WATER QUALITY ISSUES AND LIFE-CYCLE ENERGY CONSUMPTION OF GLASS CONTAINER RECYCLING IN NEW JERSEY

by

CHING-LING TSAI

A Dissertation submitted to the

Graduate School-New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

Graduate Program in Environmental Sciences

written under the direction of

Uta Krogmann

and approved by

____

____

____

____

New Brunswick, New Jersey

October, 2010

ABSTRACT OF THE DISSERTATION

WATER QUALITY ISSUES AND LIFE-CYCLE ENERGY CONSUMPTION OF GLASS CONTAINER RECYCLING IN NEW JERSEY

by CHING-LING TSAI

Dissertation Director:
Uta Krogmann

Alternative uses of cullet (crushed recycled glass containers) that is difficult to use as feedstock in new glass container production have grown rapidly. The cullet is mainly used as aggregate in construction projects and in landfills as daily cover, drainage layer, or road pavement. Despite the increasing use as aggregate, it is unclear if this practice is environmentally sustainable. In the first part of this study, water quality issues associated with this practice are assessed. Glass cullet that is stockpiled uncovered before use as aggregate can release leachate to the surrounding environment. Leachate is generated from rainwater that has percolated through the cullet stockpile and dissolved and suspended some of the contaminants, such as food/beverage residuals and paper. Field stockpiles were constructed to monitor leachate quantity and quality as well as to evaluate the cullet treatment within the stockpiles. The results of the leachate characterization showed that leachate is a potential source of water pollution. The analyzed pollutant levels were in most cases comparable to or higher than those of untreated domestic wastewater or urban stormwater. Both mechanical turning and forced aeration of cullet stockpiles can enhance the degradation of the organic constituents inside the stockpiles. However, active aeration needs to be combined with mechanical turning to be effective. The second part of the study assesses the life-cycle energy consumption associated with glass container recycling including its different end uses. A material flow and energy analysis quantifies glass container flows used and discarded in 2008 in New Jersey and its associated energy consumption from raw material extraction to final use and disposal. The results of the analysis showed that about five times more (255,600 tons) recycled glass containers were used as aggregate compared to use as feedstock in glass container or fiberglass production. Most likely this can be attributed to the quality of the cullet that cannot meet the industry specifications. However, the energy analysis confirmed the benefit of use as feedstock in glass container or fiberglass production. To allow the use of cullet as feedstock in glass container production, the quality of the cullet must be improved.

ACKNOWLEGEMENTS

I would like to first thank my advisor, Dr. Uta Krogmann for her unbiased guidance and help over the years for my doctoral research, especially for the help in constructing the field stockpiles of glass cullet in many scorching summer days. I would also like to thank my committee members, especially Dr. Peter F. Strom, my co-advisor, for his generous assistance and mentoring that always came when it was needed most, and Dr. Christopher Uchrin and Dr. Michael Aucott for their time to review and revise this dissertation.

I would also like to thank everyone else who helped me with this research, including the staff in the Rutgers EcoComplex and Burlington County Landfill, the faculty, staff, and graduate students in the Department of Environmental Sciences, and the staff of the Bureau of Recycling and Planning in the New Jersey Department of Environmental Protection.

Most importantly, I would like to thank my mother and father, my brother and sister, and my husband for their unwavering support and encouragement through difficult times, without which I would not be able to complete my studies.

DEDICATION

To my dear Mom and Dad,

for your unconditional love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1. Introduction

1.1 Rationale

Recycling of food and beverage container glass packaging is widely assumed to be environmentally beneficial around the world. Repeated use of recycled glass containers as feedstock in glass container production closes the life cycle loop of the glass material. Today, a recycled glass content in new glass containers up to 70% is feasible and new technology is under development to allow an even higher recycled glass content (Dolley, 2005; Cattaneo, 2009). The use of recycled glass in new container production reduces the consumption of virgin raw materials, achieves substantial energy savings, and decreases greenhouse gas emissions (GPI, 2008; Beerkens *et al.*, 2004; Worrel *et al.*, 2008). Moreover, glass recycling lessens the need for landfill space and helps recycling practitioners avoid paying expensive landfill tipping fees.

Several challenges, faced by many states in the United States (US), prevent the closed-loop recycling of glass containers. A challenge faced by the State of New Jersey is lack of quality cullet (crushed recycled glass containers). Cullet generated in New Jersey generally fails to meet the requirement for use as feedstock in new glass container manufacturing. Glass container manufacturing requires that cullet be color separated, low in contaminants, such as paper and plastics, and free of critical contaminants, such as ceramics, metals, or Pyrex® glass, which severely interfere with the melting process (CWC, 1997). With the nationwide recycling trend going from more source-separated towards more source-aggregated collection, the contamination increases and the quality of recycled glass deteriorates even further (Eureka Recycling, 2002).

Another challenge faced is the costly separation process for recycled glass at material recovery facilities (MRFs), which in most cases does not compensate for the cost of recycling collection. As a result, development of alternative markets that do not require high quality cullet have grown rapidly (CWC, 1998a; CWC, 1998b; Reindl, 2003). The alternative markets for cullet use as aggregate were developed because the engineering properties of glass are similar to sand (Wartman, 2004). Most popular applications include cullet use as daily landfill cover, drainage layer, or aggregate substitute for road pavement. However, issues associated with these uses have arisen. A major issue associated with the practice is the stockpiling and storage of the cullet for several months to years before it is used in a construction project. It was observed that leachate generated from large cullet stockpiles is high in organic contaminants and nutrients (Robert Simkins, Burlington County Resource Recovery Complex, 2006, personal communication).

Another issue is associated with the environmental sustainability of the practice. It has been reported that energy saved through the use of glass cullet as construction aggregate is 1 to 2 orders of magnitude lower than when utilized as new glass container feedstock (Krivtsov, 2004; Butler and Hooper, 2005; Morris, 1996). The energy savings for use as aggregate are based on the avoided energy consumption of blasting and crushing virgin aggregate, while energy savings for use as container feedstock are based on the avoided energy consumption during melting. The melting temperatures are lower when processing cullet instead of virgin raw materials. In addition, the use of glass cullet avoids energy consumption for extracting virgin raw materials.

New Jersey is the leading state on the East Coast and fifth in the US for mining of the major virgin raw material (i.e., silica sand) utilized in the production of glass containers (Dolley, 2005). Therefore, the container glass manufacturing industry in New Jersey is relatively strong, which implies a continuous demand for high quality cullet in the industry regardless whether the current recycling practice in the state can or cannot fulfill the demand.

Due to these various challenges, a re-evaluation of the current glass recycling practice is important in order to determine if glass recycling is still beneficial for the state and/or if improvements can be made. To ensure a holistic assessment, life-cycle aspects need to be considered.

1.2 Overview of Glass Container Recycling Practices

In the United States, 56% of the population has access to curbside and 64% to drop-off recycling programs (AF&PA, 2005). In some municipalities, both curbside and drop-off programs are available to the residents. In curbside recycling, recyclables are placed by residents or businesses at the curbside for pick-up and are transported to and sorted at material recovery facilities. In drop-off recycling, residents bring their recyclables and sort them into different fractions at drop-off centers. If residents are refunded for bringing the recyclables to participating stores, the recyclables are collected in a deposit-refund system, which usually collects containers only. Within the curbside system, dual-stream recycling is currently dominant over single-stream recycling. In single-stream recycling, glass containers are mixed with other recyclables, such as tin and aluminum cans, plastic bottles and paper fractions. In dual-stream recycling, glass containers are only mixed with other non-glass containers while the paper fraction is collected separately.

Curbside recycling is provided to >95% of New Jersey residents (Barlaz and Louglin 2001) and is recognized for its higher participation and thus higher recycling rate compared to drop-off or deposit-refund systems. There is currently a fast growing trend of switching from dual-stream to single-stream curbside recycling nationwide (CRI, 2009). It was found that among 567 townships in New Jersey, the communities with single-stream collection increased from 37 in 2007 to more than 125 in 2009 (Hourihan, 2009). However, compared to dual-stream recycling, single-stream recycling results in a higher breakage rate during collection, thus increasing the chance of contamination of the cullet with mixed-in non-recyclable materials such as ceramics, mirrors, pottery and Pyrex® glassware (Jamelske and Wessling, 2005). Non-recyclable contaminants such as ceramics and Pyrex® glassware are very difficult to separate and critically interfere with the melting process during container production (Worrel, 2008). Broken glass containers also cannot be cost-efficiently separated by color and thus lose their chance to be used as feedstock in new container production (Eureka Recycling, 2002; GPI, 2008).

After collection, recyclables are transported to MRFs for separation. Depending on the collection method and end markets, each MRF selects different sorting processes for separating the glass containers from other recyclables. Whole and broken glass containers can be sorted either manually or mechanically. Positive sorting, which removes the glass material from other materials, is gradually being replaced by negative sorting, which separates the other recyclables and leaves the glass containers on the conveyor belt. Compared to negative sorting, positive sorting is labor intensive and increases overall costs while it results in higher cullet quality. To sort glass containers that come from a single-stream recycling system usually requires more energy and processing steps compared to processing recyclables from dual-stream recycling (Joseph Vinyard, Hatch and McDonald, 2010, personal communication). Overall, there is a rising trend of adopting single-stream recycling and negative sorting in New Jersey.

Both intermediate cullet processing facilities, which further process recycled glass containers from MRFs, and glass container manufacturers are affected by the change in collection and processing practices. In intermediate cullet processing facilities, the increased contaminants such as paper prevent efficient separation. The lower quality cullet coming from the MRF and entering the intermediate processing facilities reduces the processing rate and causes more unprocessed cullet to be stockpiled waiting to be processed. To meet the need for high quality glass cullet, the container glass manufacturers in the New Jersey import approximately half of their cullet from states that implement a deposit-refund system. Cullet from a deposit-refund system has a low contamination level.

As a result of the reduced use of the cullet as container feedstock, non-container uses of glass cullet as aggregate have increased rapidly (Rendl, 2003). Despite the fast development of aggregate applications for cullet around the US, none of the alternative end-use markets seems to provide a stable or long-term market, except for the use of cullet as landfill daily cover (Robert Simkins, Burlington County Resource Recovery Complex, 2009, personal communication). Other applications include aggregate use as drainage layer and road pavement, or sand substitute as plant growing medium and beach sand. To use cullet as aggregate in large projects, it must be stockpiled to the desired amount for from several months to years depending on the project. Leachate from these glass cullet stockpiles was high in organics and nutrients, likely resulting from food or beverage residuals attached to the glass containers. However, studies regarding this water quality issue had not been previously reported in the US.

Investigations of the environmental impacts resulting from increased cullet use as aggregate in the US are also missing. Ruth and Dell'Anno (1997) used material flow analysis (MFA), a tool which assesses the flow of materials (e.g., glass containers) and energy of a product or system within a defined boundary, for the US glass container industry. The study modeled the energy use up to the year 2028 and found that energy savings through increasing the cullet recycling rate up to 85% would continue to offset the energy used during the increased transportation and increased container glass production. However, this study assumed stable markets for the increasing cullet use in container production, and did not consider diverting cullet for use as aggregate, a practice that was not widespread a decade ago. Two case studies conducted in Manchester, UK and Ontario, Canada have found that the life-cycle energy savings for cullet used as aggregate were one order (Morris, 1996) or two orders (Butler and Hooper, 2005) of magnitude lower than that for cullet used in new container production. However, the Canadian study covers several materials and does not provide many details, while the UK study is more a feasibility study.

1.3 Dissertation Overview

The research conducted in this dissertation addresses some of the challenges that glass container recycling in New Jersey faces. Specifically, the research provides knowledge and recommendations on handling and treatment of leachate generated from the growing stockpiles of cullet used as construction aggregate. Furthermore, the research provides information about life-cycle energy consumption of various glass recycling practices to determine how the use of cullet as aggregate compares to other practices. The work contributes important knowledge for improvements by policy makers in New Jersey and possibly can be transferred to other states.

Chapter 2 characterizes leachate released from uncovered stockpiles of recycled glass container cullet that is to be used as aggregate. Both quality and quantity of the leachate were analyzed for cullet with two different particle sizes. The analyzed parameters included basic wastewater parameters (organics, nutrients) in addition to lead, anionic surfactants, and total coliforms. The chapter provides the first large-scale field study in the United States investigating leachate from recycled cullet stockpiles. The results of the chapter help to develop best management practices for handling leachate from glass cullet stockpiles.

Chapter 3 continues the study of leachate from cullet stockpiles investigating if forced aeration can replace mechanical turning, which is labor intensive. The study provides knowledge on whether forced aeration reduces the organic and nutrient levels in the leachate compared to the mechanical turning/mixing practice.

Chapter 4 investigates and compares the life-cycle energy consumption associated with glass container recycling for various recycling strategies at a state level.

A material flow and energy analysis quantifies glass containers used and discarded in 2008 in New Jersey and its associated energy consumption from raw material extraction to final uses and disposal. The material flow analysis identifies the distribution of various end uses of the recycled glass containers and the inter-relationship between processes in the modeled system. Energy analysis confirms the benefit of using recycled glass containers as feedstock in container or fiberglass manufacturing when compared to aggregate use.

Chapter 5 summarizes the significance of the work conducted in Chapters 2, 3, and 4. Future directions and recommended work are also discussed.

1.4 References

American Forest & Paper Association (AF&PA) (2005). AF&PA Reports 86 Percent of U.S. Population Have Access to Community Recycling Programs. E-wire, July 2005. <http://www.ewire.com/display.cfm/Wire_ID/2707> (Accessed 5 January 2009)

Barlaz, M. and Loughlin, D. (2001). Strengthening Markets for Recyclables: A Worldwide Perspective. Part 1. Policies for Strengthening Recycling in the US. Department of Civil Engineering, North Carolina State University, Raleigh, North Carolina.

Beerkens, R.G.C., van Limpt, H.A.C., Jacobs, G. (2004). Energy efficiency benchmarking of glass furnaces. Glass Science and Technology (44), pp. 47-57.

Butler, J. and Hooper, P. (2005). Dilemmas in optimizing the environmental benefit from recycling: A case study of glass container waste management in the UK. Resources Conservation & Recycling (45), p. 331-355.

Cattaneo, J.J. (2009). Glass container manufacturers set 50 percent recycled content goal. Waste Age, May 1. <http://wasteage.com/Recycling_And_Processing/glass-recycled-content-goal-200905/index1.html> (Accessed 25 July 2010)

Clean Washington Center (CWC) (1997). Cullet Specifications for Container Manufacturing. Report #: GL3-01-02. Seattle, WA. < http://cwc.org/gl_bp/3-01-02.pdf> (Accessed 5 August 2010)

Clean Washington Center (CWC) (1998a). Evaluation of Recycled Crushed Glass Sand Media for High-Rate Sand Filtration. Report #: GL-98-1. Seattle, WA. <http://www.cwc.org/glass/gl981rpt.pdf> (Accessed 5 August 2010)

Clean Washington Center (1998b). A Tool Kit for the Use of Post-Consumer Glass as a Construction Aggregate. Report #: GL-97-5. Seattle, WA. <http://www.cwc.org/glass/gl975rpt.pdf> (Accessed 5 August 2010)

Container Recycling Institute (2009). Understanding economic and environmental impacts of single-stream collection systems. < http://www.container-recycling.org/assets/pdfs/reports/2009-SingleStream.pdf > (Accessed 2 February 2010)

Dolley T.P. (2005). USGS 2005 Minerals Yearbook: Silica. US Geological Survey, Government Printing Office, Washington, D.C. <http://minerals.usgs.gov/minerals/pubs/commodity/silica/silcamyb05.pdf> (Accessed 25 July 2010)

Eureka Recycling (2002). A Comparative Analysis of Applied Recycling Collection Methods in Saint Paul. <www.eurekarecycling.org/pdfs/studyreport.pdf> (Accessed 2 February 2010)

Glass Packaging Institute (2008). Commodity Market Updates: Glass Containers. NRC's 27th Annual Congress & Exposition, Pittsburgh, PA, September, 2008. < http://www.nrc-recycle.org/Data/Sites/1/2008%20Congress/Presentations/NRC%20Commodity%20Market%20Update%20Glass%202008.ppt#549,1,Commodity Market Update: Glass Containers > (Accessed 25 August 2010)

Hourihan, K. (2009). Single-stream municipalities in New Jersey, 2008 updates. Morris County Municipal Utilities Authority, Mendham, NJ.

Jamelske, E.M., Wessling, S. (2005). Assessing the support for the switch to automated collection of solid waste with single stream. Public Works Management & Policy (10) 2, p. 101-118. http://pwm.sagepub.com/cgi/reprint/10/2/101 (Accessed 25 January 2009)

Krivtsov, V., Wäger P.A., Dacombe, P., Gilgen, P.W., Heaven, S., Hilty, L.M., Banks, C.J. (2004). Analysis of energy footprint associated with recycling of glass and plastics – case studies for industrial ecology. Ecological Modelling (174), p. 175-189.

Morris, J. (1996). Recycling versus incineration: an energy conservation analysis. Journal of Hazardous Materials, 47, pp. 277-293.

Reindl, J. (2003). Reuse/Recycling of Glass Cullet for Non-Container Uses. Dane County Department of Public Works, Madison, WI. <http://www.epa.gov/epaos wer/non-hw/green /pubs/glass.pdf> (Accessed 25 August 2010)

Ruth, M. and Dell'Anno, P. (1997). An industrial ecology of the US glass industry. Resource Policy (23), p. 109-124

Wartman, J., Grubb, D.G., Nasim, A.S.M. (2004). Select Engineering Characteristics of Crushed Glass. Journal of Material in Civil Engineering (16), p.526-539.

Worrell, E., Galitsky, C., Masanet E., and Graus W. (2008). Energy Efficiency Improvement and Cost Opportunities for the Glass Industry. An ENERGY STAR® guide for energy and plant managers. Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA.

Chapter 2. Handling leachate from glass cullet stockpiles

Material in this chapter has been published previously as:

C.L. Tsai, U. Krogmann, and P.F. Strom (2009). Handling leachate from glass cullet stockpiles. Waste Management (29), p. 1296-1305.

2.1 Abstract

Mixed glass cullet (crushed recycled glass containers) is stockpiled uncovered before use as roadway construction aggregate or daily cover in landfills. Rainwater that leaches through the stockpiles dissolves and suspends contaminants such as those from food residuals and paper labels. The objective of this study was to determine leachate quantity and quality from cullet stockpiles as a basis for development of Best Management Practices (BMPs). Four 35-tonne field stockpiles were set up for leachate analysis and to determine the effects of mechanical turning treatment on the leachate. Field-collected leachate and laboratory-generated washwater of cullet (water:cullet = 3:1 by weight) were both analyzed for basic wastewater parameters, which showed pollutant levels comparable to or higher than those of untreated domestic wastewater or urban stormwater. While organic contamination decreased substantially (e.g., washwater BOD > 95% reduction), TKN and total-phosphorus levels in leachate ranged between 11.6–154 mg L^{-1} and 1.6–12.0 mg L^{-1}, respectively, and remained comparable to levels found in untreated domestic wastewater after four months. Turning enhanced the degradation of the organic constituents inside the stockpiles, which was confirmed by

elevated temperatures. Based on this study, leachate from glass cullet stockpiles should not be released to surface water. For leachate from long-term cullet stockpiles, release to groundwater should be only done after treatment to reduce nitrogen levels.

2.2. Introduction

In the United States and Europe, the use of mixed-color glass cullet (crushed glass) from material recovery facilities (MRFs) as a drainage layer or daily cover material in landfills has been growing rapidly (Reindl, 2003). However, municipalities and the recycling industry are interested in implementing higher quality and more cost efficient beneficial uses for the mixed cullet, e.g., as construction aggregate (Clean Washington Center, 1998 and Wartman *et al.*, 2004). The use of mixed cullet in landfills and in construction projects requires that sufficient cullet quantities be stored at the processing facility or on-site. Depending on the project, cullet might be stockpiled uncovered several months to years and release leachate to the surrounding environment. Leachate in this study is defined as rainwater that has percolated through the cullet stockpile, mixed with any water already present, and dissolved and suspended some of the contaminants, such as food/beverage residuals and paper labels.

There are limited data concerning the quantity and the characteristics of leachate from cullet stockpiles. In two laboratory studies, liquids leaching through cullet were analyzed to investigate the use of cullet as construction aggregates (Dames and Moore Inc., 1993 and Clean Washington Center, 1998). The first study, using serial batch extraction according to ASTM 4793 (ASTM, 1993), found that the Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), and Total Organic Carbon (TOC) levels decreased over time and concluded that the release of leachate from cullet stockpiles is not of concern (Dames and Moore Inc., 1993). The second study, using leaching columns, indicated that the mixed cullet should be stockpiled before use as construction aggregate to reduce the pollutant levels in leachate (i.e., BOD_5, COD, total Kjeldahl nitrogen (TKN), total-phosphorus), which were of the same order of magnitude as levels found in raw domestic sewage (CWC, 1998). This finding was confirmed in a preliminary test in this project where COD levels of 1905 mg L^{-1} and TKN levels of 30 mg L^{-1} in leachate collected from 2.5 m high field stockpiles were found. The leachate also released a pungent odor, resembling a mixture of garbage and detergent fragrances likely from the detergent containers that are collected commingled with the glass bottles. In addition, at ambient temperatures of −2 °C, the stockpiles self-heated to 39 °C, suggesting microbial activity inside the stockpiles similar to composting piles.

Few studies have assessed heavy metals in leachate from cullet. In one study (CWC, 1996), for one of 50 samples lead exceeded 5 mg L^{-1} in the Toxic Characteristic Leaching Procedure (TCLP); this was attributed to wine bottle capsules. In another study (Wartman *et al.*, 2004) leaching of heavy metals from cullet under landfill and soil conditions was simulated. While under soil conditions the heavy metal concentrations were below the detection limit, under landfill conditions (simulated by TCLP) trace amounts of lead, chromium, barium and mercury were detected in a very few samples. The exact source was unknown, but the metals were attributed to coloring ingredients in some commercial glassware, thermometer glass materials, printing pigments in labels, and bottle capping material.

Despite the above studies, handling of leachate from cullet stockpiles has not been addressed. Whereas several states regulate the maximum percentage of debris in the cullet when used as construction aggregate, none of them mention the handling of leachate from cullet stockpiles (CWC, 1998). Leachate from stockpiles of other reclaimed wastes such as recycled asphalt, paper mill residues, and coal piles has been evaluated (Catricala *et al.*, 1996; Curran *et al.*, 2000 and Townsend, 1998), but a comprehensive study of the quantity and quality of leachate from cullet stockpiles in the field is still needed.

The overall objective of this study was to determine leachate quantity and quality from cullet stockpiles as a basis for the development of Best Management Practices. The first specific objective was to investigate the range of cullet characteristics from six MRFs in New Jersey (USA) (including physical properties and analyses of washwater, generated in a shaker). The second specific objective was to determine leachate quantities and selected characteristics from stockpiles in the field. The third specific objective was to evaluate if a weekly mixing/turning treatment of the cullet stockpiles enhanced the biological degradation of the organic residues and therefore reduced leachate contamination. Leachate and washwater were analyzed for basic wastewater parameters (organics, nutrients) in addition to lead and anionic surfactants in selected samples. Anionic surfactants were expected because the glass containers were collected commingled with detergent bottles. Lead was analyzed to confirm that after the phase-out of tin-lead wine capsules in the 1990s (US EPA, 1996a) it is no longer an issue.

2.3. Materials and methods

To determine variability, glass cullet was sampled from six MRFs in the USA between March 1 and June 29, 2006. To determine the leachate quantity and quality from cullet stockpiles and to evaluate the effect of mixing/turning, four stockpiles were set up and monitored at the Burlington County Resource Recovery Complex (BCRRC) in New Jersey from June 28 until October 18 or November 14, 2006. An additional sampling of the stockpiles was conducted in May 2007 to examine the effect of further aging.

2.3.1. Sources of cullet

Cullet was obtained from five MRFs in New Jersey and one in Pennsylvania (USA) (A, B, C, D, E, F) that were accepting commingled containers including clear and colored glass bottles, plastic beverage containers (soda, water, milk, juice), plastic detergent bottles, and aluminum, tin and bi-metal cans. An overview of the materials is given in Table 2-1.

2.3.2. Set-up, operation and monitoring of cullet experimental stockpiles

2.3.2.1. Set-up of stockpiles

Four cullet stockpiles (initial mass: about 35 tonnes, height: 2.2 m, base diameter: 6.3 m) were set up uncovered in the field. Two lined stockpiles (one of D&E cullet (<9.5 mm) and one of $C_{fine}2$ cullet (<4.75 mm)) were placed on 45 mil (1.1 mm) Firestone Pondguard liners (Webb's Water Gardens, Fallston, MD, US) to allow the collection of leachate (Figure 2-1). The other two stockpiles of cullet D&E were unlined to allow weekly turning/mixing by a front-end loader.

2.3.2.2 Monitoring of temperature and oxygen levels in stockpiles

Thermocouple probes (Type T, Omega Engineering, Inc., Stamford, CT, US) were installed in all four stockpiles at the beginning of the experiment at 46, 91, and 137 cm (1.5, 3 and 4.5 ft) above ground. Temperatures were measured at these three heights every 61 cm (2 ft) into the pile up to the middle of the pile at two profiles (one facing to the south and one facing to the west).

Oxygen levels were monitored (model K25, Jewell Elec. Insts., Inc., Bacharach Inc., Pittsburgh, PA, US) at the same locations as the temperatures except that only 2 heights (46 and 137 cm above ground) were assessed. Oxygen was measured until near ambient levels were reached.

2.3.2.3. Precipitation quantities, leachate quantities and leachate sampling

Precipitation was determined based on two rain gauges, located on-site in Mansfield, NJ (only available for the first 2 months) and 13 km away in Easthampton, NJ. Precipitation data from Easthampton after September were considered representative, as regional precipitation differences are limited in the fall season.

Leachate quantities in two 1900-L tanks were recorded every day (except weekends and holidays) and afterwards the tanks were emptied. During the first month, leachate samples (2 L) were collected (after thorough mixing of tank contents) within 24 h of every rainfall event if there was any leachate accumulation. Subsequent sampling was reduced to 1–2 rain events per month. Samples were immediately transported to the laboratory in coolers for analysis. The leachate tanks were not rinsed or sterilized between rain events.

2.3.3 Sampling of cullet at MRFs and during the field tests

Nine fresh cullet samples (each in duplicate) from six MRFs were collected (Table 2-1) based on ASTM D75-97 (ASTM, 2003a). The sampling location was the storage area where the cullet left the last conveyor belt of each MRF. Each 30-kg sample consisted of about 2.5 kg sub-samples taken every 10 min for 2 h. The samples were immediately taken to the laboratory in a cooler for further analysis.

From field experimental stockpiles, each duplicate 30-kg cullet sample consisted of about 12 grab samples taken from the top, middle and bottom thirds of the stockpiles after complete mixing (adapted from ASTM, 2003a). Field cullet samples were collected from the lined, not-turned piles at the beginning and end (18–20 weeks) of the experiment and from the unlined, turned piles at the beginning of the experiment and after 1, 3, 8, 14, and 16 weeks. The different end dates (16, 18 and 20 weeks) eased sample processing in the laboratory. An additional sampling was conducted after 46 weeks to examine the effect of further aging.

2.3.4. Analyses of cullet, washwater, and leachate

2.3.4.1. Glass cullet

Each 30-kg sample was further reduced or sub-sampled to obtain the sample mass needed for each analysis based on ASTM C702-98 (ASTM, 2003b). The moisture content was determined in triplicate at 110 ± 3 °C according to ASTM D2216-98 (ASTM, 2003c) and the organic contamination in triplicate by ignition at 540 °C (CWC, 1997a). To determine ferrous and non-ferrous plus ceramic contaminants, non-ferrous metals and ceramics were visually identified in duplicate oven-dried cullet samples and manually removed while ferrous metals were separated by a magnet. The oven-dried cullet was also analyzed for lead based on US EPA method 3050B (USEPA, 1996b).

Analysis (in duplicate) of the cullet particle size distribution was based on a modified version of ASTM D422-63 (ASTM, 2003d). Ten US standard sieve sizes were selected for the analyses: 50.8 mm (2 in.), 19.1 mm (3/4 in.), 9.5 mm (3/8 in.), 4.75 mm (#4), 2.36 mm (#8), 2.00 mm (#10), 1 mm (#16), 0.30 mm (#50), 0.15 mm (#100), and 0.075 mm (#200). This selection includes all sieve sizes that are required to test the gradation of an I-10 soil aggregate (NJDOT, 2001).

2.3.4.2. Washwater and leachate

In order to have a relatively simple method to evaluate changes in cullet quality, a washing procedure was used. A cullet sample (~760 g wet weight) was mixed with deionized water (glass cullet:deionized water = 1:3 by weight) and shaken for 30 min in duplicate on a reciprocal shaker (G10 Gyrotory®, New Brunswick Scientific, Edison, NJ, US) at a speed of 150 rpm (modified after Mulvaney, 1996). This method also provides an estimate of maximum leaching potential that might occur in the field. In preliminary testing, a second washing confirmed that remaining contaminants in the glass cullet could be neglected. Most washwater analyses were determined according to Standard Methods for the Examination of Water and Wastewater (APHA, 1995): 2540 F (settleable solids), 2540 D (total suspended solids), 4500-Norg B (TKN), 4500-NH_3 D (NH_4^+-N), 4500-NO_3^- E (NO_3^--N), modified 4500-P E (total-phosphorus) with improved technique for combined reagent 'A' (Chowdhury, 1991), 4500-S_2^- D (reduced sulfur), 3500-Fe D (reduced iron), 5210 B (BOD_5), 5540 C (anionic surfactants), and 9222 B (total coliforms). For the COD analysis the washwater was filtered through a 0.45-μm filter (Whatman, Florham Park, NJ, US) to remove paper labels. COD, reduced sulfur, and reduced iron were analyzed with a Hach kit (Hach Company, Loveland, CO, US), followed by spectrophotometer measurements (Spectronic® 20 Genesys™ for COD; Hach, DR/850 for reduced sulfur and iron). All analyses other than the settleable solids analysis (no replicates) were performed in duplicate. The same parameters (except NO_3^--N) and analytical methods were used for the analysis of leachate.

2.4. Results and discussion

2.4.1. Characterization of fresh glass cullet from six MRFs

The selected characteristics of the glass cullet were all of the same order of magnitude for the six MRFs (Table 2-2). The moisture content ranged between 1.2% and 5.5%, which is similar to the moisture content of two samples from Pennsylvania (Wartman *et al.*, 2004) of 2.4% for mixed cullet from a quarry facility that contained virtually no debris and 4.2% for glass cullet from a MRF that accepted commingled containers. The moisture content was above the 0.3% limit recommended to avoid the generation of glass cullet dust and below 15%, the moisture content at which the release of organics-contaminated liquid was reported (CWC, 1997b).

The debris content (organic, ferrous, and non-ferrous plus ceramics contamination) in this study was similar to that reported by Wartman *et al.* (2004) of 0.8% for the quarry facility and 3.4% from the MRF. While one of the fine samples ($C_{fine}2$) had the lowest debris content, this was not true for the previous fine sample ($C_{fine}1$). Debris content was well below the 5% maximum recommended by the New

York State Department of Transportation (DOT) and the Oregon DOT for all applications as construction aggregate (CWC, 1998).

All nine samples passed through the 19-mm (3/4 in.) sieves and more than 98% through the 9.5-mm (3/8 in.) sieves (Figure 2-2). For samples $C_{fine}1$ and $C_{fine}2$ more than 99% passed through the 4.75-mm sieve (#4), while the other samples were coarser. Based on the Unified Soil Classification System (USCS) (ASTM, 2000), four samples were classed as gravel, and five samples as sand (Figure 2-2).

The analysis of the washwater from the glass cullet provides an estimate of the maximum leaching potential that might occur in the field, since the mechanical shaking dissolves and suspends labels and other debris. Both settleable and total suspended solids levels of the washwater exceeded the typical levels of raw domestic sewage (Table 2-3 and Table 2-4). The lowest settleable solids level was found in one of the samples with the smallest particle size (C_{fine} 1), as for this sample paper and plastic caps had been removed by the air classifier in the MRF, although the second sample from the same facility of this particle size ($C_{fine}2$) showed higher settable solid levels. Both of these samples, however, had the highest suspended solids level suggesting that the source of suspended solids can be found among the finer particle size fractions. Overall, as expected, the solids levels in this study are higher than levels found in leachate from leaching columns filled with glass cullet (CWC, 1998), where the column acts as a filter.

The BOD_5 levels, averaging 1080 mg L^{-1}, exceeded the high end of values for raw domestic sewage (Table 2-3 and Table 2-4), and the filtered COD, averaging 702 mg L^{-1}, exceeded the high end for urban stormwater. Based on one filtered BOD_5 sample from $C_{fine}1$ (data not shown), the ratio of filtered BOD_5 to filtered COD is around

0.4, suggesting a moderately high biodegradability of the organic constituents. Reduced iron and sulfur levels were below 1 mg L^{-1} (data not shown) for the washwater samples, indicating that the contribution of reduced iron and sulfur to BOD_5 can be neglected.

As for nutrients, phosphorus levels averaged 6.21 mg L^{-1}, which is similar to raw domestic wastewater levels. Ammonia and nitrate nitrogen levels were low, averaging 2.25 and 0.14 mg L^{-1}, respectively, comparable to levels found in urban stormwater. TKNs were only available for two samples; these were comparable to the levels for the low end of raw domestic sewage.

Anionic surfactant and total coliform levels averaged 26.3 mg L^{-1} and $1.9 * 10^7$ cfu mL^{-1}, both exceeding levels in raw domestic sewage. However, the anionic surfactants are biodegradable (Scott and Jones, 2000 and Swisher, 1987) and it is expected that they will degrade in the field storage piles. Even though the total coliform levels are high, it is possible that these are not from fecal contamination. Further research, such as speciation, is necessary to determine the sanitary significance of the coliforms found.

Total lead levels, determined for four samples (A, B, C, and D), were all below 1 mg Pb kg^{-1} glass cullet (data not shown). Lead levels in the digest (40 mL used per 30 g cullet sample) ranged between 15 and 757 µg L^{-1}. Assuming the same mass of lead would be the maximum amount extracted via TCLP (USEPA, 1992), the less stringent extraction procedure (600 mL extract with 30 g of glass cullet) than the total lead determination, lead concentrations of 1–50 µg L^{-1} would be expected. This is well below the USEPA limit of 5 mg L^{-1} for hazardous waste (USEPA, 2004), which is determined by the TCLP. Furthermore, three out of four samples were below 15 µg L^{-1}, the maximum contaminant level for the national primary drinking water standard (USEPA, 2003). Although further testing may be prudent, based on these results lead in glass storage stockpiles is no longer an issue.

2.4.2. Field stockpiles

2.4.2.1. Temperature and oxygen levels

Even though glass cullet itself is inorganic and inert, biodegradation of organics such as food and beverage residues and paper labels resulted in the type of self-heating found in composting piles of biodegradable organic wastes (Figure 2-3). Self-heating, as indicated by temperature elevation, is an indication of biodegradation, which was confirmed by a reduction of organic contaminants in the cullet over time (Table 2-5). The unturned stockpile of D&E cullet reached a higher maximum temperature (76 ^{o}C) than the weekly turned piles (68 ^{o}C), and cooled down more slowly (Figure 2-3). The stockpile of C_{fine}2 glass cullet held the elevated temperatures much longer than the other stockpiles. The initially lower temperatures in the C_{fine}2 stockpile were likely caused by insufficient oxygen (Figure 2-4d).

2.4.2.2. Leachate from glass cullet stockpiles

2.4.2.2.1. Leachate quantity

Leachate quantity was determined for the two lined stockpiles. For the first two months of the experiment, the stockpile with the finer cullet (C_{fine}2) held more rainwater and generated less leachate than the stockpile with the coarser cullet (D&E) (Figure 2-5). By that time, the D&E stockpile had generated more than twice as much leachate as the $C_{fine}2$ stockpile, and the ratios of the accumulated leachate divided by the accumulated rainfall were 0.58 and 0.21, respectively. Although the two stockpiles released different amounts of leachate initially, this was not the case after about 2 months in the fall (data not shown). The capacity of a stockpile to retain water depends on both its water holding capacity and evaporation, which is likely less in the fall than in the summer, and also less after the pile has cooled. This can also be seen in the difference between accumulated rainfall and accumulated leachate, which equals the sum of evaporated water plus water retained in the stockpile (Figure 2-6). (Note: the observed differences between the finer and the coarser cullet have not been confirmed in preliminary results from a follow-up study the next year, in which there was heavy rain.)

2.4.2.2.2. Leachate quality

Dilution of leachate with rainwater varied depending on the rain event. Generally, the smaller the rain event, the higher the pollutant concentrations of the collected leachate.

As the glass cullet stockpile acts as a filter, both settleable solids and total suspended solids levels in leachate were lower than those in the washwater from fresh cullet (Table 2-4). Settleable solids levels were low (<3 mL L^{-1}) in leachate samples from both stockpiles. However, suspended solids levels exceeded common values for urban stormwater in a few cases and New Jersey surface water quality criteria in all cases (Table 2-4).

The initial BOD_5 levels were comparable to those in washwater samples of fresh cullet and decreased over time. The BOD_5/COD ratios in the first 2 weeks were approximately 0.3–0.4 and dropped below 0.1 during the study, again indicating biodegradation.

TKN levels as high as 154 mg L^{-1} were measured in leachate from stockpile D&E 2 weeks after set-up, with somewhat decreasing levels measured thereafter. The total-P concentration did not decrease, averaging 6.6 mg L^{-1} and 7.2 mg L^{-1} for stockpiles C_{fine}2 and D&E, respectively. Both TKN and total-P levels in both piles at the end of the experiment were still comparable to levels found in untreated domestic wastewater (Table 2-4). This finding was supported by the nearly steady release rate of nutrients found in aged washwater analysis (Table 2-8).

Overall, analysis of washwater proved to be an appropriate screening method to determine the pollution potential of the cullet. BOD_5, pH, total P, and total coliforms levels were of the same order of magnitude as the levels measured in leachate (Table 2-7).

2.4.2.3. The effect of turning on cullet quality

As previously discussed, based on the temperature measurements and the oxygen levels, turning has a positive effect on the cullet stockpiles. This effect was also assessed based on washwater from aging cullet.

As expected based on the leachate analyses, BOD_5, COD, settleable solids, anionic surfactant and total coliform levels decreased substantially over time (Table 2-8). However, the TKN and total P levels declined less, with an initial decrease of 40–45% after 1 week for the turned piles, but then staying about the same or even increasing slightly until the end of the experiment. The unturned stockpiles had smaller decreases, but the rate is unknown since no representative cullet samples could be taken until the end of the experiment.

The washwater analysis confirmed that mechanical turning increased degradation rates of organic contaminants in the cullet. For example, washwater BOD_5 levels were below 10 mg L^{-1} for the turned stockpiles after 8 weeks, but for the unturned piles were still above 10 mg L^{-1} at the end of the 18–20 week experiment.

2.4.3. Fractions of total nitrogen and phosphorus released

Via the leachate approximately 86 g N (as TKN; nitrate and nitrite considered negligible) and approximately 6 g P were released from the stockpile (Table 2-6). Based on the initial stockpile mass of 35 tonnes, moisture content of 3.16% and organic content of 1.41% (Table 2-2), this represents 478 kg of organic matter. If 20% of this is considered plastic (high level observed in preliminary tests for contamination) and 2% and 0.3% of the remaining organic mass are N and P, respectively (Chang *et al.*, 2006; Eklind and Kirchmann, 2000; Frossard *et al.*, 2002; Fuentes *et al.*, 2006 and Lee *et al.*, 2004), then ~99% of the N and P still remained in the $C_{fine}2$ pile after 1 month. The assumption of 2% nitrogen in the organic fraction was based on the percentage range for paper and food waste found in the cited literature. Even though only a small percentage of the total N and P were released from the stockpile, this still produced leachate with N and P concentrations of environmental importance.

2.4.4. Best management practices for handling glass cullet stockpiles

Leachate from cullet stockpiles is a potential source of water pollution. Best management practices (BMPs) need to address the release of leachate to groundwater and surface water for both short- and long-term stockpiling.

2.4.4.1. Surface water

Leachate from stockpiles of fresh and aged (treated) cullet should not be released to surface water regardless of the length of stockpiling. Even though the BOD_5 levels in aged leachate (1 month) from both stockpiles were reduced to levels found in urban stormwater runoff, release to surface water should be avoided due to the elevated TSS and nutrient levels that are comparable to levels found in untreated domestic wastewater (Table 2-4, Table 2-5 and Table 2-6).

2.4.4.2. Groundwater

Considering BOD_5 levels of up to 1809 mg L^{-1} and COD levels of up to 6258 mg L^{-1} in the initial leachate, it is recommended that fresh cullet is treated or aged before leachate from these stockpiles infiltrates and pollutants are transported to groundwater. Enhanced biological degradation, such as composting, will reduce pollutants in the leachate. As found in this study, turning is beneficial to enhance the degradation process. Slower biological degradation in the unturned stockpile of fine glass cullet ($C_{fine}2$) was most likely due to insufficient oxygen availability (Figure 2-4). Whether regular turning, which is labor intensive, can be replaced by active aeration, needs to be further studied. The washwater extraction method developed in this study is a simple method to test the effectiveness of various treatments.

Aged leachate from the cullet stockpiles, however, can be released and allowed to infiltrate if a BMP with sufficient removal efficiency for total-N in the leachate is implemented. Retention pond and constructed wetland systems may meet these site specific requirements, mainly through assimilation into plant biomass, assuming the site conditions (e.g., soil type, permeability, groundwater table and flow, land availability) are suitable (ASCE, 2001). Nitrate was not analyzed in this study, but it is expected that it can be handled by these BMPs assuming that the nitrate–nitrogen mass does not exceed the initial mass of TKN found in the washwater. If the cullet is only stockpiled for a few months, in many cases, retention ponds and wetland systems may not be necessary because the released mass of nitrogen in that time will be low.

2.5. Conclusions

Municipalities recommend rinsing containers before they are deposited in recycling bins. However, many containers are not rinsed. As a result, leachate from glass cullet stockpiles is a potential source of water pollution caused by food/beverage and other residuals. This study showed that leachete from glass cullet stockpiles should not be released to surface water. It can be released to ground water only if treated and if BMPs are implemented to reduce the nitrogen levels in the leachete of long-term stored glass cullet stockpiles. Given the limited variation in cullet quality among the tested MRFs in New Jersey and Pennsylvania, the findings likely also apply in other states in the US.

Composting with regular turning was implemented as an effective treatment method. However, turning is labor intensive. Whether turning can be replaced by active aeration, which might reduce costs, requires further testing. It also needs to be determined whether the total coliforms found are an indicator of fecal contamination.

Handling of leachate from cullet stockpiles enables the beneficial use of glass cullet as construction aggregates, but this may add to the overall cost. Therefore, a broader assessment of glass recycling is needed. Alternatives to be assessed might include no recycling, single-stream recycling, commingled container recycling with and without color separation at the MRF, and cash deposit. Material flow analysis, life cycle assessment and cost-benefit analysis are tools that might be used in this assessment.

Acknowledgements

The authors would like to thank Robert Simkins, Coordinator, Burlington County Division of Solid Waste Management, and the Burlington County Board of Chosen Freeholders, for providing the site; Joe Hilla and his staff for constructing the site, setting up, and maintaining the stockpiles; Daniel Macready for collecting samples; and the Monmouth County Planning Board, Solid Waste/Recycling Division, the Rutgers EcoComplex, and our corporate contributors for technical and financial support.

2.6 References

American Public Health Association (APHA) (1995). *Standard Methods for the Examination of Water and Wastewater.* 19th ed., American Public Health Association, Washington, D.C.

American Society of Civil Engineers (ASCE) (2001). A Guide for Best Management Practice (BMP) Selection in Urban Developed Areas. Urban Water Infrastructure Management Committee for Evaluating Best Management Practices. Reston, VA, USA.

American Society for Testing and Materials (ASTM) (1993). Standard Test Method for Sequential Batch Extraction of Waste with Water. ASTM D 4793, West Conshohocken, PA, USA.

American Society for Testing and Materials (ASTM) (2000). Standard Classification of Soil for Engineering Purposes. ASTM D 2487-00, West Conshohocken, PA, USA.

American Society of Testing and Materials (ASTM) (2003a). Standard Practice for Sampling Aggregates. ASTM D 75-97, West Conshohocken, PA, USA.

American Society of Testing and Materials (ASTM) (2003b). Standard Practice for Reducing Samples of Aggregate to Testing Size. ASTM C702-98, West Conshohocken, PA, USA.

American Society for Testing and Materials (ASTM) (2003c). Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM D2216-98, West Conshohocken, PA, USA.

American Society for Testing and Materials (ASTM) (2003d). Standard Test Method for Particle-Size of Soils. ASTM D422-63, West Conshohocken, PA, USA.

Catricala, C.E.; Bowden, W.B.; Smith C.T. and McDowell, W.H. (1996). Chemical characteristics of leachate from pulp and papermill residuals used to reclaim a sandy soil. Water, Air, and Soil Pollution (89), p. 167-187.

Chang, J.I.; Tsai, J.J. and Wu, K.H. (2006). Thermophilic composting of food waste. Bioresource Technology (97), p. 116-122.

Chowdhury, M., (1991). An improved technique for the preparation of a combined reagent for phosphorus determination. In: Water Pollution Control Federation, 64th Annual Conference and Exposition, #AC91-066-004. October 1991, Toronto, Canada.

Clean Washington Center (1996). Contaminant Levels in Recycled Glass. Seattle, WA, USA. <http://www.cwc.org/gl_bp/1-02-02.pdf> (Accessed 25 September 2008).

Clean Washington Center (1997a). Methods for Sampling and Testing Recycled Glass. Seattle, WA, USA. <http://www.cwc.org/glass/gl979rpt.pdf#search='methods%20for%20sampling%20and%20testing%20recycled%20glass'> (Accessed 25 September 2008).

Clean Washington Center (1997b). Moisture Considerations in Glass Cullet Processing and Distribution. Seattle, WA, USA. <http://www.cwc.org/gl_bp/gbp2-0501.htm> (Accessed 25 September 2008)

Clean Washington Center (1998). A Tool Kit for the Use of Post-Consumer Glass as a Construction Aggregate. Report #: GL-97-5. Seattle, WA. <http://www.cwc.org/glass/gl975rpt.pdf> (Accessed 25 September 2008)

Curran, K.J.; Irvine, K.N.; Droppo, I.G. and Murphy, T.P. (2000). Suspended solids, trace metal and PAH concentrations and loadings from coal pile runoff to Hamilton Harbour, Ontario. Journal of Great Lakes Research (26), p. 18-30.

Dames and Moore Inc. (1993). Glass Feedstock Evaluation Project. Rep. Prepared for the Clean Washington Center, Seattle, WA, USA.

Eklind, Y. and Kirchmann, H. (2000). Composting and storage of organic household waste with different litter amendments. II: Nitrogen turnover and losses. Bioresource Technology (74), p. 125-133.

Frossard, E.; Skrabal, P.; Sinaj, S.; Bangerter, F. and Traoré, O. (2002). Forms and exchangeability of inorganic phosphate in composted solid organic wastes. Nutrient Cycling in Agroecosystems (62), p. 103-113.

Fuentes, B.; Bolan, N.; Naidu, R. and de la Luz Mora, M. (2006). Phosphorus in organic waste-soil systems. Journal of Soil Science and Plant Nutrition (6), p. 64–83.

Lee, J.J.; Park, R.D.; Kim, Y.W.; Chae, D.H.; Rim, Y.S.; Sohn, B.K.; Kim, T.H.; and Kim, K.Y. (2004). Effect of food waste compost on microbial population, soil enzyme activity and lettuce growth. Bioresource Technology (93), p. 21-28.

Metcalf and Eddy Inc. (2003). *Wastewater Engineering Treatment and Reuse*. 4th ed. Tata McGraw-Hill Publishing Company Limited, New Delhi, p. 109.

Mulvaney, R.L. (1996) Extraction of exchangeable ammonium and nitrate and nitrite. Part 3, chemical methods. In: D.L. Sparks, Editor, *Methods of Soil Analysis.* SSSA Book Series No. 5, SSSA, Madison, WI, p. 1123-1131.

New Jersey Department of Environmental Protection (2006). Surface Water Quality Standards. N.J.A.C. 7:9B. Trenton, NJ. <http://www.epa.gov/waterscience/standards/wqslibrary/nj/nj2_swqs.pdf> (Accessed 25 September 2008)

New Jersey Department of Transportation (2001). Standard Specifications for Road and Bridge Construction. Trenton, NJ. <http://www.state.nj.us/transportation/eng/specs/english/EnglishStandardSpecifications.htm> (Accessed 25 September 2008)

Novotny, W. and Chesters, G. (1981) *Handbook of Nonpoint Pollution.* Van Nostrand Reinhold, New York, USA.

Reindl, J. (2003). Reuse/Recycling of Glass Cullet for Non-Container Uses. Dane County Department of Public Works, Madison, WI. <http://epa.gov/osw/partnerships/greenscapes/pubs/glass.pdf> (Accessed 25 September 2008)

Scott, M.J. and Jones, M.N. (2000). M.J. The biodegradation of surfactants in the environment. Biomembranes (1508), p. 235-251.

Swisher, R.D. (1987). *Surfactant Biodegradation*. Second ed., Marcel Dekker, New York, USA (1987).

Townsend, T.G. (1998). Leaching characteristics of asphalt road waste. # 98-2. Florida Center for Solid and Hazardous Waste Management, Gainesville, FL.

US Environmental Protection Agency (1992). Toxicity Characteristic Leaching Procedure, Method 1311. Washington, DC.

US Environmental Protection Agency (1996a). Subpart D, 21 CFR, Part 189.301. Feb., 1996.

US Environmental Protection Agency (1996b). Acid digestion of sediments, sludges, and soils. EPA 3050B. Washington, DC. <http://www.epa.gov/sw-846/pdfs/3050b.pdf> (Accessed 25 September 2008)

US Environmental Protection Agency (1999). Protocol for Developing Nutrient TMDLs. NSCEP 841-B-99-007, Cincinnati, OH.

US Environmental Protection Agency (2003). National Primary Drinking Water Standards. Office of Water (4606M) 816-F-03-016, Washington, DC. <http://www.epa.gov/safewater/consumer/pdf/mcl.pdf> (Accessed 25 September 2008)

US Environmental Protection Agency (2004). Test Methods for Evaluating Solid Waste, Physical/Chemical Methods; Chapter Seven – Characteristics Introduction and Regulatory Definitions. SW-846 4th rev., Washington, DC. <http://www.epa.gov/epaoswer/hazwaste/test/sw846.htm> (Accessed 25 September 2008)

Wanielista, M.P. (1978). *Stormwater Management: Quantity and Quality*. Ann Arbor Science Publishing, Ann Arbor, MI, USA.

Wartman, J.; Grubb, D.G., and Nasim, A.S.M. (2004). Select engineering characteristics of crushed glass. Journal of Materials in Civil Engineering (16), p. 526-539.

Table 2-1
Overview of fresh cullet samples

Sample ID	Sampling Date (2006)	Laboratory (L) and/or field (F) test	Curbside (C) and/or drop-off centers (D)	Screen size, last screen (mm)
A	03/01	L	C (90%), D (10%)	15.88
B	03/10	L	C	12.7
C_{coar}	03/14	L	C (80%), D (20%)	9.5
$C_{fine}1$	04/19	L	C	4.75
$C_{fine}2$	06/29	L, F	C	4.75
D	03/28	L	C	9.5
E	04/10	L	C	9.5
D&E	06/28	L, F	C	9.5
F	05/05	L	C	9.5 – 12.7

C_{coar}: Coarse cullet sample from facility C. $C_{fine}1$: First sampling of fine cullet sample from facility C. $C_{fine}2$: Second sampling of fine cullet sample from facility C. D&E: Mixed sample of cullet from facilities D and E.

Table 2-2
Characterization of fresh cullet from six MRFs (% by weight)

Sample ID* Sampling date	A 3/1	B 3/10	C_{coar} 3/14	D 3/28	E 4/10	$C_{fine}1$ 4/19	F 5/5	D&E 6/28	$C_{fine}2$ 6/29	**Mean**	**S.D.****
Moisture content	1.64	4.35	2.45	2.46	5.46	2.41	1.23	5.24	3.16	**2.86**	**1.51**
Contaminants											
Organic matter	1.50	3.36	1.35	1.79	2.00	1.48	1.29	1.28	1.41	**1.82**	**0.72**
Ferrous metal	0.08	0.08	0.36	0.18	0.10	0.00	0.33	0.01	0.02	**0.19**	**0.19**
Non-ferrous metal & ceramics	0.15	0.47	1.05	0.29	0.37	0.59	0.51	0.28	0.01	**0.35**	**0.32**
Sum of Contam.	1.73	3.91	2.76	2.26	2.47	2.07	2.13	1.57	1.44	**2.26**	**0.75**

*See Table 2-1 for description of sample source.
** Standard deviation

Table 2-3
Washwater from fresh cullet (cullet to water ratio = 1:3)

Parameters	A	B	C_{coar}	D	E	$C_{fine}1$	F	D&E	$C_{fine}2$	**Mean**
Sampling date	3/1	3/10	3/14	3/28	4/10	4/19	5/5	6/28	6/29	
pH	7.9	7.8	8.0	7.8	7.2	7.6	7.5	7.4	7.8	**7.68**
Settleable solids (mL L^{-1})	ND	174	128	114	107	68	106	115	120	**117**
Total suspended solids (mg L^{-1})	ND	5630	6150	2880	4310	10620	2250	4990	7790	**5575**
BOD_5, un-filtered (mg L^{-1})	ND	ND	ND	ND	1000	2320	970	400	720	**1082**
COD, filtered (mg L^{-1})	700	990	750	940	660	1240	480	270	300	**702**
Total-P (mg L^{-1})	2.1	8.6	4.7	4.5	3.7	4.8	1.7	11.9	13.9	**6.21**
TKN (mg L^{-1})	20.3	4.4	7.7	14.6	4.3	11.2	5.0	23.3	23.0	**12.63**
Ammonia-N (mg L^{-1})	2.2	5.4	2.3	2.5	3.6	1.9	0.6	1.4	0.4	**2.25**
Nitrate+Nitrite-N (mg L^{-1})	0.27	0.07	0.19	0.26	0.06	0.07	0.07	ND	ND	**0.14**
Anionic surfactants (mg L^{-1})	ND	27.1	20.6	27.5	34.8	27.8	16.5	29.1	26.8	**26.26**
Total coliforms (cfu mL^{-1})	ND	$1.7*10^7$	$3.2*10^7$	$8.0*10^5$	$1.5*10^7$	$1.7*10^7$	$3.5*10^6$	$5.5*10^7$	$1.5*10^7$	**$1.9*10^7$**

ND: Not determined.

Table 2-4
Characteristics of washwater and leachate from this study, urban stormwater, untreated domestic wastewater and New Jersey surface water quality criteria

Parameters	This study		NJ surface water quality criteria[a]	Urban stormwater runoff	Typical range of untreated domestic wastewater[e]
	washwater (fresh cullet)	leachate			
pH	7.2 - 8.0	7.3 - 8.8	6.8 - 8.5	-	-
Settleable solids (mL L^{-1})	68 - 174	<0.1 - 2.9	-	-	5 - 20
Total suspended solids (mg L^{-1})	2250 - 10620	70 - 1850	25	630 [b]	100 - 350
BOD_5 (mg L^{-1})	970 - 2320	5 - 1810	-	10 - 250 [b]	110 - 400
COD (mg L^{-1})	480 - 1240*	370 - 6260**	-	20 - 600 [b]	250 - 1000
Total-P (mg L^{-1})	1.7 - 8.6	1.6 - 12.0	0.1	0.2 - 1.7 [d]	4 - 15
TKN (mg L^{-1})	4.4 - 20.3	11.6 - 153.5	-	3 - 10 [b,d]	20 - 85
Ammonia-N (mg L^{-1})	0.61 - 5.40	0.28 - 39.5	-	0.1 - 2.5 [c]	12 - 50
Nitrate-N (mg L^{-1})	0.06 - 0.27#	ND	-	0.01 - 1.5 [b]	0 - 1
Anionic surfactants (mg L^{-1})	16.5 - 34.8	0.61 - 2.2†	-	-	1 - 20 [f]
Total coliforms (cfu mL^{-1})	$8*10^5 - 3*10^7$	$<10^2 - 6.3*10^7$ †	-	$10^1 - 10^6$ [b]	$10^4 - 10^7$

[a] NJDEP (2006). [b] Novotny *et al.* (1981). [c] Wanielista *et al.* (1978). [d] USEPA (1999). [e] Adapted from Metcalf and Eddy (2003). [f] APHA (1995). ND Not determined. - Not reported. * Filtered samples. ** Un-filtered samples. † Selected samples. # Nitrate+Nitrite-N.

Table 2-5
Characterization of aged cullet (% by weight)

	Fresh cullet		Aged cullet, turned piles						Aged cullet, not turned piles		
Source materials	D&E	$C_{fine}2$	D&E						D&E		$C_{fine}2$
Weeks after set-up	0	0	1	3	8	14	16	46	18	46	20
Moisture content	5.2	3.2	8.1	5.0	2.1	3.4	3.7	3.6	4.6	3.5	7.5
Organic contamination	1.28	1.41	1.19	0.80	0.57	0.51	0.51	0.50	0.52	0.45	0.57

Table 2-6
Leachate from not turned, lined stockpile of $C_{fine}2$ cullet

Sampling Date	**7/6**	**7/13**	**7/19**	**7/24**	**8/30**	**9/29**	**10/28**
Volume (L)	144	11	492	379	227	30	227
pH	7.7	8.4	8.2	8.3	8.3	8.8	8.5
Settleable solids (mL L^{-1})	0.1	0.1	<0.1	<0.1	0.1	0.1	2.9
Total suspended solids (mg L^{-1})	180	1850	210	200	290	170	280
BOD_5, un-filtered (mg L^{-1})	1120	510	340	210	50	10	21
COD, un-filtered (mg L^{-1})	2540	2370	2000	1970	750	1680	750
Total-P (mg L^{-1})	5.88	8.57	7.88	2.82	3.62	9.65	7.77
TKN (mg L^{-1})	66.0	119.2	92.6	78.5	22.9	58.4	18.0
Ammonia-N (mg L^{-1})	25.9	10.0	34.4	39.5	12.0	1.3	0.3
Anionic surfactants (mg L^{-1})	ND	ND	ND	ND	2.2	ND	1.3
Total coliforms (cfu mL^{-1})	ND	ND	ND	ND	$3.5*10^6$	$2*10^2$	$<10^3$
Accumulated total-P (g)	0.85	0.95	4.82	5.89			
Accumulated TKN (g)	9.5	10.8	56.4	86.1			
Accumulated ammonia- N (g)	3.7	3.8	20.8	35.7			

ND: Not determined.

Table 2-7
Leachate from not turned, lined stockpile of D&E glass cullet

Sampling Date	**6/30**	**7/2**	**7/3**	**7/5**	**7/6**	**7/7**	**7/13**	**7/19**	**7/22**	**7/24**	**8/30**	**9/29**	**10/28**
Volume (L)	238	34	125	64	587	193	182	871	189	757	26	87	874
pH	7.3	7.8	8.0	8.1	7.7	8.1	8.3	8.5	8.5	8.1	8.0	8.7	8.2
Settleable solids (mL L^{-1})	<0.1	0.9	1.8	0.25	0.5	<0.1	0.1	<0.1	<0.1	<0.1	0.1	0.1	1
Total suspended solids (mg L^{-1})	820	930	200	450	490	230	200	550	700	70	160	740	120
BOD_5, un-filtered (mg L^{-1})	1230	1440	530	830	460	860	1810	20	280	88	15	24	5
COD, un-filtered (mg L^{-1})	4240	6260	2640	2170	1800	4430	6000	1940	3070	1310	500	1380	370
Total-P (mg L^{-1})	10.6	ND	4.9	ND	4.9	ND	10.1	ND	10.4	ND	1.6	12.0	3.1
TKN (mg L^{-1})	114.7	ND	103.6	ND	57.6	ND	153.5	ND	83.4	ND	19.9	ND	11.6
Ammonia-N (mg L^{-1})	21.7	ND	17.1	ND	6.5	ND	30.9	ND	17.1	ND	0.51	0.74	0.28
Anionic surfactants (mg L^{-1})	ND	ND	ND	ND	ND	ND	ND	2.1	ND	ND	0.61	ND	0.69
Total coliforms (cfu mL^{-1})	$1.3*10^7$	$6.0*10^5$	$6.3*10^7$	ND	ND	$<10^3$	ND	ND	ND	ND	$<10^3$	$<10^3$	$<10^3$

ND: Not determined.

Table 2-8
Washwater of aged glass cullet (glass to water ratio = 1:3)

	Initial		Turned stockpiles						Not turned stockpiles		
	D&E	$C_{fine}2$	D&E						D&E		$C_{fine}2$
Weeks after set-up	0	0	1	3	8	14	16[#]	46	18	46	20
pH	7.4	7.8	7.9	8.5	9.0	8.4	8.5	8.6	8.2	8.6	8.7
Settleable solids (mL L^{-1})	115	120	64.8	14.7	8.6	14.5	10.5	11.3	18.8	13.3	18.0
Total Suspended Solids (mg L^{-1})	4990	7790	2630	1920	2270	4000	4380	4310	4440	4630	10718
BOD_5, unfiltered (mg L^{-1})	398	716	213	74	9	6	3	4	13	5	21
COD, filtered (mg L^{-1})	265	298	66	55	40	31	24	13	32	32	46
Total-P (mg L^{-1})	11.9	13.9	6.6	5.6	4.9	7.9	7.5	7.3	7.5	7.4	8.6
TKN (mg L^{-1})	23.3	23.0	13.5	14.0	9.0	12.8	15.0	11.8	18.0	14.2	23.2
Ammonia-N (mg L^{-1})	1.37	0.37	0.20	0.75	0.19	0.14	0.09	<0.01	0.14	0.01	0.17
Anionic surfactant (mg L^{-1})	29.05	26.80	2.02	<0.25	ND	ND	ND	ND	0.46	ND	0.74
Total coliforms (cfu ml^{-1})	$5.5*10^7$	$1.5*10^7$	$1.7*10^6$	$1.17*10^4$	$1.5*10^3$	$3.4*10^2$	$5.3*10^2$	$<10^2$	$3.8*10^2$	$<10^2$	$1.4*10^2$

ND: Not Determined.
[#] Turning ceased.

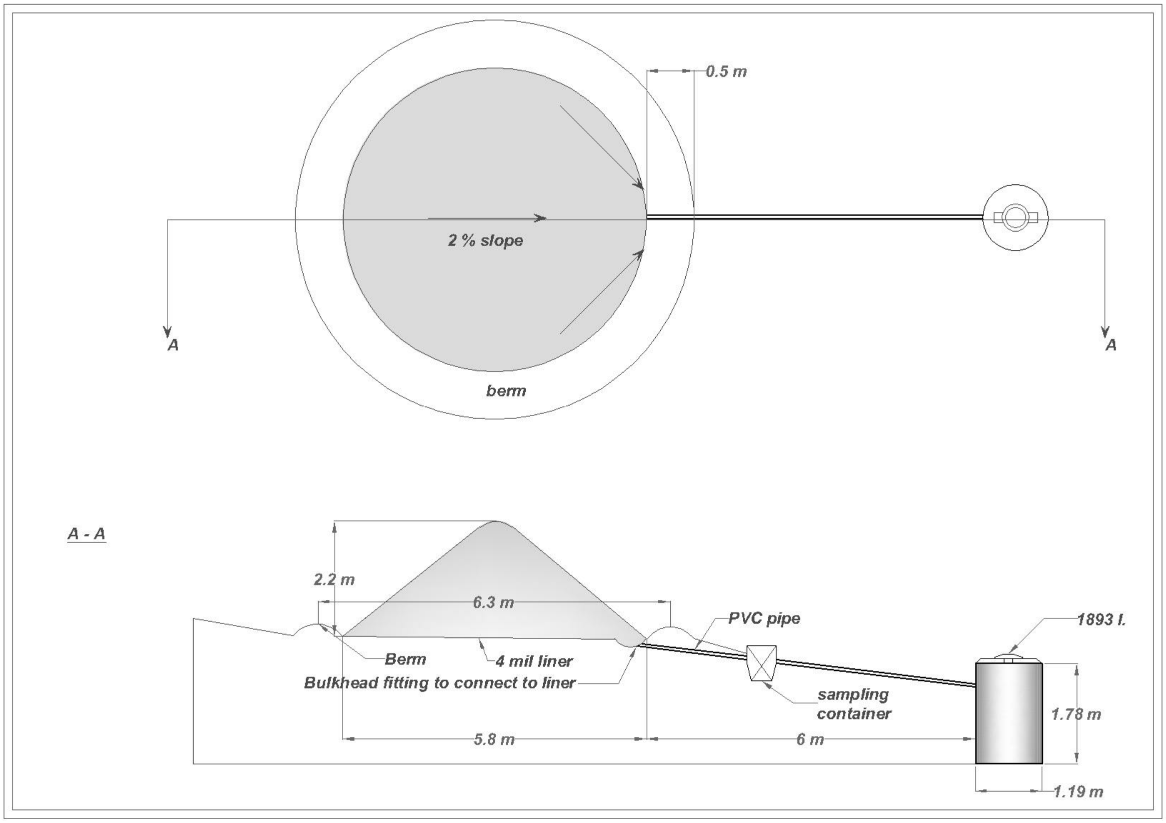


Figure 2-1. Schematic of not-turned, lined cullet stockpile.

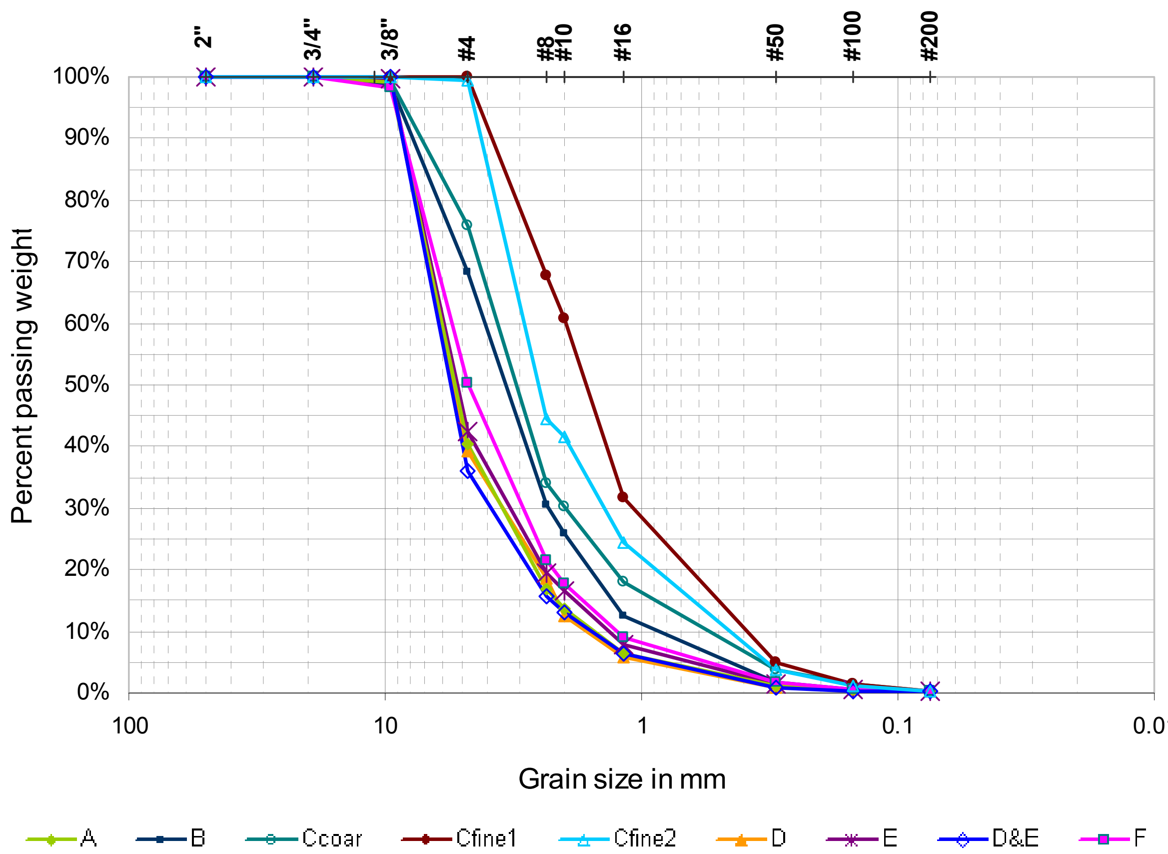


Figure 2-2. Particle size distribution of cullet samples (see Table 1 for sample ID). Based on USCS (ASTM, 2000), samples A, D, E, and D&E were classified as gravel (E as "GW", well-graded gravel, and A, D, and D&E as "GP", poorly-graded gravel); samples B, C_{coar}, $C_{fine}1$, $C_{fine}2$, and F were classified as sand (C_{coar} and $C_{fine}2$ as "SW", well-graded sand, and B and $C_{fine}1$ and F as "SP", poorly-graded sand).

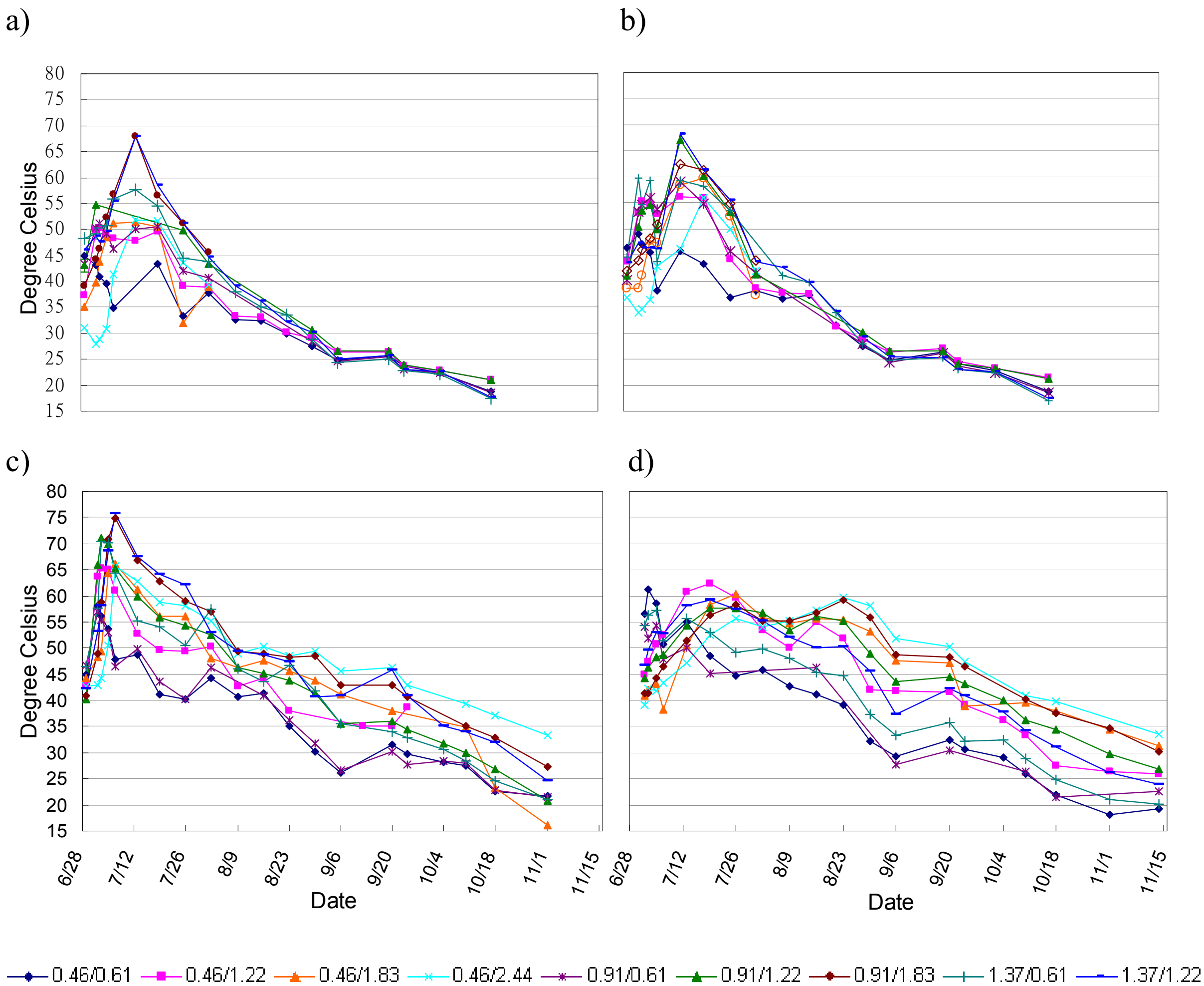


Figure 2-3. Temperatures in four field stockpiles: a) Weekly turned stockpile 1 of D&E glass cullet, unlined, b) Weekly turned stockpile 2 of D&E glass cullet, unlined. c) Not turned stockpile of D&E glass cullet, lined. d) Not turned stockpile of $C_{fine}2$ glass cullet, lined. Note: in the legend, the first number represents the height above ground and the second number the distance into the pile of the measurement point (in meters).

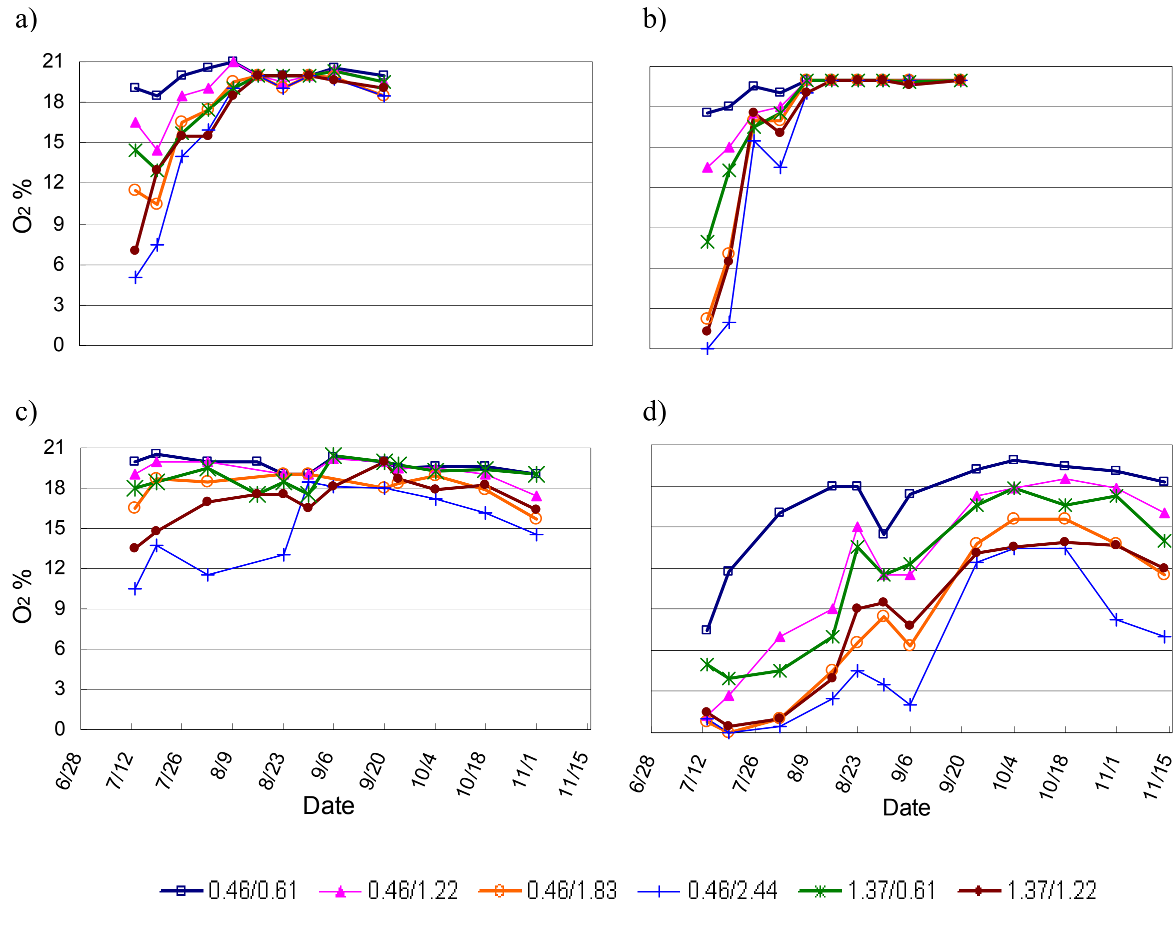


Figure 2-4. Oxygen levels in four field stockpiles: a) Weekly turned stockpile 1 of D&E glass cullet, unlined, b) Weekly turned stockpile 2 of D&E glass cullet, unlined. c) Not turned stockpile of D&E glass cullet, lined. d) Not turned stockpile of $C_{fine}2$ glass cullet, lined. Note: in the legend, the first number represents the height above ground and the second number the distance into the pile of the measurement point (in meters).

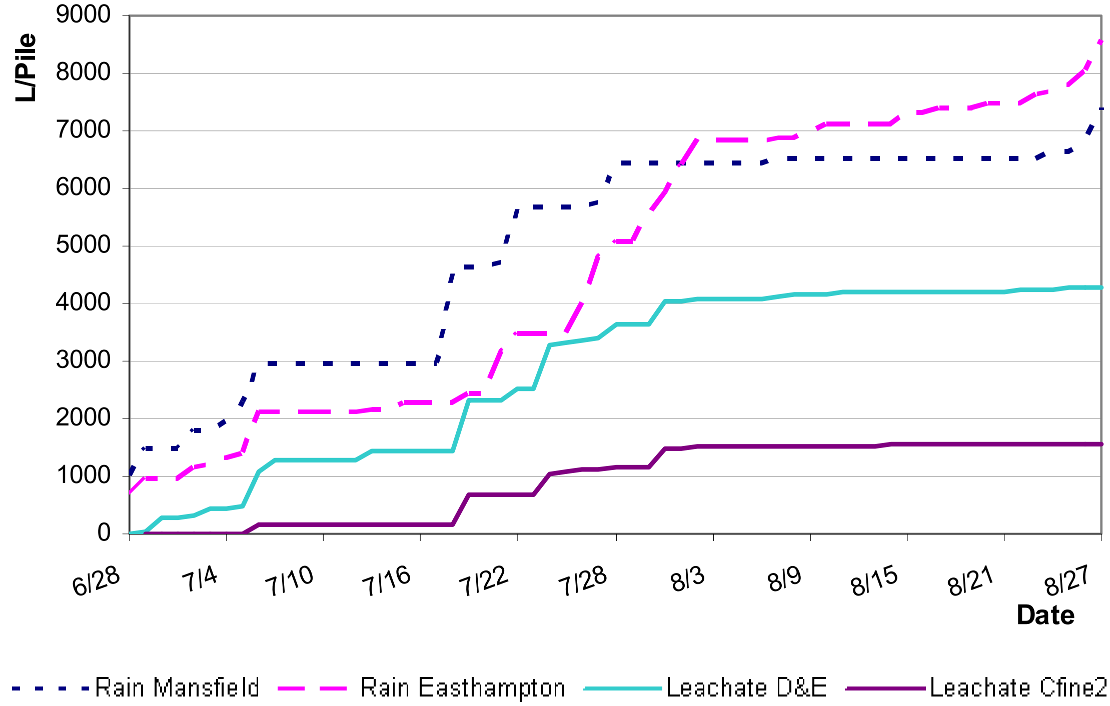


Figure 2-5. Cumulative rainfall at the Mansfield and the Easthampton weather stations and cumulative leachate of not-turned, lined stockpiles of D&E and $C_{fine}2$ glass cullet.

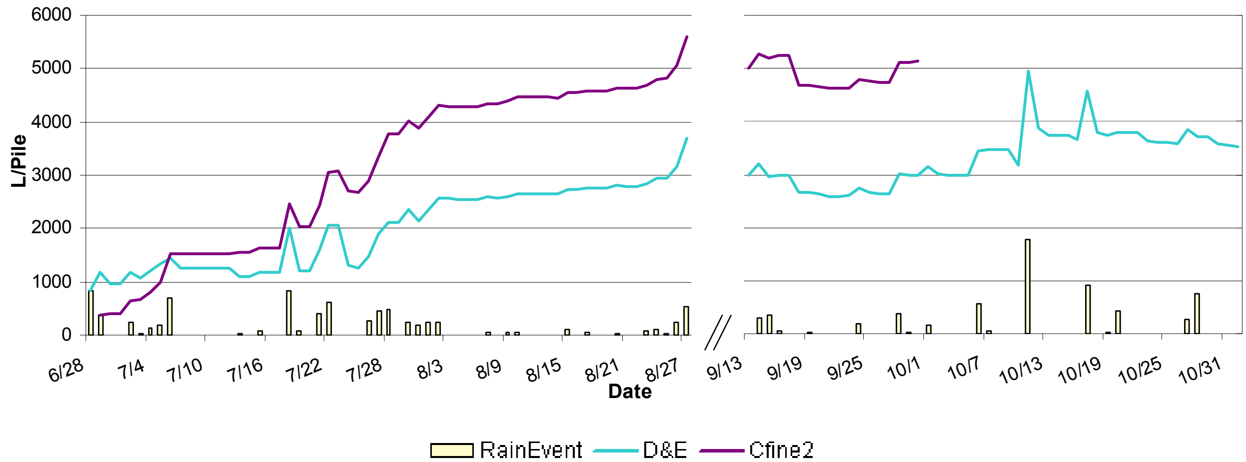


Figure 2-6. Average daily rainfall obtained from Mansfield and Easthampton weather stations and difference between cumulative rainfall and cumulative leachate (= evaporation + water retained in the stockpiles) of not-turned, lined stockpiles of D&E and $C_{fine}2$ glass cullet. Note: The stockpile of $C_{fine}2$ cullet was set up one day later and did not receive the 831 L $pile^{-1}$ rainfall as the stockpile of D&E cullet. Due to technical problems, there are no data from 8/27/06 to 9/13/06 for both piles, and from 10/1/06 to 10/31/06 for $C_{fine}2$ glass cullet. To account for the missing data, on 9/13/06 a difference of 3000 L $pile^{-1}$ and 5000 L $pile^{-1}$ was assumed for D&E and $C_{fine}2$ cullet, respectively.

Chapter 3. Effect of forced aeration and mechanical turning on leachate quantity and quality from glass cullet stockpiles

Material in this chapter has been published previously as:

C.L. Tsai, U. Krogmann, and P.F. Strom (2009). Effect of Forced Aeration and Turning on Leachate Quantity and Quality from Glass Cullet Stockpiles. Journal of Environmental Engineering (ASCE) (136), p. 1296-1305.

3.1 Abstract

Leachate from mixed glass cullet (crushed recycled, mixed-color glass containers) that is stockpiled before use as roadway construction aggregate or daily cover in landfills is a potential source of water pollution. Rainwater leaching through the stockpiles dissolves and suspends organic compounds and nutrients from the glass. The objectives of this study were to investigate 1) the effect of forced aeration on leachate quantity and quality in the glass cullet stockpiles compared to mechanical turning (mixing); and 2) whether initial high total coliform levels in leachate were an indication of fecal contamination. Three experimental stockpiles were set up in the field, two to evaluate leachate from forced aeration treatment (one with fine, the other with coarse cullet) and one (with coarse cullet) to compare the effects of forced aeration and mechanical turning. The organic and nutrient concentrations in the leachate of the aerated stockpiles were comparable to those of raw domestic wastewater in most cases. Organic constituents (e.g., BOD_5) were reduced by >70% from the initial levels (~450

mg L^{-1}) during a 1.5-month period with forced aeration, compared to an 85% decrease in the turned stockpile. Particle size affected temperature and oxygen levels under aeration conditions, resulting in more biodegradation of organic contaminants in the stockpile of coarse cullet than the fine cullet. Most of the identified isolates among the total coliforms from the glass stockpiles likely do not represent a sanitary problem, although further testing may be needed.

3.2. Introduction

In the United States and Europe, there has been a rapid increase in the use of mixed cullet (crushed glass) from material recovery facilities as a drainage layer or daily cover material in landfills (Reindl, 2003). This material is mainly produced from the mixed-color broken glass that is difficult to reuse in container manufacturing. To obtain higher quality and more cost efficient beneficial uses for the mixed cullet, municipalities and the recycling industry are interested in using this material as construction aggregate. These uses require that sufficient quantities of mixed cullet be stored at the processing facility or on-site at landfills or construction projects. Depending on the project, cullet might be stockpiled uncovered for several months to years, releasing leachate to the surrounding environment. Leachate in this study is defined as rainwater that percolated through the cullet stockpile, while mixing with any water already present, and dissolving and suspending some of the contaminants such as food/beverage residuals and paper labels.

Leachate quantity and quality from field stockpiles of cullet, and the effects of weekly mixing/turning treatments were studied by Tsai *et al.* (2009). It was found that the initial characteristics (i.e., basic wastewater parameters, total coliforms, and anionic surfactants) from the field-collected leachate were comparable to or higher than those of raw domestic wastewater or urban stormwater. The organic constituents in the leachate decreased over time, while the nutrient levels (total-N and total-P) did not change much over the four months of the study. Tsai *et al.* (2009) also suggested further study to determine whether the total coliforms found are an indicator of fecal contamination. This is in part because the original coliform test was not developed for cullet samples, and can include bacteria that are not of fecal origin. As a result of this previous study, leachate from glass cullet stockpiles is considered a potential source of water pollution. The study concluded that leachate from mixed cullet stockpiles should not be released to surface water and released to groundwater only if treated (e.g., composting with regular turning) and if best management practices (BMPs) are implemented to reduce the nitrogen levels.

Although weekly mixing/turning of the glass cullet stockpiles is an effective treatment to reduce the organic constituents in the stockpiles (Tsai *et al.*, 2009), it is labor intensive. One question is whether active aeration could replace the mixing/turning of the cullet stockpiles.

The overall objective of this study was to investigate the effect of forced aeration on leachate quantity and quality in the cullet stockpiles compared to mechanical turning (mixing). A second objective was the determination if initial high total coliform levels previously found indicated fecal contamination of the cullet.

3.3. Materials and Methods

To evaluate the effect of forced aeration on leachate quantity and quality from glass cullet stockpiles, field stockpiles were set-up and monitored from July 24 or August 1 until September 4, 11, or 12, 2007, at the Burlington County Resource Recovery Complex (BCRRC) in New Jersey. The different start and end dates eased sample processing in the laboratory. Due to reproducible findings in the study by Tsai *et al.* (2009) using duplicate stockpiles, no duplicate stockpiles were set up in this study.

3.3.1. Sources of glass cullet

The sources of the cullet were three MRFs in New Jersey that were accepting commingled containers including clear and colored glass bottles, plastic beverage containers (soda, water, milk, juice), plastic detergent bottles, and aluminum, tin and bi-metal cans. The coarse cullet in this study (<9.5 mm, denoted C) is a mixture of cullet from two of the MRFs. The fine cullet (<4.75 mm, denoted F) is from the third facility.

3.3.2. Set-up, operation and monitoring of glass cullet experimental stockpiles

3.3.2.1. Set-up of stockpiles

Three experimental cullet stockpiles (initial mass: about 35 metric tons each, height: 2.2 m, base diameter: 6.3 m) were set up uncovered in the field. Two actively aerated stockpiles (one of coarse cullet set up on July 24, denoted A_C), and the other of fine cullet set up on August 1 (denoted A_F) were placed on 45 mil (1.1 mm) Firestone Pondguard liners (Webb's Water Gardens, Fallston, MD) to allow the collection of leachate (Figure 3-1a). The third stockpile (set up on July 24, denoted T_C) also consisted of coarse cullet but was not placed on a liner to allow weekly turning/mixing by a front end loader.

Both lined stockpiles had manifold air distribution systems consisting of perforated PVC pipe, arranged to form a 1.1 m square, and placed at 0.43-m height in the middle of the stockpiles (Figure 3-1b). The pipe was connected to a blower (Model R2, Gast, Benton Harbor, MI), which operated at a maximum aeration rate of 1.19 m^3 min^{-1}. The actual aeration rate of 0.65 m^3 min^{-1} was calculated based on the measured inlet air pressure of ~7 kPa. The purpose of the forced aeration was to maintain the temperature below 55°C and to ensure aerobic conditions in the stockpiles. An automatic timer was controlled manually based on pile temperatures, oxygen levels and precipitation amounts. As a result, the stockpile A_C was aerated for 30 seconds every 30 min. from day 3 to day 8; and 30 sec. every 90-120 min. on days 11, 14 and 17 (when temperatures above 55°C were measured) with no aeration thereafter. Stockpile of A_F was aerated for 1 min. every 2 hr from day 2 through the end of week 5, after which temperatures dropped below 55°C.

3.3.2.2. Monitoring of temperature and oxygen levels in stockpiles

Thermocouple probes (Type T, Omega Engineering, Inc., Stamford, CT) were installed in the two aerated stockpiles at the beginning of the experiment at 46, 91, and 137 cm (1.5, 3 and 4.5 ft) above ground. Temperatures were measured at these three heights every 61 cm (2 ft) into the pile up to the middle of the pile at two profiles (one facing to the south and the other facing to the west. In the turned stockpile, temperatures were measured by mobile thermocouple probes (Type K, Cole Parmer, Vernon Hills, IL), since re-installation of the above probes after mixing/turning was made difficult by compaction.

Oxygen levels were monitored (model K25, Jewell Elec. Insts., Inc., Bacharach Inc., Pittsburgh, PA) at the same times and locations as temperature, except that only two heights (46 and 137 cm above ground) were used.

3.3.2.3. Leachate quantities and sampling

Leachate quantities in the 500-gal (1900-L) tanks were continuously recorded by pressure transducers (model WL16 with accuracy of ± 0.015 - 0.038 m, Global Water, Gold River, CA). Precipitation was determined using an on-site tipping bucket rain gauge (0.25 mm per tip), containing a data logger (RainWise, Bar Harbor, ME). The readings were verified by three plastic wedge-shaped rain gauges (6.35 x 5.84-cm opening, Tru-Chek®, Edwards Manufacturing Co., Albert Lea, MN).

Leachate samples (2 L) were collected within 24 hours of every rainfall event (except for the day 6 sample from stockpile of A_C, collected within 72 hrs) after thorough mixing of the tank contents. Samples were immediately transported to the laboratory in coolers for analysis. The leachate tanks were emptied after sampling, but were not rinsed or sterilized between rain events.

3.3.3. Sampling of glass cullet

Cullet samples were collected from the lined, aerated piles at the beginning and end (6-7 weeks) of the experiment. From the unlined, turned pile, sampling of the cullet was conducted at 0 (beginning), 1, 3, and 6 weeks. Duplicate cullet samples were collected based on ASTM D 75-97 (ASTM, 2003a). Each 30-kg sample consisted of about 12 grab samples taken from the top third, middle third, and bottom third of the stockpiles after they were completely mixed for about 10 minutes by front end loader.

An additional coarse cullet sample (denoted C'), freshly unloaded from an unspecified MRF at BCRRC, was collected in April 2008 for BioLog analysis only. It was collected in the same way as the other samples (July and August, 2007) to verify the reproducibility of the BioLog analysis.

3.3.4. Analyses of glass cullet, washwater, and leachate

3.3.4.1. Glass cullet

Each 30-kg sample was further reduced or sub-sampled to obtain the sample mass needed for each analysis based on ASTM C702-98 (ASTM, 2003b). The moisture content was determined in triplicate at 110±3 ºC according to ASTM D2216-98 (ASTM, 2003c) and the organic contamination in triplicate by ignition at 540 ºC (CWC, 1997a).

Analysis (in duplicate) of the cullet particle size distribution was based on a modified version of ASTM D422-63 (ASTM, 2003d). Ten U.S standard sieve sizes were selected for the analyses: 50.8 mm (2 in), 19.1 mm (3/4 in), 9.5 mm (3/8 in), 4.75 mm (#4), 2.36 mm (#8), 2.00 mm (#10), 1 mm (#16), 0.30 mm (#50), 0.15 mm (#100), and 0.075 mm (#200). This selection includes all sieve sizes that are required to test the gradation of an I-10 soil aggregate (NJDOT, 2001).

3.3.4.2. Washwater and leachate

In order to have a relatively simple method to evaluate changes in cullet quality, a washing procedure was used. A cullet sample (~760 g wet weight) was mixed with deionized water (cullet: deionzed water = 1:3 by weight) and shaken for 30 minutes in duplicate on a reciprocal shaker (G10 Gyrotory®, New Brunswick Scientific, Edison, NJ) at a speed of 150 rpm (modified after Mulvaney, 1996). This method also provides an estimate of maximum leaching potential that might occur in the field. A second washing confirmed that the remaining contaminants in the cullet could be neglected. Most washwater analyses were determined according to Standard Methods for the Examination of Water and Wastewater (APHA, 1995): 2540 F (settleable solids), 2540 D (total suspended solids), 4500-N_{org} B (TKN), 4500-NH_3 D (NH_4^+-N), modified 4500-P E (total phosphorus) with improved technique for combined reagent 'A' (Chowdhury, 1991), 5210 B (BOD_5), 5540 C (anionic surfactants), 9222 B (total coliforms). For the COD analysis the washwater was filtered through a 0.45 µm filter (Whatman, Florham Park, NJ) to remove paper labels. COD was analyzed with a Hach kit (Hach Company, Loveland, CO), followed by spectrophotometer measurements (Spectronic® 20 Genesys™). All analyses other than the settleable solids analysis (single test) were performed in duplicate. The same parameters and analytical methods were used for the analysis of leachate.

After four of the total coliform tests on washwater were conducted (fresh cullet C and F samples, a 1-week old C sample, and a 2008 C' fresh cullet sample), 20-25 colonies for each sample were randomly picked from the membrane filters, streaked for purity, and differentiated by the BioLog® microbial identification system (GN2

MicroPlate™, Hayward, CA). The results were compared to the BioLog Gram-negative enteric category (GN-ENT) database 4.01C.

3.4. Results and Discussion

3.4.1. Characterization of fresh glass cullet

The moisture content and organic contamination level of both the coarse and fine glass cullet were similar (Table 3-1). The moisture contents of 2.3% and 3.5% were below the 15% level at which release of organics-contaminated liquid has been reported (CWC, 1997b). The organic contamination of about 1% (Table 3-1) was comparable to the 0.8% for mixed glass cullet from a quarry facility in Pennsylvania reported by Wartman *et al*. (2004). More than 98% of both samples passed through the 9.5-mm (3/8 in.) sieve and less than 1% was retained on the 0.075-mm (#200) sieve (Figure 3-2). Based on the Unified Soil Classification System (ASTM, 2000) glass cullet of A_F was classified as "SW", well-graded sand, and glass cullet of A_C as "GW", well-graded gravel.

The washwater analysis from the glass cullet provides an estimate of the maximum leaching potential that might occur in the field. The contaminant levels (Table 3-2) confirm the findings by Tsai *et al.* (2009). One exception is the total coliform levels of glass cullet F with $1.42*10^2$ cfu, which are 5 orders of magnitude lower than total coliform levels of the coarse cullet and the levels found by Tsai *et al.* (2009). It is unknown why the total coliform levels of cullet F were lower. Tsai *et al.* (2009) collected their samples immediately as the cullet left the last conveyor belt, while in this study, the cullet was sampled after arrival at the experimental site.

3.4.2. Temperature and oxygen levels in stockpiles

Elevated temperatures and decreased oxygen levels are indications of aerobic biological activity in the stockpiles. Measurement of oxygen also helps in evaluating if sufficient oxygen is available for rapid decomposition and avoidance of anaerobic conditions and associated odors.

In both the weekly turned and the aerated stockpiles (Figure 3-3), biodegradation of the organic contaminants (e.g., paper labels, food and beverage residuals) led to self-heating. The highest temperature in the weekly turned pile, 68°C, was measured on day 10 in the middle and upper half of stockpile (Figure 3-3a). The analysis of washwater for aged cullet from this stockpile showed a reduction of the organic contaminants over time (Table 3-2), providing the source of the microbially generated heat.

In the aerated stockpiles the highest temperature was measured for both piles one week after setup, with the highest temperature measured in the stockpile of A_F (71°C). Compared to stockpile of A_C, generally higher temperatures and lower oxygen levels were found in stockpile of A_F (Figures 3-3 and 3-4). However, the prolonged low oxygen levels found by Tsai *et al.* (2009) in the stockpile of fine cullet were not found. Most likely due to the forced aeration, oxygen levels reached near ambient levels throughout both aerated piles within 40 - 50 days after setup (Figure 3-4), which is about 30 - 50 days earlier than in the unaerated stockpiles of Tsai *et al.* (2009).

The lower temperature and higher oxygen concentrations measured in the stockpile of coarse cullet compared to fine cullet suggests an effect of particle size on temperature and oxygen levels. As a result (higher than optimum temperatures, reduced oxygen) the biodegradation of the organic contaminants was less in the stockpile of cullet F (see BOD_5 and COD, Table 3-2).

3.4.3. Leachate from cullet stockpiles

3.4.3.1. Leachate quantity

Leachate quantities were determined for the two lined, aerated stockpiles. Due to a series of heavy rainfall events (~3000 L) in the second half of August, with little opportunity for evaporation, both stockpiles were saturated quickly and released similar amounts of leachate (Figure 3-5). There was no obvious difference in water holding capacity of the two stockpiles after these events, which likely presented a worst case scenario in terms of leachate release/wastewater treatment. Because of the difference in rainfall pattern, the findings by Tsai *et al*. (2009), that the fine cullet pile retained more water, were not confirmed. The percentages of the accumulated leachate divided by the accumulated rainfall after the intensive rain were around 76% and 80% for stockpiles of A_C and A_F, respectively (data not shown). This can also be seen in the difference between accumulated rainfall and accumulated leachate, which equals the sum of evaporated water plus water retained in the stockpile (Figure 3-6). Thus the piles delayed release of water after rain events.

3.4.3.2. Leachate quality

As expected, leachate quality is affected by the amount of rainfall and the frequency of rain events. Due to dilution, generally the heavier or the more frequent the rain events, the lower the pollutant concentrations of the collected leachate (Tables 3-3 and 3-4). The leachate quality in many cases (except for settable solids and total suspended solids) was similar to the contaminant levels in the washwater (Table 3-2).

The pH of the leachate of both aerated stockpiles ranged between 8.0 and 9.7, generally increasing over time. This was slightly higher than the pHs measured by Tsai *et al.* (2009), which ranged from 7.3 to 8.8 over 4 months.

Settleable solids levels in leachate from both stockpiles were low, presumably because the glass cullet itself acted as a filter medium. Suspended solids levels, however, in a few cases exceeded typical values for urban stormwater, i.e. 630 mg L^{-1} (Novotny *et al*., 1981), and in all cases exceeded New Jersey surface water quality criteria, i.e., 25 mg L^{-1} (NJDEP, 2006).

The initial leachate BOD_5 levels, 255 and 285 mg L^{-1}, were comparable to those of untreated domestic sewage (Metcalf and Eddy Inc., 2003). While the BOD_5 levels decreased over time, this was not true for the COD levels (Tables 3-3 and 3-4). BOD_5/COD ratios for both stockpiles, ranging from 0.14 to 0.02, also decreased over time, indicating decreases in the more easily degradable components.

Similar to the COD levels, nutrient levels did not decrease during the study (Tables 3-3 and 3-4). The TKN and the total-P levels of the leachate from both stockpiles were similar to levels in typical untreated domestic sewage (Metcalf and Eddy Inc., 2003). Both stockpiles released comparable amounts of TKN and total-P over the 6-7 weeks (Tables 3-3 and 3-4, last three rows). This is similar to the steady release of nutrients observed from unaerated stockpiles (Tsai *et al*., 2009).

Anionic surfactant levels in the leachate of both stockpiles decreased over time, but were still above 2 mg L^{-1} at the end of the study (Tables 3-3 and 3-4), similar to anionic surfactant levels in typical untreated domestic sewage (Metcalf and Eddy Inc., 2003).

The total coliform levels in the leachate of the stockpile of A_C decreased from 10^6 to 10^2 cfu mL^{-1} by the end of the experiment (Tables 3-3 and 3-4). These levels are similar to those found in urban stormwater (10^3 to 10^8 cfu mL^{-1}) (Novotny *et al.*, 1981). For the stockpile of A_F, however, lower total coliform levels were found, corresponding to the low level detected in the initial washwater (Table 3-2).

3.4.4. The effects of forced aeration and turning on cullet stockpiles

Forced aeration increased the oxygen levels and decreased the temperatures inside the stockpiles compared to the non-aerated static stockpiles in the study by Tsai *et al.* (2009). However, there was concern that the forced aeration dried out the stockpiles as observed in a pilot study (data not shown). To assess potential moisture loss (ML), the moisture loss during a 17-day dry period was calculated for the stockpile of fine cullet:

$$ML = (OSH - ISH) * [(AR * TA) / \rho_{air}]$$

$$= (0.132 - 0.015) * [(0.65 * 202) / 1.204] = 12.76 \text{ kg}$$

where

ISH = Specific humidity of inlet air, kg/kg (26°C, 74% relative humidity)

OSH = Specific humidity of off-gases, kg/kg (60°C, 100% relative humidity)

AR = Aeration rate, m^3/min.

TA = Total aeration time over 17 days, min.

ρ_{air} = Density of air, kg/m^3 (20°C)

The ISH was calculated based on average humidity and temperature monitored at the on-site weather station in Mansfield, NJ. OSH was calculated based on the assumptions of saturation in the off-gases (Haug, 1993) and the same average temperature in the off-gases as measured for stockpile A_F. Pressure is assumed to be 1 atm.

With a stockpile mass of 35 tonnes and a moisture content of 3.46% (data not shown), the stockpile contained 1211 kg of water (35 * 0.0346 * 1000). Based on these assumptions, forced aeration removed only 1% of the water (12.76 / 1211 * 100) over 17 days. Excessive drying is also not an issue for the stockpile of coarse cullet (A_C) because the aeration rate was even lower. While aeration did not remove much water with the low aeration rates used here, water is removed from the stockpile through other mechanisms, such as evaporation and natural convection.

Overall, forced-aeration for cullet stockpiles can improve the temperatures and oxygen levels inside the stockpile without resulting in excessive drying. However, biodegradation of the organic contaminants in these stockpiles during a 1.5-month period was about 70% of the initial levels (e.g., BOD_5: 438-458 mg L^{-1}), compared to the 85% decrease in the mixed/turned stockpile (Table 3-1 and 2). This suggests the importance of mixing/turning when handling cullet stockpiles. As known from composting, mixing makes more organic residues accessible to the microorganisms, resulting in an increased rate and extent of biodegradation. Therefore, occasional mixing should be considered even when forced aeration is implemented.

3.4.5. Differentiation analysis for total coliforms

Using Biolog, 19 out of the 78 washwater total coliform colonies tested matched GN-ENT database profiles. The six genera represented were *Enterobacter, Escherichia, Klebsiella, Kluyvera, Salmonella, and Serratia* (Table 3-5). The differentiated *Enterobacter* spp., *Klebsiella* spp., *Kluyvera* spp., and *Serratia* spp., representing 15 of the 19 profiles, usually are detected in natural environments, i.e., freshwater, forest soils, or plants (Bagley *et al*., 1981; Duncan and Razzell, 1972; Grimont *et al*., 1979). Thus these isolates suggest that the glass stockpiles were an organic-rich environment, perhaps with nitrogen-fixing activity, but they do not indicate that there is a sanitary problem. Likewise many of the unidentified profiles probably do not represent sanitary concerns. On the other hand, the 3 *Escherichia coli* and 1 *Salmonella typhimurium* isolates do indicate potential contamination from fecal material, possibly rodents or birds. Further serotyping/toxin tests would be needed to confirm the *Salmonella* identification, and to determine whether any of the strains were pathogenic. Many studies have reported the common occurrence of coliforms persisting in natural environments or in systems such as pulp and paper mill wastewater with no sewage input (Baudart *et al*., 2000; Byappanahalli *et al*., 2005; Gauthier and Archibald, 2001), while Yam, *et al*. (2000) reported that *Salmonella* strains isolated from environmental sources tend to be non-pathogenic.

3.5. Conclusions

Continuing interest in using mixed glass cullet in large construction projects requires a better understanding of alternative ways of handling cullet stockpiles other than mixing/turning to reduce their potential to cause water pollution. This study showed that forced-aeration for cullet stockpiles can improve the temperatures and oxygen levels inside the stockpile without resulting in excessive drying; however, biodegradation of the organic contaminants in these stockpiles did not appear to be as effective as in the mixed/turned stockpile. This also suggests the importance of incorporating mixing/turning when forced aeration is implemented in treating cullet stockpiles.

Most of the identified total coliform isolates suggest that the glass stockpiles do not represent a sanitary problem. However, a few of the isolates do indicate potential contamination from fecal material, possibly rodents or birds; further serotyping/toxin tests would be needed to confirm the one *Salmonella* identification, and to determine whether any of the strains were pathogenic. Based on other studies of natural environments, it is likely that these isolates are non-pathogenic.

Overall, the characteristics of glass cullet and leachate quantity and quality in this study confirmed the findings of Tsai *et al.* (2009) suggesting that glass cullet can be stockpiled before use as construction aggregate. However, leachate of these stockpiles should not be released to surface water and only be infiltrated to groundwater if aged and Best Management Practices are implemented to reduce the nitrogen load.

Alternatively, washing of glass cullet, applied in this study to generate washwater, may provide a way of cleaning the cullet before stockpiling. Andela Pulverizer, Ltd (Richfield Springs, NY), as an example, washes recycled cullet to obtain clean cullet for higher value markets such as the filter material for aquariums, or gardening materials for landscaping mulch. Whether the washwater can be reused for cleaning and if this approach is economical requires further assessment.

Acknowledgements

The writers would like to thank the Burlington County Board of Chosen Freeholders for providing the site; Robert Simkins, Coordinator, Burlington County Division of Solid Waste Management, and Joe Hilla for constructing and maintaining the stockpiles; Daniel Macready for collecting samples; and the Monmouth County Planning Board, Solid Waste/Recycling Division, Waste Management/Recycle America and our Corporate partners for technical and financial support.

3.6 References

American Society for Testing and Materials (ASTM) (2000). Standard Classification of Soil for Engineering Purposes. ASTM D2487-00, West Conshohocken, PA, USA.

American Society of Testing and Materials (ASTM) (2003a). Standard Practice for Sampling Aggregates. ASTM D75-97, West Conshohocken, PA, USA.

American Society of Testing and Materials (ASTM) (2003b). Standard Practice for Reducing Samples of Aggregate to Testing Size. ASTM C702-98, West Conshohocken, PA, USA.

American Society for Testing and Materials (ASTM) (2003c). Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM D2216-98, West Conshohocken, PA, USA.

American Society for Testing and Materials (ASTM) (2003d). Standard Test Method for Particle-Size of Soils. ASTM D422-63, West Conshohocken, PA, USA.

American Public Health Association (APHA) (1995). *Standard Methods for the Examination of Water and Wastewater*. 19th ed., American Public Health Association, Washington, D.C.

Baudart, J., Lemarchand, K., Brisabois, A., and Lebaron, P. (2000). Diversity of *Salmonella* strains isolated from the aquatic environment as determined by serotyping and amplification of the ribosomal DNA spacer regions. Applied and Environmental Microbiology (66), p. 1544-1552.

Bagley, S.T., Seidler, R.J. and Brenner, D.J. (1981). Klebsiella planticola sp. Nov.: a new species of Enterobacteriaceae found primarily in nonclinical environments. Current Microbiology (6), p. 105-109.

Chowdhury, M. (1991). An Improved Technique for the Preparation of a Combined Reagent for Phosphorus Determination. Water Pollution Control Federation, 64th Annual Conference & Exposition, #AC91-066-004. October 1991, Toronto, Canada.

Clean Washington Center (1997a). Methods for Sampling and Testing Recycled Glass. Seattle, WA, USA. <http://www.cwc.org/glass/gl979rpt.pdf#search='methods%20for%20sampling%20 and%20testing%20recycled%20glass'> (Accessed 22 January 2008)

Clean Washington Center (1997b). Moisture Considerations in Glass Cullet Processing and Distribution. Seattle, WA, USA. <http://www.cwc.org/gl_bp/gbp2-0501.htm> (Accessed 22 May 2008)

Byappanahalli, M.N., Whitman, R.L., Shively, D.A., Sadowsky, M.J. and Ishii, S. (2006). Population structure, persistence, and seasonality of autochthonous *Escherichia coli* in temperate, coastal forest soil from a Great Lakes watershed. Environmental Microbiology (8), p. 504-513.

Duncan, D.W. and Razzell, W.E. (1972). Klebsiella biotypes among coliforms isolated from forest environments and farm produce. Applied Microbiology (24), p. 933-938.

Gauthier, F., and Archibald, F. (2001). The ecology of "fecal indicator" bacteria commonly found in pulp mill water systems. Water Research (35), p. 2207–2218.

Grimont, P.A.D., Grimont, F. and Starr, M.P. (1979). *Serratia ficaria* sp. nov., a bacterial species associated with Smyrna figs and the fig wasp *Blastophaga psenes*. Current Microbiology (2), p. 277-282.

Haug, R.T. (1993). *The Practical Handbook of Compost Engineering*. CRC/Lewis Publishers, Boca Raton, FL, p. 267-270.

Metcalf and Eddy Inc. (2003). *Wastewater Engineering Treatment and Reuse*. 4th ed., Tata McGraw-Hill Publishing Company Limited, New Delhi, p. 109.

Mulvaney, R.L. (1996) Extraction of exchangeable ammonium and nitrate and nitrite. Part 3, chemical methods. In: D.L. Sparks, Editor, *Methods of Soil Analysis.* SSSA Book Series No. 5, SSSA, Madison, WI, p. 1123-1131.

New Jersey Department of Environmental Protection (2006). Surface Water Quality Standards. N.J.A.C. 7:9B. Trenton, NJ. <http://www.epa.gov/waterscience/standards/wqslibrary/nj/nj_2_swqs.pdf> (Accessed 22 May 2008)

New Jersey Department of Transportation (2001). Standard Specifications for Road and Bridge Construction. Trenton, NJ. <http://www.state.nj.us/transportation/eng/specs/english/EnglishStandardSpecifications.htm> (Accessed 22 May 2008)

Novotny, W. and Chesters, G. (1981). *Handbook of Nonpoint Pollution*. Van Nostrand Reinhold, New York, USA.

Reindl, J. (2003). Reuse/Recycling of Glass Cullet for Non-Container Uses. Dane County Department of Public Works, Madison, WI, USA. <http://www.glassonline.com/infoserv/Glass_recycle_reuse/Glass_reuse_recycling_doc1.pdf > (Accessed 22 May 2008)

Tsai, C.L., Krogmann, U, Strom, P.F. (2009). Handling leachate from glass cullet stockpiles. Waste Management (29), p. 1296-1305.

Wartman, J.; Grubb, D.G., and Nasim, A.S.M. (2004). Select engineering characteristics of crushed glass. Journal of Materials in Civil Engineering (16), p. 526-539.

Yam, W.C., Chan, C.Y., Bella, S.W.H., Tam, T.-Y., Kueh, C. and Lee, T. (2000). Abundance of clinical enteric bacterial pathogens in coastal waters and shellfish. Water Research (34), p. 51-56.

Table 3-1. Characterization of fresh and aged glass cullet (% by weight)

	Initial		Turned stockpiles			Aerated stockpiles	
Source materials	A_C/T_C	A_F		T_C		A_C	A_F
Weeks after set-up	0	0	1	3	6	7	6
Moisture content	2.3	3.5	2.5	2.3	2.9	4.7*	4.0*
Organic contamination	1.01	0.98	0.77	0.64	0.51	0.62	0.69

* Sample collected during heavy rainfall. C: from stockpile of coarse cullet, F: from stockpile of fine cullet.

Table 3-2. Washwater for fresh and aged glass cullet (glass to water ratio = 1:3)

	Initial		Turned stockpiles			Aerated stockpiles	
Source materials	A_C/T_C	A_F	T_C			A_C	A_F
Weeks after set-up	0	0	1	3	6	7	6
pH	8.6	9.0	9.3	9.5	9.3	9.2	9.6
Settleable solids ($mL\ L^{-1}$)	96	80	53	25	15	25	31
Total Suspended Solids ($mg\ L^{-1}$)	5039	10950	4264	4493	3585	3309	6481
BOD_5, unfiltered ($mg\ L^{-1}$)	458	438	135	84	21	47	134
COD, filtered ($mg\ L^{-1}$)	189	193	122	75	53	70	147
Total-P ($mg\ L^{-1}$)	6.3	8.2	5.5	6.0	6.6	6.1	9.0
TKN ($mg\ L^{-1}$)	19.0	31.8	17.4	16.5	14.4	10.6	26.3
Ammonia-N ($mg\ L^{-1}$)	1.5	0.8	1.6	0.3	0.2	0.2	1.3
Anionic surfactant ($mg\ L^{-1}$)	12.7	4.1	2.0	0.1	< 0.04	0.2	0.3
Total coliforms ($cfu\ mL^{-1}$)	$4.6*10^7$	$1.42*10^2$	$5.3*10^4$	$2.6*10^3$	$1.4*10^3$	$1.9*10^3$	$<10^2$

Table 3-3. Leachate from lined, aerated stockpile of coarse glass cullet (A_C)*

Sampling Date	**7/30**	**8/18**	**8/20**	**8/21**	**8/22**	**8/27**	**9/11**
Volume (L)	114	257	825	647	613	140	178
pH	8.0	9.0	8.6	8.9	9.0	9.3	9.6
Settleable solids (mL L^{-1})	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Total suspended solids (mg L^{-1})	155	260	275	420	505	965	890
BOD_5, un-filtered (mg L^{-1})	255	88	104	126	143	69	54
COD, un-filtered (mg L^{-1})	1800	1468	1518	1638	2322	3452	1966
Total-P (mg L^{-1})	8.1	7.9	7.2	10.5	11.3	21.7	6.1
TKN (mg L^{-1})	36.6	22.0	22.2	30.5	53.8	86.9	28.5
Ammonia-N (mg L^{-1})	10.9	6.4	3.8	5.2	6.7	20.3	3.1
Anionic surfactants (mg L^{-1})	9.8	ND	2.0	2.3	ND	ND	2.5
Total coliforms (cfu mL^{-1})	$2.7*10^6$	$1.7*10^5$	$8.7*10^4$	$1.9*10^4$	$8.3*10^3$	$1.7*10^2$	$2*10^2$
Accumulated total-P (g)	1.0	3.0	8.9	15.7	22.3	25.3	26.3
Accumulated TKN (g)	4.2	9.8	28.1	47.9	80.8	93.0	98.0
Accumulated ammonia- N (g)	1.2	2.9	6.0	9.4	13.5	16.3	16.9

ND: Not determined.
* Stockpile constructed on Jul-24, 2007.

Table 3-4. Leachate from lined, aerated stockpile of fine glass cullet (A_F)*

Sampling Date	**8/18**	**8/20**	**8/21**	**8/22**	**8/27**	**9/11**	**9/12**
Volume (L)	254	890	564	606	68	95	189
pH	9.3	8.7	8.3	8.4	9.3	9.7	9.3
Settleable solids (mL L^{-1})	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Total suspended solids (mg L^{-1})	865	585	260	90	390	1330	1185
BOD_5, un-filtered (mg L^{-1})	285	205	83	112	33	89	82
COD, un-filtered (mg L^{-1})	3475	1620	683	1325	978	3111	2520
Total-P (mg L^{-1})	16.4	8.5	3.8	4.5	4.8	26.2	14.5
TKN (mg L^{-1})	58.3	30.0	15.6	26.8	18.7	84.1	76.1
Ammonia-N (mg L^{-1})	34.5	17.2	3.4	6.1	12.9	4.0	23.6
Anionic surfactants (mg L^{-1})	ND	3.6	0.95	ND	ND	2.4	2.7
Total coliforms (cfu mL^{-1})	$4.7*10^3$	$5*10^2$	$< 10^1$	$7*10^2$	$8.2*10^2$	$2.2*10^3$	$1.5*10^2$
Accumulated total-P (g)	4.2	11.7	13.9	16.6	17.0	19.4	22.2
Accumulated TKN (g)	14.8	41.4	50.2	66.4	67.7	75.7	90.1
Accumulated ammonia- N (g)	8.8	24.1	26.0	29.7	30.6	31.0	35.4

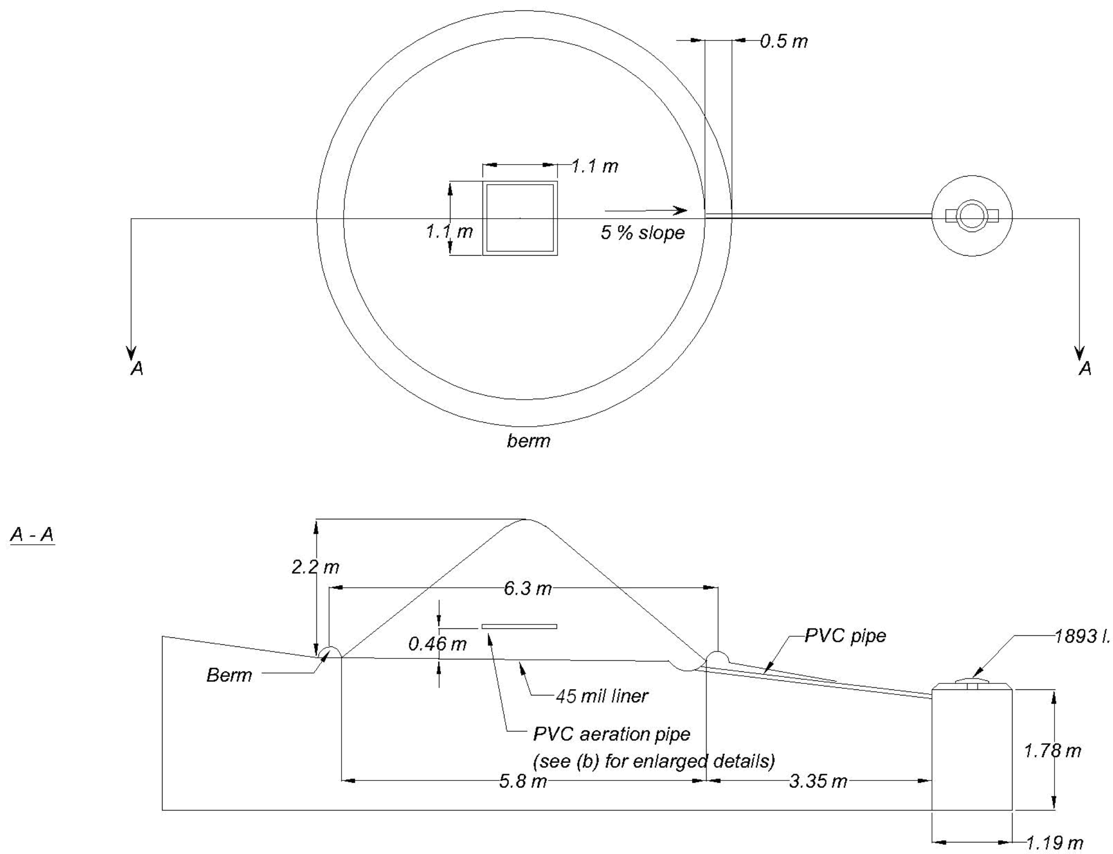
ND: Not determined.
* Stockpile constructed on Aug-1, 2007.

Table 3-5. Differentiation of total coliforms (using Biolog) from glass cullet washwater*

Species	Fresh cullet			Aged, 1-wk
	A_C	A_F	C'	A_C
Enterobacter cloacae	1	2	1	1
Enterobacter intermedius			1	
Escherichia coli			2	1
Klebsiella planticola		1		
Klebsiella terrigena	2			
Kluyvera ascorbata			2	
Kluyvera cryocrescens			2	
Salmonella GP 1 st typhimurium	1			
Serratia ficaria		1		1

C': coarse cullet from unknown source.
* Numbers of strains among 78 isolates tested; the remaining isolates were unidentified.

a)



b)

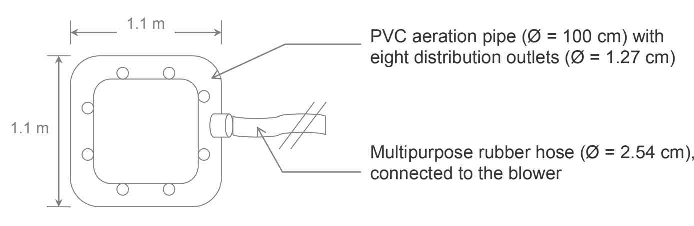


Figure 3-1. a) Schematic of lined, aerated glass cullet stockpile. b) Details of manifold distribution system, consisting of a perforated PVC pipe square (1.1 x 1.1 m) that was connected to the blower.

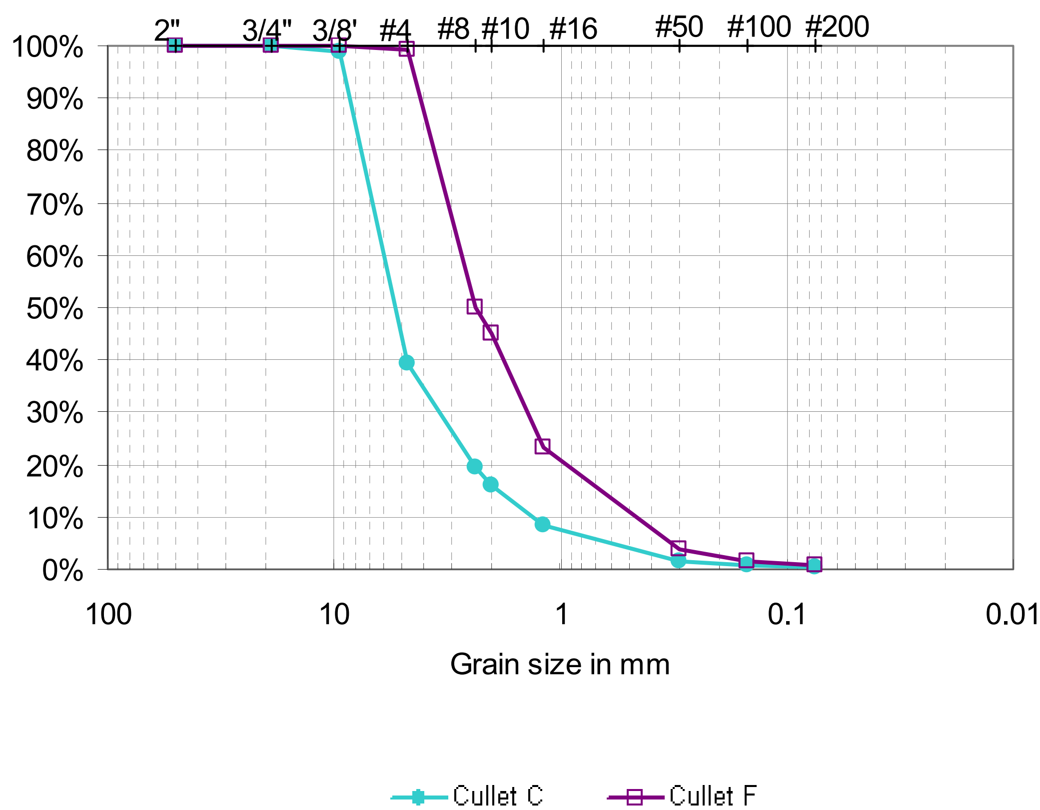


Figure 3-2. Particle size distribution of A_C and A_F glass cullet.

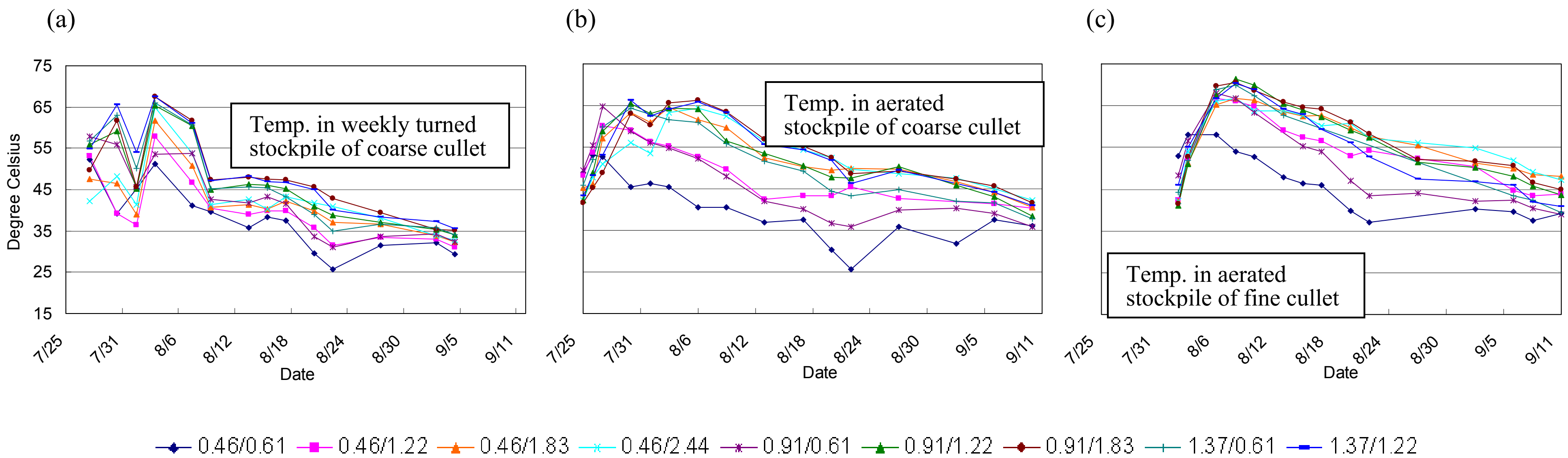


Figure 3-3. Temperatures in three field stockpiles: a) Weekly turned stockpile of coarse cullet (set up on Jul 24), b) Aerated stockpile of coarse cullet (set up on Jul 24), c) Aerated stockpile of fine cullet (set up on Aug 1). For the turned pile (a), all measurements were made at least 24 h after mixing/turning except for the third set, which were measured within 19 hours of turning . Note: In the legend, the first number represents the height above ground and the second number the distance into the pile of the measurement point (in meters).

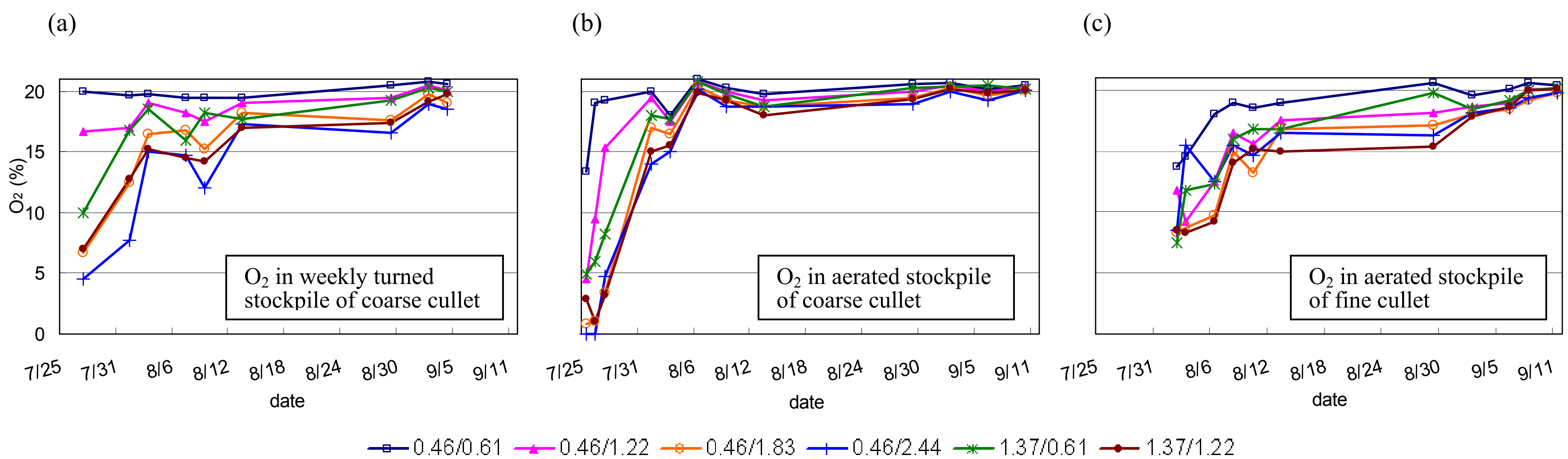


Figure 3-4. Oxygen levels in three field stockpiles: a) Weekly turned stockpile of coarse cullet, b) Aerated stockpile of coarse cullet, c) Aerated stockpile of fine cullet. For the turned pile (a), all measurements were made at least 24 h after mixing/turning except for the third set, which were measured within 19 hours of turning. Note: In the legend, the first number represents the height above ground and the second number the distance into the pile of the measurement point (in meters).

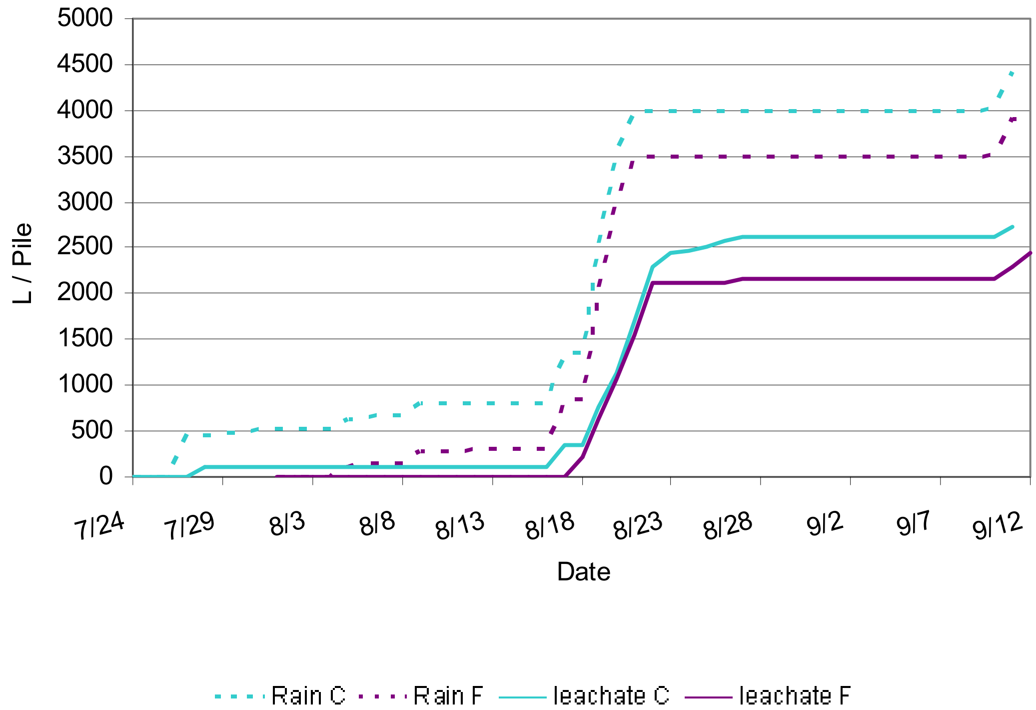


Figure 3-5. Cumulative rainfall on stockpiles and cumulative leachate from aerated, lined stockpiles of A_C and A_F glass cullet. Note: stockpile A_F was set up a week later than stockpile A_C.

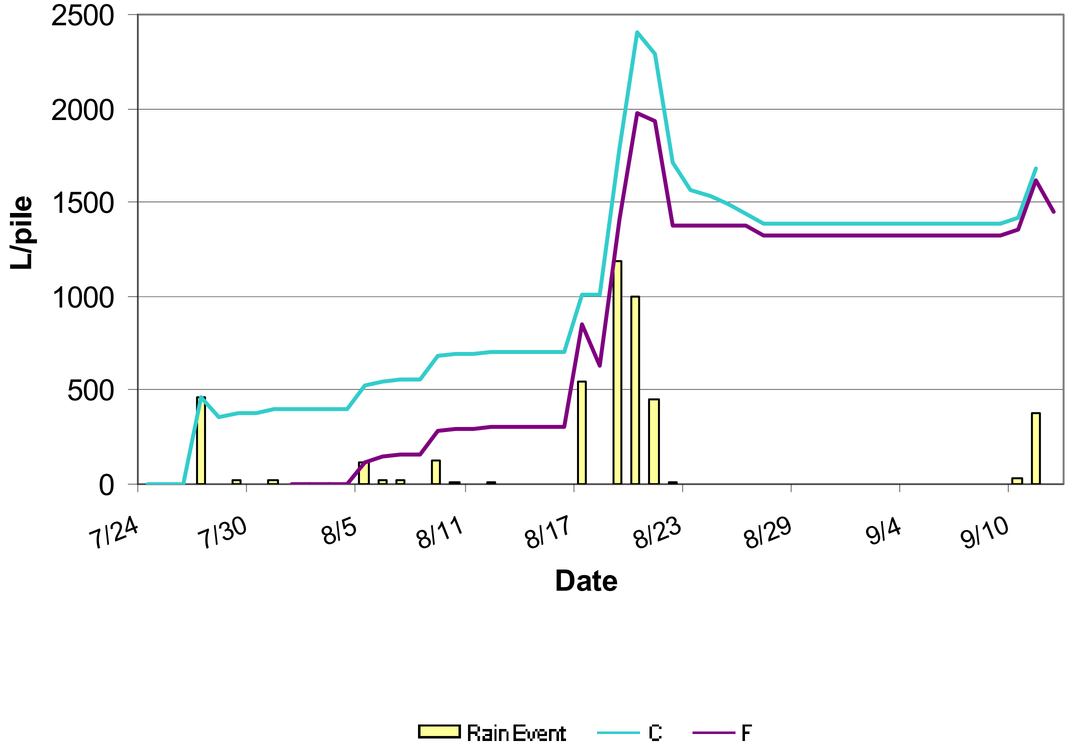


Figure 3-6. Average daily rainfall obtained from an on-site rain gauge and difference between cumulative rainfall and cumulative leachate (= evaporation + water retained in the stockpiles) of aerated, lined stockpiles of A_C and A_F glass cullet. Note: stockpile A_F was set up a week later and received 515 L less rainfall than stockpile A_C.

Chapter 4. Material Flows and Energy Analysis of Glass Containers Discarded in New Jersey, US

4.1 Abstract

Alternative uses of glass cullet (crushed recycled glass containers) that is difficult to use as feedstock in new glass container production have grown rapidly. The cullet is mainly used as aggregate in construction projects and in landfills as daily cover, drainage layer, or road pavement. Since the use of cullet as feedstock in new glass container production is energetically more sound, it is important to assess the current life-cycle energy consumption of glass container recycling in New Jersey. The first objective of this study was to model and quantify glass container flows in New Jersey and the associated life-cycle energy consumption, from the extraction of raw materials, to collection and processing of recycled glass containers to final use and disposal. The second objective of the study was to compare life-cycle energy consumption for two different recycling scenarios (i.e., current recycling practice, and single-stream recycling), and three different end use/disposal scenarios (i.e., increased container feedstock use, 100% aggregate use, and no recycling with 100% disposal). The results of material flows at the state level showed that about five times more (255,600 tons) recycled glass containers were used as aggregate compared to use as feedstock for glass container or fiberglass production. However, a lower system energy requirement can be achieved by increased use of cullet as container feedstock compared to construction aggregate, even when the cullet is transported 1,600 miles to an out-of-state glass container manufacturer.

Based on the uncertainty analysis, there is about an 80% probability for the scenario with increased use as container feedstock to have a lower system energy requirement when compared to all other scenarios. To achieve higher use of recycled glass containers in container glass manufacturing, the quality of the recycled glass must be improved.

4.2 Introduction

In 2008, 10.2 million tons of municipal solid waste (MSW) were generated in New Jersey (NJDEP, 2010a), the most densely populated state in the US. Of this, 3.9 million tons, including 317,000 tons of glass containers, were recycled (NJDEP, 2010a). The importance of improving recycling and minimizing MSW disposal has long been recognized. An effective recycling system includes not only efficient collection and processing of recyclables, but also economical and environmentally sound end uses of the recyclables.

Glass container recycling in New Jersey is dominated by commingled dual-stream curbside collection. In dual-stream recycling, used glass containers are collected at the point of generation, commingled with other containers such as high-density polyethylene (HDPE) and polyethylene terephtalate (PET) containers and aluminum, tin and bi-metal cans, but separately from the paper fraction. Recently, dual-stream recycling is being replaced by single-stream recycling, where the container stream is collected commingled with the paper fraction. This trend, however, has resulted in higher breakage rates and elevated contamination of the glass containers (CRI, 2009; Eureka Recycling, 2002; Jamelske and Wessling, 2005; Morawski, 2009; Smith-Teutsch, 2010). Broken glass containers are difficult to cost-effectively separate by color, which is necessary if the cullet is used in new glass container production, while the higher contamination complicates the separation to meet cullet specifications for glass container production. The specifications for glass container production require < 0.4% by mass of paper and plastic materials (e.g., labels and plastic caps) in the cullet, < 5 particles of metal and < 1 particle of all other contaminants (e.g., ceramic, rock, or pyrex® glass) per truck load of cullet (CWC, 1997).

As a result, use of cullet for alternative applications that do not require high quality or color-separation has grown rapidly. Cullet that does not meet the specifications for glass container production is mostly used as aggregate substitute in landfills (i.e, daily cover, drainage layer, or road pavement), the construction industry, or in wastewater treatment systems (i.e., sand filters) (Reindl, 2003).

Studies assessing the life cycle environmental impacts of the glass container recycling system with increased use as aggregate are currently lacking. Two case studies conducted in Manchester, UK and Ontario, Canada have found that the life-cycle energy savings for cullet used as aggregate were one order (Morris, 1996) or two orders (Butler and Hooper, 2005) of magnitude lower than that for cullet used in new container production. However, the Canadian study covers several materials and does not provide many details, while the UK study is more a feasibility study. In the UK study, Butler and Hooper (2005) indicated that even long-haul of cullet for use in glass container manufacturing in France can provide more energy savings than its use as aggregate substitute within the UK. However, the distances and conditions in the US might be different than in Europe.

Based on these studies and the increasing trend of no-color separation and single-stream recycling, it is important to assess the life-cycle energy consumption of glass container recycling in New Jersey. The first objective of this study was to understand, quantify, and model glass container flows in New Jersey and the associated life-cycle energy consumption, from the extraction of raw materials, to collection and processing of recycled glass containers, to final use and disposal. The second objective of the study was to compare energy consumption for two different recycling scenarios (i.e., current recycling practice, and single-stream recycling), and three different end use/disposal scenarios (i.e., increased use for higher beneficial uses such as glass container manufacturing, 100% aggregate use, and no recycling with 100% disposal). Based on the findings, implications for glass container recycling will be discussed. This study is a first step in assessing glass container recycling. A more complete assessment of other environmental impacts as well as economical and social impacts needs to be conducted.

4.3 Materials and methods

A material flow analysis (MFA) and an accompanying energy analysis were conducted to track the life-cycle of glass packaging containers discarded in New Jersey and the associated life-cycle energy use. Glass containers are used for packaging of food and beverages (i.e., jars and bottles). MFA is a method for investigating complex material flows to better manage resources, environmental impacts and wastes (Ayres and Simonis, 1994; Baccini and Brunner, 1991; OECD, 2001). In the case of glass containers, MFA tracks and quantifies glass packaging container flows throughout the entire life-cycle following the rule of a simple mass balance where input minus change in stock equals output. A flow that enters the system is an input, and a flow that leaves the system is considered an output while stock refers to storage of glass containers or cullet. A MFA includes: 1) System definition in space and time, 2) Identification of relevant flows, stocks, and processes, and 3) Determination of mass flows and stocks (Brunner and Rechberger, 2004). Processes include transformations such as melting and chemical reaction of raw materials to produce glass, transportation of raw materials or cullet, and storage of glass containers or cullet.

Energy analysis has been used to assess energy consumption patterns and impacts on energy resources (Boustead and Hancock, 1979; Michaelis and Jackson, 2000; Sundin *et al*., 2002). An energy analysis calculates system energy requirement over the entire life-cycle of a product (Boustead and Hancock, 1979) which in this case are the glass containers. System energy requirements in this study include 1) primary fuel consumption (i.e., combustion energy, including nuclear use) and energy consumption for producing the primary fuels (i.e., pre-combustion energy, including pre-use energy for nuclear fuel), plus 2) energy credits (energy savings due to use of cullet instead of virgin raw materials). Primary fuels, such as coal, natural gas, diesel, and uranium, are the fuels used to produce electricity and/or to generate power directly (e.g., for transportation or heating). Pre-combustion energy includes energy consumption for extraction, refining and processing, and final delivery of the primary fuel to the customer, while combustion energy is the energy released by the combustion of the primary fuels (Franklin Associates, 2004). To ease the comparisons of energy consumption between processes in the model, specific energy consumption is reported (i.e., energy consumption per ton of used and discarded glass containers).

4.3.1 Glass container recycling in New Jersey

Glass container recycling in New Jersey is dominated by commingled dual-stream curbside collection (88%) with some municipalities also maintaining drop-off centers, where residents can bring their glass containers (2.5%). Recently, some municipalities have implemented commingled single-stream curbside collection (9.5%, Hourihan, 2009) in which glass containers are collected together with the paper stream. In addition, some bars and restaurants collect glass containers separated by color.

Glass containers from curbside collection are processed in 32 MRFs in New Jersey. Glass containers collected at drop-off centers require in most cases further processing in MRFs before marketing. Typical process equipment for handling glass containers in MRFs includes: screen, conveyor belt, glass crusher, and air classifier. Generally, broken glass containers are removed by a screen as a first processing step in the MRF. After removal of tin cans by a magnet and the light fraction (HDPE and PET containers, aluminum cans) by air classifiers, whole bottles can be manually separated by color (positive sorting) or left on the conveyor belt (negative sorting) for further processing. Further processing might include glass crushers, trommel screens and air classifiers to remove the light fraction (e.g., labels). Compared to positive sorting, negative sorting is less labor intensive and decreases the overall costs, but currently results in cullet with higher contamination levels. Processing glass containers from a single-stream recycling system usually requires more processing steps and therefore more energy compared to processing recyclables from dual-stream recycling (Joseph Vinyard, Hatch Mott McDonald, 2009, personal communication). Reasons are the increased breakage rate and contaminant levels (CRI, 2009; Eureka Recycling, 2002; Jamelske and Kipperberg, 2006; Jamelske and Wessling, 2005; Kinsella and Gleason, 2003). Overall, there is an increasing trend of adopting single-stream recycling and negative sorting in New Jersey. Cullet from MRFs intended for higher beneficial uses is sent to intermediate cullet processing facilities for further processing to optically separate cullet by color and to remove additional contaminants. Cullet coming from single-stream recycling contains more cullet fines and increased levels of paper contaminants (Jim Yezzo, Strategic Material, 2009, personal communication) and, therefore, requires further processing. Glass containers from bars and restaurants need only limited processing in intermediate processing facilities. Due to the high quality of the cullet from bars and restaurants it is easily accepted by glass container manufacturers (Morawski, 2009).

4.3.2 System boundary and scenarios

4.3.2.1 System boundary in space and time

All up-stream and down-stream flows and processes associated with glass packaging containers consumed and discarded within the geographical boundary of New Jersey in 2008 are within the system boundary in this study. The year 2008 was chosen because the data from this year were the most recent available data. It is considered a representative year based on the fact that the recycling rate for glass containers (57%) out of the MSW recycling rate (38%) in 2008 falls in the range of the recycling rates of glass containers (49-63%) out of the MSW recycling rates (33%-40%) for the past 10 years

(NJDEP, 2010a). Based on a review of previous studies (Ruth and Dell'Anno, 1997; Dacombe *et al.*, 2005; Gaines and Mintz, 1994; Morris, 1996) the following processes were included in the system boundary: glass container raw material extraction, glass container production, glass container wholesale and retail distribution, collection of recycled glass containers, processing, end-use, and glass container disposal. Energy consumption for lighting and heating or cooling during processing and production was included within the boundary, while indirect energy consumption, such as energy to manufacture the machines and build the facilities, or to rinse glass containers by residents before recycling was excluded. In addition, this study does not account for containers that were produced inside New Jersey but exported out of New Jersey for use. Furthermore, new glass containers, cullet, and discarded glass containers that are only in transit through New Jersey were not included. The use of glass containers by residents and businesses was estimated to have a negligible effect on the system energy requirement and therefore was not taken into account. Energy consumption for bottling was allocated to the food/beverage processing industry (Koroneos *et al.*, 2005) and energy consumed for landfill operation to the waste industry. Therefore, both of these processes were excluded.

4.3.2.2 Scenarios

Five different scenarios were considered (Table 4-1): 1) Current glass container recycling practice (with predominant dual-stream collection). 2) Current glass container recycling practice with a three-fold increase in use of cullet for higher beneficial uses such as glass container manufacturing or fiberglass production. 3) Dual-stream collection replaced by single-stream collection. 4) Current glass container recycling but use as aggregate as sole end use. 5) No curbside glass container recycling. All scenarios include the same processes until the glass containers reach the consumer.

For Scenario 2, it was assumed that 70% of the recycled glass containers exiting the MRFs were sent to intermediate cullet processing facilities, in order to model a three-fold increase of cullet used for higher beneficial uses. It was also assumed that, for Scenario 2, the distribution of end uses of the cullet leaving the intermediate cullet processing facilities were the same as in Scenario 1. Contrary to previous studies (Eureka Recycling, 2002; Jamelske and Wessling, 2005), the quantity of curbside collected recycled glass containers in Scenario 3 remained unchanged after implementing single-stream recycling. This assumption is based on the fact that most of the municipalities in New Jersey implementing single-stream recycling do not inform their residents of the change and therefore residents continue to recycle as if it was a dual-stream system. (Melinda Williams, Somerset County Improvement Authority, 2010 and Enrique Angelini, Waste Management, 2009, personal communication). To handle the higher contaminant levels in the cullet in Scenario 3, it is assumed that the specific energy consumption for processing cullet at the intermediate cullet processing facilities increases by one third compared to the energy consumption in Scenario 1. A 33% decrease in recovery efficiency at the intermediate processing facility for Scenario 3 (Barker Lemar, 2010; Jim Yezzo, Strategic Materials, 2009, personal communication) and storage of 5% of incoming cullet at the intermediate cullet processing facilities for Scenarios 1, 2, and 3 were also assumed (Jim Yezzo, Strategic Materials, 2009, personal communication).

4.3.3 Modeling approach and data acquisition

4.3.3.1 Glass container flows

Glass container flows and processes associated with glass container recycling in New Jersey in 2008 were identified and quantified (Figure 4-1). The data are based on the best available information including industry and government reports, and if not available, personal communication with in-state glass container manufacturers, recycling coordinators, intermediate cullet processing facilities, and the Bureau of Recycling and Planning at New Jersey Department of Environmental Protection (NJDEP). All tonnages refer to short tons unless otherwise noted.

4.3.3.1.1 Downstream of use by consumers

The quantity of glass containers used and discarded by consumers was estimated based on the sum of the disposed of and the recycled glass container quantities in New Jersey. The quantity of disposed of glass containers was calculated based on the MSW quantity disposed of in New Jersey (NJDEP, 2010b) and the assumption that 2.5% of the disposed MSW is glass container packaging. The 2.5% level was an average based on data reported from two MSW characterization studies conducted in New Jersey as 2.2% (CDM, 2005) and 2.8% (CDM, 2008). The quantity of recycled glass containers was determined based on recycling reports submitted by the municipalities to NJDEP. The quantities of glass containers exported out of New Jersey, landfilled, and sent to waste-to-energy facilities were also based on NJDEP data (NJDEP, 2008b).

The fate of the cullet after being processed in MRFs was determined based on a survey that was sent to all 32 MRFs in New Jersey (Appendix C1). This flow included cullet from drop-off centers, because in many cases, the drop-off centers delivered their recycled glass containers also to the MRFs. The survey asked questions about the quantity of cullet sent to each end use. The results were validated by contacting the facilities that received the cullet.

Quantity of cullet delivered to and exiting intermediate cullet processing facilities and its fate was determined based on inventory reports of these facilities. The quantity of recycled glass containers collected in bars and restaurants was estimated as the difference between the quantity of cullet from New Jersey sources and the quantity of cullet from New Jersey MRFs and intermediate cullet processing facilities entering the in-state glass container manufacturers.

4.3.3.1.2 Upstream of use by consumers

As of 2008, only two food and beverage glass container manufacturers were located in New Jersey, both producing flint glass containers only. All colored glass containers and part of the flint glass containers that were used in New Jersey were imported from other states or foreign countries. Glass containers produced in New Jersey and discarded by New Jersey consumers and the associated raw material imports for the production were determined based on best available data from the literature and personal communication with experts in the glass container and mining industries. To make 1 ton of new glass containers, 1.17 tons of raw materials are required consisting of 0.65 tons of industrial sand, 0.17 tons of limestone, 0.22 tons of soda ash, and 0.13 tons of feldspar/aplite. The additional 0.17 tons of raw materials are needed per ton of glass containers because carbon dioxide is released during glass production (Gains and Mintz, 1994; Davis, 1992). The quantities of imported glass containers and of glass containers produced and used in New Jersey were determined based on information from the two in-state glass container manufacturers. It was estimated that, of the imported glass containers, 90% were imported from other states and about 10% from foreign countries with beer bottles presenting about 7% of the foreign imports (US DOE, 2002a; Goldammer, 2008; David Kesmodel, The Wall Street Journal, 2009, personal communication).

4.3.3.2 Energy analysis

Energy consumption for each process was determined based on data collected from the mining industry, the glass container manufacturing industry, MRFs, and cullet processing facilities as well as from the literature if actual data were not available. For electricity consumption in New Jersey, the New Jersey electricity grid was used: coal, 31%, nuclear, 48%, natural gas, 20%, oil, 1% (EIA 2005). The New Jersey electricity grid takes into account that 31% of New Jersey's electrical energy is produced in Pennsylvania and 69% in New Jersey. For electricity consumption in other states of the US, the average US electricity grid was used: coal, 49%, nuclear, 19%, natural gas, 22%, hydro and others, 10% (Franklin Associates, 2004). Pre-combustion energy (the energy required to produce the primary fuels) is included in calculating all primary fuel consumption that was used for producing electricity and for direct power generation (i.e., combustion of diesel, coal, and natural gas in this study). The mining industry consumed a fuel combination of coal, natural gas, and electricity, while the container industry used mainly natural gas for manufacturing (Gaines and Mintz, 1994). All transportation fuel was assumed to be in the form of diesel (Gaines and Mintz, 1994). Truck types, average masses per load and road and train transportation distances are listed in Appendix C2. An empty back haul was assumed for all transportation processes, which is a conservative assumption.

4.3.3.2.1 Downstream of use by consumers

The integrated solid waste management - decision supporting tool (ISWM-DST) (Harrison *et al.*, 2001; Solano *et al.*, 2002ab) was used to calculate fuel consumption during collection of recycled and to be disposed of glass containers. Input parameters into the ISWM-DST are disposed of and recycled glass container quantities in urban, semi-urban and rural counties separated between single family, multi-family, and commercial locations (Appendix C3).

The discarded (disposed of plus recycled) glass container quantities in urban, semi-urban and rural counties were determined as follows. Based on the percentage of the rural population in each county (US Census, 2003), all 21 counties in New Jersey were assigned to three categories: urban (<3%), semi-urban (3-40%), or rural (>40%). Due to fewer collection stops in commercial areas than in residential areas, collection in commercial areas requires less energy (Harrison *et al.*, 2001; Solano *et al.*, 2002ab). The ratio of the quantity of MSW from residential and commercial locations was based on literature values (US EPA, 1994; CA EPA, 1999; Hickman, 1999) for urban, semi-urban, and rural categories as: 40%:60% (urban), 58%:42% (semi-urban), and 88%:12% (rural). The quantity of MSW from residential locations was further separated into single-family and multi-family locations in the 3 categories: 21%:19% (urban), 44%:14% (semi-urban), and 73%:15% (rural), based on the population in the two housing types (US Census Bureau, 2003).

If the collection system of disposed glass containers included a transfer station, the fuel consumption during transport was calculated based on quantities and transport distances obtained from NJDEP (NJDEP, 2008b). A tractor-trailer transport unit with a capacity of 20 tons and a fuel economy of 6 mile/gal (US EPA, 2006a) and a rail cart transport unit with a capacity of 100 tons and a fuel economy of 3.3 mile/gal were assumed (US EPA, 2004).

A loss of energy to heat the glass containers was assumed if glass containers were disposed in waste-to-energy facilities (i.e., specific heat capacity of glass: 0.84 kJ/kg-K (0.2 Btu/lb-F) (Tipler, 1999) and 65% conversion efficiency for converting generated heat to steam (Brunner, 1984)). The average transport distance of the ash from the 5 waste-to-energy facilities was estimated at 9.5 miles (NJDEP, 2008b).

An average transport distance from MRFs to different end uses was determined based on the previously mentioned survey. The average distance for transporting processed cullet from intermediate cullet processing facilities to various end uses was based on data obtained from the intermediate cullet processing facilities.

To calculate energy consumption at MRFs and intermediate cullet processing facilities, including equipment operation, rolling stock such as front-end loader, and heating and lighting (Nishtala, 1997), data were obtained from selected MRFs and cullet processing facilities in New Jersey (Enrique Angelini, Waste Management; Vinyard, Hatch Mott McDonald; and Jim Yezzo, Strategic Materials, 2009, personal communication). When no data were available, a national average was used (Nishtala and Solano-Mora, 1999).

An energy credit was given if the cullet was used in container manufacturing (5,230 kBtu/ton, in-state manufacturers; 4,612 kBtu/ton, out-of-state manufacturers), fiberglass production (7,841 kBtu/ton), or as construction aggregate (340 kBtu/ton). The energy credit was determined based on energy savings from substituting virgin raw materials accounting for extraction and production processes and all transportation involved. Cullet that was allocated for in-state manufacturing of glass containers, which were then sold, used and discarded in the state, was not accounted for in the energy credit for container manufacturing. This is because the reduced energy consumption associated with the cullet is already taken into account when determining the energy consumption in the in-state glass manufacturing processing. No energy credit was assumed for the sand blasting industry, because savings are believed to be negligible.

4.3.3.2.2 Upstream of use by consumers

The fuel type and consumption for raw material extraction and manufacturing of glass containers by in-state glass container manufacturers and by an average out-of-state US glass container manufacturers were determined based on Department of Energy (DOE) reports (US DOE, 2002b and 2005; Gaines and Mintz, 1994) and industry information (Angela, Phillips, Solvay Chemicals, Inc., 2009, personal communication) (Appendix C4). Transportation distances of raw materials to glass container manufacturers were based on data from the in-state glass manufacturing industry for New Jersey (Russ Hunter, Anchor Glass, 2009 and John Harpula, Leone Industries, 2009, personal communication) and on national averages for the US (Appendix C4). Except for soda ash, which was transported by rail from Wyoming in rail carts with assumed capacities of 100 tons, raw materials were hauled in trucks with assumed capacities of 25 tons (USEPA, 2006b; Russ Hunter, Anchor Glass, 2010 and John Harpula, Leone Industries, 2009, personal communication).

The energy source consumed by US glass container manufacturers was assumed to be 77% natural gas and the rest electricity from the local electricity grid (US DOE, 2002a and 2006; Harpula, personal communication). On average the cullet content in new glass containers in New Jersey is 33% (Russ Hunter, Anchor Glass, 2009, John Harpula, Leone Industries, 2009, personal communication) and 30% in the US (Worrell et al, 2008). The in-house cullet (i.e., broken containers generated during manufacturing) was assumed to be 10% (US EPA, 2006a; Gains and Mintz, 1994; Russ Hunter, Anchor Glass, 2009 and John Harpula, Leone Industries, 2009, personal communication). The energy savings when using cullet as feedstock were calculated based on the assumption of on average 3.0% energy reduction when the cullet share increased by 10% by mass (Gaines and Mintz, 1994; Beerkens *et al.*, 2004; Dolley, 2006; Worrel *et al.*, 2008). BUWAL 250 (1996) data were used for the energy consumption for imported foreign glass container products, including energy consumption for raw material extraction and glass container production (i.e., cradle-to-gate energy). Energy savings for manufacturing fiberglass are similar to those of glass container manufacturing with energy savings of 3.3% for every 10% of recycled cullet (Papke, 1993). A typical cullet content of 30% (NAIMA, 1996) was assumed for the fiberglass production.

Fuel consumption for transportation from manufacturing facilities to wholesale and retail locations was based on the WAste Reduction Model (WARM) model (EPA, 2004) at 1.016 MBtu/ton. Energy consumption for transportation of imported glass containers from abroad was estimated based on rail transport for glass containers from Central/South America and ocean freight for glass containers from Europe.

4.3.3.3 Sensitivity and uncertainty analysis

The data used in this study are point estimates based on the best available data. A sensitivity analysis was performed for all point estimates used in the model and uncertainty analysis for the five most uncertain point estimates. In the sensitivity analysis a sensitivity ratio (SR) was determined, which calculates, for each input variable (e.g., distance or quantity), the ratio of percentage change in the system energy requirement to the percentage change in the input (USEPA, 2001). To calculate the ratio, each input variable in isolation was doubled and the system energy requirement recalculated. The higher the SR the more the input variable affects the system energy requirement (Appendix C6).

The uncertainty analysis determined a range for the system energy requirement for the five most uncertain parameters, which were selected based on both data quality and the sensitivity analysis (Table 4-2). The selected uncertain parameters were assumed to be independent of each other and of the triangular distribution with ranges based on experience and expert judgment. The uncertainty of the system energy requirement among scenarios was propagated by using Monte Carlo simulation. The system energy requirements calculated in the Monte-Carlo simulation are presented as cumulative distribution functions (CDFs). The y-axis of a CDF graph shows the accumulative probability that a certain system energy requirement (on x-axis) is reached.

4.4 Results

4.4.1 MFA of glass containers used and discarded in New Jersey

4.4.1.1 Current system (Scenario 1)

Only about 1.5% (7,500 tons) of the glass packaging containers discarded by consumers in New Jersey in 2008 (472,000 tons) were manufactured in-state (Figure 4-1). The majority of the glass containers were produced in other states (88.5%) or in foreign countries (10%). Most of the glass containers produced in New Jersey were exported out of the boundary (New Jersey) and are therefore not included in the model.

Of the glass containers used and discarded by consumers in New Jersey, 66.5% (314,000 tons) were recycled (Note: the 314,000 tons of recycled glass containers was estimated before the NJDEP released the actual data of 317,000 tons as of June, 2010). This amount includes glass containers collected from bars and restaurants (8,200 tons) and from residents and institutions and businesses (305,800 tons). Glass containers from bars and restaurants were directly sent to intermediate cullet processing facilities. Most of the recycled glass containers sent to MRFs were collected commingled in curbside dual-stream recycling programs (276,100 tons) and curbside single stream recycling programs (30,100 tons), while a small fraction was collected at drop-off centers (7,800 tons).

Glass containers discarded by consumers as MSW were disposed of directly or as waste-to-energy facility residuals (ash) in landfills located both in-state and out-of-state. In-state disposed glass containers accounted for 98,300 tons (i.e., 61,900 tons directly disposed in landfills and 36,400 tons to waste-to-energy facilities) and out-of-state disposed glass container for 59,700 tons.

End uses of the recycled glass containers after processing in MRFs and intermediate cullet processing facilities will be discussed below.

4.4.1.2 End uses of recycled container glass based on survey and interviews

Nineteen of the 32 MRFs returned the survey about the end uses of the processed glass cullet. Even though drop-off sites were not part of the survey, most of the glass cullet from drop-off sites was delivered to MRFs and therefore is included in the survey. The reported quantity (266,900 tons) covered about 87% of the recycled container glass excluding the glass containers separated in bars and restaurants and directly delivered to intermediate processing facilities. It was assumed that the distribution of end uses was similar for the remaining cullet not covered by the survey (Table 4-3 and Figure 4-1). Based on this assumption and the survey, only 22.9% of the recycled container glass exiting MRFs (305,800 tons) was sent to intermediate cullet processing facilities (68,400 tons) and container glass manufacturers (1,600 tons). The use of cullet as aggregate was prevailing including 14.5% (44,300 tons) in the construction industry and 61.6% (188,400 tons) in landfills (Figure 4-1). End use in landfills included use as daily landfill cover, drainage layer, or temporary road pavement.

About 1% was exported (3,100 tons) to a private recycler in Pennsylvania with possible use as feedstock for glass container production (Figure 4-1).

Despite the intention to produce an end product for higher beneficial uses of cullet in intermediate cullet processing facilities, output flows from intermediate processing facilities revealed that only 60.4% of the cullet processed at intermediate cullet processing facilities was actually used for higher beneficial uses in-state (36.3%) and out-of-state (24.1%). Therefore, the percentage of the cullet used as container and fiberglass feedstock was only 14.0% ((68,400*60.4%)+1,600 tons) of the recycled container glass exiting MRFs. Based on the overall used and discarded glass packaging containers in New Jersey, 52,100 tons (26,200+1,600+8,000+16,400-100 tons) are used for non-aggregate beneficial uses (Figure 4-1). This represented 16.6% of the recycled glass containers, including the glass containers (8,200 tons) collected from bars and restaurants. Of the 16.6%, 3.0% was used in the fiberglass industry, 13.3% in glass container industry, and 0.3% in the sand-blasting industry.

About a third (34.9%) of the cullet leaving intermediate cullet processing facilities was sent to landfills (18,300 tons), the construction industry (4,600 tons), and the sand-blasting industry (1,100 tons, part of other end markets) and 4.7% (3,200 tons) was stored as stock in intermediate cullet processing facilities (Figure 4-1). Cullet that was sent to landfills and the construction industry contained mostly rejected cullet (i.e., cullet <1/4 in. in size, which fails to be optically separated (Barker Lemar, 2010)). The cullet rejection rate (e.g., rejected cullet and residuals) at intermediate cullet processing facilities was about 34%, which was more than three times higher than the reported average of 10% (American Recycler, 2001).

Overall, 81.4% (255,600 tons) of the recycled glass containers in New Jersey in 2008 were used as aggregate in landfills (188,400+18,300) and the construction industry (4,600+44,300) (Figure 4-1). About 80% of this amount was used in landfills with the remainder used in the construction industry.

4.4.1.3 Other scenarios (Scenarios 2-5)

All flows of the glass containers before being discarded by consumers were the same in all scenarios. For Scenario 2, the three-fold increase of cullet leaving MRFs and sent to intermediate cullet processing facilities (214,100 tons) resulted in a decrease in aggregate use in the construction industry (44,300+14,500 tons) and landfills (42,700+57,400 tons) by 96,700 tons when compared to Scenario 1, while there was an increase in cullet use as container and fiberglass feedstock (=1,600+64,100+51,400+24,800*86% tons) by 87,400 tons when compared to Scenario 1 (Table 4-4). Therefore, 44.1% of the recycled glass containers in Scenario 2 were used as feedstock in the glass container and fiberglass industries. For Scenario 3, due to the decreased recovery efficiency assumed at intermediate cullet processing facilities, cullet used as aggregate in landfills (188,400+33,100 tons) and the construction industry (44,300+3,200 tons) increased by 13,400 tons when compared to Scenario 1, while cullet use as container and fiberglass feedstock (=1,600+20,400+11,200+5,500*86% tons) decreased by 13,000 tons when compared to Scenario 1 (Table 4-4).

Scenario 4, which simulated an increased end use of cullet as aggregate (except for high quality cullet collected via bars and restaurants and drop-off centers), resulted in aggregate uses in landfills of 256,800 tons. Scenario 5, which eliminated curbside recycling, resulted in a 2.9 fold increase in glass container disposal via MSW (456,000 tons) when compared to all other scenarios (Table 4-4).

4.4.2 Energy analysis

4.4.2.1 Specific energy consumption for current system (Scenario 1)

The specific energy consumption (i.e., energy consumption per ton of glass containers used and discarded by consumers in New Jersey) for the overall system was 17,300 kBtu/ton. This result is comparable to findings by Gaines and Mintz (1994), who reported a specific energy consumption of 15,900 kBtu to supply one ton of glass containers consumed in the US without including energy consumption for wholesale and retail distribution.

Due to the large portion (98.5%) of glass containers that are discarded by consumers in New Jersey but manufactured in other states or foreign countries, the highest specific energy consumption (14,865.7 kBtu/ton) was consumed outside the boundary of New Jersey and is embodied in these products (Figure 4-2). This specific energy consumption, including glass container manufacturing and raw material processing and transportation, accounted for 85.8% of the overall specific energy consumption. Glass container manufacturing in other states in the US (88.5% of all glass containers used and discarded in New Jersey) accounted for 12,118.2 kBtu/ton. The associated virgin raw material extraction and transportation were responsible for 1,104.2 and 276.4 kBtu/ton, respectively, while the associated processing, transportation, and production of the cullet accounted for 375.6 kBtu/ton (Appendix C5). Specific energy consumption embodied in foreign imported products was 1,011.2 kBtu/ton (Appendix

C5). Including in-state manufactured glass containers (1.5% of the total discarded), glass product distribution (i.e., product transportation from the point of manufacturing plants to the consumers) accounted for 1,015.2 kBtu/ton (Figure 4-2).

After glass containers were used and discarded by consumers, the highest specific energy consumption was associated with the recycled glass container collection: 749.4 kBtu/ton to MRFs and drop-off sites and 20.1 kBtu/ton to intermediate cullet processing facilities (Figure 4-2). Specific energy consumption associated with transportation of cullet between MRFs & drop-off sites, intermediate cullet processing facilities, flint glass container industry, construction industry, other end markets, landfills, and exported and imported destinations, totaled 116.4 kBtu/ton (Figure 4-2). A slightly higher specific energy consumption was required for processing the recycled glass containers in MRFs (91.5 kBtu/ton) and in intermediate cullet processing facilities (34.9 kBtu/ton) together (Figure 4-2). Overall, the specific energy consumption associated with collection, transportation, and processing of recycled glass containers presented 5.8% of overall specific energy consumption. On the other hand, specific energy consumption for collection, transportation, and associated energy of disposed of glass containers via MSW represented 206.3 kBtu/ton (export: 70.3; directly to landfills: 72.9; and as ash from waste-to-energy facilities: 63.1 kBtu/ton). This accounted for 1.2% of the overall specific energy consumption.

Specific energy credits for in-state and out-of-state cullet use as container and fiberglass feedstock (298.3+113.9+176.4+30.8 kBtu/ton) and as aggregate substitute (148.9+35.2 kBtu/ton) totaled 772.7 kBtu/ton (Figure 4-2). This offset the overall specific energy consumption by 4.6%.

4.4.2.2 System energy requirement for scenarios

The system energy requirement for glass packaging containers discarded in New Jersey in 2008 (472,000 tons) was 7.80 TBtu/yr in Scenario 1. This accounted for a total energy consumption of 8.18 TBtu/yr, and a total energy credit of 0.38 TBtu/yr (Figure 4-3).

Scenario 2 (increased beneficial uses) presented the least system energy requirement (7.46 TBtu/yr), while Scenario 4 (with aggregate as sole end use) presented the highest system energy requirement (7.97 TBtu/yr) (Figure 4-3). Although Scenario 2 showed the highest energy consumption, it also had the highest energy credits, which offset its energy consumption by 9.9%. This indicated the importance of increased beneficial uses in achieving a lower system energy requirement.

The system energy requirements among Scenarios 1, 3, and 5 appeared similar, ranging from 7.81 to 7.83 TBtu/yr. With no curbside collection, Scenario 5 avoided energy consumption associated with recycled glass collection, transportation, and processing but provided lower energy credits. Therefore, elimination of curbside collection did not result in a lower system energy requirement when compared to Scenarios 1 and 3 (Figure 4-3).

4.4.2.3 Sensitivity analysis and data uncertainty for scenarios

The sensitivity analysis showed that the five most sensitive parameters of each scenario were the same (Table 4-2). Three of the parameters were related to the manufacturing process while one was related to the wholesale and retail distribution distance and one related to percentage of import products. The dominant manufacturing-related parameters were due to the large energy consumption of the glass container manufacturing processes when compared to other processes. The most sensitive parameter was cradle-to-gate energy for glass container production in foreign countries (mostly in EU) (Appendix C6). A 100% increase in this parameter resulted in a change of system energy requirement by 6.06%. Although this large change in this parameter is unlikely considering the technology used for glass container manufacturing is similar in the US and in the EU, further investigation is required to determine if the parameter is important to the accuracy of the model.

Based on the uncertainty analysis, there is an 80% probability for Scenario 2 (higher beneficial uses) to have a lower system energy requirement when compared to all other scenarios (Figure 4-4). This indicated that increased higher beneficial uses can achieve a lower system energy requirement. The CDFs in Scenario 1, 3, 4, and 5 are very closely together and are mostly overlapping. Therefore, the probabilities are low for all these scenarios to have different system energy requirement under the conditions of uncertainty. There is a probability of less than 20% for Scenario 1 (current practice) to have a lower system energy requirement than Scenario 4 (sole aggregate use).

4.5 Discussion

4.5.1 End use of cullet as aggregate versus as feedstock in glass container manufacturing

The lower system energy requirement in Scenario 2 when compared to Scenario 4 (Figure 4-4) indicated the benefit of increased cullet use (~44% of the recycled glass containers) as container or fiberglass feedstock compared to cullet use as construction aggregate. This confirmed the UK and Canadian case studies (Butler and Hooper, 2005; Morris, 1996). The lower system energy requirement in Scenario 2 is mainly a result of the higher energy credit. The energy credit of one ton of cullet used as feedstock for container production (5,230 Btu/ton for in-state; 4,612 Btu/ton for other states in the US) is about 15 times higher than the energy credit of one ton of cullet used as aggregate (340 kBtu/ton for in-state).

Not all discarded and used glass packaging containers in New Jersey can be used as glass container feedstock. As experienced in the UK (Butler and Hooper, 2005), the US suffers from the color-imbalance of the recycled glass containers, mainly resulting from the import surplus of green glass containers from foreign countries while the green glass container manufacturing is lacking in the US (Roy, 1997). However, based on the estimated color ratio of amber: green: flint cullet of 25:25:50 (CWC, 1996), more than the current 8.8% of the recycled glass containers (Figure 4-1) could be used as feedstock for in-state flint glass container production. This is confirmed by the in-state flint glass container manufacturers who reported imports of high quality cullet from states with bottle-bills (e.g., Connecticut or New York) (CRI, 2009).

To assess transportation of the cullet used as feedstock in amber and green glass container industries, which are currently not present in New Jersey, a break-even long-haul distance was determined. To calculate this long-haul distance, the energy credit (4,612 kBtu/ton), gained from the cullet use as container feedstock, needs to have subtracted from it the energy consumption involved for additional transportation to and processing at the intermediate cullet processing facilities, which is otherwise avoided if cullet is used as aggregate. The energy credit (340 kBtu/ton), gained from the cullet use as aggregate, also needs to have subtracted from it the transportation fuel consumption from MRFs to the construction industry or landfills. The energy difference between the two adjusted energy credits for the container feedstock and the aggregate substitute is then used to provide the long-haul transportation fuel consumption for the cullet. Given the estimated fuel economy of 6 miles/gallon, the assumed truckload capacity of 22 tons, and an empty back haul, the break-even distance can be calculated using the following equation:

$[(EC_{cont} - T_i - P) - (EC_{aggr} - T_c)] / [(F_{diesel} / (E_f * tpd)] / 2$

$= [(4,612,000 - 232,276 - 240,157) - (340,000 - 82,567)] / (158,000/6/22) / 2$

$= 1,622$ (miles, one-way)

Where EC_{cont} = Energy credit of cullet as container feedstock (see section 4.3.3.2.1), Btu/ton

EC_{aggr} = Energy credit of cullet as aggregate substitute (see section 4.3.3.2.1), Btu/ton

T_i = Fuel consumption for transportation of 1 ton of cullet from MRFs to in-state intermediate cullet processing facilities (value based on the survey results from the MRFs), Btu/ton

T_c = Fuel consumption for transportation of 1 ton of cullet from MRFs to in-state construction industry or landfills (value based on the survey results from the MRFs), Btu/ton

P = Energy consumption for processing 1 ton of cullet at intermediate cullet processing facilities (value based on the report provided by the facilities), Btu/ton

F_{diesel} = Primary fuel consumption (combustion + pre-combustion) per gallon of diesel consumed (= 158,000 Btu/gal) (Franklin Associates, 2004)

E_f = Fuel economy (= 6 miles/gallon)

tpd = Truck capacity per load (= 22 tons)

The calculated long-haul distance would allow amber, green and additional flint cullet collected in New Jersey to be used by glass container or fiberglass manufacturers from the East Coast to the Midwest. The break-even distance can be even higher if partially loaded back-haul was assumed instead of the calculated worst-case scenario of an empty back-haul. In terms of energy consumption, this result confirmed suggestions by Butler and Hooper (2005) that long-haul of recycled glass cullet used as container feedstock is more beneficial compared to local use as aggregate. While energy consumption is usually used as a major environmental indicator, other environmental and economical and possibly social factors need to be taken into account when assessing this finding.

4.5.2 Single-stream recycling

An increased glass breakage rate and elevated contaminant levels are widely reported with the switch from dual-stream to single-stream curbside collection (CRI, 2009; Eureka Recycling, 2002; Jamelske and Wessling, 2006; Morawski, 2009; Smith-

Teutsch, 2010). It has also been suspected that the elevated breakage rate adds to the increased contaminant levels (CRI, 2009; Tim Goodman & Associates, 2006). If cullet is intended for higher beneficial uses in container or fiberglass production, preventing recycled glass containers from breaking during collection is therefore important to obtain more cullet that meets the stringent specifications set by the industries (CWC, 1996b and 1997). Various suggestions have been discussed to reduce the breakage rate during single-stream collection, such as implementation of padding in the collection vehicles (Barker Lemar, 2010). However, no literature was found to indicate whether the suggestions are effective in reducing the breakage rate.

Further processing of the recyclables might also result in higher quality cullet although the capital and operating costs are likely to increase. However, given the higher energy credits that can be achieved with increased higher beneficial uses, it may be important to determine if improvement in separation/sorting technology at MRFs or intermediate cullet processing facilities can produce a comparable amount of quality cullet from single-stream collected glass containers when compared to dual-stream collected glass containers, and if the energy consumption of the improved technology does not outweigh the benefit of the higher beneficial uses.

4.6 Conclusions

The material flow analysis in this study discloses the inter-relationships between complicated flows and processes in the glass recycling system on the state level and beyond. It also allows the estimation of flows, for which measurements are unavailable, such as the mass of recycled glass containers collected in bars and restaurants via a mass balance of known flows or processes. Compared to life cycle assessment (LCA), which in most cases relies on a database of national averages, the use of material flow analysis on a state level increased transparency for the studied system.

The energy analysis built upon the material flow analysis confirmed that the energy-intensive processes in container glass manufacturing account for the major energy consumption over the whole life-cycle of the glass container recycling system. To achieve a lower system energy requirement, results from this study confirm UK and Canadian case studies that use of cullet as container feedstock outweighs the benefit of use of cullet as construction aggregate even over longer transportation distances.

To increase the use of cullet as container feedstock, further assessment is needed to determine if single-stream recycling could achieve comparable glass cullet quality when compared to dual-stream recycling if further processing at MFRs and intermediate cullet processing facilities is implemented. Technologies are most likely available, but it will probably add to the overall operating costs. Alternatively, practices such as additional collection from bars and restaurants could be explored.

Currently, the recycling regulations in New Jersey require the state to reach a 50% recycling rate of residential, commercial and institutional MSW (NJDEP, 2006), assuming the mass of the recyclables is the sole indicator for the environmental impacts. However, due to the large difference in energy savings for different end uses of recycled glass containers, it may be beneficial to base future policies and regulations on life-cycle assessments.

Finally, given the continuous efforts in saving energy in manufacturing processes in industry, periodical updates for data related to manufacturing-related processes is recommended for future simulations.

4.7 References

American Recycler (2001). Glass Recycling Market Trends, Contamination Problems Discussed. <http://www.americanrecycler.com/10glassmarket.html> (Accessed 25 August 2010)

Ayres, R. and Simonis, U. (1994). *Industrial metabolism: Restructuring for sustainable development*. United Nations University Press, New York, NY.

Baccini, P. and Brunner, P.H. (1991). *Metabolism of the Anthroposphere*. Springer, New York, NY.

Barker Lemar Engineering Consultants (2010). Sustainable glass management options study. Prepared for Dubuque metropolitan area solid waste agency, Iowa. <http://dmaswa.org/UserFiles/File/Sustainable%20Glass%20Mgt%20Options%20Study%20(May%202010).pdf> (Accessed 25 August 2010)

Beerkens, R.G.C., van Limpt, H.A.C., Jacobs, G. (2004). Energy efficiency benchmarking of glass furnaces. Glass Science and Technology (44), p. 47-57.

Boustead, I. and Hancock, G.F. (1979). *Handbook of Industrial Energy Analysis*. John Wiley and Sons, New York, NY.

Brunner, C.R. (1984). *Incinerator System Selection and Design*. Van Nostrand Reinhold, New York, NY.

Brunner, P.H. and Rechberger, H. (2004). *Practical Handbook of Material Flow Analysis* Lewis Publishers, Boca Raton, FL.

Butler, J. and Hooper, P. (2005). Dilemmas in optimizing the environmental benefit from recycling: A case study of glass container waste management in the UK. Resources Conservation & Recycling (45), p. 331-355.

BUWAL 250 (1996). Ökoinventare für Verpackungen. LCI database, Schriftenreihe Umwelt 250, Bern.

CA EPA (1999). Statewide waste characterization study - Results and final report. Publication #340-00-009. California integrated solid waste management board, Sacramento, CA. < http://www.ciwmb.ca.gov/WasteChar/WasteStudies.htm#2004> (Accessed 25 August 2010)

CDM (2005). Solid waste composition – final report. Prepared for the Bergen County Utilities Authority based on field work at three transfer stations in Bergen County, NJ.

CDM (2008). Waste composition and characterization study – Monmouth County materials processing and recovery facilities. Prepared for Greenstar North America at Tinton Falls, NJ.

Container Recycling Institute (2009). Understanding economic and environmental impacts of single-stream collection systems. < http://www.container-recycling.org/assets /pdfs/reports/2009-SingleStream.pdf > (Accessed 2 February 2010)

Clean Washington Center (CWC) (1996). Typical Generation and Collection Rates for Recycled Glass. Report #: BP-GL1-01-01. Seattle, WA. <http://cwc.org/gl_bp/1-01-01.pdf> (Accessed 25 August 2010)

Clean Washington Center (CWC) (1997). Cullet Specifications for Container Manufacturing. Report #: BP-GL3-01-02. Seattle, WA. < http://cwc.org/gl_bp/3-01-02. pdf> (Accessed 25 August 2010)

Davis, J.R. (1992). *Engineered Materials Handbook: vol. 4 Ceramics and Glasses. Testing, Characterization, and NDE*. ASM International, Materials Park, OH.

Dacombe, P., Krivtsov, V., Banks, C.J., and Heaven, S. (2005). Energy and material flow of waste-processing operations. Engineering Sustainability (158), p. 17-23.

Dolley T.P. (2005). USGS 2005 Minerals Yearbook: Silica. US Geological Survey, Government Printing Office, Washington, D.C. <http://minerals.usgs.gov/minerals/pubs/commodity/silica/silcamyb05.pdf> (Accessed 25 August 2010)

Energy Information Administration (2005). Electric Power Industry Generation by Primary Energy Source. Washington, D.C.

Eureka Recycling (2002). A Comparative Analysis of Applied Recycling Collection Methods in Saint Paul. In partnership with the city of Saint Paul and the Minnesota Office of Environmental Assistance, Minneapolis, MN. <http://www.eurekarecycling.org /inf_studies.cfm> (Accessed 25 August 2010)

Franklin Associates (2004). Life cycle inventory of packaging options for shipment of retail mail-order soft goods. Prepared for Oregon Department of Environmental Quality and U.S. EPA Environmentally Preferable Purchasing Program. <http://www.deq.state.or. us/lq/sw/packaging/lifecyclereport.htm> (Accessed 12 Feb 2010)

Gaines, L.L., and Mintz, M.M. (1994). Energy implications of glass container recycling. Report ANL/ESD-18. Argonne Natioinal Laboratory, Argonne, IL. <http://www.osti.gov/bridge/purl.cover.jsp?purl=/10161731-zmoOBj/native/> (Accessed 25 August 2010)

Goldammer, T. (2008). *The Brewer's Handbook: The Complete Book to Brewing Beer*, chapter 1: US Beer Industry. 2nd ed., Apex Publisher, Clifton, VA.

Harrison, K.W., Dumas, R.D., Solano, E., Barlaz, M.A., Brill, E.D., Ranjithan, S.R. A decision support system for development of alternative solid waste management strategies with life-cycle considerations. ASCE Journal of Computing in Civil Engineering (15), p. 44-58.

Hickman Jr., H.L. (1999). *Principles of Integrated Solid Waste Management.* American Academy of Environmental Engineers, Annapolis, MD.

Hourihan K. (2009). Single-stream municipalities in New Jersey, 2008 updates. Morris County Municipal Utilities Authority, Mendham, NJ.

Jamelske, E.M. and Kipperberg, G. (2006). A contingent valuation study and benefit-cost analysis of the switch to automated collection of solid waste with single stream recycling in Madison, Wisconsin. Public Works Management Policy (11), p. 89-103.

Jamelske, E.M. and Wessling, S. (2005). Assessing the support for the switch to automated collection of solid waste with single stream. Public Works Management & Policy (10) 2, p. 101-118. <http://pwm.sagepub.com/cgi/reprint/10/2/101> (Accessed 25 August 2010)

Kennedy, B.A. (1990). *Surface Mining*. 2nd ed., Port City Press, Baltimore, MD, p. 162.

Kesmodel, D. (2009). U.S. beer imports lose their frizz. The Wall Street Journal. April 11, p. B5. Wall Street journalist, New York.

Kinsella, S. and Gleason, G. (2003). Single Stream: An Investigation into the Interaction between Single Stream Recycling Collection Systems and Recycled Paper Manufacturing. The Sonoma County Waste Management Agency, Sonoma County, CA.

Koroneos, C., Roumbas, G.,Gabari, Z., Papagiannidou, E., Moussiopoulos, N. (2005). Life cycle assessment of beer production in Greece. Journal of Cleaner Production (13), p. 433-439.

Morawski, C. (2009). Understanding Economic and Environmental Impacts of Single-Stream Collection Systems? Container Recycling Institute, Arlington, VA.

Michaelis, P. and Jackson, T. (2000). Material and energy flow through the UK iron and steel sector. Part 1: 1954–1994. Resources, Conservation and Recycling (29), p.131-156.

Morris, J. (1996). Recycling versus incineration: an energy conservation analysis. Journal of Hazardous Materials (47), p. 277-293.

NAIMA (1996). Fiberglass Insulation – Using Recycled Materials Helps Maintain Environmental Balance. North American Insulation Manufacturers Association, Alexandria, VA.

Nishtala (1997). Design and analysis of material recovery facilities in an integrated solid waste management system. Master's thesis, North Carolina State University, Raleigh, North Carolina.

Nishtala, S. and Solano-Mora, E. (1999). Description of the material recovery facilities process model: Design, cost, and life-cycle inventory. Internal Rep., Dept. of Civil Engineering, North Carolina State University, Raleigh, NC.

New Jersey Department of Environmental Protection (NJDEP) (2008). 2008 Monthly reports of all solid waste facilities in New Jersey. Trenton, NJ.

New Jersey Department of Environmental Protection (NJDEP) (2010a). New Jersey generation, disposal and recycling statistics & Material specific recycling rates, 1998-2008. Solid and Hazardous Waste Program, Bureau of Recycling and Planning. Trenton, NJ. <http://www.nj.gov/dep/dshw/recycling/stats.htm> (Accessed 25 August 2010)

New Jersey Department of Environmental Protection (NJDEP) (2010b). New Jersey generation, disposal and recycling statistics & Material specific recycling rates, 2008. Solid and Hazardous Waste Program, Bureau of Recycling and Planning. Trenton, NJ <http://www.nj.gov/dep/dshw/recycling/stats.htm> (Accessed 25 August 2010)

OECD (2001). OECD-Organization for Economic Co-operation and Development. Extended Producer Responsibility: A Guidance Manual for Governments. Paris, France.

Papke, C. (1993). *Glass Recycling and Reuse From Municipal Wastes*. Recycling Sourcebook, Gale Research Inc., New York, NY.

Reindl, J. (2003). Reuse/Recycling of Glass Cullet for Non-Container Uses. Dane County Department of Public Works, Madison, WI. <http://www.epa.gov/epaoswer/non-hw/green/pubs/glass.pdf> (Accessed 25 August 2010)

RMCT (2003). Material recovery facility handbook. Recycling Marketing Cooperative for Tennessee, Lexington, Tennessee. <http://ctasgis02.psur.utk.edu/Environment/solid%20waste%20documents/recycling/material%20recovery%20facility%20handbook.pdf> (Accessed 25 August 2010)

Roy, N.U. (1997). *Municipal Solid Wastes: Problems and Solutions.* Recycling Realities and the Glass container: New Technologies and Trends. CRC Press publisher, Boca Raton, FL.

Ruth, M. and Dell'Anno, P. (1997). An industrial ecology of the US glass industry. Resource Policy (23), p. 109-124

Smith-Teutsch, A. (2010). CRI Study takes a critical look at single-stream. Waste & Recycling News, January 4, 2010.

Solano, E., Dumas, R.D., Ranjithan, S. R., Barlaz, M. A. and Brill, E.D. Jr. (2002a). Life-cycle-based solid waste management I: Model development. Journal of Environmental Engineering (128), p. 981-992.

Solano, E., Dumas, R.D., Harrison, K.W., Ranjithan, S. R., Barlaz, M. A. and Brill, E.D. Jr. (2002b). Life-cycle-based solid waste management II: Illustrative applications. Journal of Environmental Engineering (128), p. 993-1005.

Sundin, E., Svensson, N., McLaren, J., and Jackson, T. (2002). Materials and energy flow analysis of paper consumption in the United Kingdom, 1987-2010. Journal of Industrial Ecology (5), p. 89-105.

Tipler, P.A. (1999). Physics *for Scientists and Engineers*. 4th Ed., W.H. Freeman, Sanfrancisco, CA.

The Gob (2010). Collection of glass packaging steadily increases in Europe. Published by the European Container Glass Federation (FEVE-AISBL), January, 2010. Alexander Mohr Avenue Louise, Brussel. <http://www.feve.org/images/stories/pdf2010/thegob-01-2010.pdf> (Accessed 25 August 2010)

U.S. Census Bureau (2003). 2000 census of population and housing: population and housing unit counts, New Jersey. PHC-3-32. Department of Commerce, Washington, DC. <http://www.census.gov/prod/cen2000/phc-3-32.pdf> (Accessed 25 August 2010)

U.S. Department of Energy (2002a). Glass Industry of the Future: Energy and environmental profiles of the US glass industry. Office of Industrial Technologies, Energy Efficiency and Renewable Energy, US Department of Energy, Washington DC. <http://www1.eere.energy.gov/industry/glass/pdfs/glass2002profile.pdf> (Accessed 25 August 2010)

U.S. Department of Energy (2002b). Energy and Environmental Profile of the U.S. Mining Industry. Office of Energy Efficiency and Renewable Energy. <http://www1.eere.energy.gov/industry/mining/analysis.html> (Accessed 25 August 2010)

U.S. Department of Energy (2005). Mining Industry of the Future: Industrial Sand Mining and Processing, Fiscal Year 2004 Annual Report. <http://www1.eere.energy.gov/industry/about/pdfs/mining_fy2004.pdf> (Accessed 25 August 2010)

U.S. Department of Energy (2006). Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery. Office of Industrial Technologies, Energy Efficiency and Renewable Energy, US Department of Energy, Washington DC.

<http://www1.eere.energy.gov/industry/imf/pdfs/teg_final_report_13.pdf> (Accessed 25 August 2010)

U.S. Environmental Protection Agency (1994). Waste prevention, recycling, and composting options: lessons from 30 communities, Chapter 2, p. 7. EPA 530-R-92-015. Solid waste and emergency response, Washington, DC. <http://www.epa.gov/epawaste/conserve/downloads/recy-com/index.htm> (Accessed 25 August 2010)

U.S. Environmental Protection Agency (2001). Risk assessment guidance for superfund: volume III – Part A, process for conducting a probabilistic risk assessment. EPA 540-R-02-002. Office of emergency and remedial response, Washington, DC. <http://www.epa.gov/oswer/riskassessment/rags3adt/pdf/rags3adt_complete.pdf> (Accessed 25 August 2010)

U.S. Environmental Protection Agency (2004). WARM model transportation research - Draft. Memorandum from ICF Consulting to US EPA. Background documents for solid waste management and greenhouse gases, Washington, DC. <http://epa.gov/climatechange/wycd/waste/downloads/retail_transport-memo.pdf> (Accessed 25 August 2010)

U.S. Environmental Protection Agency (2006a). Application of life-cycle management to evaluate integrated municipal solid waste management strategies. Prepared by Research Triangle Institute, North Carolina State University, and University of Wisconsin, Madison for Office of Research and Development, Washington, DC.

Worrell, E., Galitsky, C., Masanet E., and Graus W. (2008). Energy efficiency improvement and cost saving opportunities for the glass industry. An ENERGY STAR® guide for energy and plant managers. Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA.

Table 4-1. Scenarios and key assumptions.

Scenarios		% of fuel savings during curbside collection compared to current practice	% of cullet exiting MRFs and drop-off centers used as aggregate	% of cullet existing MRFs and drop-off centers processed at intermediate cullet processing facilities	% increase in specific energy consumption at intermediate cullet processing facilities
1	Current practice	0%	77%	23%	0%
2	Current practice with increased use of recycled glass containers as feedstock in new container or fiberglass production	0%	30%	70%	0%
3	Single-stream curbside collection replacing dual-stream curbside collection	17%†	77%	23%	33%
4	Current practice with all recycled glass containers used as aggregate substitute	0%	100%	0%	0%
5	No curbside glass recycling	0%	0%	0%	0%

Note: Glass container collection in Scenario 2-5 the same as in Scenario 1. Percentage of cullet processed at intermediate cullet processing facilities plus that of cullet used as aggregate equal 100%, which excludes cullet export and direct cullet use in glass container manufacturers. Storage of cullet at the intermediate cullet processing facilities was 5% in Scenario 1, 2, and 3.

† Based on interviews with both recycling coordinators and private waste haulers in New Jersey (range: 10-25%).

Table 4-2. Selected uncertainty parameters and their ranges

Uncertainty parameters	Units	Range
Percentage of foreign imported glass containers	%	[8 - 12]
Cullet content in glass containers in the US	%	[28 - 32] [a]
Energy reduction in (domestic) glass manufacturing process by using cullet to replace virgin raw materials	%	[27 - 33] [b]
EU cradle-to-gate energy consumption for glass containers	Btu/ton	[$9.6x10^6$ - $1.3x10^7$] [c]
Domestic wholesale & retail distribution distance	Miles	[632 - 1,174] [d]

[a] Worrel *et al.* (2008).
[b] Beerkens *et al.* (2004); Dolley (2006); Worrel *et al.* (2008).
[c] 95% - 130% of the baseline value.
[d] 70% - 130% of the baseline value.
1 Btu = 1055.06 J
1 short ton = 0.9072 metric tons.
1 mile = 1.6093 km

Table 4-3. Fate of recycled glass containers exiting MRFs (survey results).

	Reported mass [tons]	Mass used in MFA [tons][†]	Comments
Intermediate cullet processing facility	50,400	68,400	Glass cullet processing for use as container or fiberglass feedstock
Glass container manufacturer	1,400	1,600	Food/beverage glass container manufacturing
Quarry or aggregate processing facilities	40,000	44,300	Road pavement
Landfills	172,200	188,400	Landfill cover, drainage layer, temporary road pavement
Export	2,900	3,100	Glass container manufacturing
Total	**266,900**	**305,800**	

[†] 87% of cullet was reported. The same end use distribution was assumed for the not reported cullet.
1 short ton = 0.9072 metric tons.

Table 4-4. Discarded glass container flows in five scenarios (tons).

Flows	Scenarios				
	1	2	3	4	5
Recycled Glass Collection and Transportation					
Recycled glass container collection to MRFs & drop-off sites	305,800	305,800	305,800	305,800	7,800[*]
Recycled glass container collection directly to intermediate cullet processing facilities (bars and restaurants)	8,200	8,200	8,200	8,200	8,200
Cullet exported from MRFs to other states	*3,100*	*3,100*	*3,100*	*3,100*	*0*
Cullet transported from MRFs to intermediate cullet processing facilities	*68,400*	*214,100*[†]	*68,400*	*0*	*0*
Cullet transported from MRFs to construction industry	*44,300*	*44,300*	*44,300*	*44,300*	*0*
Cullet transported from MRFs to flint glass container industry	*1,600*	*1,600*	*1,600*	*1,600*	*7,800*[‡]
Cullet transported from MRFs to landfills (for aggregate use)	*188,400*	*42,700*	*188,400*	*256,800*	*0*
Cullet Transportation from Intermediate Cullet Processing Facilities					
Cullet transported to flint glass container industry	26,100[a]	64,100[a]	20,400[a']	8,200	8,200
Cullet transported to other end markets[§]	8,000[b]	24,800[b]	5,500[b']	0	0
Cullet exported to other states[#]	16,400[c]	51,400[c]	11,200[c']	0	0
Cullet transported to construction industry	4,600[d]	14,500[d]	3,200[d']	0	0
Cullet transported to landfills	18,300[e]	57,400[e]	33,100[e']	0	0
Unprocessed cullet (stock) stored in intermediate cullet processing facilities	3,200[f]	10,100[f]	3,200	0	0
Glass Containers Disposed as MSW	158,000	158,000	158,000	158,000	456,000

Note: Sum of the values in italics equals the mass of recycled glass containers exiting MRFs.

[*] Collection through drop-off sites only.

[†] 70% of 305,800 tons.

[‡] Assuming all recycled glass containers collected via drop-off centers were processed in MRFs.

[§] 86% of the cullet sent to other end markets was used in in-state fiberglass industry.

[#] 86% and 14% of the exported cullet was used as feedstock in the container and fiberglass industries.

[a] 26.1% of the input flow from MRFs to intermediate cullet processing facilities, plus 8,200 tons from bars and restaurants to intermediate cullet processing facilities.

[b] 11.6%, [c] 24.0%, [d] 6.8%, [e] 26.8%, and [f] 4.7% of the input flow from MRFs to intermediate cullet processing facilities (Note: Tonnage is rounded to the hundredth digit).

[a'b'c'd'] A 32.5% decrease from [a b c d] in Scenario 1; [e'] Input flow from MRFs to intermediate cullet processing facilities minus all other end uses and unprocessed cullet.

1 short ton = 0.9072 metric tons.

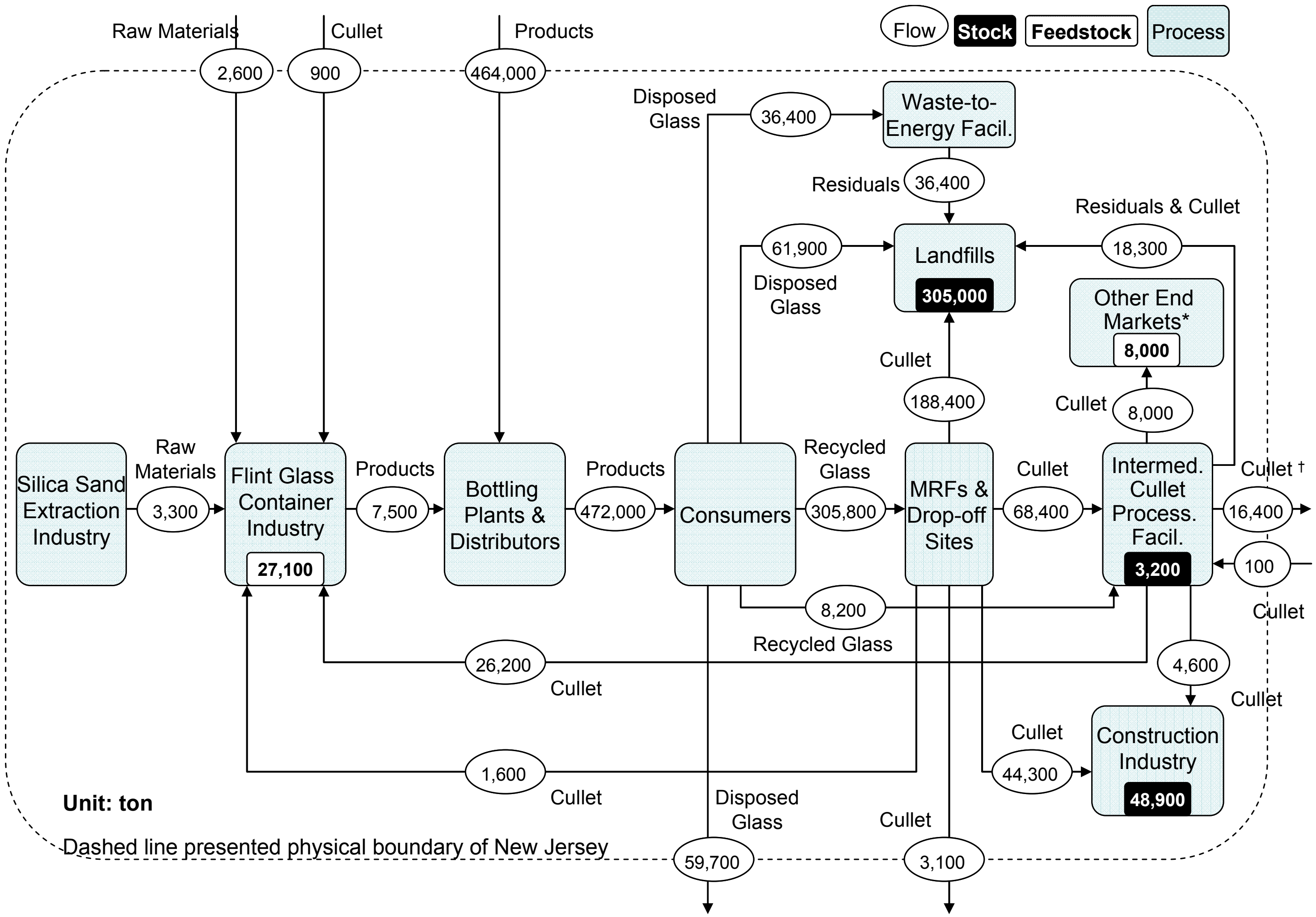


Figure 4-1. MFA of glass packaging containers used and discarded in New Jersey in 2008.

Note: Material flows and processes which occurred outside New Jersey border were not specified in the figure for simplicity.

* Other end markets include fiberglass and sand blasting industries. † Cullet was sent to container (86%) and fiberglass (14%) industries.

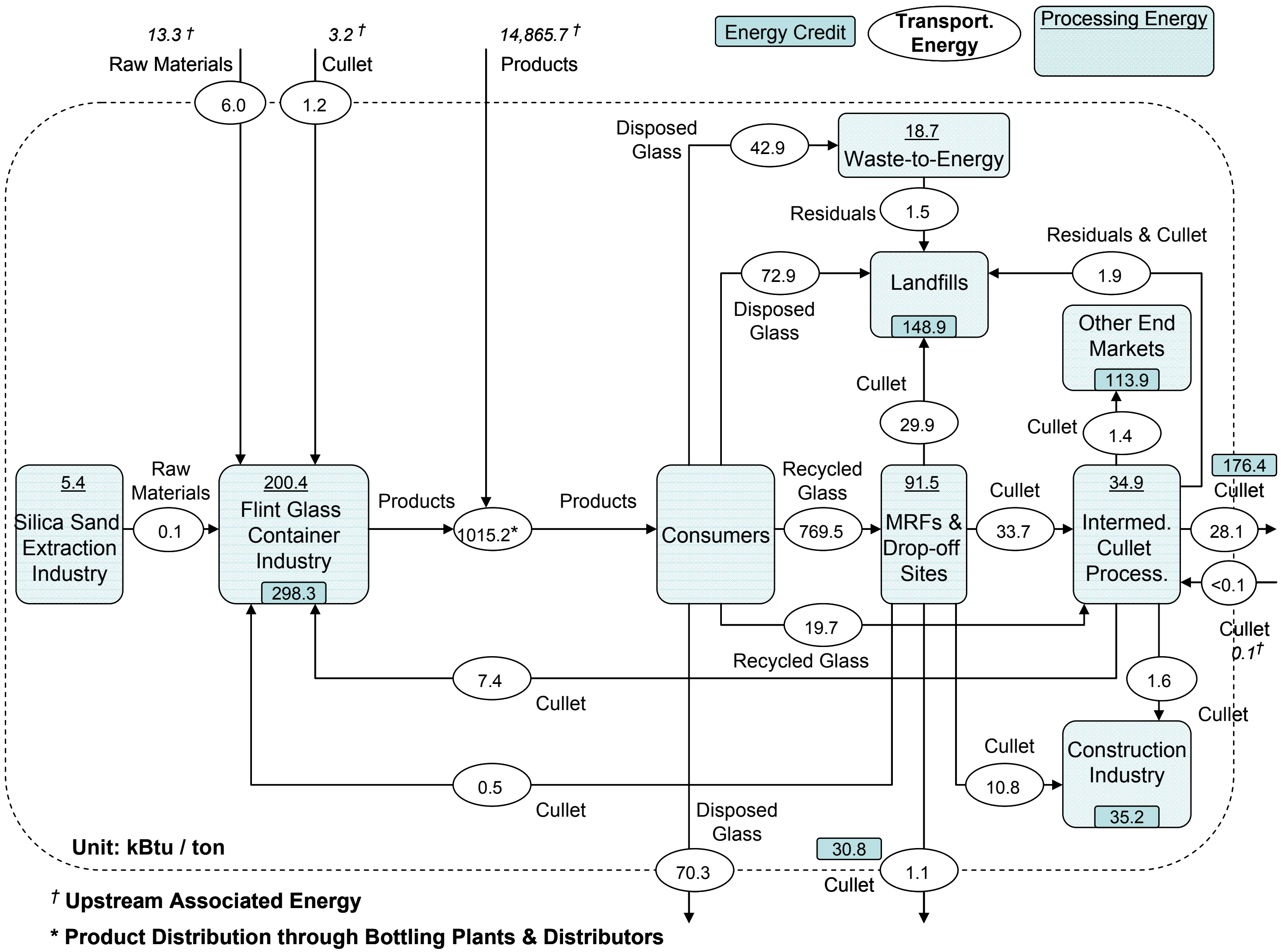


Figure 4-2. Specific energy consumption of glass containers used and discarded in New Jersey in 2008.

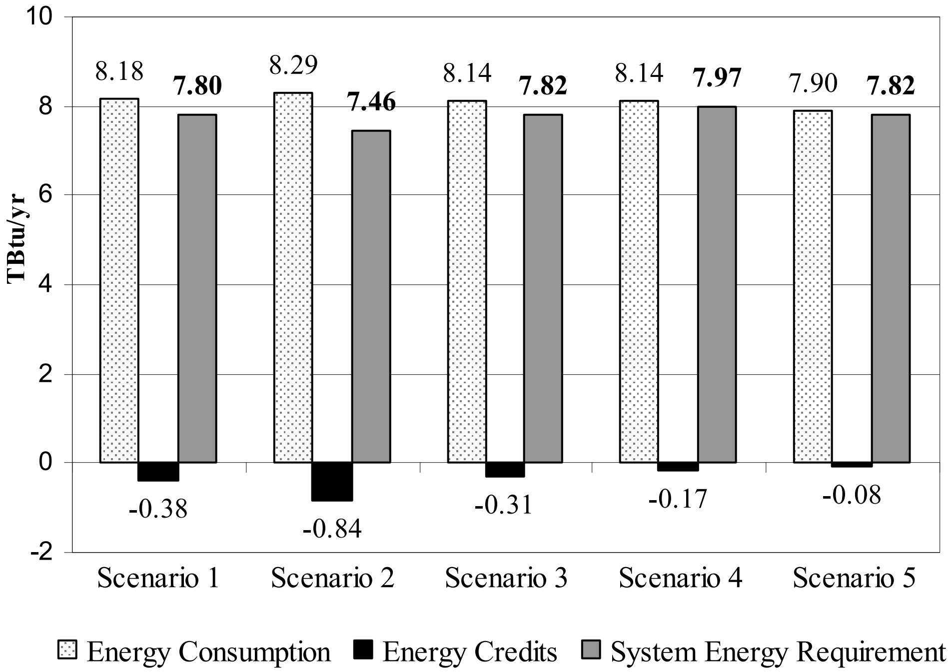


Figure 4-3. System energy requirements for various scenarios. Scenario 1: current system; Scenario 2: increased use as container feedstock; Scenario 3: single-stream recycling; Scenario 4: aggregate as sole end use; Scenario 5: elimination of curbside collection.

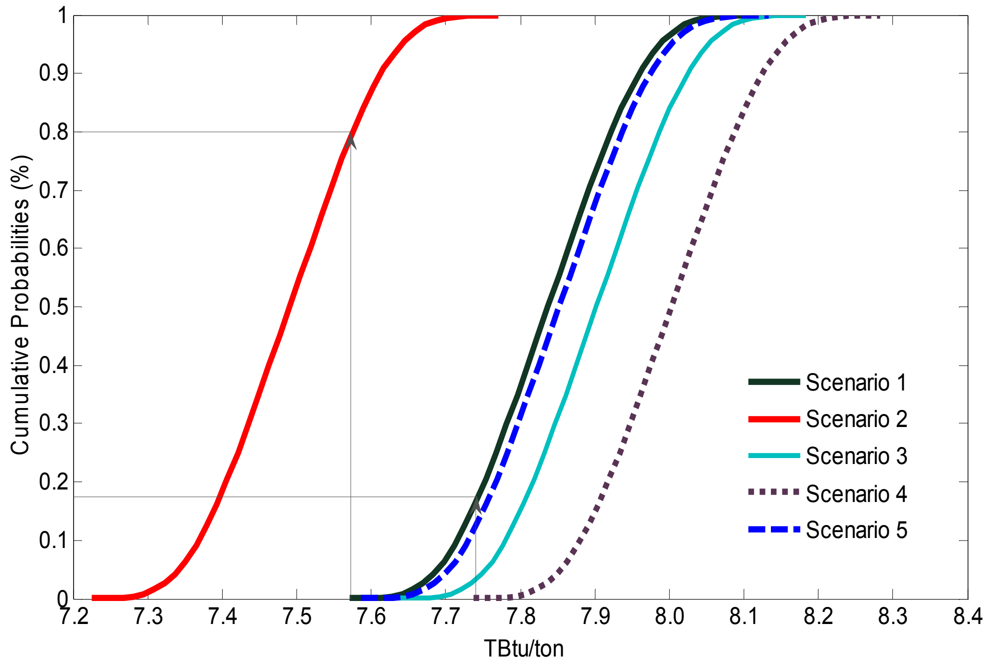


Figure 4-4. Cumulative distribution functions (CDFs) for system energy requirements under conditions of uncertainty. Scenario 1: current system; Scenario 2: increased use as container feedstock; Scenario 3: single-stream recycling; Scenario 4: aggregate as sole end use; Scenario 5: elimination of curbside collection.

Chapter 5. Summary, Future Directions, and Conclusions

5.1 Summary

This dissertation verifies, based on the results from the first field study, that glass cullet can be stockpiled before use as construction aggregate. However, leachate of these stockpiles is a potential source of water pollution caused by food/beverage and other residuals and therefore should not be released to surface water (Chapter 2). It can be infiltrated to groundwater only if aged and if Best Management Practices are implemented to reduce the nitrogen levels in the leachate of large long-term stored glass cullet stockpiles. Given the limited variation in cullet quality among the tested MRFs in New Jersey and Pennsylvania, the findings are likely to also apply in other states in the US.

Based on the second field study, composting with regular turning was shown to be an effective treatment method. The alternative method of composting with forced-aeration of cullet stockpiles can improve the temperatures and oxygen levels inside the stockpile without resulting in excessive drying (Chapter 3). However, biodegradation of the organic contaminants in these stockpiles did not appear to be as effective as in the turned stockpile. Therefore, incorporating some turning even with forced-aeration is important.

Handling of leachate from cullet stockpiles enables the beneficial use of glass cullet as construction aggregate, but the energy savings of this practice did not appear to outweigh the energy savings of cullet use as container or fiberglass feedstock (Chapter 4). Based on the material flow and energy analysis, which quantifies flows of glass containers used and discarded in New Jersey and the associated energy consumption from raw material extraction to final use and disposal, about five times more recycled glass containers were used as aggregate than as feedstock in container or fiberglass production. Most likely this can be partially attributed to the quality of the cullet that cannot meet the container or fiberglass industries' specifications. To achieve greater energy savings, the quality of the cullet must be improved. Another reason for the high percentage of cullet used as aggregate are likely the costs associated with cullet processing and transportation to end markets, which needs to be further assessed.

5.2 Future Directions

With the ultimate goal to achieve an environmentally sound recycling system for glass containers, recommendations regarding energy savings for different end uses for the system have been discussed in this dissertation. Although energy is used as the major environmental indicator in this dissertation, other environmental indicators/impacts such as water emissions, but also economic and social impacts, need to be determined for a more complete assessment of the glass container recycling system. To make the cullet suitable for use as feedstock in the container or fiberglass industries, advanced processing of the cullet is necessary, which might be cost prohibitive for municipalities. A life-cycle cost analysis might be needed to further explore which recycling practice would be more favorable for municipalities.

Currently, the market value of glass cullet in New Jersey is relatively low as also experienced by other states (Barker Lemar, 2010). This is most likely caused by the increased use as aggregate and the lack of access to other non-aggregate markets for the glass cullet. With an increasing trend in adoption of single-stream recycling collection, which contributes to increased breakage and higher contaminant levels and thus reduces the opportunities for cullet to be used as higher market-valued container or fiberglass feedstock, the market value of the glass cullet has been further reduced (Barker Lemar, 2010). In addition, green and amber cullet is especially low in market value because no container manufacturers in the state are producing glass containers of this color. At the same time, the markets for use in container and fiberglass manufacturing are dwindling. After the shut down of at least half of the glass manufacturing plants across the US due to a consolidation of the glass industry which began in the 1990s (US Census Bureau, 1995 and 2005; US DOE, 2002), there were as of 2009 only two glass container manufacturers left in New Jersey. The major fiberglass manufacturer in New Jersey also closed in 2009. Although there are container or fiberglass manufacturers out of the state, it requires long-haul of glass cullet and thus increases the overall cost of the recycling. In addition, competition with the aluminum and plastic industries (Freas, 2006), and high transportation costs associated with raw materials (US DOE, 2002) have also lead to the consolidation of the glass container industry.

In order to obtain higher quality of glass cullet and improve the low market values, strengthening practices of glass containers that are recycled with less contaminants at source may be important. This may require the supporting legislation and regulation. Currently, the State of North Carolina and about 10 cities (e.g., Indianapolis, IN or Houston, TX) in the US have enacted regulations that all glass containers be collected in bars and restaurants. This practice has increased the quantity of high quality of recycled glass containers because of the separation by color at the point of generation (GPI, 2009). Another option to increase the quantity of quality cullet may be through the drop-off or deposit refund systems. Compared to curbside recycling, glass containers recycled through drop-off or deposit refund systems have been reported to contain less contamination and thus have increased glass cullet use in the container or fiberglass industries (CRI, 2009; Cattaneo, 2009). Despite these benefits, there are currently only 11 states in the US that implement the deposit refund system.

Solutions for increase of use of all color cullet in glass container manufacturing have been discussed by other researchers (Butler and Hooper, 2005; Roy, 1997). The replacement of clear glass by green-hued glass has been mostly discussed. This allows manufacturers to mix and use glass cullet of all three colors, flint, green and amber. This idea would help states such as New Jersey where only flint glass container manufacturers exist. However, studies of the acceptability of this change by consumers are needed.

This dissertation discusses life-cycle energy and material uses of the glass container recycling system. However, there are other disposable container packaging materials such as aluminum, PET (polyethylene terephthalate), steel, and HDPE (high density polyethylene), which environmental impacts might be less when compared to glass packaging materials. Based on a study conducted by Berry and Makino (1974), to produce a 16 oz (approximately 473 mL) container made of glass consumes 4060 BTU of energy at the plant, compared to 2143 BTU of energy for a container made of HDPE, 4948 BTU made of PET, and 8695 BTU made of aluminum. If the collection and processing of the used glass containers is taken into account, given its heavy nature, possibly the benefit of other packaging materials outweighs glass as a packaging material.

More recent studies reported varying results (Huang and Ma, 2004; Humbert *et al.*, 2009; Owens-Illinois, Inc., 2010; Pai, 2001), likely caused by different system boundaries and waste handling and recycling practices (e.g., recycled content or disposal strategies).

5.3 Conclusions

The first part of the work described in this dissertation examines water quality issues of the current glass container recycling practice in New Jersey. It presents the first large-scale field study for characterization and handling leachate generated from recycled glass cullet stockpiles. This allows beneficial use of cullet as aggregate in large construction projects such as for landfills or the construction industry. It also provides a framework for future leachate characterization and quantification of leachate from other stockpiled recycled materials, such as recycled wood chips.

The second part of the work in this dissertation presents a systematic evaluation of the life-cycle energy requirement of discarded glass containers in New Jersey. The work contributes to the state-level modeling of both material and energy flows of glass container recycling. The system energy requirement calculated for different recycling strategies and end uses in the model can be used to support future improvements in recycling-related decisions.

Future directions for this research may include a variety of projects. Systematic energy and material consumption studies of other competitive packaging materials can be compared to these of glass container packaging materials to fill the knowledge gap on the environmental impacts of the various packaging materials.

Besides environmental analysis, life-cycle cost analysis, or social studies for the glass container recycling system can also complement the studies in this dissertation.

5.4 References

Barker Lemar Engineering Consultants (2010). Sustainable glass management options study. Prepared for Dubuque metropolitan area solid waste agency, Iowa. <http://dmaswa.org/UserFiles/File/Sustainable%20Glass%20Mgt%20Options%20Study%20(May%202010).pdf> (Accessed 25 August 2010)

Berry, R.S. and Makino H. (1974). Energy thrift in packaging and marketing. Technology Review (76), p. 1-13, 32-43.

Butler, J. and Hooper, P. (2005). Dilemmas in optimizing the environmental benefit from recycling: A case study of glass container waste management in the UK. Resources Conservation & Recycling (45), p. 331-355.

Cattaneo, J. (2009). Glass container manufacturers set 50 percent recycled content goal. Waste Age, May.<http://wasteage.com/Recycling_And_Processing/glass-recycled-content-goal-200905/index1.html> (Accessed 25 August 2010)

Freas, R.C. (2006). Glass Container. *Industrial Minerals and Rocks: Commodities, Markets, and Uses*, 7th ed., part 3, p. 1365. SME publisher, Littleton, CO.

Glass Packaging Institute (GPI) (2009). Bars and restaurant recycling. GPI, Alexandria, VA. <http://www.gpi.org/recycle-glass/barrestaurant-recycling/barrestaurant-recycling.html> (Accessed on 25 September, 2010).

Huang, C.-C. and Ma H.-W. (2004). A multidimensional environmental evaluation of packaging materials. Science of the Total Environment (324), p. 161-172.

Humbert, S.; Rossi, V.; Margni, M.; Julliet, O.; Loerincik, Y. (2009). Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots. International Journal of Life Cycle Assessment (14), p. 95-106.

Kogel, J.E. *et al.* (2006). *Industrial Minerals & Rocks: Commodities: Markets, and Uses.* 7th ed., SME, p. 181.

Owens-Illinois, Inc. (O-I) (2010). Packaging: The complete LCA. O-I, Perrysburg, OH.

Pai, P.P. (2001). Environmental implications of packaging material choice and associated solid waste management alternatives. Master thesis, University of North Carolina, Raleigh, NC.

Roy, N.U. (1997). Recycling Realities and the Glass container: New Technologies and Trends. Municipal Solid Wastes: Problems and Solutions. CRC Press publisher.

US Census Bureau (1995). 1992 Census of manufacturers: industry series - glass container. MC92-I-32A. Economics and Statistics Administration, Bureau of the Census, U.S. Department of Commerce, Washington, DC. <http://www.census.gov/prod/1/manmin/92mmi/mci32af.pdf> (Accessed 25 August 2010)

US Census Bureau (2005). Glass container manufacturing 2002: 2002 economic census – Manufacturing industry series. EC02-31I-327213 (RV). Economics and Statistics Administration, Bureau of the Census, U.S. Department of Commerce, Washington, DC.

US Department of Energy (2002). Glass Industry of the Future: Energy and environmental profiles of the US glass industry. Office of Industrial Technologies, Energy Efficiency and Renewable Energy, US Department of Energy, Washington DC. <http://www1.eere.energy.gov/industry/glass/pdfs/glass2002profile.pdf> (Accessed 25 August 2010)

Appendix A

SOPs for Selected Washwater and Leachate Analyses

Appendix A1

Total Phosphorus Test
(Ascorbic Acid Method)

Reagent Preparation

a. Reagent A: 0.2908 g Antimony Potassium tartrate + 12 g Ammonium Molybdate → 1500 ml diH_2O + 133 ml concentrated H_2SO_4 → 2000 ml diH_2O
b. Reagent B: (Only stable for 4 hrs) Dissolve 1.056 g of Ascorbic Acid in 200 ml of Reagent A
c. Reagent B*: 0.6 g Ammonium Molybdate + 6.65 ml H_2SO_4 → bring the vol. w/ diH_2O to 100 ml
d. P-std Stock: Dissolve 0.4393 g of anhydrous KH_2PO_4 (dried for 1 hr at 105 ^oC)
e. 5N H_2SO_4: Add 133 ml concentrated H_2SO_4 to 750 ml diH_2O → bring vol. to 1000 ml w/ H_2O
f. Phenophthalein: (Not necessary if 1-ml 5N-H_2SO_4 is used) 0.05 g Phenophthalein in 50 ml EtOH and 50 ml H_2O (Phenophthalein is colorless under acidic conditions and pink under basic conditions)

Phosphorus Standard Curve Preparation

1. Prepare 10 x dilution of P-std (100 mg//L): 5 ml 1000-mg/L stock + 45 ml diH_20
2. Take 0, 1, 2, 3, 4, and 5 ml of above 100 mg/L standard sol. into five 50 ml-flasks containing 8 ml of reagent B → mixing well and bring the final volume to 50 ml with diH_2O
3. The five flasks should contain concentration of phosphorus of 0, 2, 4, 6, 8, and 10 mg/ L.
4. Measure the absorbency at 880-nm after 10 but less than 30 minutes.
5. Calculate the formula for P-std Curve (e.g. $y = 0.8404x – 0.0057$)

Procedure (Persulfate Digestion Method)

1. Take 50 ml of wash water from the sample into 250-ml flask. (At least in duplicate)
2. Add 1 ml (3000ml/1000ml) H_2SO_4 + 0.5 g solid $K_2S_2O_8$
3. Autoclave for 30 min. w/ loose aluminum foil cap → cool
4. Blank : Take 8.4ml treated sample + 1.6 ml Reagent B*
   Sample : Take 42 ml treated sample + 8 ml Reagent B
5. Final dilution factor = 11.9 x
6. Measure the absorbency at 880-nm after 10 but less than 30 minutes.
7. Make sure the sample absorbance falls right in the standard curve
8. Calculate the sample concentration from the formula calculated from the standard curve
9. Record the test results in mg/L

Appendix A2

TKN Test
(Semi-Micro Kjeldahl Method)

Principle

In the presence of H_2SO_4, K_2SO_4 and $CuSO_4$, amino nitrogen of many organic materials is converted to ammonium. By raising pH to above 11 with a strong base, dissolved ammonia ($NH_{3(aq)}$ and NH_4^+) is converted to $NH_{3(aq)}$.

Storage of samples

The most reliable results are obtained on fresh samples. If an immediate analysis is not possible, preserve samples by acidifying to pH 1.5 to 2.0 with concentrated H_2SO_4 and storing at 4°C.

Reagents preparation

a. Ammonium–free water: DI H_2O (distilled & R.O. water don't qualify for ammonium-free water). Do not store ammonium-free water; always take it freshly.
b. Digestion reagent: Dissolve 134 g K_2SO_4 (potassium sulfate) + 7.3 g $CuSO_4$ (Cupric sulfate) in ~800ml water → add 134 ml concentrated H_2SO_4 → cooled to 20 degree C → dilute to 1 L, and store at 20 °C to prevent crystallization.
c. 10N NaOH: Dissolve 400 g NaOH in 800 ml water and dilute to 1000 ml (stored in plastic bottles).

Samples digestion

Preheat TKN digester at ~ 300 °C for 30 minutes

↓

50-ml sample + 10-ml digestion reagent + 5~6 glass beads (3~4 mm size)

↓ mixing well

Capped with aluminum foil; heat under fume hood at ~ 375 °C for 1 hr, then turn down to 300 °C for another 30 min.

↓

Let cool (while still warm), rinse and dilute to 100 ml with diH_2O

↓

Add 10 N NaOH ~5 ml and record the volume for later calculation
→ Use pH paper to be sure sample pH >11.0

↓

Measure converted $NH_{3(aq)}$ by ammonia-selective electrode method.
(For calculation of original concentration, refer to Ammonia Test)

Appendix A3

Ammonia Test
(Ammonia-Selective Electrode Method)

Principle

$NH_{3(aq)}$ diffuses through the membrane and changes the internal solution pH that is sensed by a pH electrode. This method is applicable to the measurement of 0.03 to 1400 mg NH_3-N/L.

Sample preservation

Refrigerate at 4 °C for samples to be analyzed within 24 hrs. For longer storage, lower pH to 2 or less with conc. H_2SO_4.

Reagents preparation

a. Stock ammonium chloride solution: Dissolve 3.819 g anhydrous NH_4Cl (dried at 100 °C) in water, and dilute to 1000 ml; 1.00 ml – 1.00 mg N = 1.22 mg NH_3.
b. 10N NaOH.

Preparation of standard curve

Prepare a series of standard solutions covering the concentrations of 100, 10, 1, and 0.1 mg NH_3-N/L. Plot ammonia concentration in milligrams NH_3-N/L on the log axis vs. potential in millivolts on the linear axis. If the electrode is functioning properly a 10-fold change of NH_3-N concentration produces a potential change of about 59 mV.

Measurement of samples

1. Dilute if necessary to bring NH_3-N concentration to within calibration curve range
2. Place 100 mL sample in 150-L beaker and immerse electrode with a magnetic stirrer
3. Maintain the same stirring rate and a temperature of about 25°C throughout testing
4. Add sufficient volume of 10N NaOH solution (1 mL is usually sufficient) to raise the pH about 11 (check with pH paper)
5. Record volume of 10N NaOH added.
6. Read NH_3-N concentration from standard curve

Appendix A4

Nitrate Test
(Cadmium Reduction Method)

Sample preservation

Refrigerate at 4 °C for samples to be analyzed within 48 hrs. For longer storage, lower pH to 2 or less with conc. H_2SO_4.

Principle

NO_3^- is reduced almost quantitatively to nitrite (NO_2^-) in the presence of cadmium (Cd). The NO_2^- produced is determined by diazotizing with sulfanilamide and coupling with N-(1-naphthyl)-ethylenediamine dihydrochloride to form a highly colored azo dye that is measured colorimetrically.

Preparation of reagents

a. Color reagent: To 40 mL water, add 0.5 g sulfanilamide and 5 mL 85% phophoruc acid and. After dissolving sulfanilamide completely, add 0.5 g N-(1-naphthyl)-ethylenediamine and dilute to 50 mL. This solution is stable for ~1 month when stored in a dark bottle in refrigerator.
b. Ammonium chloride-EDTA solution: Dissolve 13g NH_4Cl and 1.7g disodium ethylenediamine tetraacetate in 900 mL water. Adjust pH to 8.5 with conc. NH_4Cl and dilute to 1 L.
c. Copper sulfate solution, 2%: Dissolve 20g $CuSO_4.5H_2O$ in 500 mL water and dilute to 1L.

Procedure

1. Preparation of reduction column: Insert a glass will plug into bottom of reduction column and fill with water. Add sufficient Cu-Cd granules to produce a column 18.5 cm long. Maintain water level above Cu-Cd granules to prevent entrapment of air. Wash column by passing through it at 7-10ml/min. at least 100 mL of a solution composed of 25% 1.0 mg NO_3^--N/L standard and 75% NH_4Cl-EDTA solution.
2. Sample reduction: To 25 mL sample add 75 mL NH_4Cl-EDTA solution and mix. Pour sample into column and collect at a rate of 7 to 10 mL/min. Discard first 25 mL. Collect the rest in original sample flask. There is no need to wash column between samples.
3. After finishing the measurement, store the Cu-Cd column in NH_4Cl-EDTA solution and never let it dry.
4. Color development and measurement: As soon as possible and not >15 min. after reduction, add 2.0 mL color reagent to 50 mL sample and mix. After 10 min. and before 2 h, measure absorbance at 543 nm against a distilled water reagent blank.

Appendix A5

Total Coliforms Test
(Membrane Filter Method)

Preparation of reagents

a. Dilution water (buffered water)
- Stock phosphate buffer solution: Dissolve 34.0 g potassium dihydrogen phosphate (KH_2PO_4) in 500 ml diH_2O, adjust pH to 7.2 ± 0.5 with 1N NaOH and dilute to 1 liter with diH_2O.
- Stock magnesium chloride buffer solution: Dissolve 81.1 g magnesium chloride ($MgCl_2 \cdot 6H_2O$) in 1 liter with diH_2O.

Note: - For preparing 1-L dilution water, add 1.25 ml stock KH_2PO_4 and 5 ml stock $MgCl_2 \cdot 6H_2O$.
- For preparing 3-L dilution water, add 3.75 ml stock KH_2PO_4 and 15 ml stock $MgCl_2 \cdot 6H_2O$.

b. Preparation of broth (M-endo medium-> CAUTION! CARCINOGENIC!)
- Rehydrate 4.8 g medium in 100 ml diH_2O containing 2 ml 95% ethanol (Do not use denatured ethanol), which reduces background growth and coliform colony size.
- Bring to a near boil, the promptly remove from heat and cool to 45°C - 50°C
- (Do not autoclave)
- Adjust to pH = 7.2 ± 0.2 (May skip this step as it always falls in this range)
- Dispense 2 ml liquid medium onto pads (remember to include the blank as control)
- Broth may be stored at 4°C up to 4 days.

Procedure

1. Prepare dilution water and medium.
2. Autoclave everything that will be used in the procedure the day before: 50- & 100-ml beakers, graduated cylinders, 1000µl & 5ml disposable tips, 500 ml bottles, tweezers, stir bars, filtration receptors (2x) and dilution water (3 liter for ~ 3 dilution-folds).
3. Make serial dilution for samples: 10^{-3}, 10^{-4}, and 10^{-5} in 100 ml dilution water.
4. Do triplicate for each diluted sample (10^{-3}, 10^{-4},and 10^{-5}) plus a blank as control.
5. Using sterile forceps, place the membrane filter (grided side up) ocer porous plate of receptacle.
6. Wet the filter paper with dilution water and leave some on the paper → add 1 ml of diluted sample onto membrane filter → turn on the vacuum to suck out the water.
7. Rinse the membrane filter 3x by 20-30 ml dilution water → dry another 5 minutes.
8. Transfer the membrane filter to medium plate (grided side up) → invert dish.

9. Incubate for 22-24 hr at 35 ± 0.5 °C (to keep enough of moist, put a glass of water in).
10. Typical coliforms colony is pink to dark-red with a metallic surface sheen.

Appendix A6

BioLog Protocol for Gram Negative Bacteria
(Enteric)

Day 1

After total coliforms test is complete:

a. Select the most appropriately diluted samples (e.g., 10^{-4} or 10^{-5}) from total coliforms test of different sample sources (A, B, C and D). Making a cross mark on the back of each plate and pick the single and independent colonies in the middle of each sector /or randomly choose 5 colonies from each total coliforms plate. 20 colonies were chosen in total for total coliforms test of 4 sample sources.

b. Streak BUG 5% sheep blood agar plates.

   P.S. Streak plates heavily so that the most growth will occur. If your culture is not pure, streak from this plate on to another plate for a pure culture.

c. Incubate plates in 35 degree Celsius incubator with a beaker of water to maintain moisture conditions for 4-24 hours.

Day 2

a. Set out your innoculum fluid and MicroPlates to get them to room temperature.
b. Turn on your spectrometer.
c. Set wavelength at 590 nm.
d. Blank your spectrometer with the innoculum fluid.
e. Slowly add colonies from the BUG agar plates until the OD reads .256 (absorbance)/61% (Transmitance).
f. Aseptically pour the innoculum fluid into a sterile Petri dish.
g. Use the muli-pipet to dispense 150 uL into each well in the MicroPlate.
h. Incubate the MicroPlates for 22-24 hrs at 35 ºC.

Day 3

a. Read the plates after incubation.

Appendix A7

Lead Test
(GFAA Acid Digestion, 3050B Method)

For graphite furnace atomic absorption (GFAA)

Dry sample weight 14.8 – 38.76 grams to obtain 0.5 grans of dry organic matter
(Alternatively, take 30 grams of dry sample weight for each sample)

↓

In 200 mL beaker, add 20 mL of 1:1 HNO_3 mix the slurry, and cover with a watch glass

↓

Heat the sample to 95 ± 5 °C and reflux for 10-15 min. without boiling

↓

Allow the sample to cool → And add 10 mL of conc. HNO_3; cover it; reflux for 30 min.
(Repeat this step over and over until no brown fumes are given off by the sample; this indicates the complete reduction with HNO_3)

↓

Heat at 95 ± 5 °C without boiling for 2 h
Allow the solution to evaporate to ~10 mL without boiling

↓

Cool the sample and add 4 mL water and 6 mL of 30% H_2O_2
Cover the beaker with a watch glass and warm it

↓

Repeat to add 30% H_2O_2 in 2 mL aliquots with warming until the effervescence is minimal or until the general sample appearance is unchanged (DO NOT ADD > A TOTAL OF 20 ML 30% H_2O_2)

↓

Continue hating the acid-peroxide digestate until volume reduced to ~5 mL or heat at 95 ± 5 °C without boiling for 2 h. Cover at all times.

↓

After cooling, dilute to 100 mL with H_2O

↓

Centrifuge to remove particulate at 2000-3000 rpm for 10 min.

↓

Run GFAA (follow instruction manual by the machine)

Appendix B

Field Measurements for Glass Cullet Stockpiles

Appendix B1

Oxygen levels in turned stockpile of coarse cullet - I (2006)*

Stockpile set up on 28-Jun-2006

Date	Pile	Turned Stockpile (Coarse1)-A (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	09:00	19	17	14	10	16	10
19-Jul-06	08:30	19	16.5	12	6	13	13
26-Jul-06	10:00	19	18	16	15	17.5	14
02-Aug-06	09:30	20	18	17	16	15	15
09-Aug-06	12:00	21	21	20	19	20	18
16-Aug-06	09:30	20	20	20	20	20	20
23-Aug-06	09:00	19	18	18	18	20	20
30-Aug-06	09:00	20	20	20	20	20	20
06-Sep-06	10:00	20.5	20.5	19.5	19.5	19.8	19.2
20-Sep-06	14:30	20	19	18	18	19	18

Date	Pile	Turned Stockpile (Coarse1)-B (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	09:00	19	16	9	0	13	4
19-Jul-06	08:30	18	12.5	9	9	13	13
26-Jul-06	10:00	21	19	17	13	14	17
02-Aug-06	09:30	21	20	18	16	20	16
09-Aug-06	12:00	21	21	19	19	18	19
16-Aug-06	09:30	20	20	20	20	20	20
23-Aug-06	09:00	21	21	20	20	20	20
30-Aug-06	09:00	20	20	20	20	20	20
06-Sep-06	09:00	20.5	20.3	20.2	19.9	20.8	20
20-Sep-06	14:30	20	20	19	19	20	20

*Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west.

Appendix B2

Oxygen levels in turned stockpile of coarse cullet - II (2006)*

Stockpile set up on 28-Jun-2006

Date	Pile	Turned Stockpile (Coarse2)-A (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	09:00	18	12	1.5	0	3	1
19-Jul-06	08:30	20	19	11	1	16	2
26-Jul-06	10:00	19	17	17	16	18	16
02-Aug-06	09:30	19	18	17	14	17	17
09-Aug-06	12:00	20	20	20	19	20	19
16-Aug-06	09:30	20	20	20	20	20	20
23-Aug-06	09:00	20	20	20	20	20	20
30-Aug-06	09:00	20	20	20	20	20	20
06-Sep-06	09:00	20	20	20.5	20.5	19.8	19.5
20-Sep-06	14:30	20	20	20	20	20	20

Date	Pile	Turned Stockpile (Coarse2)-B (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	09:00	17	15	3	0	13	1.5
19-Jul-06	08:30	16	11	3	3	10.5	11
26-Jul-06	10:00	20	18	17	15	15	19
02-Aug-06	09:30	19	18	17	13	18	15
09-Aug-06	12:00	ND	ND	ND	ND	ND	ND
16-Aug-06	09:30	20	20	20	20	20	20
23-Aug-06	09:00	20	20	20	20	20	20
30-Aug-06	09:00	20	20	20	20	20	20
06-Sep-06	09:00	20	19.9	19.5	19.5	19.8	19.8
20-Sep-06	14:30	20	20	20	20	20	20

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. ND: not determined.

Appendix B3

Oxygen levels in lined stockpile of coarse cullet (2006)*

Stockpile set up on 28-Jun-2006

Date	Pile	Lined Stockpile (Coarse)-A (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	10:00	20	19	15	5	18	12
19-Jul-06	10:30	20	20	18.5	10.5	18	14
02-Aug-06	10:15	20	20	18	3	19	18
16-Aug-06	10:30	20	19	1	0	17	17
23-Aug-06	10:00	19	19	19	13	18	17
30-Aug-06	09:00	18	18	18	18	17	16
06-Sep-06	10:30	20.2	20	0.9	18.5	20	17
20-Sep-06	15:00	20	20	20	20	20	20
24-Sep-06	09:30	20	20	18.3	18	20	18.5
04-Oct-06	10:00	20	19.8	19	17.9	19.1	17.5
18-Oct-06	10:00	19.3	18.5	17.2	17.2	18.7	17.5
01-Nov-06	08:30	19	16	13.8	13	19	16

Date	Pile	Lined Stockpile (Coarse)-B (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	10:00	20	19	18	16	18	15
19-Jul-06	10:30	21	20	19	17	19	15.5
02-Aug-06	10:15	20	20	19	20	20	16
16-Aug-06	10:30	20	1	0	0	18	18
23-Aug-06	10:00	19	19	19	13	19	18
30-Aug-06	09:00	20	20	20	19	18	17
06-Sep-06	10:30	20.5	20.5	20	17.8	20.8	19.3
20-Sep-06	15:00	20	20	16	16	20	20
24-Sep-06	09:30	19	19	18.3	3.5	19.5	18.8
04-Oct-06	10:00	19.3	19.3	18.9	16.5	19.5	18.2
18-Oct-06	10:00	20	19.5	18.5	15.2	20	19
01-Nov-06	08:30	19	18.8	17.5	16	19	16.8

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west.

Appendix B4

Oxygen levels in lined stockpile of fine cullet (2006)*

Stockpile set up on 29-Jun-2006

Date	Pile	Lined Stockpile (Fine)-A (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	10:00	8	1	0.5	1	3	1
19-Jul-06	10:30	15	3.5	0	0	4	0
02-Aug-06	10:15	17	12	2	1	4	1
16-Aug-06	10:30	18	15	8	4	14	8
23-Aug-06	10:00	20	17	10	7	15	9
30-Aug-06	09:00	13	13	11	7	12	9
06-Sep-06	10:30	17.2	11.2	6.2	3.2	10	5.6
20-Sep-06	15:00	20	20	17	17	20	20
24-Sep-06	09:30	19.5	18	16.8	14.3	19	15
04-Oct-06	10:00	20	18.7	16.9	14.8	18.2	13.9
18-Oct-06	10:00	19	18.3	16.2	14.2	16	12.5
01-Nov-06	08:30	19	17.8	13.8	7.2	16.5	13.2
14-Nov-06	08:00	18	15	11	7	14	12

Date	Pile	Lined Stockpile (Fine)-B (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
13-Jul-06	10:00	7	1.5	1	1	7	2
19-Jul-06	10:30	8.5	2	0	0	4	1
02-Aug-06	10:15	15	2	0	0	5	1
16-Aug-06	10:30	18	3	1	1	0	0
23-Aug-06	10:00	16	13	3	2	12	9
30-Aug-06	09:00	16	10	6	0	11	10
06-Sep-06	10:30	17.5	11.8	6.5	0.9	14.6	10
20-Sep-06	15:00	20	20	20	20	20	20
24-Sep-06	09:30	18.8	16.5	10.7	10.5	14.2	11.3
04-Oct-06	10:00	19.8	16.9	14.3	12.1	17.5	13.2
18-Oct-06	10:00	19.8	18.7	15	12.7	17.3	15.2
01-Nov-06	08:30	19.2	17.8	13.8	9.2	18	14.2
14-Nov-06	08:00	18.5	17	12	7	14	12

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west.

Appendix B5

Temperature in turned stockpile of coarse cullet - I (2006)*

Stockpile set up on 28-Jun-2006

Date	Pile	Turned Stockpile (Coarse)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
29-Jun-06	12:00	NA	35.8	NA	30.8	42.4	42.2	38.7	NA	44.2
02-Jul-06	11:45	NA	49.8	NA	27.1	50.8	54.7	43.8	NA	48.2
03-Jul-06	14:00	NA	51.3	NA	27.9	53.2	71.8	45.7	NA	46.2
05-Jul-06	09:00	NA	NA	51.4	29.7	51.4	NA	52.1	NA	49.1
07-Jul-06	09:10	34.9	46.6	51.2	45.1	46.2	NA	59.5	55.8	57.1
13-Jul-06	09:00	NA	45.7	51.3	53.4	47.2	NA	64.9	57.6	67
19-Jul-06	08:00	43.4	50.8	50.6	50.5	50.5	NA	56.6	55.3	55.8
26-Jul-06	09:00	32.8	39.2	33.4	44.8	41.7	NA	49.5	37.2	50.3
02-Aug-06	09:30	37.8	38	39	39.8	40.1	NA	45.8	43.2	44.6
09-Aug-06	12:30	31.6	32.3	NA	NA	NA	NA	NA	37.1	38.5
16-Aug-06	10:30	31.3	32.2	NA	NA	NA	NA	NA	35.2	35.6
23-Aug-06	09:00	29.9	29.7	NA	NA	NA	NA	NA	32.3	31.5
30-Aug-06	09:00	27.6	29.2	NA	NA	28.7	30.6	NA	29.1	30.8
06-Sep-06	09:15	25.5	26.7	NA	NA	25.3	26.7	NA	24.6	24.9
20-Sep-06	14:00	25.9	26.3	NA	NA	25.4	26.8	NA	24.3	24.9
04-Oct-06	09:30	24.1	24.8	NA	NA	23.8	24.7	NA	23.7	23.2
18-Oct-06	10:00	22.7	22.9	NA	NA	23.1	23.3	NA	22.8	23

Date	Pile	Turned Stockpile (Coarse)-B (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
29-Jun-06	12:00	44.9	38.7	35	31.3	44.4	43.9	39.7	48.2	47.8
02-Jul-06	11:45	43.2	49.9	39.7	28.8	49.6	NA	44.8	49.2	49.4
03-Jul-06	14:00	40.8	49.1	43.9	29.6	49.1	NA	46.8	50.3	49.2
05-Jul-06	09:00	39.6	49.1	45.6	31.8	47.1	NA	52.4	50.8	50.3
07-Jul-06	09:10	NA	50.1	NA	37.4	NA	NA	54.2	NA	53.8
13-Jul-06	09:00	NA	50.1	NA	50.4	52.8	NA	70.8	NA	68.7
19-Jul-06	08:00	NA	48.4	NA	52.6	NA	NA	56.7	53.7	61.2
26-Jul-06	09:00	33.7	38.9	30.6	42.4	42.2	49.8	52.8	51.9	51.9
02-Aug-06	09:30	37.8	39.8	NA	38.8	41.1	43.4	45.3	44.4	44.8
09-Aug-06	12:30	33.8	34.4	NA	NA	NA	NA	NA	39.1	39.9
16-Aug-06	10:30	33.5	33.8	NA	NA	NA	NA	NA	35.1	37
23-Aug-06	09:00	30.2	30.6	NA	NA	NA	NA	NA	34.8	33.1
30-Aug-06	09:00	27.2	28.8	NA	NA	28.3	30.7	NA	28.6	29.6
06-Sep-06	09:30	24.2	26.2	NA	NA	24.1	26.7	NA	24	25.1
20-Sep-06	14:00	25.6	26.6	NA	NA	25.4	26.3	NA	25.6	26.6
04-Oct-06	09:30	23.1	22.6	NA	NA	22.1	23.3	NA	22.1	22.9
18-Oct-06	10:00	22.1	22.7	NA	NA	21.6	22.4	NA	21.3	22.2

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. NA: not available.

Appendix B6

Temperature in turned stockpile of coarse cullet - II (2006)*

Stockpile set up on 28-Jun-2006

Date	Pile	Turned Stockpile (Coarse)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
29-Jun-06	12:00	46.6	40.2	38.3	35.8	35.3	40.4	44.3	44.7	44.1
02-Jul-06	11:45	50.6	49.7	35.5	31.9	52.6	51.1	44.8	44.8	47.9
03-Jul-06	14:00	49	53	37.2	32.3	53.7	53.6	47.7	45.2	48.3
05-Jul-06	09:00	NA	52.9	NA	33.5	53.9	54.9	48.9	49.3	44.2
07-Jul-06	09:10	31.8	50.2	NA	39.8	NA	50.2	50.9	42.7	NA
13-Jul-06	09:00	47.8	57.4	NA	41.3	60.4	67.2	65.2	59.3	68.2
19-Jul-06	08:00	43.2	51.2	NA	57.6	54.2	58.3	63.9	NA	NA
26-Jul-06	09:00	37.4	46.3	52.5	52.4	49	56.1	56.2	54.3	NA
02-Aug-06	09:30	38	36.9	NA	39.8	41.7	41.2	43.6	NA	43.6
09-Aug-06	13:30	35.6	37.7	NA	NA	NA	NA	NA	41.1	42.2
16-Aug-06	10:30	37.2	37.2	NA	NA	NA	NA	NA	39.7	39.4
23-Aug-06	09:00	31.7	31.4	NA	NA	NA	NA	NA	34.4	33.6
30-Aug-06	09:00	27.8	28.9	NA	NA	27.7	29.5	NA	27.3	28.8
06-Sep-06	09:00	25.7	27.1	NA	NA	25	27.3	NA	25.6	25
20-Sep-06	14:00	27.1	27.4	NA	NA	26.8	26.8	NA	24.9	23.2
24-Sep-06	09:30	24.6	25.2	NA	NA	24.5	24.4	NA	23.3	23.3
04-Oct-06	10:00	23.5	23.7	NA	NA	23.5	23.7	NA	23.2	22.8
18-Oct-06	09:30	19.5	21.3	NA	NA	19.3	21.5	NA	17.3	17.1

Date	Pile	Turned Stockpile (Coarse)-B (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
29-Jun-06	12:00	46	47.2	38.8	38	44.9	41.6	39.4		43.1
02-Jul-06	11:45	47.6	56.4	41.5	36	53.8	49.7	43	74.7	46.8
03-Jul-06	14:00	45.3	57.4	45.1	36.9	55.6	53.3	44.1	64.2	44.4
05-Jul-06	09:00	45.6	56.7	47.7	39.1	58.1	54.3	47.4	69.4	48.4
07-Jul-06	09:10	44.7	55.7	47.3	46	53.7	49.9	50.7	44.9	46.2
13-Jul-06	09:00	43.8	54.9	58.4	51.1	57.6	26.6	59.6	NA	NA
19-Jul-06	08:00	NA	60.7	59.8	54.4	55.7	62.2	58.6	58.2	61.3
26-Jul-06	09:00	36.4	41.9	NA	47.6	42.4	50.3	53.6	52.6	55.5
02-Aug-06	09:30	38.1	40.2	37.3	43.9	41.2	NA	44.2	NA	43.9
09-Aug-06	13:30	37.8	37.7	NA	NA	NA	NA	NA	40.8	42.8
16-Aug-06	10:30	37.2	37.9	NA	NA	NA	NA	NA	39.8	40.1
23-Aug-06	10:00	31.2	31.1	NA	NA	NA	NA	NA	33.3	34.6
30-Aug-06	09:00	27.2	28.8	NA	NA	28.3	30.7	NA	28.6	29.6
06-Sep-06	09:00	23.8	25.7	NA	NA	23.6	25.8	NA	23.8	25.8
20-Sep-06	14:00	25.6	26.5	NA	NA	25.3	26.2	NA	25.8	27.3
24-Sep-06	09:30	23.7	24	NA	NA	22.8	23.8	NA	22.7	22.9
04-Oct-06	10:00	21.9	22.6	NA	NA	21.3	22.6	NA	21.3	22.4
18-Oct-06	09:30	18.1	21.5	NA	NA	17.8	20.9	NA	16.8	17.6

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. NA: not available.

Appendix B7

Temperature in lined stockpile of coarse cullet (2006)*

Stockpile set up on 28-Jun-2006

Date	Pile	Lined Stockpile (Coarse)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
29-Jun-06	12:00	NA	44.2	45.7	45.9	47.9	40.1	40.3	46.4	42.2
02-Jul-06	11:45	NA	64.6	47.2	NA	58.3	65	47.9	57.7	53.3
03-Jul-06	14:00	NA	65	53.1	NA	57.4	71.6	55	65.2	58.2
05-Jul-06	09:00	NA	65.7	64.3	NA	54.7	71.6	67.7	70.2	68.5
07-Jul-06	09:10	NA	61.2	66.1	NA	45.6	66.8	74.8	64.4	74.6
13-Jul-06	09:00	NA	52.7	61.2	62.9	44.4	59.9	67.4	55.1	67.6
19-Jul-06	08:00	NA	49.7	56.2	57.5	43.6	56.7	63.3	54	64.1
26-Jul-06	09:00	NA	49.3	56.1	57	40.2	54.7	58.8	50.6	62.2
02-Aug-06	09:30	NA	50.2	54.3	55.4	46.3	53.6	58	53.4	52.9
09-Aug-06	13:30	NA	42.7	46.2	48.2	NA	46.7	49.1	46.1	49.3
16-Aug-06	10:30	NA	44.3	47.6	50.2	40.9	45.5	49.2	44.4	48.8
23-Aug-06	09:00	35.1	39.1	45.7	48.3	36.2	43.4	48.3	42.1	46.7
30-Aug-06	10:00	29.7	NA	46.7	48.9	31.8	42.9	47.8	41.7	40.6
06-Sep-06	10:00	25.6	NA	41.2	45.2	26.7	37.1	42.9	34.6	41
12-Sep-06	10:00	NA	36.1	NA	NA	NA	NA	NA	NA	NA
20-Sep-06	14:00	31.9	35.2	41.6	46.6	30.2	37.2	44.9	35.4	41.9
24-Sep-06	09:30	29.9	38.7	NA	42.9	27.7	35.7	42.9	33.9	40.3
04-Oct-06	10:00	28.8	NA	NA	NA	27.7	32.4	NA	31.2	35.2
10-Oct-06	17:00	29.1	NA	34.9	40.1	28	31.3	36.5	29.7	33.1
18-Oct-06	10:00	24.4	NA	NA	37.9	22.9	29.5	34.7	25.8	30.3
01-Nov-06	08:00	25.3	NA	NA	33.9	21.4	24.4	29.2	22.2	24.5

Date	Pile	Lined Stockpile (Coarse)-B (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
29-Jun-06	12:00	45	41.4	42.7	39.5	45.5	40.6	41.6	NA	NA
02-Jul-06	11:45	58.1	62.9	49.3	42.9	55.6	66.8	50.2	NA	NA
03-Jul-06	14:00	56	65.6	45.9	44.3	53.4	70.6	62.7	75.6	NA
05-Jul-06	09:00	53.6	64.2	NA	50.6	51.3	68.4	73.9	NA	NA
07-Jul-06	09:10	47.8	60.8	NA	65.6	47.3	63.8	NA	NA	76.9
13-Jul-06	09:00	48.8	NA	NA	NA	55.2	59.7	66.3	NA	NA
19-Jul-06	08:00	41.2	NA	NA	60	NA	54.9	62.1	NA	NA
26-Jul-06	09:00	40.2	NA	NA	59.3	NA	54.1	59.4	NA	NA
02-Aug-06	09:30	44.3	NA	41.8	54.8	NA	51.4	55.8	61.6	NA
09-Aug-06	13:30	40.6	NA	NA	49.5	NA	45.8	49.7	46.1	NA
16-Aug-06	10:30	41.3	NA	NA	50.3	NA	45	48.8	42.8	NA
23-Aug-06	10:00	NA	36.9	NA	48.8	NA	44.1	48.4	51.2	48.1
30-Aug-06	10:00	30.9	NA	41.1	50.1	NA	39.9	49.4	NA	NA
06-Sep-06	10:00	26.6	NA	NA	46.2	NA	34.1	43.1	36.3	NA
12-Sep-06	10:00	NA	34.1	NA	NA	NA	NA	NA	NA	NA
20-Sep-06	14:00	31.1	NA	34.3	45.9	NA	35	40.9	32.6	49.9

24-Sep-06	09:30	29.4	NA	NA	42.9	NA	33.3	38.6	31.7	41.3
04-Oct-06	10:00	27.7	NA	NA	NA	29.1	31.1	NA	30	NA
10-Oct-06	17:00	26.1	NA	NA	38.8	NA	28.6	33.8	27.3	34.7
18-Oct-06	10:00	20.8	NA	23.3	36.3	NA	24.4	30.9	23.3	33.8
01-Nov-06	08:00	18.2	NA	16.1	32.7	NA	17.4	25.2	19.7	NA

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. NA: not available.

Appendix B8

Temperature in lined stockpile of fine cullet (2006)*

Stockpile set up on 29-Jun-2006

Date	Pile	Turned Stockpile (Fine)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
02-Jul-06	11:45	57.3	44.9	41.2	40.3	NA	41.8	NA	56.6	46.4
03-Jul-06	14:00	65.6	47.8	42.2	41.7	NA	42.8	NA	57.7	49.7
05-Jul-06	09:00	59.2	50.8	43.9	41.7	NA	44.7	NA	58	52.8
07-Jul-06	09:10	51.4	52.6	45.2	43.3	NA	46.8	NA	52.3	52.1
13-Jul-06	09:00	55.2	60.9	51.1	47.1	NA	51.8	NA	53.1	58.1
19-Jul-06	08:00	47.2	62.4	60.5	52.5	NA	57.3	NA	51	58.5
26-Jul-06	09:00	44.7	59.7	62.5	55.7	NA	58.6	NA	47.9	58.7
02-Aug-06	09:30	45.3	53.4	57.8	54.2	NA	56.8	NA	48.8	55.3
09-Aug-06	13:30	42.3	50.1	55.3	55.2	NA	41	NA	NA	52.3
16-Aug-06	10:30	40.3	48.2	41.2	57.3	NA	56	NA	43.6	50.1
23-Aug-06	09:00	38.9	47.2	53.4	59.7	NA	57.9	NA	41.7	50.7
30-Aug-06	10:00	31.4	42.1	51.7	58.1	NA	53.9	NA	35.1	45.6
06-Sep-06	10:00	29.1	41.9	46.7	51.8	NA	47.7	NA	32.2	40.8
20-Sep-06	14:00	32.5	41.6	46.6	50.2	NA	47.9	NA	35.2	42.7
24-Sep-06	09:30	31.2	39.2	45.8	47.3	NA	47	NA	32.2	41
04-Oct-06	10:00	29.3	36.2	NA	NA	NA	43.4	NA	31.6	37.4
10-Oct-06	17:00	26.9	33.3	39.1	40.9	NA	40	NA	27.8	34.4
18-Oct-06	10:00	22.2	31.9	37.6	39.9	NA	38.7	NA	23.9	31.1
01-Nov-06	08:00	19.1	26.3	34.4	NA	NA	34.8	NA	21.2	26.9
14-Nov-06	08:00	19.7	25.9	30.7	33.6	NA	31.1	NA	19.5	NA

Date	Pile	Turned Stockpile (Fine)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
02-Jul-06	11:45	55.7	NA	40.6	38.1	54.1	46.6	41.4	52.2	47.1
03-Jul-06	14:00	57	47	41.9	42.8	51.9	49.6	41.3	54.8	49.6
05-Jul-06	09:00	57.8	NA	42.5	NA	54.3	51.7	44.2	56.3	53
07-Jul-06	09:10	50.1	NA	31.4	NA	47.8	50.6	46.4	50.7	53.3
13-Jul-06	09:00	54.8	NA	49.8	NA	50.1	56.9	51.3	58.1	NA
19-Jul-06	08:00	49.7	NA	56.3	NA	45.1	58.2	56.3	54.9	59.8
26-Jul-06	09:00	44.7	NA	58.2	NA	NA	56.8	58.3	50.3	56.2
02-Aug-06	09:30	46.2	NA	54.1	NA	NA	NA	55.3	51.1	55.3
09-Aug-06	13:30	43.1	NA	54.4	NA	NA	53.5	55.1	48.1	51.7
16-Aug-06	10:30	42	61.7	55.6	38.2	46.2	NA	56.7	47	50.1
23-Aug-06	09:00	39.4	56.7	57.6	NA	NA	52.3	59.2	47.9	49.8
30-Aug-06	10:00	32.9	42.1	54.9	NA	NA	44	55.9	39.7	45.6
06-Sep-06	10:00	29.7	NA	48.4	NA	27.7	39.5	48.7	34.3	33.9
20-Sep-06	14:00	32.5	NA	47.6	NA	30.5	40.9	48.3	36.5	41.7
24-Sep-06	09:30	29.9	NA	31.8	NA	NA	39.5	46.4	NA	NA
04-Oct-06	10:00	28.8	NA	NA	NA	NA	36.5	NA	33.1	38.3
10-Oct-06	17:00	25.2	NA	40.2	NA	26.4	32.5	40.3	29.7	33.8

18-Oct-06	10:00	21.7	22.9	38.2	NA	21.5	30.1	37.6	25.8	31.1
01-Nov-06	08:00	17	NA	34.6	NA	14.9	24.8	34.7	20.9	25.5
14-Nov-06	08:00	19	NA	32.1	NA	22.6	22.7	30.1	20.7	24

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. NA: not available.

Appendix B9

Oxygen levels in turned stockpile of coarse cullet (2007)*

Stockpile set up on 24-Jul-2007

Date	Pile	Turned Stockpile (Coarse)-A (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
27-Jul-07	14:00	19.8	16.2	9.3	4.3	14	9.2
30-Jul-07	15:30	20	19.5	18.3	16.1	20.1	18.8
01-Aug-07	09:30	19.3	16	10	7.5	14	12.5
03-Aug-07	13:00	20	19	16	17	20	15.5
07-Aug-07	10:30	20	18.5	16.5	14	16	16
09-Aug-07	10:00	20	20	19	14.5	18.5	13
13-Aug-07	11:00	19.5	18.5	17.5	16	16.5	15.5
29-Aug-07	12:30	20.4	18.9	17.3	16.5	19	17.3
02-Sep-07	17:00	20.7	20.5	19.4	18.7	20.2	18.9
04-Sep-07	09:30	20.7	20	18.4	18.1	19	19.2

Date	Pile	Turned Stockpile (Coarse)-B (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
27-Jul-07	14:00	20.2	17.1	4	4.8	5.9	4.9
30-Jul-07	15:30	20.5	20	18.8	15.8	15.5	17.9
01-Aug-07	09:30	20	18	15	8	19.5	13
03-Aug-07	13:00	19.5	19	17	13	17	15
07-Aug-07	10:30	19	18	17	15.5	16	13
09-Aug-07	10:00	19	15	11.5	9.5	18	15.5
13-Aug-07	11:00	19.5	19.5	19	18.5	19	18.5
29-Aug-07	12:30	20.6	20	17.9	16.6	19.4	17.5
02-Sep-07	17:00	20.8	20.5	20.1	19.1	20.3	19.4
04-Sep-07	09:30	20.4	20.2	19.6	19	20.9	20.3

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. Note: Stockpiles turned on Jul-26, Jul-31, Aug-7, Aug-13, and Sep-7. Measurements taken immediately before turning if on the same day.

Appendix B10

Oxygen levels in lined stockpile of coarse cullet (2007)*

Stockpile set up on 24-Jul-2007

Date	Pile	Lined Stockpile (Coarse)-A (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
25-Jul-07	15:00	14.3	6	0.5	0	6.9	3.2
26-Jul-07	10:00	19	15	1	0	7	1
27-Jul-07	13:30	18.6	15.7	3.9	4.4	10.5	4
30-Jul-07	15:30	20.5	20.1	17.9	19	19.8	17.2
01-Aug-07	09:00	20	19.5	17	14	18	15
03-Aug-07	11:00	17.5	17	16	15	17	15
06-Aug-07	15:30	21	21	20.8	20.5	20.5	19.8
09-Aug-07	09:00	20	19.5	19	18.5	19.5	19
13-Aug-07	10:00	19.5	18.5	18	18.5	18.5	18
29-Aug-07	12:00	20.4	19.7	19.2	18.7	19.8	19.4
02-Sep-07	17:00	20.7	20.4	20.3	20	20.3	20.2
06-Sep-07	13:00	20.2	20	19.7	19.4	20.4	19.9
10-Sep-07	19:00	20.5	20.5	20.2	20.2	20.3	20.1

Date	Pile	Lined Stockpile (Coarse)-B (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
25-Jul-07	15:00	12.5	3.1	1.2	0	3	2.6
26-Jul-07	10:00	19	4	1	0	5	1
27-Jul-07	13:30	19.9	14.9	2.8	5.1	6	2.3
30-Jul-07	15:30	20.2	18.8	18.8	20.1	17.6	17.8
01-Aug-07	09:00	ND	ND	ND	ND	ND	ND
03-Aug-07	11:00	18.5	18	17	15	18.5	16
06-Aug-07	15:30	21	20.5	20	19.8	21	20
09-Aug-07	09:00	20.5	20.5	19.5	19	20	19.5
13-Aug-07	10:00	20	20	19.5	19	19	18
29-Aug-07	12:00	20.7	20.2	19.7	19.1	20.8	19.4
02-Sep-07	17:00	20.7	20.5	20.2	19.9	20.5	20.2
06-Sep-07	13:00	20.1	19.9	19.6	19.1	20.5	19.8
10-Sep-07	19:00	20.4	20.2	20	20	20.1	20.1

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. ND: not determined.

Appendix B11

Oxygen levels in aerated lined stockpile of fine cullet (2007)*

Stockpile set up on 01-Aug-2007

Date	Pile	Lined Stockpile (Fine)-A (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
02-Aug-07	13:00	13.5	11	6	7	9	11
03-Aug-07	11:00	15	10	10.5	14.5	9.5	6
06-Aug-07	15:30	17.5	11	7.5	11	10.5	9.5
08-Aug-07	10:00	18	15	13	13.5	15.5	14
10-Aug-07	11:00	18.9	16.2	15.3	15.4	17.2	15.9
13-Aug-07	10:00	19.5	18	17.5	16.5	16.5	15
29-Aug-07	12:00	20.3	18	16.9	16.3	19.3	15.8
02-Sep-07	17:00	19.8	18.5	18.2	18	18.4	17.9
06-Sep-07	13:00	20.1	19	18.5	18.6	19.2	18.6
08-Sep-07	11:00	20.4	19.6	18.9	20.2	19.6	20.4
11-Sep-07	13:00	20.4	20	19.6	19.7	19.9	19.9

Date	Pile	Lined Stockpile (Fine)-B (% O_2)					
	Height (ft)	1.5				4.5	
	Depth (ft)	2	4	6	8	2	4
02-Aug-07	13:00	14	12.5	10.5	10	6	6
03-Aug-07	11:00	14	8.5	7	16.5	14	10.5
06-Aug-07	15:00	18.5	14	12	14	14	9
08-Aug-07	10:00	20	18	17	17.5	16.5	14
10-Aug-07	11:00	18.1	15	11.2	13.8	16.5	14.5
13-Aug-07	10:00	18.5	17	16	16.5	17	15
29-Aug-07	12:00	20.8	18.3	17.3	16.3	20.2	15
02-Sep-07	17:00	19.4	18.8	17.8	18.2	18.4	17.7
06-Sep-07	13:00	20.1	18.9	18.3	18.4	19.1	18.7
08-Sep-07	11:00	20.7	20.5	19.5	18.5	20.4	19.5
11-Sep-07	13:00	20.3	20.1	19.9	19.9	20.4	20.2

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west.

Appendix B12

Temperature in turned stockpile of coarse cullet (2007)*

Stockpile set up on 24-Jul-2007

Date	Pile	Turned Stockpile (Coarse)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
27-Jul-07	13:30	51.6	51	43.3	36.5	57.2	56.4	48.4	57.1	55.4
30-Jul-07	15:00	43.4	37.1	52.6	51.9	58.3	61.2	64.9	62.6	NA
1-Aug-07	09:00	43.4	37.3	43	47.3	44.9	47.1	49.6	47.7	52.4
3-Aug-07	13:00	53.4	58.9	62.2	64.7	55.6	66.6	67.3	66.1	67.3
7-Aug-07	10:30	42.5	47.2	49.5	49.6	55.7	62.1	61.8	61.7	62.1
9-Aug-07	10:00	40.5	39.3	37.4	37.2	42.3	42.3	45.2	42.7	47.2
13-Aug-07	11:00	39.4	42.7	45.1	46.8	42.3	47.1	48.4	48.3	49.4
15-Aug-07	10:30	38.7	40.4	39.9	38.6	42.9	46.6	47.9	44.3	46.3
17-Aug-07	11:00	38.4	41.3	42.7	43.5	41.6	46.3	48.1	42.3	46.6
20-Aug-07	12:00	30.4	36.7	39.9	41.6	33.1	42.1	46.2	39.2	44.9
22-Aug-07	14:00	26.2	32.4	37.4	42.3	31.1	38.3	41.9	33.8	37.5
27-Aug-07	12:30	31.2	33.6	35.8	38.2	32.8	36.3	38.7	35.4	37.2
2-Sep-07	17:00	33.4	33.8	34.9	34.4	34.9	35.6	34.9	35.9	37.2
4-Sep-07	09:30	29.3	31.7	33.4	33.8	33.2	34.8	35.8	34.7	35.6

Date	Pile	Turned Stockpile (Coarse)-B (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
27-Jul-07	13:30	53.1	55.2	52	48.1	58.7	55.3	51	56.3	54.5
30-Jul-07	15:00	35	41.5	40.6	44.5	53.6	56.9	58.6	63.4	65.6
1-Aug-07	09:00	47.2	35.6	35.2	35.3	46.6	43.2	41.8	52.7	55.6
3-Aug-07	13:00	49	56.7	61.3	65.3	51.7	64.2	67.8	66.1	67.7
7-Aug-07	10:30	39.8	46.3	51.9	57.8	51.9	58.7	61.6	59.4	60.2
9-Aug-07	10:00	38.7	41.5	44.1	45.4	43.2	47.8	49.7	47.8	47.3
13-Aug-07	11:00	32.3	35.3	37.5	38.4	41.3	45.3	47.7	43	47.1
15-Aug-07	10:30	38.1	39.3	40.7	41.8	43.6	45.5	47.4	46.4	47.7
17-Aug-07	11:00	36.4	38.4	41.7	43.2	41.5	44.2	46.7	44.4	47
20-Aug-07	12:00	28.8	34.9	39.9	42.1	34.1	39.9	45.1	38.7	45.3
22-Aug-07	14:00	25.4	30.8	36.8	39.4	31.1	39.3	43.9	36.2	42.7
27-Aug-07	12:30	32	33.1	37.4	38.3	34.3	37.7	40.3	38.1	39.4
2-Sep-07	17:00	30.9	32.1	32.7	33.2	33.7	35.1	36	35.6	37.3
4-Sep-07	09:30	29.6	30.4	31.2	31.6	31.5	33.3	34.6	33.4	35.6

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west.
Note: Stockpiles turned on Jul-26, Jul-31, Aug-7, Aug-13, Aug-20, and Sep-4. Measurements taken immediately before turning if on the same day.

Appendix B13

Temperature in aerated lined stockpile of coarse cullet (2007)*

Stockpile set up on 24-Jul-2007

Date	Pile	Lined Stockpile (Coarse)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
25-Jul-07	15:00	47.2	51.1	43.3	43.8	49.6	45.9	41.6	48.5	42.5
26-Jul-07	10:00	51.6	35.7	49.6	49.1	56.9	52.6	46.7	53.8	48.3
27-Jul-07	12:30	50.4	59.1	57.2	52.3	65.1	61.7	49.5	62.4	53.1
30-Jul-07	15:00	44.9	60	63.2	53.5	60.5	64.8	62.6	64.3	65.8
1-Aug-07	09:00	46.4	57.9	61.6	50.7	57.8	62.3	59.8	61.7	61.8
3-Aug-07	11:00	44.6	56.6	63.4	62.3	56.2	63.6	65.3	61	64.2
6-Aug-07	15:30	39.3	52.7	61.6	63.6	53.4	63.2	65.4	60.1	65.8
9-Aug-07	09:00	41	50.7	59.7	62.3	51.6	60.8	63.1	57.8	63.2
13-Aug-07	10:00	37.7	36.2	52.5	55.6	44.3	52.9	56.7	51.1	55.7
17-Aug-07	10:30	36.3	43.4	50.3	53.7	42.8	50.6	54.8	49.3	54.4
20-Aug-07	13:30	30.4	43.4	49.4	52.4	39.7	48.6	52.5	45.8	51.8
22-Aug-07	12:30	27.1	44.4	50	49.8	40.4	48.9	47.8	45.3	46.3
27-Aug-07	12:30	37.1	42.7	49.6	47.9	42.4	50.4	49.1	45.3	49.5
2-Sep-07	17:00	NA	35.8	46.6	47.2	40.4	45.9	47.2	43.8	NA
6-Sep-07	13:00	39.2	42.7	44.9	45.3	41.2	44.4	45.9	41.9	43.9
10-Sep-07	19:00	35.9	36.6	39	45.1	35.4	37.9	39.7	36.7	41.4

Date	Pile	Line Stockpile (Coarse)-B (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
25-Jul-07	15:00	50.3	45.2	47.3	40.7	49.3	38.7	41.5	43.2	44.3
26-Jul-07	10:00	54.4	53.8	42.4	46.5	54	45.1	43.7	50.4	48.1
27-Jul-07	12:30	54.9	61.3	NA	49.8	64.3	55.8	48	57.2	NA
30-Jul-07	15:00	46	58.2	NA	58.7	57	66	63.4	NA	66.7
1-Aug-07	09:00	46	54.8	60.2	56.2	54.3	63.8	60.9	64.2	63.1
3-Aug-07	11:00	46.4	53.7	65.9	64.5	53.3	65.2	65.9	62	NA
6-Aug-07	15:30	41.6	52.8	61.8	65.3	50.9	65.3	67.1	62	NA
9-Aug-07	09:00	39.9	48.7	NA	62.4	44.2	52.2	63.8	54	NA
13-Aug-07	10:00	36.1	42.4	NA	57.2	39.8	54.3	57.2	52.2	NA
17-Aug-07	10:30	38.6	NA	NA	55.1	37.3	NA	55.6	49.1	NA
20-Aug-07	13:30	NA	NA	NA	52.3	33.6	47.1	52.2	43.1	NA
22-Aug-07	12:30	24.2	46.6	NA	49.6	31.5	46.4	49.4	41.2	NA
27-Aug-07	12:30	34.5	NA	NA	49.2	37.6	NA	49.3	44.3	NA
2-Sep-07	17:00	31.9	NA	NA	47.8	NA	35.3	47.6	40.2	NA
6-Sep-07	13:00	35.7	40	43.4	44.7	37	41.6	45.3	41.1	44.3
10-Sep-07	19:00	36.2	40.3	42	39.2	36.2	38.9	43.7	38.8	40.6

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west.
NA: not available.

Appendix B14

Temperature in aerated lined stockpile of fine cullet (2007)*

Stockpile set up on 01-Aug-2007

Date	Pile	Lined Stockpile (Fine)-A (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
02-Aug-07	13:00	52.1	41.7	41.8	40.1	45.1	40.9	40.9	44.2	47.9
03-Aug-07	11:00	57.8	50.3	51.3	55.6	57.6	47.8	51.2	NA	52.7
06-Aug-07	15:00	57.2	66.8	65.6	66.1	69.7	69.2	69.3	68.8	67.2
08-Aug-07	10:00	54	66	66.7	66.7	66.9	70.1	69.8	70	70.1
10-Aug-07	11:00	52.8	64.8	64.2	63.8	63.4	69.2	67.5	67.3	68.2
13-Aug-07	10:00	47.9	59.1	62.3	63.7	NA	64.6	65.6	62.8	64.6
15-Aug-07	13:00	46.4	57.4	61.2	62.6	NA	63.4	64.1	NA	63.3
17-Aug-07	10:30	46	56.6	63.2	60.2	55.9	62.1	64.2	NA	61.8
20-Aug-07	13:30	39.9	52.9	59.8	60.8	NA	59.6	61.2	NA	57
22-Aug-07	12:30	37.1	54.3	57.4	57.2	NA	58.1	58.7	NA	53.5
27-Aug-07	12:30	NA	52.3	56	56.2	NA	52.7	53.2	NA	47.6
02-Sep-07	17:00	40.2	50.5	49.1	54.8	NA	52.2	52.9	NA	47.7
06-Sep-07	13:00	38.1	45.1	48.9	50.7	43.6	49.2	51.1	43.9	46.1
08-Sep-07	11:00	37.8	46.3	50.3	51.7	43.2	48.2	48.6	42.9	42.3
11-Sep-07	13:00	39.1	43.6	48.4	47.8	39.7	44.7	46.5	41.1	42.1

Date	Pile	Lined Stockpile (Fine)-B (°C)								
	Height (ft)	1.5				3.0			4.5	
	Depth (ft)	2	4	6	8	2	4	6	2	4
02-Aug-07	13:00	53.7	43	42.4	44.1	51.4	41.3	41.9	NA	44.2
03-Aug-07	11:00	58.3	54.2	51.3	52.4	55.4	54.1	54.1	51.8	57.3
06-Aug-07	15:00	59	NA	64.9	NA	66.5	65.5	70.1	NA	66.2
08-Aug-07	10:00	NA	NA	NA	NA	66.5	72.5	71.3	NA	70.4
10-Aug-07	11:00	NA	NA	68.5	NA	63.2	70.7	69.9	NA	69.5
13-Aug-07	10:00	33.1	NA	64.8	32.8	31.4	66.3	66.2	NA	63.9
15-Aug-07	13:00	39.4	NA	63.8	37.4	55.3	64.7	65.2	NA	62.7
17-Aug-07	10:30	NA	NA	62.2	38.5	52.3	62.3	64.3	NA	57
20-Aug-07	13:30	NA	NA	59.8	NA	47.1	58.6	60.8	NA	55.2
22-Aug-07	12:30	NA	NA	57.8	NA	43.5	56.8	57.8	NA	52.1
27-Aug-07	12:30	NA	NA	55	37.1	44.1	50.2	51.1	NA	47.2
02-Sep-07	17:00	NA	NA	53.3	NA	42.1	48.4	50.4	NA	45.7
06-Sep-07	13:00	40.9	44.3	51.1	53.2	41.3	47	50.2	42.9	45.7
08-Sep-07	11:00	37.1	40.7	46.7	46.7	37.7	43.2	44.5	41.8	41.4
11-Sep-07	13:00	39.4	44.2	47.6	46.8	38.1	42.4	43.5	37.5	39.5

* Temperatures were measured at two profiles (A and B), one facing to the south and one facing to the west. NA: not available.

Appendix B15

On-site rain gauge readings

Date/time	Rainfall (inch)	Date/time	Rainfall (inch)	Date/time	Rainfall (inch)
6/1/07 0:00	0.00	7/10/07 0:00	0.00	8/13/07 0:00	0.00
6/2/07 0:00	0.00	7/11/07 0:00	0.45	8/14/07 0:00	0.00
6/3/07 0:00	0.00	7/12/07 0:00	0.01	8/15/07 0:00	0.00
6/4/07 0:00	0.00	7/13/07 0:00	0.00	8/16/07 0:00	0.00
6/5/07 0:00	0.00	7/14/07 0:00	0.00	8/17/07 0:00	0.69
6/6/07 0:00	0.00	7/15/07 0:00	0.00	8/18/07 0:00	0.00
6/7/07 0:00	0.00	7/16/07 0:00	1.21	8/19/07 0:00	1.50
6/8/07 0:00	0.00	7/17/07 0:00	0.28	8/20/07 0:00	1.26
6/9/07 0:00	0.00	7/18/07 0:00	1.10	8/21/07 0:00	0.57
6/10/07 0:00	0.00	7/19/07 0:00	0.10	8/22/07 0:00	0.01
6/11/07 0:00	0.00	7/20/07 0:00	0.00	8/23/07 0:00	0.00
6/12/07 0:00	0.00	7/21/07 0:00	0.02	8/24/07 0:00	0.00
6/13/07 0:00	0.00	7/22/07 0:00	0.44	8/25/07 0:00	0.00
6/14/07 0:00	1.95	7/23/07 0:00	0.15	8/26/07 0:00	0.00
6/15/07 0:00	0.00	7/24/07 0:00	0.00	8/27/07 0:00	0.00
6/16/07 0:00	0.00	7/25/07 0:00	0.00	8/28/07 0:00	0.00
6/17/07 0:00	0.00	7/26/07 0:00	0.00	8/29/07 0:00	0.00
6/18/07 0:00	0.00	7/27/07 0:00	0.59	8/30/07 0:00	0.00
6/19/07 0:00	0.12	7/28/07 0:00	0.00	8/31/07 0:00	0.00
6/20/07 0:00	0.35	7/29/07 0:00	0.03	9/1/07 0:00	0.00
6/21/07 0:00	0.00	7/30/07 0:00	0.00	9/2/07 0:00	0.00
6/22/07 0:00	0.00	7/31/07 0:00	0.03	9/3/07 0:00	0.00
6/23/07 0:00	0.00	8/1/07 0:00	0.00	9/4/07 0:00	0.00
6/24/07 0:00	0.00	8/2/07 0:00	0.00	9/5/07 0:00	0.00
6/25/07 0:00	0.00	8/3/07 0:00	0.00	9/6/07 0:00	0.00
6/26/07 0:00	0.05	8/4/07 0:00	0.00	9/7/07 0:00	0.00
6/27/07 0:00	0.23	8/5/07 0:00	0.15	9/8/07 0:00	0.00
6/28/07 0:00	0.44	8/6/07 0:00	0.03	9/9/07 0:00	0.00
6/29/07 0:00	0.02	8/7/07 0:00	0.02	9/10/07 0:00	0.04
6/30/07 0:00	0.00	8/8/07 0:00	0.00	9/11/07 0:00	0.48
7/1/07 0:00	0.00	8/9/07 0:00	0.16	9/12/07 0:00	0.00
7/2/07 0:00	0.00	8/10/07 0:00	0.01		
7/3/07 0:00	0.00	8/11/07 0:00	0.00		
7/4/07 0:00	0.23	8/12/07 0:00	0.01		
7/5/07 0:00	0.27	8/13/07 0:00	0.00		
7/6/07 0:00	0.00	8/14/07 0:00	0.00		
7/7/07 0:00	0.00	8/15/07 0:00	0.00		
7/8/07 0:00	0.00	8/16/07 0:00	0.00		
7/9/07 0:00	0.00	8/17/07 0:00	0.69		

Appendix B16

Pressure transducer readings of leachate quantities

Date	Leachate in Coarse Stockpile (feet)	Leachate in Fine Stockpile (feet)	Date	Leachate in Coarse Stockpile (feet)	Leachate in Fine Stockpile (feet)
7/24/07	0	NC	8/19/07	1.23	1.18
7/25/07	0	NC	8/20/07	2.31	2.46
7/26/07	0	NC	8/21/07	1.69	1.45
7/27/07	0	NC	8/22/07	1.71	1.65
7/28/07	0.33	NC	8/23/07	0.43	0.33
7/29/07	0	NC	8/24/07	0.1	0.1
7/30/07	0	NC	8/25/07	0.12	0.12
7/31/07	0	NC	8/26/07	0.15	0.14
8/01/07	0	0	8/27/07	0.14	0.14
8/02/07	0	0	8/28/07	0	0
8/03/07	0	0	8/29/07	0	0
8/04/07	0	0	8/30/07	0	0
8/05/07	0	0	8/31/07	0	0
8/06/07	0	0	9/01/07	0	0
8/07/07	0	0	9/02/07	0	0
8/08/07	0	0	9/03/07	0	0
8/09/07	0	0	9/04/07	0	0
8/10/07	0	0	9/05/07	0	0
8/11/07	0	0	9/06/07	0	0
8/12/07	0	0	9/07/07	0	0
8/13/07	0	0	9/08/07	0	0
8/14/07	0	0	9/09/07	0	0
8/15/07	0	0	9/10/07	0	0
8/16/07	0	0	9/11/07	0.36	0.36
8/17/07	0.69	0.3	9/12/07	-	0.47
8/18/07	0	0.65			

NC: not constructed yet.
- : report terminated

Appendix C

Supplemental Information for Chapter 4

Appendix C1

Survey of MRFs about the fate of their glass cullet

Dear Class A Recycling Facility Manager:

I would like to ask you if you would voluntarily share information about the end markets of your recycled glass. This survey is administered by me, a professor at Rutgers University, and Ching-Ling Tsai, one of my graduate students.

The purpose of this survey is to quantify the end markets of recycled glass containers in New Jersey. I expect that the results of the survey together with other data will improve recycling in New Jersey. All Class A recycling facilities in New Jersey are contacted. I would appreciate it if you quantified your end markets for glass containers in the table below, and provided your contact information:

Contact:	**Tel:**	**Email:**

Please check in the box if single-stream or/and dual-stream is the collection method for your facility in 2008:
□ Single-stream curbside collection □ Dual-stream curbside collection

	Quantity in tons per year (2008)					
	In New Jersey (Please specify locations)			**Outside** New Jersey (Please specify locations)		
End Markets	**Clear**	**Brown**	**Mixed-color**	**Clear**	**Brown**	**Mixed-color**
1. Container glass manufacturers	Location: Quantity:					
2. Glass fiber manufacturers	Location: Quantity:					

3. Construction aggregates (e.g., road pavement, drainage backfills, septic tank filtering system, etc.)	Location: Quantity:					
End Markets	**Clear**	**Brown**	**Mixed-color**	**Clear**	**Brown**	**Mixed-color**
4. Daily cover in landfills	Location: Quantity:					
5. Drainage layer in landfills	Location: Quantity:					
6. Disposal in landfills	Location: Quantity:					
7. Other uses (specify:……… ……………….)	Location: Quantity:					

Confidentiality. All information will be kept confidential and anonymous. Survey responses will not be linked to an individual's identity. Your decision to fill out the survey or not will have no effect on you either now or in the future.

Appendix C2

Distance and transportation type for collection and transport of glass containers, cullet, and raw materials

Material	From	To	Travel distance (mi)	Transport type
Glass container product	P_A, P_B, foreign countries, or other states	P_C	903 (other states); 2000-3645 (other countries)	Tractor-trailer (domestic), rail‡ (Mexico), or ocean freighter# (EU)
Recycled glass containers	P_C	P_D	10[a]	Recycling truck[a]
Disposed glass containers	P_C	P_E, P_F, or other states	10[a]	Refuse collection truck[a]
MSW	Transfer station	P_F, P_E, or other states	110[f] (tractor-trailer) 366[f] (rail)	Tractor-trailer[b] or rail[c]
Cullet	P_D or other states	P_I	73 (optical sorter)-126 (non-optical sorter)[g]	Tractor-trailer[d]
Cullet	P_I	P_A, or container or fiberglass manufacturing plants in other states	364[g]	Tractor-trailer[d]
Raw material	Mining sites (in or out of NJ)	P_A, or container manufacturing plants in other states	10-2020[h] (for P_A in NJ); 200-2200[i] (for container manuf. plants in other states)	Tractor-trailer[e] or rail[c]

P_A, container manufacturers; P_B, bottling/distribution ; P_C, consumers (residents or businesses); P_D, MRFs and drop-off centers; P_E, waste-to-energy facilities; P_F, landfills; P_G, construction industry; P_H, other end markets, and P_I, intermediate cullet processing facilities.

‡ Rail: 374-388 Btu/ton-mi (US EPA, 2006a), including pre-combustion energy for fuel acquisition.

Ocean freighter: 330 Btu/ton-mi (US EPA, 2004), including pre-combustion energy for fuel acquisition.

[a] Based on ISWM-DST (Solano *et al.*, 2002ab; Kaplan *et al.*, 2004). Recycling trucks: 1.60-1.65 tons per load; refuse collection trucks: 5.6 tons per load.

[b] Average mass per load: 20 tons (NJDEP, 2008b).

[c] Average mass per load: 100 tons per cart (Ruth and Dell'Anno, 1997; NJDEP, 2008b).

[d] Average mass per load: 22 tons (Gaines and Mintz, 1994; RMTC, 2003).

[e] Average mass per load: 25 tons (Russ Hunter, Anchor Glass, 2009, personal communication).

[f] NJDEP (2008a).

[g] Facility reports (Jim Yezzo, Strategic Materials, 2009, personal communication).

[h] Appendix C4.

[i] Gaines and Mintz (1994).

1 short ton = 0.9072 metric tons.

1 mile = 1.6093 km

Appendix C3

Contribution of single family home areas, multifamily house areas and commercial areas to generated MSW in New Jersey

	Contribution to generated MSW[a] (%)	Disposed glass containers (Tons)	Recycled glass containers (Tons)
Urban counties[1]			
Single-family	21%	17,352	35,488
Multi-family	19%	15,699	32,108
Commercial	60%	49,576	101,395
Semi-urban counties[2]			
Single-family	44%	30,129	56,481
Multi-family	14%	9,586	179,71
Commercial	42%	28,417	53,272
Rural counties[3]			
Single-family	73%	4,978	12,148
Multi-family	15%	1,023	2,496
Commercial	12%	818	1,997

Note: Single-family housing are structures containing only 1 housing unit; multi-family housing are structures containing 2 or more housing units (Census Bureau, 2003).
1 short ton = 0.9072 metric tons.
[a] Adapted from US EPA (1994) and US Census Bureau (2003).
[1] Included Bergen, Camden, Essex, Hudson, Passaic, Middlesex, and Union; [2] Atlantic, Burlington, Cape May, Cumberland, Gloucester, Mercer, Monmouth, Morris, Ocean, and Somerset; [3] Hunterdon, Salem, Sussex, and Warren counties.

Appendix C4

Energy consumption for raw materials extraction and processing and transportation distances

	Quantities for the production of 1 ton of glass containers	Estimated one-way transportation distances to glass container manufacturers in NJ and in the US[‡]	Energy (combustion only) to mine and process for raw materials (Btu/ton)
Silica sand [a]	0.65	NJ: 2-18 miles (from Bridgeton, Newport, Mauricetown, or Millville, NJ) US: 100 miles	710,000 [*]
Soda ash [b]	0.22	NJ: 2020 miles (from Green River, WY) US: 1100 miles	7,200,000 [†]
Limestone [a]	0.15 - 0.19	NJ: 199 miles (from Strasburg, VA), or 221 miles (from Middletown, VA) US: 150 miles	32,013[†]
Feldspar [a] or aplite [a]	0.11 - 0.15	NJ: 245 miles (from closest source of feldspar), or 212 miles (Aplite from Milfore, VA) US: 430 miles	1,370,000 [√ ‡] (feldspar and aplite)

[a] Transport via tractor-trailer with a capacity of 25 ton/truck; [b] Transport via rail with a capacity of 100 ton/cart.
1 short ton = 0.9072 metric tons.
1 mile = 1.6093 km.
1 Btu = 1055.06 Joules
[*] Estimated based on US DOE (2005).
[†] US DOE (2002b).
[√] Aplite is a commercial term which essentially contains feldspar (60%) and quartz (30%) (Kogel *et al.*, 2006). Exploration, mining and processing of feldspar and aplite deposits are fairly similar (Kennedy, 1990).
[‡] Gains and Mintz, 1994.

Appendix C5

Specific energy consumption for current glass container recycling system in New Jersey (2008)

Process category	Sub-process	Specific energy consumption (kBtu/ton)
Raw Material Extraction, Transport, & Associated Upstream Energy[‡]	Virgin raw material extraction (for NJ)	18.7
	Virgin raw material extraction (for US)	1,085.5
	Virgin raw material transportation to NJ container manuf.	6.2
	Virgin raw material transportation to US container manuf.	276.4
	Cullet transport from out-of-state source to NJ glass container manuf.	1.2
	Cullet transport from NJ MRFs/intermediate processing facilities to NJ glass container manuf.	0.2
	Cullet transport to US glass manuf.	69.3
	Upstream energy[‡] for cullet from out-of-state sources to NJ glass container manuf.	3.2
	Upstream energy[‡] for cullet from New Jersey MRFs/intermediate cullet processors to New Jersey glass manuf.	3.1
	Upstream energy[‡] for cullet to US glass container manuf.	305.1
Container Glass Manuf.	Manufacturing energy for NJ in-house cullet	20.7
	Manufacturing energy for US in-house cullet	1,277.2
	Cradle-to-gate energy (raw material extraction plus manufacturing) for foreign imports with 63% cullet	1,011.2
	NJ manufacturing energy with 33% cullet content	179.7
	US manufacturing energy with 30% cullet content	10,841.0
Product Distribution & Transportation	Domestic glass container wholesale and retail distribution[#]	914.4
	Foreign glass container product import/transport[Δ]	100.8
Discarded Glass Container Disposal & Transportation	Discarded glass container collection in MSW	86.6
	Discarded glass container transportation in MSW	99.4
	Waste-to-energy (= energy loss)	18.7
	Residual (glass) transport from waste-to-energy facilities to landfills	1.5
Recycling Collection and Cullet Processing at MRFs	Recycled glass collection & transport[†]	769.5
	Recycled glass container processing/sorting[*]	91.4

Sorted Cullet Transportation from MRFs	Transport to intermediate cullet processors	33.5
	Transportation to construction sites	10.8
	Transportation to glass container manuf.	0.5
	Transportation to landfills for aggregate use	29.9
	Export to other states (export)	1.1
Cullet Re-processing at Intermediate Cullet Processing Facilities	Recycled glass (re)processing in intermediate cullet processing facilities with optical sorting	32.9
	Recycled glass processing in intermediate cullet processing facilities without optical sorting	1.7
Re-processed Cullet Transportation from Intermediate Cullet Processing Facilities	Transportation to glass manuf.	7.2
	Transportation to other end markets in NJ	1.4
	Transportation to construction sites	1.6
	Transportation to other state (export)	28.1
	Residuals transport to landfills	1.9
Energy Credits for Cullet Reuse	Cullet used at NJ glass container manuf.	-298.3
	Cullet used in NJ landfills as daily cover or at construction industries as aggregate	-184.1
	Cullet used in NJ fiberglass manuf.	-113.9
	Cullet exported to out-of-state container glass manuf.	-138.2
	Cullet exported to out-of-state fiberglass manuf.	-38.2

Negative values: energy credits.
‡ Upstream energy includes energy associated with collection, processing, and manufacturing.
# Based on WAste Reduction Model by US EPA (2004).
Δ Mainly from Mexico, Holland, Germany, France and Italy.
† Assuming 97.5% curbside (including collection for bars and restaurants) and 2.5% drop-off collection (by mass).
* Assuming 90% dual-stream processing and 10% single-stream processing (by mass).
1 kBtu = 1.0551 kJ

Appendix C6

Sensitivity ratios (SR)

Input (X_1)	X_1*200%	Unit	Output‡	SR†	Input Description
Virgin Raw Material Extraction and Transportation					
781,082	1,562,163	Btu/ton	7,947,656	1.84%	Specific energy for sand extraction (combustion + pre-combustion)
4,267,943	8,535,886	Btu/ton	8,100,962	3.80%	Specific energy for soda ash extraction (combustion + pre-combustion)
69,572	139,144	Btu/ton	7,807,577	0.04%	Specific energy for limestone extraction (combustion + pre-combustion)
1,370,000	2,740,000	Btu/ton	7,854,543	0.64%	Specific energy for feldspar extraction (combustion + pre-combustion)
100	200	Miles	7,844,267	0.51%	Transport distance from sand mining sites to US container manufacturers
1,100	2,200	Miles	7,871,959	0.87%	Transport distance from soda ash mining sites to US container manufacturers
150	300	Miles	7,811,401	0.09%	Transport distance from limestone mining sites to US container manufacturers
430	860	Miles	7,819,904	0.20%	Transport distance from feldspar mining sites to US container manufacturers
164	328	Miles	7,837,072	0.42%	Transport distance of cullet to US container manufacturers
Manufacturing					
10,018,427	20,036,854	Btu/ton	8,277,137	6.06%	BUWAL250 cradle-to-gate energy for glass containers (Swiss average w/ EU electricity grid)
30.0	60.0	%	7,438,028	-4.69%	Percent of reduction in melting energy with every 100% increase use of cullet (by weight) to replace raw materials (for US glass)
30	60	%	7,461,743	-4.39%	Percentage of cullet content per ton of container produced in US
10	20	%	7,537,112	-3.42%	Percentage of foreign imported glass containers products over all NJ glass consumption
7,500	15,000	Tons	7,796,657	-0.10%	Glass containers that produced by New Jersey glass manufacturers
Collection and Transportation					
100	200	Tons/load	7,748,148	-0.72%	Mass of MSW or virgin raw materials per load of rail cart
20	40	Tons/load	7,790,934	-0.17%	Mass of MSW per load of long-haul transfer truck
25	50	Tons/load	7,783,889	-0.26%	Mass of virgin raw materials per load of long-haul transfer truck
22	44	Tons/load	7,753,175	-0.65%	Mass of cullet per load of dump truck
903	1,806	Miles	8,235,758	5.53%	Wholesale & retail distribution distance for US glass container products

6	12	MPG	7,731,285	-0.94%	Fuel economy for tractor trailer transport
3.3	6.6	MPG	7,748,148	-0.72%	Fuel economy for rail transport
3,400	6,800	Miles	7,827,571	0.30%	Transport distance of foreign imported glass products from all other countries (exclude Mexico, Holland, and Germany) to New Jersey
Decision Supporting Tool					
15.79	31.58	Tons/vehicle-d	7,796,058	-0.11%	Mass collected per vehicle per day for single-family housing, MSW collection
27.73	55.46	Tons/vehicle-d	7,801,513	-0.04%	Mass collected per vehicle per day for multi-family housing, MSW collection
18.77	37.54	Tons/vehicle-d	7,794,794	-0.12%	Mass collected per vehicle per day for commercial stops, MSW collection
2.54	5.08	Tons/vehicle-d	7,689,355	-1.47%	Mass collected per vehicle per day for single-family housing, recycling collection
5.02	10.04	Tons/vehicle-d	7,782,558	-0.28%	Mass collected per vehicle per day for multi-family housing, recycling collection
7.33	14.66	Tons/vehicle-d	7,735,247	-0.88%	Mass collected per vehicle per day for commercial stops, recycling collection
31.28	62.56	Gals/vehicle-d	7,820,687	0.21%	Fuel consumed per vehicle per day for single-family housing, MSW collection
36.76	73.52	Gals/vehicle-d	7,809,778	0.07%	Fuel consumed per vehicle per day for multi-family housing, MSW collection
28.56	57.12	Gals/vehicle-d	7,823,215	0.24%	Fuel consumed per vehicle per day for commercial stops, MSW collection
30.59	61.18	Gals/vehicle-d	8,047,925	3.12%	Fuel consumed per vehicle per day for single-family housing, recycling collection
30.38	60.76	Gals/vehicle-d	7,856,045	0.66%	Fuel consumed per vehicle per day for multi-family housing, recycling collection
31.95	63.90	Gals/vehicle-d	7,942,309	1.77%	Fuel consumed per vehicle per day for commercial stops, recycling collection
Dicarded Glass Disposal					
2.5	5.0	%	7,900,896	1.24%	Glass fraction in type 10 MSW in NJ
65	100	%	7,795,443	-0.21%	Waste-to-energy heat conversion efficiency
Recycled Glass Processing					
20	40	Facilities	7,811,618	0.09%	Numbers of MRFs in New Jersey that process/sort glass containers
5	10	%	7,817,764	0.17%	Drop-off fraction of recyclable fraction
17	34	%	7,796,771	-0.10%	Percentage of fuel reduction switching from dual-stream to single-stream

261	522	Days/yr	7,799,783	-0.06%	Operation days in a MRF in NJ
106	212	Sq ft/ton	7,823,217	0.24%	Sq ft/ton for (average medium) NJ MRF's "Processing Building" area
11	22	Sq ft/ton	7,809,050	0.06%	Sq ft/ton for (average medium) NJ MRF's "Office" area
44	88	HP/hr	7,805,436	0.01%	Horse power used in single-stream processing MRFs
12.5	25	HP/hr	7,805,022	0.01%	Horse power used in dual-stream processing MRFs (negative sorting)
31	62	HP/hr	7,809,739	0.07%	Horse power used in dual-stream processing MRFs (positive sorting)
31	62	HP/hr	7,805,055	0.01%	Horse power used in non-optical sorting cullet processors (negative sorting)
25	50	%	7,803,205	-0.01%	Percentage of negative sorting in dual-stream processing MRFs
Energy Conversion					
11,154	22,308	Btu/kWh	7,903,069	1.27%	Primary energy consumption for producing 1 kWh of NJ electricity grid (combustion + pre-combustion)
Energy Credits					
-340,000	-680,000	Btu/ton	7,717,363	-1.11%	Specific energy credit of recycled glass as landfill cover/construction aggregate
-7,840,693	-15,681,386	Btu/ton	7,732,472	-0.92%	Specific energy credit of recycled glass as fiberglass feedstock

‡ Output = Y_2 (see footnote below).
† Sensitivity ratio (SR) was calculated by the following equation (US EPA, 2001):

$$SR = \frac{\left(\frac{Y_2 - Y_1}{Y_1}\right)}{\left(\frac{X_2 - X_1}{X_1}\right)}$$

Where Y_1 = the baseline value of the output variable using baseline values of input variables (= $7.81*10^{12}$ Btu)
Y_2 = the value of the output variable after changing the value of one input variable
X_1 = the baseline point estimate for an input variable
X_2 = the value of the input variable after changing X_1 (=X_1*200%)

Curriculum Vita

Ching-Ling Tsai

Education

2004-2010 Ph.D. Environmental Sciences
Rutgers University, New Brunswick, NJ, the USA

2001-2003 M.Sc. Environmental Sciences
Environmental Technology Focus, Tuition Waiver Program
Wageningen University, Wageningen, the Netherlands

1997-2001 B.S. Plant Pathology
Minor in Biotechnology, 1998-2001
National Taiwan University, Taipei, Taiwan

Publications

- Tsai, C.L., Krogmann U., Strom, P.F. (2010). Effect of Forced Aeration and Mechanical Turning on Leachate Quantity and Quality from Glass Cullet Stockpiles. Journal of Environmental Engineering (136), p. 854-859.

- Tsai, C.L., Krogmann U., Strom, P.F. (2009). Handling Leachate from Glass Cullet Stockpiles. Waste Management (29), p. 1296-1305.

- Plugge, C., Jiang, B., de Bok, F.A.M., Tsai, C.L., Stams, A.J.M. (2009). Effect of Tungsten and Molybdenum on Growth of a Syntrophic Coculture of *Syntrophobacter fumaroxidans* and *Methanospirillum hungatei*. Archives of Microbiology (191), p. 55-61.

- Master's thesis, 2003. The Effects of Tungsten and Molybdenum on Syntrophic Growth of *Syntrophobacter fumaroxidans.*

Professional Experience

2009 Quality Assurance/Quality Control Officer for project # U4R07 at Columbia University. Water Environmental Research Foundation (WERF), Alexandria, VA

2003, Fall Teaching Assistant. Department of Life Sciences, National Taiwan University

2003, Spring Environmental Consultant. World and Environmental Consulting Engineers, Inc., Taipei, Taiwan

1998-2001 Research Assistant and intern. Clinical Microbiology Laboratory, National Health Research Institute, Taipei, Taiwan

Honors/ Awards

2010 Post-qualifying tuition waiver, Rutgers University, New Brunswick, NJ.

2008 2008 Wilbur M. Runk Scholarship, Rutgers Cooperative Extension, New Brunswick, NJ

2006 First Prize Award for Poster Presentation. Investigation of Stormwater Runoff from Storage Piles of Mixed Glass Cullet. New Jersey Water Environment Association, 91^{st} Annual Conference & Exposition, Atlantic City, NJ

2001-2003 Tuition Waiver Program, Wageningen University, Wageningen, the Netherlands

2001 Outstanding Student Award in Biotechnology Core Techniques Program, National Taiwan University, Taipei, Taiwan