such as tissue and printing and writing papers.

This report presents some results of the pilot demonstration study at the Rabanco Recycling Company. The Forest Products Laboratory (FPL) was involved with two aspects of this study. First, the FPL conducted exploratory experiments for selecting separation equipment for the Rabanco pilot study. Second, after the pulp was recovered at the Rabanco demonstration plant and the recovery process was assessed, FPL studied the effectiveness of various cleaners in removing contaminants from the reclaimed pulp.

BACKGROUND

The purpose of the pilot-scale study at Rabanco %cycling Company was to verify that a process using conventional separation equipment could successfully recover the feedstock materials from post-consumer diapers. The recycling equipment and process are illustrated in Figs. 1 and 2.

Pulp Recycling Process

The process for recycling diaper pulp is described in the Arthur D. Little report (3).

The operator first fills the pulper with 1,500 gal (6,342 L) of recycled water. About 240 diaper collection bags, containing approximately 30 diapers each, are placed onto a conveyor belt that drops them into the pulper. Nine gallons of 12.5% sodium hypochlorite solution are added for sanitation, and the mixture is agitated. After five minutes, an additional 1,000 gal (4,228 L) of recycled water are added to improve mixing efficiency. The operator monitors free and total chlorine residuals and adds more sodium hypochlorite solution as needed to maintain a concentration of free chlorine between 5 and 15 parts per million (ppm). After a total of 30 min, the operator adds an additional 1,000 gal (4,228 L) of recycled water to ensure adequate contact of the sanitizing agent. The blending is continued for another 25 min to adequately sanitize the solution and break up the absorbent gel material (AGM) sufficiently to pass through subsequent screens.

The pulped mixture flows through an extraction plate with 1/8-in. (3.2-mm)-diameter holes. The plastic retained in the pulper consists of pieces of the collection bags, the outside shell of the diaper, the adhesive strips, and the elastic bands.

The operator initiates a closed-loop cycling process as the slurry solution is pumped to the first side-hill screen. The flow rates are shown in Fig. 1. The

FIGURE 1: **Step-by-step diaper recycling operation. Courtesy of Rabanco Recycling Company, Seattle, WA; reprinted with permission.**

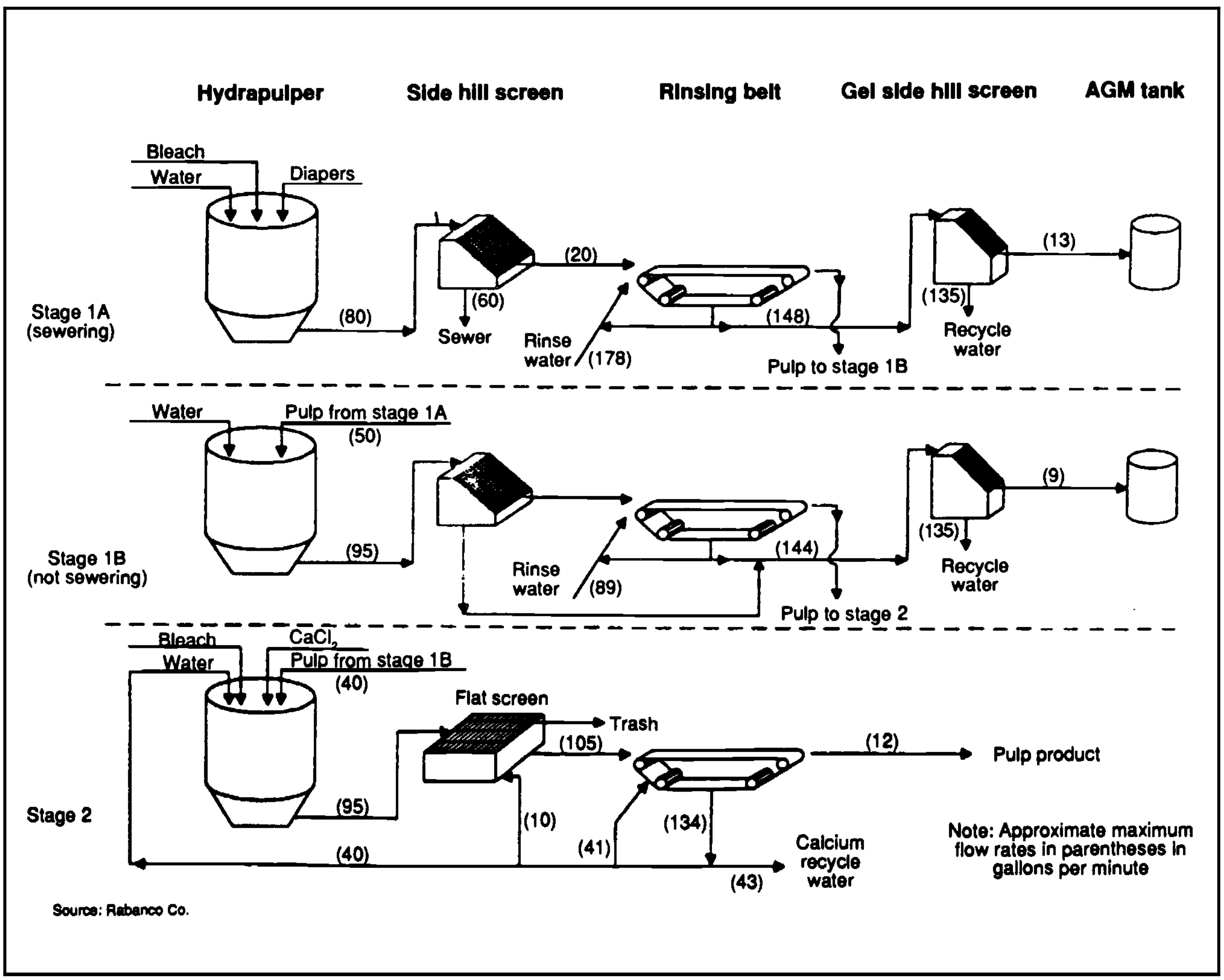
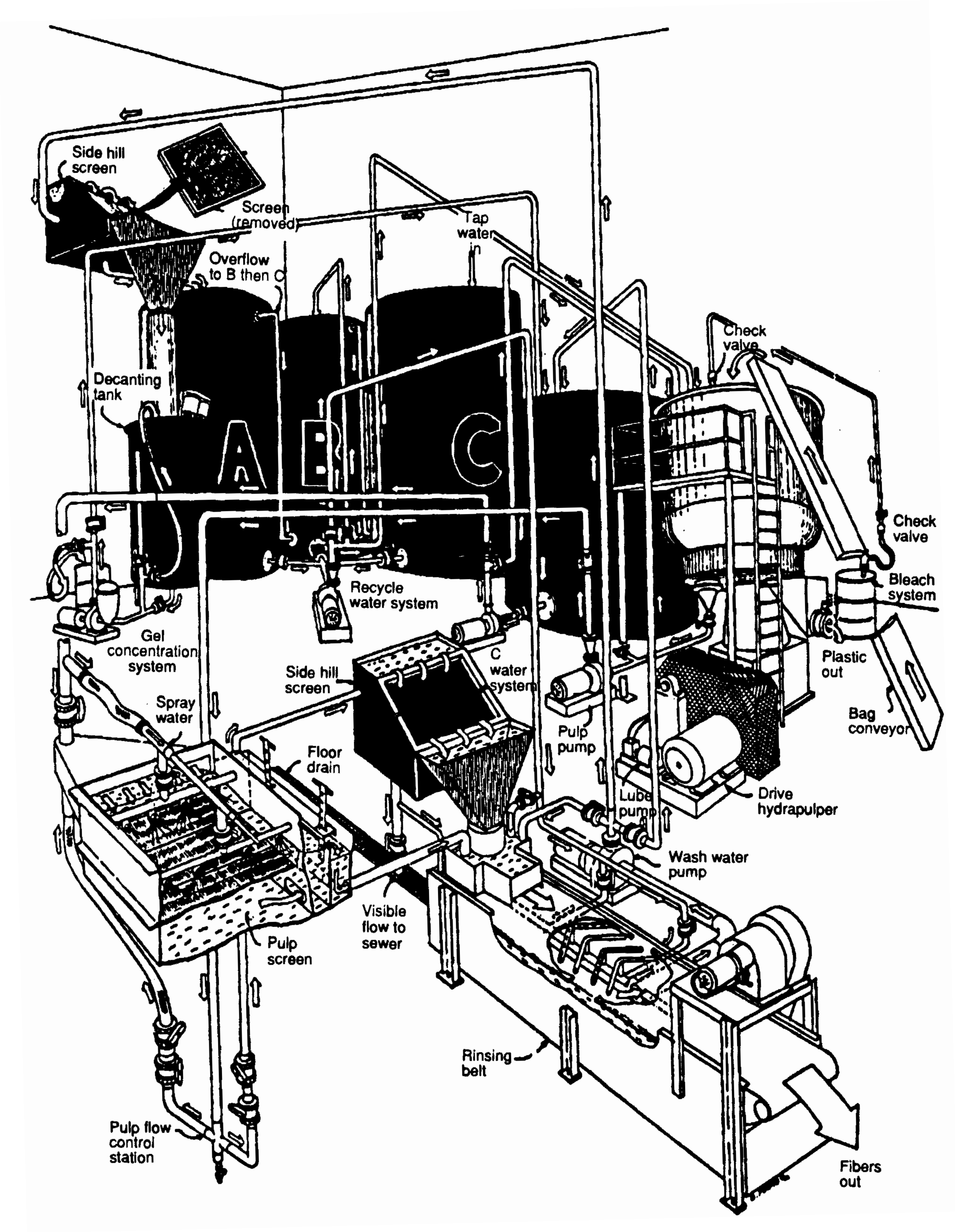


FIGURE 2: **Equipment for recycling post-consumer diapers at Rabanco demonstration plant. Courtesy of Rabanco Recycling Company; reprinted with permission.**



wastewater drains through the screen and flows to the local sewer. The wet solids that contain the pulp and AGM remain on the screen and discharge onto a woven nylon conveyor rinsing belt. The belt is supported on chevron-shaped pipes which are slotted to form waterjets. These forcerecycled water up through the belt, lifting and rinsing the pulp and carrying much of the AGM through the rinsing belt to the collection tank.

The wash water and AGM collected under the rinsing belt flow to a second side-hill screen. The water passing through the screen collects in a recycle tank and is reused as feed water to the pulper in subsequent batches. The AGM collects on this screen and falls into a gel decanting tank.

The cycle is repeated as the wet solids retained on the conveyor belt are returned to the pulper for further pulping and washing. The operator adds sodium hypochlorite if needed to maintain a chlorine residual in the slurry and adds recycled water to maintain a liquid volume of about 3,000 gal (12,684 L) in the pulper. The purpose ofthe continued mixing is to take advantage of the shearing action of the agitator to further break down the AGM particle size. Simultaneously, the slurry continues to flow out of the pulper and through the closed-loop process.

The pilot scale process continues this cycle of rinsing and sewering for about 50 min until the pulp is relatively clean of all contaminants, At this point, the operator stops sewering and sends the water passing through the first side-hill screen to the water recycle tank for later reuse.

The treatment continues for about another hour and mixing continues to further break apart the AGM and separate it from the pulp. During this time, the rate of water added to the pulper is slowly decreased, thus reducing the overall slurry volume and increasing the pulp concentration. The cycle continues until the pulp begins to roll down the first side-hill screen instead of sliding down. This action indicates that most of the gel has been removed from the pulp and is ready for chemical treatment. At this point, volume of the pulp slurry has been reduced to about 1,500 gal (6,342 L), and the material is returned to the pulper. The AGM that can be recovered has been collected in the gel holding tank.

In Stage 2, the operator treats the cleaned pulp in the pulper, which also contains the retained plastic, by adding about 1,000 gal (4,228 L) of recycled calcium chloride water and 10-20 lb (4.5-9 kg) of calcium chloride. The calcium chloride reacts with any remaining AGM particles to form calcium polyacrylate, which is not a supersorber and, therefore, much smaller in size. Additional sodium hypochlorite, usually about 1 gal (4.3 L), is added to maintain a free chlorine residual, and the solution is mixed for about 30 min in the pulper. Additional calcium chloride is added to maintain a calcium concentration of about 700 ppm. The solution then passes to a flat screen with 0.014-in. (0.35-mm)-wide slots. The pulp fibers pass but some calcified AGM is retained, as well as other small particles such as vegetable hulls that have not been separated through previous operations. The pulp solution then passes over the rinsing belt one final time to remove any residual AGM. The wash water collected under the rinse belt contains a high concentration of calcium and is collected in a separate calcium chloride water recycle tank for future use.

The remaining pulp collects on a drain box. The operator then removes excess water by applying 1,000 lb (454 kg) of weight to the drain box. The remaining block of pulp is at about 15% solids.

Depending on market demands, the recovered AGM, with concentrations in excess of 50% by weight, can be sold in this form or chemically treated to reduce its volume. Because research is still underway to determine uses for recycled post-consumer AGM, the pilot facility performed chemical treatment to reduce the volume and water content of all the AGM. The calcium chloride, which binds with the AGM, releases the absorbed water and reduces the volume of the AGM. The calcified AGM settles to the bottom of the tank. and the operator decants off the separated water. This chemical treatment reduces the AGM to 1/20th of its original volume, thereby reducing handling and disposal costs for the materials not marketed.

Feasibility of Diaper Pulp Recycling

The Seattle pilot-scale diaper recycling program was managed as an evolving process development effort rather than as a commercial operation. The engineering and operational information generated by the work completed to date serves as the foundation for planning a commercial facility. Before a commercial facility can be designed in detail, additional data should be collected. These data should address the development of internally consistent material and water balances and the tracking of bleached kraft pulp. These losses go to the sewer, report out with the plastic product stream, and settle out in the recycle tanks. This information can then be used to develop a reliable and economical process.

From the large amount of information generated to this point, Arthur D. Little identified several technical issues that need further discussion:

- cross contamination of end products,
- variability in system operation,
- water use and recycling,
- system optimization, and
- equipment limitations.

RESULTS AND DISCUSSION

The Rabanco demonstration plant was able to recover contaminated bleached softwood pulp from discarded diapers. This pulp consisted of bleached hardwood kraft (12.7%), bleached softwood chemical (3.0%), bleached hardwood alpha (0.3%), and softwood mechanical (0.3%) pulps, as well as bleached softwood kraft pulp (83.4%). This pulp became the feedstock for the research on pulp cleaners at FPL.

The fact that reclaimed pulp had been subjected only to screening and washing suggested that separations based on different physical principles would be more effective in removing the balance of contaminants than would further screening and washing. Preliminary experiments at FPL showed that vegetable hull, absorbent gel material (AGM), and synthetic fiber contaminants could be removed from the pulp. The results confirmed that hydrocyclone cleaners were more effective in removing the contaminants than were screens or flotation units. However, we observed that different cleaners, each with different operating conditions, were required for efficient removal of each contaminant. A process sequence, based on using three different cleaners, was developed (Fig. 3). This design allowed continuous treatment of the pulp until visual examination showed significant removal of all primary contaminants.

The purpose of using such an unconventional recirculation scheme was to obtain a sufficient amount of clean pulp for further processing. We were trying to study cleaner performance at lower pressure drop and lower reject rates. We compensated for this by using multiple passes through the cleaners. We understand that this is not standard industrial practice. Nevertheless, we were able to discern the nature of the contaminants removed by commercially available cleaners.

The brightness and fiber length of the pulp after various processing intervals are given in Table 1. The results show a slight increase in brightness after 30 min processing time, followed by a leveling off in brightness with further processing time. Final brightness was measured after side-hill screening and cleaning with the 76-mm-diameter forward cleaner (see Fig. 3). The pulp may have become mixed with some pulp in the pipes from earlier processing, which may have reduced the final brightness. Processing time had no apparent effect on fiber length.

Vegetable hulls were mainly concentrated in rejects from the 152-mm-diameter forward cleaner. Large-diameter cleaners, such as those used in this demonstration, are typically used to remove large and dense contaminants. In general, forward cleaners are also

Table 1. Pulp Brightness and Fiber Length After Processing.

Processing Stage	Brightness[a] (percent ± SD)	Fiber Length Weighted Average[b] (mm)
Throughflow cleaner		
30 min	84.1 ± 0.1	2.35
90 min	84.3 ± 0.4	2.41
120 min	84.7 ± 0.2	2.43
135 min	84.6 ± 0.2	2.31
Forward cleaner[c]		
200 min	83.7 ± 0.2	2.57

[a]Brightness determined according to TAPPI Standard T 452. SD is standard deviation.
[b]Fiber length determined using FS-100 Kajaani Fiber Length Analyzer.
[c]Final 76-mm-diameter cleaner.

effective in removing plate-like materials (like hulls), which unfortunately pass easily through slotted screens.

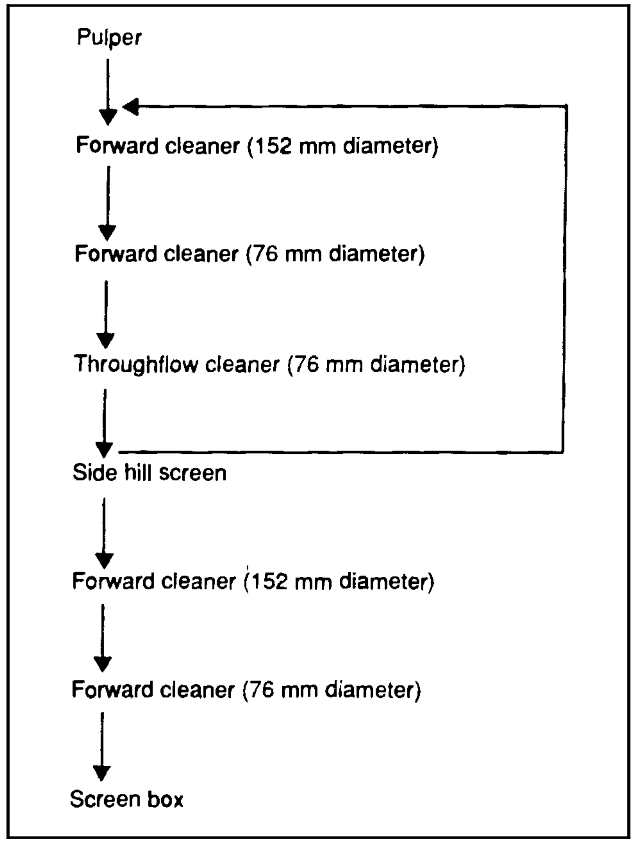
A separation unit that has a much higher shear field while maintaining laminar flow might result in an acceptable removal of hulls. Disk separation is an example of high shear separation under laminar flow conditions. During the initial phase of the study for selecting separation equipment for the Rabanco pilot plant, use of disk separation was briefly explored. Preconsumer diapers were slurried and more than 90% calcified and noncalcified AGM material was removed with less than 10% fiber loss. Visually, this was by far the most effective separation investigated in the FPL pilot plant.

Alternatively, reducing the friable hulls by refining and removing them by washing would also improve the hull removal. Image analysis results of handsheets prepared from samples taken at various stages during processing are listed in Table 2. The processing reduced the area covered by the hulls from 1170 ppm in the pulper to 413 ppm in the screen box after about three passes through the cleaners.

Most AGM was concentrated in rejects from the 76-mm-diameter forward cleaner. Forward cleaners of this small diameter are effective in removing contaminants that have slightly higher densities than do wet pulp fibers. Screening, on the other hand, leaves a significant quantity of gel particles because the particles deform and pass through screen openings. Image analysis results of AGM on handsheets made from identical samples are listed in Table 3. The AGM particles were most heavily concentrated in the rejects of the 76-mm-diameter forward cleaner. The results show that AGM was reduced from 971 ppm in the pulper to22 ppm in the screen box after the equivalent of about four passes of cleaning. This is slightly higher than the 1-20 ppm limit tolerated in fine paper. The AGM specks appeared as a depression in the sheet and were somewhat darker than the high brightness diaper pulp.

Synthetic fiber was concentrated in rejects from the 76-mm-diameter throughflow cleaner. Throughflow cleaners are typically used to remove contaminants with a lower density than that of wet pulp fibers. Such cleaners also have low reject rates. Fiber analysis of a sample taken from the pulper and a sample taken from the screen box at the end of processing is given in Table 4. Synthetic fiber was reduced from 0.3 to 0.2% of the total pulp weight. This reduction could be improved by further processing. Increasing the extremely low reject rate of the throughflow cleaner

FIGURE 3: **Process for removing contaminants from post-consumer diapers.**



would probably increase the removal of synthetic material. Note that the pulp was much more homogenous after processing: the alpha and mechanical pulps did not appear in the final fiber analysis. These pulps were probably rejected from the 152-mm-diameter cleaner.

After pulp processing, the pulp was blended with a commercial market pulp and made into a bond paper on the pilot paper machine. Microbiological testing for fecal coliform bacteria, yeast, and mold showed only mold (600 colonies/g pulp) after pulp processing. Testing of the pulp sample after papermaking revealed no fecal coliform bacteria, yeast, or mold. The combination ofthe low pH used in sizing and the high temperature of the paper machinedryers apparently killed the organisms. The results of microbiological tests for pathogens on a sample from the papermaking stock and a test paper sample are given in Table 5. These results show that the pathogens routinely tested for in food were not present in the paper produced on the pilot paper machineabove the levels considered harmful in food.

The strength and optical properties of handsheets prepared from samples taken from the pulper and screen box after processing were comparable to those

Table 2. Image Analysis of Vegetable Hulls in Processed Diaper Pulp.

Processing Stage	Speck Range (mm²)	Number of Specks[a] Below Range	Above Range	Total	Speck Area Mean (mm²)	Standard Deviation	Specks per gram	Area Covered by (mm²/g)	(ppm)
Pulper	0.1-1.0	0	3	126	0.273	0.176	--	--	--
	0.1-2.0	0	0	129	0.297	0.239	157.89	46.82	1,170
Throughflow Cleaner									
0 min	0.1-1.0	0	1	79	0.307	0.216	--	--	--
	0.1-2.0	0	0	80	0.321	0.250	97.92	31.48	787
90 min	0.1-1.0	0	0	69	0.344	0.219	--	--	--
	0.1-2.0	0	0	69	0.344	0.219	84.45	29.03	725
120 min	0.1-1.0	0	3	39	0.328	0.206	--	--	--
	0.1-2.0	0	0	42	0.383	0.282	51.41	19.69	492
135 min	0.1-1.0	0	0	56	0.284	0.199	--	--	--
	0.1-2.0	0	0	56	0.284	0.199	68.54	19.49	487
Forward Cleaner (76 mm, 200 min)	0.1-1.0	0	2	35	0.292	0.179	--	--	--
	0.1-2.0	0	0	37	0.354	0.321	45.29	16.02	400
Screen Box	0.1-1.0	0	2	40	0.277	0.202	--	--	--
	0.1-2.0	0	0	42	0.322	0.281	51.41	16.53	413

[a]Each handsheet measured with transmitted light on eight 400-mm fields per handsheet. Results are average of five handsheets per sample.

Table 3. Image Analysis of AGM Particles in Processed Diaper Pulp.

Processing Stage	AGM Range (mm^2)	Number of AGM Particles: Below Range	Number of AGM Particles: Above Range	Number of AGM Particles: Total	AGM Area: Mean (mm^2)	AGM Area: Standard Deviation	AGM Particles per gram	Area Covered by AGM (mm^2/g)	Area Covered by AGM (ppm)
Pulper	0.1-1.0	0	0	206	0.154	0.060	--	--	--
	0.1-2.0	0	0	206	--	--	252.14	38.86	971
Throughflow Cleaner									
0 min	0.1-1.0	0	4	30	0.371	0.197	--	--	--
	0.1-2.0	0	0	34	--	--	41.61	20.22	505
90 min	0.1-1.0	0	0	25	0.302	0.201	--	--	--
	0.1-2.0	0	0	25	0.302	0.201	30.60	9.23	23 1
120 min	0.1-1.0	0	0	8	0.200	0.078	--	--	
	0.1-2.0	0	0	8	0.200	0.078	9.79	1.96	49
135 min	0.1-1.0	0	0	7	0.508	0.282	--	--	--
	0.1-2.0	0	0	7	0.508	0.282	8.57	4.35	109
Forward Cleaner	0.1-1.0	0	0	7	0.245	0.201	--	--	--
(76 mm, 200 min)	0.1-2.0	0	0	7	0.245	0.201	8.57	2.09	52
Screen Box	0.1-1.0	0	0	5	0.140	0.020	--	--	--
	0.1-2.0	0	0	5	0.140	0.020	6.12	0.86	22

[a]Each handsheet measured with transmitted light on eight 400-mm^2 fields per handsheet. Results are average of five handsheets per sample.

Table 4. Pulp Fiber Analysis.

Pulp Type	Weight Percentage of Pulp Per Total Pulp	
	Pulper	Screen Box
Bleached softwood kraft	83.4	85.8
Bleached hardwood kraft	12.7	10.6
Bleached softwood chemical	3.0	3.4
Bleached hardwood alpha	0.3	---
Softwood mechanical	0.3	---
Polypropylene (some polyester) synthetic	0.3	0.2

of bleached softwood kraft market pulp. Those results are given in Table 6.

CONCLUSIONS

The results of the Rabanco pilot-scale disposable-diaper recycling project in Seattle indicate that a commercial operation is technically feasible. However, more work is needed to evaluate the economic viability of the process.

Our study showed that the three main contaminants of reclaimed disposable-diaper pulp - vegetable hulls, absorbent gel material (AGM), and synthetic fiber - can be removed by hydrocyclone cleaners and concentrated in cleaner rejects.

Vegetable hulls were removed from the pulp using a 152-mm-diameter forward centrifugal cleaner. The hulls were reduced by 65%. Operating the forward cleaner without a pressure drop resulted in a low reject rate and a high concentration of hulls. Further process development is indicated for developing a more efficient method for removing hulls on a commercial basis.

Most AGM was concentrated in rejects from the 76-mm-diameter forward centrifugal cleaner. This process effectively removed almost 98% of the AGM. Although operating the 76-mm-diameter forward cleaner at a high pressure drop results in a high reject rate, it results in a high concentration of rejected AGM.

Synthetic fiber tended to be concentrated in the rejects from the 76-mm-diameter throughflow cleaner. This fiber type was reduced about 33%. The synthetic fiber was identified as polypropylene and is a problem in the manufacture of paper.

Paper made from the processed pulp was free of organic contaminants and had acceptable strength and optical properties. Of the initial feedstock, about 35% (dry basis) was recovered after hydrocyclone processing. This recovery level is consistent with single-pass cleaning practices found in the paper industry. The paper industry typically uses secondary and tertiary recovery loops to recover pulp fiber. If standard fiber recovery loops are used to recover reject diaper material, the potential final yield is estimated to increase from 35% to approximately 85%.

EXPERIMENTAL

Reclaimed pulp was obtained from Rabanco Recycling Company of Seattle, Washington, in the form of moist reclaimed pulp laps at about 15% by weight solids. The pulp was fiberized in the Morden[1] pulper, with hydrogen peroxide added for hygienic purposes. The fiberized pulp (454 kg) was diluted to about 3.75% solids at 50° C. Sodium hydroxide (680 g) was added to the pulp, along with 2.04 kg sodium silicate, 320 g DTPA chelating agent, and 700 g hydrogen peroxide.

The pulp was pumped to a 3,780-L storage tank. It was then diluted to about 1.0% solids and screened through a 0.3-mm slotted vibrating screen with dilution water for a solids content of about 0.75%. The pulp was then passed through a 152-mm-diameter centrifugal cleaner, followed by a 76-mm-diameter cleaner.

[1] *The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.*

Table 5. Microbiological Test Results.

Sample	Organism (colonies/g)[a] Fecal Coliform Bacteria	Yeast	Mold
Papermaking stock	<0.2	600	<10
Test paper	<0.2	<10	<10

[a]Most probable number, based on probability statistics of colonies observed in consecutive dilution samples.

A portion of the pulp slurry was then passed through a pressure screen using a 0.2-mm slotted basket. The screen was fed to the outside of the basket, and the rotor was located on the inside of the basket. After screening, the pulp was washed on a side-hill screen (210 µm [70 mesh] at a 40° angle. This procedure was performed to evaluate the effectiveness of fine screening on contaminant removal. The balance of the pulp was then subjected to a series of cleaners and side-hill washings to determine their effectiveness in removing the contaminants.

Anew pulp batch was preparedin an identical manner to the first batch. Pulping was followed by the procedure in Fig. 3. This process was selected as the most effective for removing contaminants. The 152-mm-diameter cleaner was operated without a pressure drop and rejects were measured at 6 L/min. The four parallel 76-mm-diameter cleaners were operated at 103 kPa input pressure and 21 kPa outlet pressure. The rejects were measured at 11 L/min. The throughflow cleaner was operated at 207 kPa input pressure and 34 kPa outlet pressure. The rejects were measured at 2 L/min.

The process loop was continued for 200 min. The loop constituted about four cycles through the 76-mm-diameter cleaners. The 152-mm-diameter cleaner was operated only intermittently to keep pace with the other cleaners. After 200 min, the pulp appeared to be free of contamination; the husks were apparently removed by the 152-mm-diameter cleaner, the gel by the 76-mm-diameter forward cleaner, and the synthetic fiber by the 76-mm-diameter throughflow cleaner. After the continuous loop processing, the pulp slurry was washed on a side-hill screen. The pulp was then diluted to 0.7% solids at 25” C and passed through two centrifugal cleaners. The 152-mm-diameter cleaner and the 76-mm-diameter cleaners were operated at the same pressure drops as in the continuous loop. The pulp was then dewatered and saved for papermaking.

Handsheets for evaluating properties of resultant pulps were prepared according to TAPPI Method 205 om-88. Handsheets were conditioned according to TAPPI T 402 om-88; burst index was obtained according to TAPPI T403 om-85, tear index by TAPPI T414 om-88, tensile breaking length by TAPPI T494 om-88,

Table 6. Physical Properties of Handsheets Made From Processed Diaper Pulp.

Processing Stage	Basis Weight (g/m^2)	Brightness (%)	Burst Index (kPa m^2/g)	Tensile Breaking Length (km)	Stretch (%)	Tear Index (mN m^2/g)	Fiber Length, Weighted Average (mm)
Pulper	67.3	84.0 ± 0.2	2.43 ± 0.14	3.58 ± 0.13	3.72 ± 0.14	16.9 ± 0.6	2.26
Screen Box	66.6	83.7 ± 0.2	2.94 ± 0.19	3.74 ± 0.27	3.91 ± 0.21	20.8 ± 1.0	2.61

and brightness by TAPPI T452 om-87. Fiber lengths were obtained using a Kajaani FS-100 Fiber Length Analyzer (5). Fiber analysis for wood pulp and synthetic fibers was performed by Integrated Paper Services of Appleton, Wisconsin, according to TAPPI T 401 om-88. Image analysis was performed on 1-g handsheets. The AGM particle and vegetable hull contaminants were measured using a Quantimet 970 image analyzer manufactured by Cambridge Instruments Ltd. (6), using transmitted light on handsheets (see Tables 2 and 3 for lighting conditions and size and number of fields). Microbiological testing was performed by Northland Food Laboratory Inc., Manitowoc, Wisconsin, using standard methods for microbiological examination of foods.

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