Creating markets for recycled resources

R&D Report: Glass

Recovered container glass: Development of test methods and inorganic contamination limits

Project code: GLA0025

Date of commencement of research: 24 November 2003
Finish date: 19 March 2004

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GTS
SERVING THE WORLD OF GLASS

Published by:

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Published: (May 2004)

ISBN: 1-84405-101-3

Executive Summary

The importance of promoting sustainable lifestyles cannot be understated. Recycling otherwise waste material is an important element in achieving a more sustainable society. The glass industry has a very significant role to play in this effort. In simple mass terms the quantities of glass that enters the waste stream are not hugely significant. However glass has a very high public profile and it is essential that a material that sets great store by its claim to be completely recyclable does indeed achieve exemplary recycling rates.

The majority of glass that enters the waste stream is container glass, principally used for foodstuffs. The industry has a long history of recycling and now has targets formalised by the Packaging Waste Regulations. The recycling target for 2008 is 60% of all glass packaging. This represents an approximate doubling in the recycling rate as compared to a 2002 base, and will require that 1.32 million tonnes of glass (cullet) be recycled.

The Waste and Resources Action Programme (WRAP) was established to promote sustainable waste management. WRAP believe that the rates of waste glass collection would benefit from a more transparent trading market in the commodity. To this end they recently commissioned the British Standards Institute (BSI) to prepare a Publicly Available Standard (PAS) entitled 'PAS 101 Recovered Container Glass: Specification for quality and guidance for good practice in collection', which sets out maximum permissible contamination limits for organics, ferrous and non ferrous metals. However, setting limits for the inorganic fraction together with an appropriate test method proved to be problematic. The Specification is only intended to cover "raw," typical container cullet that is received by the processors. WRAP anticipated that the PAS would serve the interface between the waste glass supplier (collector) and the cullet processor and would be used as a quality control document at the processor gate.

As a follow on to the publication of PAS 101 , WRAP identified that the PAS would benefit from the inclusion of maximum permissible limits for the inorganic fraction together with a simplified testing method to determine the level of inorganic contamination that are of particular concern to the glassmakers. To this end WRAP commissioned Glass Technology Services (GTS) to investigate the practicalities of such a simplified testing procedure.

Specifically GTS was tasked with the following objectives:

1. To develop a rapid test methodology able to determine the inorganic contamination levels in recovered container glass

2. To use the developed method to determine typical contaminant levels

Discussions with senior technical personnel in the glass processing industry, who comprised the project steering committee, guided the GTS team to focus efforts into the finer fraction of the cullet, the area where the problematic, smaller fragments of ceramic contamination concentrate.

The investigative work undertaken by the GTS team involved extensive sampling works on several glass processing sites. The GTS team were able to formulate the basis of a simplified testing methodology that targeted the finer fraction and should yield reliable results. However, for this method to gain credibility and acceptance a much larger database of test results will be required. The draft test methodology was also based on a nominal 5kg sample which, following a detailed evaluation of all the test data, is now considered to be insufficient to yield meaningful results.

The work has also produced a simple spreadsheet-based model that relates the level of ceramic contamination to the resultant rejection rate in the glass bottle manufacturing plants.

With knowledge of the current levels of ceramic contamination arising at the processing plants, and with aid of the model, a series of limits have been proposed for the permissible levels of inorganic matter that may be associated with recovered glass.

Finally the experience gained during the practical site work has led the GTS workers to conclude that the standard test method outlined in the current PAS is also based upon an insufficient sample size and have recommended that the method as described be amended.

The report is able to propose upper limits for the level of inorganic material that could be tolerated by the processing plants. A two-tier limit is proposed. The first limit relates to the sample as a whole the second is intended to be used in conjunction with the proposed test method and as such relates only to the level of inorganics that would be found concentrated in the sub-10mm fraction. Obviously the adoption of this second tier limit is somewhat contingent on the adoption of the test methodology proposed.

The limits as proposed are given below.

PAS 101 Class	Gross limit (full load) (g/tonne)	Fraction < 10mm (%)	Proposed Limits (minus 10 mm fraction only)	
			(ppm)	(%)
A	150	2	250	0.025
B	150	2	250	0.025
C	150	2	250	0.025
D	150	10	50	0.005

Proposed limits for the inorganic content of recovered glass as delivered to the cullet processing plant

Contents

1 Introduction

The recovery and subsequent recycling of post consumer glass is a large, growing and important activity. Many glass items can be recycled directly back to the original manufacturer (closed-loop) whilst glass recovered from some sources is best reused as a substitute feedstock in other processes (open-loop). Diverting otherwise waste material from landfill into any productive activity brings obvious environmental benefits. Reusing recovered glass saves raw materials. Returning the glass the melting furnace brings additional benefits in terms of energy savings and reductions in carbon dioxide emissions.

The market for cullet is relatively large with some 654,863 tonnes of recycled glass being re-melted in the year 2002. The most common use for glass is the production of containers (bottles and jars) and the collection and recycling of these items is a long established practice. An extensive collection and distribution infrastructure has developed to handle the large volumes arising nationally.

The glass recycling industry essentially comprises the cullet processors who process the recovered glass into a useable form, and the collecting organisations that provide the glass. Typically the processors sort and wash the glass to remove unwanted materials such as metals, paper, plastics and various stones and other ceramic matter. Glass destined for re-melting at container plants will undergo some form of colour separation. Finally the processors crush the glass to the desired size.

Until recently glass collection was an activity confined to an arrangement between the processors and the local council through either the bottle bank system or their waste disposal service. With the increase in awareness in the benefits of recycling, and with the availability of funds from central government paid to schemes that are able to divert material from landfill, many more organisations, including charities, are now involved in the collection of glass.

The cullet ultimately replaces virgin raw materials of a known and relatively stable price. However this stability does not translate into the price received by the various collection agencies. Historically the local agreements are stuck between the collectors and the processors or some intermediary. (It is however important to understand that much of the price fluctuation can be attributed to the working of the Packaging Waste Regulations. These regulations set legally binding recovery and recycling obligations on the various sectors of the packaging industry and use a voucher system (PRN's) as proof of compliance).

The Waste and Resources Action Programme (WRAP) was established to promote sustainable waste management. WRAP believe that the rates of waste glass collection would benefit from a more transparent trading market in the commodity. To this end they recently commissioned the British Standards Institute (BSI) to prepare a Publicly Available Standard (PAS) for Cullet: PAS 101. WRAP anticipated that the PAS would serve the interface between the waste glass supplier (collector) and the cullet processor and would be used as a quality control document at the processor gate. Various grades of cullet would be established which would ultimately be reflected in the price the processor would pay for the waste glass prior to processing.

In addition to establishing a series of classifications for cullet, including maximum permissible levels of the various common contaminants (organic, ferrous and non-ferrous fraction), the PAS document contained a standardised sampling and testing methodology. The testing methodology as described is very rigorous and would undoubtedly be capable of producing reliable results. Unfortunately few operators have the necessary resources available to employ this standard test procedure. The inability of operators to reliably sample and test the cullet is seen by WRAP as a major obstacle to the widespread adoption of the PAS by the glass collecting community. WRAP thus commissioned Glass Technology Services (GTS) to investigate the feasibility of developing such a (simplified) sampling and testing methodology. Contamination by inorganic materials (grit, stones and porcelain) are of particular concern to the glass makers and was the focus of this initial development work.

The project received support from The Waste and Resources Action Programme (WRAP).

The project was run by a steering committee comprised from interested parties through the process including:

- WRAP – Funding body
- Glass Technology Services Ltd (GTS)
- Glass processors including:
    - Viridor Richardson
    - Glass Recycling UK
    - Reuse Collection Ltd
    - Biffa
- Local Authorities represented by LARAC (Local Authorities Recycling Advisory Committee)

GTS was tasked with the following objectives:

To encourage the adoption of PAS 101 by:

1) Identifying relevant stakeholders and establishing a working (steering) group.
2) Developing a rapid test methodology able to determine the inorganic contamination levels in recovered container glass
3) Using the developed method to determine typical contaminant levels

2 Publicly Available Specification (PAS) 101

PAS 101 specifies the minimum requirements for waste container glass to be used for further processing.

The PAS seeks to provide good practice guidance for the collection and delivery of waste glass to a glass processor. The document introduces a grading system for raw cullet: premium, intermediate and low grade, and specifies certain quality criteria for each grade. A principal objective of the specification is to provide a reference point which, in absence of existing specification or quality standards, may form part of a contractual agreement between the sellers and purchaser.

The publication was based on existing quality practices and on information provided by UK glass processors and was intended to provide an accepted industry-wide good practice for collection and delivery to a glass cullet processor.

Classification systems require some form of agreed testing methodology in order to distinguish between the various sub-classes. To this end the PAS incorporated a detailed series of testing procedures.

The specification identifies various contaminants that are commonly associated with recovered glass including: organic and inorganic materials, ferrous and non-ferrous metals. The authors of the PAS were able to propose maximum permissible levels for most of the common contaminants. However insufficient data was available relating to (acceptable) inorganic levels associated with recovered glass and consequently no limits were proposed and a statement to the effect that any limits would be “subject to agreement between the processor and collector” was inserted into the PAS.

The lack of such data is, in a large part, attributable to the practical difficulties associated with the measurement of this parameter.

The work reported herein is thus intended to establish practical (upper) limits to the levels of inorganic contaminants that should apply to recovered glass delivered to the glass processing facility under the auspices of PAS 101.

3 The Glass Recycling Industry

The glass recycling industry essentially comprises the cullet processors who process the recovered glass into a useable form, and the collecting organisations that provide the glass. Typically the processors sort and wash the glass to remove unwanted materials such as metals, paper, plastics and various stones and other ceramic matter. Glass destined for re-melting at container plants will undergo some form of additional colour separation. Finally the processors crush the glass to the desired size.

Until recently glass collection was an activity confined to an arrangement between the processors and the local council through either the bottle bank system or their waste disposal service. With the increase in awareness in the benefits of recycling, and with the availability of funds from central government paid to schemes that are able to divert material from landfill, many more organisations including charities are now in the business of collecting glass.

Historically the glass container manufacturing plants, and to a lesser extent the fibre plants, were the sole end-users of the recovered glass. The arrival of the Packaging Waste Regulations with the attendant obligations to achieve a target rate of recycling has had a significant effect on the established industry. The regulations have spawned a number of so called compliance schemes that take on companies recycling obligations. VALPAC is the largest and perhaps best known of these compliance schemes. In order to meet their member's obligations these schemes have not only been instrumental in increasing the volume of glass collected but also in diversifying the ultimate end uses of the glass. The growth in the use of mix-coloured glass for aggregate use has been the largest beneficiary from this new source. It is estimated that approximately 100,000 tonnes per year of glass is currently being used as road making aggregate substitutes.

Approximately 20 companies are registered by the environment agency as accredited glass processors. An accredited processor can convert glass into a new product and is able to issue Packaging Waste Recovery Note [PRN]. These notes are only associated with glass used for packaging i.e. container glass.

The principal cullet processors include:

Reuse Collection Ltd (formerly Berryman)	W. Yorks & London
Day Aggregates	London
Glass Recycling UK	S. Yorks
Midland Glass Processing	Notts
MacGlass Recycling	Dalkeith
Viridor Richardson Limited	Merseyside
Biffa	Harlow

Local Authorities have a duty to collect household waste. They also must collect commercial waste if asked and, at their discretion, can collect industrial waste. All the waste collected by local authorities is collectively termed "municipal waste" and currently amounts to some 30 million tonnes each year. Since 1996/7, the amount of municipal waste collected has been growing at an annual rate of 3.4% per year. 60% of municipal waste comes from regular household collections, a further 15% from civic amenity sites. Most of this waste goes to landfill. Local Authorities are also duty bound to prepare and publicise a waste recycling plan which details the arrangements made for recycling household and commercial waste. Most local councils have in place a "bring" system of recycling banks collecting such items as glass, paper, metal cans, plastic and even textiles in addition to the growing % that operate kerbside recycling schemes.

4 Inorganic Material and the Glassmaking Process

The glass manufacturing process centres on large furnaces which are essentially refractory box-like structure operating at temperatures up to 1,600°C. The furnaces run continuously, providing glass 24 hours a day 7 days a week, and all activities within a factory are entirely dependent upon its output. A typical container glass furnace will be capable of producing 300 tonne per day of molten glass which will be converted into over one million bottles and jars per day. The furnaces cost in the order of £8 million and are designed to operate a "campaign" lasting typically 10 years.

Glassmaking has an advantage over other packaging material in that the container forming process requires no intermediate steps i.e. raw materials fed in one end bottles out the other. The raw materials in question are abundant, relatively cheap and can be obtained to a high degree of purity. A further advantage enjoyed by the glassmaker is the fact that glass is totally recyclable, suffers no loss in quality due to the remelting process and recycling glass saves energy and reduces greenhouse gas emissions. However the advantages of using recovered glass as a furnace feedstock must be tempered by the problems that arise from the presence of unwanted contaminants that are invariably associated with a material largely collected via a public "bring" system and kerbside schemes.

Commercially recovered glass (cullet) typically collected from the bottle bank system or from pubs and clubs is susceptible to contamination from individuals discarding inappropriate material into the glass receptacles. In certain circumstances this inorganic material can represent a serious problem to glassmaker. However the high temperature melting process has some tolerance to the presence of some inorganic materials. Essentially the furnace has a large capacity and the incoming feedstock takes around 16 hours to pass through the melting stage. Many small (less than 2mm) stones dissolve into the melt during this period. The propensity of inorganic fragments to dissolve in the glass is principally a function of the chemical composition of the material; in general the more refractory materials being the least soluble. Fragments that do not dissolve pass through the furnace and into the subsequent bottle forming process where they eventually become embedded into the wall of a bottle or jar. These stones are an obvious blemish to an otherwise perfect container but unfortunately it is not the aesthetics that concerns the glassmaker but rather the threat to the structural integrity of the container. The embedded stone represents a weakness and will be focus for stress related failure. Bottles containing such flaws could fail in use and the glassmakers have invested heavily in inspection equipment that will detect and reject any bottle not meeting stringent quality requirements.

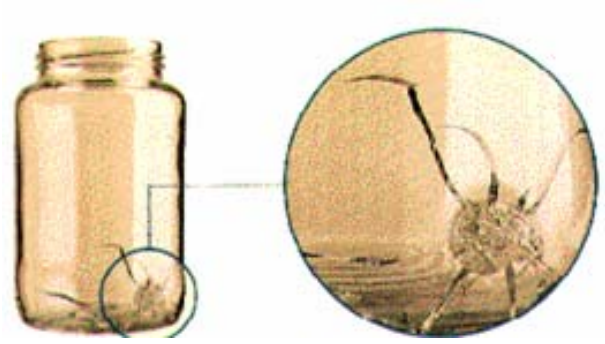


Figure 1 Typical stone inclusion in a glass container

The cullet processors are acutely aware of the problems associated with inorganic contamination and for their part have also invested heavily in detection and separation equipment. Typically the first line of defence is a manual "picking" line where the incoming cullet passes between a team of pickers whose job it is to remove any unwanted items. The nature of the raw cullet at this stage in its processing (unbroken bottles and jars mixed with large pieces of broken bottles) means that the pickers are only able to remove the larger items. Whilst few in number these large pieces actually represent the bulk of the inorganic contamination which, if allowed to proceed to subsequent stages in process, would be crushed into many

hundreds of pieces and constitute a far more difficult removal problem. The size analysis of a sample of ceramic material removed by the pickers is given below in Table 1.

Size Fraction (mm)	Oversize (% cumulative)
+ 65	44.1
+ 30	81.4
+ 9.5	99.1
- 9.5	0.9

Table 1 Size analysis of ceramic material removed by manual picking station.

Having passed through the picking stage the glass is subjected to a range of other processing stages designed to remove contaminants and in some cases improve the colour separation. The number and nature of these stages is dependant on the quality of the incoming glass, the end use of the recovered glass and on the sophistication of the processing plant. Removal of contaminants at this stage is automatic and typically involves scanning a moving conveyor belt carrying the glass with some form of detection device which, when activated, triggers a small air jet which removes the contaminant from the main stream. In the case of inorganics the separation technology will be targeting those smaller pieces missed by the pickers. At this stage in the process inorganic matter will be present in tiny quantities covering a size range of perhaps 20mm down to sub-1mm “dust”. No technology is capable of removing the very small particles, nor is there any reason to do so as, outlined above, these small particles will dissolve in the furnace. Ideally the separation technology will remove unwanted inorganic fragments above 2 mm; in practice and, with the plant operating at economic throughputs, current technology is able to achieve separation at around 8mm.

5 Size Distribution Theory

The size distribution of the picked material can be described by simplified particle size distribution theory which takes the form:

$$R = e^{-bx^n}$$

Where
R = Fraction Retained on Sieve mesh size x
x = Sieve Size
b and n = Constants

Using this simplified theory and deriving the constants from the actual size analysis given in Table 1 it is possible to extrapolate the data to predict the size distribution at smaller fractions. Using this calculated data in conjunction with knowledge of the levels of removed ceramics it is possible to calculate the amount and, of more significance, the number-count of particles that will arise at any given size fraction.

The calculated data below (Table 2) is derived from the size analysis for the picked ceramics (Table 1). The particle count data however only relates to those particles having a mean size greater than 2 mm (i.e. particles having the potential to cause problems) as the number count increases exponentially when extended to include “dust-sized” particles.

Particle Size (mm)	Retained (mass %)	Retained (particle count %)
+65	43.1	0.1
65 - 20	46.2	2.1
20 – 10	7.3	7.7
10 - 5	2.4	20.0
5 - 2	0.8	70.1

Table 2 Calculated size and number distribution of ceramic contaminants

Thus whilst large (= 20 mm) particles comprise almost 90 % by weight of the ceramic contaminants by number count they constitute only 2.2%. Conversely small particles (2 to 5 mm) comprise just 0.8 % of the weight fraction but over 70% of the number count.

6 Recycled Glass Quality

Recovered and recycled glass is an important resource for the glassmakers. The glassmakers do not collect the glass directly leaving this task to specialist glass processors. These processors collect the untreated glass from bottle banks, pubs and clubs and add value to the material by a series of treatment stages which include the removal of unwanted items, colour separation and washing and crushing. The majority of quality specifications that exist relate to the processed glass rather that to the incoming material.

No universally accepted standard for furnace ready cullet currently exists in the UK: although Table 3 is a typical specification used by most manufacturers.

Standard	**Typical Limits**	**Typical Levels**
Ferrous metals	<50 g/tonne	clear 20-40 g/tonne amber 20-35 g/tonne green 20-35 g/tonne
Non-ferrous metals	<20 g/tonne	<1 g/tonne
Ceramics and stones	<20 g/tonne	clear 20-40 g/tonne amber 20-35 g/tonne green 20-35 g/tonne
Organics	3,000 g/tonne	clear 1,000-1,500 g/tonne amber 1,000-1,800 g/tonne green 1,200-1,800 g/tonne
Moisture	shows no drainage	shows no drainage (<2%)
Particle size	<50 mm	<50 mm
Principal Colour	**Typical Limits**	**Typical Levels**
Clear	amber <2% green <2%	amber negligible green 0.5%
Amber	green <10% clear <12%	green 0-10% clear 2-8%
Green	amber <10% clear <12%	amber 0-10% clear 0-10%

Table 3 Typical glass manufacturer cullet quality specification.

The glass processor's task of achieving these quality specifications will be greatly influenced by the quality of the incoming, untreated, recovered glass. Ideally the glass will be perfectly colour separated, unbroken, washed and have no contaminants. In practice the glass will inevitably have adhered labels; bottle tops and increasingly be plastic sleeved. Additionally the bottle bank system attracts many unwanted items including crockery, bricks and magazines. Traditionally the processors will be seeking to sell the glass on to the relatively higher value markets of the container or fibre glass manufactures. Cullet falling short of the glassmaking specifications would hopefully find an outlet in the aggregate market albeit for a much reduced price. A quality specification for incoming recovered glass would thus be of use to the processors and should bring some transparency to price paid to collectors of glass. A stable or at least predictable market for glass would give confidence to agencies such as local authorities when drafting their business plans, and agreeing contract terms for the sale of collected material.

To this end WRAP commission PAS 101 which established 4 classes of recovered glass. Classes A and B relate to colour separated glasses with class B having less stringent specifications for colour and

contamination levels. Classes C and D relate to colour-mixed glasses with class D having less stringent specifications for contamination levels.

The PAS does not set limits on the inorganic contamination. The problem caused by inorganic contaminants if more a function of their number rather than a simple mass fraction. A single 100 x 100 mm piece of crockery would weigh around 130g yet would be very unlikely to evade the picking station or the subsequent optical sorting process. However a 5mm fragment would weigh around 0.3g and but has far more potential to pass though the system and ultimately produce an inclusion in a glass container.

6.1 A mathematical model of cullet derived "stones" in the glassmaking process

The number of container faults caused by inorganic inclusions "stones" can usefully be estimated from knowledge of the overall mass concentration of the inorganic fraction, the size distribution of this faction, the cullet ratio employed by the recipient glass melter and the average weight of the container being manufactured. An example of the methodology is given below.

Assume	Incoming cullet load to processor	12 tonnes
	Inorganic contamination level	150 g/tonne glass
	Fraction of inorganics sized between 10 and 2 mm	2.9%
	Average mass of fragment between 10 and 2 mm	0.3 g
	Cullet ratio of recipient glass melting furnace	40%
	Average container weight manufactured by furnace	250g
	All fragments greater than 10mm are removed by the processing plant	

Mass of inorganic material received by the processor per load

= 12 x 150 = 1,800g

Mass of critical sized inorganic particles delivered to glass furnace

= 1,800 x 0.029 = 52g

Number of critical sized inorganic particles delivered to glass furnace

= 52 / 0.3 = 174

Total glass into which inorganic particles are dispersed (40% cullet)

= 12 / 0.40 = 30 tonnes (30,000,000g)

Total bottles produced into which inorganic particles are dispersed

= 30,000,000 / 250 = 120,000

Faults produced due to inorganic inclusions

= 174 / 120,000 x 100% = 0.15%

A more sophisticated version of this methodology has been developed which predicts the particle size distribution using the simplified size distribution theory described in section 5. The model is spreadsheet based and allows the users to vary several parameters including lower removal size, removal efficiency, furnace cullet levels and size distribution characteristics. A printout of the model is given in Appendix 1.

The constants used to derive the size distribution are based on very limited data. The method could be improved and refined by tuning the model with routine data collected at the processing and glass plants

including: the amount picked, the levels rejected by the automatic sorting equipment (inferred from gun activity?) and the number of faults detected at the glass plant.

7 A practical sampling and testing methodology

A cullet classification system that sets various levels for contaminants requires a testing methodology to verify that material is within the agreed specification. PAS 101 does stipulate standard testing methods which appear to be very rigorous and which ought to be capable of producing reliable results. Unfortunately few operators have the necessary resources available to employ these standard test procedures. The inability of operators to reliably sample and test the cullet is seen by WRAP as a major obstacle to the widespread adoption of the PAS by the glass collecting community. The development of a (simplified) sampling and testing methodology is thus the objective of this work.

7.1 Current Industry Practice

No standard method has been established in the UK for the routine testing of incoming recovered cullet to glass processing plants. Industry practice involves a simple visual inspection of the load as it is tipped. Should disputes occur then a large sample would be obtained via a bucket loader. This sample would then be spread on the floor and "walked" and/or sub-sampled or, in some better equipped facilities, would be hand sorted in a dedicated sample picking station.

Some insight into international practices was revealed by various literature and web-based searches. Whilst many procedural differences are apparent in the various standard testing methodologies, essentially our continental colleagues adopt the same bucket and shovel approach favoured in the UK.

7.2 PAS 101 Standard Methodology

The "standard" sampling and test methodology as described in PAS 101 involves obtaining a representative sample by taking several large increments from around the tipped load. The increments are mixed and then reduced to a manageable size by the process of coning and quartering.

In the process of developing an alternative "practical" test methodology the GTS team undertook standard sampling exercises and were able to make the following observations relating to this standard method:

- Sampling time of 2 minutes per increment = 12 minutes per load
- Sampling operation is by necessity a 2-man operation
- 1 sample comprises 6 large tubs = 100 kg
- Storage of multiple bulk samples would be impracticable
- Time to mix and reduce large sample = 30 minutes
- Sample contamination likely if mixing is performed on the yard floor
- Time to hand sort reduced sample = 60 minutes

Additional observations were drawn from discussions with those site personnel having responsibility for quality testing:

- Large lumps of brick or stone not really problematic as they are readily screened/removable
- Small well dispersed contamination recognised as main problem

The principal conclusion drawn from sampling activity is that the sampling methodology as described in PAS 101 is too time consuming and labour intensive to be widely adopted as a routine test procedure at a working glass processing site.

Additionally, none of the “standard” samples taken by the GTS workers yielded any ceramic material despite evidence to the contrary. The inhomogeneity of the sample combined with the large particle size and a typical load of 12 tonnes would suggest that the recommended 100 kg sample is actually insufficient to guarantee a representative sample.

Figure 2 Sampling equipment for “Standard” method

7.3 Proposed (size restricted) Methodology

Based on the experience gained in applying the standard sampling methodology and following discussions with involved personnel the GTA team concluded that any workable system would have to restrict sampling to the finer fractions in which the inorganic contaminants are concentrated.

A restricted size sampling methodology would have several advantages including:

- Relatively quick sample time
- Small sample [5-10 kg]
- No ground contamination
- 1 man operation
- Simple, robust and low cost apparatus

The principal disadvantage identified was that such a sample would not be representative of the whole and some “factor” would have to be introduced in order to determine the weighting that should be given to the restricted sample. Thus whilst it would be possible to determine the level of any contaminant in the restricted sample one could not necessarily translate this into a value representative of the whole. However a possible solution lay with basic size distribution theory. If one made the assumption that the size distribution of bulk sample could be described in mathematical terms then it should be possible to infer the bulk size distribution from that of the restricted sample.

7.3.1 Sample Thief

Sample thieves are routinely employed to obtain samples of powdered material from heaps and drums. The most common type comprises a long narrow slotted cylinder which is pushed into the bulk sample. Turning a simple mechanism opens the slots and powder falls into the thief which is then closed and retracted. This methodology would restrict the sample size taken to that of the slot(s) but was seen as impractical for use with bottle bank cullet which often comprised whole or broken containers

The concept of a size restricted sample grab technique remained attractive and the GTS team proposed a simple and robust alternative which essentially involved forcing a narrow hollow cone into the sample which, on retraction, would drag out some of the smaller glass fragments. The actual size of the fraction withdrawn would be a function of the cone diameter.

Figure 3 below illustrates the design and ease of use of the basic GTS design sample thief.

Figure 3 Design and use of a simplified sample thief

8 Results of On-Site Testing

8.1 Testing Methodology

In order to evaluate the usefulness of the proposed sample thief testing methodology it was necessary to compare the results of "thief" taken samples with those obtained from the standard PAS defined method. To this end the GTS team undertook duplicate testing of incoming loads using both sampling techniques. The testing regime comprised:

1 Standard Method

1) Nominal 100 kg sample obtained from 6 large increments
2) Increments bulked together
3) Sample weighed
4) Number of whole bottles counted
5) Whole bottles sorted by colour (classified as correct/incorrect colour)
6) Broken glass size on 30 and 9.5mm mesh
7) Minus 9.5 mm fraction retuned to laboratory for detailed examination.
8) Minus 9.5 mm fraction inspected visually for inorganic inclusions

2 Thief Method

1) Nominal 5 kg sample obtained via 12 increments
2) Sample weighed
3) Significant sized pieces of incorrectly coloured glass removed and weighed
4) Sample reconstituted and inspected for obvious inorganic inclusions (weighed if present)
5) Sample sized on 30 and 9.5 mm mesh
6) Sample washed through a 1.7mm sieve
7) Detailed optical examination of washed minus 1.7 mm fraction - inorganic particles counted

This duplicate testing methodology was performed on 18 samples taken from 3 processor sites. In addition some preliminary testing was undertaken at a forth site.

8.2 Test Results

Detailed results of the tests undertaken are given in Appendix 2.

8.2.1 Degree of Bottle Breakage

Recovered glass is best processed intact, in practice some degree of breakage is inevitable and this increases as the load is handled. The economics of collecting glass however is generally improved by compacting the glass, thereby getting more glass onto the wagon and reducing the number of trips. There is thus a potential conflict of interests between the collector and the processor. Classes A, B & C of the PAS101 specify "whole or broken" containers. The sampling activity provided an opportunity to gather data on the degree on "intactness" of delivered bottles. Caution must be exercised in interpreting this data as the result is obviously greatly influenced by the degree of handling suffered by the load prior to sampling.

The large bulk sample was used to determine the proportion of unbroken containers delivered in each tested load. Having carefully aggregated the increments the whole sample was weighed then all the intact containers were removed, counted and re-weighed.

The results of exercise are given below in Figure 4

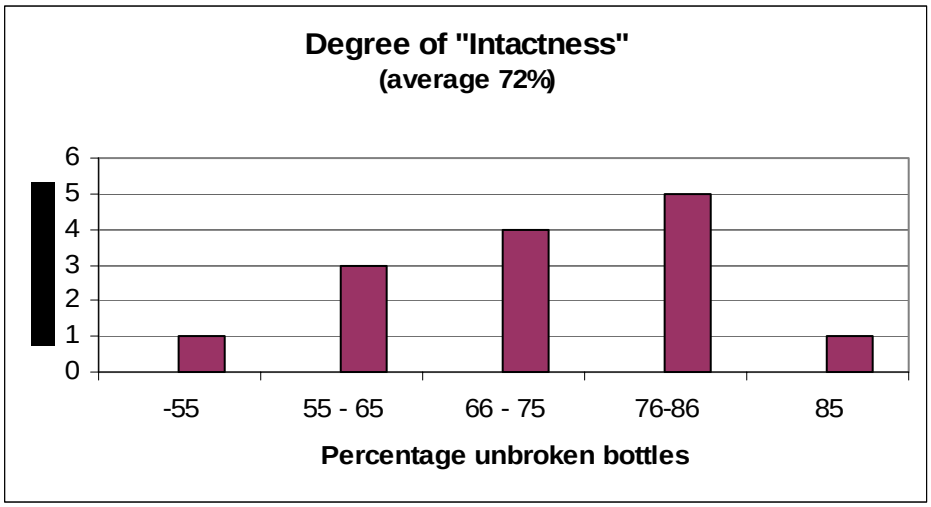


Figure 4 Proportion of bottles delivered intact

8.2.2 Degree of colour separation

The majority of the incoming loads that were tested comprised colour-sorted glass usually originating from bottle bank sources. The degree to which the bottles had been correctly sorted (at the bottle banks) was simply determined from a count of the intact bottles within the bulk sample. The fraction reported is thus based upon a count rather than a mass fraction although the statistical difference should be negligible. A second estimate of the colour separation was made from the smaller sample taken by the thief. The principal aim of this secondary colour exercise was as a check on the ability of the thief to deliver a representative sample.

A summary of the results of exercise are given below in Figure 5.

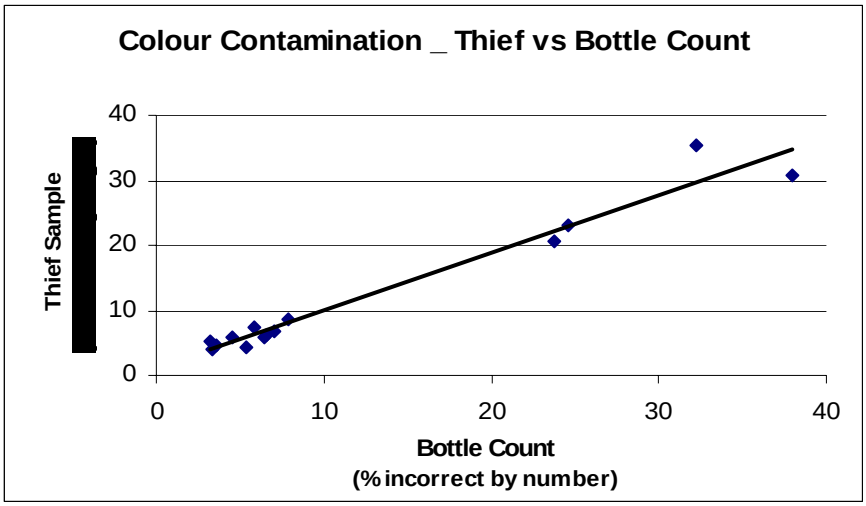


Figure 5 Degree of correct colour separation - whole bottle count and thief sample

8.2.3 Bulk "Standard" Sampling Methodology

A total of 18 samples were obtained using the methodology outlined in PAS 101. A nominal 100 kg sample was taken from 6 positions around a tipped 12 tonne load. The samples were mixed, inspected and sized on-site. Any large ceramic pieces would have been removed and returned to the laboratory for more detailed examination. In the event no large i.e. plus 10 mm particle was found in any of the bulk samples.

The samples were sorted to determine the proportion of unbroken and incorrectly coloured containers then sized using 30 and 9.5 mm mesh sieves. The minus 9.5 mm fraction was retained and returned to the laboratory for a more rigorous examination using a back-lit light-table. This procedure would enable the identification of inorganic particles with a mean diameter of approximately 5mm. The presence of dried beer and other foodstuffs tended to make smaller particles adhere to their larger neighbours thus limiting the effectiveness of the inspection system.

inorganic fragments were identified in only 3 samples of the 18 that were tested, and in all cases these were small fragments found in the laboratory during the detailed examination of the minus 9.5 mm fraction.

The inability to detect inorganic particles could be a simple indication that that no inorganic matter was present. However given that the picking stations and optical systems generally detect some ceramic contaminants in most loads the most likely explanation is that the sampling/testing method employed was inappropriate for the level of contamination present.

The reported level of removal of ceramic (mainly porcelain) at the picking stations was between 350 and 150 g per tonne of glass which is the equivalent of between 1 and 3 large (100mm square) pieces per tonne of glass. Thus, if the inorganic contamination is in the form of large pieces in loads of unbroken glass containers, the chances of capturing a single piece in a 100 kg sample are statistically small.

8.2.4 Thief Sampling Methodology

The thief sampling methodology has the advantage of targeting only the smaller fraction of the load thereby effectively concentrating the sampling effort. The thief is not the ideal sampling method if the target material is in the form of large fragments. However the consensus of amongst the processors was that larger fragments are efficiently removed by a combination of the pickers and the optical technology. The thief sampling methodology was thus designed to extract only a reduced size fraction. The presence of ceramic inclusions in this reduced fraction would be an indication of a wider presence in the bulk sample, the concentration of which could be estimated from that measured in the reduced fraction.

The thief extracted material with a maximum size of approximately 50 mm. A nominal 5 kg sample was obtained in each case, the product of approximately 12 increments.

The 5 kg sample was then sized on a 9.5mm sieve. Any large fragments being removed counted and weighed. In the event no large fragments were caught in any of the 18 samples.

The minus 9.5 mm fraction was then inspected with the aid of a light-bench.

The level of contamination was then be determined by a simple count of the significantly sized particles in that part of the thief sample that passed through the 9.5mm sieve.

This stage of the procedure was envisaged as the basis for a workable test.

However of the 18 samples tested just 4 contained inorganic contamination that was readily observable. Whilst this result is arguably consistent with those of the "standard" bulk sampling method, the evidence from the picking stations and glass manufacturers suggests that (both) tests as performed are not producing reliable results. A summary of the number and size of the ceramic particles captured by the thief is given below in Table 4

Sample Taken	Number of samples in which inorganic material was detected		
	Plus 9.5 mm	9.5 to 1.7 mm	Minus 1.7 mm
18	0	4	15

Table 4 Thief extracted sample - detection of inorganic material by size fraction

As a further check the thief sample was wet sieved through a 1.7 mm mesh and the fine fraction subject to a detailed analysis with the aid of a bench magnifier.

It is not proposed that such a wet method should be included in any practical test method to determine the inorganic content of cullet. Rather the purpose of this stage of the investigation was as a check on the validity of the earlier stages.

The size distribution theory outlined previously would predict that, if present, the majority of the particles by number would be found in the very fine fraction. Based on a 5 kg thief sample sampling only from a minus 50mm fraction, an inorganic level of 150 g/tonne itself having a size distribution as described in table 2 it was calculated that this fine, washed fraction should contain between 3 and 12 particles. The range is a function of the size distribution of the cullet. A 5 kg thief sample removed from a load comprising 90% unbroken containers will proportionally have much more of the fine fraction than a similar 5kg sample taken from a 50% unbroken load and would thus contain more small inorganic fragments.

This phase of the investigation did consistently identify inorganic contamination with some presence found in 15 of the 18 samples.

A simple particle count was used to quantify the contamination level in this small size fraction. In general the level detected was below that predicted from the model based upon the simple size distribution theory. However on 2 occasions counted particulate numbers exceeded the calculated levels. In both these cases the glass cullet, and by inference, the inorganic contamination, was well compacted. As the model was based on largely uncrushed (porcelain) the presence of more fines is consistent with more generation through attrition. A comparison on actual and calculated particle numbers is given above in Table 5.

Sample Classification	Sample Number
Total number of samples	18
Samples containing more than the calculated number of stones	2
Samples containing exactly the calculated number of stones	2
Samples containing less than the calculated number of stones Of which - number containing zero stones	14 (3)

Table 5 Stones detected in the minus 1.7 mm fraction – actual vs calculated

The consistent presence of inorganic material in the very fine fraction lends weigh to the belief that it was present thought the full size range of the majority of the loads and as such should have been detected in more of the bulk and thief samples. As with the standard methodology the thief sample size appears to have been insufficient to guarantee a representative sample.

8.2.5 Identification of the Inorganic Material

A number of the fine inorganic particles were subjected to a detailed examination by a scanning electron microscope (SEM). The SEM can provide semi-quantitative data on the chemical composition of fragments. Again there was no intention of suggesting that such a technique be incorporated into any standard test methodology. The intention here was simply to provide some guidance as to the origins of the inorganic contaminants. Figures 6 to 9 below show SEM derived details of 2 “typical” inorganic matter fragments.

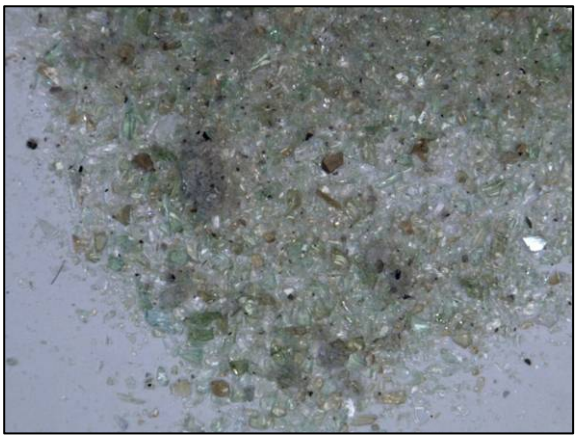


Figure 6 Washed minus 1.7 mm sample

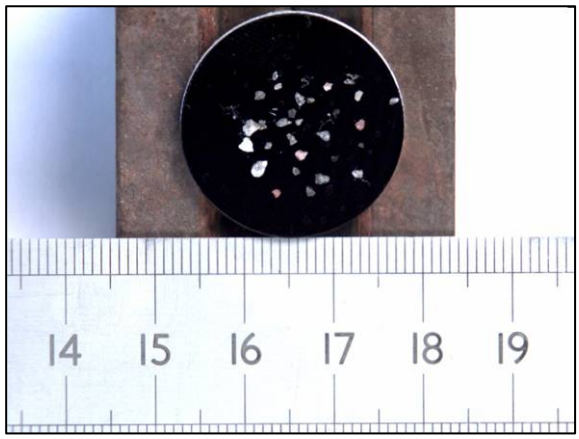
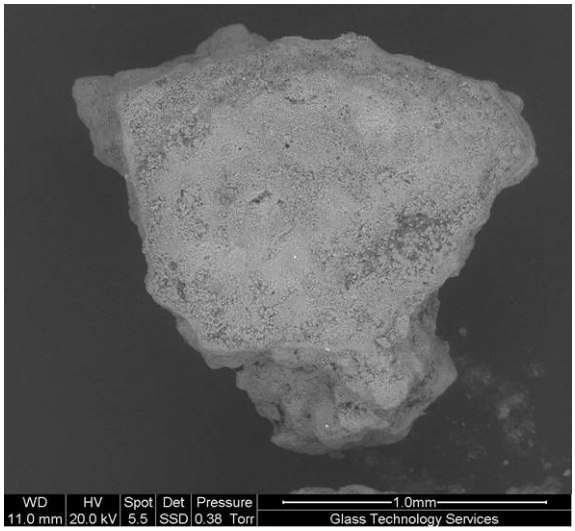
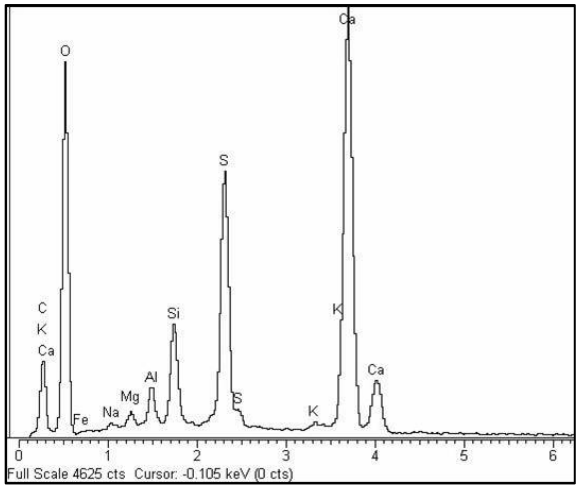
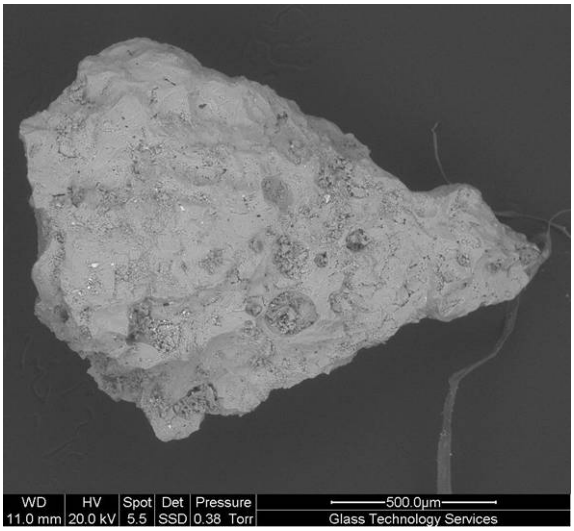


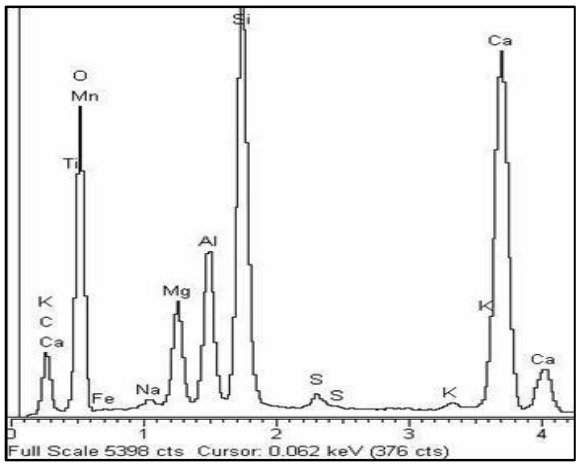
Figure 7 Fragments mounted for SEM analysis





Figures 8 1.7 mm fragment – cement-based material





Figures 9 1.7 mm fragment – alumina-silica material

The chemical compositions of the inorganic fragments analysed were typical of those obtained from cement and porcelain based objects. In general terms cementatious material has higher calcium content and is thus more soluble and less problematic than the high alumina material characteristic of porcelain contamination.

9 Suggested Limits for Inorganic Contaminants

A principal objective of this work was to propose upper (acceptable) limits to the level of inorganic material that could be accommodated in the various grades of recovered glass as delivered to the glass processors. The intention was to derive the limits from the results of the tests of the new methodology. Unfortunately these results do not provide the basis to set such limits. The work done on the size distribution of the cullet and the inorganic contaminants does however provide a mechanism whereby an acceptable limit could be proposed based on the observed results. The proposed simplified test methodology would selectively look at the minus 10 mm fraction. Assuming that a typical and therefore acceptable level of total inorganic material is 150g/t as removed by the pickers the model can be used to predict the equivalent concentration in a minus 10mm fraction. It must be remembered that the size distribution of the inorganic material is different to that of the glass and thus the contaminants are not distributed evenly amongst the various size fractions. An overall concentration of 150g/tonne of inorganic matter in the bulk sample would place 5g of the inorganic material in the minus -10 mm range of the glass. On average, for class A, B & C, some 2% of the glass was sized below 10mm. Thus the concentration of inorganic material found in the minus 10mm fraction of a glass sample would be the 5g (inorganic) divided by 2% (glass) which gives a concentration of 0.025% or 250 ppm i.e. the inorganic material is concentrated into the finer fraction. This 250 ppm concentration in the minus 10mm fraction would thus be the equivalent of the 150g/t limit set for the bulk sample.

The model would further predict that these 5 grams would include 32 fragments in the critical "stone-forming" size range of 1.5 to 8.5 mm. Should these stones go forward into the glass making furnace to produce 32 faults then, then they would produce a rejection rate of 0.3% (based on 40% cullet ratio and a bottle weight of 260g). Details of this calculation are given in Appendix 3.

Class D material has been compacted, so a much larger proportion of glass falls within the sub-10mm fraction (10%). Consequently any fine inorganic contamination will be more "diluted" by the additional glass at this size fraction and, to compensate for this effect, the limits, based on the 10mm fraction, need to be proportionally lower to obtain the same gross limit of 150g/tonne. In this case the 5 g of inorganic material sized below 10mm would be dispersed into 10% of the glass making a limit of 0.005% or 50 ppm the minus 10mm fraction, again the equivalent of a bulk concentration of 150 g/tonne.

Table 6 below sets out the proposed limits based on the methodology outlined above.

PAS 101 Class	Gross limit (full load) (g/tonne)	Fraction < 10mm (%)	Proposed Limits (minus 10 mm fraction only)	
			(ppm)	(%)
A	150	2	250	0.025
B	150	2	250	0.025
C	150	2	250	0.025
D	150	10	50	0.005

Table 6 Proposed limits for the inorganic content of recovered glass as delivered to the cullet processing plant

10 Proposed Simplified Testing Methodology (Inorganic Matter)

Principle	The inorganic content of the load shall be determined from the inorganic content of the sub-10mm fraction. The sub-10mm sample shall be obtained from the main body of the load by use of a cone-shaped sample thief.

10.1 Test Details

Using the sample thief and taking increments from around the heap a sample of no less than 20 kg shall be obtained.

1) The sample will be weighed.
2) The sample will be sieved on a 10mm mesh.
3) The over and undersized fractions will be reweighed.
4) The oversize fraction will be visually inspected and any inorganic material removed and weighed.
5) The presence of any inorganic particle larger than 10mm will indicate that the material does not meet the specification.
6) The undersized fraction will be subject to a detailed visual inspection using a back-lit light table.
7) All inorganic particles will be removed and weighed.
8) The mass of inorganic particles removed shall be expressed as a percentage of the total mass of the undersized fraction.
9) The recorded concentration of any inorganic material shall be compared with the limits published in the agreed specification.

11 Conclusions

Based upon the experience gained during the onsite work, the subsequent laboratory analysis and extensive discussions with the members of the steering group the following conclusions are advanced:

1) The recommended “standard” sampling method as outlined in PAS 101 is based upon an insufficient sampling weight of a (nominal) 100kg. The test method should be revised and a value of 1000kg recommended as an appropriate sample size for largely unbroken bottles.
2) Best practice would involve a larger sample manually sorted though a dedicated test picking line.
3) The project generated insufficient data from which acceptable limits could be directly generated.
4) The inorganic content of the recovered glass could be reliably estimated from a representative sample of a reduced size fraction. A minimum sample of a least 10 kg would be needed to ensure a representative sample.
5) The size distribution data, in conjunction with process information, has provided a method whereby limits have been proposed that befit the proposed simplified test methodology.

12 Recommendations

The project thus far represents the first stages in the adoption of limits for recovered container glass. A basis for a working test methodology has been established and a limited mathematical model developed which could provide useful information on the occurrence of ceramic inclusions in glass containers.

The recommendations listed below are designed to promote the adoption of the limits and the associated testing method.

It is therefore recommended that:

- ✓ The GTS hosts a seminar to disseminate the results of the project. All interested stakeholders would be invited.

- ✓ The proposed test methodology was developed from a statistically limited sample and based on an inadequate sample size. Additional testing of the thief methodology will be required to improve its standing as an acceptable method. This testing would need some form of parallel validation possibly involving the simultaneous testing of incoming loads with the use of a dedicated test picking facility as found on some of the larger processing sites.

- ✓ The mathematical model should be developed. The model would require a large volume of data to produce a useful tool. Such a volume of data could only arise from routine plant records e.g. daily/hourly log sheets of picker activity, computer-logged data on the activity of the optical sorting system and, if practical, by following the cullet though the glass manufacturing process and analysing the resultant faults. Such a process would undoubtedly face difficulties in resolving issues of confidentiality but the rewards for success would be significant.

- ✓ The sampling methodology as currently outlined in PAS101 is based on a (nominal) sample size of 100kg which is insufficient to gain a representative sample. PAS101 should be revised and a sample size of 1,000 kg is recommended.

- ✓ Identification of inorganic fragments at the laboratory-scale is still based on a manual picking and sorting technique which is laborious and somewhat subjective. Significant advances have been made in the automatic detection of ceramic inclusions for use in the processing plants. An attempt should be made to automate the laboratory testing possibly based on the technology incorporated in the sorting plants.

13 Circulation List

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John Marley	Berryman
Stuart McLean	UG/BGRC
Tim Gent	Midland Glass
Richardson	Viridor Richardson
Adam Day	Day Aggregates
Jim Walker	Allglass

14 Appendices

Appendix 1

This sheet calculates the particle size (number) distribution of ceramic inclusion in bottle bank cullet. The calculations are based upon the degree of handling (broken-ness) of the cullet and the level "picked" from the belt. Having calculated the number if particles the programme converts these into container forming faults based upon cullet ratio and bottle weight.

Delivered cullet load	12	tonnes	b	n
"Intactness" of load [1,2,3]	1		0.0008	1.6
Density of inclusions	2800	kg/m3		
"Picked" ceramics [above 20mm]	150	g/tonne		
Total Ceramics	1982	g/load		
Removal efficiency +20mm	90	%	20 to 10 mm	80 %

Mesh size mm	Retention (%)	Retention (g)	Ret (g)	Particle (g)	Particle count	Particles cum
200						
100	0.28	558	558	4949	0	0
80	0.41	816	258	1069	0	0
60	0.57	1132	316	503	1	1
40	0.75	1479	347	183	2	3
20	0.91	1800	320	40	8	11
15	0.94	1865	65	8	8	19
14	0.95	1877	12	4	3	22
13	0.95	1888	11	4	3	25
12	0.96	1899	11	3	4	29
11	0.96	1910	11	2	5	34
10	0.97	1920	10	2	6	40
9	0.97	1929	10	1	8	47
8	0.98	1938	9	1	10	57
7	0.98	1947	8	1	13	71
6	0.99	1954	8	0	19	90
5	0.99	1961	7	0	29	118
4	0.99	1967	6	0	46	165
3	1.00	1973	5	0	85	250
2	1.00	1977	4	0	191	440
1	1.00	1980	3	0	650	1090
0	1.00	1982	2	0	8648	9738

Container Faults		
Av container weight	268	g
Cullet level	40	%
Total glass	30	tonnes
Total containers	111940	number
Total inclusions + 10 mm missed by processors	7	number
At 8.5 mm	57	number
At 2.5 mm	440	number
Total inclusions	390	number
Inclusion Rate	0.3	%

Summary	Number	Weight Fraction (%)
Pickers + 20mm	11	91
Optical system +8 mm	46	7
Critical 2.5 - 8.5 mm	383	1.7
Soluble -3mm	9297	0.5

Appendix 2

Date	10-Feb-04		**Sample Data**	**1**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA10feb/1					
Glass Colour	Green					
PAS spec	A	Broken colour separated		88%		
Source	Bottle bank					
Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	71.5	197	7	3.6	9
	broken	10				
	+30	7.5				
	-30	2.5				
	-9.5	0.31				
Thief Sample		4.86	4.64	0.22	4.5	
	+30	2.56				
	-30	2.3				
	-9.5	0.42				
		Fraction of whole sample			6.9%	
Inorganic particles			** Detected (actual) **		** Calculated **	
			Number	Mass	Number	Mass
Bulk sample - All		dry	0	0	23	16
Bulk sample -9.5 mm		dry	0	0	6	16
Thief 60 to 9.5 mm		dry	0	0	0.9	13
Thief minus 9.5 to 1.7mm		dry	0	0.31	7.5	0.9
Thief minus 1.7 to 0.5 mm		wet	4		12	0.1
Size %		bulk				
	75	0.88				
	50	0.09				
	15	0.03				
	3	0.00				
	0	0.00				

Date	10-Feb-04		**Sample Data**	**2**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA10feb/2					
Glass Colour	Flint					
PAS spec	B	Broken colour separated		72%		
Source	Bottle bank					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	75	184	10	5.4	12
	broken	28.5				
	+30	20				
	-30	8.5				
	-9.5	2.2				
Thief Sample		5.11	4.89	0.22	4.3	
	+30	2.63				
	-30	2.48				
	-9.5	0.46				
		Fraction of whole sample			15.9%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	29	16
Bulk sample -9.5 mm	dry	0	0	7	21
Thief 60 to 9.5 mm	dry	0	0	0.4	6
Thief minus 9.5 to 1.7mm	dry	0	0	3.3	0.4
Thief minus 1.7 to 0.5 mm	wet	2		5	0.0

Size %	
75	0.72
50	0.19
15	0.06
3	0.01
0	0.01

Date	11-Feb-04		**Sample Data**	**3**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA10feb/3					
Glass Colour	Green					
PAS spec	B	Unbroken colour separated		82%		
Source	Bottle bank					
Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	76	196	13	6.6	12
	broken	17				
	+30	12				
	-30	5				
	9.5	1.8				
Thief Sample		4.21	3.95	0.26	6.2	
	+30	2.2				
	-30	2.01				
	9.5	0.37				
		Fraction of whole sample			10.1%	
Inorganic particles			** Detected (actual) **		** Calculated **	
			Number	Mass	Number	Mass
Bulk sample - All		dry	0	0	26	19
Bulk sample -9.5 mm		dry	0	0	6	18
Thief 60 to 9.5 mm		dry	0	0	0.5	8
Thief minus 9.5 to 1.7mm		dry	0	0	4.4	0.6
Thief minus 1.7 to 0.5 mm		wet	3		7	0.0
Size %						
	75	0.82				
	50	0.13				
	15	0.03				
	3	0.01				
	0	0.01				

Date	11-Feb-04		**Sample Data**	**4**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA10feb/4					
Glass Colour	Green					
PAS spec	B	Unbroken colour separated		79%		
Source	Bottle bank					
Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	85	215	17	7.9	15
	broken	22				
	+30	16				
	-30	6				
	-3/8	0.65				
Thief Sample		5.13	4.69	0.44	8.6	
	+30	2.67				
	-30	2.46				
	-3/8	0.45				
		Fraction of whole sample			11.8%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	30	21
Bulk sample -9.5 mm	dry	0	0	7	21
Thief 60 to 9.5 mm	dry	0	0	0.4	7
Thief minus 9.5 to 1.7mm	dry	0	0	3.8	0.5
Thief minus 1.7 to 0.5 mm	wet	2		6	0.0

Size %	
75	0.79
50	0.15
15	0.05
3	0.00
0	0.00

Date	11-Feb-04		**Sample Data**	**5**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA11feb/5					
Glass Colour	Flint					
PAS spec	B	Unbroken colour separated		73%		
Source	Bottle bank					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	82	214	14	6.5	17
	broken	31				
	+30	21				
	-30	10				
	9.5	0.64				
Thief Sample		4.86	4.57	0.29	6.0	
	+30	2.42				
	-30	2.44				
	9.5	0.46				
		Fraction of whole sample			26.0%	

Inorganic particles		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	32	23
Bulk sample -9.5 mm	dry	0	0	8	22
Thief 60 to 9.5 mm	dry	0	0	0.2	3
Thief minus 9.5 to 1.7mm	dry	1	0	2.0	0.3
Thief minus 1.7 to 0.5 mm	wet	0		3	0.0

Size %	
75	0.73
50	0.19
15	0.08
3	0.00
0	0.00

Date	11-Feb-04		**Sample Data**	**6**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA11feb/6					
Glass Colour	Green					
PAS spec	A	Unbroken colour separated		83%		
Source	Bottle bank					
Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	68	184	6	3.3	6
	broken	14				
	+30	11				
	-30	3				
	-3/8	0.52				
Thief Sample		5.23	5.02	0.21	4.0	
	+30	2.55				
	-30	2.68				
	-3/8	0.52				
		Fraction of whole sample			31.8%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	23	16
Bulk sample -9.5 mm	dry	0	0	6	16
Thief 60 to 9.5 mm	dry	0	0	0.2	3
Thief minus 9.5 to 1.7mm	dry	0	0	1.6	0.2
Thief minus 1.7 to 0.5 mm	wet	3		3	0.0

Size %	
75	0.83
50	0.13
15	0.03
3	0.00
0	0.00

Date	11-Feb-04		**Sample Data**	**7**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA11feb/7					
Glass Colour	Flint					
PAS spec	B	Unbroken colour separated		78%		
Source	Bottle bank					
Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	67	172	10	5.8	10
	broken	19				
	+30	12				
	-30	7				
	9.5	1.1				
Thief Sample		4.84	4.48	0.36	7.4	
	+30	2.43				
	-30	2.41				
	9.5	0.45				
		Fraction of whole sample			24.0%	
Inorganic particles			** Detected (actual) **		** Calculated **	
			Number	Mass	Number	Mass
Bulk sample - All		dry	0	0	24	17
Bulk sample -9.5 mm		dry	0	0	6	17
Thief 60 to 9.5 mm		dry	0	0	0.3	4
Thief minus 9.5 to 1.7mm		dry	0	0	2.1	0.3
Thief minus 1.7 to 0.5 mm		wet	2		3	0.0
Size %						
	75	0.78				
	50	0.14				
	15	0.07				
	3	0.01				
	0	0.01				

Date	11-Feb-04		**Sample Data**	**8**		
Samplers	WAH + MP		**Location**	Site A		
Sample ref	PAS/SiteA11feb/8					
Glass Colour	Flint					
PAS spec	B	Unbroken colour separated		73%		
Source	Bottle bank					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	87	230	16	7.0	18
	broken	33				
	+30	25				
	-30	8				
	-3/8	0.52				
Thief Sample		5.24	4.89	0.35	6.7	
	+30	2.57				
	-30	2.67				
	-3/8	0.51				
		Fraction of whole sample			30.1%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	34	24
Bulk sample -9.5 mm	dry	0	0	8	24
Thief 60 to 9.5 mm	dry	0	0	0.2	3
Thief minus 9.5 to 1.7mm	dry	0	0	1.7	0.2
Thief minus 1.7 to 0.5 mm	wet	0		3	0.0

Size %	
75	0.73
50	0.21
15	0.06
3	0.00
0	0.00

Date	25-Feb-04		**Sample Data**	**1**		
Samplers	WAH + MP		**Location**	Site B		
Sample ref	PAS/SiteB25feb/1					
Glass Colour	Green					
PAS spec	C	Unbroken colour separated		76%		
Source	Brewery warehouse					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	96	258	99	38.4	9
	broken	30				
	+30	12				
	-30	18				
	-9.5	0.8				
Thief Sample		5.21	3.61	1.6	30.7	
	+30	1.2				
	-30	4.01				
	-9.5	0.47				
		Fraction of whole sample			15.2%	

Inorganic particles		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	36	25
Bulk sample -9.5 mm	dry	0	0	9	25
Thief 60 to 9.5 mm	dry	0	0	0.4	6
Thief minus 9.5 to 1.7mm	dry	0	0	3.7	0.5
Thief minus 1.7 to 0.5 mm	wet	0		6	0.0

Size %	bulk
75	0.76
50	0.10
15	0.14
3	0.00
0	0.00

Date	25-Feb-04		**Sample Data**	**2**		
Samplers	WAH + MP		**Location**	Site B		
Sample ref	PAS/SiteB25feb/2					
Glass Colour	Green					
PAS spec	C	Broken colour separated		78%		
Source	Bottle bank					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	80	209	49	23.4	16
	broken	22				
	+30	16				
	-30	6				
	-9.5	1.2				
Thief Sample		5.32	4.22	1.1	20.7	
	+30	0.94				
	-30	4.38				
	-9.5	0.47				
		Fraction of whole sample			12.3%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	29	20
Bulk sample -9.5 mm	dry	0	0	7	20
Thief 60 to 9.5 mm	dry	0	0	0.5	8
Thief minus 9.5 to 1.7mm	dry	0	0	4.5	0.6
Thief minus 1.7 to 0.5 mm	wet	3		7	0.0

Size %	
75	0.78
50	0.16
15	0.05
3	0.01
0	0.01

Date	25-Feb-04		**Sample Data**	**3**		
Samplers	WAH + MP		**Location**	Site B		
Sample ref	PAS/SiteB25feb/3					
Glass Colour	Flint					
PAS spec	A	Unbroken colour separated		60%		
Source	Bottle bank					
Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	72	186	6	3.2	16
	broken	48				
	+30	34				
	-30	14				
	9.5	1.84				
Thief Sample		5.65	5.36	0.287	5.1	
	+30	1.8				
	-30	3.85				
	9.5	0.53				
		Fraction of whole sample			24.3%	
Inorganic particles			** Detected (actual) **		** Calculated **	
			Number	Mass	Number	Mass
Bulk sample - All		dry	0	0	34	24
Bulk sample -9.5 mm		dry	0	0	8	24
Thief 60 to 9.5 mm		dry	0	0	0.3	4
Thief minus 9.5 to 1.7mm		dry	0	0	2.5	0.3
Thief minus 1.7 to 0.5 mm		wet	2		4	0.0
Size %						
	75	0.60				
	50	0.28				
	15	0.10				
	3	0.01				
	0	0.01				

Date	25-Feb-04		**Sample Data**	**4**		
Samplers	WAH + MP		**Location**	Site B		
Sample ref	PAS/SiteB26feb/4					
Glass Colour	Flint					
PAS spec	B	Unbroken colour separated		59%		
Source	Bottle bank					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	88	268	12	4.5	18
	broken	62				
	+30	35				
	-30	27				
	-3/8	1.22				
Thief Sample		4.92	4.631	0.289	5.9	
	+30	1.1				
	-30	3.82				
	-3/8	0.47				
		Fraction of whole sample			25.8%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	42	30
Bulk sample -9.5 mm	dry	0	0	10	30
Thief 60 to 9.5 mm	dry	0	0	0.3	4
Thief minus 9.5 to 1.7mm	dry	1	0	2.3	0.3
Thief minus 1.7 to 0.5 mm	wet	3		4	0.0

Size %	
75	0.59
50	0.23
15	0.17
3	0.00
0	0.00

Date	11-Feb-04		**Sample Data**	**5**		
Samplers	WAH + MP		**Location**	Site B		
Sample ref	PAS/SiteB26feb/5					
Glass Colour	Amber					
PAS spec	C	Unbroken colour separated		55%		
Source	Bottle bank					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	78	236	76	32.2	8
	broken	64				
	+30	49				
	-30	15				
	9.5	0.7				
Thief Sample		4.95	3.2	1.75	35.4	
	+30	2.2				
	-30	2.75				
	9.5	0.48				
		Fraction of whole sample			30.6%	

Inorganic particles		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	40	29
Bulk sample -9.5 mm	dry	2	0.59	10	28
Thief 60 to 9.5 mm	dry	0	0	0.2	3
Thief minus 9.5 to 1.7mm	dry	0	0	1.7	0.2
Thief minus 1.7 to 0.5 mm	wet	2		3	0.0

Size %	
75	0.55
50	0.35
15	0.10
3	0.00
0	0.00

Date	11-Feb-04		**Sample Data**	**6**		
Samplers	WAH + MP		**Location**	Site B		
Sample ref	PAS/SiteB26feb/6					
Glass Colour	Amber					
PAS spec	C	Unbroken colour separated		58%		
Source	Bottle bank					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	97	284	70	24.6	18
	broken	70				
	+30	44				
	-30	26				
	-3/8	1.2				
Thief Sample		5.23	4.02	1.21	23.1	
	+30	0.94				
	-30	4.29				
	-3/8	0.49				
		Fraction of whole sample			23.9%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	47	34
Bulk sample -9.5 mm	dry	0	0	11	33
Thief 60 to 9.5 mm	dry	0	0	0.3	4
Thief minus 9.5 to 1.7mm	dry	1	0	2.2	0.3
Thief minus 1.7 to 0.5 mm	wet	2		3	0.0

Size %	
75	0.58
50	0.26
15	0.15
3	0.00
0	0.00

Date	02-Mar-04		**Sample Data**	**1**		
Samplers	SP + MP		**Location**	Site C		
Sample ref	PAS/SiteC_2march1					
Glass Colour	Green					
PAS spec	B	Compacted colour separated		26%		
Source	Local Authority					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	30	63	6	9.5	2
	broken	85.5				
	+30	60				
	-30	25.5				
	-9.5	1.5				
Thief Sample		4.82	4.43	0.39	8.1	
	+30	2.13				
	-30	2.69				
	-9.5	0.55				
		Fraction of whole sample			52.6%	

Inorganic particles		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	33	23
Bulk sample -9.5 mm	dry	0	0	8	23
Thief 60 to 9.5 mm	dry	0	0	0.1	2
Thief minus 9.5 to 1.7mm	dry	1	0	1.0	0.1
Thief minus 1.7 to 0.5 mm	wet	2		2	0.0

Size %	bulk
75	0.26
50	0.52
15	0.21
3	0.01
0	0.01

Date	02-Mar-04		**Sample Data**	**2**		
Samplers	SP + MP		**Location**	Site C		
Sample ref	PAS/SiteC_2march2					
Glass Colour	Flint					
PAS spec	B	Broken colour separated		41%		
Source	Local Authority					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	45	118	5	4.2	6
	broken	65				
	+30	42				
	-30	23				
	-9.5	1.2				
Thief Sample		5.13	4.83	0.3	5.8	
	+30	2.43				
	-30	2.7				
	-9.5	0.53				
		Fraction of whole sample			38.9%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	31	22
Bulk sample -9.5 mm	dry	0	0	8	22
Thief 60 to 9.5 mm	dry	0	0	0.2	2
Thief minus 9.5 to 1.7mm	dry	0	0	1.3	0.2
Thief minus 1.7 to 0.5 mm	wet	3		2	0.0

Size %	
75	0.41
50	0.38
15	0.20
3	0.01
0	0.01

Date	02-Mar-04		**Sample Data**	**3**		
Samplers	SP + MP		**Location**	Site C		
Sample ref	PAS/SiteC_2march3					
Glass Colour	Green					
PAS spec	D	Compacted colour separated		33%		
Source	Local Authority					
Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	33	66	4	6.1	9
	broken	66				
	+30	44				
	-30	22				
	9.5	1.62				
Thief Sample		5.18	4.84	0.34	6.6	
	+30	2.38				
	-30	2.8				
	9.5	0.56				
		Fraction of whole sample			45.4%	
Inorganic particles			** Detected (actual) **		** Calculated **	
			Number	Mass	Number	Mass
Bulk sample - All		dry	0	0	28	20
Bulk sample -9.5 mm		dry	5	1.24	7	20
Thief 60 to 9.5 mm		dry	0	0	0.1	2
Thief minus 9.5 to 1.7mm		dry	0	0	1.2	0.2
Thief minus 1.7 to 0.5 mm		wet	1		2	0.0
Size %						
	75	0.33				
	50	0.44				
	15	0.21				
	3	0.01				
	0	0.01				

Date	02-Mar-04		**Sample Data**	**4**		
Samplers	SP + MP		**Location**	Site C		
Sample ref	PAS/SiteC_2march4					
Glass Colour	Green					
PAS spec	D	Compacted colour separated		5%		
Source	Local Authority					

Bulk Sample		**kg**	**units**	**wrong col**	**%**	**cans**
	unbroken	4.4	11	2	18.2	3
	broken	92				
	+30	40				
	-30	52				
	-3/8	1.98				
Thief Sample		4.98	4.17	0.81	16.3	
	+30	1.65				
	-30	3.33				
	-3/8	0.81				
		Fraction of whole sample			81.8%	

Inorganic particles found		** Detected (actual) **		** Calculated **	
		Number	Mass	Number	Mass
Bulk sample - All	dry	0	0	27	19
Bulk sample -9.5 mm	dry	3	0.45	7	19
Thief 60 to 9.5 mm	dry	0	0	0.1	1
Thief minus 9.5 to 1.7mm	dry	0	0	0.7	0.1
Thief minus 1.7 to 0.5 mm	wet	3		1	0.0

Size %	
75	0.05
50	0.41
15	0.52
3	0.01
0	0.01

Appendix 3

Critical sized fragments associated with a level of 150g/tonne at the picking station. This sheet calculates the particle size (number) distribution of ceramic inclusion in bottle bank cullet. The calculations are based upon the degree of handling (broken-ness) of the cullet and the level "picked" from the belt. Having calculated the number if particles the programme converts these into container forming faults based upon cullet ratio and bottle weight.

Delivered cullet load	1	tonnes	b	n	
"Intactness" of load [1,2,3]	1		0.0008	1.6	
Density of inclusions	2800	kg/m3			
"Picked" ceramics [above 20mm]	150	g/tonne			
Total Ceramics	165	g/load			
Removal efficiency +20mm	100	%	20 to 10 mm	100	%

Mesh size mm	Retention (%)	Retention (g)	Ret (g)	Particle (g)	Particle count	Particles cum
200						
100	0.28	46	46	4949	0	0
80	0.41	68	22	1069	0	0
60	0.57	94	26	503	0	0
40	0.75	123	29	183	0	0
20	0.91	150	27	40	1	1
15	0.94	155	5	8	1	2
14	0.95	156	1	4	0	2
13	0.95	157	1	4	0	2
12	0.96	158	1	3	0	2
11	0.96	159	1	2	0	3
10	0.97	160	1	2	0	3
9	0.97	161	1	1	1	4
8	0.98	161	1	1	1	5
7	0.98	162	1	1	1	6
6	0.99	163	1	0	2	7
5	0.99	163	1	0	2	10
4	0.99	164	1	0	4	14
3	1.00	164	0	0	7	21
2	1.00	165	0	0	16	37
1	1.00	165	0	0	54	91
0	1.00	165	0	0	720	811

Container Faults		
Av container weight	260	g
Cullet level	40	%
Total glass	3	tonnes
Total containers	9615	number
Total inclusions + 10 mm missed by processors	0	number
At 8.5 mm	5	number
At 2.5 mm	37	number
Total inclusions	32	number
Inclusion Rate	0.3	%

Summary	Number	Weight Fraction (%)
Pickers + 20mm	1	91
Optical system +8 mm	4	7
Critical 2.5 - 8.5 mm	32	1.7
Soluble -3mm	774	0.5