ONLINE SORTING OF RECOVERED WOOD WASTE USING AUTOMATED X-RAY TECHNOLOGY

FINAL REPORT
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<th>Description</th>
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<tr>
<td>ACQ</td>
<td>Alkaline Copper Quat</td>
</tr>
<tr>
<td>As</td>
<td>Arsenic</td>
</tr>
<tr>
<td>BS</td>
<td>Belt Speed</td>
</tr>
<tr>
<td>CBA</td>
<td>Copper Boron Azole</td>
</tr>
<tr>
<td>CCA</td>
<td>Chromated Copper Arsenate</td>
</tr>
<tr>
<td>C&amp;D</td>
<td>Construction and Demolition</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>DPP</td>
<td>Digital Pulse Processor</td>
</tr>
<tr>
<td>FDEP</td>
<td>Florida Department of Environmental Protection</td>
</tr>
<tr>
<td>FR</td>
<td>Feeding Rate</td>
</tr>
<tr>
<td>MSDS</td>
<td>Material Data Safety Sheet</td>
</tr>
<tr>
<td>PAN</td>
<td>1-(2-pyridylazo)-2-naphthol, an orange-red solid with a molecular formula $C_{15}H_{11}N_3O$</td>
</tr>
<tr>
<td>pc</td>
<td>Piece</td>
</tr>
<tr>
<td>Pcf</td>
<td>Pounds per Cubic Foot</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable Frequency Drive</td>
</tr>
<tr>
<td>XRF</td>
<td>X-Ray Fluorescence</td>
</tr>
</tbody>
</table>
ABSTRACT

Dimensional waste wood is frequently contaminated with wood treatment preservatives including chromated copper arsenate (CCA). Because of difficulties in visually identifying treated wood especially after the wood has been weathered, wood treatment preservatives frequently contaminate dimensional waste wood, thereby limiting recycling options for Construction and Demolition (C&D) wood waste. The purpose of the proposed project is to evaluate the use of automated X-ray fluorescence (XRF) systems for identifying and removing CCA- and ACQ- treated wood within recovered C&D wood waste. The study was conducted within a vicinity of a mid-sized wood waste recycling facility (Florida Wood Recycling) located within the Town of Medley, Florida. The sorting system consisted of two full-scale motorized belt conveyors, an XRF-detection chamber mounted in the top of one of the conveyors, and a pneumatic slide-way diverter mounted at the end of the conveyor that holds the XRF unit. The system was designed to divert treated wood with untreated wood falling onto a second conveyor which then moved the untreated wood to a separate area. Experiments were conducted according to a randomized factorial design with 1000 pieces of wood sorted per experiment. The composition of the infeed was 50:50 or 95 (untreated):05 (treated). Results show that online sorting efficiencies (amount in sorted pile/amount in infeed) by XRF technology are high based on number of pieces (>70%) and more important based upon metals contents, where results showed that 90 to 99% of arsenic was diverted for experiments utilizing a 50:50 infeed and 80 to 96% was diverted for experiments utilizing a 95:05 infeed. Results also show that efficiency of copper diversion ranged from 63 to 92% and chromium diversion was 80 to 98%. Observations during the sorts indicates that the vast majority of the wood that was incorrectly sorted was due to either mechanical issues associated with the movement of the wood or background concentrations of metals in the conveyor belt (e.g. copper in the seam and rivets, interferences from zinc in the rubber belt). Future work should focus on the materials of conveyor construction to minimize background interferences and to improve the wood conveyance system so that near perfect sorting efficiencies can be obtained.

ACKNOWLEDGEMENTS

Funding for this project was received from the Town of Medley through the Florida Department of Environmental Protection Innovative Recycling Grants Program. This project was a collaborative effort between several different organizations including the Town of Medley, Florida Wood Recycling, Austin AI Inc., the University of Miami, and the University of Florida. We thank the many individuals who assisted with the administration of this project, and the attendees of the technical advisory group (TAG) meeting held on October 16, 2008 in the Town-Hall of the Town of Medley.
MAIN REPORT
I. MOTIVATION

Numerous studies have shown that recovered wood waste, in particular C&D wood waste (a.k.a. sawn wood), in many instances is contaminated with wood treatment preservatives (Tolaymat et al. 2000; Solo-Gabriele et al. 2004), the most predominant of which is chromated copper arsenate (CCA). The amount of arsenic, chromium, and copper contained in the wood is high varying from 1,000 to 10,000 mg/kg for each metal. Given the high concentrations in the wood product, even small quantities of CCA-treated wood within recycled wood waste would cause significantly elevated metals concentrations. For example, if the goal is to meet Florida SCTL residential guidelines for land application of recycled materials, the amount of CCA-treated wood that can be commingled with untreated wood must be less than 0.05% or in other words there must be less than 1 pound of arsenic-treated wood per U.S. ton of wood processed (Townsend et al. 2003). If the goal is to produce a wood fuel, with a resultant ash that does not fail US regulatory requirements for hazardous waste (e.g. Toxicity Characteristic) then the tolerance is 5% (5% CCA-treated wood and 95% untreated wood) (Solo-Gabriele et al. 2002).

Because of the strict regulatory levels for arsenic, compliance with the regulatory guidelines is difficult, especially given that CCA-treated wood is very common within C&D wood waste representing up to 30% of the C&D wood waste stream (Blassino et al. 2002). As a result, sorting of CCA-treated wood will be required if C&D waste wood is to be recycled. Identification of CCA-treated wood is not always easy, in particular for wood that has been weathered (Solo-Gabriele et al. 2006). Thus in order to maintain the viability of the C&D wood recycling market, technologies should be implemented to effectively sort and remove CCA-treated wood from recycled C&D wood waste.

Earlier research showed that visual sorting was effective for removing the small amounts of treated wood present in relatively uncontaminated piles of source separated C&D wood (<1% treated wood), but cost associated with visual sorting is considered relatively high, laborious and time consuming (Jacobi et al. 2007a). This project focused on developing on-line sorting systems for commingled C&D wood. The on-line systems should be able to increase the throughput of a particular XRF unit due to more rapid analysis times and will also greatly decrease the amount of labor required thereby reducing costs.

II. OBJECTIVES

The primary objective of the current study was to document the performance of a full-scale online sorting system for recovered wood waste utilizing the XRF technology. The study focused on evaluating operational parameters such as wood loading rate and conveyor belt speed. Recommendations are provided for the improved design of on-line sorting systems.

III. BACKGROUND

The simplest form of sorting C&D wood is based upon “visual” methods. Visual identification is based upon several factors including a judgment concerning the possible original use, noting “identifiers” for treated wood, and noting the color of the wood. Original intended use of the wood is important since wood is almost exclusively treated when used for outdoor settings, industrial applications, and some indoor settings (e.g. in contact with the foundation of a
home or exterior concrete walls). Thus if a waste load contains the remnants of an exterior structure, such as portions of a fence or a dock, then that load likely contains treated wood, and should be sorted accordingly. Other criteria for evaluating the original use include noting the dimensions of the wood. In general, wood characterized by very large dimensions had likely been used for industrial applications and are almost exclusively treated. Examples include railroad ties which are 8 inches x 8 inches x 3 feet or more and utility poles which are typically 1 foot in diameter or more. In some cases, landscape timbers which are also typically treated can be identified by their shapes which in many cases are characterized by rounded edges for decorative purposes. Also, wood characterized by dimensions of 4 inches by 4 inches or more are commonly used as structural components and in many cases are treated. Notable “identifiers” in wood waste include end-tags and incisions (Figure 1). End tags typically list the type of chemical contained in the wood. If the wood is incised, it is also treated. Incising is a process by which uniform cuts are made in the wood to improve the penetration of the preservative chemical during treatment. Incising is typically used for denser wood species, such as Douglas Fir, which is primarily used in the Western U.S (Figure 1). In some cases treated wood can be identified by its color, which if not treated, typically has a light yellow hue. If treated with CCA or other non-arsenic copper-containing preservative (e.g. ACQ and CBA) the wood would be characterized by an olive color which is faint for lower retention levels and very distinct for wood treated at high retention levels (Figure 2). However, once CCA-treated wood has been weathered in many cases the color of the wood is almost indistinguishable from weathered untreated wood. This is particularly the case for wood treated at low retention levels (0.25 and 0.40 pounds of chemical per cubic foot of wood, pcf) which was the most common retention level used for residential uses of treated wood in the U.S. (Figure 3).

Sorting based upon visual methods is helpful but not adequate for situations where the wood is weathered and the use of the wood is unknown. Given the low tolerances for CCA-treated wood within recycled wood, augmentation technologies were introduced earlier as a requirement for the production of recycled C&D wood that meet regulatory guidelines (Jacobi et al. 2007a; Solo-Gabriele et al. 2004). “Augmentation” refers to the visual sorting method as described above supplemented by another technology to assist in the identification of treated wood. Several augmentation technologies have been evaluated through earlier studies (Solo-Gabriele et al. 2006; Omae et al. 2007). The most promising technologies evaluated in earlier studies were identified as PAN Indicator Stain and handheld XRF. These technologies have been evaluated most extensively through two prior Innovative Recycling Grants, one awarded to Sarasota County during 2000 and 2001 (http://www.eng.miami.edu/~hmsolo/sarasota/index_sara.htm) and another awarded to the Town of Medley (http://www.eng.miami.edu/~hmsolo/medley/) during 2006.

During the Sarasota study both x-ray and laser technologies were evaluated in their efficiency to identify treated wood. The x-ray technology was found have certain advantages over the laser system (Solo-Gabriele et al. 2004), in particular with respect to its capability to detect CCA in wet and painted wood. The x-ray instrument used in the Sarasota County study (ASOMA Model 400) was large and bulky weighing about 25 pounds. Since the work in Sarasota County, smaller more portable hand-held units (3.5 pounds) have since become available. These newer units (Figure 4) are capable of identifying up to 15 metals including arsenic, chromium, copper, lead, and mercury within seconds.
During the 2006 Innovative Recycling Grant awarded earlier to the Town of Medley the chemical stain (PAN Indicator) was found as a useful tool for identifying CCA-treated wood within C&D wood waste (Jacobi et al. 2007). When PAN stain is applied to the wood, the wood stains a magenta color if treated with copper and orange if untreated (See Figure 4). The stain is not capable of distinguishing between CCA and other copper-containing preservatives. Results from Medley-2006 project showed that visual sorting was effective for removing the small amounts of treated wood present in relatively uncontaminated piles of source separated C&D wood (<1% treated wood). For piles of source separated wood that were contaminated with 50% treated wood, visual sorts were not accurate and benefited from augmented sorting using PAN indicator stain. For commingled loads of C&D wood, visual sorts and visual sorts augmented with PAN indicator were not effective due to the excessive amount of dust and dirt on the wood which inhibited the visual identification of the wood color and also inhibited the performance of the stain. For the case of commingled C&D wood, the handheld XRF units were found to be the augmentation technology of choice due to their ability to detect preservative treatment, even when the wood was dirty and wet. For relatively uncontaminated loads, visual sorting was estimated to cost $22 per U.S. ton without augmentation and $44 per U.S. ton with PAN stain augmentation. For more contaminated loads, visual sorting augmented with PAN stain was estimated to cost $84 per U.S. ton, and for commingled wood, visual sorting augmented with hand-held XRF units was estimated at $103 per U.S. ton. The bulk of these costs were associated with labor.

Figure 1: Treated Wood “Identifiers” in C&D wood waste. End tags show the type of chemical contained in treated wood (left). Wood that contains incisions (right) is also treated.

Figure 2: Untreated and Treated Wood with Various Wood Chemical Formulations. Wood preservatives that contain copper impart a green color to the wood. Wood treated with less chemical (e.g. 0.25 pcf, pounds per cubic foot) has a lighter olive green color in comparison to wood treated with a greater amount of chemical (e.g. 2.5 pcf). The copper-based alternatives, ACQ and CBA, also impart an olive green color to the wood. Borate treated wood does not contain copper and so this chemical does not impart a green color.
Figure 3: Wood Color after 3 Years of Weathering. Once CCA-treated wood at the 0.25 pcf level is weathered, the green color tends to turn towards a silver grey tone typical of weathered untreated wood.

Figure 4: Illustrations of Augmentation Technologies Used in the Medley-2006 Study. PAN Indicator Stain (left) and handheld XRF units (right).
IV. ON-LINE SORTING EQUIPMENT USED FOR CURRENT STUDY

The sorting system was installed in a temporary area away from commercial sorting activities at Florida Wood Recycling facility. The system consisted of an infeed motorized belt-conveyor of 20’ length, 42.5” width and 117” height (Figure 5). Because of the need for guard rails (6” high) to maintain the wood on the belt, the effective width of the belt was 32”. In addition, an inclined conveyor, 45° incline of 10’ length and 42.5” width and 65” highest end (Figure 6) was installed perpendicular to the discharge end of the infeed conveyor. The infeed conveyor was designed to convey wood to the XRF detection unit, and the inclined conveyor to convey the untreated to a separate pile for further processing as mulch. The XRF detection unit was installed on the top end of the infeed conveyor (Figure 7) and enclosed in a compartment that was connected on the top channels of the conveyor using vibration absorbers to minimize interference from the moving parts of the system. The XRF detection unit consisted of an X-ray tube that emitted X-rays downward when energized. The diffracted ray was monitored by a detector that was connected to a digital pulse processing (DPP) unit (Figure 8); the DPP by itself is connected to a control panel (Figure 9). The control panel has a central computer and the system is operated and controlled by special software (AAI-UofM; Figure 10). After inspection of wood pieces conveyed by the belt of the infeed conveyor and passing through the inspection chamber, treated wood was sorted once discharged from the end side of the conveyor by a slide-way diverter (Figure 11) which consisted of a steel sheet of 32x32x1/4” which was pneumatically driven by a piston connected to an air compressor and controlled by the software. Sorted treated wood would be moved by the diverter to bypass the inclined conveyor and would thus fall in the front of the system. Belt motors were wired to a 3-phase 480 volt generator (Figure 12) through a variable frequency drive (VFD) that controlled the belt speed (Figure 13). The whole sorting system was setup under a canopy as shown in Figure 14.

Figure 5: Large conveyor during the installation
Figure 6: Inclined conveyor

Figure 7: XRF-unit enclosure in the top of the large conveyor
Figure 8: XRF-unit components.
Figure 9: XRF-unit enclosure in the top of the large conveyor

Figure 10: Screen photo of AAI-UofM software
Figure 11: Slide-way diverter (operated pneumatically)

Figure 12: one and three phase generators
Figure 13: Variable frequency drives assembly

Figure 14: Final setup of the sorting system
V. THEORY OF TREATED WOOD SORTING BY XRF AND ASSOCIATED DEFINITIONS

The theory of XRF detection is presented here as this information should be known in order to understand the logic behind the experimental design. The discussion below focuses on arsenic and copper as both are found in CCA-treated wood and copper is found in ACQ-treated wood.

XRF technology works at the atomic level by knocking out electrons from the innermost orbital of atoms in the treated wood changing the atoms into unstable ions. A more energetic electron from outer orbital will move into the newly vacant space in the inner orbital in order to reach the lowest stable energy state and so releasing the extra energy possessed before. The emitted energy is equal to the difference in energies between the innermost orbital and the outer one, thus it is a characteristic of the element fluorescing. Emitted energy as photons can be detected by X-ray detector and so the count of emitted energies is proportional to the concentration of the metal in wood pieces and is simulated by a spectrum representing the number of counts according to the dispersed energy in KeV. The time during which the emitted energy is counted, the measurement time, is held constant from sample to sample in order to compare the emitted energies from one sample to another.

The software has a previously stored spectrum of As and Cu (Figure 15 and 16). The ratio of area under the measured counts-curve to the reference area is called the threshold. Minimizing the threshold is important for detection and diversion of weathered wood pieces, but may increase the interference from other metals that has a spectrum overlapping or very close to the one of concern. The overlap from other elements is of particular concern in the case of lead (Pb) which overlaps the arsenic reference spectrum, and zinc (Zn) which overlaps the copper reference spectrum.

Figure 15: As spectrum with a peak of interest highlighted in yellow (source: http://ie.lbl.gov/xray/as.htm).
Figure 16: Cu spectrum with a peak of interest highlighted in yellow (source: http://ie.lbl.gov/xray/cu.htm).

Incorporating the detection of the signal into diversion of the wood on a conveyor system requires an understanding of the timing between detection and diversion of the wood piece. Once As or Cu are detected in the wood, the wood must travel from the detector to the slide-way diverter. This time is called the delay time. The delay time is a function of the belt speed. Thus the diverter was designed to open (45° to the horizontal level) after the delay time. It would then remain open for a time equal to the sum of measurement times providing consecutive detection of each treated wood piece, plus the pulse adjust time. The pulse adjust time is the time needed for the wood to transition from the belt to the diverter. The total time the diverter remained open in the sorting position is called the dwell time (Figure 17).

Figure 17: Schematic diagram for treated wood detection by online XRF system.
VI. INFEED WOOD CHARACTERISTICS

Each treated wood piece used in this research was given a unique identifying code. This code was linked to the characteristics of that piece of wood. These characteristics included the wood piece dimensions, type of treatment (CCA, ACQ or Other) and the concentration of arsenic, chromium and copper in ppm using a handheld XRF (Innov-X type alpha, Woburn, MA, USA). Thus, the quantity in grams for each metal was calculated for each piece of wood from the volume of each piece and its metals’ content assuming all pieces are Southern Yellow Pines of density 511 kg/m³. Since the handheld XRF readings are relevant to the surface concentration of metals and this is usually higher than the entire concentration in the wood piece due to natural tendency of metals to migrate to the surface, arsenic concentration was corrected using Block’s formula (Block et al., 2007). Chromium and copper were modified using unpublished formulas of the author.

Two sets of wood were used as infeed. Both sets consisted of a 1000 pieces of wood. One set was characterized by 50% untreated wood and 50% treated wood (50:50) and another set was characterized by 95% untreated wood and 5% treated wood (95:05). Treated wood included CCA-treated wood, ACQ-treated wood, and “Special”-treated wood (also referred to as “other” treated wood) which were extremely weathered wood samples that contained elevated levels of chromium and low levels of arsenic. Most of these special-treated wood pieces appeared very weathered and could have been CCA-treated wood where the arsenic was depleted. Table 1 summarizes the chemical characteristics of the treated wood pieces.

Table 1: Treated wood characteristics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>No. of Pieces</th>
<th>Arsenic content (g)</th>
<th>Copper content (g)</th>
<th>Chromium content (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCA-treated</td>
<td>417 44</td>
<td>1252 137</td>
<td>682 50</td>
<td>736 71</td>
</tr>
<tr>
<td>ACQ-treated</td>
<td>66 5</td>
<td>2.9 0.1</td>
<td>403.1 7.1</td>
<td>11.6 0.3</td>
</tr>
<tr>
<td>Others</td>
<td>17 1</td>
<td>0.74 0.01</td>
<td>3.74 0.00</td>
<td>4.72 0.13</td>
</tr>
<tr>
<td>Total</td>
<td>500 50</td>
<td>1,256 137</td>
<td>1,089 57.1</td>
<td>752 71</td>
</tr>
</tbody>
</table>

Wood pieces were chosen based on their length to range from 5 cm to 150 cm, in order to minimize the effects from the different sizes of wood pieces. Each wood infeed used (50:50 and 95:05) had the same probability distribution with respect to their length, since the length was found as the most important characteristic to affect proper sorting. Figure 18 shows the length distribution of the 50:50 infeed set. The length distribution for the 95:05 infeed was very similar to that of the 50:50.
Fig. 18. Distribution of wood length for the 50:50 infeed set
VII. EXPERIMENTAL DESIGN

Two sets of experiments were conducted: preliminary and main experiments. The primary goals of the preliminary experiments were to trouble-shoot the system so that it was operational and to determine the following.

- The minimum thresholds for sorting treated wood based on the presence of As and/or Cu.
- The effect of changing the measurement time of the digital pulse processing (DPP) unit on the sorting efficiency.

The main experiments were designed to evaluate the efficiency of wood sorting using a combination of different feeding rates (FR, 20, 40 and 60 pc./min) and belt speed of the infeed conveyor (BS, 0.25, 0.375 and 0.5 m/s). These experiments were designed as randomized factorial block design with replication. The first set included nine experiments each with a different combination of FR and BS and the second set include four experiments of the array FR (20 and 60 pc./min) and BS (0.375 and 0.5 m/s). Each experimental run was conducted by sorting 1000 pieces of wood with 50:50 of treated wood vs. untreated wood for the first set and 95:05 for the second set.

After each experimental run through the XRF system, wood-pieces in the two piles (presumed treated and presumed untreated) were manually sorted to confirm actual treatment, counted, and weighed. Within each “presumed” pile from the XRF system, wood was identified as either correctly sorted or incorrectly sorted. For example, within the presumed untreated pile, the wood would be identified as truly untreated. Treated wood in the presumed untreated pile were further separated into various categories including truly CCA-, ACQ-, and Other- treated wood. Manual sorting of the presumed treated and presumed untreated wood was based upon the unique identifier established for each wood piece and the piece numbers were thus recorded allowing the researchers to track each individual piece of wood within the set of 1000. Although the actual experiments were relatively quick (on the order of an hour or two) documentation after each experiment was very time consuming because of the need to manually sort and record the location of each wood piece.

Sorting efficiencies were calculated for each experimental run based on the number of pieces, weight, and metal contents of As, Cu and Cr. Treated wood efficiencies by number were calculated based on the fraction of true treated pieces that ended up in the presumed treated pile to the total number of pieces (500 in the 50:50 exp or 50 in the 95:05 exp.). Untreated wood efficiencies by number were calculated based on the fraction of true untreated pieces that ended up in the presumed untreated pile to the total number of pieces (500 or 950, accordingly). Untreated pieces usually ended up in the treated pile due to two mechanisms, either overlapping over the belt with treated pieces and so these pieces were diverted together or the untreated pieces bounced from the inclined conveyor because of their forward momentum. Because of the forward momentum the wood pieces would bounce sideways over the inclined conveyor into the treated pile. Bounced wood pieces were usually longer than 80 cm. Based on these observations, an estimated overlapping rate was calculated as percentage fraction of untreated
pieces of length less than 80 cm which ended up in the presumed treated pile, and the estimated bouncing rate was calculated the same but for pieces of length greater than 80 cm.

VIII. EXPERIMENTAL RESULTS

VIII.a Preliminary Results

Qualitative Results Associated with System Operation and Trouble-Shooting

After the installation of the sorting system, the system was operated using software provided through Austin AI. The system was shown to detect arsenic at lower threshold limits and low concentrations in the treated wood and above the natural-background levels in wood. Several problems were encountered and resolved, below is a summary:

- The system was not capable of achieving lower threshold limits of copper due to the background levels of copper in the belt material, in particular due to high levels of copper in the seam, rivets and lacing of the belt. This issue decreased the sorting efficiency of copper-based treated wood. Future refinements should correct these issues.

- The system was operated by the available software. This software however required several steps to initiate, and included upload of the software, initiation of the sorting software, hooking the XRF-components with electricity, and starting communications with the system. Troubleshooting was necessary during system initiation which frequently required resetting the system by a previously installed reset-button. The system operation required trained personnel who are familiar with software operations. Future refinements should simplify the system initiation process.

- The XRF unit was installed in the middle right half above the large conveyor which made the farthest side of the conveyor to be limited in its sensitivity to metal detection. An infeed slide-way was manufactured and installed by University of Miami research staff to help guide the wood to the right half of the conveyor. Future refinements should include an improved material feed delivery system to assure that the wood in fact falls within the field of view of the XRF unit.

- Untreated wood was found to bounce from the inclined conveyor and end up in the treated wood pile, and so guard slides were manufactured in the University of Miami workshop and installed on the three sides of the lower part of the inclined conveyor, in addition a discharge slide-way was manufactured and installed and found to help in decreasing the bouncing rate of untreated wood. However, even with the slide-way, large pieces of untreated wood, in particular during higher conveyor belt speeds, were observed to bounce from the inclined conveyor (which was intended to carry the untreated wood) into the treated wood pile. Future refinements of the system will require improved design of the conveyance system on the output side of the XRF unit.

- During the operation of the system, the diverter would occasionally start to observe As alone or both As and Cu, even with a bare belt. This problem caused several delays of
the research activities and required trouble-shooting investigations and literature reviews. Continuous detection of both As and Cu is believed to be associated with overheating due to high ambient temperature, heat production by the X-ray, and the poor cooling system of the XRF-chamber. This problem was resolved by increasing the air flow rate into the chamber and aiming the air injection into the body of the X-ray tube. Continuous detection of As only is believed to be due to the corrosion of the lead sheets installed inside the XRF-chamber and production of lead dust that fell in the field view of the detector. Lead corrosion was believed to occur due to the low quality of the purge air and catalysis of the lead sheeting by the X-ray. Air can be contaminated with low levels of landfill gases due to the location of Florida Wood Recycling near the Medley landfill. The lead corrosion issue was minimized by frequent cleaning the XRF chamber with a vacuum and through wiping the XRF components with alcohol wipes. The production of lead dust was minimized by replacing the lead parts with polyvinyl-coated lead sheets and by painting the small lead pieces with polyurethane spray paint.

**Qualitative Evaluation of Threshold and Measurement Time**

XRF parameters such as threshold and measurement time have significant effects on the sorting efficiencies. Lower threshold limits will allow higher efficiencies of treated wood sorting, allowing for the separation of treated wood that contains lower levels of metals. However, too low of a threshold causes false positives due to the interference from the background levels of targeted elements (arsenic or copper) or from elements of overlapping spectra (such as the detection of false As due to interference from the lead spectra and the detection of false copper due to interference from the zinc spectra). Both As and Cu were found to have finite background levels in the rubber belt; As was on the order of 100 ppm, and Cu was on the order of 250 ppm. Also, Cu was found at high levels in the belt seam and its rivets. Zinc was found as a major component of the rubber belt material. The lowest achieved threshold for As in this research was 0.02 and 0.05 for Cu. At the 0.05 limit for Cu, the sorting system was detecting Cu in the revolving seam at a rate of one over three consecutive times.

Reducing the measurement time was observed to increase the capacity or speed of the system. However a reduction in the measurement time resulted in a decrease of the sensitivity, so that very weathered pieces of treated wood would go undetected. A benefit of the reduced sensitivity was that background interferences were reduced (e.g. presence of zinc in the belt, copper in the belt seam, etc..). Qualitative experimentation was thus conducted to find a measurement time that would provide a balance between speed and sensitivity. From the preliminary experimentation a measurement time of 250 ms was found to be an optimum value and this value was used for most of the subsequent experiments.

**VIII.b Main Results**

*Wood Distribution in Presumed Treated and Presumed Untreated Piles*

Figure 19 shows the wood distribution in the presumed treated and presumed untreated piles for one of the experimental runs in this research (50:50 infeed, BS = 0.25 m/s, FR = 20 pc/min). Figure 20 shows results for the same experiment except that the 95:05 infeed was used.
For the 50:50 infeed, the presumed treated pile mostly consisted of treated wood, 96% by number of pieces (89%+5%+2%) and 95% by weight. Similarly the presumed untreated pile was characterized by 86% untreated wood by number of pieces and 84% by weight. For the 95:05 infeed, the presumed untreated pile showed 99% untreated wood by number of pieces and 98% by weight. The presumed treated pile had significantly different results showing less than half of the pile was in fact treated wood. Since treated wood represents such a small fraction of the untreated wood portion for the 95:05 the incorrect diversion of a small fraction of the untreated wood can result in a significant contribution to the treated wood pile. In practice, the main priority is to keep the treated wood out of the untreated wood pile. The loss of some untreated wood within the treated wood pile is acceptable, especially if it assures a conservative sort resulting in a majority of the true treated within the treated wood pile. Within the results of both experiments (Figures 19 and 20), ACQ- and Other- treated wood pieces were mostly shown to be located in the untreated pile. This was likely because of the high threshold set for copper (because of interferences from the belt) and because of the very low levels of arsenic characteristic of the “other” treated wood pieces which was not detected by the XRF system.

Fig. 19. Wood distribution in presumed treated and presumed untreated piles after an experiment conducted using a 50:50 wood infeed. Experimental parameters included a belt speed of 0.25 m/s and a feeding rate of 20 pieces per minute. Wood distribution is based on number of pieces (above) and weight (below).
Fig. 20. Wood distribution in presumed treated and presumed untreated piles after an experiment conducted using a 95:05 wood infeed. Experimental parameters included a belt speed of 0.25 m/s and a feeding rate of 20 pieces per minute. Wood distribution is based on number of pieces (above) and weight (below).

**Affects of Wood Dimensions**

Wood dimensions were found to affect the correct sorting of treated and untreated wood. The dimension of treated wood affects the number of times a piece will be detected. The longer the wood piece the greater the number of times that the wood piece would be evaluated by the XRF unit and thus the more accurate the detection. Furthermore, the length also impacted the ability of the conveyor system to divert the wood. It was found that even with a correct XRF identification, pieces of wood that were very small or very large were not sorted properly because of the mechanical aspects of the diverter. For example, small treated pieces would cause the diverter to open; however in the process these small pieces would bounce on the divertor and instead of moving forward (as intended) they would bounce sideways and ultimately fall on the inclined conveyor causing them to be sorted into the untreated pile. In such cases, the XRF unit identified the piece correctly, the diverter opened as intended, but because of the momentum and
small size of the piece it would bounce and end up in the incorrect location. When considering the overall amount of metals in each pile due to incorrectly sorted treated wood, the actual amount of metals contributed by the small pieces was relatively low because the pieces were so small.

The “bouncing” problem was also very apparent for long pieces of untreated wood (>80cm). Such long pieces carried a considerable momentum from the primary conveyor and as a result had a tendency to continue moving in the longitudinal direction. In order to be sorted properly these long pieces of untreated wood would be needed to fall and remain on the incline conveyor and be carried in a direction perpendicular to the direction of the primary conveyor. These long pieces had a tendency to fall on their end on the incline conveyor and bounce sideways out of the incline conveyor into the treated wood pile. The deficiencies associated with “bouncing” does not represent a deficiency in the actual XRF detection. It is a reflection of the need to improve the mechanical aspects of the conveyor and diverter system. In general, bouncing was estimated to be the 2.2 to 5.8% of the incorrect identification within the presumed treated/untreated piles.

Another issue to consider is the potential for wood pieces to overlap, where a treated wood piece overlaps an untreated wood piece. In general, overlapping was estimated to be the cause of 0.6-29% of the incorrect identification within the presumed treated/untreated piles. Generally, both overlapping and bouncing rates increase with increasing the belt speed and the feeding rates, hereby, reducing the sorting efficiency.

**Sorting Efficiencies**

Based on the randomized block design with replication, and according to the combination of threshold limits and measurement times, sorting efficiencies were very high based on the fraction of CCA wood-pieces (figure 21 a and b) and were higher for the 50:50 infeed experiments (92-96%) in comparison to 95:05 infeed experiments (77-86%). A much lower sorting efficiency was observed based on the number of ACQ-treated pieces correctly sorted (figure 22) and Other-treated wood correctly sorted (20-61% for the 50:50 infeed). When observing the amount of copper, the efficiency increases (generally above 75%) as the ACQ-treated wood that contained very high levels of copper was sorted out correctly in comparison to ACQ-treated wood that contained low levels of copper. Efficiencies of sorting both treated and untreated wood based on number of pieces was generally above 76% (figure 23). Sorting efficiencies in terms of the metallic contents of three elements of concern were very high and higher for the experiments conducted with the 50:50 infeed in comparison to experiments conducted with the 95:05 infeed. In summary for all experiments, sorting efficiencies based on As content ranged from 82-99%, and when based on Cu content ranged from 63-92%. The higher efficiencies based upon metal content are due to the fact that wood samples with higher levels of metals were correctly sorted more often in comparison to wood samples with low levels of metals. With respect to chromium, 80-98% was diverted, since chromium is a major component of the CCA-treated wood.

In general, sorting efficiency based on number of pieces was found to increase for treated wood and to decrease for untreated wood with increasing feed rate from 20 to 60 pc/min. The primary reason for the decrease in untreated wood sorting efficiencies is believed to be a greater
amount of wood overlapping (more pieces of untreated wood overlapped with treated wood pieces on the belt and so both were diverted into the treated wood pile). Overlapping rate also helps in the diversion of very weathered treated wood pieces (under detection limit) and is the primary reason for increasing treated wood efficiency at higher feeding rates. In contrary to what was expected, belt speed did not have a measured effect on the different efficiencies with the studied ranges.

![Diagram](image)

Fig. 21. Treated wood sorting efficiencies based on number of CCA pieces and their metallic content, a) As and b) Cr
IX. SUMMARY AND RECOMMENDATIONS

The overall results of this study show that the online sorting of recovered wood waste by XRF technology is a promising process and achieves high efficiencies based on number of pieces sorted (>70%) and more important, based on the metal contents, where results showed that 90-99% of arsenic was diverted for the experiments utilizing 50:50 infeed and 80-96% was diverted for experiments utilizing a 95:05 infeed. Similar results achieved for the copper and chromium.

Operational parameters, in particular feeding rate had an effect on the recovery rate of untreated wood from the waste stream, which in turns affects the economics of the facility. Medium feeding rates (such as 0.375 m/s) and lower feeding rates will allow a more accurate sorting and less bouncing and overlapping rates of untreated wood but less material processed per given period of time.
The following recommendations are provided given the observations obtained during both the preliminary and main experimental phases of this study.

- **Minimize Background Signal from Conveyor:**
  1. Replace the belt of the infeed conveyor with one containing less background concentrations of As, Pb, Cu and Zn.
  2. Replace the seam, lacing and rivets with another material (maybe stainless steel) with one containing less background concentrations of As, Pb, Cu and Zn.
  3. Equip the infeed conveyor with a roller brush (best location at the bottom middle side of conveyor's belt). Cleaning the belt with a water hose and sprinkler system at the end of working day would help in minimizing dust buildup which may contain interfering metals.

- **Wood bouncing:**
  1. Replace the discharge belt with another one of a rougher surface. This should minimize the roll-back of the wood going up the incline conveyor.
  2. Decrease the height of the discharge conveyor while maintaining the location of the diverter and the slide-way.
  3. Increase the height of the guard slides.
  4. Improve wood materials movement through an entirely new conveyor design. Consider a conveyor manufacturer that specializes in construction and demolition materials handling.

- **Lead corrosion:**
  1. Replace the lead inside the XRF-chamber with another material like thick stainless steel or vinyl coated lead sheets (must be coated on all surfaces to avoid lead corrosion).
  2. Or/Separate the XRF-tube and the detector into different chambers with thick steel barriers.
  3. Take the digital pulse processor outside the XRF chamber to avoid damage from the ionized aggressive air.
  4. Consider the use of a high purity aluminum filter to help protect the system from interferences.

- **Wiring and safety:**
  1. Enclose all wires and air hoses by conduits and use labels to distinguish between them.
  2. Install additional emergency stops near the diverter and outlet conveyor. Also, consider wiring which will prevent accidents associated with the need to remove residual pressure from air tank. The system should automatically turn-off the unit including the X-rays when it gets blocked or jammed.
  3. Although no issues associated with X-ray exposures were encountered, the system should be designed with more X-ray monitoring in mind, in addition to body badges for individuals. This monitoring system should provide some type of automated warning in the event of X-ray releases.
  4. Require XRF and conveyor manufacturer to install more safety warning signs which are more permanent. In this study the warning signs were prepared through U.Miami
and were taped to the system at various points; however the manufacturer should provide these signs in the future to assure that the can be affixed in a more permanent manner to the equipment.

- **Sorting capacity:**
  1. Replacing the conveyors with wider ones, as wide as the picking line’s chutes or a little bit wider.
  2. Use slides along with infeed conveyor to avoid wood bouncing once thrown from the chutes.
  3. Increase the length of the infeed-conveyor chute to avoid wood blockage due to long wood pieces.
  4. Double the XRF-components (tube, detector, digital pulse processing unit, wires and control panel) so that scanning can occur across a wider width of the conveyor.

- **Software Upgrades:**
  1. Simplify start up procedures by replacing the several operational steps mentioned above by one power button (ON/OFF) and a nearby reset button.
  2. Upgrade software to provide improved sorting efficiency for the detection of Cu treated wood (in addition to the option to sort based upon As or As plus Cu).

- **System Robustness:**
  1. Problems were encountered during days of extreme heat. Add a cooling system to the XRF unit to minimize problems associated with extreme heat.
  2. Problems were encountered with dust. Addressing the lead corrosion issue listed above may alleviate this issue. However, the system needs to be made less sensitive to dust or dust is to be further minimized from the XRF chamber. Consideration must be given to further minimizing dust, even beyond resolving the issue associated with lead corrosion.
  3. The system should be designed with extreme weather conditions in mind including extreme rainfall events and hurricanes. The system should be weather proof, withstanding direct rainfall. The system should also be designed to minimize wind resistance and should be stable enough to withstand hurricane wind conditions.
REFERENCES


