April 7th, 2013
University of New Brunswick Faculty of Engineering
ENGG 4025: Group 3
Fredericton, N.B.

Mark Hymers, P.Eng
Senior Engineer
City of Fredericton Engineering and Operations
Fredericton, N.B.

Mr. Hymers,

We received your proposal in September 2012 for an investigation into the viability of recycling glass in the City of Fredericton. We have completed an engineering design and analysis of a recycling and processing system. Our proposed system includes the collection, processing, and manufacturing of waste glass, and the creation of value added end products.

We have determined that the most viable end products for recycled glass in the region are sandblasting media and a 100% recycled glass tile product. From our economic analysis, the ability to implement this system and produce profits is feasible.

Your feedback throughout the academic year has been appreciated. We hope that you will continue to work with the University of New Brunswick Faculty of Engineering in the future.

Sincerely,

Amin Azahar

Michael Barrett

Scott Bell

Carolyn McKenna

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Smart. Sustainable.
Fredericton
Ingéniosité. Durabilité.

ENGG 4025: Senior Design - Glass Recycling

Client: City of Fredericton

Final Design Report (Revision 8)

Amin Mat Azahar, Michael Barrett, Scott Bell, Carolyn McKenna

UNB Faculty of Engineering

Disclaimer

This material has been created by a group of engineering students from the University of New Brunswick for the course *ENGG 4025: Multidisciplinary Senior Design.* This product and the recommendations made should be treated accordingly and reviewed by a professional engineer before implementation. No responsibility is taken for any issues encountered if this product is implemented.

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Executive Summary

This report documents the completed design project of Group 3 for ENGG 4025: Multidisciplinary Senior Design at the University of New Brunswick, Fredericton. The objective of the project was to develop a recycling process to divert Fredericton's waste glass from the regional landfill and turn it into a value added product. All glass is currently disposed of in the regional landfill, along with other refuse, at a rate of $74/tonne at the city's expense. Based on a recent waste audit performed by the Fredericton Regional Solid Waste Commission (FRSWC), the amount of glass disposed is approximately 4% of this waste. Paper, plastic, and metal containers are currently recycled, but glass is not.

After clearly defining the performance criteria and project constraints, the next step included an extensive literature review to investigate existing technology that could provide an alternative to placing glass in the landfill. Several end products were considered; however, the literature review focused on what looked to be the six most favorable solutions: sandblasting media production, fiberglass manufacturing, replacing aggregate with recycled glass in asphalt and/or concrete, bottle or container manufacturing, 100% recycled glass tile, and cullet sale. Each of these technologies was researched and compared on aspects such as the level of sorting required, performance benefits, particle size required, quantity of recycled glass used in the final product, quality of recycled glass required, the selling price, and market available for the end product.

As a tool to aid in discovering the optimal solution, four evaluation criterion were used to rate the possible solutions. These included economic viability, market potential, technological risk, and safety. Each evaluation criterion was weighted and evaluated for all of the possible end products using a decision matrix and the completed research. The resulting decision matrix totals and associated errors were assessed and a creative combination of end products formed the final solution.

The proposed solution is to create a glass collection and crushing process that will utilize glass cullet to produce three different end products. The clear glass will go to 100% recycled glass tile, the coloured glass will go to sandblasting, and any waste or unused glass will have the third option of being sold for aggregate. The third option is in place to ensure the sustainability of the process and will only be used if the market does not absorb a portion of the glass from the other two end products.

The designed manufacturing process takes an input of glass of approximately 1260 tonnes/year from the Greater Fredericton Area. The glass will be collected at the bottle redemptions centers in the region. The collected glass (colour separated) will be transported to site (FRSWC as proposed location for crushing), and will be put in storage. When the process begins, the glass will be taken through a crushing equipment line that will include breaking, washing, drying, and crushing.

The glass, depending on the colour of the batch, will then be processed into the desired end product. The clear glass will continue to tile manufacturing, which will include a mixer to incorporate colorants

into the batch, a furnace in which the glass tile will sinter, a cooling line, and a packaging machine. The coloured glass will proceed to the sandblasting media production. This glass will go through a ball mill for addition crushing and will then be sifted into the four main size fractions which will be packaged separately. Any extra glass will be stored for aggregate substitution with no further processing required.

The detailed design of this report includes a thorough process flow diagram (PFD) which follows each streamline of the process through the complete manufacturing of the end products. Equipment was sized and specified to the level of detail required to send the request to tender. Completed equipment summary tables are listed in the report. The subsystems required for the successful completion of the production facility are listed and discussed.

An economic analysis was prepared. The factorial method, using data from literature, was used for its completion. Equipment costing, physical plant costs, fixed capital costs, operating costs, working capital, revenue, and key economic parameters such as ROI (Return on Investment) and IRR (Internal Rate of Return) were all calculated. A summary of the economics is shown below:

- Fixed Capital Cost - $2.57 M
- Working Capital - $90.5 k
- Return on Investment – 18.2%
- Internal Rate of Return – 19.9%
- Pay Back Period – 4.5 Yrs

A design optimization was completed following the economic analysis. A sensitivity analysis examining the effect of uncertainties in the inputs on the viability of the project showed that the most sensitive parameter is the sale price of glass tile. Variations in fixed capital investment also contributed to the viability of the project. Design trade-offs were also analyzed in order to determine if the process could be optimized. It was found that singling out tile manufacturing could be a more profitable investment, but also includes a significantly higher risk due to market size and sustainability.

Safety was considered throughout the design process. This report contains multiple safety sections at different stages of the design process, and finishes with a Failure Modes and Effects Analysis (FMEA) report including health and safety, environmental impact, and production impact.

Overall, an economically viable solution was found that satisfies the performance criteria and constraints that were defined in the project scope. The proposed solution has a high capital cost, but a favorable return on investment and an attractive internal rate of return. A business and marketing plan to accompany the project would be crucial to allow success. In addition, due to fluctuations in the tile market, there is an extent of risk associated with the proposed investment.

1.0 Introduction

1.1 Problem Definition

The City of Fredericton, with approximately 56,000 residents, is the capital city of New Brunswick. The city offers municipal waste collection services, with domestic waste collection totaling approximately 13,000 tonnes annually, of which an estimated 4% is glass. There is currently no specific recycling program for glass products offered by the City of Fredericton. While some glass bottles may be returned to a local bottle depot, other used glass products are designated as regular refuse and are disposed of in the regional landfill operated by the Fredericton Regional Solid Waste Commission (FRSWC). This disposal costs the City of Fredericton $74/tonne. Refuse is collected weekly, with two streams of recyclable materials. The recyclable materials collected alternate weekly between (1) metal and plastic, and (2) fiber containing paper and cardboard materials. The city hires an outside contractor to collect all materials, both recycling and refuse, to be sent to the FRSWC (FRSWC, 2011).

In recent years, some citizens of Fredericton have been questioning the city's current glass refuse policy. There has been pressure to develop a recycling system for glass; however, no significant research has been completed to assess its economic potential (Hymers, 2012). Glass is not currently recycled because of its relative lack of environmental impacts. It is inert and causes no harmful effects to groundwater, surface water, or soil when landfilled, and does not produce any greenhouse gas emissions. In addition, the current refuse and recycling collection system is poorly suited for the separation and handling of glass for recycling. There is a safety concern associated with glass collection due to the fact that separation is done manually (FRSWC, 2011).

Mark Hymers, an engineer from the City of Fredericton's Engineering and Operations department, has requested an investigation into glass recycling to determine if it is economical to implement such a process into the City of Fredericton's current waste collection system. If this proves to be uneconomical, the scope may be broadened beyond the city of Fredericton to investigate the economic potential for a joint glass recycling venture with other cities in New Brunswick.

1.2 Scope of the Project

The design team has been commissioned by the Department of Engineering and Operations of the city of Fredericton to determine if there is an economically feasible process that can be implemented to divert used glass materials from the landfill and use them as recycled materials to produce a valuable product. To this end, the client has requested a full technical evaluation and economic assessment of glass recycling for the region. The most feasible system will be designed and investigated to determine if there is an economically viable outcome. Our scope will include collection of recyclable glass, processing of the collected glass (sorting, cleaning, etc.), and conversion of the recycled glass into a valuable end product.

1.3 Performance Specifications

The design of this glass recycling process will follow the specifications listed below:

- Result in a reasonable cost for collection and diversion (target current cost of disposal, $74/tonne)
- Divert at least 50% of the waste glass currently entering the landfill (FRSWC, 2011)
- Clean and crush waste glass intake achieving a 90% recovery rate
- Convert the recycled glass into a value added product
- Have sufficient capacity and operating time to process all glass collected

1.4 Constraints

The following constraints limit the scope of the design:

- Economics (reasonable payback period of approximately 5 years)
- Time (design must be completed by April 7, 2013)
- Current technology (only proven technology will be used in this design)
- Safety (abide by all applicable codes and standards)
  - National Building Code of Canada
  - OSHA
  - ASTM International Standards
  - Air Quality Standards (NB Clean Air Act)
- Environmental impact (abide by all applicable codes and standards)
  - Canadian Environmental Quality Guidelines (CEQG)
  - Canadian Environmental Protection Act (CEPA)
  - NB Clean Environment Act
- Resources (the amount of recyclable glass available)
  - Approximately 1260 tonnes per year of domestic recyclable glass for The Greater Fredericton Area
  - Collection and transportation costs need to be considered in order to obtain more volume from destinations further away.

The design will require utility services such as fuel and electricity. The following rates will be used in all calculations. The electricity rate is 5.76 cents/kWh (NB Power, 2012). Fuel prices in the region at the present time are 128.3 cents/L for gasoline, 136.0 cents/L for diesel fuel, and $11.68/GJ for natural gas (Natural Resources Canada, 2012). Processing facilities for the design would ideally be located at the current FRSWC site as it would allow for integration into the current recycling system.

1.5 Schedule and Milestones

The project schedule is displayed below and shows the project milestone completion dates. Figure 1 is a Gantt chart covering the week by week scheduling as well as client meetings for the full eight months of the project. The project schedule is subject to minor changes only if it is agreed upon by the client, course mentors, and all members of the project team.

TABLE 1: PROJECT MILESTONE COMPLETION DATES

Milestone	Due Date
Project Scope	September 30, 2012
Literature Review	October 21, 2012
Proposed System and BFD	November 11, 2012
Detailed Design I	December 2, 2012
Detailed Design II	January 27, 2013
Capital & Operating Costs	February 17, 2013
Economic Analysis and Optimization	March 17, 2013
Final Report	April 7, 2013

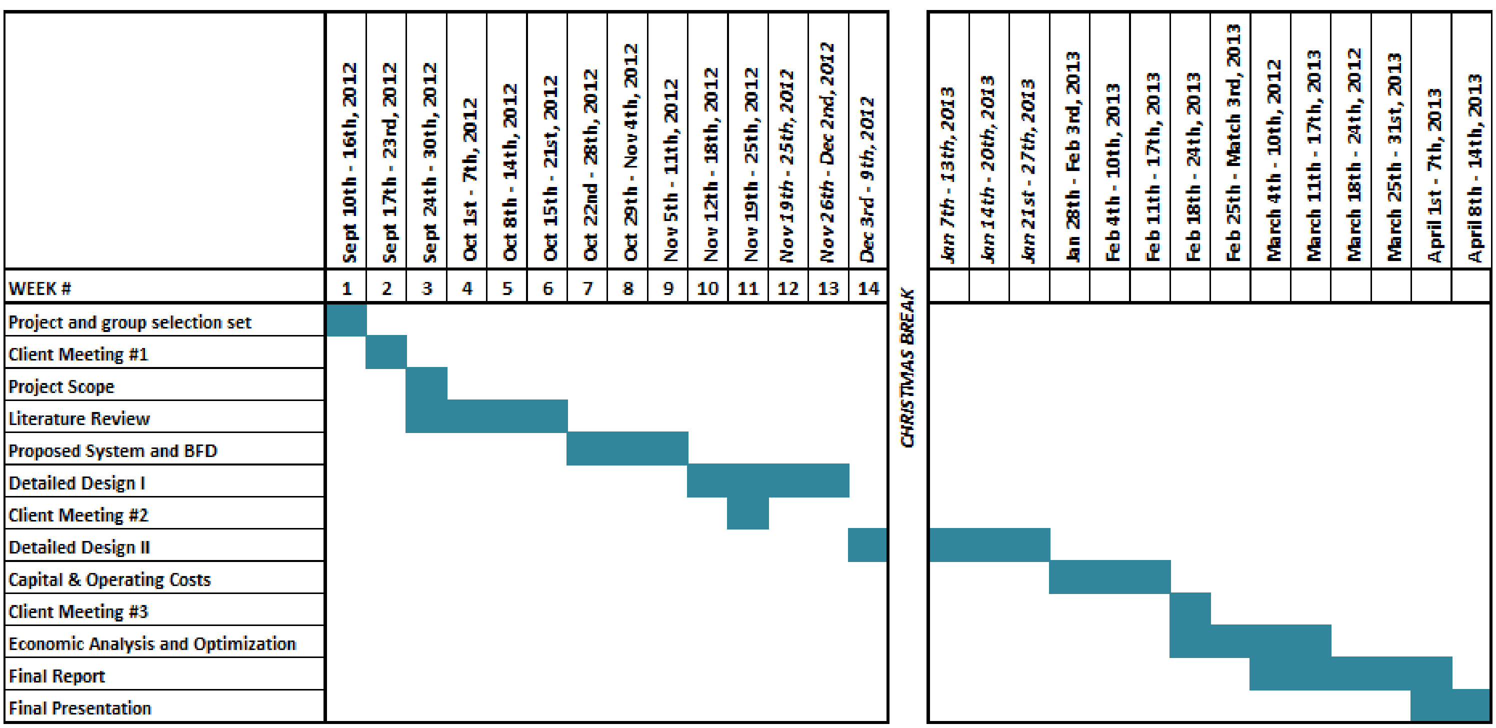


FIGURE 1: GANTT CHART FOR THE GLASS RECYCLING PROJECT

2.0 Literature Review

2.1 Assessment of Existing Technologies

2.1.1 Roadbed Aggregate (Asphalt)

Using recycled glass as a replacement for aggregate in asphalt production, often termed glassphalt, was originally developed in the 1960's, being used primarily in Europe and the United States as an alternative to landfill disposal (Sicoe & Leek, 2011). When used in the proper quantities and particle sizes, the addition of glass cullet to asphalt does not change the manufacturing process of asphalt. This makes it easy for current asphalt producers to incorporate the recycled glass in their product.

Quantity and quality of the cullet is extremely important for glassphalt production. Research on these specifications has been completed by a number of organizations such as the US Environmental Protection Agency and Transport Research Limited in Berkshire, UK. Their research and testing has determined that high quantities of glass or large particles sizes in the asphalt mix result in reduced skid resistance and an increase of asphalt stripping. Although between 5 and 40% of recycled glass has been used to replace the rock and/or sand in asphalt; the ideal amount of recycled glass content is around 10% at a size fraction of 9.5mm (3/8") or finer (Clean Washington Center, 2012). The size and quantity listed above is ideal for regular roads with a speed limit of 65 km/h or below and would result in decreased skid resistance at higher speeds.

If it is desirable to use more than a mix with 10% recycled glass, modifications can be made to the glassphalt production system that can increase the amount of recycled glass that can be used. The skid resistance of the road can be increased by crushing the recycled glass to a smaller grain size. Stripping can be reduced by adding an anti-stripping agent to the mixture (ex. 2% hydrated lime), although this is generally not recommended because it has been reported to cause problems such as decreased friction coefficient and bonding strength in the glassphalt (Huang, Bird, & Heidrich, 2007). Larger grain sizes are more welcome if the glassphalt is intended for a base course – an asphalt layer beneath the driving surface which helps to provide a stable base for other layers. Larger size particles do make it more difficult to screen the recycled glass so this can lead to cullet with a higher level of contamination (Chen, 2002).

Some additional advantages and disadvantages to using recycled glass to make glassphalt are listed in the table below.

Table 2: Advantages and Disadvantages to Using Recycled Glass in Asphalt

Advantages	Disadvantages
• Can use mixed colours of glass (doesn't need to be sorted) • Could be used by current asphalt companies (less capital cost) • Road surface dries slightly faster • Road surface is more reflective (may improve night time visibility slightly) • Depending on the particular use of the road and the amount of recycled glass used, the cullet doesn't need to be ground too finely • Same manufacturing equipment and paving method can be used • It will hold heat longer than normal asphalt (easier to compact over longer distances)	• The cullet would have to be sold at the cost of aggregate (≈$15.00/tonne) at the most because there are no enhanced properties associated with using recycled glass • Can cause skid resistance issues if used in too high of a quantity or two large of a grade (below 10% with less than 10mm (3/8") is recommended depending on use of road) • May need to use an anti-stripping agent (ex. 2% hydrated lime) to prevent stripping caused by using the recycled glass (additional costs) • Can cause issues such as insufficient friction and bonding strength

In recent years, many companies have tried to incorporate glass recycling into asphalt production. Pioneer Road Services' location in Hazelmere, WA, Australia has developed a fairly successful glass recycling program using asphalt as an end product. Although they faced initial challenges (ex. completion date was delayed while trying to find a crusher that gave the size of grain they required and trying to find the proper mixture to prevent stripping), it has become a functional process. With the help of a government grant, they have continued to research new mixes, and install new crushers to increase the capacity of the system beyond its original size of about 3000 tonnes per year (Pioneer Road Services Pty Ltd., 2009).

In order to understand the application of glassphalt production in Fredericton we must understand the local market. North America produces more asphalt than any other continent at 550 million tonnes per year (National Asphalt Paving Industry, 2011). Asphalt paving in Canada has also grown by 3.2% annually from 2001-2010 (Industry Canada, 2010). In Fredericton the largest local producer of asphalt is Perfection Paving Ltd. Sewells Paving opened a new paving plant in spring of 2012, and Hogan Paving is another local asphalt company.

Since there are no changes in the asphalt manufacturing process when recycled glass is used, and there are several asphalt companies in the region, it would make the most sense economically to collect, crush and clean the glass and then sell it to a local company as a replacement for aggregate. While there is a large market for asphalt, it must also be considered that glassphalt as an end product has limitations in the region:

- Can only be used on roads for use under 65km/h
- 95% of asphalt mix is aggregate and only about 10% can be used as recycled glass (0.095 tonne of recycled glass/tonne of asphalt produced)
- To use 500 tonnes of cullet annually, 10 km of glassphalt road would need to be laid every year
- Asphalt production is a seasonal business

This analysis shows there is a risk of saturating the local market, and therefore for glassphalt production to be a stand-alone feasible way of glass recycling in Fredericton we would have to look beyond local asphalt producers.

Creating cullet to sell for asphalt production for a 500 tonne per year system has an approximate equipment cost of $60,000, an annual operations cost of around $15,000, and revenue of about $45,000 which includes the $74 tipping fee that would be avoided by not landfilling the glass. This gives a gross annual profit of approximately $14,000 based on a 5 year payment for the equipment. The payback period including the savings associated with the $74 tipping fee is around 2 years. If that savings is not considered, then the model cannot be profitable. More detailed figures, assumptions and calculations for this analysis can be seen in Appendix A-1.

Overall, glassphalt is an innovative way of recycling glass, but does not appear to be an ideal solution on its own.

2.1.2 Glass Manufacturing (Melting and Reforming)

Glass manufacturing is a process that consists of four main stages: batch mixing, batch melting, shaping and molding, and cooling. The materials used to make a batch of glass include sand, soda ash, limestone, and often cullet together with small quantities of various other minor ingredients (Wansbrough & Borham, 2006). In recent years, recycled glass has become an important part of glass manufacturing. The reason for this is that, in most reported cases, using recycled glass as an ingredient actually lowers the melt temperature of the batch. The melt temperature can be as high as 1600^{o}C for a normal batch and can be reduced to as low as 1100^{0}C depending on the quantity of recycled glass used. This decreases the energy used to melt the batch by approximately 30% (Vellini & Savioli, 2008), and provides an incentive for glass manufacturing companies to seek out reliable sources of recycled glass.

The quantity of cullet used for glass manufacturing varies depending on the manufacturer. Anywhere from 10%-70% is currently used in various companies across North America. While cullet for glass manufacturing may be of mixed sizes, the ideal size range of the cullet is between 10 mm (3/8" inch) and 19 mm (3/4" inch) (Clean Washington Center, 2012). Contamination is an important consideration when using recycled cullet in glass manufacturing since even small amounts of contaminants such as particles of ceramic or metal can completely ruin an entire batch.

Glass manufacturing is a complicated and capital intensive process so the combined cost of an intense cleaning process for the recycled glass and a new glass manufacturing plant is high. The US glass industry has significantly slowed their new capital investments and focused its investments on rehabilitation of existing plants. Although glass manufacturing using recycled glass is a high volume, proven way to recycle glass, the market in North America is in a declining period. The industry also faces difficulties such as rising energy costs, stringent environmental regulations, competition from plastic and other materials, and competition from manufacturers in low cost producing regions (Ross & Tincher, 2004).

According to Industry Canada, the glass and glass manufacturing market has seen a compound annual shrinkage rate of 5.7% from 2001 to 2010. As well, the amount of employees in glass manufacturing in Canada has declined from 9,205 to 4,973 in this time (Industry Canada, 2010). Glass plants in Moncton and Toronto have closed in 2006, among others.

A summary of the advantages and disadvantages of glass manufacturing as method of glass recycling are shown in the table below.

TABLE 3: ADVANTAGES AND DISADVANTAGES TO GLASS MANUFACTURING WITH RECYCLED GLASS

Advantages	Disadvantages
• Using recycled glass cullet in the manufacturing process reduces energy consumption of the process • There are options for the final product to be produced (bottles, food and other beverage containers, etc.) • Glass can be recycled endlessly which makes this one of the best solutions when taking a lifecycle analysis point of view • A proven process that has been used for years	• The quality of the cullet must be extremely high (contamination is a big issue) • Very high capital cost making it difficult to make a new plant economically feasible • Declining market • Cullet must be sorted by colour

An economic assessment of building a glass manufacturing plant in Fredericton or the surrounding region was completed in order to determine its feasibility. A 500 tonne/ year system resulted in an approximate capital equipment cost of $1,080,000 and an annual operations cost of around $140,000. The sale price for this option is about $220/tonne which creates revenue of about $148,000, including the $74 tipping fee that would be avoided by not landfilling the glass. This gives a gross annual revenue of approximately -$280,000 based on a 5 year payback time for the equipment. The volume of recycled glass was increased and it was found that a glass manufacturing plant would break even at around 2000 tonnes. Seeing as the market is already declining, and just below 40% of glass manufacturers in Canada are currently not profitable, another 2000 tonnes integrated into the already saturated market would not be beneficial (Industry Canada, 2010). This solution seems to be a dead end. Assumptions and calculations for this analysis can be seen in Appendix A-2.

2.1.3 Fiberglass Manufacturing

Fiberglass is one of the main products for consuming recycled glass, second worldwide to glass container manufacturing. The amount of recycled glass used in its production varies from 20-80% depending on the quality and the end market for the fiberglass product. Fiberglass used in industry, such as pipe insulation, requires tighter specifications that reduce the amount of recycled glass that can be used. This higher standard for fiberglass is to be expected since it has to work in a more stressful environment. Higher volumes of recycled glass can be used in residential insulation.

Fiberglass is the leading type of insulation in the market for residential purposes. The fiberglass market is expected to grow by 9.1% annually from 2009-2014 (Petitt, 2010). In Canada, the fiberglass market is dominated by large producers such as Owens-Corning. Owens Corning itself has been the main user of recycled glass in North America as their product has up to 40% of recycled glass which is the highest in North American fiberglass manufacturing (Owens Corning, 2008).

Homeowners have been using fiberglass for generations as it offers many advantages over competitive insulation products, such as foam glass, mineral wool, expanded polystyrene (XPS) and cellulose. The most obvious advantages would be its low purchase price, low thermal conductivity and low safety risk. Fiberglass can be purchased at a local retailer for a price of $0.37 per kg, compared to mineral wool that is priced at $0.50 per kg depending on the R-values for insulation. Fiberglass is also fire resistant, containing non-combustible fibers that do not add to the fuel load of a building (Bradford, 2012). Other advantages include good performance as a sound insulator in the house, ease of handling, and that it can be recycled, although the practice is not often used (EPA, 2010).

In order to be used in fiberglass manufacturing, recycled cullet must meet specific criteria, including major and minor oxide chemical composition, color consistency and low contamination. Chemical composition of the glass cullet should fall in the range in the table below.

TABLE 4: CHEMICAL COMPOSITION RANGE OF GLASS CULLET (CLEAN WASHINGTON CENTER, 1996)

Material	Minimum (% by weight)	Maximum (% by weight)
SiO_2	70.0	None
Fe_2O_3	None	0.5
CaO&MgO	11.0	None
Na_2O	13.0	None
PbO	None	0.2
H_2O	None	2.0

Carbon	None	0.1
FeO	None	0.1
Ag_2O	None	0.05
Cr_2O_3	None	0.1
CoO	None	0.05

Colour consistency is important due to different level of oxidization of glass cullet in the different colours. Flint glass has the highest oxidization followed by green glass that is slightly reduced and lastly amber glass that is highly reduced. The furnace can operate over a wide range of oxidization states, but adjustments must be made to accommodate mixtures with significantly different compositions (Clean Washington Center, 1996). Contaminants such as metals and ceramics sometimes melt at higher temperatures than glass and cause clogging in the furnace. Glass batches normally melt between 1200^{o}C – 1500^{o}C depending on the quantity of recycled glass used. So for example, if a batch is using a large portion of recycled glass and a piece of steel goes through the furnace, it will stay solid (melting temperature around 1500^{o}C) and cause issues.

Other raw materials that are used in fiberglass insulation production include sand, soda ash, limestone, borax and binder coatings. The weight percentage of each material is shown in the table below.

TABLE 5: MATERIAL COMPOSITION OF FIBERGLASS

Material	% Composition of Fiberglass
Recycled Glass Cullet	40%
Sand	28%
Soda Ash	11%
Limestone	8%
Borax	8%
Binder Coatings	5%

SOURCE: TABLE FROM (EPA, 2010)

These raw materials are mixed and melted in the furnace, from which the melt proceeds to a spinner for fiberizing the melted mixture, the fiber collector, the curing oven, the longitudinal and cross cutter and the stacking and packaging machine (HiSuccess International, 2009).

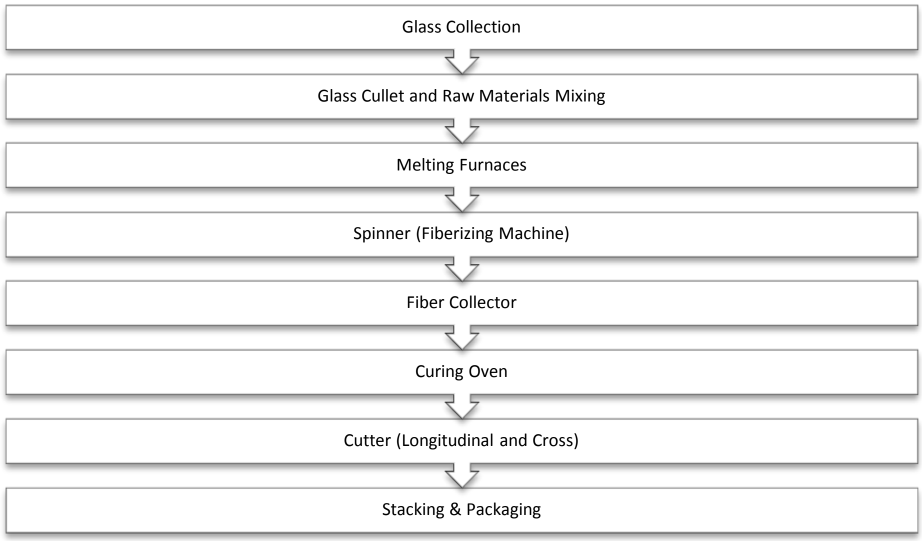


FIGURE 2: PRODUCTION LINE OF FIBERGLASS

The estimated price for a 500 tonne/year plant was found to be $1.48M. From the estimated jobs available in a 46450 m^2 (500,000 ft^2) plant (Design and Build with Metal, 2007), it was estimated that the plant would require five workers. This led to a gross annual revenue of about -$12 300 per year making the plant not economically viable. The scope was expanded to investigate at what point the plant would become economically viable. Based on an estimated 1,500 tonnes per year waste glass collection in New Brunswick, the plant would generate around $240,000 revenue per year for $2.5M plant, allowing the payback period to be about eight years. The calculation method to obtain the cost of the plant to be built in Fredericton is shown in detail in Appendix A-3.

Since the fiberglass market is dominated by large companies, it may be difficult for such a small plant to penetrate the existing market. Other factors to be considered include health and safety of the workers. For example, fiberglass is known to cause irritation to unprotected skin.

2.1.4 Concrete Aggregate

Concrete is the most consumed man-made material and is primarily used in building construction. The market for concrete plummeted in 2009 but has since recovered (iBisWorld US, 2012). The continued growth in building construction will provide higher usage of concrete in the future. In Canada, the construction industry is expected to grow by an average of 5% per year between 2011 and 2014 (Wood, 2010), which will drive growth in the concrete sector. However, studies have shown that using glass as partial replacement of the coarse aggregate offers no improvement to the concrete's properties (Vitro Minerals, 2011). From the manufacturer's perspective, it makes little sense to use recycled glass as a substitute for other aggregates such as sand and gravel unless it was sold at an equal or lesser value.

Other studies have been developed to test the ability to use waste glass as a pozzolan material in concrete. Pozzolan materials act in the same way as cement does in concrete mixtures by reacting with alkali in the mixture to create extra calcium silicate hydrate binder pore structure in concrete (Vitro Minerals, 2011). Using waste glass powder to replace cement provides a much cheaper alternative in production costs of concrete. A study has shown that 30% of glass powder can be incorporated as the replacement of cement (Ahmad Shayan, 2006). However the process took a long time for the glass powder to be effective as pozzolan as significant results of the alkali-silica reaction mitigation can only be seen after 28 days (Zainab Z. Ismail, 2008). Higher volumes of glass powder can be used to speed up the pozzolan effect, but also reduce the strength of concrete. (Vitro Minerals, 2011). The delayed effect of pozzolan has made it an ineffective material to be used as cement replacement. Waiting for the concrete to cure can result in higher labour costs which outweigh the material cost benefits.

The inability of glass to offer a distinctive advantage in the production of concrete limits the marketability of the recycled glass in concrete production. It can, however, be used to make lower strength, decorative concretes. Companies like Dawn Enterprises and Vetrazzo offer alternative solutions for recycled glass in products such as concrete benches, vases and even designed countertops.

The economic evaluation for a plant to recycle the glass into cullet to sell to cement companies in the region would be almost identical to that of asphalt (seen in Appendix A-1). In both cases the cullet is replacing similar size aggregate and offers no advantages to the product and therefore must be sold at approximately $15/tonne (the regional price for aggregate). This means that it has the potential to be profitable but may not be an ideal solution on its own.

2.1.5 Ceramic and 100% Recycled Glass Tile

Studies have been conducted on using recycled glass cullet as a feedstock for the production of ceramics. Academic results have been favorable, showing similar mechanical properties and reduced melting temperature requirements of 60°C to 240°C for the use of 50% to 70% recycled glass (Bernardo, 2008). Fireclay Tile has capitalized on California grant money and LEED certification criteria to bring such products to market, including a 100% recycled glass tile released in 2011 (Fireclay Tile, 2011).

Producing glass-ceramic tiles generally involves the following steps (Bernardo, 2008):

- Preparation of glass cullet (color sorting not necessary)
- Mixing ingredients with water and deflocculant
- Milling mixture to reduce particle size
- Drying to reduce moisture
- Crushing & sieving
- Re-addition of water to produce wet clay
- Pressing clay into desired forms

- Firing the forms and cooling
- Application of glazes
- Secondary firing of glazed forms and cooling
- Quality assurance

Ingredients include specific clays, feldspar sands, and fluxing agents. The production of 100% recycled glass tiles requires the following steps (Bedrock Industries, 2010):

- Preparation of glass cullet (color sorting required)
- Additional crushing of glass cullet
- Pouring crushed glass into molds
- Addition of dyes or colorants
- Firing molds and cooling
- Quality assurance

Production of pure glass tiling is a simple process; however, the product has less desirable mechanical properties, and has a smaller market than glass-ceramic tiles. Depending on the tile to be produced, the cullet quality may vary. For example, bubbles in a glass tile caused by organics may be seen as aesthetically pleasing; however, metal fragments or labels would not be tolerated in a final product.

The use of recycled glass in these end products has a significant competitive advantage due to its qualification for LEED building points. According to IBIS reports, the commercial and industrial construction markets will expand steadily through to 2017, increasing demand for decorative tiling. This growth will be compounded by increased use of sustainable building materials, which IBIS categorizes as a quality growth market. Municipal building markets are expected to decline, although since government projects only account for 27% of all LEED projects (US Green Building Council, 2011), the impact of this will be outweighed by the growth in other sectors. By using a baseline consumption of 185,806,000 square meters of ceramic tile in the US per year, the demand of ceramic tile in New Brunswick is expected to approximately 445,000** square meters per year.

With 500 tonnes per year of recycled glass and a 1cm thick tile product, either 50,000 square meters of ceramic tile (50% recycled glass) or 25,000 square meters of glass tile (100% recycled content) could be produced. Using the project cost of a 3.7 million square meter per year facility in Tennessee (Mitchell, 1998) and adjusting it to the relative cost of a facility in 2012, the cost of a ceramic tile facility would be $7.4 million. If this plant were to compete on the global bulk ceramic tile market, where prices range from $3 to $20 per square meter (Alibaba, 2012), it would have no payback potential.

Approaching economic viability from a different angle, a glass tile plant would cost $2.5 million, and its product would need to be sold $42.17 per square meter for ($3.92 per square foot) in order to break even in 5 years. This may be possible in the North American market where decorative mosaic tiling often sells for $107.64 to $215.28 per square meter which is equivalent to about $10 to $20 per square foot (The Home Depot, 2012), although not likely at the scale of hundreds of thousands of square feet. Since this product would meet LEED criteria, it may be possible to successfully market it for an even higher price; however, this approach would require intensive marketing and a highly motivated management staff. Supporting calculations can be seen in Appendix A-4.

2.1.6 Sandblasting Medium

Sandblasting is the process of using compressed air to force a projection of small particles at an object's surface to remove contaminants or surface coatings. There are several media used for sandblasting particles including silica sand, coal slag, various metal particles, organic compounds, as well as crushed recycled glass.

The production of sandblasting media from crushed class is a relatively simple process that does not require complex, expensive, or technologically advanced equipment. Turn-key production systems are available or separate machines can be combined to meet the production facility's needs. The necessary production steps after the collection process are: sorting and debris removal; crushing; washing; drying; grinding; sifting and packaging.

A typical production facility with a maximum capacity of 12 tonnes per day, assuming ten operating hours a day, can be assembled for an approximate cost of $110,000. With an input from the City of Fredericton of approximately 500 tonnes per year, or 10 tonnes weekly, the production line would need to run for one day a week. If we continue to assume an input of 500 tonnes per year and a production efficiency of 1 tonne per hour the variable cost of producing one tonne of product is $47.35. If a sale price of $100/tonne wholesale is achieved, the payback period for the production facility is 4.18 years or 2090 tonnes of produced product. After the payback period has passed the net revenue will be $52.65/tonne. More detailed calculations for this analysis can be seen in Appendix A-5.

Using this same production facility with an increased throughput of 1500 tonnes annually the payback period becomes 1.4 years or 17 months. After that time the net revenue will be $52.65/tonne. This does not include any additional collection costs which may occur.

The finished product can be sold as bulk or can be packaged in bags for lower volume customers or distributers. Fine, medium and course grits are available on the market and a production facility should be able to produce varying particle sizes. Blasting media is typically used in industry and is highly marketable in industrial cities, port cities, and locations with aging infrastructure. Due to its advantages over pure silica sand, crushed glass media has a market value of $100/tonne (CWC, 1997).

Crushed glass blasting media has an advantage over silica sand blasting media due to the molecular structure of the material. Silica sand is in the crystalline state while glass is in the amorphous state.

Amorphous silica is less dangerous to workers in that it will not cause the same health risks associated with crystalline silica (Vitro Minerals, 2012). Workers exposed to breathable crystalline silica are at risk of developing a fibrotic lung condition (Hubbs, 2005). Industry is seeking an alternative blasting medium which is less likely to cause negative health effects and recycled glass medium could fill this void in the market.

Crushed glass medium, in one study, produced an embedment rate of 2.1% compared to 4.9% embedment from silica sand (KTA-Tator, 1999). This means the sandblasting material is more efficient and less of it becomes embedded in the material being sand blasted. These numbers were based on an average of multiple tests done both in the laboratory and out in the field on different materials. Other sources indicate an embedment rate of merely 0.4% (CWC, 1997). This is another proven benefit of using crushed glass. The resulting surface finish when using crushed glass medium is comparable to that produced by a silica sand medium (KTA-Tator, 1999).

2.1.7 Cullet Sale

It may also be possible to sell cullet to existing manufacturers. Before the closure of their Moncton plant in 2008, Owens-Corning was reported to purchase quality, color sorted, glass cullet at $85 to $90 per tonne for use in bottle manufacturing (SNC Lavalin, 2006). Owens-Corning operates a glass container manufacturing plant in Candiac, QC, and Owens-Illinois operates a fiberglass manufacturing plant in Montréal. In order for cullet to be sold to a fiberglass or bottle manufacturing market it would need to meet the following criteria:

TABLE 6: CULLET QUALITY STANDARDS FOR GLASS AND FIBERGLASS MANUFACTURERS (REMADE SCOTLAND, 2003)

	Glass Manufacturing	Fiberglass
Particle Size	<20mm	<10mm
Ferrous Metals	No tolerance	No tolerance
Non-Ferrous Metals	No tolerance	No tolerance
Ceramic	<50 g/tonne	<30 g/tonne
Organics	<3000 g/tonne	<120 g/tonne
Color	98% purity (clear) 95% purity (other)	Consistent mixture

Using bulk shipping costs of 2.05 cents per tonne-km for rail and 11.27 cents per tonne-km for trucking (State Smart Transportation Initiative & Smart Growth America, 2012) gives an approximate shipping cost to these facilities of $44.66 per tonne from Fredericton. While operations costs for this option are expected to outweigh potential profits ($24,000 operating cost versus $17,670 in revenue using $80 per tonne sales price), this would end up saving money due to the $74 per tonne tipping fee at the

Fredericton landfill. By spreading the equipment cost over 5 years, and if there is a market present, this option would save the city roughly $11,700 per year.

2.1.8 Economic Summary

The table below contains a summary of the economic evaluation for each existing technology discussed in the literature review. It should be considered that these are preliminary calculations and are expected to have a substantial margin of error.

TABLE 7: ECONOMIC ANALYSIS RESULTS

Economic Analysis Results for Glass Recycling Options (500 tonnes/yr)						
End Market	Capital cost ($) [1]	Operating Costs ($/yr) [2]	Sales Price ($/tonne) [3]	Annual Revenue ($/yr) [4]*	Gross Profit ($/yr) [5] = [4] – [2]	Payback Period (years) [6]=[1]/[5]
Aggregate	$57,500	$15,375	$15	$44,500	$29,125	2.0
Sandblasting Medium	$110,000	$24,000	$100	$87,000	$63,000	1.7
Glass Manufacturing	$1,081,500	$140,400	$222	$148,000	$7,600	142.3
Fiberglass Insulation Production	$1,297,162	$348,390	$374	$224,000	-$124,390	N/A
Glass Tiles	$2,497,647	$377,382	$2,324	$1,199,000	$821,618	3.0
Cullet Sale	$73,000	$40,980	$80	$77,000	$36,020	2.0

*Revenue includes the $74/tonne tipping fee that the client would avoid which totals to $37,000/year

2.2 Comparison and Evaluation

2.2.1 Analysis Criteria

To aid in the selection of the optimal solution, the design team developed a set of criteria to evaluate the different existing technologies that were researched. Four main categories of analysis were chosen. These categories are listed below with brief explanations of their importance and focus.

- Economic Viability:
    - Does this end product offer an improvement compared to tipping fees?
    - Does the project have a reasonable payback?
- Safety:
    - What is the inherent level of safety in the process?

- Market Risk:
  - Is the market for the end product sustainable?
  - How does market size match output potential?
  - How easy is it to integrate with the existing market?
- Technological Risk:
  - Is the technology proven to be reliable?
  - How complex and specialized is the process?

2.2.2 Decision Matrix

Each glass recycling option investigated was evaluated based on the above criteria. Numbers from one to six were assigned, where a one represents an option that does not satisfy the given criteria, and a six represents the best possible satisfaction of the criteria. Each criterion was given a weight depending on the importance to deliver on that particular criterion. Economic viability and market potential were ranked highest since the client is seeking a profitable investment. Safety was ranked lowest since it can be addressed with proper safety equipment. Each rating was multiplied by the category weight and then summed together to achieve the total. The category weights were chosen by importance of the given criterion in reference to solving the given problem (the higher the weight, the more important the criterion). A sensitivity analysis was done and the associated sensitivity is shown in the last column. This error was calculated based on our confidence in each of the ratings and weightings. This is important to take into consideration when evaluating the results.

TABLE 8: DECISION MATRIX

Glass Recycling Decision Matrix						
	Economic Viability	Market Potential	Technological Risk	Safety	Total	Associated Sensitivity
Weight Factor	**7**	**5**	**3**	**2**	**102**	
Asphalt (cullet)	4	2	6	4	64	±4.5
Concrete (cullet)	4	3	6	4	69	±4.9
Sandblasting Media	6	4	4	4	82	±7.1
Glass Manufacturing	1	1	5	4	35	±1.8
Fiberglass Manufacturing	3	4	4	3	59	±6.8
Ceramic and 100% recycled Glass tile	4	4	3	3	63	±3.5
Glass / Fiberglass Cullet	5	3	4	4	70	±4.9

Sandblasting media was ranked the highest. Other than a glass manufacturing plant, which was rated far below other options, all of the results following sandblasting obtained similar ratings. Taking the sensitivity into consideration confirms that the results are interchangeable in ranking.

In conclusion of our literature review, the results show that a combination of the proposed glass recycling methods would likely be the most beneficial application for the City of Fredericton. Since all the processes include collection and crushing the cullet, the design team believes that the optimal solution will include a cullet manufacturing plant, distribution to one main market, and having one or more backup markets for expansion and sustainability. The proposed solution is to use 100% glass tile as the main market (only clear glass), sandblasting as a secondary market, and aggregate substitution in asphalt and concrete as a backup in order to ensure the sustainability of the solution.

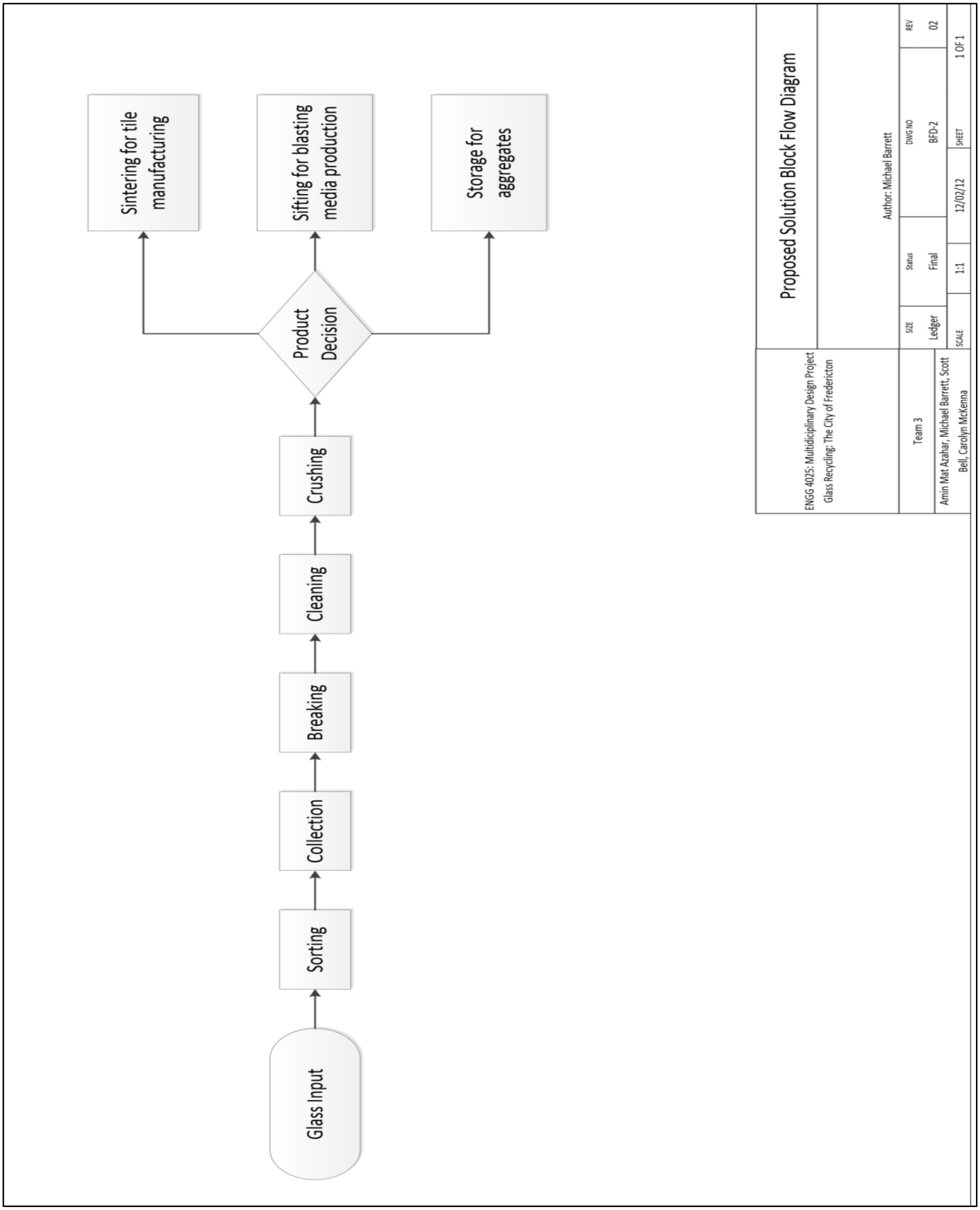
3.0 Proposed Solution

3.1 Base-Case Design

The design team, after reviewing the results of the literature review, concluded that the optimal solution would involve the production of two main products and one back up product. From the economic analysis, it was found that glass tiles would provide the greatest potential for success without flooding the current market demand. Considering that glass tiles are manufactured using only recycled flint glass, a use for amber and green glass was needed. Sandblasting media is not colour dependent and is also a profitable option; therefore it was selected as a second product. Finally, selling cullet as an aggregate substitute in either asphalt and/or concrete is a potential back up market to ensure a sustainable design.

3.2 Block Flow Diagram (BFD)

The following block flow diagram illustrates the base-case process design. This design includes collection, processing, and manufacturing of both end products. The process will run as a batch process depending on the desired end product.


Glass Input
Sorting
Collection
Breaking
Cleaning
Crushing
Product Decision
Sintering for tile manufacturing
Sifting for blasting media production
Storage for aggregates
Proposed Solution Block Flow Diagram
ENGG 4025: Multidiciplinary Design Project
Glass Recycling: The City of Fredericton
Author: Michael Barrett
Team 3
Amin Mat Azahar, Michael Barrett, Scott Bell, Carolyn McKenna
SIZE
Ledger
Status
Final
DWG NO
BFD-2
REV
02
SCALE
1:1
12/02/12
SHEET
1 OF 1

The process BFD begins with an input of glass to be collected from consumers. This input comes from a Fredericton based collection that will take place at the bottle depots. The function of this block is to collect as much of the available glass in Fredericton as possible. In the proposed solution, sorting of the glass will be integrated into the collection process. The collection step ends when the glass is delivered to the production facility where the following functions of the process will occur.

The next function of the proposed process is to clean the glass. The goal of this function is to remove the organic waste and labels. The first step of the washing process is to break the glass into large pieces so that any containers with lids will be able to be cleaned. The glass then needs to be washed using both water and the abrasion of the particles to aid in removing the labels and organic contamination. After the glass has been washed it must be dried before it can enter the crushing stage. The material will be exposed to heated air in order to remove the moisture.

The subsequent function of the proposed solution is to crush the glass to the appropriate size applicable for all three end products. As discovered in our literature review, the optimal cullet size for our end product selection is 5mm. Bottle caps that were streamed into the crusher will be filtered out as waste. This can be easily done as the caps will not crush into small pieces in comparison to the glass. Most crushers contain a filter that will gather these caps and lids so this contamination can be removed.

The end product of 100% glass tile requires additional processing. The first function includes sintering the glass at around 900^{o}C. In order to do so, clear glass cullet needs to be poured into refractory molds made from a fireclay or calcined kaolin clay based aggregate (Clean Washington Center, 1995). Depending on the target market, designs may be included in these molds, but they must have no overhangs and the surfaces must be kept smooth and relatively pore free. The amount and layout of glass poured into the molds should be consistent in order to meet product specifications. Any colorants would need to be added during this step. The ability to produce a satisfying palette of colors is critical in decorative markets. Most colored glass is made by adding small amounts of metal oxides such as chromium, iron, or cobalt, and trace amounts of other metals to control the oxidation states of the coloring oxides (Scholes & Greene, 1975). These oxides are mixed with the cullet before firing and diffuse throughout the glass during the sintering process.

The most critical step in making glass tiles is the sintering process. Firing times can vary dramatically depending on the size of glass particles and the furnace temperature. The temperature is the most critical factor and should be kept as close as possible to the melting point of the cullet, which is 920^{o}C (Clean Washington Center, 1995). Depending on the control system used, 900^{o}C is expected to be a safe operating temperature. If the cullet is allowed to reach 920^{o}C, it will melt and become attached to its mold, consuming unnecessary amounts of energy and ruining the tile and its mold. Release agents, which inhibit sticking between molten glass and the mold, may be used to mitigate this problem if higher operating temperatures are found to be more economical. After the tiles are created through the sintering process they must be packaged before they are stored and sold.

The end product of sandblasting media requires additional crushing processes to achieve the fine grain sizes required. Sifting is also required to separate the product into size fractions of: extra coarse, coarse, medium and fine. Each of these sizes will be packaged separately before they are stored and sold.

The final back-up solution is the production of an aggregate substitute. Cullet, coming from the crushing system, can be sold directly as aggregate. Most aggregates are sold and delivered by truck load. If more leverage is required to convince local companies to use cullet in their mixtures, then a possible option would be to create pre-measured bags of aggregate to match the quantity required for their batch. This would allow for easy integration into the existing concrete or asphalt mixing process.

3.3 Underlying Principles

3.3.1 Overview

Behind any process lay key physical and chemical principles which must be controlled and optimized to have optimal performance, process reliability, and product consistency. The underlying principles behind cullet preparation and glass tile manufacture are discussed in this section.

3.3.2 Crushing and Sorting Equipment

Crushing equipment generally has a short lifespan and the equipment required to crush recycled glass is no exception. Glass is a very abrasive material, with a Mohs hardness between 5.5 and 7, which is higher than many natural minerals (Clean Washington Center, 2012). Due to this, crushers that use an impact breaking mechanism, such as hammer mills, are generally favored over those that use an abrasion mechanism, such as jaw crushers and cone crushers. High hardness alloys should also be favored for all impact surfaces to reduce equipment wear. Figure 3 below demonstrates the effects of hammer hardness on equipment wear in a hammer mill crusher. Sieving equipment can also be damaged by abrasive materials. A successful design should minimize exposure of the screens to abrasion, and where exposure is unavoidable, high hardness alloys should be used.

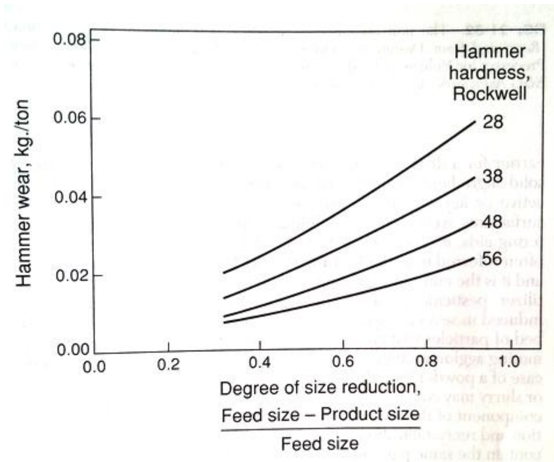


FIGURE 3: EFFECT OF HAMMER HARDNESS ON EQUIPMENT WEAR (GREEN & PERRY, 2008)

3.3.3 Sintering Furnace Operation

Glass tile production from cullet involves heating the crushed glass and providing enough residence time for the glass particles to bond to one another, taking the shape of a refractory mold. Temperatures must be kept below 920°C, at which point the cullet will melt completely and bond to its mold (Clean Washington Center, 1995). This process is governed by the following non-crystalline sintering rate relationship (Kingery, 1958):

EQUATION 1

$$\frac{\Delta V}{V_o} = \frac{9\gamma t}{4\eta r}$$

Where: ΔV = change in volume of glass (m^3)

V_o = initial volume of glass (m^3)

r = mean particle radius (m)

t = time exposed to conditions (s)

γ = surface tension of glass ($N\ m^{-1}$)

η = viscosity of glass ($kg\ m^{-1}\ s^{-1}$ or Pa s)

According to Kingery, glass particle size and viscosity are the key control parameters since surface tension remains relatively constant for all normal operating conditions. Viscosity, on the other hand, decreases significantly as the glass is heated. A 100°C increase decreases the viscosity by 1000 times and increases the sintering rate similarly. By using a consistent particle size and temperature profile throughout the sintering furnace, a consistent glass tile product can be achieved. The impact of these parameters on glass densification is shown in Figure 4 and 5:

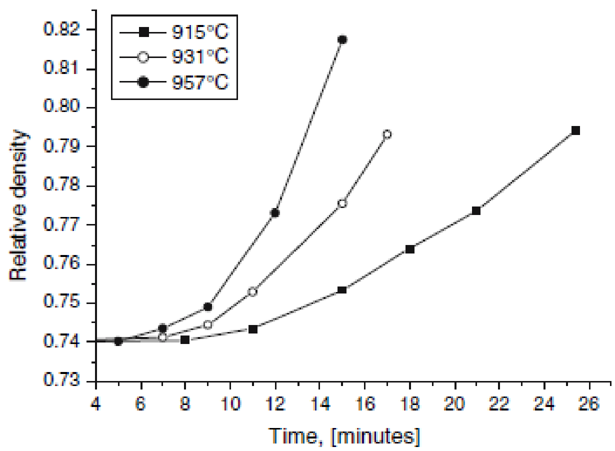


FIGURE 4: EVOLUTION OF RELATIVE DENSITY VERSUS TIME AND TEMPERATURE (BARG, KOCH, PULKIM, & GRATHWOHL, 2008)

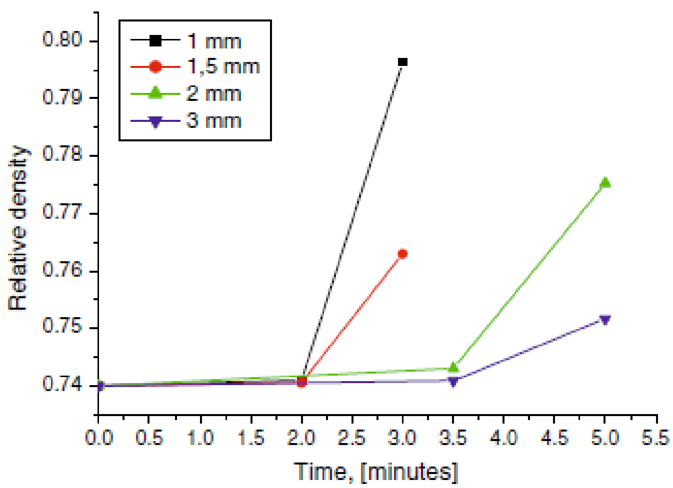


FIGURE 5: EVOLUTION OF DENSITY OF SODA-LIME GLASS AS A FUNCTION OF TIME AND SIZE OF BEADS (BARG, KOCH, PULKIM, & GRATHWOHL, 2008)

From the data above, it is apparent that high relative densities can be reached by sintering processes in reasonable periods of time. Given the strong temperature dependence of viscosity, it is desirable to operate glass sintering furnaces at temperatures close to the glass melting temperature. A control system should be used to keep the temperature as high as possible, but below 920^{o}C. It should be noted that the temperatures used in literature were achieved with the use of a release agent to prevent glass from sticking to the molds used.

3.4 Health, Safety, Environment, and Social Issues

3.4.1 Health and Safety

Potential health and safety issues that are associated with recycling glass (processing from product to cullet) are normally related to the inhalation of glass dust, potential cuts from handling glass pieces and particles, and mechanical equipment safety hazards, particularly the crusher. These are serious concerns, but have been studied extensively to implement preventative measures in order to design a process that is safe.

Glass dust is an inert dust and has no significant biological effect on the body. Some perceived concerns arise from the concept of crystalline silica, which is the cause of silicosis and a known carcinogen in the manufacture of glass containers. Crystalline silica dust, when inhaled, damages the lungs and can cause fluid buildup and scar tissue. While silica sand is a raw material used in the production of glass, the manufacturing process converts the crystalline structure to an amorphous state, resulting in recycled glass containing less than 1% crystalline silica (Department of Environmental and Climate Change NSW, 2007). The amorphous state of silica is significantly less harmful. Due to the silica's amorphous structure, the body's respiratory system can get rid of this form of silica the same as it does with normal dust inhalation. Many reports have concluded that the dust generated by glass cullet is not considered hazardous and does not contribute to silicosis or cancer (Department of Environmental and Climate Change NSW, 2007).

Although glass dust is not directly destructive to the respiratory system, it can still cause discomfort and an irritation, which is not acceptable in the workplace. With respect to occupational health and safety, consideration should be given to prevent such effects. Some prevention methods are listed below:

- Using moisture to help prevent dust clouds or travelling dust
- Appropriate ventilation
- Dust masks
- Efficient storage and transportation of the cullet
- Enclosing the process

As mentioned above, another significant safety concern when dealing with glass is its ability to create sharp shards when broken and cause incisions to skin. The collection and conveyor process before the crushing is the focal area of the process for this issue because after the glass is crushed, the particles are small enough that they are dull and not harmful in this manner. It is reported that particles smaller than 19mm (3/4") are no more harmful than a typical aggregate and particles less than 6mm (¼") are completely benign (Department of Environmental and Climate Change NSW, 2007).

In the collection process it will be very important to require that broken glass be placed in a separate bag or bin and labeled. This will help prevent injuries to the collection workers. In addition, sorting the glass during the collection process, rather than after drop off, can help prevent cuts. Breaking glass is an unavoidable part of the collection process and so it is best to sort it before it has been thrown into bins and become a possible danger. Contact with the glass during any point of the collection and conveyer processes should be done with cut resistant gloves to prevent any accidents.

The equipment used to crush the glass can provide a hazard to workers as well. If someone was to accidentally place one of their limbs in the crushing machine the results would be severe. This particular safety hazard can be mitigated by following OSHA’s requirements for machine guarding. It is important to keep the employees of the manufacturing facility well informed about the safety hazards and educate them on the preventive measures used. Some of the OSHA requirements for machine guarding are listed below (Olver, Lant, & Plant, 2013):

- Prevent contact
- Be secure and durable
- Create no new hazard
- Create no interference
- Allow safe maintenance

There are many options for safeguards that can be put in place for a machine such as a crusher. An interlocked guard is most applicable. This is a guard that will not allow the machine to start if the guard is not properly in place. This ensures that if the machine is running, no human interaction can occur with operation points that are potentially hazardous. Other options for safeguarding the crusher include fixed guards (permanent barrier between workers and the point of operation), and adjustable guards (provide a barrier against a variety of different hazards associated with different production operations). (Olver, Lant, & Plant, 2013)

The glass recycling process requires large machinery to clean and crush the glass. These machines will likely produce a significant amount of noise which will create an issue of worker safety. The maximum exposure level allowable for an 8 hour shift is 80 dB (Olver, Lant, & Plant, 2013). Anything above this amount will require worker protection. Sound protection can be attained by physical barriers that block and contain sound waves, by creating distance between the noise creating object and the workers, or by ear protection such as ear plugs and sound blocking ear muffs.

These are the largest health and safety concerns with a process regarding glass crushing. More information on safety with the material in particular can be seen in the MSDS sheet on crushed glass in Appendix B-1.

Another portion of the process with safety related issues is the glass melting process for the 100% glass tile production. Similar to the crusher, the furnace and cooling process will most certainly have to be safeguarded to prevent burns. The sintering process reaches 900^{o}C which can be detrimental to humans. In cooperation with safeguarding, personal safety equipment such as eye, hand and clothing protecting should be worn at all times while working with the sintering and cooling processes. In addition, the use of furnaces can cause a fire hazard (Olver, Lant, & Plant, 2013). In order to mitigate fire hazards, an automatic sprinkler system and fixed extinguishing systems must be in place. Flame resistant building materials and proper ventilation are also recommended for increased fire prevention.

3.4.2 Environmental and Social Issues

Environmental and social issues associated with the project are important considerations in the early stages of design. Socially, the problem presented by the client is due to the public perception of recycling. "Doing your part" to contribute to the protection of the environment is a huge movement at the moment. Many citizens take recycling seriously and sort their garbage to prevent as much as possible from going into the landfill. The city has received numerous calls wondering why the city does not currently recycle glass (Hymers, 2012). In order to mitigate this social concern, this design project will have to be fact based. This way the City of Fredericton can present its conclusions as to whether or not glass recycling should be implemented and have it thoroughly supported and well understood.

Some social aspects of the project are tied to the environmental portion of it as well. Although it seems that recycling is the best option for the environment, it is important to consider the full lifecycle impact of recycling glass. Additional emissions from the trucks in collection and transport, additional electricity consumed and emissions released from the plant required to crush the glass, and the environmental impact of the glass used in the chosen end market are all sections of the lifecycle that the client should be aware of. Considering whether these negative environmental impacts are balanced by positive portions of the process (re-using materials, lowering garbage volume entering landfills, etc.) gives us a high level of understanding of the environmental lifecycle of recycling glass. For glass in particular this is a subject of interest because when landfilled, it is inert and causes no harmful effects to groundwater, surface water, or soil, and does not produce any greenhouse gas emissions (FRSWC, 2011). This issue would be an entirely separate project on its own and is not the focus of the scope of this project, but it is good to keep social issues like this in mind when completing the project.

Another social issue is potentially created by the choice in location of the crushing plant. Noise pollution must be considered during this portion of design. If the plant is in proximity of a residential area, then working hours and noise levels must be changed accordingly. The FRSWC is a likely location for the crushing plant, therefore noise pollution would not be a concern as it is a fairly remote location.

4.0 Detailed Design

4.1 Process Flow Diagram

4.1.1 Diagram Overview

The process flow diagram for the proposed production facility has been prepared to provide a detailed description of all required equipment and their processes (see insert). Mass and energy balances were derived from fundamental engineering equations and calculations. Sample calculations are provided in Appendix C. Spreadsheets have been developed for each calculation to enable modifications to the key values throughout the design process. They also provide a more clear representation of the overall mass and energy balance. All spreadsheets used for calculations are provided in Appendix D.

The following sections will discuss the process flow diagram in detail. The processing facility has been divided into five sections for clarity. These sections include the collection process, cullet production process, aggregate preparation, blasting media processing, and tile manufacturing. It is important to note that aggregate preparation, blasting media processing, and tile manufacturing are the possible routes for the cullet produced at the proposed facility. Batch processes, represented by gates in the process flow diagram, enable the cullet to be diverted to the proper value added process whether it is due to market demand or the physical characteristics of the cullet such as colour.

4.1.2 Collection Process

The proposed process has an expected raw material input of 1264 tonnes of recycled glass per year. This input comes from a Fredericton based collection that will take place at the bottle depots. There are four main bottle depots: Best Metals, Northside Redemption Center, Southside Redemption Center, and SWC Recyclables. When citizens go to the bottle depots to return their glass bottles for refund, they will also have the opportunity to recycle other glass products that would otherwise be landfilled. Just as the refundable bottles are sorted by workers, the recyclable glass that is dropped off will be sorted by a worker into two separate bins (T-101) for clear and mixed/coloured glass. It will be requested that the citizens clean containers, remove caps and lids, and presort glass, keeping any broken glass in a separate bag to prevent hazards. Realistically these requests will not always be followed, but they will help the process run much smoother. Once the bin is full, a truck will drop off an empty bin and take the full bin of glass to be stored at the production facility. Frequency of glass pick up from the depots will depend on how long the program has been implemented as participation is expected to increase over time. At maximum capacity the bins will be collected weekly. There are four bottle depots in Fredericton and two bins will be required per depot. The rotation of bins as they are transported to the FRSWC will cause a requirement of 16-24 bins depending on the frequency of bin collection from the depots.

The input of the system is supported by statistics provided by the FRSWC. The FRSWC landfills 80,000 tonnes of garbage per year from the City of Fredericton and the surrounding greater Fredericton area. It is estimated from waste audits that about 4% of the material landfilled is glass (FRSWC, 2011). This leaves a total of 3200 tonnes of glass per year that is available for collection and recycling. The FRSWC expects that approximately 50% of the available glass would actually be collected (FRSWC, 2011). Then, considering that the bottle depots will be the location of our drop off, and the refundable program has a current success rate of 79%, this leaves us with a total of 1264 tonnes of glass collected per year. Through research it was determined that a reasonable estimate of 55% clear glass and 45% coloured glass can be expected to be collected (Zero Waste, 2012). Our final input streams become approximately 695 tonnes of clear glass per year (shown in stream 1 and 4) and 570 tonnes of coloured (or mixed) glass per year (shown in stream 2 and 5).

There will no doubt be some discrepancies in the sorting. Clear glass ending up in the mixed batch causes no issues. If a small amount of coloured glass ends up in the clear glass batch then the process can still continue as normal. If large amounts of coloured glass contaminate a batch that is supposed to be clear glass, then it will have to be used as mixed/coloured glass and processed for sandblasting media. Based on an analysis of the tile market, the goal for quantity of clear glass converted into tiles per year is around 500 tonnes. This leaves almost 200 tonnes per year as a margin of error for colour contamination of a clear glass batch, which is sufficient.

The bins at each bottle collection depot would need to be able to fit one quarter of the expected volume of glass as there are four main depots in the greater Fredericton area. Based on a working year of 52 weeks and 6 days a week (the number of days the bottle depots are currently open), it can be expected, at maximum intake, to collect about 1000 kg of glass per day per depot. For weekly pick up, this would require two bins of approximately 6 m^3 at each depot at maximum intake. Each bin would collect only clear or coloured/mixed glass. This is a high estimate as a large quantity of the glass will likely break when being thrown into the bin, and therefore there will be less volume occupied by air gaps than expected. In addition, it will likely take a year or two of program implementation before maximum participation and intake can be expected from citizens. Calculations supporting the expected glass input and the collection bin sizing are present in Appendix C-1.

Once the bins are filled, they will be picked up at the bottle redemption site and brought to the processing facility location. The bins will be placed on forklift pallets for easy transfer. The bottle redemption centers already have forklift pallets and forklifts for their day to day collection. Currently Trius Disposal collects recyclable material for the City of Fredericton. Were they to be contracted for glass transportation as well, they have cube and cargo trucks that could easily be used for transportation. One of these trucks is a 5 tonne that has an electric lift gate which could be used as another option for transporting the bins in and out of the truck.

In the case where expansion is desired or not enough glass is being collected from The Greater Fredericton Area, more cullet can be retrieved from alternate sources including the following:

- **Moncton:** Moncton has an additional quantity of glass stock piled at their facility from when they recycled glass in the past. The quality of the glass is unknown, but it could be cleaned and used as mixed or colour glass for sandblasting at the least.
- **Expansion to nearby cities:** The bottle depot non-refundable collection program could be implemented in cities nearby such as Oromocto, Woodstock, and Saint John to obtain a larger quantity of glass.

4.1.3 Cullet Processing

Once the glass is collected and stored at the processing facility, the next step is to turn the recycled glass into cullet. The cullet plant, with the input of recycled glass discussed above, and an approximate throughput of one tonne per hour, requires 1200 operating hours per year. This is achieved by running the machinery 3 days per week, 8 hours a day, for 50 weeks in a year. The cullet forming process will be done as a batch process alternating between clear glass and mixed coloured glass as required. This batch process is represented by a gate labeled “clear or mixed” on the PFD. Sample calculations and explanations for the facility production hours and quantities can be found in Appendix C-2.

B-101 - Breaking

Raw material processing at the facility begins by taking a new batch of glass (either coloured [stream 7] or clear [stream 6]) from storage and processing it into cullet. The stream entering the process is first emptied onto conveyor C-101 which will lift the glass to the top of a breaker tower (B-101). All ramp conveyors in the process are expected to use about 140 W each (conveyor assumptions and calculations are located in Appendix C-3). B-101 represents an enclosed tower, three meters in height, with metal bars dispersed throughout. The glass (stream 8) will be dropped through the tower in order to break the containers into large pieces. Upon exiting the breaking tower (stream 10), the largest pieces of glass are expected to have an average radius of 50 mm. This is the size of the bottom of an average beverage or food container which contains the thickest glass and would be the hardest to break. The breaker tower step will allow the glass to be cleaned much more effectively. A simple schematic of the break tower is shown in Figure 6 below.

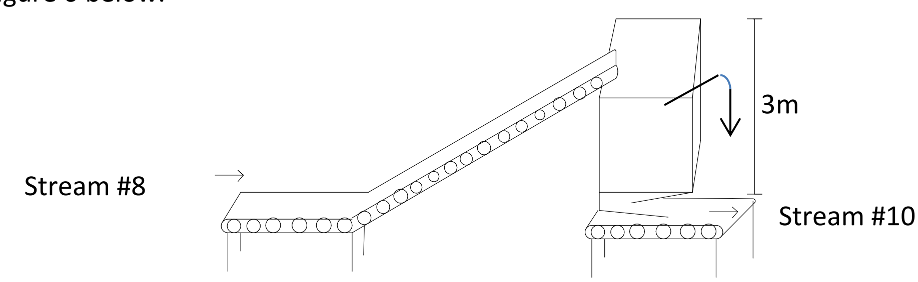


FIGURE 6: BREAKER TOWER SCHEMATIC

During this process, some dust will be created (stream 9) and captured by the dust collection system in filter FD-102 or FD-103. Clean air will exit this air filtration system to atmosphere (stream 51), reducing any health or safety hazards posed by the glass dust. The filters of the dust collection subsystem will be changed periodically and disposed in the landfill. Mass and energy balance sample calculations for the breaking process are shown in Appendix C-4.

W-101 – Washing

Conveyor C-102 transports the glass cullet (stream 10) to the washing stage (W-101). The washer will be designed to use a combination of warm water (stream 11), soap (stream 13), and abrasion to separate the labels, glue and organic materials from the glass throughout the washing process. The amount of soap required for the process is approximately 0.2 % of the solution (Zhangjiagang Kezheng Trading Co., Ltd., 2012). The water supplied to the washer will be pumped (P-101) to the washer and electrically heated to around 60^0C by the washer design.

The exit stream of water (stream 14) will contain the solution and a small amount of solids that fit through the draining system (about 1 % of solids removed in cleaning process). The rest of the solids continue on to be dealt with in the drying stage. One percent of the solids removed is only 52 g. When comparing this to the flow rate of the water going through the washer, approximately 2000kg/hr, there will be no issue in pumping this small amount of solid. The exit water stream (stream 14) is pumped (P-102) to a municipal waste water collection sanitary sewer as there are no harmful chemicals to be concerned about. The cleaned glass then exits the washer, shown by stream 16. Sample calculations for the washing process can be seen in Appendix C-5. An example of a continuous rotary drum washer is shown below.

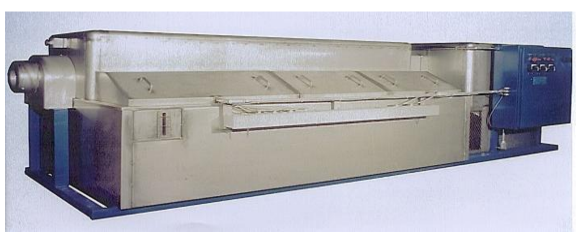


FIGURE 7: ROTARY DRUM WASHER

E-102 – Drying

Conveyor C-103 takes the glass stream (stream 16) to the drying stage. Air (shown by stream 17-18) is blown into the combustion chamber (E-101) and natural gas (stream 19) is added. The output stream from the chamber (stream 21) is a mixture of the combustion gas and clean air (stream 20) and enters the dryer at 400^oC. This heating process is expected to require 3.2 kg/hr of natural gas. The air is used by a rotary dryer to reduce the moisture content of the glass from 5% to 0%. Labels separated during the washing process will enter the dryer. These will partially combust due to the high temperature of the incoming air stream. The rotary dryer will be made of stainless steel to ensure that this does not affect the life or function of the dryer. The air out (stream 22) will pass through FD-10, a knock out box, which will remove any solids from the airstream. The hot gas (stream 23) will be directed to a vent and the waste (stream 24) will be periodically put in the landfill. The glass entering the dryer (stream 16) is at approximately 60°C from heating in the washing stage. The glass exits the dryer (stream 25) at about 90°C. A schematic of a continuous rotary drum dryer is shown in Figure 8 below. The glass is then placed on conveyor C-104 to be transported to the crushing stage. Sample calculations for drying process can be seen in Appendix C-6.

The combustion of the labels due to the high temperature is slightly unpredictable, and will depend on what temperature of air they contact. Since the air cools to 120°C throughout the process, some solids may contact hotter air causing them to burn, and some may not burn at all. Regardless of the state of combustion, the solids will be filtered through the knock out box and removed as desired. The density difference between the air and glass will allow the labels to become separated from the glass stream and removed. The heater should be slightly oversized on this piece of equipment, so that the temperature can be increased if operational difficulties are experienced.

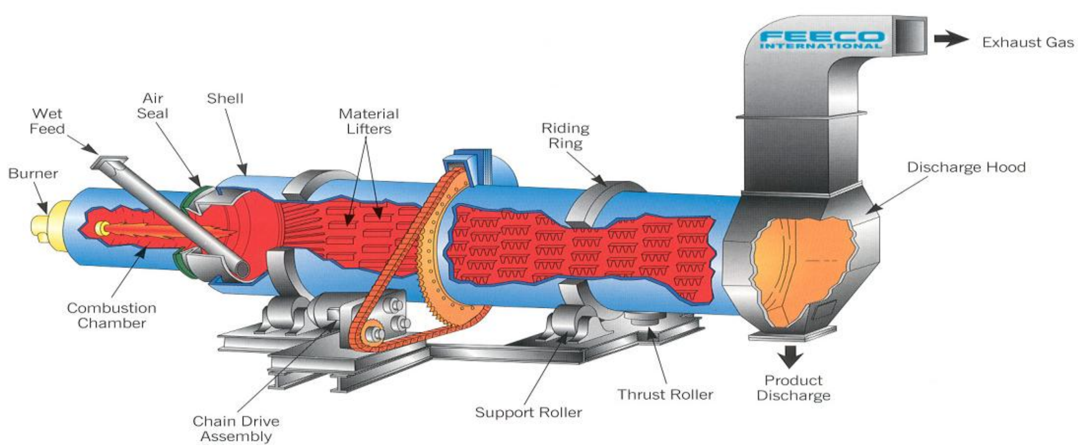


FIGURE 8: ROTARY DRUM DRYER

B-102 – Crushing

Stream 25 enters the crusher (B-102) at a rate of 1038 kg/hr. The input particle size is 5 cm and is being reduced to a target of 5mm. The stream exiting the crusher depends on the batch being processed. Streams 28, 30 and 32 represent cullet which is destined for aggregate, tile manufacturing, or sand blasting media production, respectively. Conveyor C-105 transports aggregate cullet to a designated storage area (T-104) where it will be picked up by the customer. Conveyor C-106 transports clear crushed cullet to a hopper (T-105) for storage to be used in glass tile manufacturing. Conveyor C-109 is used to transport mixed colour crushed cullet to the next step in the blasting media processing (which is a continuous ending to the crushing process when coloured/mixed glass is being processed).

The crusher (B-102) will be connected to a central dust collection system to reduce the amount of fines dispersed into the ambient air. The percentage of fines entering the dust collection system is 1% and is represented as stream 26. A built in trommel screen system integrated in the crusher provides a waste removal process which diverts any metal contaminates (stream 27). Sample calculations for the crushing process are shown in Appendix C-7. Figure 9 below shows a schematic of a hammer mill crusher.

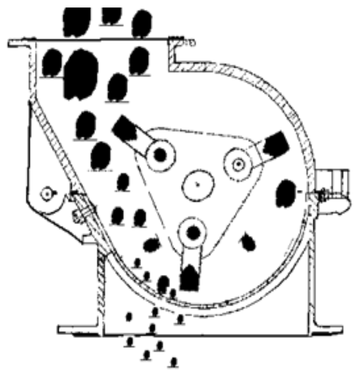


FIGURE 9: HAMMER MILL

4.1.4 Blasting Media Production

S-101 – Additional Crushing and Sifting

From the crusher, stream 32, consisting of mixed colour cullet, is emptied onto a conveyor (C-109) where it continues to the ball mill (B-103). This will reduce its size again so that the crushed glass meets the specifications for sandblasting medium. Next, stream 33 is put on a ramp conveyor to be transported to the trommel screen (S-101) for sifting. The ball mill and the sifter are connected to the facility dust collection system to reduce airborne dust (streams 34 and 39). The dust volume is approximated at 1%.

The trommel screen (S-101) uses rotating meshes to separate the cullet into the proper particles sizes for sandblasting media. The separated blasting media falls from the trommel screen into hoppers (T-106). Streams 35, 36, 37, and 38 represent the different sizes of media. A mobile packaging system (Z-101) that is capable of bag sizes up to 20kg then bags the sand, one size at a time, to complete the sand blasting process.

Sample calculations to accompany blasting media production are located in Appendix C-8. Figure 10 below give a visual representation of the equipment used in this portion of the process.

FIGURE 10: VISUAL REPRESENTATION OF SANDBLASTING MEDIA PROCESSING

4.1.5 Tile Production

T-108 – Mixer / Dispenser

At the beginning of the tile manufacturing process, clear glass cullet (stream 31) is sent from storage (T-105) to the blending station on a chute (C-107). The clear cullet is mixed with the desired colorant in an aggregate blender (T-201). The blender is loaded with the desired colorant (stream 70) before the start of the batch process. Empty molds pass under a metering machine which injects the proper amount of the crushed glass/colorant mixture into the mold. An actuator arm then lifts to allow the mold to be picked up by the furnace conveyor (C-201). A schematic of a typical metering machine is shown below in Figure 11.

FIGURE 11: MIXER/DISPENSER

E-104 - Furnace

The operating conditions of the electric furnace are 900°C with a design throughput of 250kg/hour of glass, and the required mold weight of 500kg/hr, resulting in a total of 750kg/hr. Stream 71 represents the input of filled molds into the furnace as stated in the mixer section.

The furnace has three sections to provide heating. The first section gradually brings the temperature of the input material to 900°C. After the sintering temperature is reached, the molds stay at 900°C for approximately 10 minutes to achieve complete sintering. This time depends on the size of tiles being produced. The third section of the furnace will gradually bring the temperature of the tiles from 900°C to 200°C. This gradual cooling is required to prevent cracking of the product.

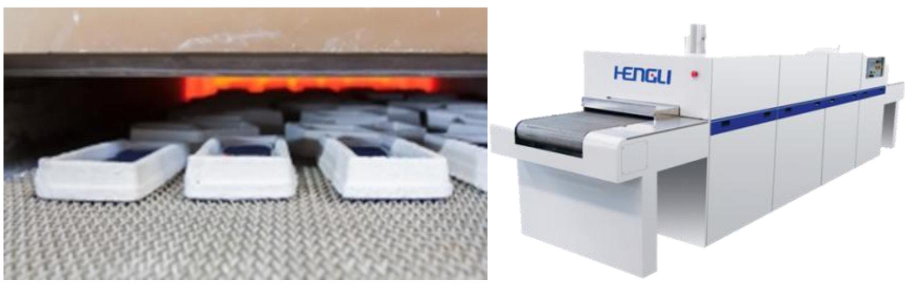


FIGURE 12: BELT FURNACE

E-107 – Removal and Cooling

The molds, containing the now sintered tiles, (stream 73) exit the furnace on a conveyor (C-202). Tiles are removed from the molds using a multi-axis robotic arm with a vacuum nozzle (R-201). The hot tiles (stream 74) are placed on a separate conveyor (C-203), where they pass under cooling fans (A-201). The tiles are inspected for any defects as they cool on this conveyor. Empty molds are rerouted to the filling station (stream 71).

T-109 - Packaging

Cooled tiles (stream 78) are picked up by the robot arm (R-201) and packaged into cardboard boxes with a sheet of packing paper between each tile to reduce scratching. Boxes and packing paper enter this step as streams 79 and 80, respectively. A person assists the packaging process and moves the boxes of packaged tile on to pallets so they can be sent to the warehouse for storage. The rate at which packaging occurs depends on the size of the tiles being produced in the batch (1000 tiles per hour for 100mm x 100mm).

Figure 13 below shows an example of a multi-axis robot arm. Tile production supporting calculations are found in Appendix C-9.

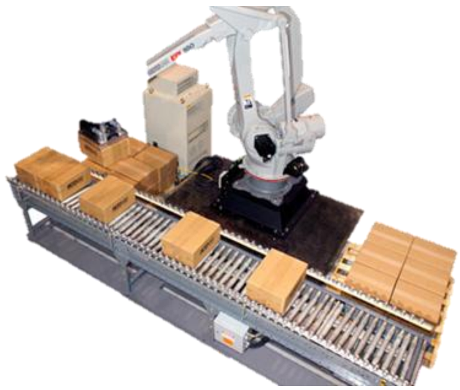


FIGURE 13: MULTI-AXIS ROBOTIC ARM

4.2 Design Evaluation

4.2.1 Health and Safety

Potential health and safety issues when dealing with crushing and processing glass were discussed in section 3.4.1. In order to address these issues, our process must be designed to prevent any serious health and safety risks posed to workers and the public.

Working with glass is a health and safety concern due to the potential for lacerations from broken glass. In the collection process, sorting is done at the bottle collection depots, which addresses the possible risk of hand sorting at the facility. Any workers at the facility that are required to come in contact with the glass will be required to wear cut resistant gloves to prevent injury.

Glass also poses the threat of creating dust that, when inhaled, can cause discomfort within a person's respiratory system. As shown in the process flow diagram, in order to prevent this, a dust collection system will be implemented that will collect these harmful particles from the breaking, crushing and sifting processes. The particles will be removed through this centralized sub-system with two filters, and the clean air will be released to atmosphere.

Machine guarding will be implemented in several areas of the processing facility as there are a number of large pieces of machinery required to process the glass. Interlocking guards will be put in place to prevent injuries with the crusher, washer and dryer. This will help prevent worker contact with dangerous parts of the machinery when it is functioning. For tile making, much of the process is automated to prevent human contact with the dangerous conditions of the furnace (900^{o}C) and hot tiles before they cool. The only person in this area of the process is working on inspecting the tiles for quality assurance. An interlocking barrier will be placed at the entrance and exit of the furnace. Barriers are also required around the functional area of the robot arm that is used to remove the cooling tiles from the molds. This will help prevent accidental human contact with these areas of risk as well.

Due to the large machinery, it is likely that workers will be exposed to sound levels above the 80 dB 8 hour limit. Sound tests will be done when the equipment is installed to obtain the exact sound levels. Workers will be required to wear ear protection as the sound tests dictate. The interlocking barriers on many pieces of machinery will also help with noise issues as they will create an additional barrier for the sound waves.

The proposed process contains quite a few instances where high heat is required. The dryer uses natural gas and deals with temperatures that are hundreds of degrees higher than room temperature. The furnace also deals with such high temperatures. Fire protection will be an important part of the health and safety design in the processing plant and will be one of the most crucial subsystems.

4.3 Subsystem and Components

The proposed glass recycling process is a complex system. It will include many additional subsystems and components that complement the main systems shown in the detailed design of the PFD. These systems are outside of the scope of this project but will be discussed briefly to insure they are considered in design discussions. Estimates for these systems are included in the overall capital costs and economics section.

4.3.1. Building

A building will need to be designed and built to accommodate glass processing at the FRSWC site. This building will house all of the equipment and storage for the crushing, sandblasting and tile production processes. Some specifications of the building subsystem are listed below:

- Temperature controlled to 20^{o}C
- Dust collection system to accommodate 31 kg/hr of glass from equipment (calculated from mass balance shown in Appendix D)
- Central ventilation system providing fresh air to building
- Additional dust collection for ambient air built into central ventilation system
- In the summer months the heat from the processing equipment will need to be exhausted from the building to ensure a comfortable working environment. In the winter months supplementary heat can be supplied by a natural gas burning furnace in the central ventilation system.
- Flame resistant building materials

4.3.2. Water and Sewer System

A water system will be required to provide water to the washer and other typical plumbing fixtures in the glass processing system. Municipal water and sewer are already present at the proposed site. Some of the specifications for this system are listed below:

- Flow rate required of 2000 kg/hr for washer
- Water does not need to be temperature controlled prior to arrival at glass processing plant
- Centrifugal pump will supply pressure difference to obtain the required head and flow rate

In addition to the water required for the washing process, water for a fire protection system will be required. As discussed in the health and safety section 4.2.1, the manufacturing process contains equipment where high heat is required. The dryer and furnace both deal with temperatures in the hundreds of degrees Celsius. Fire protection is therefore a necessary subsystem to ensure that the health and safety requirements are met. The fire protection system will be a wet fire sprinkler system that will follow the specifications in the National Fire Code of Canada.

4.3.3. Natural Gas System

Natural gas is required in the process to run the dryer. Enbridge Gas supplies natural gas to the general vicinity of the proposed location of the FRSWC, but a new supply line will need to be directed towards the new glass processing building. Some specifications for the natural gas system required are shown below:

- Flow rate required is 2.7 kg/hr
- The distance from current natural gas distribution system, and resulting pressure required to transport the natural gas to the location of the new glass processing building, are currently unknown, but will be required for proper design of this subsystem.

4.3.4. Electrical System

The majority of the equipment in the process runs off of electricity (ie. conveyors, pumps, crushers, blowers, sifter, packaging unit, colorant mixer, furnace, robotic arm, cooling fan, etc.). Some specifications for the electrical requirements are listed below:

- Total electricity peak load for the equipment is 1.6 MW. This number does not include the lighting for the building and other subsystem requirements for the electrical system which will need to be determined for its design.
- Equipment voltage requirements are 120V for conveyors, 240V for larger equipment and 480V for the furnace.

4.4 Equipment Summary Tables

4.4.1 Storage Bins

TABLE 9: COLLECTION BINS SUMMARY TABLE

24x Divided Collection Bins (T-101)	
Material	Steel
Volume	≈ 6 m^3 (± 0.1m^3)
Dimensions	H ≈ 1.5 m L, W ≈ 2 m
Capacity	≈ 3000 kg (± 100kg)
Product life	10 - 15 years
Additional Information	• Intended to be used for glass collection

4.4.2 Conveyor Belts

TABLE 10: FLAT CONVEYOR SUMMARY TABLE

10x Conveyor (Flat)	
Type	Rubber, fixed speed
Material to be transported	Glass
Belt type	Rubber - Cut resistant ≈ 6 mm thick (See Appendix B)
Flow rate required	1000 kg/hr
Belt Speed	≈ 10 m/min
Belt Width	≈ 0.5 m
Unit Height	≈ 1 m
Length of unit	≈ 3 m
HP	≈ 0.16 hp (120 W)
Product life	10 - 15 years
Additional Information	• Belt speed is open to change for optimal efficiency of the conveyor while transporting the required flow rate • Height should be adjustable to accommodate equipment of various heights

TABLE 11: RAMP CONVEYOR SUMMARY TABLE

2x Conveyor (Ramp)	
Type	Rubber, fixed speed
Material to be transported	Glass
Belt type	Rubber - Cut resistant ≈ 6 mm (see Appendix B) - ridged
Flow rate required	1000 kg/hr
Belt Speed	≈ 10 m/min
Belt Width	≈ 0.5 m
Ramp height increase	3 m
Length of inclined portion	6 m
Incline	$\Theta \approx 30^o$
HP	≈ 0.2 hp (150 W)
Product life	10 - 15 years
Additional Information	• Must have 1 m flat section of conveyor before the rise begins (in addition to the inclined length) • Belt speed is open to change for optimal efficiency of the conveyor while transporting the required flow rate

4.4.3 Breaker Tower

TABLE 12: BREAKER TOWER SUMMARY TABLE

1x Breaker Tower (B-101)	
Material	Steel
Volume	$\approx 3\ m^3\ (\pm 0.1\ m^3)$
Dimensions	H = 3 m (±0.05 m) L, W ≈ 1 m (±0.1 m)
Metal bar quantity	8
Metal bar dimension	W ≈ 0.03 m (±0.03 m) L ≈ 1 m (±0.1 m →Must match L above) H ≈ 0.03 m (±0.03 m)
Product life	10 - 15 years
Additional Information (see figure 6 in section 4.1.3)	• Locate metal bars in lower 2/3rds of the tower • Length of breaker bars should go in different direction in two levels • 4 breaker bars in each level • Levels about 1 m apart in height • Tower must 'catch' the glass at the end by an angled guide (see figure 6 in section 4.1.3) to slow down glass before it drops on the conveyor • A stand must be built for the 3m high breaker tower to sit above a conveyor

4.4.4 Washer System

TABLE 13: ROTARY WASHER SUMMARY TABLE

1x Rotary Washer (W-101)	
Type	Continuous, rotary/drum
Washing chemicals	Water, Soap (0.19 %)
Material washed	Glass – metal, plastic, paper & other organic contaminants
Mass washed	1000 kg/hr
Water required	2000 kg/hr
Heat required	110 kW
Estimated residence time	10 mins
Dimensions	D ≈ 0.57 m L ≈ 1.70 m
Product life	10 - 15 years
Additional Information	• Should have built-in electric water heating – other heating configurations may be discussed • Water requirement, heat requirement, residence time and dimensions may be discussed • Design should resist clogging from 5 kg/hr bottle labels and food-based organic contaminants

TABLE 14: PUMP SUMMARY TABLE

2x Pumps (P-101 & P-102)	
Type	Dynamic pump (rotary: centrifugal)
Fluid Type	Water, Soap (0.2%)
Flow rate required (@ ≈ 60ft (18m) of head)	2000 kg/hr
Pipe size	1” (≈ 25mm)
Power	≈ 0.75 hp (560 W)
Product life	10 - 15 years
Additional Information	• Flow velocity should be between 1 – 3 m/s • Turbulent flow • Needs to be able to handle ≈ 55 g of fibrous solid per hour • Flow rate must match water requirements of washer

4.4.5 Dryer System

TABLE 15: ROTARY DRYER SUMMARY TABLE

1x Rotary Dryer (E-102)	
Type	Continuous, rotary/drum
Mass Flow	1000 kg/hr
Moisture content	5%
Dryer air conditions (in)	0.16 m^3/s 400 °C 0.009 kg moisture / kg dry air
Dryer air conditions (out)	150 °C 0.085 kg moisture / kg dry air
Heat Transfer Area Required	38.7 m^2
Power	5kW of electricity 0.16 GJ of natural gas
Product life	10 - 15 years
Additional Information	• Dryer must handle <5 kg/hr of labels entering. Partial combustion expected • Dryer air conditions may be discussed • Dimensions specified by manufacturer. (4m^3 approx.)

TABLE 16: AIR BLOWER SUMMARY TABLE

1x Blower (P-103)	
Type	Centrifugal
Fluid Type	Air
Flow rate required	0.16 m^3/s
Pressure	15 kPa
Power	≈ 3.25 hp (2.4 kW)
Product life	10 - 15 years
Additional Information	• Pressure is open to change for optimal efficiency for the blower

TABLE 17: COMBUSTION CHAMBER SUMMARY TABLE

1x Combustion Chamber (E-101)	
Fuel	Natural gas
Oxidizing agent	Air (21% O_2)
Heat required	38 kW
Product life	10 - 15 years
Additional Information	• Ambient heat losses should be minimized within reason.

TABLE 18: KNOCKOUT BOX SUMMARY TABLE

1x Knockout Box (FD-101)	
Flow rate	0.16 m^3/s
Particles to remove	Ash; partially combusted labels
Removal method	Gravity / flow obstructers
Product life	10 - 15 years
Additional Information	• Should remove visible impurities from dryer emissions • Design must resist high temperatures (400 °C max.)

4.4.5 Crusher

TABLE 19: CRUSHER SUMMARY TABLE

1x Glass Hammer Mill Crusher (B-102)	
Capacity	1000 kg/hour
Material Input	Broken glass with possible plastics and metal
Material input size	5 – 10cm
Crushed glass output size	< 5mm
Power required	175 kW
Dimensions	H ≈ 4 m L, W ≈ 2 m
Product Life	10 – 15 years (hammers replaced every 2 years)
Additional Information	• Long life hammers required

4.4.6 Sifter System

TABLE 20: STORAGE BIN SUMMARY TABLE

1x Divided Collection Bins (T-104)	
Material	Steel
Volume	≈ 6 m^3 (± 0.1m^3)
Dimensions	H ≈ 1.5 m L, W ≈ 2 m
Capacity	≈ 3000 kg (± 100kg)
Product life	10 - 15 years
Additional Information	• Intended to be used for glass collection

Table 21: Ball Mill Summary Table

1x Glass Ball Mill Crusher (B-102)	
Capacity	1000 kg/hour
Material Input	Broken glass with possible plastics and metal
Material input size	≈ 5 mm
Power required	≈ 84 kW (45 rpm)
Crushed glass output size	Distribution of extra course (2.4 mm), course (1.7mm), fine (0.6 mm), and extra fine (0.2mm) grades
Dimensions	Approximate internal volume of 785 litres H ≈ 1.5 m, L≈ 2 m, W ≈ 1.0 m
Product Life	10 – 15 years (balls replaced annually)
Additional Information	• Long life crushing balls required (1.3cm diameter)

Table 22: Screener Summary Table

1x Trommel Screen (S-101)	
Capacity	1000 kg/hour
Number of screens	5
Screen sizes	< 0.2mm < 0.6mm < 1.7mm < 2.4mm < 5mm
Material Input	Crushed glass < 5mm
Input location	Top feed
Output location	Bottom feed
Power Required	≈ 5 kW
Product Life	10 - 15 years (screens replaced every 2 years)
Additional Information	• Screen bypass required

Table 23: Sand Blasting Media Storage Bin Summary Table

1x Sand Blasting Media Storage	
Material	Steel
Volume	≈ 10 m^3 (± 0.1m^3)
Capacity	≈ 4800 kg (± 100kg)
Product life	10 - 15 years
Additional Information	• Intended to be used for holding crushed glass • The bin will have 3 divisions (4 compartments) so that the compartment size will meet 40%, 20%, 20% and 20%

Table 24: Bag Filling Station Summary Table

1x Bag Filling Station	
Capacity	1000 kg/hr
Material Input	Crushed glass of various sizes, bags
Material output	Full bags of blasting media (20 kg)
Dimensions	H ≈ 2 m, L≈ 1.0 m, W ≈ 0.5 m
Product Life	10 – 15 years
Additional Information	• Must be on wheels to be moved to proper location under hopper • Electronic weigh scale and feeder valve preferred

4.4.7 Tile Production

Table 25: Glass Tile Storage Bin Summary Table

1x Glass Tile Cullet Storage	
Material	Steel
Volume	≈ 18 m^3 (± 0.1m^3)
Capacity	≈ 8600 kg (± 100kg)
Product life	10 - 15 years
Additional Information	• Intended to be used for holding crushed glass

Table 26: Colorant Mixer Summary Table

1x Colorant Mixer(T-201)	
Capacity	500kg glass (2 hours of production)
Material Input	Crushed glass < 5mm, colorant
Material output	1000 ppm colorant/crushed glass (varies)
Dimensions	H ≈ 0.5 m, L≈ 0.75 m, W ≈ 1.0 m
Additional Information	• Colorant will be added to crushed glass in batches

Table 27: Mold Filler Summary Table

1x Mold Filler (S-201)	
Capacity	250 kg/hour
Material Input	Crushed glass < 5mm, colorant
Dimensions	H ≈ 1.5 m, L≈ 0.75 m, W ≈ 1.0 m
Additional Information	• Orientation of heads should be adjustable for different mold configurations

Table 28: Belt Furnace Summary Table

1x Belt Furnace (E-201)	
Capacity	250 kg/hr (est. 450 kg/hr molds)
Section temperatures	Heating: 20 °C in, 900 °C out Sintering: 900 °C in, 900 °C out Cooling: 900 °C in, 200 °C out All are +/- 10 °C
Residence time	30 mins sintering
Estimated Furnace Area	20 m^2
Heat input	74 kW
Natural gas required	5.3 kg/hr
Additional Information	• Thermal efficiency should be high • Orientation of heads should be adjustable for different mold configurations • Furnace area, heat input, and temperature sensitivity may be discussed

Table 29: Cooling Belt Summary Table

1x Cooling Belt (C-202)	
Material to be transported	Glass tiles
Capacity	250 kg/hr (10 m^2/hr of tile area)
Belt type	Heat resistant – Standard high temperature
Belt Dimensions	Width = 0.5 m Length = 20 m
Air speed	4 m/s
Tile temperature in	200°C
Tile temperature out	<35 °C
Approximate cooling time	1 hour
Power required	0.215 hp (160 W)
Additional Information	• Simple setup may be used, such as fans providing ambient air flow • Dust disturbance should be minimized • Open burn hazard must be appropriately managed (signage etc.)

TABLE 30: MANIPULATOR ARM SUMMARY TABLE

1x Manipulator Arm with Suction Nozzles (T-201)	
Capacity	1000 tiles/hour
Maximum lifting capacity	6.25 kg
Temperature of tiles	<35°C
Additional Information	• Orientation of nozzles must be adjustable depending on tile size and orientation in mold • Power consumption is to be determined by the manufacturer based on most efficient robotic arm design for the specific tasks (listed in detail design)

TABLE 31: FORK LIFT SUMMARY TABLE

1x Fork Lift	
Lifting capacity	≈ 3175 kg (7000 lb)
Additional Information	• Used for lifting collection bins from storage to the start of the process

5.0 Economic Evaluation

5.1 Equipment Cost and Installation Cost

The total equipment cost was calculated using installation factors that consider the extra costs of delivery and installation in addition to the purchased equipment cost. The purchased equipment costs were obtained from numerous references for each piece of equipment required for the glass processing plant. These purchased equipment costs were multiplied by the quantity of each piece of equipment that is needed, and then by an installation factor found from literature for that specific piece of equipment. These were all summed together to form the total installed equipment cost. These results can be seen in Table 32 below.

Note: References and detailed calculations for each piece of equipment, and references for the installation factors can be seen in Appendix E.

TABLE 32: EQUIPMENT COST SUMMARY TABLE

Equipment #	Equipment Name	Quantity	Purchased Equipment Cost	Installation Factor	Total with Installation
	Fork Lift	1	$38,900	1.0	$38,900
T-101	Collection Bins	24	$6,000	1.1	$157,800
C- 102-C204	Flat Conveyors	10	$4,800	1.4	$68,000
C-101/109	Ramp Conveyors	2	$8,500	1.4	$23,800
B-101	Breaker Tower	1	$6,100	1.1	$6,700
W-101	Rotary Washer	1	$37,300	1.6	$59,700
P-101/102	Centrifugal Pumps	2	$14,600	1.2	$35,000
E-102	Rotary Dryer	1	$202,300	1.6	$323,700
B-102	Crusher	1	$43,100	1.3	$56,000
T-104	Storage bin (6m3 for waste/extra glass)	1	$6,000	1.1	$6,600
B-103	Ball Mill	1	$43,100	1.3	$56,000
S-101	Trommel Screen	1	$1,800	3.1	$5,500
T-107	Storage bin (4 divisions - 10 m3)	1	$8,000	1.1	$8,700
Z-101	Bag Filling Station	1	$16,500	3.1	$51,100
T-105	Storage bin (18m3)	1	$11,000	1.1	$12,000
T-201	Colorant Mixer	1	$16,200	3.1	$50,500
E-201	Belt Furnace	1	$275,900	1.45	$400,000
A-201	Cooling Fan	1	$800	1.2	$960
R-201	Manipulator Arm (with Suction)	1	$62,000	2	$124,000
C-203/204	Long flat Conveyor	2	$20,000	1.4	$56,100

Total Purchased Equipment Cost	**$ 1,047,000**
Total Installed Equipment Cost	**$ 1,541,000**

5.2 Total Capital Cost Estimates

5.2.1 Capital Cost

The total capital cost of the proposed facility was determined by using the factorial method, whereby the purchased costs of major pieces of equipment are found, and the remaining expenses between conception and operation of the facility are accounted for by multiplying the total purchased equipment cost by representative factors. For example, the cost of the instrumentation is cited as 10% of the purchased equipment cost. Comprehensive calculations for all results presented can be found in Appendix E.

TABLE 33: BREAKDOWN OF FIXED CAPITAL COST

Fixed Capital Cost	
Purchased Equipment Cost	**$1,047,000**
Installation Cost	$494,000
Instrumentation Cost (10%)	$105,000
Electrical Cost (10%)	$105,000
Process Buildings Cost (10%)	$105,000
Site Development Cost (5%)	$52,000
Physical Plant Cost	**$1,908,000**
Design & Engineering (20%)	$382,000
Contractor's Fee (5%)	$95,000
Contingency (10%)	$191,000
Fixed Capital Cost	**$2,575,000**

As shown above, the physical plant cost will be approximately $1.91 M. This cost is multiplied by additional factors to reflect engineering and design work, contractor's fee, and a 10% contingency, bringing the Fixed Capital Cost (FCC) of the facility to $2.57 M.

5.2.2 Working Capital and Start-up Cost

A method similar to the factorial method discussed above was used to determine the working capital of the proposed facility. The working capital was approximated by considering the following:

- Payments for products sold will not be received for four weeks
- Product will be stored onsite for two weeks before being shipped to suppliers, providing a buffer for times of unexpected demand
- The cost of one week's production will be kept as cash on hand
- Spare parts will be kept on hand for key pieces of equipment, costing roughly 1% of the Fixed Capital Cost

This gives a total working capital equivalent to the cost of production for seven weeks plus spare parts, the results of which are shown in Table 34. The cost of land was approximated as $500,000, which was found online for small industrial sites near the FRSWC's landfill site. The ideal site for cullet processing would be at the landfill site, so this is a conservative estimate.

TABLE 34: WORKING CAPITAL AND COST OF LAND

Startup Costs	
7 weeks of production costs	$66,000
Spare Parts	$26,000
Working Capital	**$92,000**
Land	$500,000
Total Startup Cost	**$592,000**

5.3 Annual Operating Cost

The utilities needed for the proposed plant design include electricity, water, sewer, and natural gas. Each utility has a service charge as well as a usage charge. Service charges are treated as fixed annual costs while the consumption charges will be variable, depending on the amount of annual production.

Municipal water from the City of Fredericton is supplied at a rate of $0.82/kL and sewer is charged at the same rate. Both of these utilities have a service charge of $30.05 quarterly, or $360.60 annually. Natural gas is supplied by Enbridge Gas at a rate of $11.68/GJ with a $192 annual service charge. Electricity is supplied at a rate of $0.0633/kwh. The total fixed annual costs from services are $913.20.

The washer uses 2000 litres of water per tonne of glass cleaned resulting in a cost of $3.28 including sewer disposal. An extra $2.00 is added for detergents. The washer consumes 109kW of electricity for a cost of $6.92 an hour. The total operating cost of the washer is $3.64 per tonne of throughput. Electricity consumption of conveyors and minor equipment are not included because there consumption is negligible in comparison to the rest of the operating costs.

The dryer consumes approximately 3.2 kg (0.16 GJ) of natural gas per tonne of glass dried at a total cost of $1.51. An additional 4.8kW of electricity is required to run the drier at a cost of $0.30. The total cost to dry one tonne of material is $1.81.

The energy requirement of the crusher is 61.8kW which results in a cost of $3.91 per tonne of material crushed. The ball mill runs at 78.2kW and costs $4.95 per tonne of blasting material produced. The 75kW furnace has a throughput of 250kg/hour. For one tonne of production the furnace consumes 300kWh at a cost of $18.99.

Labour estimates were taken from data on operator requirements for the necessary process equipment (Ulrich). These values are shown in table 35. An approximate labour rate of $20/hour is used. It should be noted that the labour requirements are adjusted based on the required throughput of each major processing step.

The energy requirement, labour, and material costs for each piece of equipment were calculated on a per tonne basis to determine the production costs, and are shown below in table 35.

TABLE 35: ANNUAL OPERATING COSTS

Utilities and Raw Materials				
Process	**Amount (t)**	**Materials ($/t)**	**Energy ($/t)**	**TOTAL**
Procurement	1264	$ 30.00	$ -	$ 37,920
Washing	1264	$ 3.64	$ 6.92	$ 13,348
Crushing	1264	$ -	$ 10.62	$ 13,426
Drying	1264	$ -	$ 1.81	$ 2,293
Milling	764	$ -	$ 5.62	$ 4,295
Tiles	500	$ 45.96	$ 75.96	$ 60,960
Labour				
	Persons/hour	**Hours per year**	**Rate ($/h)**	**TOTAL**
Crushing	1.6	1200	$ 20.00	$ 38,400
Sandblast	1.4	700	$ 20.00	$ 19,600
Tiles	2	2000	$ 20.00	$ 80,000
Service Charges				
	Annual			
Water	$ 360.60			
Sewar	$ 360.60			
Electricity	$ -			
Gas	$ 192.00			
TOTAL	$ 913.20			$ 913
TOTAL				**$ 271,000**
Product	**Tonnes/year**	**Additional Processing ($/t)**		**Cost ($/t)**
Cullet	1264	$ -		**$ 83**
Sand blast	700	$ 34		**$ 118**
Tiles	500	$ 282		**$ 365**

The first process in the facility is to turn used glass into glass cullet. The cullet specifications require it to be cleaned and crushed to a size of 5mm and less. To determine the cullet production cost, the procurement cost and the cost of running equipment from the conveyors to the end of the crusher are summed (Table 35). The result is $95.38/tonne. Further processing of the cullet produces the sand blasting media. This requires an additional processing cost of $34.13/tonne which results in a total cost of $129.51/tonne. The production of glass tiles requires further processing of clear cullet resulting in additional costs of $281.92/tonne. The total production cost for tiles is $377.30/tonne. This does not include the milling costs of sandblasting media since the smaller size fractions are not needed for sintering. Assuming a 10cm square tile which is 1cm thick, there will be approximately 4000 tiles per tonne. The tile production cost translates to $0.094/tile or $9.43/m² ($0.88/ft²). These values do not, however, include maintenance or overhead staffing costs.

5.4 Annual Revenue and Net Cash Flows after Taxes

The financial viability of the proposed facility is reviewed for a 15 year period, including a six month initial period of construction and troubleshooting with no production revenues. Table 36 shows an example of the net income calculation for year two of operation. It should be noted that some of these figures change year to year due to a moving cost of depreciation. As can be seen, 93% of facility revenues come from the production of glass tile, which is priced at five dollars per square foot (or $53.79/m^2). It was found that 72% of production costs for the facility are fixed, and the cost of production requires 40% of the total annual revenue, not including depreciation. Sample calculations can be found in Appendix E.

TABLE 36: BREAKDOWN OF FACILITY'S FINANCES IN YEAR 2 OF OPERATION

Facility Finances for Year 2 of Operation	
Total Glass Diversion Revenue	$0
Total Sandblasting Media Revenue	$76,400.00
Total Glass Tile Revenue	$1,060,800
Total Annual Revenue	**$1,137,200**
Total Fixed Costs	$325,600
Total Variable Costs	$128,100
Cost of Production	$453,700
Total Gross Profit	**$683,500**
Equipment Depreciation	$241,900
Building Depreciation	$18,800
Total Depreciation	$285,400
Taxable Income	$398,100
Provincial Income Tax*	$17,900
Federal Income Tax*	$43,800
Total Tax	**$61,700**
Net Income After Taxes	**$336,400**
Net Cash Flow After Taxes	**$621,800**

*Details on Tax rates used in following discussion

Depreciation is accounted for separately due to taxation purposes. The government of Canada allows for depreciation to occur at a fixed percent of an item's value. For example, process equipment can be depreciated at 30% of its current value for any given year, and buildings can be depreciated at 10% of their value. Subtracting this from the total gross profit gives a taxable income of roughly $398k, which is beneath the small business income limit of $500k, and results in low taxation rates provincially (4.5% in New Brunswick) and federally (11%). After year 5, taxable income exceeds this limit, and higher taxation rates are applied to taxable income in excess of this limit (10% for New Brunswick and 28% for Canada).

The net income after taxes, which includes the cost of equipment depreciation, is $336k, and represents 30% of the total annual revenue. The net cash flow after taxes is $622k, and represents 55% of the total annual revenue. Again, due to a moving depreciation, some of these figures change depending on the year of operation.

Table 37 shows key profit indicators for years one through fifteen. As can be seen, as depreciation decreases, taxation increases albeit at a slower rate. The net income therefore grows with time, while the net cash flow decreases slowly to reflect the increased taxes.

TABLE 37: NET INCOME AND CASH FLOW FOR YEARS 1 THROUGH 15 OF OPERATION

Facility Totals ($/yr)						
Year	Total Annual Revenue	Total Gross Profit	Total Depreciation	Total Tax	Net Income After Taxes	Net Cash Flow After Taxes
1	$568,608	$341,741	$341,741	$-00	$-00	$341,741
2	$1,137,215	$683,482	$285,398	$61,703	$336,381	$621,779
3	$1,137,215	$683,482	$186,257	$77,070	$420,155	$606,412
4	$1,137,215	$683,482	$133,772	$96,390	$453,320	$587,092
5	$1,137,215	$683,482	$96,694	$110,480	$476,309	$573,002
6	$1,137,215	$683,482	$70,433	$120,459	$492,590	$563,023
7	$1,137,215	$683,482	$51,776	$127,548	$504,158	$555,934
8	$1,137,215	$683,482	$38,469	$132,605	$512,408	$550,877
9	$1,137,215	$683,482	$28,931	$136,229	$518,321	$547,253
10	$1,137,215	$683,482	$22,055	$138,842	$522,585	$544,640
11	$1,137,215	$683,482	$17,061	$140,740	$525,681	$542,742
12	$1,137,215	$683,482	$13,403	$142,130	$527,949	$541,352
13	$1,137,215	$683,482	$10,696	$143,159	$529,627	$540,323
14	$1,137,215	$683,482	$8,670	$143,928	$530,883	$539,553
15	$1,137,215	$683,482	$7,134	$144,512	$531,836	$538,970

5.5 Economic Analysis

5.5.1 Payback Period, Future Worth, and Returns on Investment

Figure 9 shows a cumulative net cash flow diagram for the proposed facility. The Fixed Capital Investment is reflected as expenditure over the first six months, followed by an immediate decrease for the working capital, followed by steady facility operation. Taking into account the recovery of working capital and property value, the after tax payback period for the facility is 4.8 years.

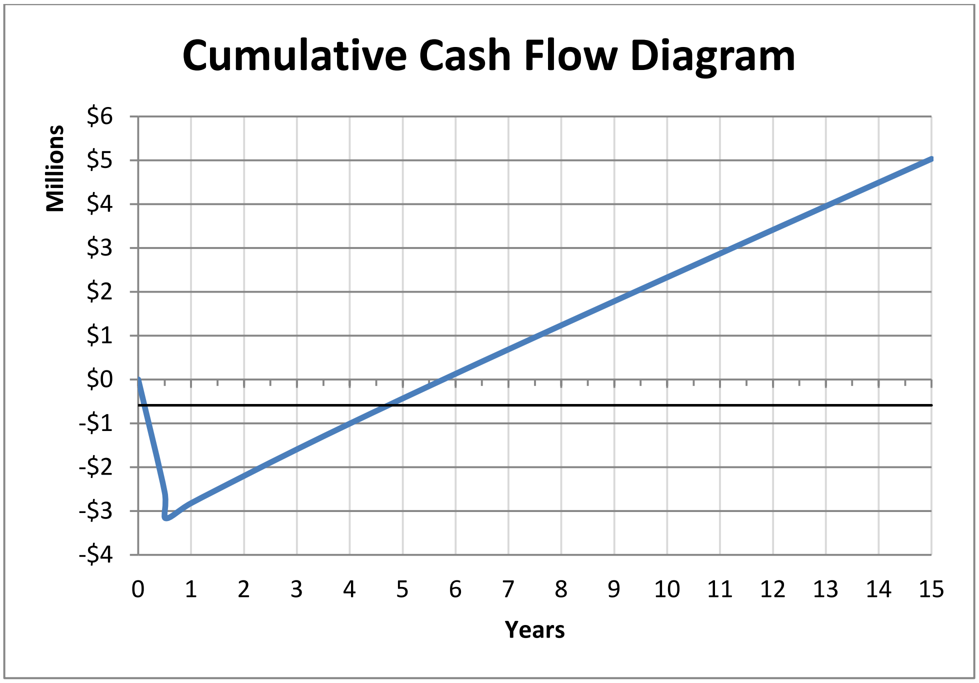


FIGURE 9: CUMULATIVE CASH FLOW OF OVERALL FACILITY

As previously stated, total depreciation changes with the age of the facility. For this reason, the after tax return on investment (ROI), which depends on the net income after taxes, changes yearly as well. The average ROI for fifteen years of operation is 17.8%. Sample calculations can be found in Appendix E.

The future worth of the investment was also compared to the future worth of the net cash flows after tax generated by the facility's operations. A base rate of return of 8% was used, reflecting the rate of return available to investors in safe, low risk investments. Table 38 shows the results of these calculations, demonstrating that the future worth of the facility's cash flows more than double those of a safe investment alternative.

TABLE 38: FUTURE WORTH OF PROPOSED FACILITY

Future Worth of Facility	
Base Rate of Return	8.0%
Fixed Capital Cost	$2,574,972
Years of Assessment	15
Future Worth of Capital Cost	$8,168,246
Future Worth of Cash Flows	$14,767,293
Net Future Worth	$6,599,048
Net Present Worth	$2,080,295
Internal Rate of Return	**18.9%**

By adjusting the base rate of return until the facility's net present worth was zero, an internal rate of return of 18.9 % was found. If glass tile product can indeed be sold for five dollars per square foot, or $53.80 per square meter, this investment appears favorable. Given that recycled glass tiles sell for between $15 and $22 per square foot online[1], this price point allows for reseller markup, and appears reasonable.

[1] $14.80 per square foot at backsplashtogo.com and $22.00 per square foot at susanjablon.com

6.0 Design Optimization

6.1 Sensitivity Analysis

A sensitivity analysis on the business model is shown below, using the internal rate of return as a measure of profitability. Key factors were varied by 15% to determine the most sensitive factors in the business model, giving a better idea of the risks to the proposed facility's financial success.

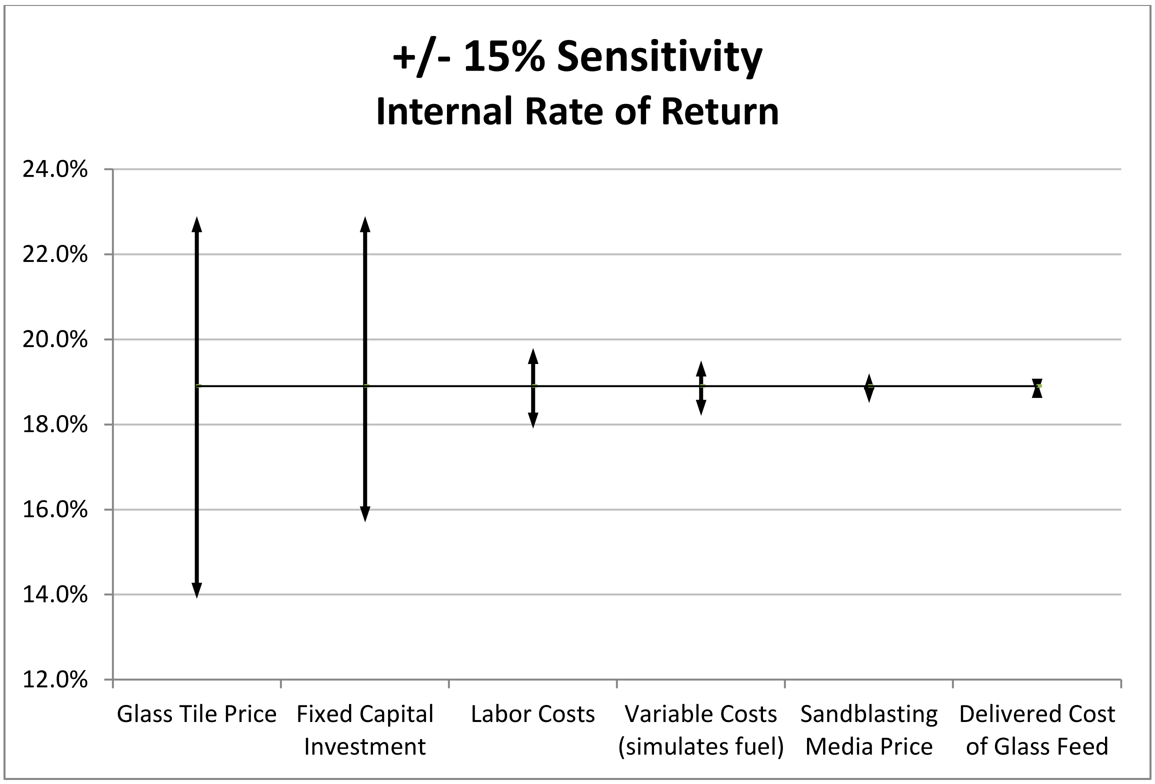


FIGURE 14: SENSITIVITY OF INTERNAL RATE OF RETURN TO KEY PARAMETERS

As can be seen in Figure 14, the most important parameters are the selling price of glass tile* ($\$5/ft^2$ or $\$53.80/m^2$, shown adjusted to $\$4.25/ft^2$ and $\$5.75/ft^2$), and the fixed capital investment. A 15% change in one of these factors can change the internal rate of return by up to 5%. Labour and fuel costs, simulated by changing all variable costs, have a minor effect on the facility's profitability, with 15% swings changing the internal rate of return by up to 2%. The price of sandblasting media and the cost of glass as delivered to the facility had a negligible impact on profitability at a variability level of 15%. Similar results are found when using payback period or rate of return as indicators of profitability. These results are shown in Figures 15 and 16 below.

*Note: Glass tile is most commonly sold commercially in ft^2 (not m^2), therefore the following discussions uses imperial units.

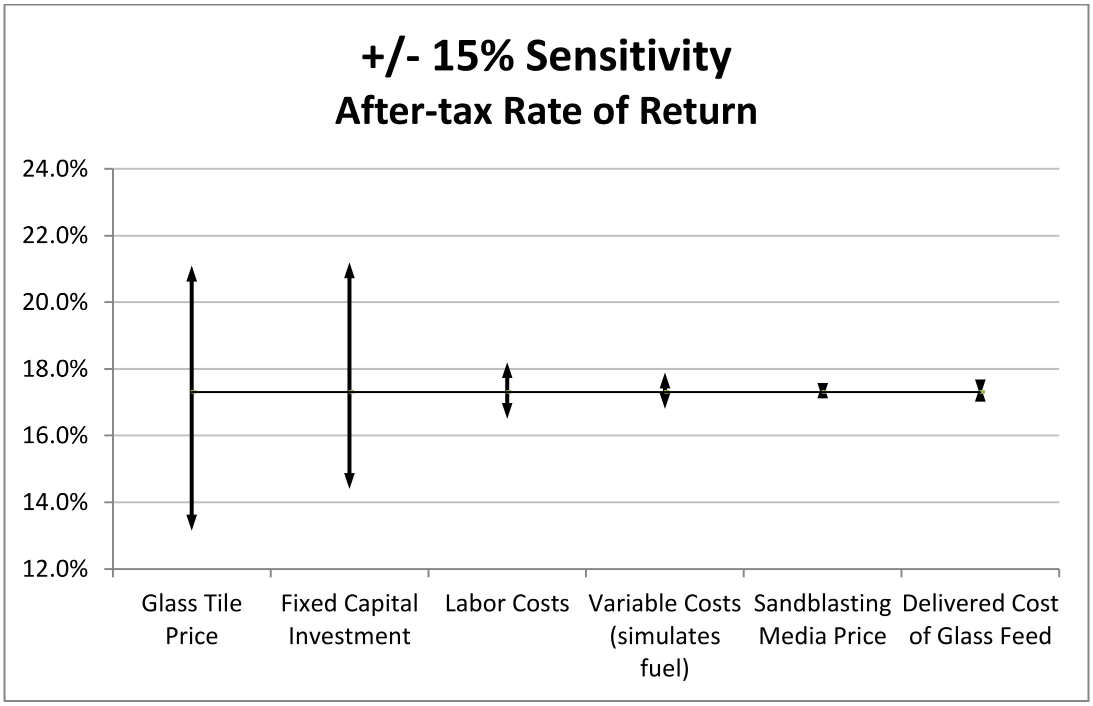


FIGURE 15: SENSITIVITY OF AFTER-TAX RATE OF RETURN TO KEY PARAMETERS

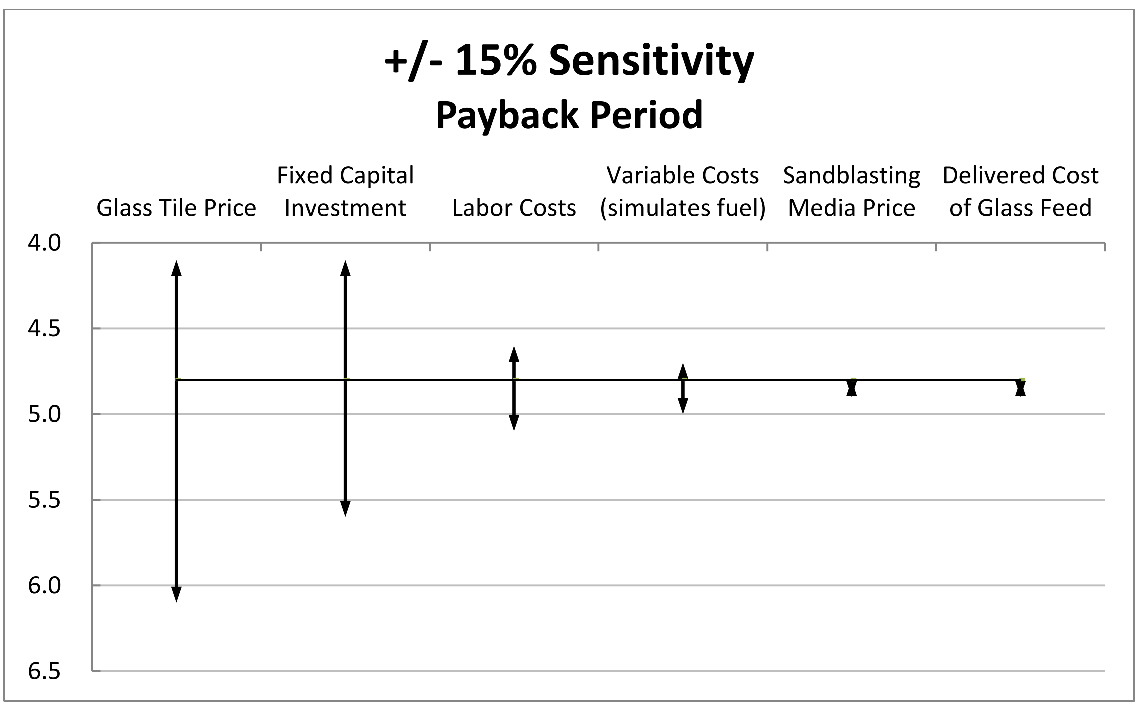


FIGURE 16: SENSITIVITY OF PAYBACK PERIOD TO KEY PARAMETERS

To further understand the financial risks to such a facility, a number of specific worst-case-scenarios were analyzed. These include events such as the price of oil doubling, a labor shortage in New Brunswick, and reductions in glass tile demand. The results of these analyses, presented from least severe to most severe financial impact, are shown in Table 39.

TABLE 39: WORST-CASE SCENARIO ANALYSES

Scenario	Parameter Changed	Payback Period (years)	Internal Rate of Return	Average After Tax Return on Investment
Baseline	n/a	4.8	18.9%	17.3%
No market for sandblasting media	Sandblasting media price changed from $100 to $0 per metric tonne	5.3	16.6%	15.4%
Difficulty selling all tile	Tile price changed from $5/ft2 to $4.50/ft2	5.6	15.7%	14.6%
Labor Shortage	All labor costs increased by 50%	5.7	15.4%	14.3%
Energy price/oil doubles	All variable costs doubled	6.0	14.4%	13.5%
Fixed Capital Investment is 30% higher than predicted	FCI changed from $2.6M to $3.3M	6.2	13.2%	12.2%
Tile demand lessens	Tile price changed from $5/ft2 to $4/ft2	6.7	12.0%	11.5%
Labor Shortage and energy cost doubles	Labor costs +50% and variable costs doubled	7.5	9.9%	9.8%
Tile market shrinks	Tile price changed from $5/ft2 to $3.50/ft2	8.6	7.7%	8.1%

The impact from producing sandblasting media without an end market is a manageable worst-case scenario; however, contractions in the tile market could have severe consequences on the facility. The simulation of a labor shortage, resulting in labor costs increasing from $20/hr to $30/hr, is manageable, as is the doubling of all variable costs. A labor shortage combined with doubling energy costs would reduce the facility's internal rate of return from 18.9% to 9.9%.

The most significant results from the worst-case scenario analysis is that the proposed facility is most sensitive to tile price, that the facility's viability has no relation to the production of sandblasting media, and that it would take a compounding of several increased operating costs to lower the proposed facility's internal rate of return below 10%.

6.2 Optimization

In design optimization, a few designs were considered in order to observe which of them had the best economic viability for the plant. One option included scaling the input of the plant to a larger size, which requires a higher amount of glass input. Others included researching the effects of only producing each of the end products on their own. For scaling up the plant, higher amounts of glass can be obtained by collecting in a wider region than just Fredericton. This is discussed in more detail in Section 4.1.2. For the optimization, it was estimated that the amount of glass that can be collected from surrounding regions is approximately triple the amount of glass that would be collected in the Greater Fredericton Area. In order to achieve this larger input, it is necessary to consider the transportation cost of getting the glass from other regions. A price of $30/tonne of glass was used to represent this transportation cost.

The cost of equipment that is needed to operate the plant with a bigger input was calculated by using the cost of the original equipment multiplied by a size scale and an exponential factor as can be shown in sample calculations in Appendix F. This method of calculation was also used in designing the plant for different combinations of output products. In addition, having a bigger plant means more products need to be sold in the market, thus a decrease in the price of the product is a reasonable assumption and was used in this analysis. Some of the equipment can also be neglected when calculating the equipment cost since different output products will only need particular equipment as can be seen in the PFD. Other considerations that have been taken into account are the labour cost and utility and raw material costs.

TABLE 40: ECONOMIC ANALYSIS FOR DIFFERENT DESIGN OPTIMIZATION

Plant Design	Net Income after taxes	Net Cash Flow after taxes	Payback period	IRR
Original Design	$311,901.00	$606,956.00	4.7 years	19.1%
3x size of original design	$840,132.00	$1,547,347.00	3.8 years	24.4%
100 % Sandblasting media production	-$283,253.00	-$162,733.00	-	-
3x size of sandblasting media production	-$354,035.00	-$234,661.00	-	-
100 % Tile production	$534,262.00	$558,283.00	2.8 years	26.9%
3x size of tile production	$1,196,254.00	$1,239,860.00	2.4 years	28.4%

*based on year 2 of production

Table 40 shows the economic viability of different designs considered for optimization. Scaling up the plant to a bigger plant that handles much more glass input significantly increases the economic viability of the plant. The payback period was reduced to only 3.8 years while IRR increased by more than 5% making the plant a more appealing investment than the original design. A similar trend can be observed when scaling up the size of tile production only. This result was as expected since the revenue increases far outweigh the slight increase in equipment cost that is associated with scaling up; however, trying to operate the plant with a bigger input will put higher risk in getting the amount of glass that is needed.

Other municipalities might handle the glass collection differently and they might charge fees in order to collect glass from their city. In addition, it is important to consider the market size and how much tile the current market will absorb. To produce more than can be sold will only cause excess glass and no increase in revenue. During the early stages of the project, a high level market analysis was done for glass tile. The designed process was based off an input that is expected to be absorbed by the local market. The size and distance required to sell all of the product produced should be analyzed thoroughly before considering a scaling up of the plant.

Operating the plant solely to produce sandblasting media is not a viable option as can be seen in Table 40. Further changes in the plant design could be done such as using different types of equipment in the plant in order to make this design viable. It is a fair suggestion since the original design was designed to produce glass tiles that needed to follow tighter specifications. The inability of sandblasting media production to be economically viable by itself in the current situation makes it a reasonable suggestion to design a plant that produces tiles only. It is possible that this is the optimal design since it neglects the effect of lost profit in sandblasting media production. The payback period of this design reduced to only 2.8 years with IRR increases close to 8% from original design of 19.1% to 26.9%. Further analysis shows that scaling up this plant to three times of the original size gives an even more viable option with payback period of only 2.4 years with 28.4% IRR. Although removing sandblasting is another viable solution, the sandblasting medium gave a level of sustainability to the overall project. It also gave an outlet to coloured glass, excess glass, and poor quality batches.

While it is most appealing to design the plant to the optimum design, it is important to consider the amount of risk that will come with it. Scaling up the plant to a bigger size will create higher risk due to the transportation procedure. In addition, producing a single product in the plant could only work if the market is strong and stable in the present and into the near future. Further market analysis and design consideration would be required were this project to continue on, for weighing the risks compared to the economic viability of each particular optimized design.

6.3. Failure Modes and Effects Analysis

A failure modes and effects analysis was performed. Failure modes for each piece of equipment were analyzed for health and safety, impact on production, and environment or property damage. The causes for failure were determined, and the effects ranked by severity from 1-10. The occurrence was also ranked from 1-10 with 10 being the most severe. The ability to detect the issue was also ranked on a 1-10 scale, with 10 meaning the issue is undetectable. The scores for each piece of equipment and failure mode were then multiplied to achieve a final score. The Lean Six Sigma Academy suggests that action be taken for any score over 100. The complete FMEA can be seen in Appendix F.

From our results, one piece of equipment to achieve a score of over 100 is the robot arm. The recommended actions are to increase employee training and provide additional workspace barriers. The robot arm, being a technical piece of equipment, requires training to be able to set it up properly and make necessary adjustments as its productions requirements change. For example, a change in tile size or changes in the speed at which tiles are moving on the conveyors. For the safety failure modes, additional barriers will protect workers and ensure that they avoid zones where contact with the robot arm could occur. Object detection could be an additional consideration but would be very costly.

Other failure modes that effect production are associated with lost production time or un-usable product. Lost production time results from equipment malfunctions. For example, if the dust collection system was to stop working (rated 100 in the FMEA), production would need to be stopped. This type of issue is remedied by increased maintenance and inspection. If the failure still occurs, spare parts are stocked and maintenance staff can repair the equipment so lost time is minimized. When a failure results in un-usable product it can often be used in another part of the facility. For example, if a batch of tiles were to be malformed they could be crushed and sent to sandblasting media production. A failure in the trommel screen causing mixed size fractions can be re-routed and re-screened after the equipment is repaired.

The FMEA was effective in identifying areas of improvement. This process should be utilized during the detailed design, setup and operation of the facility to further improve on safety and operations.

7.0 Conclusions and Recommendations

7.1. Conclusions

The FRSWC processes approximately 80,000 tonnes of refuse on an annual basis. From waste audits, the glass portion of this refuse has been determined to be 4%. Of that glass, it is expected that about 50% would be recycled. With an estimated program participation rate of 79% (based on the refundable program) the result is 1264 tonnes available for collection in the Greater Fredericton Area.

Implementing a curbside collection program would require a large investment in equipment and training. With two streams of recycling already collected at curbside it would be difficult to implement a third and have citizens participate effectively. To avoid the large investment and difficult implementation of curbside collection, an alternate collection system has been proposed at the bottle redemption centers in the area. The expertise of local redemption centers, and the good will of citizens who already visit these locations on occasion, results in an effective glass collection system.

After thorough literature reviews and brainstorming, the most promising methods of glass recycling and reuse were analyzed. The most valuable and cutting edge product, glass tiles, was selected as it met the selection criteria and scored high in the decision matrix for economic viability and market potential.

The proposed processing facility is designed in such a way that the various processing steps could be performed by different parties. For example, the crushing and milling could take place at one facility and the tile manufacturing could be a separate business entity. This is beneficial since the City of Fredericton and the FRSWC would not have to supply the majority of the initial project investment. It also allows other more specialized organizations to become involved.

The manufacturing of a high value end product from inexpensive raw materials with small scale production equipment results in an economically viable project. The glass tile market is in high demand which also plays in favor of the project. It allows much of the product to be consumed locally thus reducing transportation and marketing efforts. The production cost of the tiles is $0.88/ft^2 and the anticipated sale price is approximately $5.00/ft^2. The project has a total capital cost of $2.6 M, a payback period of 5.8 years, and an internal rate a return on investment of 18.9%.

7.2. Recommendations

Throughout the design and evaluation of the processing facility and final product, marketing has been a minimal concern. We advise that market research is used to ensure a viable market exists. An investor in the building materials industry would be in ideal partner to implement the project. Our proposed product has a competitive edge since it is made from recycled materials and will be made in Canada. These facts will aide in the marketing and should allow for the product to be sold at a premium price.

The potential for profit from sandblasting media is minimal. To achieve more profit, the use of coloured glass in tile manufacturing could be investigated. There are chemical processes which can remove the colour from the glass. It could also be possible to use small amounts of coloured glass mixed in with the clear glass when manufacturing darker coloured tiles. Another alternative would be to only collect clear glass and only manufacture tiles.

References

Ahmad Shayan, A. X. (2006). Performance of glass powder as a pozzolanic material in. *Cement and Concrete Research*.

Alibaba. (2012). *Ceramic Tile*. Retrieved from Alibaba: http://www.alibaba.com/showroom/ceramic-tile.html

Bedrock Industries. (2010). *Blazestone Tile*. Retrieved from Bedrock Industries: http://bedrockindustries.com/products/blazestone-tile/

Bernardo, E. (2008). Recycle of Wast Glass into "Glass-Ceramic Stoneware". *The American Ceramic Society*, 2156-2162. doi:10.1111/j.1551-2916.2008.02460.x

Bradford. (2012, April). *Bradford Insulations.* Retrieved from www.bradfordinsulation.com.au

Chemical Engineering. (2012, October). Economic Indicators. *Chemical Engineering*, p. 64.

Chen, J. (2002). Engineering properties of asphalt concrete made with recycled glass. *Elsevier*.

Clean Washington Center. (1996, November). Cullet Specification for Fiberglass Insulation Manufacturing. Seattle, Washington, United States.

Clean Washington Center. (2012). *Recycled Glass*. Retrieved from CWC: http://www.cwc.org/gl_bp/gbp4-0201.htm

CWC. (1997). *Using Glass as a Blasting Abrasive.* Retrieved October 2012, from Clean Washington Center: http://www.cwc.org/gl_bp/gbp4-0402.htm

Department of Environmental and Climate Change NSW. (2007). *Trial of Recycled Glass as Pipe Embedment Material.* Sydney South: Department of Environment and Climate Change NSW.

Design and Build with Metal. (2007, October). Retrieved from Unlimited Reach Media Inc.: www.designandbuildwithmetal.com/industrynews/archives/2007/10_October/guardian_fiberglass_plant_wa.aspx

EPA. (2010, October 28). Fiberglass Insulation.

Fireclay Tile. (2011). *Fireclay Tile's Newest 'Crush'.* San José: Fireclay Tile.

FRSWC. (2011). *Recycling*. Retrieved September 2012, from Fredericton Region Solid Waste Commisson: http://www.frswc.ca/home.asp

Glass Aggregate Systems. (2012). *H 100-VT*. Retrieved from Glass Aggregate Systems.

HiSuccess International. (2009). *Glass Wool Production Line*. Retrieved from www.hisuccess.cn

Huang, Y., Bird, R., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Elsevier*.

Hubbs, A. A. (2005). Abrasive Blasting Agents: Designing Studies to Evaluate Relative Risk. *Journal of Toxicology and Environmental Health, Part A: Current Issues*, 999-1016.

Hymers, M. (2012, September 20). Glass Recycling Client Meeting #1. (U. E. Group 3 & 4, A. Steeves, & M. Couturier, Interviewers)

iBisWorld US. (2012). *US Industry Reports (NAICS)-Ready-Mix Concrete Manufacturing.* iBisWorld US.

IBISWorldUS. (2012). *Industry Outlook*. Retrieved from IBISWorld: http://clients1.ibisworld.com/reports/us/industry/industryoutlook.aspx?entid=1916#IO

Industry Canada. (2010). *Canadian Industry Statistics: Asphalt Paving*. Retrieved from Industry Canada: http://www.ic.gc.ca/cis-sic/cis-sic.nsf/IDE/cis-sic32412empe.html

KTA-Tator, I. (1999). *Evaluation of Substitute Materials for Silica Sand in Abrasive Blasting.* Pittsburgh PA.

Lee, G., & Fitzner, B. (2010, June 8). *Provincial Asphalt Plant Operation*. Retrieved from Nova Scotia Transportations and Infrastructure Renewal: http://www.gov.ns.ca/tran/highways/pavingplant/Provincial_Asphalt_Plant_Opeations.pdf

Mitchell, W. (1998). *The Thailand Ceramic Tile Industry in 1992*. Retrieved from University of Michigan Business School: http://www-personal.umich.edu/~afuah/cases/case16.html

National Asphalt Paving Industry. (2011). *The Asphalt Paving Industry: A Global Perspective.* Lanham, Maryland: NAPA/EAPA.

Natural Resources Canada. (2012, September). *Energy Sources - Retail Fuel Prices on 25-Sept-2012 - New Brunswick*. Retrieved from Natural Resources Canada: http://www2.nrcan.gc.ca/eneene/sources/pripri/prov_map_e.cfm?ProvCode=NB

NB Power. (2012, September). *Rates*. Retrieved from NB Power: http://www.nbpower.com/html/en/business/rates/rates.html

NewPoint Group Management Consultants. (2009). *Market Analysis for Recycled Beverage Containers: 2009 Update.* California: Department of Conservation; Division of Recycling.

Olver, J., Lant, T., & Plant, R. (2013). *ME 4861 Mechanical Health & Safety UNB - Fredericton.* Boston, MA: Pearson Learning Solutions.

Owens Corning. (2008). *Sustainability at Owens Corning.*

Petitt, M. (2010, November). *ICIS.* Retrieved from www.icis.com/articles/2011/02/02/9431919/stimulus-and-builidng-codes-to-drive-insulation-growth.html

Pioneer Road Services Pty Ltd. (2009). *Project Evaluation Report: Recycled Glass in Asphalt.* Hazelmere, WA, Australia. Retrieved from Pioneer Road Services: http://www.zerowastewa.com.au/documents/external_docs/SWIS_2007_Final_Report_Pioneer_Road_used_glass.pdf

Reed Construction Data. (2012). *Guardian Fiberglass Insulation Plant*. Retrieved from www. reedconstructiondata.com/building-types/manufacturing/michigan/projects/1000297180

Remade Scotland. (2003). *Glass Recycling Handbook: Assessment of Existing Technologies.* Glasgow, UK: Remade Scotland.

Ross, P., & Tincher, G. (2004). *Glass Melting Technology: A Technical and Economic Assessment.* Westerville, OH: Glass Manufacturing Industry Council.

Sicoe, M., & Leek, C. (2011). *A Convenient Truth: Asphalt*. Retrieved from Fulton Hogan: http://www.aapaq.org/docs/FPC2011/S1D1_1400_Colin_Leek_A_convenient_truth-glass_asphalt.pdf

SNC Lavalin. (2006). *Nova Scotia Glass Study.* Truro: Resource Recovery Fund Board Inc.

State Smart Transportation Initiative & Smart Growth America. (2012). *The Innovative DOT, Focus Area 6: Providing Efficient, Safe Freight Access.* USA: State Smart Transportation Initiative & Smart Growth America.

The Home Depot. (2012). *Tile*. Retrieved from The Home Depot : http://www.homedepot.com/webapp/catalog/servlet/Navigation?storeId=10051&langId=-1&catalogId=10053&N=5yc1vZbbcuZ1z0zizaZ1xr5#/?c=1&1z0ziza=1z0ziza

United States Environmental Protection Agency. (1992). *Markets for Recovered Glass.* EPA.

Unknown. (2012). *Complete Tile Production Facility For Sale or Lease* . Retrieved from Access Used Furnaces: http://www.usedfurnaces.com/buy-quality-used-thermal-processing-equipment-furnaces-ovens-kilns/industrial-kilns-used-refurbished-ceramic-kiln-dryer-systems-technology-roller-hearth-tunnel-shuttle-batch-car-envelope-bell-elevator-bottom-multiple-zone-fire-

US Green Building Council. (2011). *USGBC: Policy and Government Resources*. Retrieved from http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1779

Vellini, M., & Savioli, M. (2008). Energy and environmental analysis of glass container production and recycling. *Elsevier*.

Vitro Minerals. (2011). *The Use of Recyled Glass in Concrete.* Retrieved from www.vittominerals.com/wp-content/uploads/Recylced-Glass-in-Concrete-110302.pdf

Vitro Minerals. (2012, May 18). *100% Recycled Crushed Glass Blast Media - Technical Data*. Retrieved from Vitro Minerals.

Wansbrough, H., & Borham, K. (2006). *Glass Manufacturing.* New Zealand: ACI Glass Manufacturers.

Western Conveyor Projects. (2012). *Conveyors*. Retrieved from Western Converyor Projects.

Wood, L. (2010). *Construction Growth in Canada will continue to Recover over the Medium TErm with 5% on Average Growth Expected for Tear 2011 and 2014.* Business Wire.

Zainab Z. Ismail, E. A.-H. (2008). Recycling of waste glass as a partial replacement for fine aggregate in concrete. *Waste Management*.

Report Appendices

Appendix A – Preliminary Cost Analysis

A-1: Economic Analysis for making cullet to be distributed to an asphalt company

Calculations Completed by:	Calculations Reviewed by:	Date: 10/18/2012
Carolyn McKenna	Michael Barrett	

<u>500 tonne/year plant</u>

+ saved cost of landfilling the glass
  - $74/tonne in Fredericton →≈ $ 37,000

– Equipment Cost
  - Conveyer →≈ $6000
  - Crushing→≈ $40,000 for 1 tonne/hour capacity that crushes to a max on 3/8" and includes an in-feed conveyer as well as a secondary screen to separate the sand sized (1/8") particles
  - Cleaning
    - Metal removal →≈$3,000
    - Washing →≈$8,000
  - Dust Control →≈ $500.00

- Operational Costs
  - Labor (1 worker, $18/hour for 500tonnes of glass) →≈ $9,000
  - Electricity ($.25/tonne) →≈ $125
  - Maintenance (assume 10% of fixed cost) →≈ $5750
  - Transportation (local regions) →$500

+ Selling product
  - Asphalt companies in the region pay approximately $15/tonne for aggregate. As there is no enhanced properties we would have to charge the same or less
    → $7,500

**If the $74 tipping fee is not taken into consideration then the model is not economically profitable

Summary

End Market	Tonnage	Capital Cost ($)	Operating Cost ($/year)	Sales Price ($/tonne)	Gross Revenue	Payback Period (years)
Asphalt	500	$ 57,500	$15,375	$15	$44,500	2**

Cost estimate references (CWC, 1997),(Glass Aggregate Systems, 2012), (Western Conveyor Projects, 2012)

A-2: Economic Analysis for glass manufacturing plant

Calculations Completed by:	Calculations Reviewed by:	Date: 10/18/2012
Carolyn McKenna	Michael Barrett	

<u>500 tonne/year plant</u>

+ saved cost of landfilling the glass
  - $74/tonne in Fredericton → ≈ $ 37,000

- Separation
  - Glass would have to be separated by colour, which would be done during collection. This means the recyclable collection process time would take longer and the truck drivers would have to be paid more (52 weeks a year, 5 days a week, 8 hours a day, assume addition of $5/hour for extra time/increased pay) → ≈ $ 10,000

– Equipment Cost
  - Conveyer → ≈ $6000
  - Crushing → ≈ $40,000 for 1 tonne/hour capacity that crushes to a max on 3/8" and includes an in-feed conveyer as well as a secondary screen to separate the sand sized (1/8") particles
  - Cleaning (must be high quality cullet)
    - Metal removal → ≈$5,000
    - Washing → ≈$10,000
    - Dust Control → ≈ $500.00
  - Melting (for furnace, shears, scoop, based off of scale of NS study) → ≈ $500,000
  - Reforming (preliminary mold, blow mold, cooling process to prevent cracking) → ≈ $500,000
  - Packaging → ≈ $10,000

- Operational Costs
  - Labor (3 workers for crushing, melting and packaging procedures, $18/hour for 500 tonnes of glass) → ≈ $27,000
  - Electricity ($.50/tonne) → ≈ $250
  - Maintenance (assume 10% of fixed cost) → ≈ $108,150
  - Transportation (to breweries, Moncton, Saint John, Halifax, etc.) → ≈$ 5,000

+ Selling product
  - Depends on container type (say average of $0.10/container, 4.5e-4 tonnes of glass/container means 1,111,111 containers)
    → $111,111

**Other volumes were analyzed → 2000 tonne plant begins to break even, but would definitely saturate the market, as it is declining already

Summary

End Market	Tonnage	Capital Cost ($)	Operating Cost ($/year)	Sales Price ($/tonne)	Gross Revenue	Payback Period (years)
Glass Manufacturing (containers/bottles)	500	$1,081,500	$140,400	$220	$148,100	142

*Cost estimate references (CWC, 1997),(Glass Aggregate Systems, 2012), (Western Conveyor Projects, 2012)

A-3: Economic Analysis of Fiberglass Plant

Calculations Completed by:	Calculations Reviewed by:	Date: 12/02/2012
Amin Azahar	Michael Barrett	

Created by : Aminnurasyid Mat Azahar

Contents

Date: Nov 7th, 2012

Revised:Dec 2nd,2012

```
clear
clc
```

Calculation for Fiberglass Manufacturing Plant

```
% The calculation is based on manufacturing R-13 fiberglass
% insulation


% Providing known informations

Mf = 1.07; % mass of fiberglass in kg/m^2

Mg = 0.4*Mf; % amount of glass used per kg/m^2 of fiberglass

Tg = 500000; % total glass in Fredericton per year in kg

Pricem = 0.4; % price of fiberglass per m^2
%                    (price from alibaba.com)
```

Calculations for revenue per year

```
% Price of glass in fiberglass per kg

Pricekg = Pricem/Mf;

% Gross revenue for fiberglass per year.

TotalRevenue = Pricekg*Tg;
```

Calculation for capital cost and annual operating cost

```
% Known informations :
```

```
% 1) A plant size of 10000m^2 can produce 8000 tonne/year
%      of fiberglass (http://www.wiley.com.au/)
% 2) A plant size of 13006.4256m^2 cost 5.9 M$
%       (http://www.reedconstructiondata.com)
% 3) A plant size of 46451.6m^2 requires 130 workers


% Calculating the required size for the plant
Size = ((10000*(Tg/1000))/8000)/0.6;

% Calculating the plant cost using power exponent of 0.6

PlantCost = 5900000*((Size/13006.4256)^0.6);


% Calculating amount of workers for required plant size

Workers = 130/(46451.62/Size);

% Calculating total salary per year
% Assume operation 8hrs/day, 5days/week with 15$/hr salary

Salary = 8*5*15*48*Workers;

% Maintainance cost = 5$/tonnage

MaintCost = 5*(2*Tg/1000);

% Annual Operating Cost

AnnualOpCost = Salary + MaintCost + (PlantCost/5);
```

Total Annual Revenue and Payback period

```
% Include revenue of 74$/tonne saving from not landfilling
% the glass

GAR = TotalRevenue - AnnualOpCost + (74*(Tg/1000));


PYP = PlantCost/GAR;




disp(['Price of fiberglass per kg = ' num2str(Pricekg) '$']);
disp(['Gross revenue = ' num2str(TotalRevenue) '$']);
disp(['Required size of plant = ' num2str(Size) 'm^2']);
disp(['Capital cost of plant = ' num2str(PlantCost) '$']);
disp(['Amount of workers needed = ' num2str(Workers) 'worker(s)']);
disp(['Annual operating cost = ' num2str(AnnualOpCost) '$/year']);
disp(['Total annual revenue = ' num2str(GAR) '$/year']);
disp(['Payback period = ' num2str(PYP) 'years']);
```

```
Price of fiberglass per kg = 0.37383$
Gross revenue = 186915.8879$
Required size of plant = 1041.6667m^2
```

```
Capital cost of plant = 1297162.829$
Amount of workers needed = 2.9152worker(s)
Annual operating cost = 348390.8863$/year
Total annual revenue = -124474.9985$/year
Payback period = -10.4211years
```

Published with MATLAB® 7.12

Created by : Aminnurasyid Mat Azahar

Contents

Date: Nov 7th, 2012

Revised: Dec 2nd, 2012

```
clear
clc
```

Calculation for Fiberglass Manufacturing Plant for greater area in NB

```
% The calculation is based on manufacturing R-13 fiberglass insulation


% Providing known informations

Mf = 1.07; % mass of fiberglass in kg/m^2

Mg = 0.4*Mf; % amount of glass used per kg/m^2 of fiberglass

Tg = 1500000; % total glass in Fredericton per year in kg

Pricem = 0.4; % price of fiberglass per m^2
              % (price from alibaba.com)
```

Calculations for revenue per year

```
% Price of glass in fiberglass per kg

Pricekg = Pricem/Mf;
```

```
% Gross revenue for fiberglass per year.

TotalRevenue = Pricekg*Tg;
```

Calculation for capital cost and annual operating cost

```
% Known informations :
% 1) A plant size of 10000m^2 can produce
%    8000 tonne/year of fiberglass insulation
%       (http://www.wiley.com.au/)
%
% 2) A plant size of 13006.4256m^2 cost 5.9 M$
%         (http://www.reedconstructiondata.com)
% 3) A plant size of 46451.6m^2 requires 130 workers

% Calculating the required size for the plant
Size = ((10000*(Tg/1000))/8000)/0.6;

% Calculating the plant cost using power exponent of 0.6

PlantCost = 5900000*((Size/13006.4256)^0.6);


% Calculating amount of workers for required plant size

Workers = 130/(46451.62/Size);

% Calculating total salary per year

Salary = 8*5*15*48*Workers;
% Assume operation 8hrs/day, 5days/week with 15$/hr salary

% Maintainance cost = 5$/tonnage

MaintCost = 5*(2*Tg/1000);

% Annual Operating Cost

AnnualOpCost = Salary + MaintCost + (PlantCost/5);
```

Total Annual Revenue and Payback period

```
% Include revenue of 74$/tonne saving from not
% landfilling the glass

GAR = TotalRevenue - AnnualOpCost + (74*(Tg/1000));

PYP = PlantCost/GAR;



disp(['Price of fiberglass per kg = ' num2str(Pricekg) '$']);
disp(['Gross revenue = ' num2str(TotalRevenue) '$']);
disp(['Required size of plant = ' num2str(Size) 'm^2']);
```

```
disp(['Capital cost of plant = ' num2str(PlantCost) '$']);
disp(['Amount of workers needed = ' num2str(Workers) 'worker(s)']);
disp(['Annual operating cost = ' num2str(AnnualOpCost) '$/year']);
disp(['Total annual revenue = ' num2str(GAR) '$/year']);
disp(['Payback period = ' num2str(PYP) 'years']);
```

```
Price of fiberglass per kg = 0.37383$
Gross revenue = 560747.6636$
Required size of plant = 3125m^2
Capital cost of plant = 2507651.8904$
Amount of workers needed = 8.7457worker(s)
Annual operating cost = 768405.3396$/year
Total annual revenue = -96657.6761$/year
Payback period = -25.9436years
```

Published with MATLAB® 7.12

A-4: Economic Analysis for Ceramic Tile and 100% Recycled Glass Tile Manufacturing

Calculations Completed by:	Calculations Reviewed by:	Date: 11/06/2012
Scott Bell	Michael Barrett	

SCB1

Ceramic Tile Market Size Estimate

US Tile market size: 2 000 000 000 ft^2/yr

US Population: 311.6 mil. Tiles per capita: 6.42 ft^2/person

NB Population: 750 000

∴ NB Tile demand ≅ 4 815 000 ft^2/yr

Ceramic Tile Manufacturing Plant Profitability

Plant Cost (1992): \$60mil For 40 000 000 ft^2/yr tile

CPI: 1992 - 358 2012 - 585.6

$$\therefore \text{2012 Plant Cost} = \$60\,000\,000 \times \frac{585.6}{358} = \$98\,145\,250$$

For 40mil ft^2/yr

Required Plant Size: Assume 50% recycled glass content
Assume all glass can be used, regardless of color.

$$\therefore 500\,t/yr \times \frac{1}{0.5} = 1000\,t/yr \text{ of tiling}$$

Use ~~Assume~~ tile thickness of ~~[illegible]~~ 1cm. ~~Assume~~ Tile density 2000kg/m³

$$\left(\frac{3.28\,ft}{m}\right)^2 \times \frac{m^3}{2000\,kg} \times \frac{1}{0.01\,m} \times \frac{1\,000\,000\,kg}{yr} = 537\,920\,\frac{ft^2}{yr}$$

As we can see, this facility would supply a significant portion (>10%) of tile demand in New Brunswick. It would be necessary to reach out for other markets, and scaling the plant up might lead to difficulty selling all the product.

SCB2 Ceramic Tile Manufacturing Plant Profitability (con't)

Knowing the output of the facility, we can now find its cost from the 1992 plant. $\frac{6}{10}$ is used as a scaling factor - as suggested in "Systematic Methods of Chemical Process Design":

$$C_{Plant} = \$98\,145\,250\left(\frac{537\,920\ ft^2/yr}{40\,000\,000\ ft^2/yr}\right)^{0.6}$$

$$C_{Plant} = \$7\,397\,141$$

Now for the facility's gross annual revenue:

Bulk ceramic tile cost = \$3 - 20/m² (Alibaba) Approximate \$15/m².

$$\frac{537\,920\ ft^2}{yr} \times \left(\frac{m}{3.28\ ft}\right)^2 \times \frac{\$15}{m^2} = \$750\,000/yr$$

We can see already that ceramic tiles would not be a feasible product, if we were to compete in the bulk tile market. And while it would be possible to seek out LEED projects, certification requirements are such that the material must have 50% recycled content at minimum. Ceramic tiles also require many inputs, and often a secondary firing step to set the glaze.

Another similar product, sintered glass tile, has 100% recycled content, and does not require a secondary firing step. By eliminating the need for numerous other feed materials, reducing the energy requirements (sintering @ >1200°C for ceramics, ~900°C for glass), and cutting the cost of startup equipment, we feel that glass tile offers the greater potential to a small business venture.

SCB3

100% Glass Recycled Tile Profitability

Cost of Plant: Assume tile thickness is still 1cm. Approximate plant costs as 50% of those for ceramic tiles (no glazing, less mixing, simpler molding)

$$\therefore C_{Plant} = \frac{\$98\ 145\ 250}{2}\left(\frac{537\ 920\ ft^2/y \div 2}{40\ 000\ 000\ ft^2/yr}\right)^{0.6}$$

$$C_{Plant} = \$2\ 440\ 147$$

Don't know how many workers would be needed. Would likely require at minimum three: one to mix colors & pour molds, one to remove and package finished tiles, and one for misc. tasks & troubleshooting. Also don't know maintenance costs, but 5 to 10% are common estimate figures. Assume 5% due to relatively low temperatures, compared to equipment design (glass processed at roughly 300°C less than ceramics).

Approximating operating costs with 3 employees and 5% annual maintenance:

Employees: \$80 000/yr with training, benefits, absenteeism, etc.

$$\therefore C_{ops} = \left(\frac{\$80\ 000}{yr}\right)\times 3 + (\$2\ 440\ 147)\times 0.05 = \$362\ 007/yr$$

Now for gross annual revenue. First use \$15/m²

$$\left(\frac{266\ 960\ ft^2}{yr}\right)\times\left(\frac{m}{3.28\ ft}\right)^2\times\frac{15\$}{m} = \$375\ 000/yr$$

Again, bulk market is not feasible. But what if the price for tile were tripled due to LEED certification status?

SCB 3.5 Glass Recycled Tile Profitability (cont')

At $45/m^2$ for LEED approved tile:

$3 \times \$375{,}000/yr = \$1\ 125\ 000$

Note: online site Susan Jablon sells recycled tile at $17-28/ft^2$ or $183-301/m^2$. Compared to $6-$15/ft^2$ (for non-recycled) at Home Depot ($65-$161/m^2$), getting $45/m^2$ for local, recycled tile may be possible.

Sales Price: $\$\frac{1\ 125\ 000}{yr} \times \frac{yr}{500t} + \$\frac{74}{t} = \$\frac{2324}{t}$

Capital Cost: $2 440 147 + $57 500 = $2 497 647
(↑ cullet production)

Operating Cost: $362 007 + $15 375 = $377 382/yr
(↑ cullet production)

Gross Revenue: $\$\frac{2324}{t} \times 500t = \$1\ 162\ 000/yr$

Payback Period (Pre-tax): $\frac{\text{Capital Cost}}{\text{Gross Revenue} - \text{Ops Cost}} = \frac{\$2\ 497\ 647}{(\$1\ 162\ 000 - \$377\ 382)/yr} = 3.18\ yrs$

Sensitivity Analysis: If product sold for $30/m^2$, PBP = 6.1 yrs
If " " " $15/m^2$, PBP = 72 yrs.

A-5: Economic Analysis for sandblasting media

Calculations Completed by:	Calculations Reviewed by:	Date: 11/10/2012
Michael Barrett	Carolyn McKenna	

Production Line for Sandblasting Medium			
	Description	Cost	
Fixed Costs	feedstock conveyor	$ 6,000.00	
	pulveriser	$ 40,000.00	
	debris removal	$ 3,000.00	
	dust control	$ 3,000.00	
	washing station	$ 8,000.00	
	forced air drying	$ 5,000.00	
	grinding equipment	$ 20,000.00	
	trommel screen	$ 15,000.00	
	packaging equipment	$ 10,000.00	
		$ 110,000.00	
Variable Costs	labour	$15/hour	$30/tonne
	fuel	$0.80/litre	$2/tonne
	electricity	$0.08/kWH	$0.25/tonne
	maintenance	$7550/year	$15.10/tonne
			$47.35/tonne

*Cost estimates obtained from Clean Washington Center report (CWC, 1997).

A-6: Economic Analysis for cullet transport and sale

Calculations Completed by:	Calculations Reviewed by:	Date: 11/25/2012
Scott Bell	Michael Barrett	

SCB 4

Bulk Shipping Costs

$$3¢/\text{tonmile} \text{ for rail} \times \frac{1.1\text{ tons}}{\text{tonne}} \times \frac{\text{mile}}{1.61\text{km}} = \frac{2.05¢}{\text{tonne}\cdot\text{km}}$$

$$16.5¢/\text{ton}\cdot\text{mile} \text{ for trucking} \times \frac{1.1\text{ tons}}{\text{tonne}} \times \frac{\text{mile}}{1.61\text{ km}} = \frac{11.27¢}{\text{tonne}\cdot\text{km}}$$

Fredericton to Moncton: 170km

Moncton to Montréal: ~ 1000km

Trucking to Moncton: $\frac{\$0.1127}{\text{tonne}\cdot\text{km}}$ 170km = \$19.16/tonne

Train to Montreal: $\frac{\$0.0205}{\text{tonne}\cdot\text{km}} \times 1000\text{km} = \$20.50/\text{tonne}$

Trucking to Plant: Approximate at \$5/tonne

Total Shipping = \$44.66/tonne

Note: These costs are calculated to evaluate the economic potential of shipping cullet to a glass manufacturing facility in Montreal.

SCB 5

Bulk Shipping - Processing Costs

(Sale to Montreal for Fiberglass & Glass Manufacturing)

Equipment: Capacity of 1 tonne/hr.

Cost of Equipment =

Feedstock Conveyor	\$6000
Pulverizer	\$40 000
Debris Removal	\$3000
Dust Control	\$1000
Washing	\$8000
Drying	\$5000
Packaging (Bagging) Equipment	\$10 000
	\$73 000

Note: Color sorting performed by hand if necessary.

$\frac{\$73\,000}{5} = \$14\,600/yr$ Fixed cost.

Operating Cost: 2 laborers at \$15/hr, $500t \times \frac{hr}{t} = 500hrs$

Staff = $2 \times \$15 \times 500 = \$15\,000/yr$

→ Cops = \$18 650

Assume Maintenance = 5%

Assume cullet sale at \$80/tonne.

SCB 6 Bulk Shipping - Profitability

To summarize:

Sales Price: $\frac{\$80}{t} + \frac{\$74}{t} - \frac{\$44.66}{t} = \$109.34/t$

Capital Cost: $73 000

Operating Cost: $\frac{\$15\,000}{yr} + \$73000(0.05) = \$18\,650/yr$ (based on assumptions from sandblasting & aggregate sections)

Gross Revenue: $\frac{\$109.34}{t} \times 500t = \$54\,670/yr$

Payback Period: $\frac{\$73\,000}{(\$54\,670 - \$18\,650)/yr} = 2.03\,yrs$

Sensitivity Analysis: This option is very sensitive to the price that a Montreal based manufacturer would pay for cullet.

If they would pay $40/t : PBP = 4.6 yrs
" " " " $0/t : PBP = ∞ (loss of $3980/t)

Unless a large buyer could be found, willing to pay for glass cullet, (at least $10/t ... Costs us $37.30 for processing, $44.66 shipping, and pays back $74/t in tipping fee avoidance... $10/t means no net loss) this option is not economically viable. From an economic standpoint, it offers no benefits over local aggregate uses.

Appendix B – Supporting Literature

B-1: MSDS for Crushed Glass

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Updated: 12/21/06

MSDS SHEET - CRUSHED GLASS

I. Product Identification

Material Name: Crushed Glass
Manufacturer: Glass Plus LLC
3602 McKay Road
Tomahawk, WI 54487
Emergency and Information Phone Number: 800-252-7848

HMIS: Health: 1 **Flammability:** 0 **Reactivity:** 0

II. Composition & Information on Ingredients

CAS #	Chemical Name	Percent	TLV	PEL	Cancer
65997-17-3	Glass, amorphous	100.0%	10 mg/m3 TWA (total)	10 mg/m3 TWA	No
7631-86-9	Silicon dioxide	72.5%	10 mg/m3 TWA (total)	15 mg/m3 TWA (total) 5 mg/m3 TWA (resp)	No
1313-59-3	Sodium oxide	13.7%	Not established	Not established	No
1305-78-8	Calcium oxide	9.75%	2 mg/m3 TWA	5 mg/m3 TWA	No
1309-48-4	Magnesium oxide	3.3%	10 mg/m3 TWA (fume)	10 mg/m3 TWA (fume) 5 mg/m3 TWA (resp)	No
1344-28-1	Aluminum oxide	0.4%	10 mg/m3 TWA (total)	10 mg/m3 TWA (total) 5 mg/m3 TWA (resp)	No No
11135-81-2	Potassium oxide	0.1%	Not established	Not established	

III. Hazards Indentification

Effects of Overesposure
Eyes: Irritation **Skin:** Irritation
Inhalation: Irritation, coughing **Ingestion:** Irritaiton
Effects of Chronic Overexposure: Respiratory irritation, pneumoconiosis
Routes of Entry: Contact, inhalation
Target Organs: Eyes, skin, respiratory
Cancer Rating: This material contains no ingredients listed by NTP, IARC or OSHA as being carcinogenic.
Additional Information: None

IV. First Aid Measures

Eyes: Immediately flush eyes with large amounts of water, occasionally lift the upper and lower lids. Contact lenses should not be worn when working with this material. Seek medical care if necessary.
Skin: Remove contaminated clothing. Flush with water. Seek medical care if necessary.
Inhalation: Move to fresh air. Seek medical care if necessary.
Ingestion: Seek medical care if necessary.

V. Fire Fighting Measures

Flash Point: None **Method Used:** N/A
Flammable Limits (Percentage in air): **UEL:** N/A **LEL:** N/A
Extinguishing Media: Suitable for surrounding fire
Control measures: Use SCBA and full protective equipment.
Unusual Hazards: N/A

VI. Accidental Release Measures

Spills: Use personal protective equipment. Ventilate area. Sweep up and discard as solid waste. Avoid generating or accumulating dust.
Releases to air: Not applicable

VII. Spill or Leak Procedures

Handling: Avoid personal contact. Use with adequate ventilation. Wash after handling
Storage requirements: Store in a dry area. Avoid generating and accumulating dust.

MSDS SHEET - CRUSHED GLASS

VIII. Exposure Controls and Personal Protection

Protective Equipment*
Eye Protection: Safety glasses or chemical goggles.
Skin: Gloves may be worn to preent prolonged or repeated skin contact.
Respiratory: A NIOSH/MSHA approved dust respirator if exposure limits exceeded
Ventilation: Good general ventilation should be sufficient to control airborne levels. Use process enclosures, local exhaust venilation, or other engineering controls to maintain airborne levels below recommended exposure limits.
Additional Information: None.
*Protective equipment should be determined by conditions of exposures.

IX. Physical & Chemical Properties

Appearance & Odor: Tan granules with no odor
Boiling Point: N/A
Percent volatile: N/A
Vapor density (air = 1): N/A
pH: N/A
Specific gravity (H_2O = 1): Not determined
Melting/freezing point: N/A
Vapor Pressure: N/A
Evaporation Rate: N/A
Solubility in Water: Insoluble

X. Stability and Reactivity

Stability: Stable
Hazardous Polymerization: N/A
Incompatibility: N/A
Unusual Hazards: N/A
Conditions to Avoid: N/A
Conditions to Avoid: N/A
Hazardous Decomposition Products: Not determined

XI. Toxicological Information

Crushed glass is recycled glass cullet. It is primarily made up of amorphous silica and does not contain and crystalline silica *(NIOSH Evaluation of Substitue Materials for Silica Sand in Abrasive Blasting)*. Amorphous silica is considered nontoxic.

XII. Ecological Information

No information available at this time.

XIII. Disposal Procedures

Material and containers should be disposed in accordace with Local, State & Federal regulations.

XIV. Transportation Information

DOT Hazard Classification: N/A

XV. Other Information

CAS #	Chemical Name	SARA 302	SARA 304	SARA 313	RCRA
65997-17-3	Glass, oxide	No	No	No	No
7631-86-9	Silicon dioxide	No	No	No	No
1313-59-3	Sodium oxide	No	No	No	No
1305-78-8	Calcium oxide	No	No	No	No
1309-48-4	Magnesium oxide	No	No	No	No
1344-28-1	Aluminum oxide	No	No	No	No
11135-81-2	Potassium oxide	No	No	No	No

DISCLAIMER: The information in this MSDS was obtained from sources, which we believe are reliable. However, the information is provided without any representation or warranty, expressed or implied, regarding accuracy. These conditions or methods of handling, storage use and disposal of the product are beyond our control and may be beyond our knowledge. For this and other reasons, we do not assume responsibility and expressly disclaim liability for loss, damage or expense arising out of or in any way connected with the handling, storage, use or disposal of the product. Customers/users of silica must comply with all applicable health and safety laws, regulations and orders, including the OSHA Hazardous Communication Standard.

WARNING: Silicosis Warning - Breathing dust from silica sand causes silicosis, a fatal lung disease. Breathing dust during blasting operations may also cause asbestosis and/or other serious or fatal diseases. A NIOSH approved, well-maintained air-supplied respirator should be used by anyone blasting, anyone handling or using the sand and anyone in the area of the dust. Harmful dust can remain suspended in the air for long periods of time after the blasting has ceased causing serious injury or death.

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B-2: Belt Thickness Sizing

RECOMMENDATIONS FOR COLD BULK MATERIALS WITH NORMAL LOADING CONDITIONS

Frequency Factor	Cover Grade (RMA)	Non Abrasive Material such as lime, charcoal, wood chips, bituminous coal, grain				Abrasive Material such as salt, anthracite, coal, phosphate rock, limestone, fullers earth				Very Abrasive Material such as slag, copper ore, sinter, coke, sand, fine dust				Very Sharp Abrasive Material such as quartz, some ore, foundry refuse, glass batch, iron borings			
		Material Class 5 (CEMA)				Material Class 6 (CEMA)				Material Class 7 (CEMA)				Material Class 8 (CEMA)			
		Lump size, inch				Lump size, inch				Lump size, inch				Lump size, inch			
		Dust to 1/4	1/2 to 1 1/3	2 to 5	6 and over	Dust to 1/4	1/2 to 1 1/3	2 to 5	6 and over	Dust to 1/4	1/2 to 1 1/3	2 to 5	6 and over	Dust to 1/4	1/2 to 1 1/3	2 to 5	6 and over
0.2	2 1	3/32 1/16	3/16 1/8	3/16 1/4	3/8 5/16	3/16 1/8	3/8 1/4	▪ 3/8	▪ 3/8	3/16 7/32	▪ 3/8	▪ 3/8	▪ 3/8	3/8 5/16	▪ 3/8	▪ 3/8	▪ 3/8
0.4	2 1	1/16 1/16	3/32 3/32	3/16 1/8	1/4 3/16	3/32 3/32	1/16 1/8	3/8 1/4	▪ 3/8	3/16 1/8	3/16 1/4	▪ 3/8	▪ 3/8	7/32 3/32	3/8 5/16	▪ 3/8	▪ 3/8
0.6	2 1	1/16 1/16	3/32 3/32	1/8 1/8	3/16 3/16	3/32 3/32	1/8 1/8	1/4 3/16	3/8 1/4	1/8 1/8	7/32 3/32	3/8 1/4	▪ 3/8	3/16 1/8	3/16 7/32	▪ 3/8	▪ 3/8
0.8	2 1	1/16 1/16	3/32 3/32	1/8 1/8	3/16 3/16	3/32 3/32	1/8 1/8	3/16 3/32	9/32 3/16	1/8 1/8	3/32 1/8	3/16 7/32	▪ 3/8	1/8 1/8	7/32 3/32	3/8 5/16	▪ 3/8
1.0	2 1	1/16 1/16	3/32 3/32	1/8 1/8	3/16 3/16	3/32 3/32	1/8 1/8	3/32 3/32	7/32 3/16	1/8 1/8	1/8 1/8	1/4 3/16	3/8 1/4	1/8 1/8	3/16 1/8	3/8 1/4	▪ 3/8
1.5	2 1	1/16 1/16	3/32 3/32	1/8 1/8	3/16 3/16	3/32 3/32	1/8 1/8	5/32 5/32	3/16 3/16	1/8 1/8	1/8 1/8	3/16 3/16	1/4 7/32	1/8 1/8	1/8 1/8	1/4 3/16	3/8 1/4
2.0	2 1	1/16 1/16	3/32 3/32	1/8 1/8	3/16 3/16	3/32 3/32	1/8 1/8	3/32 3/32	3/16 3/16	1/8 1/8	1/8 1/8	3/16 3/32	7/32 3/16	1/8 1/8	1/8 1/8	3/16 3/16	3/8 1/4
3.0	2 1	1/16 1/16	3/32 3/32	1/8 1/8	3/16 3/16	3/32 3/32	1/8 1/8	3/32 3/32	3/16 3/16	1/8 1/8	1/8 1/8	3/16 3/32	7/32 3/16	1/8 1/8	1/8 1/8	3/16 3/16	1/4 1/4
4.0 and over	2 1	1/16 1/16	3/32 3/32	1/8 1/8	3/16 3/16	3/32 3/32	1/8 1/8	3/32 3/32	3/16 3/16	1/8 1/8	1/8 1/8	3/16 3/32	7/32 3/16	1/8 1/8	1/8 1/8	3/16 3/16	1/4 1/4

NOTE: *THE FREQUENCY FACTOR INDICATES THE NUMBER OF MINUTES FOR THE BELT TO MAKE ONE COMPLETE TURN OR REVOLUTION.*

Appendix C – Detailed Design Sample Calculations

C-1: Expected Glass Input and Collection Bin Sizing

Calculations Completed by:	Calculations Reviewed by:	Date: 12/04/2012
Carolyn McKenna	Michael Barrett	

Collection Process (Quantity)

↳ 77% recovery rate for redemption center (legislation NB)

↳ 3200 tonnes of glass available in Fredericton (4% of 80,000 → FRSWC)

↳ 50% recovery rate (FRSWC)

↳ 55% clear, 45% mixed (Zero Waste, 2012)

$$80{,}000 \text{ tonnes of garbage} \times 4\% \text{ glass} \times 50\% \times 79\% = 1264 \text{ tonnes/year}$$

Mass Collected

$$1264 \frac{\text{tonnes}}{\text{year}} \approx 24 \frac{\text{tonnes}}{\text{week}} = 4.0 \frac{\text{tonnes}}{\text{day}} \approx 1.0 \frac{\text{tonne}}{\text{bin/day}}$$

→ 52 weeks / year
→ redemption centers are open 6 days a week
→ 4 main redemption centers

Volume Required

→ 1 tonne = 1000kg
→ $\rho_{air} = 1.2 kg/m^3$
$\rho_{glass} = 2500 kg/m^3$
→ 1 average container has ≈ 300mL air ($0.0003 m^3$) and ≈ 170g glass ($0.000071 m^3$)

$$1000 \text{kg glass} \times \frac{1}{2500 \text{kg/m}^3} \approx 0.40 \text{ m}^3 \text{ glass}$$

$$0.40 \text{ m}^3 \text{glass} \times \frac{0.0003 \text{ m}^3 \text{air}}{0.000071 \text{ m}^3 \text{glass}} = 1.7 \text{ m}^3 \text{ air}$$

The total volume required / bin / day ≅ 2.1m³ at maximum intake

- Assuming weekly pick up + one bin for colour/mix + one for clear → $2 \times 6m^3 \frac{\text{bins}}{\text{depot}}$
- Bins will be heavy (≈3000kg), but liftable by a forklift. At max capacity the bins will have to be emptied weekly. When starting off bins will be emptied much less frequently (whenever they are filled).
- 6m³ is an overestimate as the glass will likely break when thrown into the bin resulting in less volume occupied by air gaps
- This is for the whole greater Fredericton area. For the first phase, promotion in the city of Fredericton should be the focus.

C-2: Processing Hours and Quantities

Calculations Completed by:	Calculations Reviewed by:	Date:
Scott Bell	Carolyn McKenna	04/01/ 2013

Several factors were taken into account to come up with an appropriate facility throughput and operating schedule. Some key criteria are as follows:

- The smallest crushing equipment available processes one metric tonne of glass per hour
- Tile production furnaces are available at throughputs as low as
- The Fredericton Regional Solid Waste Commission's site operates on a 5 day work week schedule
- The glass collection estimated for the city of Fredericton is roughly 1200 metric tonnes per year - additional glass collection would require expansion to other municipalities.

We also accounted for market demand. Our estimates of glass tile market size indicate that a 500 tonne per year production rate would exceed local demand, but may be appropriately sized to meet demand in the Maritimes, parts of Quebec, and small portions of New England. For example, Home Depot in Fredericton sold 13,000 ft^2 of glass tile in 2011. If 10% of sales are high-end tiles, then the facility could meet demand for 210 similar sized stores. A summary of these calculations is shown below. A larger facility would carry an increased risk, while smaller facilities would not present as attractive of financial projections.

Tile Production Throughput			Market Info	
(t/yr)	(m^2/yr)	(ft^2/yr)	Equivalent Stores (# supplied /yr)	Population Supplied (#)
250	12,500	134,480	103.45	2,241,333
350	17,500	188,272	144.82	3,137,867
500	25,000	268,960	206.89	4,482,667
1000	50,000	537,920	413.78	8,965,333
2000	100,000	1,075,840	827.57	17,930,667

Assumptions:			
Tile density	2000	kg/m3	
Tile thickness	0.01	m	(1 cm)
USA Ceramic Tile Demand	6	ft^2/person/yr	
High-End Glass Tile Deman	0.06	ft^2/person/yr	
Tile Price	45	$/m^2$	

TABLE 1: TILE PRODUCTION VS. MARKET SIZE NEEDED

Plant Economics							
Gross Profit ($/yr)	Cost of Plant ($)	Maintenance ($/yr)	Staff (#)	Staffing Cost ($/yr)	Operating Cost ($/yr)	Net Profit ($/yr)	Payback Period (yrs)
562,500	$1,649,385	$ 82,469	3	$ 240,000	$ 322,469	$ 240,030.76	6.9
787,500	$2,018,361	$ 100,918	3	$ 240,000	$ 340,918	$ 446,581.95	4.5
1,125,000	$2,500,000	$ 125,000	3	$ 240,000	$ 365,000	$ 760,000.00	3.3
2,250,000	$3,789,291	$ 189,465	5	$ 400,000	$ 589,465	$ 1,660,535.43	2.3
4,500,000	$5,743,492	$ 287,175	10	$ 800,000	$ 1,087,175	$ 3,412,825.41	1.7

Sensitivity Analysis - double # of staff							
Gross Profit ($/yr)	Cost of Plant ($)	Maintenance ($/yr)	Staff (#)	Staffing Cost ($/yr)	Operating Cost ($/yr)	Net Profit ($/yr)	Payback Period (yrs)
562,500.00	$1,649,385	$ 82,469	6	$ 480,000	$ 562,469	$ 30.76	53628.8
787,500.00	$2,018,361	$ 100,918	6	$ 480,000	$ 580,918	$ 206,581.95	9.8
1,125,000.00	$2,500,000	$ 125,000	6	$ 480,000	$ 605,000	$ 520,000.00	4.8
2,250,000.00	$3,789,291	$ 189,465	10	$ 800,000	$ 989,465	$ 1,260,535.43	3.0
4,500,000.00	$5,743,492	$ 287,175	20	$ 1,600,000	$ 1,887,175	$ 2,612,825.41	2.2

Sensitivity Analysis - double # of staff & cost of maintenance							
Gross Profit ($/yr)	Cost of Plant ($)	Maintenance ($/yr)	Staff (#)	Staffing Cost ($/yr)	Operating Cost ($/yr)	Net Profit ($/yr)	Payback Period (yrs)
562,500.00	$1,649,385	$ 164,938	6	$ 480,000	$ 644,938	-$ 82,438.49	-20.0
787,500.00	$2,018,361	$ 201,836	6	$ 480,000	$ 681,836	$ 105,663.91	19.1
1,125,000.00	$2,500,000	$ 250,000	6	$ 480,000	$ 730,000	$ 395,000.00	6.3
2,250,000.00	$3,789,291	$ 378,929	10	$ 800,000	$ 1,178,929	$ 1,071,070.86	3.5
4,500,000.00	$5,743,492	$ 574,349	20	$ 1,600,000	$ 2,174,349	$ 2,325,650.82	2.5

TABLE 2: PAYBACK PERIOD ESTIMATES OF TILE FACILITIES

By combining the above factors, it was decided to proceed with a 500 tonne per year glass tile facility. It was also decided that, due to our diverse markets, we would recycle 100% of glass that could be obtained in Fredericton. It was then calculated that, at one metric tonne per hour of throughput, it would take a cullet plant 1200 hours per year to process this glass. This led to the adoption of a three day per week operation schedule for cullet production.

However, it was anticipated that glass tile production equipment would cost significantly more for such a throughput. It was therefore decided to operate the glass tile facility on a five day per week operating schedule. At 500 metric tonnes per year, this led to a 250 kilogram per hour throughput.

Since studies demonstrated that roughly 55% of glass collected is clear, it was decided that the cullet production facility would switch between clear and mixed cullet on a weekly basis. Twenty-four metric tonnes of clear cullet would be produced to feed the glass tile facility every two weeks. At a production rate of 250 kg/hr, 20 tonnes of this would be turned into glass tile product. To use the full 24 tonnes, it would be possible to increase production by moving to a 6 day per week operating schedule without any additional equipment or collection costs. If enough markets could be found, this would be a logical step.

In summary:

- 500 tonnes of yearly glass tile production provides a desirable payback period while meeting a reasonable market demand
- The use of 1200 tonnes, a full 100% of what could be expected for collection, is logical for our facility, and requires three days of operation per week based on the smallest crushing equipment available
- Glass tile production for five days a week would help to maximize revenues from expensive equipment, while not requiring a change in hours of operation at the FRSWC
- Tile production could be scaled up by running six days per week, at no additional cost of collection or equipment

C-3: Conveyors

Calculations Completed by:	Calculations Reviewed by:	Date: 01/22/2013
Carolyn McKenna	Michael Barrett	

Conveyor sample calculation

Mass flow required = 1053 kg/hr → * max is used so all conveyors can be sized the same to simplify process

Required capacity

$1053 \frac{kg}{hr} \times \frac{0.001 tonne}{1 kg} = 1.053 \frac{tonnes}{hr}$

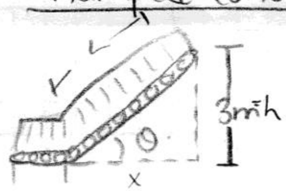
$1053 \frac{kg}{hr} \times \frac{m^3}{500 kg} \times \frac{1h}{60 min} \approx 0.03 m^3/min = \dot{V}$

(500 kg: uncrushed density)

Belt speed

Choose from standard → 10 m/min (can handle twice the capacity required)

Ramped conveyors



$\theta = 30°$ (standard maximum)

$L = 3/\sin 30° = 6m.$ $x = 3/\tan 30° = 5.2m$

Power required (ramped)

$hp = (X + 150)(V_b/30000) + (L)(\dot{V}/16000) + (h)(\dot{V}/500)$ → imperial unit based equation

(X in ft, V_b in ft/min, L in ft, $\dot{V}$ in tons/hr, h in ft, $\dot{V}$ in tons/hr)

$= (17.1 + 150)(30/30000) + (19.7)(1.158/16000) + (9.84)(1.158/500)$

$\therefore hp \approx 0.19 hp$

$0.19 hp \times \frac{745.7 W}{hp} = 141.7 W$ per ramp conveyor.

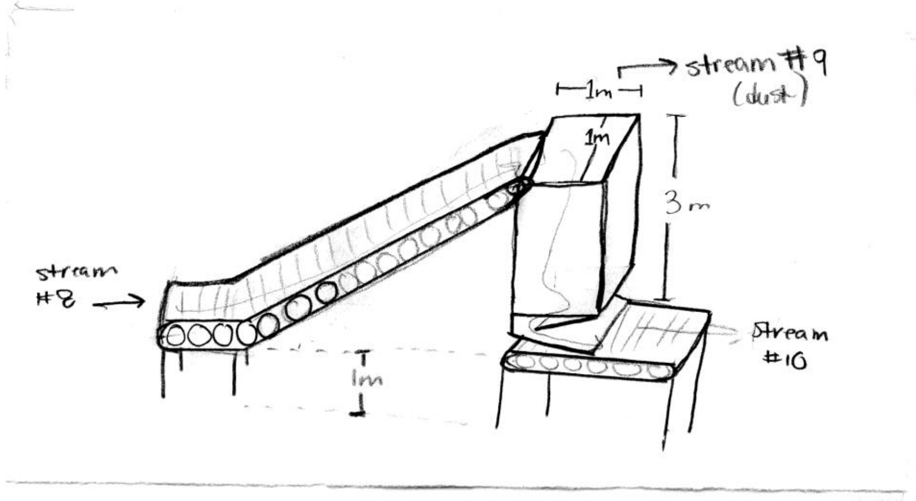
Same equation & method used for flat conveyors yields...

$hp \approx 0.16 hp$ per flat conveyor

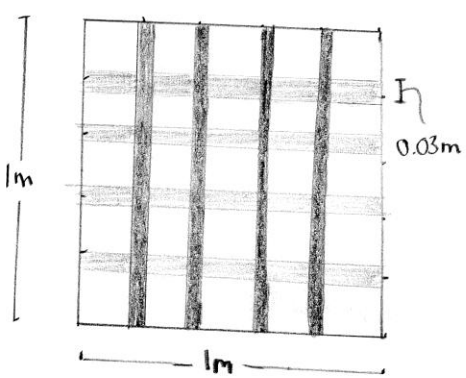
C-4: Breaking Process

Calculations Completed by:	Calculations Reviewed by:	Date: 01/17/2013
Carolyn McKenna	Michael Barrett	

Breaker Tower



- Glass → 5.5 Moh's Scale (1550HB)
- Metal → Steel (6.5 Moh's Scale)



top view

- Locate metal bars in lower 2/3rds of the tower (≈1m apart)
- 2 levels of bars with 4 bars each
- metal bars : w & h ≅ 0.03m
  L = 1m
- tower must 'catch' the glass with c angled guide to slow the glass down before it drops onto the conveyor

mass balance

① glass in : 1053.3 kg/hr (stream #8)

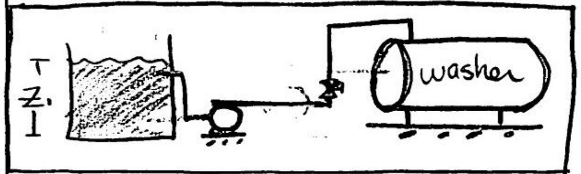
② Dust out (1%) = 10.53 kg/hr (stream #9)

Glass out (①-②) = 1042.8 kg/hr (stream #10)

C-5: Washing Process

Calculations Completed by:	Calculations Reviewed by:	Date: 01/23/2013
Carolyn McKenna	Michael Barrett	

Pump consumption example



Knowns/Assumptions

$T_{water} \cong 10°C$

$\dot{V}_{water} = 2085.6\ kg/hr$

$\rho_{water} \cong 1000\ kg/m^3$

$Q = 2.09\ m^3/h$

$D = 0.025\ m\ (1")$

$L = l_1 + l_2 = 50m + 50m = 100m$

$\eta_{pump-motor} = 70\%$

$\mu_{water} = 1.307 \times 10^{-3}\ kg/ms$

$z_1 = 0m$

$z_2 = 60m$

$e = 0.05mm = 0.00005m$

Fittings	# of fittings
$K_{L\ entrance} = 0.5$	1
$K_{L\ elbow} = 0.3$	5
$K_{L\ valve} = 0.2$	1
$K_{L\ exit} = 1.06$	1

$P_1 = P_2 = P_{atm}$

$V_1 = 0\ m/s$

$V_2 = 1\ m/s$

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_L$$

$$h_p = (z_2 - z_1) + h_L + \frac{V_2^2}{2g}$$

$$h_p = (60m) + h_L + (1m/s)^2/2(9.81m/s^2)$$

$$\therefore h_p = h_L + 60m + 0.05m$$

$$h_L = \left(f\frac{L}{D} + \Sigma K_L\right)\frac{V^2}{2g}$$

$$V = \frac{\dot{V}}{\pi D^2/4} = \frac{(2.09\frac{m^3}{h} \cdot \frac{h}{3600s})}{\pi(0.025m)^2/4} \cong 1.18m/s$$

$$Re = \frac{\rho V D}{\mu} = \frac{(1000kg/m^3)(1.18m/s)(0.025m)}{(1.307 \times 10^{-3}kg/ms)}$$

$$\therefore Re \cong 22574 \rightarrow \text{turbulent}$$

$$\frac{\varepsilon}{D} = \frac{0.00005m}{0.025m} = 0.002$$

from the moody chart $f \cong 0.03$

$$\Sigma K = K_{L\,entrance} + K_{L\,elbow} + K_{L\,valve} + K_{L\,exit} = 0.5 + 5(0.3) + 0.2 + 1.06 = 3.26$$

$$h_L = \left(0.03 \cdot \frac{100m}{0.025m} + 3.26\right)\frac{(1.18m/s)^2}{2(9.81m/s^2)} = 8.75m$$

$$h_p = 8.75m + 60m + 0.05m \cong 68.8m$$

$$\dot{W}_{elec} = \frac{\rho \dot{V} g h_p}{\eta_{p-m}} = \frac{(1000kg/m^3)(2.09/3600\ m^3/s)(9.81m/s^2)(68.8m)}{0.7}$$

$$\therefore \boxed{\dot{W}_{elec} = 558.6W}$$

Calculations Completed by:	Calculations Reviewed by:	Date:01/15/2013
Amin Azahar	Michael Barrett	

Operating condition: water @ 60°C.

Inlet water - 15°C.

Washing capacity = 1042.8 kg/hr.

C_p of water = 4.187 kJ/kgK.

Water usage = 2085.6 kg/hr

Heat Load = $mC\Delta T$.
(for water).

$$= (2085.6)(4.187)(60-15)$$

$$= 392958.3 \text{ kJ/hr}$$

Power capacity - $\frac{392958.3}{3600}$ = 109.16 kW.

max resident time = 600s (Ulrich textbook). = 0.17 hr

max capacity of glass = $1042.8 \frac{kg}{hr} \times 0.17$ hr

$$= 177.28 \text{ kg}$$

max capacity of water = 2085.6 kg/hr × 0.17 hr.

$$= 354.55 \text{ kg}.$$

using density of glass and water to calculate volume

ρ_{glass} = 2500 kg/m3

ρ_{water} = 1000 kg/m3.

$$\Sigma \text{ volume} = \frac{177.28 \text{ kg}}{2500 \text{ kg/m}^3} + \frac{354.55 \text{ kg}}{1000 \text{ kg/m}^3} = 0.43 \text{ m}^3$$

assume washing machine is cylinder:

$$V = \pi r^2 L = \pi \frac{D^2}{4} L$$

ratio of L to D: $L/D = 3$ (ulrich).

$L = 3D$

Find diameter

$$V = 0.43\,m^3 = \pi \frac{D^2}{4} 3D$$

$$0.43 = \frac{3}{4}\pi D^3$$

Diameter $D = 0.57m$

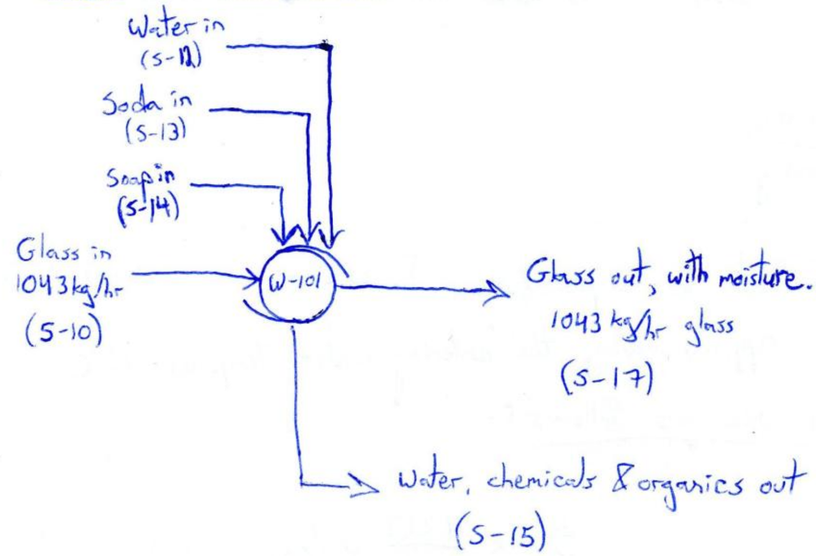
length, $L = 3D$

$L = 3(0.57)$

$= 1.7m$

Calculations Completed by:	Calculations Reviewed by:	Date: 04/01/2013
Scott Bell	Michael Barrett	

Mass Balance for Washer (W-101)



Did research to determine approximate water, soap, & chemical consumption

Water in (S-12): According to BC Hydro[1], the water use of new, energy efficient dishwashers is roughly 15L per cycle. By our estimates, each cycle can wash ~ 7.5kg of dishes.

Therefore:

$$S_{12} = S_{10} \times \frac{15L}{7.5kg} = 2086 L \text{ of water/hr} \cong 2086 \text{ kg/hr}$$

Soda in (S-13): Zhangjiagang Kezheng Trading Co.[2] offers a bottle label remover which uses soaking in a solution of 2.5% soda.

Therefore:

$$S_{13} = S_{12} \times \frac{2.5}{100} = 52.1 \text{ kg/hr soda}$$

[1] BC Hydro - www.bchydro.com/powersmart/residential/guides_tips/green-your-home/appliances_guide/washing_dishes.html

ZK Trading Co - see references.

Soap in S-14 :

1.9 kg of dish soap is used per 1000L of water.

Therefore:

$$S_{14} = S_{12} \times \frac{1.9\,kg}{1000\,kg} = 3.96\,\frac{kg}{hr}\ \text{soap.}$$

Research also indicated that the temperature of water in dishwashers is roughly 50 - 60°C. Approximating the entering water temp as 15°C gives a washer power use as follows:

$$Q = \dot{m} C_p \Delta T = 2086\,\frac{kg}{hr} \times \frac{hr}{3600\,s} \times \frac{4.2\,kJ}{kg \cdot K} \times (60°C - 15°C)$$

$$\boxed{Q = 114.2\,kW}$$

It is approximated that [1% of] all labels will be removed in the washer, for the purposes of the mass balance. (See detailed discussion in section 4.1.3) Research showed that labels weighed roughly 1g, compared to 200g for a bottle.)

Therefore:

$$\text{Mass of Labels}_{S_{15}} = S_{10} \times \frac{1\,g\ \text{label}}{200\,g\ \text{bottle}} \times 1\% = 0.052\ kg/hr\ \text{labels}$$

Approximate that all liquids & chemicals are in S_{15}, except for moisture retained by the glass. Research shows that glass particles can hold a maximum of 15% moisture by weight. Since this assumes smaller particle sizes than what would be present in our process at this stage, we assume that the glass holds 5% moisture by weight.

oisture in S_{17}

herefore: Moisture in $S_{17} = S_{10} \times 5\% = 52.14\ kg/hr$

And: $S_{17} = S_{10} + 52.14\ kg/hr = 1094.9\ kg/hr$ total

(Labels are small, and are neglected. 0.05 kg/hr changes nothing due to sig. figs.)

d, for S_{15}:

S_{15} = Water + Labels + Soda + Soap

$= 2086 - 52.14 + 52.14 + 3.96 + 0.052\ kg/hr$

(Water to washer; Moisture w/glass; Soda; Soap; Labels)

$$S_{15} = 2090\ kg/hr$$

se Mass Balance:

$In = 1043\ \frac{kg}{hr} + 2086\ \frac{kg}{hr} + 52\ \frac{kg}{hr} + 4\ \frac{kg}{hr} = 3185\ \frac{kg}{hr}$

(Glass; Water; Soda; Soap)

$Out = 1095\ \frac{kg}{hr} + 2090\ \frac{kg}{hr} = 3185\ \frac{kg}{hr}$ ✓

(S_{17}; S_{15})

rgy balance is unimportant here - hot water is sent to dr
heat quality means it's likely not worth recovering. The glass is
60°C, and is further heated in the dryer in the next s

C-6: Drying Process

Calculations Completed by:	Calculations Reviewed by:	Date: 02/03/2013
Amin Azahar	Michael Barrett	

throughput (feed) = 1021.94 kg/hr
moisture removed = 5% → 0%.

[calculation based on Handbook of Chemical engineering calculations 3rd Ed by Nicolas P. Chopey]

inlet glass $temp_{in}$ = 60°C.
outlet glass temp = 70°C.

$C_{p_{glass}} = 0.84$ kJ/kg·K. $C_{p_{water}} = 4.19$ kJ/kg·K.

Heating medium = 400°C steam.

Heat transfer rate @ heating = 3.61 W/m·K

constant-rate drying = 5.77 W/m·K.

falling-rate-drying = 2.166 W/m·K.

Surface loading @ heating = 100%

CRD = 80%

FRD = 60%.

Evaporation enthalpy = 2257 kJ/kg

water enthalphy = 419 kJ/kg → @ 100°C

Water-vapor enthalpy average ~~for~~ over 100°C to 370°C = 1349 kJ/kg

Solids temp. during constant-rate-drying = 100°C.

Product moisture @ falling-rate-drying = 5%

Calculation: $W_s = 1021.94(1-0.05)$

$= 970.84$ kg/hr.

$W_p = W_s$.

Amount of liquid to be removed = 1021.44 − 970.84

= 52.14 kg/hr.

Moisture in process material from CRD to FRD

$$= \left[\frac{970.84}{(1-0.025)}\right] 0.025$$

= 24.89 kg/hr

moisture leaving the final product = 970.84 × 0

= 0 kg/hr.

moisture removed in FRD

= 24.89 − 0

= 24.89 kg/h.

moisture removed in CRD

= 52.14 − 24.89

= 27.25 kg/hr.

Q_{HS} in heating zone

$$Q_{HS} = 970.84(0.86)(100-60)$$

$$= 32620.2 \text{ kJ/h} = 9.06 \text{ kW.}$$

$$Q_{HL} = [(52.14)(4.19)(100-60)]$$

$$Q_{HL} = 8738.6 \text{ kJ/h} = 2.43 \text{ kW}$$

Total in heating zone = 9.06 + 2.43

= 11.49 kW.

Heat in CRD

$$Q_c = (27.25)(2257)$$

$$= 61503.25 \text{ kJ/hr} = 17.08 \text{ kW.}$$

Heat in FRD

$$Q_{FS} = (970.84)(0.84)(90-60)$$

$$= 24465.168 \text{ kJ/hr} = 6.80 \text{ kW}$$

Heat load of vaporization in falling rate zone

$Q_{FE} = 0 \rightarrow$ no moisture in falling rate zone

$$\therefore \Sigma Q_F = Q_{FS} = 6.80 \text{ kW.}$$

Calculating ΔT_{mH} in heating zone.

$T_i = 400°C = T_o$
$t_o = 100°C$
$t_i = 60°C$

$$\Delta T_{mH} = [(400-100)-(400-60)] / \ln((400-100)/(400-60))$$

$$\Delta T_{mH} = 319.58 °C$$

Surface area in Heating zone

$$A_H = \frac{Q}{U \Delta T L} = \frac{11.49 \times 10^3}{(3.61)(319.58)(1.0)}$$

$$A_H = 9.96 \text{ m}^2$$

Surface area in CRD $= \frac{17.08 \times 10^3}{(5.77)(319.58)(0.8)}$

$A_c = 11.58\ m^2$

Calculating ΔT_{mF} in FRD

$T_i = 400°C = T_o$

$t_i = 90°$

$t_o = 100°C$

$\Delta T_{mF} = [(400-100)-(400-90)] / \ln((400-100)/(400-90))$

$\Delta T_{mF} = 304.97\ °C$

$A_F = \frac{6.8 \times 10^3}{(2.166)(304.97)(0.6)}$

$A_F = 17.16\ m^2$

Total surface area $= 9.96 + 11.58 + 17.16\ m^2$

$A = 38.69\ m^2$

Total Heat load $= 6.8\ kW + 17.08\ kW + 11.49\ kW$

$= 35.37\ kW$

Dryer Blower Calculation

P-103

$\dot{V} = 0.161 m^3/s = 5.686 ft^3/s$ $\quad$ - $\rho_{air} = 1.2 kg/m^3$

$\Delta P = 15 kPa = 2.18 lb/in$ (ulrich textbook)

$$H_p = \frac{0.262\ V(\Delta P)}{EFF}$$

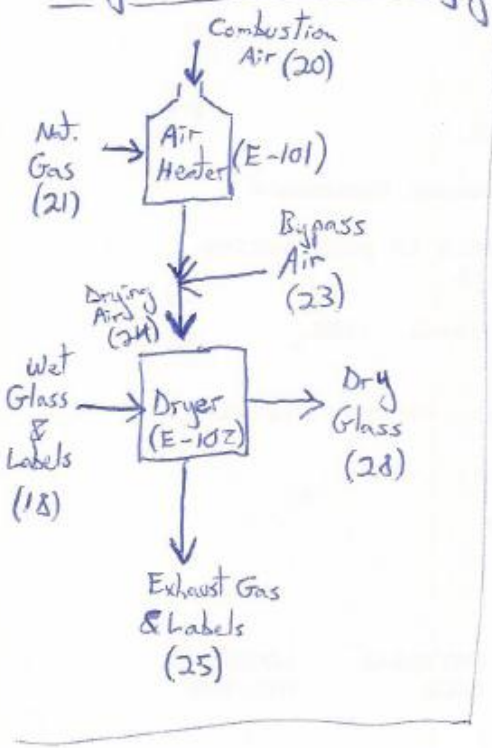
Efficiency, $\varepsilon = 75\%$ (ulrich textbook)

$$\therefore H_p = \frac{0.262\,(5.686\ ft^3/s)(2.18\ lb/in)}{0.75}$$

$H_p = 3.25\ HP$

Calculations Completed by:	Calculations Reviewed by:	Date: 04/01/2013
Scott Bell	Michael Barrett	

Dryer Mass & Energy Balance   Check by: Amin Mat Azahar.



First, determine the drying conditions.

Will use: 400°C air in
150°C exhaust at 1% RH
15°C air supply at 87% RH *
5% glass moisture in
0% glass moisture out.
100% CH_4 for natural gas.

Using psychrometric charts, this gives:

$H_{air\ supply} = 40$ kJ/kg dry air

$H_{drying\ air} = H_{exhaust} = 236$ kJ/kg dry air

With water content of:

Air Supply: 0.009 kg water/kg dry air
Drying air: 0.009 kg water/kg dry air
Exhaust gas: 0.085 kg water/kg dry air

① We can use this information to determine the flow of drying air required.

$$\text{Water in} = \text{Water removed} = 1042.8 \frac{kg\ glass}{hr} \times \frac{5\ kg\ water}{100\ kg\ glass} = 52.14 \frac{kg\ water}{hr}$$

$$S_{24} = \frac{52.14 \frac{kg\ water}{hr}}{\left(0.085 \frac{kg\ water}{kg\ dry\ air} - 0.009 \frac{kg\ water}{kg\ dry\ air}\right)} = 686 \frac{kg\ dry\ air}{hr}$$

(2) Determine heat required to warm drying air (15°C to 400°C) & heat glass (60°C to 90°C)

From psychrometric charts: $H_{air\ supply} = 40\ kJ/kg$ dry air

$H_{drying\ air} = 236\ kJ/kg$ dry air

$$Q_{air} = S_{24} \Delta H = 686 \frac{kg}{hr} \times \left(236 \frac{kJ}{kg} - 40 \frac{kJ}{kg}\right)$$

$$= 134\ 466 \frac{kJ}{hr} \times \frac{hr}{3600 s} = 37.35 kW$$

$Q_{glass} = S_{28}\ C_p\ \Delta T$ Approximate $C_{p_{20°C}} = C_{p_{60°C}} = C_{p_{90°C}}$

$\therefore C_p = 0.84 \frac{kJ}{kg \cdot K}$ (Engineering Toolbox)

$$Q_{glass} = 1037.586 \frac{kg}{hr} \times 0.84 \frac{kJ}{kg°C} \times (90°C - 60°C)$$

$$= 26\ 147 \frac{kJ}{hr} \times \frac{hr}{3600 s} = 7.26 kW$$

$$\therefore Q_{combustion} = 37.35 kW + 7.26 kW = 44.61 kW$$

(3)

Determine natural gas required to generate heat

$$\Delta H_{combustion} = 50000 \frac{kJ}{kg}$$

$$S_{21} = \frac{44.61 kW}{50\ 000\ kJ/kg} = \frac{160\ 613\ kJ/hr}{50\ 000\ kJ/kg} = 3.2\ kg/hr$$

See Furnace M&E Balance for sample combustion calculations

Assume that ~~dryer~~ air heater uses 5% excess oxygen.

$\therefore$ Combustion air requirements are:

O_2: 13.5 kg/hr

N_2: 44.4 kg/hr

$\} S_{21} = 57.9 \frac{kg}{hr}$

④ Close mass balance around air heater (E-101) (S_{24} incl.)

Note: Approximate that combustion products do not significantly affect properties of bypass air.
Since lower heating value was used for combustion, this should be acceptable.
Approximate that combustion products do not contribute to drying. $\therefore S_{23} = 686 \frac{kg}{hr}$ dry air.

$$S_{24} = S_{23} + S_{21} + S_{20} = 686 \frac{kg}{hr} + 3.2 \frac{kg}{hr} + 57.9 \frac{kg}{hr}$$

$$S_{24} = 747.1 \frac{kg}{hr}$$

$\therefore In = Out$ ✓

⑤ Close mass balance around dryer (E-102)

S_{18}/ Glass: $1037.6 \frac{kg}{hr}$
Water: 52.14 kg/hr
Labels: 5.214 kg/hr
$\therefore S_{18} = 1094.954 \frac{kg}{hr}$

S_{28}/ Glass: $1037.6 \frac{kg}{hr}$

S_{24}/ $747.1 \frac{kg}{hr} = S_{24}$

S_{25}/ ~~Air: 686~~
Drying Air + Combustion Products: $747.1 \frac{kg}{hr}$
Water: $52.14 \frac{kg}{hr}$
Labels: 5.214 kg/hr
$\therefore S_{25} = 804.454$ kg/hr

$$S_{18} + S_{24} = S_{25} + S_{28} \rightarrow 1094.954 + 747.1 = 1037.6 + 804.454$$ ✓

(6) Close energy balance on air heater & dryer
(E-101) (E-102)

Combustion energy: $160\,613 \frac{kJ}{hr}$

Exhaust Gas energy: $134\,466 \frac{kJ}{hr}$

Glass temperature increase: $26\,147 \frac{kJ}{hr}$

Generated = Exhaust Energy + Glass added energy

$160\,613 = 134\,466 + 26\,147$

✓

C-7: Crushing Process

Calculations Completed by:	Calculations Reviewed by:	Date: 03/07/2013
Michael Barrett	Carolyn McKenna	

Crushing design

Reference – Perry's Chemical Engineering Handbook Section 21-58

input – 0.05 m

output – 0.005m

$$E = 100 E_i \left(\frac{1}{\sqrt{X_p}} - \frac{1}{\sqrt{X_f}} \right)$$

X_f = particle size feed (μm)
X_p = particle size product (μm)

E_i = bond work index = 3.08 (perry's p21-48)

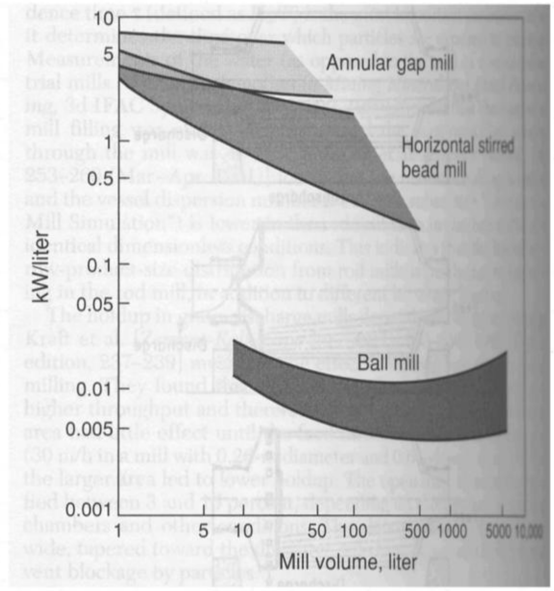
$$E = 100(3.08)\left(\frac{1}{\sqrt{0.005 \times 10^6}} - \frac{1}{\sqrt{0.05 \times 10^6}} \right)$$

= 2.978 kWh/t

Assume 5% efficiency

C-8: Blasting Media Production

Calculations Completed by:	Calculations Reviewed by:	Date: 04/01/2013
Michael Barrett	Carolyn McKenna	



Ball Mill or Tumbling Mill

20:1 → 200:1 reduction ratio

max input typically 1cm

largest balls ≈ 13cm

ball diameter

$$D_b = \sqrt{\frac{X_p E_i}{K n_r}} \sqrt{\frac{\rho_s}{\sqrt{D}}} \quad (cm)$$

D - mill diameter

E_i - work index of feed 3.08 (p 21-48 Perry's)

ρ_s - feed specific gravity 2.58 (p21-48 Perry's)

K - constant 143 for ball mill

n_r = speed (percent of critical)

N_c = critical speed

$N_c = 42.3/\sqrt{D}$

Actual N_c ranges from 65% → 80% of critical (p 21-64 Perry's)

Ball Mill Continued.

input - 0.005m

output - 0.001m

$$E = 100\,E_i \left(\frac{1}{\sqrt{x_p}} - \frac{1}{\sqrt{x_f}} \right)$$

$$= 100(3.08) \left(\frac{1}{\sqrt{0.001 \times 10^6}} - \frac{1}{\sqrt{0.005 \times 10^6}} \right)$$

$$= 5.38 \text{ Kwh/t}$$

Assume 7% efficiency and 1016 Kg/hr (wet ball mill is 10% so less)

Power = 84Kw

Size - 1m diameter
- 1m length
volume = 785 litres

From fig 21-76.

(785 litres)(0.0075 Kw / l) = 5.89 Kw ≈ 5.38.

Ball diameter

0.9489

(0.79)(1.606

$$D_b = \sqrt{\frac{(0.001)^{\frac{1}{2}}(308)}{143\,(33.84)}}\ \sqrt{\frac{2.58}{\sqrt{1}}} = 1.268 \text{ cm}$$

$N_c = 42.3/\sqrt{1} = 42.3$ rpm

$0.8(42.3) = 33.84$

Ball diameter = 1.3 cm

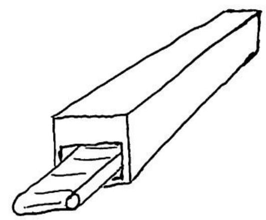
Speed = 35 rpm

C-9: Tile Production

Calculations Completed by:	Calculations Reviewed by:	Date: 01/23/2013
Scott Bell	Amin Azahar	

Furnace Sizing Calculations

Check by: Amin Mat Azahar
Performed by: Scott Bell



Requirements:
- 250 kg/hr output
- 900°C internal temp.
- High thermal efficiency
- Residence time: 30 mins @ 900°C
- Cools glass tile before exit, avoid cracking of tile when it contacts 20°C air (expected 200°C temp. out)

Sizing:

$$Area_{Furnace} = \frac{\dot{m} \times t_{res}}{l \times \rho \times \varepsilon}$$

where: $\dot{m}$ = mass produced $\left(\frac{kg}{hr}\right)$
t_{res} = residence time (hr)
l = tile thickness (m)
ρ = tile density (kg/m³)
ε = packing efficiency

Packing Efficiency – Assume 4"x4" tile, 5"x5" mold and 0.5" spacing between molds.

$$\therefore \varepsilon = \frac{4^2}{(5+0.5)^2} \times 100\% = 53\%$$

Residence Time – Approximate that preheating & cooling time = sintering time. This gives total residence time of 1 hour.

We know that previous approximations are: $l = 0.01m$, $\rho = 2500\ kg/m^3$

$$\therefore A_{Furnace} = \frac{250 \times 1}{0.01 \times 2500 \times 0.53} = 18.9\ m^2 \cong 20m^2$$

Parameters of belt speed & furnace width & heating/cooling sections are not covered, but are left to more qualified equipment manufacturers & suppliers.

Tile Cooling Time

Done by: Scott Bell
Check by: Amin Mat Azahar.

If tiles are cooled on a conveyor belt, with one ~~sid~~ face exposed to a cross-flow of blown ambient air:

Approximate using Lumped-Capacitance cooling model.

$$t = \frac{\rho V c}{h A_s} \ln\left(\frac{\theta_i}{\theta_o}\right)$$

where:
t = cooling time (s)
ρ = density (2500 kg/m³ for glass)
V = volume of glass (m³)
c = heat capacity (Approximate 1000 J/kg·K)
h = heat transfer coefficient (W/m²·K)
A_s = surface area (m²)
$\theta_i = T_i - T_\infty$
$\theta_o = T_o - T_\infty$
T_∞ = Temperature of bulk fluid (°C)
T_i = Temp. of glass tile at $t=0$ (°C)
T_o = Temp. of glass at $t=t$ (°C)
Z = Tile thickness (m)

Simplify formula by cancelling A_s with area from volume in numerator:

$$t = \frac{\rho Z c}{h} \ln\left(\frac{\theta_i}{\theta_o}\right)$$

A graph of h versus surface air velocity was found at http://people.csail.mit.edu/jaffer/SimRoof/Convection/ for glass plates. As an example, at air velocity of 2 m/s, $h = 14$ W/m·K

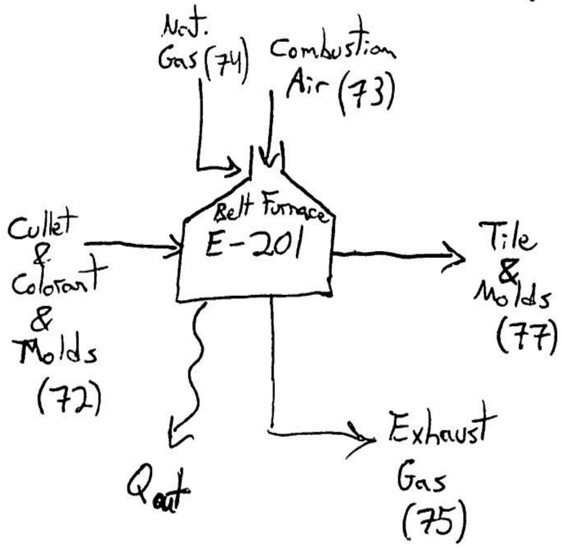
For sample calculation; $h = 14$ W/m·K $T_\infty = 20°C$ $T_i = 200°C$ $T_o = 35°C$

$$t = \frac{2500\frac{kg}{m^3} \times 0.01m \times 1000\frac{J}{kg \cdot K}}{14\frac{W}{m \cdot K}} \times \ln\left(\frac{200-20}{35-20}\right)$$

$$t = 4437s \times \frac{min}{60s} \cong 74 \text{ minutes.}$$

Furnace Mass & Energy Balance

Check by: Amir Mat Azahar.
Done by: Scott Bell



① Determine heat requirements

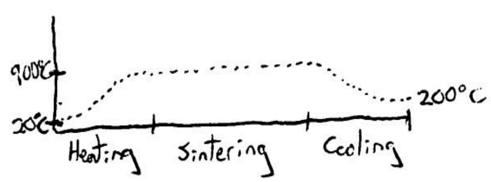
S_{72} is at 20°C

S_{77} is at 200°C

Need to find C_p of S_{72} and S_{77}.

Note: S is used to denote streams, where stream number is indicated by subscript. Ex. S_{72} is cullet, colorant, and molds entering the furnace

Furnace has temperature profile as follows:



Approximate 1.89 kg mold/kg cullet.

Approximate 1000 ppm (0.001 kg/kg cullet) Colorant.

∴ Have: Glass = 242.79 kg/h

Molds = 242.79 × 1.89
= 465.44 kg/h

Colorant = 242.79 × 0.001
= 0.25 kg/h

S_{72} = 242.79 + 465.44 + 0.25
= 711.94 kg/h

Approximate C_p for colorant as C_p of glass.

C_p of glass at 20°C = 0.84 kJ/kg·K (Engineering Toolbox)

C_p of glass at 200°C = 0.953 kJ/kg·K (SciGlass Database For 100% SiO_2)

Approximate C_p of refractory molds as C_p of concrete, and as constant from 20°C to 200°C.

C_p of molds at 20°C = C_p of molds at 200°C = 0.96 kJ/kg·K (Engineering Toolbox)

Now we can determine the heat required.

$$Q_{ideal} = m\,C_p \Delta T = S_{72}\, C_{p_{72}} \Delta T$$

$$= m_{Glass} C_{p_{Glass}} \Delta T + m_{Molds} C_{p_{molds}} \Delta T$$

$$= 243.04 \frac{kg}{h} \times \left(\frac{0.84 + 0.953}{2}\right) \frac{kJ}{kg \cdot k} \times (200 - 20)\,k$$

$$+ 465.44 \frac{kg}{h} \times 0.96 \frac{kJ}{kg \cdot k} \times (200 - 20)\,k$$

$$Q_{ideal} = \underbrace{39\,779 \frac{kJ}{hr}}_{Q_{glass\ ideal}} + \underbrace{80\,427 \frac{kJ}{hr}}_{Q_{molds\ ideal}} \times \frac{hr}{3600\,s}$$

$$= 11.0\,kW + 22.3\,kW$$

$$Q_{ideal} = 33.3\,kW$$

Now determine the heat required to melt the glass.

Approximate $Q_{sintering} = Q_{melting}$. From "Modeling Glass Furnace Operation for Energy Efficiency" (1979) Furnace used 8.4% of energy to heat glass and 2.7% of energy to melt glass.

$$\therefore Q_{sintering} = Q_{glass\ ideal} \times \frac{2.7\%}{8.4\%} = 3.6\,kW$$

And, according to "Glass: A Clear Vision for a Bright Future", modern glass furnace efficiency is 50%.

$$\boxed{\therefore Q_{real} = (33.3\,kW + 3.6\,kW)/50\% = 73.88\,kW}$$

This tells us also that $Q_{Lost} = 73.88 kW - 33.3 kW - 3.6 kW$
$= 36.94 kW$

② Determine Natural Gas requirement (74 or S_{74})

$Q_{real} = 73.88 kW$

Approximate natural gas as 100% CH_4, which has a Lower Heating Value of 50 000 kJ/kg (Engineering Toolbox)

$$S_{74} = \frac{Q_{real}}{\Delta H} = \frac{73.88 \text{ kW}}{50\,000 \text{ kJ/kg}} = 5.3 \text{ kg/h}$$

③ Determine Combustion Air requirement (73 or S_{73})

Approximate that combustion uses 5% excess oxygen.
Combustion reaction is as follows:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

MW: 16 32 18 44

Convert S_{74} to moles: $S_{74} = 5.3 \frac{kg}{h} \times \frac{kmol}{16 kg} = 0.33 \frac{kmol}{hr}$

Air has 79% N_2 and 21% O_2 approximately.

Oxygen required $= 0.33 \frac{kmol}{hr} \times \frac{2 kmol\ O_2}{kmol\ CH_4} \times 1.05 = 0.70 \frac{kmol}{hr}$

Nitrogen added $= 0.70 \frac{kmol}{hr} \times \frac{0.79}{0.21} = 2.63 \frac{kmol}{hr}$

Convert to kg: $S_{73} = 0.70 \frac{kmol\ O_2}{hr} \times \frac{32 kg\ O_2}{kmol\ O_2} + 2.63 \frac{kmol\ N_2}{hr} \times \frac{28 kg\ N_2}{kmol\ N_2}$

$$\boxed{S_{73} = 95.9 \frac{kg}{hr}}$$

④ Determine exhaust gas (75 or S_{75})

Oxygen: Will contain the remainder...

$$\text{Oxygen out} = \left[\left(0.70\frac{kmol}{hr} \times 1.05\right) - 0.70\frac{kmol}{hr}\right] \times \frac{32\,kg}{kmol} = 1.06\frac{kg}{hr}$$

Nitrogen: In = Out ∴ $\text{Nitrogen Out} = 2.63\frac{kmol\,N_2}{hr} \times 28\frac{kg}{kmol} = 74\frac{kg}{hr}$

Water: $\text{Water out} = 0.33\frac{kmol\,CH_4}{hr} \times \frac{2\,kmol\,H_2O}{kmol\,CH_4} \times \frac{18\,kg\,H_2O}{kmol\,H_2O} = 12.0\frac{kg}{hr}$

Carbon Dioxide: $CO_2\text{ out} = 0.33\frac{kmol\,CH_4}{hr} \times \frac{1\,kmol\,CO_2}{kmol\,CH_4} \times \frac{44\,kg\,CO_2}{kmol\,CO_2} = 14.6\frac{kg}{hr}$

$$\therefore S_{75} = 1.06\frac{kg}{hr} + 74\frac{kg}{hr} + 12.0\frac{kg}{hr} + 14.6\frac{kg}{hr} = 101.21\frac{kg}{hr}$$

⑤ Close mass balance

$S_{72} = S_{77} = 711.94\frac{kg}{hr}$ ✓

Gases: $S_{74} = 5.3\frac{kg}{hr}$, $S_{73} = 95.9\frac{kg}{hr}$ } $101.2\frac{kg}{hr}$

$S_{75} = 101.2\frac{kg}{hr}$

∴ $S_{74} + S_{73} = S_{75}$ ✓

⑥ Find $Q_{exhaust}$.

Approximate gas exit temperature as 200°C, and inlet temp as 20°C.
Approximate that, for all gases, $C_{p_{200°C}} = C_{p_{20°C}}$.

From Engineering Toolbox: At 20°C

$C_{p_{O_2}} = 0.919\ kJ/kg \cdot K$ $\quad C_{p_{N_2}} = 1.04\ kJ/kg \cdot K$ $\quad C_{p_{CO_2}} = 0.844\ kJ/kg \cdot K$

$C_{p_{H_2O}} = 1.97\ kJ/kg \cdot K$

$$Q_{exhaust} = \left[\left(1.06\frac{kg}{hr} \times 0.919\frac{kJ}{kg \cdot K}\right) + \left(74\frac{kg}{hr} \times 1.04\frac{kJ}{kg \cdot K}\right) + \left(12\frac{kg}{hr} \times 1.97\frac{kJ}{kg \cdot K}\right) + \left(14.6\frac{kg}{hr} \times 0.844\frac{kJ}{kg \cdot K}\right)\right] \times (200-20)K$$

$$= 20\ 501\ \frac{kJ}{hr} \times \frac{hr}{3600\,s} = 5.695 \cong 5.7\ kW$$

$Q_{exhaust} = 5.7\ kW$

⑦ Close Heat Balance

$$Q_{out} = 73.88 - 33.3 - 3.6 - 5.7$$
$$= 31.28\ kW$$

Heat in (combustion) = 73.88 kW

Heat consumed (sintering) = 3.6 kW

Heat out: tiles = 11.0 kW

molds = 22.3 kW

convection/conduction/radiation = 31.28 kW

5.7 kW

→ 73.88 kW

Heat in = Heat out + con ✓

Appendix D – Mass and Energy Balance Spreadsheets

Calculations Completed by:	Calculations Reviewed by:	Date: 04/04/2013
Scott Bell	Michael Barrett, Carolyn McKenna, Amin Azahar	

Heater - Washer						
Mass				**Energy**		
Water in	2085.6	kg/hr		Water Temp to heater	15	°C
				Water Temp from heater	60	°C
				Water Cp	4.2	kJ/kg°C
				Heat added	394178.4	kJ/hr
				Heat added	114.1803	kW

Washer						
Mass				**Energy**		
Water in	2085.6	kg/hr		Glass Temp in	20	°C
Glass in	1042.8	kg/hr		Glass Temp out**	60	°C
Soap in	3.96	kg/hr		Glass Cp	0.84	kJ/kg°C
Glass out	1037.586	kg/hr				
Moisture of glass	52.14	kg/hr		Water Temp in	60	°C
Labels out with glass	5.16186	kg/hr		Water Temp out**	60	°C
Liquid out	2037.42	kg/hr				
Labels out with liquids	0.05214	kg/hr				
Waste calculations						
Bottle mass	200	g/bottle				
Label mass	1	g/bottle				
Approximations						
*Water usage	2	t water/t glass				
Soap Usage	0.19%	% Soap				
***Moisture content	5%	mass in glass out stream				
Label removal	1%					

Notes:

*Water requirements are calculated based on estimates from efficient household dishwasher requirements.

*Estimates of load size are below:

Item	No.	Mass (kg)
Plates	16	0.25
Cutlery	20	0.025
Cups	20	0.15
Total		7.5
Water usage (L)		15
*Water usage (kg water/kg dishes)		2

**Note that washer is assumed to be countercurrent, allowing the glass exiting to be 50 degrees while the water exiting is only 47 degrees.

***Glass particles can, according to the UK recycling handbook, retain up to 15% moisture by weight. We are washing mostly large particles, so the moisture content should be much lower.

Links

Label removal:

http://www.popularmechanics.com/home/skills/how-to-remove-a-bottle-label

Water usage of dishwasher:

http://www.bchydro.com/guides_tips/green-your-home/appliances_guide/washing_dishes.html

Water content of exiting glass:

UK Recycling Glass Handbook (see references)

Dryer - Preheater						
Mass				**Energy**		
Air in	686.0526	kg dry air /hr		Air Temp to heater	15	°C
Air in	571.7105	m3/hr		**%RH	87%	
Vapor in	6.174474	kg/hr		Mass water	0.009	kg water/kg dry air
				Cp	40	kJ/kg Dry Air
Natural Gas required	3.2	kg/hr				
Natural Gas in	3.2	kg/hr		Air Temp from heater	400	°C
Natural Gas in	0.20	kmol/hr		%RH	0.006%	
				Mass water	0.009	kg water/kg dry air
Oxygen required	0.40	kmol/hr		Cp	236	kJ/kg Dry Air
Oxygen in	0.42	kmol/hr				
N2 in	1.59	kmol/hr		Heat added	160613.5	kJ/hr
Combustion air in	2.01	kmol/hr		Heat added	44.61486	kW
Oxygen in	13	kg/hr				
N2 in	44	kg/hr		Natural Gas - LHV	50000	kJ/kg
Combustion air in	58	kg/hr				
N2 Out	44	kg/hr				
O2 Out	1	kg/hr				
H2O Out	7	kg/hr				
CO2 Out	9	kg/hr				
CH4 Out	0	kg/hr				

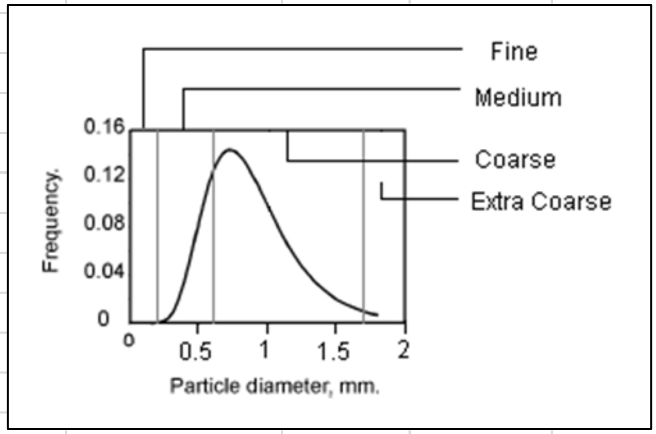
Dryer						
Mass				**Energy**		
Glass in	1037.586	kg/hr		Glass Temp in	60	°C
Water in	52.14	kg/hr		Glass Temp out	90	°C
Moisture in	5%			Glass Cp	0.84	kJ/kg°C
				Heat added to glass	26147.17	kJ/hr
Glass out	1037.586	kg/hr		Heat added to glass	7.263102	kW
Water out	0	kg/hr				
Moisture out	0%			Temp of air in	400	°C
				Temp of air out*	150	°C
Air in	0.009	kg water/kg dry air		%RH out	1%	
Air in	686.0526	kg dry air/hr				
Air out	0.085	kg water/kg dry air				
Approximations				**Links**		
Stoichiometric Excess Oxygen	5%			**Enthalpy of air at 400 deg. C:**		
Oxygen in combustion air	21%	by mole		http://www.uigi.com/WebPsycH.html		
Natural Gas CH4 Content	100%	by mass		**Label burning for aluminum cans:**		
Dry air density	1.2	kg/m3		http://www.wisegeek.com/how-		
				are-aluminum-cans-recycled.htm		

Notes:									
*see psychrometric chart for visual representation of air properties during preheating and drying									
**It is assumed that supply air is 15 degrees C, taken from outside on a dreary fall/spring day with 87% relative humidityhumidity.									
In this calculation, a preheater is used to raise the air temperature from 15 to 400 degrees C.									
It is approximated that the dryer removes all water from the glass, and that the drying air reaches 1% relative humidity.									
Blower sizing shows that these approximations are reasonable.									
Blower sizing...		0.158808	m3/s						
		9.528509	m3/min						
		336.24	cfm						

Crusher - Hammer Mill						
Mass				**Energy**		
Glass in	1037.586	kg/hr		Wi	3.08	*Bond Work Index
D_in	0.05	m		Theoretical Work	2.9783599	kWh/t
D_out	0.005	m				
Waste out	10.37586	kg/hr		Energy	61.806091	kW
Dust out	10.37586	kg/hr		Energy	222501.93	kJ/hr
Glass out	1016.83428	kg/hr				
Reduction Ratio						
10.0						
Waste calculations						
Bottle mass	200	g/bottle				
Cap mass	2	g/bottle				
Approximations						
Crusher Efficiency	5%					
Source: Perry's (Hammer mills usually less than 5% energy used in crushing material)						

Crusher - Ball Mill						
Mass				**Energy**		
Glass in	1016.83428	kg/hr		Wi	3.08	*Bond Work Index
D_in	0.005	m		Theoretical Work	5.3840374	kWh/t
D_out	0.001	m				
Dust out	10.1683428	kg/hr		Energy	78.209626	kW
Glass out	1006.66594	kg/hr		Energy	281554.65	kJ/hr
Reduction Ratio						
5						
Approximations						
Crusher Efficiency	7%					
Source: Perry's (Wet ball mill is 10% efficient, approximate 7% for dry ball mill)						

Sifters						
Mass				**Energy**		
Glass in	1006.6659	kg/hr		Power Required	5	kW
Maximum Diameter (D) in	0.0024	m				
Extra Coarse Glass out	19.931986	kg/hr				
Extra Coarse max D	2.4	mm				
Tyler Screen Size	8					
Coarse Glass out	707.58549	kg/hr				
Coarse max D	1.7	mm				
Tyler Screen Size	12					
Med Glass out	229.21783	kg/hr				
Med max D	0.6	mm				
Tyler Screen Size	30					
Fine Glass out	39.863971	kg/hr				
Fine max D	0.21	mm				
Tyler Screen Size	-70					
Dust out	10.066659	kg/hr				
Assumptions						
Extra Coarse Fraction	2%					
Coarse Fraction	71%					
Med Fraction	23%					
Fine Fraction	4%					
Links						
Particle Size Distributions:	http://www.particles.org.uk/particle_technology_book/chapter_2.pdf					
Trommel Screen Info:	http://www.brentwood.com.au/trommels-101					
Power requirements:	Materials Handling Handbook					
Dust	1%	10.06666	kg/hr			
Glass Out		996.5993				
Average Glass Diameter Out		1.387386				



Furnace						
Mass				**Energy**		
Glass in	246.26	kg/hr		Glass temp to furnace	20	°C
Colorant added	0.25	kg/hr		Glass temp out	200	°C
Refractory molds in	465	kg/hr		Glass Cp (20 °C)	0.84	kJ/kg°C
Refractory molds out	465	kg/hr		Glass Cp (200 °C)**	0.953	kJ/kg°C
Tiles out	246.51	kg/hr		Heat to warm glass	39779.119	kJ/hr
Tiles out	9.86	m2/hr		Heat to warm glass	11.0	kW
Tiles out	1.8	ft2/min		Heat to sinter glass	3.6	kW
Natural Gas required	5.3	kg/hr		Mold temp to furnace	20	°C
Natural Gas in	5.3	kg/hr		Mold temp out	200	°C
Natural Gas in	0.33	kmol/hr		***Mould Cp (20 °C)	0.96	kJ/kg°C
Oxygen required	0.66	kmol/hr		Heat to warm molds	80427	kJ/hr
Oxygen in	0.70	kmol/hr		Heat to warm molds	22.3	kW
N2 in	2.63	kmol/hr				
Combustion air in	3.32	kmol/hr		Heat Required	73.88	kW
Oxygen in	22.3	kg/hr		Natural Gas - LHV	50000	kJ/kg
N2 in	73.5	kg/hr				
Combustion air in	95.9	kg/hr		LHV reference temp	25	°C
				Gas Temp out	200	°C
N2 Out	74	kg/hr		****Gas Cp	1.238721156	kJ/kg°C
O2 Out	1.06	kg/hr		Heat loss from gas	21939.35344	kJ/hr
H2O Out	12.0	kg/hr		Heat loss from gas	6.1	kW
CO2 Out	14.6	kg/hr				
CH4 Out	0	kg/hr				
Total out	101	kg/hr				
Approximations						
Colorant required	1000	ppm				
Colorant	0.001	kg/kg glass				
Tile Thickness	0.01	m				
Tile Density	2500	kg/m3				
Refractory molds	1.89	kg/kg glass				
Furnace Efficiency*	11%					
Heat glass to melting point*	8%	BTU/imperial ton				
Melt (sinter) glass*	3%	MWh/metric ton				
Modern Furnace Efficiency*****	50%					
Stoichiometric Excess Oxygen	5%					
Oxygen in combustion air	21%	by mole				
Natural Gas CH4 Content	100%	by mass				
Dry air density	1.2	kg/m3				

Notes:

It is assumed that atmospheric air will be used - change the oxygen in combustion air if this is not the case.

*Furnace efficiency was found for a glass melting process - this may be higher for a modern sintering furnace.

*Note that the 11% of heat used for the sintering furnace includes that required to heat refractory molds.

*Also gives:	Blower sizing…	0.0222	m3/s
		1.33	m3/min
		47.0	cfm

**SciGlass for 100% SiO2:

**Interpolated for glass Cp at 900 deg. C, and assumed linear Cp increase.

Temp	Cp
20	749
200	953
400	1104
600	1214
800	1302
1000	1375

***Approximate that molds are made of light concrete, and approximate that the Cp value remains the same upwards of 20 degrees.

****Approximate gas Cp values as those at 20 deg C, approximate them as constant

Links

Sintering, Sticking, etc with Recycled Glass

http://www.cwc.org/glass/gl002rpt.pdf

Modern Furnace Efficiency

***** US DOE report - Glass: A Clear Vision for a Bright Future

Heat to Sinter Glass

Modeling Glass Furnace Operation for Energy Efficiency (1979)

Heat Capacities of Glass, Concrete, and Gases

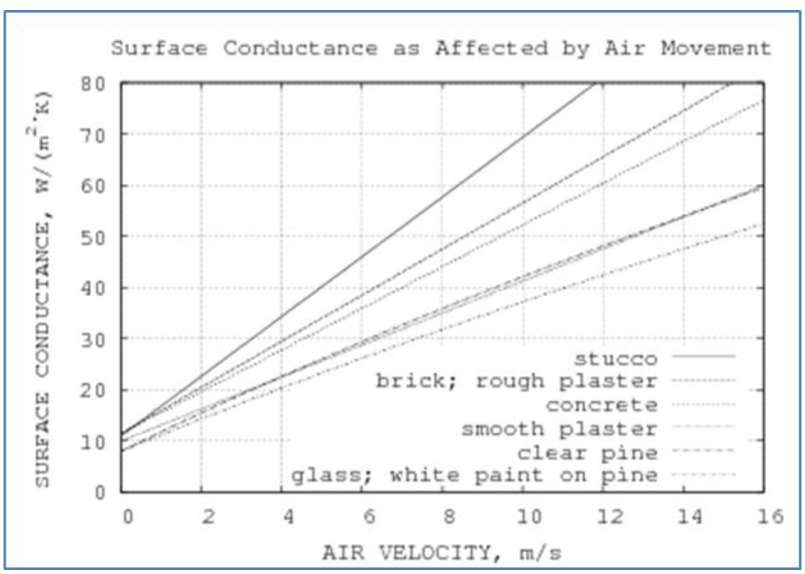
**Source - SciGlass Database (Numbers for 100% SiO2)

***http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html

****http://www.engineeringtoolbox.com/spesific-heat-capacity-gases-d_159.html

Cooling						
Mass				**Energy**		
Tiles in	242.6	kg/hr		Tile temp in	300	°C
Refractory molds in	485	kg/hr		Tile temp out	20	°C
Tiles out	242.6	kg/hr		Tile Cp (20 °C)	0.84	kJ/kg°C
Refractory molds out	485	kg/hr		Tile Cp (300 °C)	1.0285	kJ/kg°C
Cooling air in	2	kg/s		Heat released from tiles	63449	kJ/hr
**Cooling air in	6397	kg/hr		Heat released from tiles	17.6	kW
**Cooling air out	6397	kg/hr				
				Mold temp in	300	°C
				Mold temp out	20	°C
				*Tile Cp (20 °C)	0.96	kJ/kg°C
				Heat released from molds	130395	kJ/hr
				Heat released from molds	36.2	kW
				Air temp in	20	°C
				Air temp out	50	°C
				Air Cp	1.01	kJ/kg°C
				Cooling required	53.8	kW

Cooling Belt (C-202)						
Mass				**Energy**		
Tiles in	246.51	kg/hr		Tile temp in	200	°C
Tiles in	9.86	kg/hr		Tile temp out	35	°C
				Glass Cp (20 °C)	0.84	kJ/kg°C
Mass of air heated	7263.783	kg/hr		Glass Cp (200 °C)	0.953	kJ/kg°C
Mass of air heated	2.017718	kg/s				
Minimum air flow	1.681431	m3/s		Heat to be removed	10.12894	kW
Minimum air flow	3560.016	cfm				
				Air temp in	20	°C
Approximations				Air temp out	25	°C
Tile Density	2500	Kg/m3		Air Cp (20 °C)	1.004	kJ/kg°C
Tile Thickness	0.01	M				
Density of air	1.2	kg/m3				
Cooling Time						
Cooling of glass plates by forced convection. Air surface velocity vs. heat transfer coefficient:						
Velocity of air	H	time				
M/s	W/m2*K	s				
2	14	2836.524				
4	20	1985.567				
6	26	1527.359				
8	32	1240.979				
10	37	1073.279				
Source for h vs velocity for glass plates:						
http://people.csail.mit.edu/jaffer/SimRoof/Convection/						



Is a Stack Needed?						
<u>Sum of gas flows</u>						
Dryer	753	kg/hr				
Temperature	150	°C				
Density*	0.85	kg/m3				
Volumetric Flow**	886.283	m3/hr				
	14.77138	m3/min				
	521.2459	cfm				
*Source: http://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html - Approximate as 100% air. This calculation is a verification						
**521 cfm requires only a vent cap, not a dedicated stack. To compare, the exhaust of a car on the highway is in the range of 300 to 800 cfm, and at a higher						

Appendix E – Economic Analysis Sample Calculations

E-1: Equipment Cost Calculation

Calculations Completed by:	Calculations Reviewed by:	Date: 02/09/2013
Carolyn McKenna	Michael Barrett	

→ CONVEYORS (flat)

Reference: Chemical Engineering Design (RK Sinnott) (4th ed) p. 259

$$\text{Price (2004)} = (\$1900)(m)^{0.75}$$
$$= (\$1900)(3m)^{0.75} = \$4331.06$$

$$\text{Price (2013)} = \text{Price (2004)} \times \frac{CI\ (2013)}{CI\ (2004)}$$
$$= (\$4331.06) \times \frac{112.9}{101.2}$$

Conveyer Cost = $4831.79

* CI reference for equipment as per Bank of Canada

→ COLLECTION BINS

Reference: Chemical Engineering Design (4th ed) RK Sinnott (p. 259)

$$\text{Price (2004)} = (\$2000)(m^3)^{0.55}$$
$$= (\$2000)(6m^3)^{0.55} = \$5358.13$$

$$\text{Price (2013)} = \text{Price (2004)} \times \frac{CI\ (2013)}{CI\ (2004)}$$
$$= \$5358.13 \times \frac{112.9}{101.2}$$

Collection Bin Cost = $5977.60

→ CRUSHER/BALL MILL

Reference: Chemical Engineering Design (4th ed) RK Sinnott (p. 259)

$$\text{Price (2004)} = (\$3400)(kg/h)^{0.35}$$
$$= (\$3400)(1037.6)^{0.35} = \$38\,644.65$$

$$\text{Price (2013)} = \text{Price (2004)} \times \frac{CI\ (2013)}{CI\ (2004)}$$
$$= \$38\,644.65 \times \frac{112.9}{101.2}$$

Crusher Cost = $43 112.46

Calculations Completed by:	Calculations Reviewed by:	Date: 02/09/2013
Carolyn McKenna	Scott Bell	

→ CONVEYOR (RAMP)

Reference: RS Means – Facilities Construction Cost Data 2013 – 28th Edition (41-21-23)

* Ramp Conveyor with
- 10 ft rise (3m)
- 27.5ft length (8.4m)
- 18 in belt (0.5m)

costs $8500

We need
- 3m rise
- 6m ramp length
- 0.5m belt

} see conveyor calculations

So this cost is accurate.

Ramp conveyor cost = $8500

→ BREAKER TOWER

Reference: Chemical Engineering Design (4th Ed) RK Sinnott (p. 259)

* breaker tower is very similar to storage bin, plus the addition of welding on the breaker bars.

Storage bin portion...

$$\text{Price (2004)} = (\$2000)(m^3)^{0.55}$$
$$= (\$2000)(3\,m^3)^{0.55} = \$3659.71$$

$$\text{Price (2013)} = \text{Price (2004)} \times \frac{CI(2013)}{CI(2004)}$$
$$= \$3659.71 \times \frac{112.9}{101.2}$$
$$= \$4082.82$$

↳ add equipment erection factor $f_i = 0.5$ for adding the metal bars (welding)

$$\$4082.82 + \$4082.82(0.5)$$

Breaker Tower Cost = $6124.23

Calculations Completed by:	Calculations Reviewed by:	Date: 02/09/2013
Amin Azahar	Carolyn McKenna	

Assuming washing machine as a process vessel.

from figure 5.44 (Ulrich): pg. 387

for L = 1.7m and D = 0.57m

C_p @ 2004 = 10700 \$

Assuming vessel made from carbon steel.

$\therefore C_{BM} = C_p \times 3 = 10700 \times 3 = 32100$ \$

→ Have to consider heating coil since washing machine operate @ 60°C temp.

coil surface area $= 2\pi D = 2\pi(0.57)$

$= 3.58 m^2$

from figure 5.23 (b) pg. 376.

C_p @ 2004 = 11300 \$

$C_{BM} = C_p$ → assuming coil made from carbon steel.

Total cost of washing machine @ 2004

$C_{BM_{vessel}} + C_{BM_{coil}} = 32100\$ + 11300\$$

$C_{BM} = 33400\$$

Total cost of washing machine @ 2012

$C_{2012} = C_{2004}\left(\frac{CI_{2012}}{CI_{2004}}\right)$

$= 33400\left(\frac{112.9}{101.2}\right) = 37027.13\$$

Calculations Completed by:	Calculations Reviewed by:	Date: 02/09/2103
Carolyn McKenna	Michael Barrett	

→ ROTARY DRYER

Reference: Chemical Engineering Design (4th ed) RK Sinnott (p. 259)

$$Price\ (2004) = (\$35,000)(m^2)^{0.45}$$
$$= (\$35,000)(38.7m^2)^{0.45}$$
$$= \$181\ 358.53$$

$$Price\ (2013) = Price\ (2004) \times \frac{CI\ (2013)}{CI\ (2004)}$$
$$= \$181,358.53 \times \frac{112.9}{101.2}$$

Cost of Drier = $202, 325.87 → includes natural gas combustion and blower

→ CENTRIFUGAL PUMP

Reference: RS Means – Plumbing Cost Data (36th Ed) 2013 – 22-11-23.10 (p. 247)

$$0.16\frac{m^3}{s} \times \frac{264.2gal}{1m^3} \times \frac{60s}{1min} = 2536.32\ gal/min$$

For Domestic Water, General Utility Pumps
↳ Centrifugal
↳ 3000gal/min, 100hp

Cost of pump = $14,600

→ COLOURANT MIXER

Reference: Chemical Engineering Process Design and Economics, Ulrich (2004)

Power (kW) (required for mixing) $= 2.0(m^3)^{0.8} = 2.0(1m^3)^{0.8} = 2kW$

Figure 5.42 → a 2kW mixer will cost $5000.00 (2004)

* This includes motor, speed reducer and impeller ready for installation in a vessel

cont →

Colourant Mixer cont.

vessel cost (Sinnott) → $(\$2300)(m^3)^{0.55}$

$$\text{Cost (2004)} = (\$2300)(1\,m^3)^{0.55} = \$2300$$

$$\text{Total cost (2004)} = (\$5000.^{00}) + (\$2300) = \$7300$$

$$\text{Cost (2013)} = \text{Cost(2004)} \times \frac{CI(2013)}{CI(2004)}$$

$$= \$7300 \times \frac{112.9}{101.2}$$

Cost of colourant mixer = $8143.97

↳ computer controlled mold filler to distribute coloured mixture into the mold will be incorporated to this mixing / storage equipment.

↳ based off of the price of control systems, a factor of 2.0 will be applied to the colourant mixer cost to account for this equipment

Colourant mixer & mold filler = $16,287.94

→ TROMMEL SCREEN

Reference: Chemical Engineering Process Design and Economics, Ulrich (2004)

$$P(kW) = 5\times10^{-6}\,\rho_s^{2} A / D_p^{0.3} \rightarrow$$

$\rho \cong 1290\,kg/m^3$ (crushed glass)

$A = 1\,m^2$

$D_1 = 0.0002\,m = 200\,\mu m$

$D_2 = 600\,\mu m$

$D_3 = 1700\,\mu m$

$D_4 = 2400\,\mu m$

$$P_1(kW) = \frac{(5\times10^{-6})(1290\,kg/m^3)^2(1\,m^2)}{(200\,\mu m)^{0.3}} = 1.7\,kW$$

Same calculation...

$P_2 = 1.2\,kW$

$P_3 = 0.9\,kW$

$P_4 = 0.8\,kW$

Trommel screen cont.

$P_{total} = 1.7 + 1.2 + 0.9 + 0.8^{kW} = 4.6kW$

↳ From Fig 5.59

Cost (2004) = $1600.00

Cost (2013) = $1600.00 $\left(\frac{112.9}{101.2}\right)$

Cost of trommel screen = $1784.98

→ BAGGING MACHINE

1 chute gravity fed sand bag filler

↳ $5,500.00 (Reference: 1st Army Supply Sandbag filling machines)
↳ www.1starmy.com

* A factor of 3.0 is applied to incorporate the cost of a scale and bag sealer into this model.

Cost of the baggine machine : $16,500.00

→ BELT FURNACE

Reference: beltfurnace.com/prices (model HSK-6305-0711)

Installed + delivered cost = $400,000.00 → confirmed as reasonable on alibaba

Installation Factor for furnace
↳ 1.45

cost (before installation + delivery → for comparison)

Cost of Furnace = $ 275 862.07

→ COOLING FAN

Reference: McMaster-Carr (Model 2214K51)

↳ 36" industrial jet stream fan.

↳ Mass + Energy balance shows that 1 fan exceeds the minimum air flow necessary

| Cost of Cooling Fan = \$800.00 |

→ MANIPULATOR ARM

Reference: Trend Robotics (model → arm52800 controller4100)

| cost of manipulating arm = \$62,000.00 |

---

* Factorial Method used to find installed cost.

↳ installation factors found using the following references

① Chemical Engineering Design (RK Sinnott) 4th ed

② Rules of Thumb in Engineering Practice (Donald R. Woods)

$$\text{Installed cost} = C_P * f_i$$

where $C_P \equiv$ purchased equipment cost (calc. shown above)
$f_i \equiv$ installation factor.

*When an installation factor could not be found for a specific piece of equipment the Lang Factor was used for a solids processing plant

↳ $f_L = 3.1$ (Sinnott)

E-2: Fixed Capital Cost Calculation

Calculations Completed by:	Calculations Reviewed by:	Date: 02/01/2013
Scott Bell	Michael Barrett	

Fixed Capital Cost Calculation

- Have installed equipment cost.
- Assume that Fredericton Region Solid Waste Commission's Property [FRSWC] would be used (existing site).
- Use Factorial method, excluding costs already considered.
- Since facility has one wet process (washer), cost it as a dry handling (solids) facility.

Factor	Weight	Included?	Reason
Equipment Erection	0.50	No	Installation factors used for individual equipment already.
Piping	0.20	No	Conveyors would be the bulk of this cost. We have priced them already.
Instrumentation	0.10	Yes	While costs for much of our computer control systems are included, these don't include a total control system for the process.
Electrical	0.10	Yes	Not yet costed
Buildings, Process	0.10	Yes	Not yet costed. While 0.05 is used in the reference, we feel that 0.10 would better represent the costs of process buildings.
Utilities	0.25	No	The FRSWC's site has electricity, water, and natural gas service already.
Storages	0.25	No	We've costed enough bins in our collection system to provide us with raw material storage, and the FRSWC site has space available for other needs.
Site Development	0.05	Yes	Despite using an existing site, some prep work would be necessary.
Ancillary Buildings	0.30	No	We've assumed that the buildings onsite for FRSWC staff would be sufficient & available.
TOTAL	0.35		

Fixed Capital Cost Calculation (con't)

Now, calculate physical plant cost (PPC)

$$PPC = (PCE \times [1+Factor]) + ICE - PCE$$

where: PCE = purchased cost of equipment ($1 046 977)

Factor = 0.35 (see previous page)

ICE = installed cost of equipment ($1 501 244)

$$\therefore PPC = (\$1\,046\,977)(1.35) + \$1\,501\,244 - \$1\,046\,977$$

$$= \$1\,867\,686$$

Apply all Factors for Fixed Capital Cost or Investment (FCI):

$$Factor = F_1 + F_2 + F_3$$ where $F_1 = 0.20$ (Design & Engineering)

$F_2 = 0.05$ (Contractor's Fee)

$F_3 = 0.10$ (Contingency)

$$\therefore FCI = PPC \times [1+Factor] = (\$1\,867\,866)(1.35)$$

$$\boxed{FCI = \$2\,521\,377}$$

E-3: Working Capital and Land Cost Calculation

Calculations Completed by:	Calculations Reviewed by:	Date: 02/03/2013
Carolyn McKenna	Michael Barrett	

Working Capital & Land Cost Calculation

Calculate working capital as follows:

- spare parts (1% of FCI)
- buyers pay 1 month late (4 weeks of product values)
- cash on hand (1 week of product values)
- inventory onsite (2 weeks of product values & raw material cost)
- accounts payable (1 month of delivered costs for inputs credit, we haven't paid yet.)

Assume that credit from accounts payable is negligible... Costs would be soap, caustic soda, tile colorant, etc. All used in quite small volume.

∴ Working Capital = 7 weeks of product value + spare parts

$$WC = \frac{7}{50} \times \text{Total Annual Revenue} + 0.01(\$2\,521\,377)$$

$$= \frac{7}{50} \times \$1\,091\,579 + \$25\,214$$

Working Capital = $230 152

Approximate the cost of land as $0; that it will be land on the FRSWC site.

E-4: Annual Operating Cost Calculation

Calculations Completed by:	Calculations Reviewed by:	Date: 02/09/2013
Michael Barrett	Carolyn McKenna	

Per tonne of glass	materials	energy	labour	
collection delivery				
handling (conveyors) 15		neg	1.5	
washing	$3.28 $12.00 $ 2.00	$6.92	0.1	
drying		$1.51 $0.30	0.1	
crushing		$10.62	0.3	
			2.0	2.0
Sand Blast (tonne)				
milling		$5.31	0.3	
sifting		$0.31	0.1	
packaging		neg	1.0	1.4
Tile (1000 tiles (250Kg)) (107.64ft²)				
mixing		neg	0.2	
molding		neg	included above	
sintering (furnace)		$18.99	0.3	
removal		neg	0.1	
packaging		$11.49	1.0	
		$30.48		1.6

Ancillary Resources

manager / safety 1.0

1200 hours 1.053t / hr

1264 tonnes / year

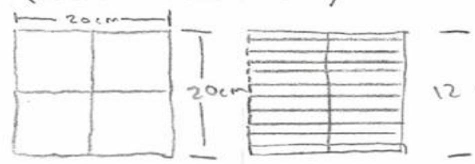
Tile Packaging.

1000 tiles per hour

packaging paper 18" × 1050 ft => 14000 tiles => \$50 => \$3.57/1000

cardboard boxes 8" × 8" × 5" => \$0.38

48 tiles / box = 48 (10cm × 10cm × 1cm)



20cm = 7.87 inch → 8 inch box width
12cm = 4.72 inch → 5 inch box height

$$\text{Cost for 1000 tiles} = \left(\frac{1000}{48}\right)(0.38) + \$3.57$$

$$= 7.92 + 3.57$$

$$= \$11.49$$

Tiles / year = 2,000,000

Total paper cost / year \$ 7140

Total box cost / year \$ 15 946

Dryer

Natural gas 50000 KJ / Kg

2.589 Kg / tonne

$\frac{50\,000\ KJ}{Kg} \times \frac{2.589\ Kg}{tonne} = \frac{129450\ KJ}{tonne}$

Natural gas consumed in drying 1 tonne of glass = 129450 KJ

1264 tonnes / yr × 0.129450 GJ = 163.62 GJ = 13.635 GJ / month

Enbridge Gas Small General Service < 60GJ / month (naturalgasnb.com)

costs $16.00 / month fixed

$11.6763 / GJ operating

1 tonne of glass = (0.129450 GJ)($11.6763 / GJ) = $1.51

Annual (1264 tonnes) = $1908.64

Washer

2000 litres of water / tonne glass www.fredericton.ca

$30.05 / 3 months = 360.60 / yr water
$30.05 / 3 months = 360.60 / yr sewar

$0.82 ¢/ KL = $1.64 / tonne glass water
$0.82 ¢/ KL = $1.64 / tonne glass sewer

E-5: Total Annual Revenue Calculation

Calculations Completed by:	Calculations Reviewed by:	Date: 02/09/2013
Scott Bell	Michael Barrett	

Total Annual Revenue Calculation

Revenue will come in 3 parts: ① From glass diverted from the landfill, or tipping fee avoided, ② from sale of sandblasting media, and ③ from sale of glass tile.

① Glass Diversion (Annual Revenue 1/AR_1)

AR_1 = mass diverted × tipping fee

$$\text{mass diverted} = 13\,000 \frac{t}{yr} \times 4\%\text{ glass} \times 50\%\text{ participation} \times 77\%\text{ bottle depot participation}$$

$$= 200.2\ t/yr$$

$$\therefore AR_1 = 200.2 \frac{t}{yr} \times \frac{74\$}{t} = \$14\,815/yr$$

② Sandblasting Media (AR_2)

AR_2 = production × price, where approx. price = \$100/t

production = collection − tile production

$$= 1264\ t/yr - 500\ t/yr = 764\ t/yr$$

$$\therefore AR_2 = 764\ t/yr \times \$100/t = \$76\,400/yr$$

③ Glass Tile (AR_3)

AR_3 = tile production × price, where price = \$5/ft² (\$53.80/m²)

$$\text{tile production} = 9.86\ m^2/hr \times 2000\ hr/yr = 19\,721\ m^2/yr$$

$$\therefore AR_3 = 19\,721 \frac{m^2}{yr} \times \$53.80/m^2 = \$1\,060\,815/yr$$

$$\therefore \text{Total Annual Revenue } (AR_T) = \$14\,815 + \$76\,400 + \$1\,060\,815$$

$$\boxed{AR_T = \$1\,075\,630/yr}$$

3

E-6: Net Cash Flow after Taxes and Economic Analysis Calculation

Calculations Completed by:	Calculations Reviewed by:	Date: 02/09/2103
Scott Bell	Michael Barrett	

Total Gross Profit Calculation

Total Gross Profit = ~~ATx~~ Total Annual Revenue − Fixed Costs − Variable Costs

Fixed Costs = \$ 332 559/yr
Variable Costs = \$ 133 671/yr

See Mike's Operating Costs section. Depreciation of equipment not included here; calculated separately in tax section.

∴ Total Gross Profit = (\$ 1075 630 − \$332 559 − \$ 133 671)/yr

Total Gross Profit = \$ 609 399

Total Capital Cost Allowance (Depreciation) Calculation

Reference: www.cra-arc.gc.ca/tx/bsnss/tpcs/slprtnr/rprtng/cptl/dprcbl-eng.html

Rates of Depreciation:

Process equipment (incl instrumentation)	30%	Class 43
Process building (incl electrical)	10%	Class 1

Equipment & Instrumentation cost = \$ 1 151 675
Building & electrical cost = \$ 209 395

15

Total Capital Cost Allowance (Depreciation) Calculation

Year 1 CCA:

Equipment = $1 151 675 × 0.30 = $345 502

Building = $209 395 × 0.10 = $20 940

Total CCA = $366 442

Year 2 CCA:

Equipment = ($1 151 675 − $345 502) × 0.30 = $241 852

Building = ($209 395 − $20 940) × 0.10 = $18 846

Total CCA = $260 697

Etc.

Income Tax Calculation

Provincial (New Brunswick) Lower rate (income < $500 000) = 4.5%

Upper rate (income > $500 000) = 10%

Year 1 : Assume 6 months for installation & troubleshooting. Approximate year 1 production = ½ year × production.

∴ Total Gross Profit = $609 399/2 = $303 101.

Taxable Income = Gross Profit − CCA

= $303 101 − $366 442

= < 0$

∴ Total NB Income Tax = $0.

∴ Total Canadian Income Tax = $0.

Income Tax Calculation (Con t')

Federal Tax rates: Small Business Deduction (income <$500 000) 11%

Basic Rate, after abatement (income > $500 000) 28%

Year 2: Taxable Income = Gross Profit − Depreciation

= $609 399 − $260 697

= $348 702

Provincial Tax = $348 702 × 0.045

= $15 692

Federal Tax = $348 702 × 0.11

= $38 357

∴ Total Income Tax = $15 692 + $38 357

= $54 049

And so on, for years 3 − 15.

Higher rates are applied to taxable income portions in excess of $500,000, which occurs in years 5 and onward.

Net Income After Taxes Calculation

Net Income After Taxes = Gross Profit − Total Income Tax − Total Depreciation

Year 1: = $303 101 − $0 − $366 442

Year 1 Net Income After Taxes = − $63 341

Year 2: = $609 399 − $54 049 − $260 697

Year 2 Net Income After Taxes = $294 653

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Net Cash Flow After Taxes Calculation

Net cash flow after taxes = Gross Profit − Total Income Tax

Year 1: = $303 101 − $0

Year 1 Net cash flow after taxes = $303 101

Year 2: = $609 399 − $54 049

Year 2 Net cash flow after taxes = $593 707

After Tax Payback Period Calculation

As stated in Income tax calculation section, it is approximated that 6 months will be taken for equipment installation & troubleshooting. The cumulative cash flow diagram reflects this time as follows:

- $2 521 377 spent in first 6 months
- $226 585 in working capital subtracted immediately thereafter
- $303 101 Net cash flow added to this over the following six months.
- All other net cash flows added over a full 1 year period.

From this diagram, it can be seen that the payback period falls between years 4 and 5. We can interpolate between the two cumulative cash flows to determine the payback period, solving not for zero, but for the negative of the working capital, −$226 585.

See next page for calculation.

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After Tax Payback Period Calculation (cont')

Our interpolation setup is as follows:

Year	$	$ + Working Capital
4	-$446 215	-$219 630
x	-$226 585	0
5	$139 413	$365 999

Giving an equation of:

$$\frac{5-x}{5-4} = \frac{\$365\,999 - 0}{\$365\,999 - (-\$219\,630)}$$

$$5 - x = \frac{\$365\,999}{\$585\,628}$$

$$\therefore x = 5 - 0.62 = 4.38 \text{ years}$$

After tax payback period = 4.4 years

After Tax Return on Investment (ROI) Calculation

Due to depreciation & changing income tax brought about by it, this will depend on the age of the plant. A suitable approximate is found here by averaging the ROI

From excel sheet:

$$\text{Year 2 ROI} = \frac{\text{Net After Taxes}}{\text{Fixed Capital Investment}}$$

$$\text{Year 2 ROI} = \frac{\$294\,653}{\$2\,521\,377} \times 100\% \cong 11.7\%$$

$$\text{15-Yr Average ROI} = \sum_{i=1}^{15} ROI_i / 15 = 16.28\% \cong 16.3\%$$

∴ After tax Return on Investment (ROI) = 16.3%

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Internal Rate of Return (IRR) Calculation

Future worth of Capital Cost (FW_{cc}):

Use a base rate of 8%. Use a 15 year assessment.

$$\therefore FW_{cc} = FCI(1+0.08)^{15}$$
$$= \$2\ 521\ 377(1+0.08)^{15}$$
$$= \$7\ 998\ 233$$

Future Worth of Cash Flows (FW_{CF}):

The value of each cash flow is:

$$FW_{CF_n} = CF_n(1+0.08)^{15-n}$$

Ex/ Year 2 Cash Flow's future worth:

$$FW_{CF_2} = \$593\ 707(1+0.08)^{15-2}$$
$$= \$1614\ 661$$

And the future worth of all cash flows is:

$$FW_{CF} = \sum_{n=1}^{15} CF_n(1+0.08)^{15-n}$$
$$= \$15\ 015\ 530 \quad \text{(See excel sheet)}$$

Net Future Worth (NFW)

$$NFW = FW_{CF} - FW_{cc} = \$15\ 015\ 530 - \$7\ 998\ 233$$

$$\boxed{NFW = \$7\ 017\ 297}$$

Net Present Worth (NPW)

$$NPW = \frac{NFW}{(1+0.08)^{15}} = \$2\ 212\ 145$$

$$\boxed{NPW = \$2\ 212\ 145}$$

10

Internal Rate of Return (IRR) Calculation (cont')

The IRR is found by changing the base rate (i, used 0.08 in previous page) until the investment's Net Present Worth (NPW) becomes 0.

This was done by trial & error in excel.

The main influencing factor is the sales price of glass tiles.

At NPW = 0, i = 19.8%

∴ IRR = 19.8%

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Appendix F – Design Optimization

Calculations Completed by:	Calculations Reviewed by:	Date: 03/15/2013
Amin Azahar	Carolyn McKenna	

Sample calculation (for scaling up the plant)

Equipment costing

→ Rotary Washer:

Original Price: \$ 37,261.46

Original throughput: 1264 tonnes

New throughput: 3792 tonnes

$$\text{New price: } 37\,261.46 \times \left(\frac{3792}{1264}\right)^{0.6}$$

$$= \$\ 72,033.16$$

Transportation Cost

Price/tonne = \$ 30

Amount of glass transported = 3 X original input − original input.

= 3 × 1264 − 1264 tonnes

= 2528 tonnes.

Total transportation cost = \$ 30 × 2528

= \$ 75,840

Total Gross Profit calculation

→ Use year 2 for example

→ total expense and revenue calculated in spreadsheet

Total Gross Profit = Total Annual revenue − Operating Expense −

− Total transportation Cost

= \$2775156 − \$376273.20 − \$442227 − \$75840

Total Gross Profit = \$1,880,815

→ Further economic analysis for each design was calculated with the same method in Appendix E.

Appendix G - Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA)

Part #	Function	Potential Failure Mode	Potential Failure Effects	Severity (1-10)	Causes/Mechanisms	Occur (1-10)	Current design controls/tests	Detection (10-1)	Recommended actions	RPN
T-101	Collection Bins	Dropped by fork lift	broken glass spilled (cuts)	2	poor training on forklift, distractions	4	proper training for employees, proper safety equipment	1	none	8
			fall on somone (bruising, broken bones)	5		4		1	none	20
C- _ _ _	Conveyors	moving too fast	glass spilled on floor (cuts)	2	accidental adjustment of speed	2	lock out tage out for controls, proper safety equipment	1	none	4
		accidental/surprise start up	nip points (ripped clothing, cuts/burns from belt)	3	unauthorized startup that didn't follow procedure	5	lock out tag out for start up controls	1	none	15
B-101	Breaker Tower	structural failure (bar breaks)	large metal piece continuing along in	2	poor manufacturing, overuse	2	none	1	none	4
		glass clogging tower	slows production	4	poor design, overuse	4	none	3	none	48
			required maintenance to de-clog (cuts)	2	long term use, unsafe maintenance procedures	6	proper safety equipment for maintenace workers	5	none	60
W-101	Rotary Washer	projectile glass	broken glass (cuts)	3	machine malfunction	2	proper safety equipment	5	emergency shut off	30
		clogged draining system	Pressure back up, leaks, pipe breakage	3	improper design, lack of maintenance	2	proper maintenance scheduling	5	pressure guages in piping system	30
		Corrosion	corrosion contaminated water, leaks, pipe breakage (eye contact with contaminated water)	3	lack of maintenance, poor material choice	2	proper maintenance scheduling, eye protection	5	Could use corrosion inhibitor (ex. orthophosphate) if corrosion is really bad	30
P-101/102	Centrifugal Pumps	clogged pump	worker has to clean pump	3	improper design, filter malfunction	2	pump design handles solids	2	none	12
		corrosion	contaminates in water	2	improper design	3	designed from corrosion resistant materials	3	none	18
E-102	Rotary Dryer	clogged filter system	dust and label particles released into the air (bad for respiration)	5	poor maintence and cleaning	5	dust collection subsystem	1	none	25
		human contact with high heat	burns of varying severity	8	poor training, no barrier protection	4	machine guarding (interlocking)	1	none	32
		human contact with moving parts	broken bones, friction burns, cuts	5	poor training, no barrier protection	4	machine guarding (interlocking)	1	none	20

B-102/103	Crusher/Ball Mill	projectile glass	broken glass (cuts)	3	machine malfunction	2	none	5	emergency shut off	30
		accidental start up	someone in the working area (broken bones, cuts,	5	software error, operator override, power outage	5	lock out tag out for start up	1	none	25
		metal removal clogging	workers have to remove metal, cuts	3	too many contaminates	2	clean feedstock	2	ewear gloves	12
S-101	Trommel Screen	human contact with moving parts	broken bones, friction burns, cuts	5	poor training, no barrier protection	4	machine guarding (interlocking)	1	none	20
Z-101	Bag Filling Station	spilled sandblasting media	excess dust particles in the air (respiratory health	5	poor training, machine malfunction (power outage, software error)	5	dust collection subsystem	1	none	25
			unsafe walking conditions (slip and fall)	2		5	none	4	none	40
T-201	Colorant Mixer	skin or eye contact with colourant	could irritate skin	5	poor training, lack of safety equipment	2	provide safety equipment (gloves, and eye protection)	1	provide eye washing station near by	10
E-201	Belt Furnace	human contact with high heat	burns of varying severity	8	poor training, no barrier protection	4	machine guarding (interlocking)	1	none	32
		conveyor moving too fast	glass spilled on floor (cuts)	2	accidental adjustment of speed	2	lock out tage out for controls	1	none	4
		accidental/surprise start up	nip points (ripped clothing, cuts/burns from belt)	3	unauthorized startup that didn't follow procedure, power outage	5	lock out tag out for start up controls	5	power outage shut down	75
A-201	Cooling Fan	lack of blade protection	human contact with moving blades (cuts, bruises)	2	poor design	2	buy properly protected fan and replace if blade protection is damanged	1	none	4
R-201	Manipulator Arm (with Suction)	unexpected motion	drop glass (cuts)	3	software error, operator override, power outage	5	lock out tag out for controls	8	Power outage shut down system	120
		someone in the workspace while arm is in motion	hit person (bruising, broken bones, death)	10	uneducated employee ignoring guard	4	workspace guard	5	Object detection	200
FD-102/103	Dust Collection System	system down for a period of time	poor air quality, possibility of dust inhilation	5	poor maintenance, part malfunction	5	two filters so the system can still be running when one filter is being changed/cleaned	4	have back up parts	100

FMEA - Production

Part #	Function	Potential Failure Mode	Potential Failure Effects	Severity (1-10)	Causes/Mechanisms	Occur (1-10)	current design controls/tests	detection , (10-1)	recommended actions	RPN
C- _ _ _	Conveyors	motor failure	lost production time	7	component wear, lack of maintenance	1	spare parts	1	regular maintenance	7
		spillage	lost production	4	belt speed	1	operators	4	regular inspection	16
B-101	Breaker Tower	glass glogging tower	lost production time, equipment damage	4	poor design, overuse	4	operator removes large objects from stream	1	regular inspection	16
W-101	Rotary Washer	glass not clean	lost/contaminated	3	machine malfunction	3	operator inspection	3	regular inspection	27
		clogged draining system	lost/contaminated production	3	improper design, lack of maintenance	3	operator inspection	3	regular inspection	27
E-102	Rotary Dryer	wet glass leaving system	clogged components in crusher	10	sensor error	1	moisture sensor on dryer	1	none	10
B-102/103	Crusher/Ball Mill	crusher screen broken	metal not removed	4	machine malfunction	4	none	4	re-route product	64
		size fraction not correct	un-usable product	7	improper setup	1	none	4	product testing	28
S-101	Trommel Screen	holes in screen	mixed size fractions	4	lack of inspection	4	inspections, re-screaning	4	inspect screens regularly	64
T-201	Colorant Mixer	wrong colour mixture	un-usable product	4	operator error	4	crush waste for sandblasting	4	none	64
E-201	Belt Furnace	furnace temp too cool	tiles not sintering	7	equipment malfucntion	1	inspections, re-route product	1	none	7
		furnace temp too hot	waste of energy, increase	4	equipment malfucntion	1	inspection	1	none	4
A-201	Cooling Fan	motor failure	tiles not cooling properly	4	lack of maintenace	1	spare parts	4	none	16
R-201	Manipulator Arm (with Suction)	missalignmnet	power interuption, software error	4	software error, operator error	4	moved components	4	none	64
		improper programming	power interuption, software error	7	operator error	4	initial programming	4	train employee	112

Calculations Completed by:
Carolyn McKenna

Calculations Reviewed by:
Michael Barrett

Date: 04/04/2013

Sample Calculation for Risk Probability Number (RPN)

RPN = Severity * Occurrence *Detection

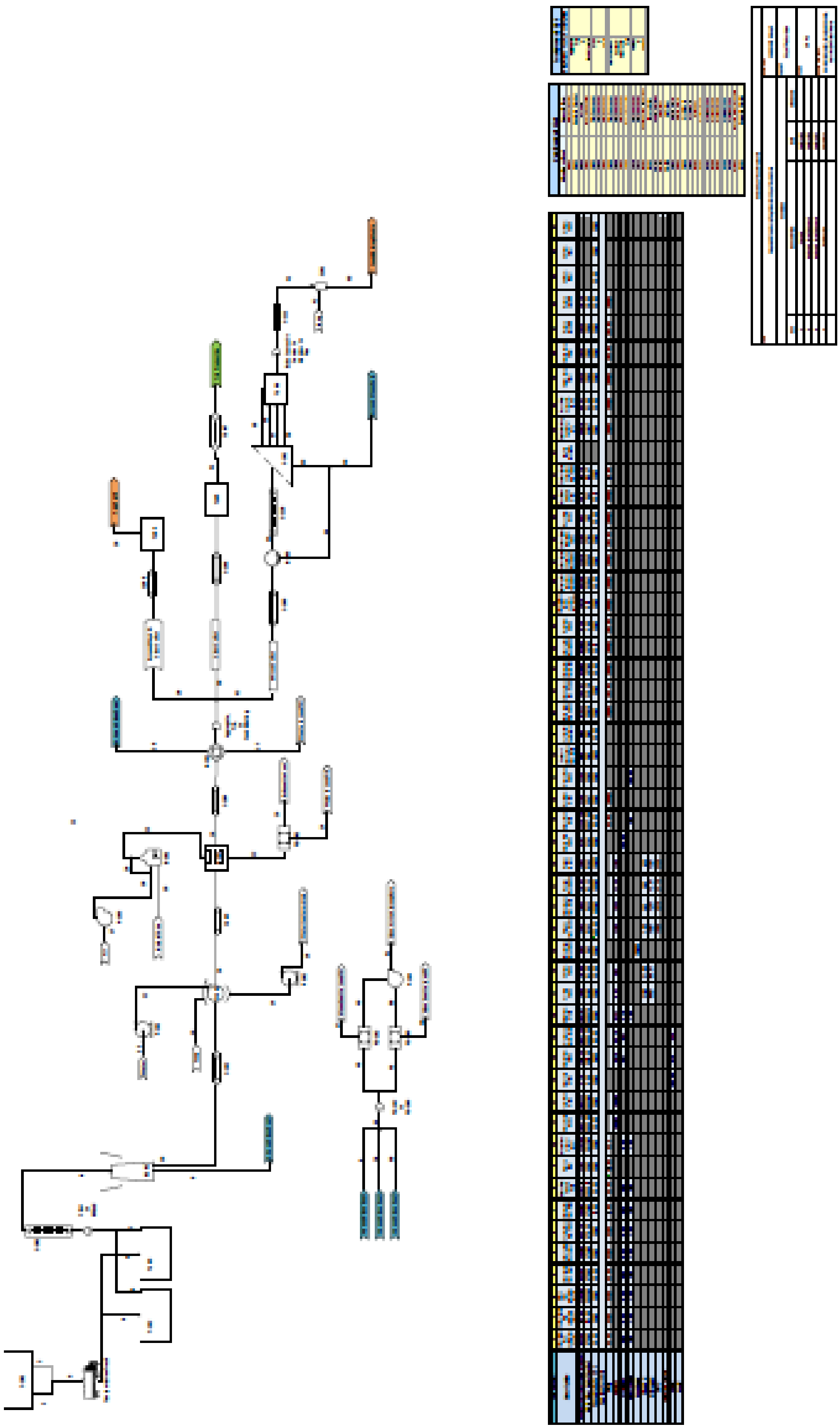
Ex. For T-101

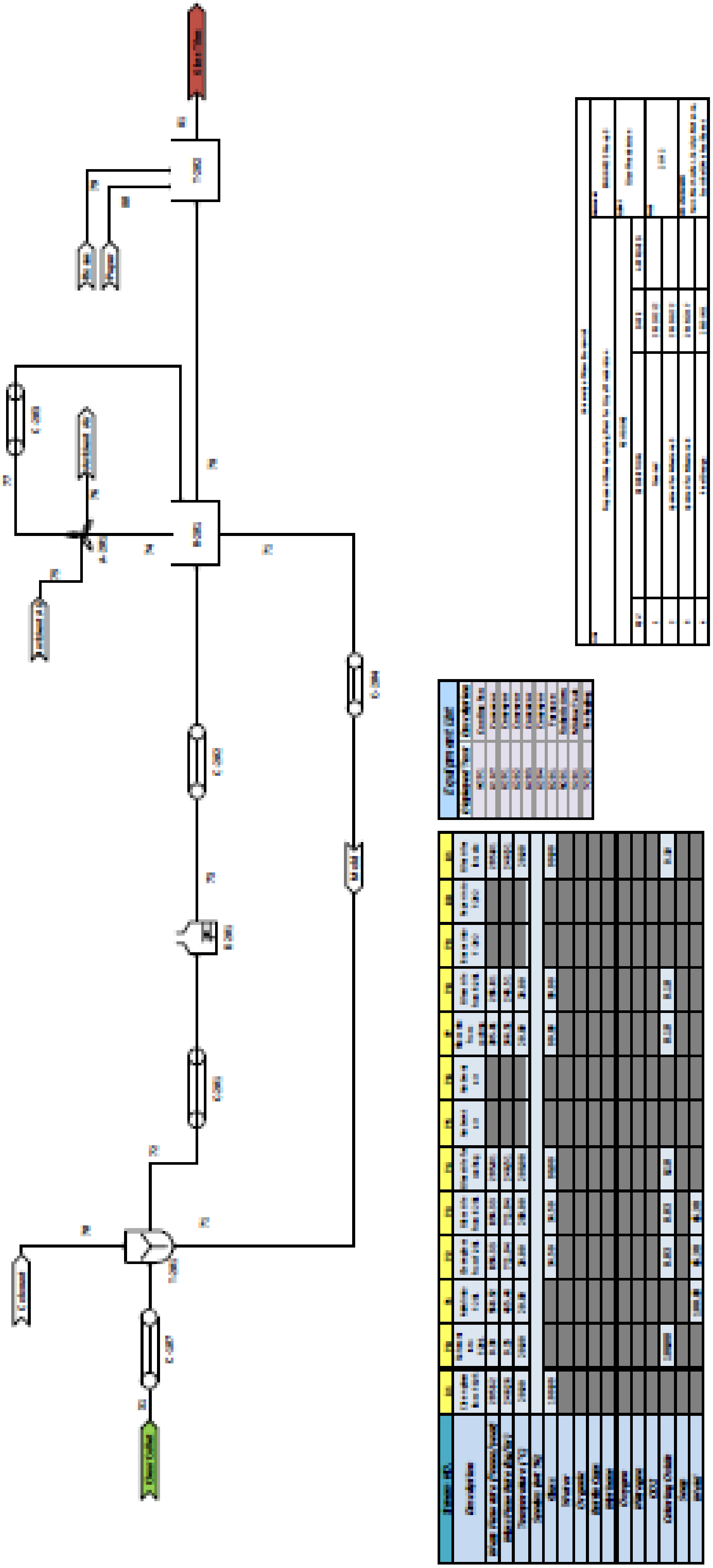
Severity = 2
Occurrence = 4
Detection = 1

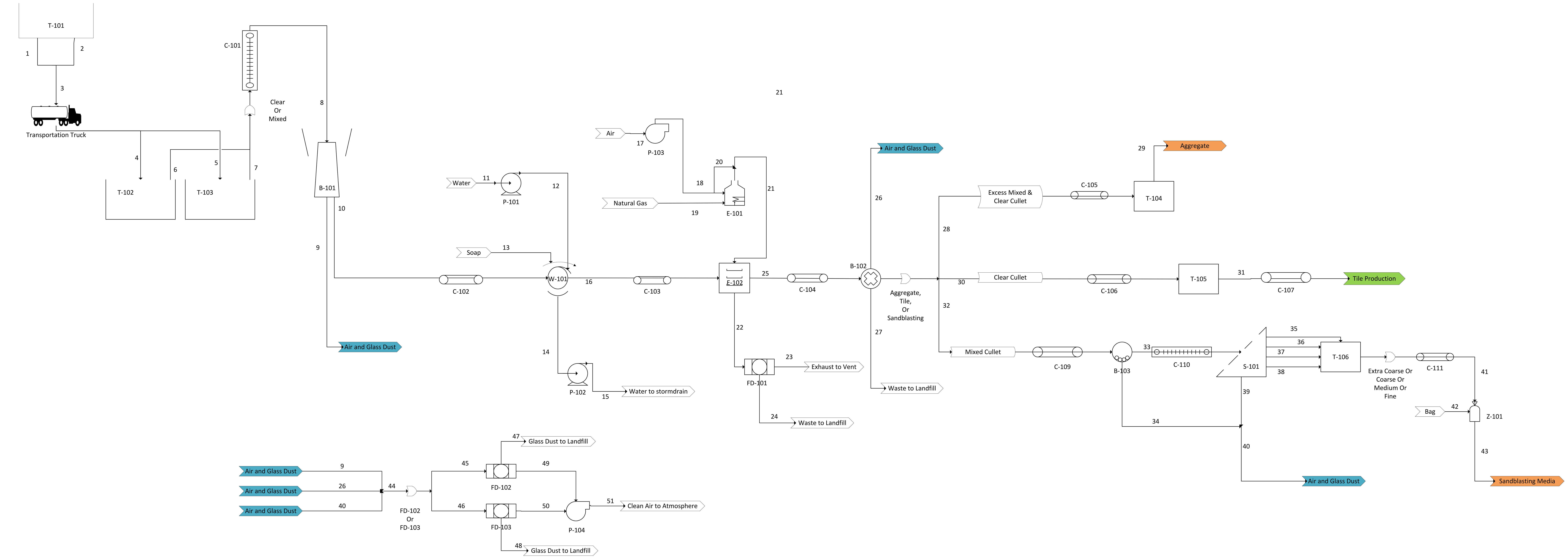
RPN (T-101) = 2*4*1 = 8

Appendix H: Process Flow Diagrams

(See Inserts)







Stream NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Description	Clear glass from Collection Center	Colour glass from collection center	Glass from collection center	Clear glass from truck	Colour glass from truck	Clear glass from T-102	Colour glass from T-103	Glass from T-102 & T-103	Dust to filter	Glass from breaker tower	Water into P-101	Water from P-101	Soap into W-101	Waste from W-101	Waste to stormdrain	Glass from W-101	Air into P-103
Mass Flow rate (Tonne/year)	695.20	568.80	1264.00	695.20	568.80	695.20	568.80	1264.00	12.64	1251.36	2502.72	2502.72	4.76	2507.48	2507.48	1307.67	76.89
Mass Flow Rate (kg/hr)	579.33	474.00	1053.33	579.33	474.00	579.33	474.00	1053.33	10.53	1042.80	2085.60	2085.60	3.96	2089.56	2089.56	1089.73	64.08
Temperature (°C)	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	60.00	60.00	60.00	20.00
Species (wt %):																	
Glass	98.50	98.50	98.50	98.50	98.50	98.50	98.50	98.50	100.00	98.5							
Water											100.00	100.00		99.79	99.79	94.22	9.64
Organic	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50		0.50				0.02	0.02	4.78	
Bottle Caps	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		1.00						1.00	
Methane																	
Oxygen																	21.06
Nitrogen																	69.31
CO2																	
Coloring Oxide																	
Soap													100.00	0.19	0.19		
Mold																	

Stream NO.	19	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Description	Air from P-103	Natural gas into E-101	Hot gas from E-101	Exhaust gas from E-101	Hot gas from E-102	Hot gas to vent	Waste from E-102	Glass from E-102	Dust from B-102	Waste from B-102	Colour/ Clean glass from B-102	Cullet for aggregate	Clean glass from B-102	Clean glass from T-105	Colour glass from B-102	Colour glass from B-103	Dust from B-103
Mass Flow rate (Tonne/year)	76.89	3.85	73.34	73.34	73.34	73.34	62.57	1245.10	12.20	12.45	0.00	0.00	671.11	295.52	549.09	549.09	5.49
Mass Flow Rate (kg/hr)	64.08	3.21	61.11	61.11	61.11	61.11	52.14	1037.59	10.17	10.38	0.00	0.00	559.26	246.26	457.58	457.58	4.58
Temperature (°C)	20.00	20.00	400.00	400.00	150.00	150.00	90.00	90.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Species (wt %):																	
Glass								99.00	100.00				100.00	100.00	100.00	100.00	100.00
Water	9.64		11.83	11.83	11.83	11.83											
Organic							100.00										
Bottle Caps								1.00		100.00							
Methane		100.00															
Oxygen	21.06		1.05	1.05	1.05	1.05											
Nitrogen	69.31		72.67	72.67	72.67	72.67											
CO2			14.45	14.45	14.45	14.45											
Coloring Oxide																	
Soap																	
Mold																	

Stream NO.	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Description	Colour glass (extra coarse) from S-101	Colour glass (coarse) from S-101	Colour glass (medium) from S-101	Colour glass (fine) from S-101	Dust from S-101	Dust from B-103 & S-101	Colour glass (mix size) from T-106	Bag for packaging	Sandblasting media for sale	Dust from Stream 9, 26,40	Stream into Filter	Stream into Filter	Dust to Landfill	Dust to Landfill	Air from Filter	Air from Filter	Air from P-104
Mass Flow rate (Tonne/year)	10.76	382.10	123.78	21.53	5.44	10.93	538.16		538.16	38.51	19.25	19.25	19.25	19.25			
Mass Flow Rate (kg/hr)	8.97	318.41	103.15	17.94	4.53	9.11	448.47		448.47	32.09	16.05	16.05	16.05	16.05			
Temperature (°C)	20.00	20.00	20.00	20.00	20.00	20.00	20.00		20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Species (wt %):																	
Glass	100.00	100.00	100.00	100.00	100.00	100.00	100.00		100.00	100.00	100.00	100.00	100.00	100.00			
Water																	
Organic																	
Bottle Caps																	
Methane																	
Oxygen																	
Nitrogen																	
CO2																	
Coloring Oxide																	
Soap																	
Mold																	

Equipment List

Displayed Text	Description
B-101	Breaker Tower
B-102	Hammer Crusher
B-103	Grinder
C-101	Ramp Conveyor
C-102	Flat Conveyor
C-103	Flat Conveyor
C-104	Flat Conveyor
C-105	Flat Conveyor
C-106	Flat Conveyor
C-107	Flat Conveyor
C-109	Ramp Conveyor
C-110	Flat Conveyor
C-111	Flat Conveyor
E-101	Combustion Chamber
E-102	Rotary Dryer
FD-101	Knock-Out Box
FD-102	Air Filter
FD-103	Air Filter
P-101	Water Pump
P-102	Water Pump
P-103	Air Blower
P-104	Air Blower
S-101	Screener
T-101	Storage Tank
T-102	Storage Tank
T-103	Storage Tank
T-104	Storage Tank
T-105	Storage Tank
T-106	Storage Tank
W-101	Rotary Drum Washer
Z-101	Bagging Station

Instrument List

Displayed Text	Description
Aggregate, Tile, Or Sandblasting	
Clear Or Mixed	
Extra Coarse Or Coarse Or Medium Or Fine	
FD-102 Or FD-103	

University of New Brunswick

TITLE: Proposed Glass Recycling Plant for City of Fredericton

DRAWN BY: ENGG4025 Group 3

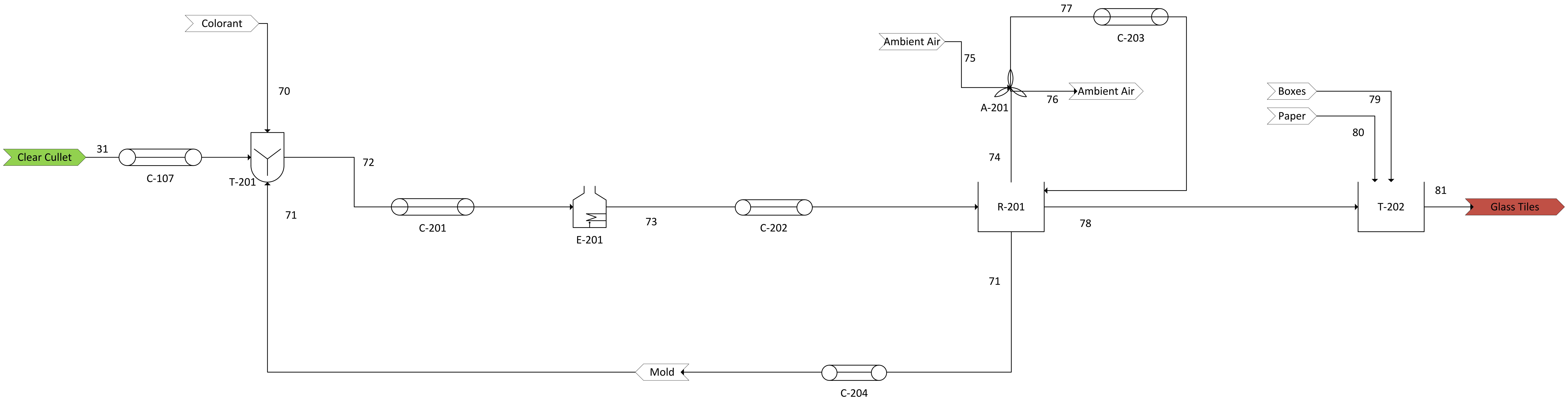
CLIENT: City of Fredericton

PAGE: 1 OF 2

GROUP MEMBERS: Amin Mat Azahar, Carolyn McKenna, Scott Bell, Michael Barret

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
1	Created	2012/12/2	
2	Updated for Milestone 5	2013/1/22	
3	Updated for Milestone 6	2013/2/17	
4	Final Design	2013/4/1	



Stream NO.	31	70	71	72	73	74	75	76	77	78	79	80	81
Description	Clean glass from T-105	Colorant into T-201	Mold into T-201	Clean glass from T-201	Glass tile from E-201	Glass tile for cooling	Ambient air	Ambient air	Glass tile from cooling	Glass tile from R-201	Boxes into T-202	Paper into T-202	Glas tiles for sale
Mass Flow rate (Tonne/year)	295.52	0.30	558.52	854.33	854.33	295.81			295.81	295.81			295.81
Mass Flow Rate (kg/hr)	246.26	0.25	465.44	711.94	711.94	246.51			246.51	246.51			246.51
Temperature (°C)	20.00	20.00	20.00	20.00	200.00	200.00			20.00	20.00			20.00
Species (wt %):													
Glass	100.00			34.59	34.59	99.90			99.90	99.90			99.90
Water													
Organic													
Bottle Caps													
Methane													
Oxygen													
Nitrogen													
CO_2													
Coloring Oxide		100.00		0.03	0.03	0.10			0.10	0.10			0.10
Soap													
Mold			100.00	65.38	65.38								

Equipment List

Displayed Text	Description
A-201	Cooling Fan
C-107	Conveyor
C-201	Conveyor
C-202	Conveyor
C-203	Conveyor
C-204	Conveyor
E-201	Furnace
R-201	Robotic Arm
T-201	Mixing Tank
T-202	Packaging

University of New Brunswick

TITLE	DRAWN BY
Proposed Glass Recycling Plant for City of Fredericton	ENGG4025 Group 3

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
1	Created	2012/12/2	
2	Updated for Milestone 5	2013/1/22	
3	Updated for Milestone 6	2013/2/17	
4	Final Design	2013/4/1	

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