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Uncertainty Considerations with the GRIM

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ABSTRACT

Uncertainty Considerations with Glass Refractive Index

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Refractive index has been chosen as a comparison technique in glass analysis for many years. Hidden in this comparison is a quantitative measurement that requires the assessment of uncertainty. In this experiment, refractive index was performed on 63 samples from 41 sources of glass. Pairwise comparisons were calculated to illustrate the difference between using a conventional approach like standard deviation to using uncertainty. The amount of pairwise comparisons more than tripled from standard deviation to uncertainty showing the need to consider all possible sources of uncertainty in a refractive index measurement.

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Introduction

Glass is a common form of physical evidence that is easily transferred. Glass samples can come from many sources like house windows, car windows, glass bottles, eye glasses, and glass fiber optics, to name a few. The most common glass encountered is soda lime glass which is found in house windows and glass bottles (1). The next most common is laminated and tempered glass which comes from different windows in an automobile (1). Currently, the most common forensic analysis method for glass is the determination of refractive index (RI) (2). This technique has evolved from being manual with use of the Becke line method to current automated methods with the GRIM (Glass Refractive Index Measurement). Each type of glass can have a different RI based on its composition but the RI range for glass is narrow, typically a range from 1.4735-1.5600 (1). Because this range is so narrow, RI alone is often of limited value for discrimination and other techniques are needed (3). The techniques of X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), and scanning electron microscope energy dispersive X-ray spectrometry (SEM-EDX), have shown promise as supplemental techniques to RI (2).

The National Academy of Sciences issued a report in 2009 (4) regarding the use of uncertainty when reporting a quantitative measurement. Thus, even though RI is used for comparison, it is a quantitative method. As such, the uncertainty of that measurement must be known to insure the utility and reliability of the data. To address this, an uncertainty budget will be created in this project and utilized in the results to show the effect that it does have.

Background

The formation of glass is a multi-step process. All the materials that are used in forming the glass are combined, heated, and then cooled extremely quickly. Some of the main components in a glass sample are sand, soda, lime, and other elements that are more distinct to the individual company that is producing the glass. Glass can be formed into many shapes and sizes based on the type of glass and size needed. Soda lime glass is the most common contributing to house windows and glass bottles. Windshields are formed from two pieces of soda lime glass with a plastic sheet in between the layers, called laminated glass. One of the final forms of glass is tempered glass. Tempered glass is designed so that when it breaks it does so into small little pieces. This is advantageous for automobile windows as a safety feature. The production of these types of glass, flat glass and container glass, can be done through the processes of blowing, casting, pressing, or spinning (1). Problems with the striations in flat glass due to the rolling were resolved by the float process. In the float process the liquid glass slides down onto a molten layer of tin or nickel and “floats” on it until it hardens. This is the primary way in which flat glass is produced in the United States (1).

RI is the main way in which glass is differentiated in forensic science (2). RI is a non-destructive technique that has generally been accepted as having sufficient accuracy and precision for casework (2). Refractive index is based on the concept that as light passes from one medium to another, it changes direction, wavelength, and speed due to the composition of that medium. Using Snell’s Law (Figure 1) and knowing the angle, velocity, or RI of the first medium, the RI can be calculated for the second medium, which is this case is glass.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Figure 1: Snell's Law

There are a number of ways to measure RI like automated or manual temperature variation or the Becke line method, to name a few (5). The second method of the Becke line involves a set of calibrated immersion liquids in which the analyst training and expertise are huge factors. The analyst starts by immersing the glass in the liquid and places it under the microscope. A bright "halo ring" or Becke line appears around the glass sample and as the focus of the microscope changes so does the location of the Becke line (5). This change, either movement toward the glass or the oil, indicates whether the glass has a higher or lower RI than the oil. The contrast between the oil and the glass then tells the analyst the magnitude of the difference. After this is performed, the glass is removed from the oil, cleaned, and placed in the next oil that is believed to be closer in RI based on the previous results. This procedure is repeated until the match point has been reached or it has been bracketed by two different oils (5). A plot of the results can then be made to determine the RI of the glass.

The first method above of temperature variation was perfected with the creation of the GRIM. It is based on similar principles but is carried out differently. The GRIM utilizes an immersion oil that changes refractive index as a function of temperature. The glass however changes very little with temperature, so when the glass "disappears" in the oil or the glass and oil have the least amount of contrast, the oil and glass have the same

RI (5). These oils are calibrated using glass standards and the temperature can then be converted to an RI using the calibration curve.

Each type of glass produced has a different range of refractive indices and the refractive index range for those types of glasses are narrowing as the production processes are shrinking as manufacturing becomes more uniform. RI can also vary within a single sample (such as within a pane of window glass) because glass does not have a distinct crystal structure and is not homogeneous, especially float glass (6). As a result of glass not being homogeneous and becoming more similar in manufacturing, further classification by other techniques such as elemental analysis is often needed.

Techniques such as XRF (7, 8) and SEM-EDX (9, 10) are two methods used to perform elemental analysis on glass. XRF and EDX allow for elemental analysis through bombarding the sample with an electron beam, X-ray beam, or another excitation source. When a sample is bombarded, the electrons or X-rays interact with the sample and can cause the ejection of one of the electrons in the shells of the atoms present. This causes an electron hole in which another election from a higher energy level of that atom falls "down" to fill the hole. When this happens, characteristics X-rays are emitted from the atom to release the energy between the higher and lower energy levels. These X-rays are then measure and collected by the detector. Elemental analysis can be gathered from this data because the X-rays emitted are specific to the atoms present and the quantities of the X-rays are reflective of the abundance of the atom in the sample.

There are many other techniques however that are used to determine the elemental analysis of glass. Some of these techniques are atomic absorption, inductively coupled plasma atomic emission spectrometry (ICP-AES), inductively coupled plasma mass spectrometry (ICP-MS), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The latter two techniques, ICP-MS and LA-ICP-MS, provide the most information regarding the elemental analysis of glass. One of the main advantages of these two techniques is the ability to detect isotopes of elements at low limits of detection (2). The main disadvantage of the ICP-MS is the destructive nature of the sample. The sample has to be crushed between low density polyethylene sheets and dissolved, heated and dried, and then dissolved again before putting into the instrument (9). LA is one way to counter this limitation. With LA, a small part of the sample to be ablated away using a high energy laser. The small particles that are produced are carried away by an argon gas, taken to a column of heated plasma and separated into atoms, before being analyzed by a mass spectrometer. This is an advantage because not only is a small part of the sample being used, but less time is needed to prepare the sample. For these reasons, LA-ICP-MS is currently considered to be ideally suited for elemental analysis of glass (10). Many studies have been done showing different sampling strategies that work best for LA-ICP-MS including tests done regarding micro-homogeneity (3) and also sample size and shape considerations (11). Due to its high capital cost, LA-ICP-MS is not found in most crime laboratories even though it is the best technique for elemental analysis of glass. The primary method used for elemental analysis is SEM-EDX.

Materials and Methods

Sixty three random samples from forty one sources of glass were gathered from a combination of local glass and window companies, beer bottles, and drinking glasses. RI analysis was performed on the samples using a Foster and Freeman GRIM 3 coupled to a Foster and Freeman TA-1 phase contrast microscope using a FP82HT Mettler Toledo hotstage. A 590 nanometer(nm) filter was used to narrow the wavelengths of light emitted by the light source. Kohler illumination and lighting was confirmed daily. The glass slides and cover slips used for the calibration and samples were cleaned using ethanol and deionized water.

The calibration was performed using the Locke B oil, 590 nm light, Locke glass standards, and the certified RI values for each standard based on the conditions above. A total of 6 measurements of each glass standard (B1-B12) were performed to create a calibration curve using a least squares method. According to the procedure recommended by Foster and Freeman, the calibration curve could be accepted once all the values fell within the accepted +/- 10 maximum dri (deviation from RI) range. The FBI recommends calibrating using only a select set of the B1-B12 standards due to inconsistent responses close to room temperature. However in this study, all of the standards were used and in all cases, the dri maximum was within +/- 10 dri. Once the calibration curve was within the acceptable limits, it was used to analyze the glass samples. At the start of each day of measurement, the microscope was turned on for an hour before any measurements were taken to allow for the area around the microscope to be heated to the temperature it would be at for the measurements. A glass standard was analyzed each day to make sure that the GRIM was working properly and that the RI fell within two standard deviations of the calibration curve for that standard to measure for any day-to-day variation.

All of the samples were first rinsed using deionized water and then crushed into smaller pieces using a mortar and pestle. The samples and standards were then prepared by placing a drop of the B oil on the cleaned slide and then placing a small piece of the desired glass in the B oil and crushing in into even smaller pieces on the slide. A cover slip was then placed on top of the sample and oil and placed in the hot stage that was placed on the microscope. The location of the glass from each sample used for this RI analysis, whether it be from the bulk of the sample or edge, was not considered here as in casework there may not be the ability to have this knowledge or choice.

Eight RI measurements were taken for each sample to get a representative sampling of the glass while making sure the edge count value for each measurement was acceptable. The GRIM converts the contrast between the oil and the glass edge to counts, the higher number the better, and this gives an indication of how distinct the edge was for contrast analysis. The average RI for each measurement was taken by averaging the cool-down and heat-up RI value. A screen shot of the analysis of a standard is below in Figure 2. The upper left box indicated by the green arrow is the view from the microscope to select the class samples for analysis. The colors/numbers of the points selected coincide with the graphs of the heating and cooling process to the right of the microscope view. The graphs are a measure of temperature versus contrast between the oil and glass.

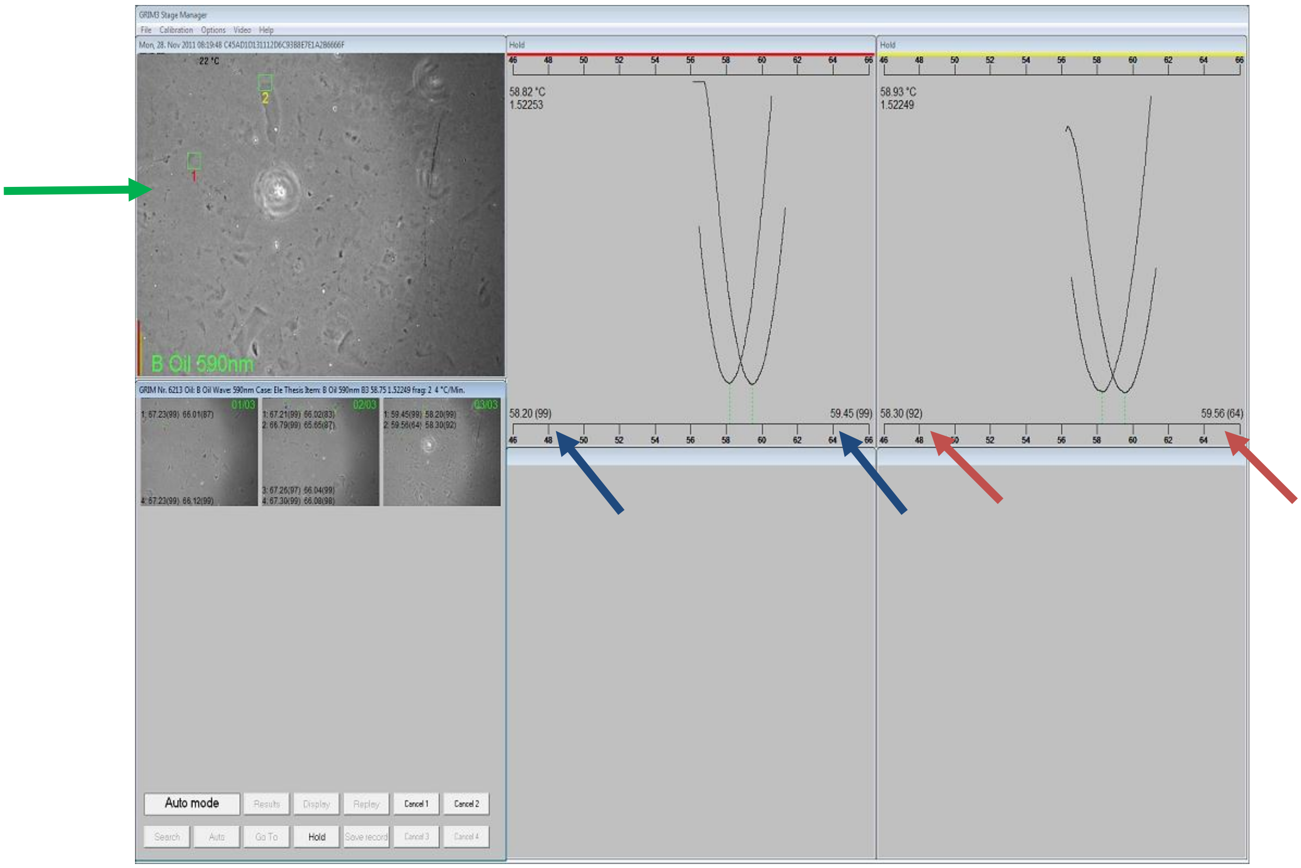


Figure 2: Screen Shot of GRIM software

In the lower left and right corner of each of those boxes, indicated by the blue and red arrows, are the heating and cooling RI values. The value in parenthesis that follows the RI value indicates the edge count value described above, with 99 being the highest and 1 the lowest. This is the reason for the use of a phase contrast microscope. The difference in contrast between the glass and oil is measured to determine when the glass and oil have the same RI and a phase contrast microscope is needed to distinguish these minute differences. If the curve does not yield an edge count of 99 then the curve will be smoothed and not as pointed at the lowest point. This does not allow for a minimum contrast to be determined between the oil and glass and thus it was not accepted as being an accurate RI value. The red arrows show a value that was rejected and not used as it did not produce edge counts of 99 for both values, where the blue arrows indicate an acceptable measurement

Results

All of the RI measurements for each sample and source are listed in Appendix A. Figure 3 shows the frequency of the RI measurements for flat glass samples in this experiment and shows that glass manufacturing is improving and as a result, the range of RI's seen in case samples is becoming smaller.

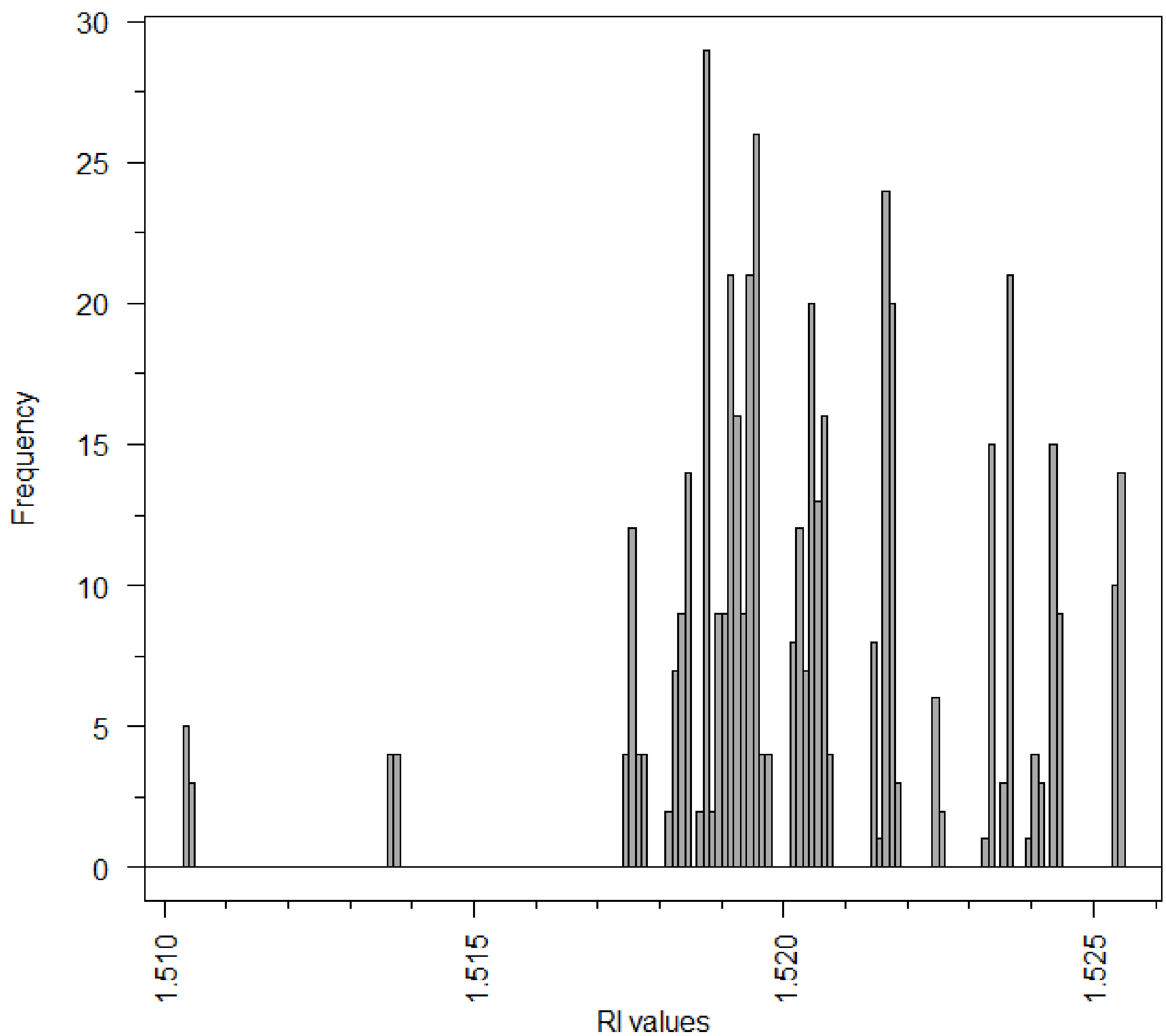


Figure 3: Frequency of RI values of float glass samples in this experiment

This is a problem because as the expected range decreases, so does the ability to differentiate between glasses. These values are similar to the distribution of RI's that the FBI found in flat glass from 1980-1997. This database that the FBI created since the 1960's showed that the distributions of RI measurements have narrowed, and even though this study contains fewer sources than the FBI database, the same trends are seen (12). Figure 4 below illustrates a box plot of all of the samples and their average RI values.

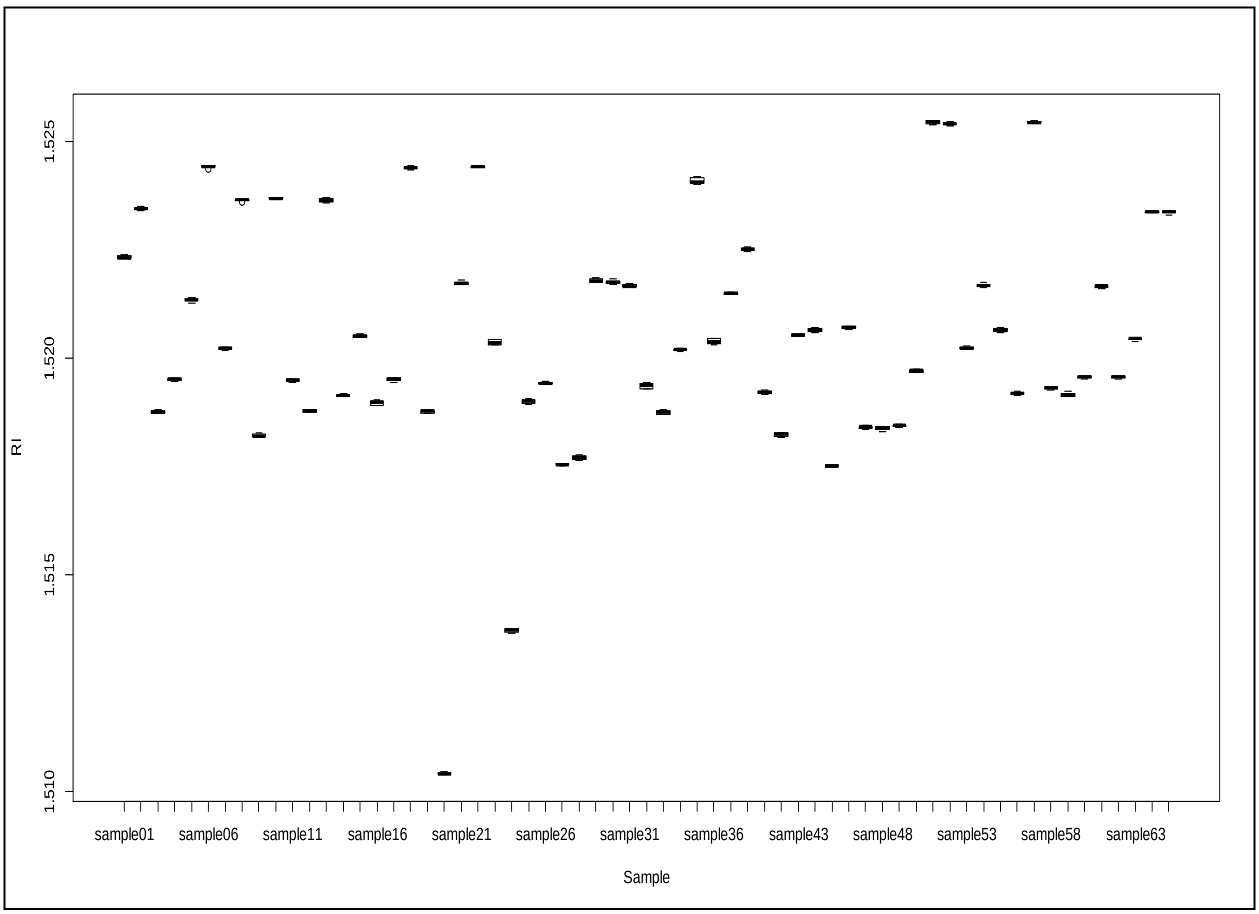


Figure 4: Box plot of all samples and their RI

Given that sample 20 and 24 were much lower in RI than the rest of the bulk of the samples, the data is re-plotted in Figure 5 which shows the RI distribution of the bulk of the samples without those two included. These values in Figures 4 and 5 are the median and distribution of the 8 RI measurements taken for each sample. Some of these samples however are from the same source as there were 63 samples from only 41 sources.

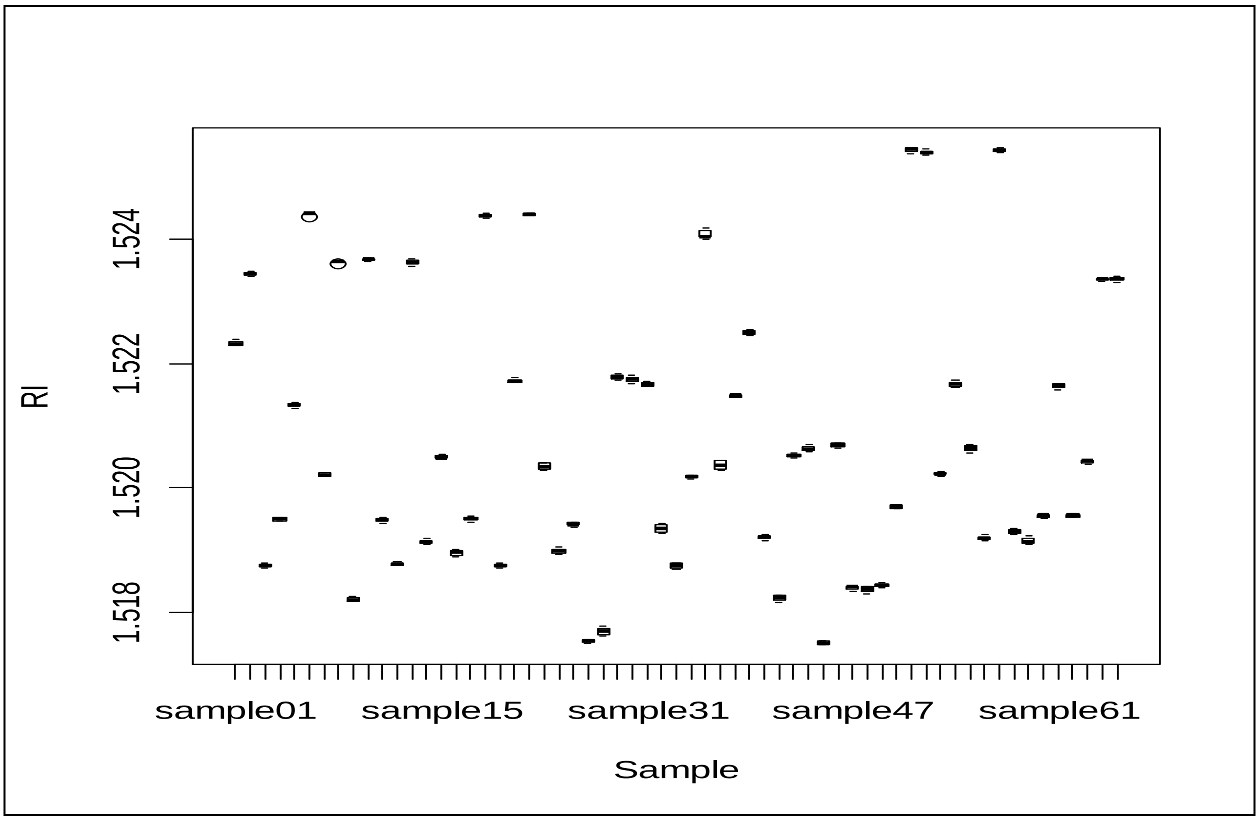


Figure 5: Box plot of samples and their RI re-plotted

Some of the sources of glass were sampled more than once to determine the homogeneity of the glass sources. Figures 6, 7, and 8 show a boxplot of 3 different sources of glass that were sampled 3 times. The box represents 25% to 75% of the RI values with the dark line in the center being the median RI value.

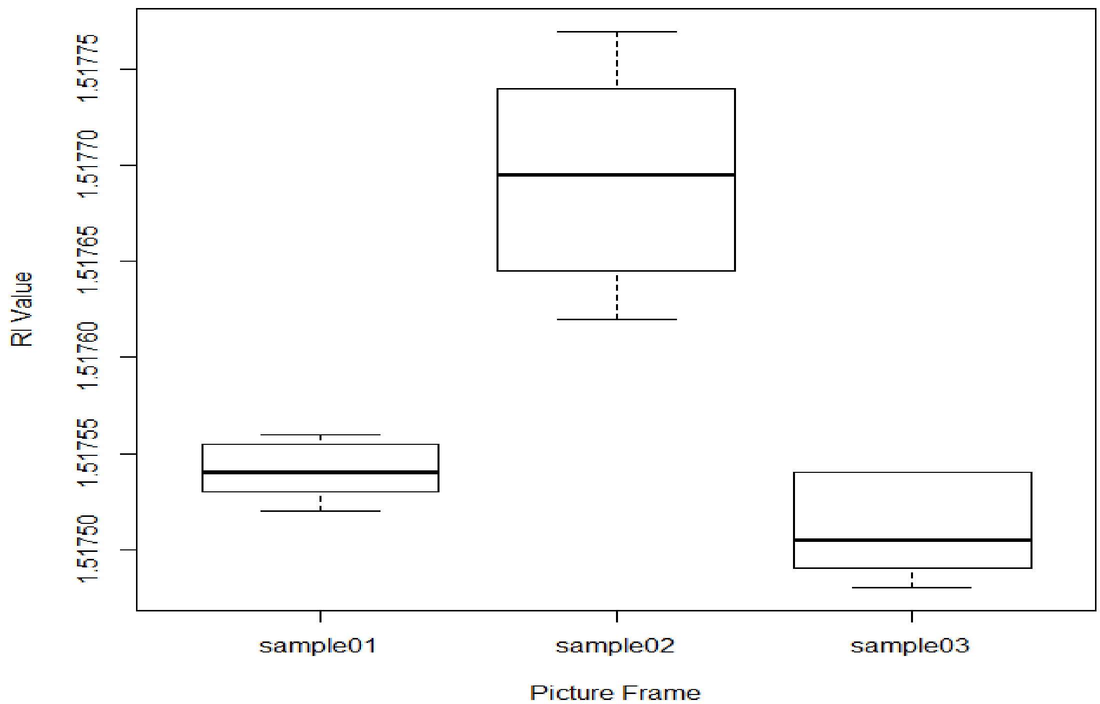


Figure 6: Box plot of 3 different samples of a picture Frame

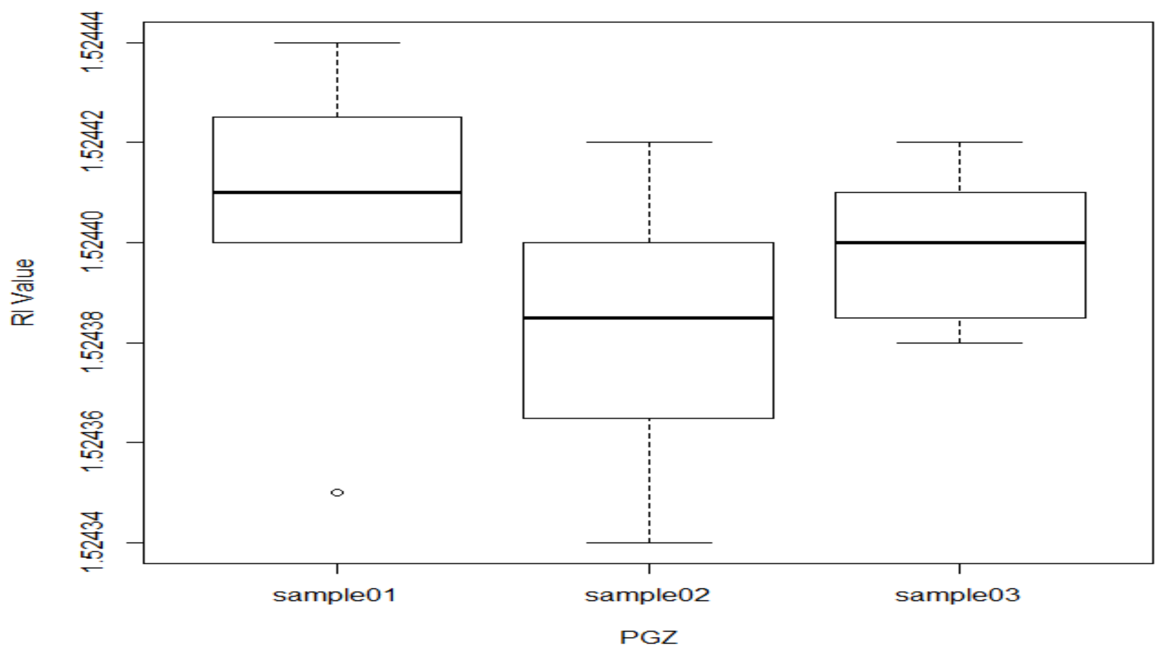


Figure 7: Box plot of 3 different samples of PGZ glass

In Figure 6, which was glass from a South African picture frame, the distribution of the RI of the glass was larger than in any other sample. A t-test of the sample means assuming unequal variances showed that all 3 of the samples were statistically significantly different at the 95% confidence level. However, in Figure 7, which was PGZ glass, all 3 samples were not found to be statistically significantly different using the same test. Figure 8, which was burlap glass, had a mixed result. Samples 1 and 3 were found to be from the same grouping according to the t-test while sample 2 was found to be statitistically significantly different at the 95% confidence than both samples 1 and 3. The amount of intrasample variation was different for each source of glass however the sources of glass where only one sampling took place did not have the ability to show this variability between samples.

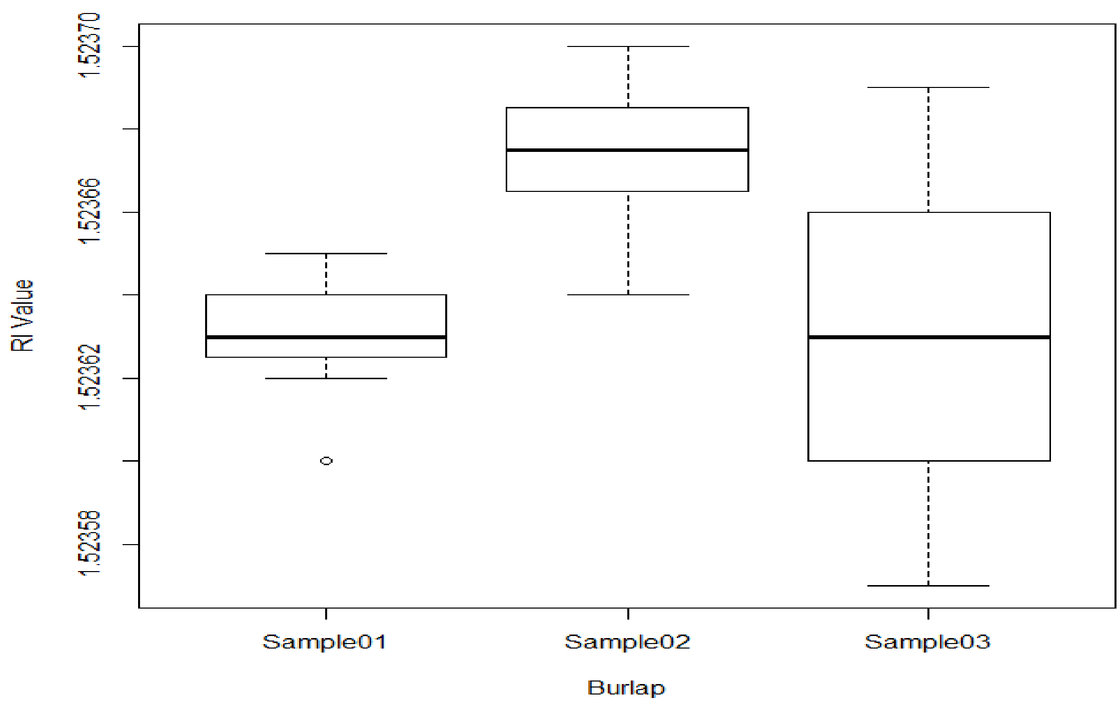


Figure 8: Box plot of 3 different samples of Burlap

When RI determinations are performed using the oils and Becke line and not the GRIM, the RI is measured to 2 or 3 decimal places. Accordingly, if the samples in this study were evaluated using these methods, there would be no differentiation among any of the samples. With the ability of the GRIM to determine RI using 5 decimal places, the homogeneity of glass with regards to RI becomes a critical factor. This is shown in the glasses above where samples that are known to have come from the same source have statistically significantly different RI's and this further validates all of the previous studies about glass inhomogeneity (13). This presents the question of sampling and how many samples and measurements for a source of glass need to be performed to determine the range of RI values expected within a sample.

When a quantitative measurement is preformed, many factors contribute to the expected spread or uncertainty associated with that measurement. One method used to characterize this spread is to perform replicate measurements and calculate a standard deviation. However the standard deviation alone is an incomplete representation of the total uncertainty expected to be associated with an RI. Currently, the recommended standard for the estimation of uncertainty associated with a measurement is the ISO/BIPM *Guide to the Expression of Uncertainty in Measurement* (referred to as GUM or *Guide*) (14). The GUM provides a guideline for evaluating all the parameters that can affect a measurement value from start to finish. The first step is to develop a list of all the possible factors of uncertainty in the given measurement. These can come from many sources including the instrument and the operator. The *Guide* groups the uncertainty factors determined in two different groups, type A and type B uncertainty. Type A uncertainty have replicate measurements and are characterized by standard deviation and type B are those which are evaluated by other means (14). A value for each factor is determined based on the type of uncertainty. If the uncertainty is type A, then the standard deviation of that factor is known and is used as the value for that factor. The values for factors with type B uncertainty are based on scientific judgment using information based on the manufacturer, other data analyses and measurements, experience or general knowledge of the instrument and material, or even handbooks(15).

The next step is to determine the kind of distribution of each contributing factor. The distributions can be many different possibilities from normal to rectangular to triangular, to name a few. They type of distribution determines the divisor of the value assigned to the uncertainty factor. An example would be if the value assigned to an uncertainty factor was 5 and it was a rectangular distribution, the divisor of a rectangular distribution is the $\sqrt{3}$ so the uncertainty (u) for that factor would be 5 divided by the $\sqrt{3}$. The need for the divisor is to allow for all of the factors to be adjusted so that they are expressed as standard deviation units.

Once the uncertainty contribution for each factor has been estimated, the combined uncertainty for the system or measurement is estimated by taking the square root of the sum of the squares of each factor's uncertainty. This number can then be multiplied by a specific coverage factor to determine the expanded uncertainty. A coverage factor of 2 or 3 is generally chosen where 2 is equivalent to 95% confidence and 3 is equivalent to 99% confidence.

Many areas of science have already adopted the idea of expressing uncertainty in measurement from areas in chemistry like neutron activation analysis (16), to social psychology (17), to analytical method validation (18). In the NAS report, any laboratory that was performing quantitative analysis was encouraged to use uncertainty with their measurements and results (4). For this research the uncertainty factors that were considered were the uncertainty with the calibration curve, the day to day variation, and the sample variation. Figure 9 is an example of an uncertainty budget for one of the 41 sources of glass.

Factor	Value (x)	Distribution	Divisor	u	u2	%Relative contribution	
Calibration	0.0001	Rectangular	1.73	5.77E-05	3.33E-09	63.28	
day-to-day	0.00006	Rectangular	1.73	3.46E-05	1.20E-09	22.78	
Within-Sample variation	2.71E-05	Normal	1	2.71E-05	7.34E-10	13.94	
				sum	5.27E-09		
				Square root	4.4E-05		
				k=2	8.8E-05		

Figure 9: Uncertainty Budget for 1 of the 41 sources

The uncertainty factors are listed with the value assigned to that factor next to it. The calibration and day-to-day variation were treated as rectangular because they had an equal probability of being anywhere +/- the value listed from the mean. A normal distribution which was assigned to the within-sample variation, has a divisor of 1 while a rectangular has a divisor of $\sqrt{3}$. The values of the uncertainty for each factor are listed under the column u with the next column being the square of the uncertainty for each factor. All of the uncertainties were then added to calculate the % relative contribution to the overall uncertainty. There are differing opinions as to the elimination of certain factors that contribute to the overall uncertainty based on this percentage. For this research, all of the percent contributions were greater than 10% except for one, and all factors were considered when calculating the overall uncertainty.

The calibration uncertainty and day–to-day uncertainty remained constant throughout each budget for each sample as all the samples were based on the same calibration curve and well as run on the same instrument with the same day-to-day variation. The sample variation or within sample repeatability was dependent on the source of glass and could be the result of anywhere from 8-24 measurements depending on the source.

Figure 10 lists the percent relative contribution for each factor as well as the number of measurements for each source. After the uncertainty for each source was calculated, the square root of the squares of each factor was used to calculate the overall uncertainty. A coverage factor of k=2 was used to express a 95% confidence of uncertainty for each source for that RI.

A pairwise comparison was then performed on all of the sources to be able to determine what samples could or could not be eliminated from each other based on the 95% confidence achieved through the uncertainty budget. Figure 11 shows the list of all the pairwise comparison of all the sources against one another. A total of 820 comparisons were made and 82 of those 820 produced an overlap in RI's and thus a need to do further analysis. For example, if a piece of glass from group 1 was chosen, the only group that had a "yes" result was group 33. This means that when considering the +/- range of group 1, only group 33 of the 41 sources had a +/- range that overlapped according to the 95% confidence in the uncertainty result. Figures 12 and 13 show what the pairwise comparisons would have looked like had it been based on just the standard deviations of the samples without any uncertainty and then 68% confidence or k=1, respectively. If the same analogy is used as above, then group 1 would have yielded no overlap between any of the other sources in either case. In the same way, if a random piece of glass was chosen from the set of forty one sources without replacement, the highest number of pairwise comparisons according to just the standard deviation would have been 3 for group/source 11, as seen in Figure 12. If that same sample was drawn at random without replacement and the uncertainty value with a 95% confidence value was used, the number of pairwise comparisons would have been 7. This is a significant difference in that the number is more than double what it would have been originally had uncertainty not been taken into account.

When a quantitative measurement such as RI is taken, a mean and standard deviation is obtained. However, if the standard deviation alone is used to establish uncertainty, it could lead to a false positive result where a piece of glass could be excluded when in fact it should be included. The results in Figures 11-13 show that there is a notable difference between the number of pairwise comparisons that would have been done had the analysis just been done solely on the standard deviation of the RI measurements and not based on the uncertainty to 95%. The number increases from a total of 18 pairwise comparisons to 74.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12	Group 13	Group 14
Calibration	64.75	59.22	56.55	58.1	64.31	50.83	57.32	33.35	38.51	60.74	37.33	61.42	50.62	26.35
Day to Day	23.31	21.32	20.36	20.92	23.15	18.3	20.64	12.01	13.86	21.87	13.44	22.11	18.22	9.49
Repeatability	11.95	19.46	23.1	20.99	12.54	30.88	22.04	54.64	47.62	17.4	49.23	16.47	31.16	64.17
n=	24	24	24	24	16	16	24	16	16	16	16	24	24	24
	Group 15	Group 16	Group 17	Group 18	Group 19	Group 20	Group 21	Group 22	Group 23	Group 24	Group 25	Group 26	Group 27	Group 28
Calibration	57.53	62.02	54.35	62.16	59.7	61.28	62.56	47.06	66.14	58.03	53	52.3	63.21	56.26
Day to Day	20.71	22.33	19.57	22.38	21.49	22.06	22.52	16.94	23.81	20.89	19.08	18.83	22.76	20.25
Repeatability	21.75	15.65	26.09	15.47	18.8	16.66	14.92	36	10.05	21.08	27.92	28.87	14.03	23.48
n=	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	Group 29	Group 30	Group 31	Group 32	Group 33	Group 34	Group 35	Group 36	Group 37	Group 38	Group 39	Group 40	Group 41	
Calibration	51.46	41.1	52.44	65.85	37.33	37.67	66.9	56.76	57.61	53.14	62.22	50.27	63.28	
Day to Day	18.52	14.8	18.88	23.7	13.44	13.56	24.08	20.43	20.74	19.13	22.4	18.1	22.78	
Repeatability	30.02	44.1	28.68	10.45	49.23	48.77	9.02	22.81	21.66	27.72	15.38	31.63	13.94	
n=	8	8	8	8	8	8	8	8	8	8	8	8	8	

Figure 10: Percent relative contribution of all factors for each source

	count	Total		Overall
	Yes	74		
	No	746		820

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	Yes
1	x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	1
2		x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	2
3			x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	4
4				x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
5					x	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	1
6						x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes	3
7							x	No	No	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No	No	No	Yes	No	No	5
8								x	Yes	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	Yes	5
9									x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes	2
10										x	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No	Yes	No	Yes	No	No	5
11											x	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	Yes	Yes	No	No	Yes	No	No	No	No	No	No	Yes	No	No	Yes	No	7
12												x	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	3
13													x	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	2
14														x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
15															x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	1
16																x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
17																	x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	1
18																		x	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	Yes	3
19																			x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	1
20																				x	No	Yes	No	No	No	Yes	Yes	No	No	Yes	No	No	No	No	No	No	Yes	No	No	Yes	No	6
21																					x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
22																						x	No	No	No	Yes	No	No	No	No	Yes	No	No	No	No	No	Yes	No	No	Yes	No	4
23																							x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
24																								x	No	No	No	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	3
25																									x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
26																										x	No	No	No	No	Yes	No	No	No	No	No	Yes	No	No	Yes	No	3
27																											x	No	No	Yes	No	No	No	No	No	No	Yes	No	Yes	Yes	No	4
28																												x	Yes	No	No	No	No	No	No	No	No	No	No	No	No	1
29																													x	No	No	No	No	No	Yes	No	No	No	No	No	No	1
30																														x	No	No	No	No	No	No	Yes	No	No	Yes	No	2
31																															x	No	No	No	No	No	No	No	No	No	No	0
32																																x	No	Yes	No	No	No	No	No	No	Yes	2
33																																	x	No	No	No	No	No	No	No	No	0
34																																		x	No	No	No	No	No	No	Yes	1
35																																			x	No	No	No	No	No	No	0
36																																				x	No	No	No	No	No	0
37																																					x	No	No	Yes	No	1
38																																						x	No	No	No	0
39																																							x	No	No	0
40																																								x	No	0
41																																									x	

Figure 11: Pairwise comparison for uncertainty of k=2

			count	Total		Overall																																				
			Yes	18																																						
			No	802		820																																				
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	Yes
1	x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
2		x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
3			x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
4				x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
5					x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
6						x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	1
7							x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	1
8								x	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	2
9									x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
10										x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
11											x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No	No	Yes	No	3
12												x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	1
13													x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
14														x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
15															x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
16																x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
17																	x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
18																		x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	1
19																			x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	1
20																				x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	1
21																					x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
22																						x	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	1
23																							x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
24																								x	No	No	No	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	2
25																									x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
26																										x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
27																											x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	1
28																												x	Yes	No	No	No	No	No	No	No	No	No	No	No	No	1
29																													x	No	No	No	No	No	No	No	No	No	No	No	No	0
30																														x	No	No	No	No	No	No	No	No	No	No	No	0
31																															x	No	No	No	No	No	No	No	No	No	No	0
32																																x	No	No	No	No	No	No	No	No	No	0
33																																	x	No	No	No	No	No	No	No	No	0
34																																		x	No	No	No	No	No	No	Yes	1
35																																			x	No	No	No	No	No	No	0
36																																				x	No	No	No	No	No	0
37																																					x	No	No	Yes	No	1
38																																						x	No	No	No	0
39																																							x	No	No	0
40																																								x	No	0
41																																									x	

Figure 12: Pairwise comparison of standard deviation

			count	Total		Overall																																				
			Yes	35																																						
			No	785		820																																				
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	Yes
1	x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
2		x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
3			x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	3
4				x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
5					x	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	1
6						x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	1
7							x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	2
8								x	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	Yes	4
9									x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	1
10										x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	2
11											x	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No	No	Yes	No	4
12												x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	1
13													x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
14														x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
15															x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
16																x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
17																	x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	1
18																		x	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	2
19																			x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	1
20																				x	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	3
21																					x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
22																						x	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	1
23																							x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
24																								x	No	No	No	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	2
25																									x	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	0
26																										x	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes	No	1
27																											x	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	1
28																												x	Yes	No	No	No	No	No	No	No	No	No	No	No	No	1
29																													x	No	No	No	No	No	No	No	No	No	No	No	No	0
30																														x	No	No	No	No	No	No	Yes	No	No	No	No	1
31																															x	No	No	No	No	No	No	No	No	No	No	0
32																																x	No	No	No	No	No	No	No	No	No	0
33																																	x	No	No	No	No	No	No	No	No	0
34																																		x	No	No	No	No	No	No	Yes	1
35																																			x	No	No	No	No	No	No	0
36																																				x	No	No	No	No	No	0
37																																					x	No	No	Yes	No	1
38																																						x	No	No	No	0
39																																							x	No	No	0
40																																								x	No	0
41																																									x	

Figure 13: Pairwise comparison for uncertainty of k=1

The categories of glass used in this study were window glass, which was the type of glass made for a house or building window, bottle glass, which was from a glass bottle, car window glass, which came from the side or rear windows, laminated glass, which came from windshields or other glass that needed to be laminated, and drinking glass, which was from drinking glasses. Appendix B shows a boxplot of all of the RI's for each of these categories of glass. T-tests of means assuming unequal variances were performed again for the three largest categories of glass; bottle, window, and car window. Of these three groups, only the car window and window glass were statistically significantly different. If a random piece of glass was found that had a RI of 1.52125 for example, it could be from any one of those 3 main categories. A probability however could be assessed as to the likelihood of the glass being from each one of the categories based on the RI.

Discussion

When statistical tests were performed on the 3 major categories of glass, only car windows and windows were found to have a statistically significant difference. However, even though they were found to be statistically significantly different, there was overlap in the range of possibilities of RI's for all 3 of these categories. This significant difference does not correlate to the groups being from different sources however. This all is discouraging for forensic glass analysts because if glass of unknown origin is recovered on a suspect, RI may not give an indication as to the type of glass it is unless a probability of occurrence is used. Although this set of 41 sources does not comprise all of the possible sources that one could encounter in casework, the major categories of glass are present. This is also a smaller sample size compared to the larger picture but the same types of trends are found here that is seen in the FBI study of float glass dating back to the 1960's.

A procedure for assessing the sample variation/repeatability needs to be developed by each laboratory and guidelines to establishing an accurate measure of RI. The number of measurements can be different based on the type of glass and intra-sample variation of the source, but a procedure for determining when this is achieved is needed as the results of this experiment and past experiments show the intra-sample variations that can occur. In the past, RI measurements were out to three decimal places, however with the GRIM these measurements are now out to 5 decimal places. This increased precision however has presented the homogeneity problem and the need for a laboratory to develop a procedure for handling this. Bennett and Curran sum up numerous studies and perform their own study relating to the inhomogeneity of glass and how it can or can’t vary from center to edge of the pane as well as the float or non-float side to the bulk of the glass (13). They also recommend the need to develop a procedure for sampling a known piece of glass in order to achieve proper sampling and an accurate RI measurement. This also raises another important question with casework when one shard of glass is recovered, can that shard be attributed to a source when only one set of measurements can be made? The intra-sample variation found here as well as with Bennett and Curran show that one set of 8 measurements may be insufficient.

All of the standard values for the calibration curve fell within the required dri values, however the highest dri value, which was used for the calibration part of the uncertainty budget, could have been reduced as it came from one of the standards that the FBI omits. Also, the day-to-day variation was the highest using one of the standards that tends to me omitted as well, so the day-to-day variation could be reduced using only the select standards to make the curve. For the purpose of creating a basic fundamental and conservative approach to uncertainty, all of the standards were used in making the calibration curve, including the standards that tend to cause a lot of problems for scientists. As a result, the 95% confidence values have the opportunity to be reduced, however to what extent would need to be further studied.

Refractive index is traditionally thought of as a classification method and in reality it is, however underneath this source determination is a quantitative measurement. As a result of good analytical practice and the NAS report, uncertainty should be estimated for any RI measurement. Garvin and Koons recently completed a match criteria study using 8 different criteria for RI (19). It included options such as standard deviations and fixed ranges to determine the best way to compare RI of glass fragments taking into account the inhomogeneity of the glass but reducing false negatives (19). Uncertainty was not one of the match criteria options considered in this study. As seen in Figures 11-13, there is a difference in the number of pairwise comparisons when using just the standard deviation compared to assessing the uncertainty, and it is here that the problem lies. Had this have been casework and just the standard deviation was evaluated and used, false positives or exclusions would have been made. One might have concluded that based just on the standard deviation that two pieces of glass were from different sources when in reality they were from the same source and using the 95% confidence uncertainty would have shown that. Limiting the number false positives and false negatives was the goal of Garvin and Koons and should be the goal of every match criteria, however a laboratory would need to consider when it cannot eliminate both, which one it considers to be more important.

Conclusions

As the values show in this study, the impact of using an uncertainty budget and applying it RI, greatly affects the result that one might conclude when performing RI measurement. The inhomogeneity of glass and the problems that it can cause was further validated here. RI is looked at as a source determination and seldom acknowledged as quantification, but to make the source determination, the RI value needs to be determined. Each glass source had a different intra-sample variation and using match criteria of fixed intervals and just a standard deviation does not account for all the possible variations. The ability of uncertainty to cover all the factors associated with RI are seen here and need to be applied to all RI measurements in the future for both research and casework.

Appendix A

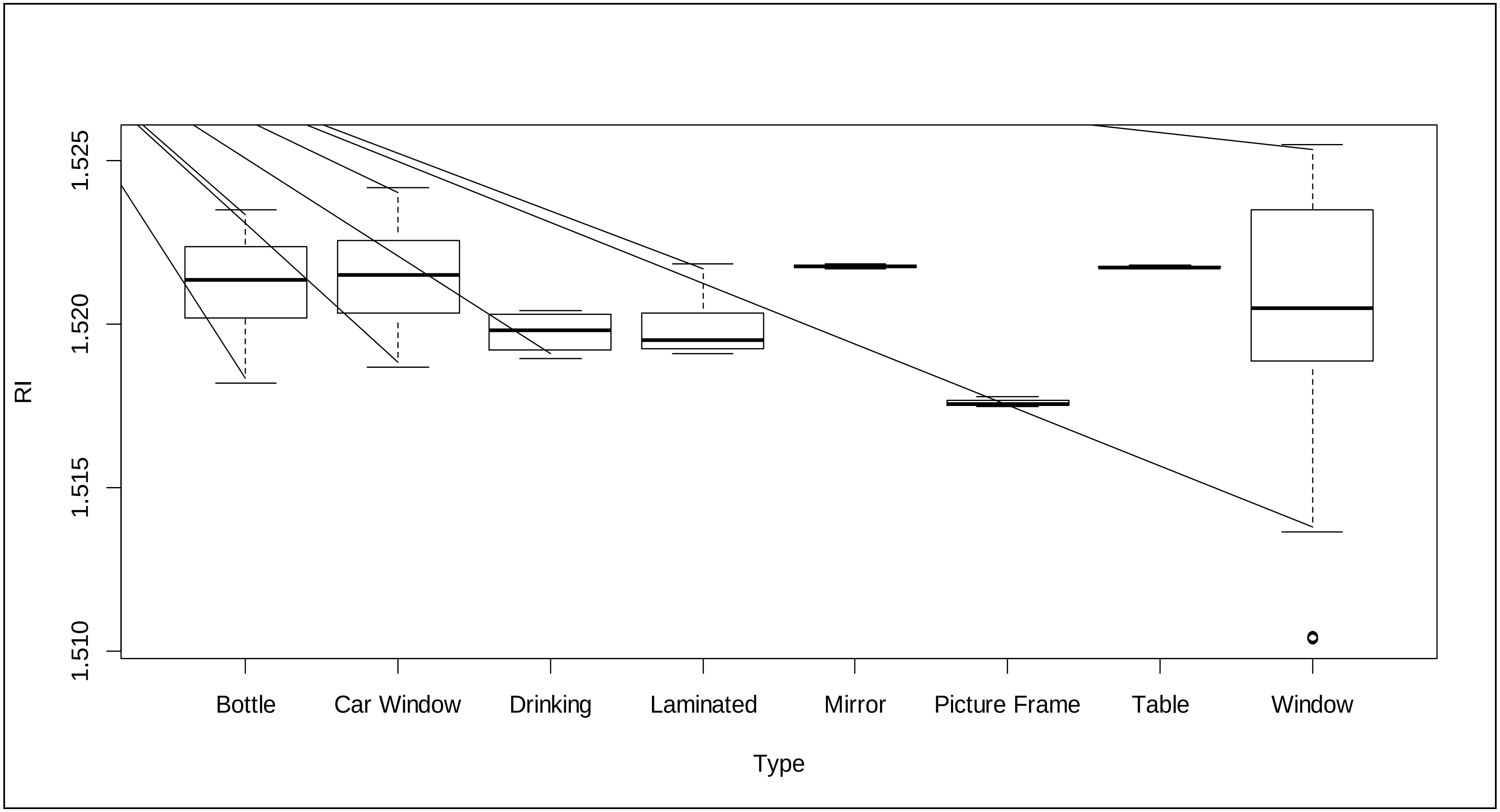
sample01	run1	1.52231	sample22	run1	1.52440	sample43	run1	1.51754
sample01	run2	1.52230	sample22	run2	1.52438	sample43	run2	1.51749
sample01	run3	1.52237	sample22	run3	1.52442	sample43	run3	1.51749
sample01	run4	1.52238	sample22	run4	1.52438	sample43	run4	1.51754
sample01	run5	1.52230	sample22	run5	1.52441	sample43	run5	1.51751
sample01	run6	1.52232	sample22	run6	1.52441	sample43	run6	1.51748
sample01	run7	1.52229	sample22	run7	1.52440	sample43	run7	1.51750
sample01	run8	1.52229	sample22	run8	1.52439	sample43	run8	1.51754
sample02	run1	1.52346	sample23	run1	1.52035	sample44	run1	1.52071
sample02	run2	1.52344	sample23	run2	1.52041	sample44	run2	1.52072
sample02	run3	1.52343	sample23	run3	1.52030	sample44	run3	1.52072
sample02	run4	1.52348	sample23	run4	1.52032	sample44	run4	1.52069
sample02	run5	1.52341	sample23	run5	1.52041	sample44	run5	1.52065
sample02	run6	1.52342	sample23	run6	1.52029	sample44	run6	1.52068
sample02	run7	1.52340	sample23	run7	1.52041	sample44	run7	1.52065
sample02	run8	1.52347	sample23	run8	1.52029	sample44	run8	1.52071
sample03	run1	1.51877	sample24	run1	1.51368	sample45	run1	1.51835
sample03	run2	1.51879	sample24	run2	1.51370	sample45	run2	1.51841
sample03	run3	1.51871	sample24	run3	1.51375	sample45	run3	1.51840
sample03	run4	1.51875	sample24	run4	1.51375	sample45	run4	1.51843
sample03	run5	1.51872	sample24	run5	1.51365	sample45	run5	1.51841
sample03	run6	1.51879	sample24	run6	1.51375	sample45	run6	1.51838
sample03	run7	1.51875	sample24	run7	1.51366	sample45	run7	1.51843
sample03	run8	1.51873	sample24	run8	1.51373	sample45	run8	1.51833
sample04	run1	1.51948	sample25	run1	1.51896	sample46	run1	1.51841
sample04	run2	1.51946	sample25	run2	1.51902	sample46	run2	1.51829
sample04	run3	1.51951	sample25	run3	1.51898	sample46	run3	1.51835
sample04	run4	1.51947	sample25	run4	1.51901	sample46	run4	1.51835
sample04	run5	1.51950	sample25	run5	1.51893	sample46	run5	1.51842
sample04	run6	1.51952	sample25	run6	1.51905	sample46	run6	1.51840
sample04	run7	1.51952	sample25	run7	1.51902	sample46	run7	1.51841
sample04	run8	1.51953	sample25	run8	1.51894	sample46	run8	1.51831
sample05	run1	1.52134	sample26	run1	1.51943	sample47	run1	1.51845
sample05	run2	1.52138	sample26	run2	1.51937	sample47	run2	1.51843
sample05	run3	1.52128	sample26	run3	1.51941	sample47	run3	1.51840
sample05	run4	1.52136	sample26	run4	1.51945	sample47	run4	1.51847
sample05	run5	1.52137	sample26	run5	1.51942	sample47	run5	1.51841
sample05	run6	1.52134	sample26	run6	1.51940	sample47	run6	1.51843
sample05	run7	1.52134	sample26	run7	1.51945	sample47	run7	1.51844
sample05	run8	1.52127	sample26	run8	1.51940	sample47	run8	1.51843
sample06	run1	1.52441	sample27	run1	1.51751	sample48	run1	1.51967
sample06	run2	1.52444	sample27	run2	1.51756	sample48	run2	1.51972
sample06	run3	1.52444	sample27	run3	1.51754	sample48	run3	1.51972
sample06	run4	1.52440	sample27	run4	1.51756	sample48	run4	1.51972
sample06	run5	1.52435	sample27	run5	1.51752	sample48	run5	1.51973
sample06	run6	1.52441	sample27	run6	1.51752	sample48	run6	1.51967
sample06	run7	1.52440	sample27	run7	1.51755	sample48	run7	1.51968
sample06	run8	1.52441	sample27	run8	1.51754	sample48	run8	1.51966
sample07	run1	1.52024	sample28	run1	1.51771	sample49	run1	1.52546
sample07	run2	1.52019	sample28	run2	1.51771	sample49	run2	1.52540
sample07	run3	1.52018	sample28	run3	1.51777	sample49	run3	1.52541

sample07	run4	1.52019	sample28	run4	1.51777	sample49	run4	1.52543
sample07	run5	1.52020	sample28	run5	1.51762	sample49	run5	1.52547
sample07	run6	1.52025	sample28	run6	1.51767	sample49	run6	1.52537
sample07	run7	1.52025	sample28	run7	1.51762	sample49	run7	1.52547
sample07	run8	1.52022	sample28	run8	1.51768	sample49	run8	1.52545
sample08	run1	1.52364	sample29	run1	1.52178	sample50	run1	1.52539
sample08	run2	1.52364	sample29	run2	1.52174	sample50	run2	1.52542
sample08	run3	1.52362	sample29	run3	1.52179	sample50	run3	1.52535
sample08	run4	1.52364	sample29	run4	1.52174	sample50	run4	1.52538
sample08	run5	1.52365	sample29	run5	1.52176	sample50	run5	1.52545
sample08	run6	1.52360	sample29	run6	1.52182	sample50	run6	1.52540
sample08	run7	1.52363	sample29	run7	1.52184	sample50	run7	1.52537
sample08	run8	1.52363	sample29	run8	1.52175	sample50	run8	1.52537
sample09	run1	1.51824	sample30	run1	1.52178	sample51	run1	1.52024
sample09	run2	1.51818	sample30	run2	1.52174	sample51	run2	1.52022
sample09	run3	1.51818	sample30	run3	1.52169	sample51	run3	1.52019
sample09	run4	1.51820	sample30	run4	1.52181	sample51	run4	1.52022
sample09	run5	1.51817	sample30	run5	1.52174	sample51	run5	1.52024
sample09	run6	1.51826	sample30	run6	1.52177	sample51	run6	1.52022
sample09	run7	1.51823	sample30	run7	1.52176	sample51	run7	1.52027
sample09	run8	1.51820	sample30	run8	1.52168	sample51	run8	1.52023
sample10	run1	1.52370	sample31	run1	1.52163	sample52	run1	1.52162
sample10	run2	1.52364	sample31	run2	1.52163	sample52	run2	1.52161
sample10	run3	1.52367	sample31	run3	1.52165	sample52	run3	1.52168
sample10	run4	1.52369	sample31	run4	1.52172	sample52	run4	1.52173
sample10	run5	1.52368	sample31	run5	1.52171	sample52	run5	1.52166
sample10	run6	1.52368	sample31	run6	1.52165	sample52	run6	1.52169
sample10	run7	1.52367	sample31	run7	1.52164	sample52	run7	1.52166
sample10	run8	1.52366	sample31	run8	1.52169	sample52	run8	1.52169
sample11	run1	1.51950	sample32	run1	1.51941	sample53	run1	1.52060
sample11	run2	1.51946	sample32	run2	1.51934	sample53	run2	1.52061
sample11	run3	1.51946	sample32	run3	1.51939	sample53	run3	1.52066
sample11	run4	1.51952	sample32	run4	1.51928	sample53	run4	1.52069
sample11	run5	1.51949	sample32	run5	1.51927	sample53	run5	1.52065
sample11	run6	1.51942	sample32	run6	1.51942	sample53	run6	1.52070
sample11	run7	1.51952	sample32	run7	1.51929	sample53	run7	1.52057
sample11	run8	1.51947	sample32	run8	1.51936	sample53	run8	1.52064
sample12	run1	1.51880	sample33	run1	1.51869	sample54	run1	1.51922
sample12	run2	1.51877	sample33	run2	1.51870	sample54	run2	1.51924
sample12	run3	1.51875	sample33	run3	1.51871	sample54	run3	1.51917
sample12	run4	1.51880	sample33	run4	1.51879	sample54	run4	1.51914
sample12	run5	1.51875	sample33	run5	1.51880	sample54	run5	1.51919
sample12	run6	1.51876	sample33	run6	1.51875	sample54	run6	1.51918
sample12	run7	1.51879	sample33	run7	1.51878	sample54	run7	1.51919
sample12	run8	1.51881	sample33	run8	1.51876	sample54	run8	1.51915
sample13	run1	1.52369	sample34	run1	1.52016	sample55	run1	1.52545
sample13	run2	1.52363	sample34	run2	1.52014	sample55	run2	1.52540
sample13	run3	1.52359	sample34	run3	1.52019	sample55	run3	1.52542
sample13	run4	1.52367	sample34	run4	1.52020	sample55	run4	1.52546
sample13	run5	1.52365	sample34	run5	1.52019	sample55	run5	1.52542
sample13	run6	1.52363	sample34	run6	1.52019	sample55	run6	1.52544
sample13	run7	1.52357	sample34	run7	1.52021	sample55	run7	1.52542
sample13	run8	1.52361	sample34	run8	1.52017	sample55	run8	1.52540
sample14	run1	1.51913	sample35	run1	1.52405	sample56	run1	1.51927
sample14	run2	1.51910	sample35	run2	1.52400	sample56	run2	1.51931

sample14	run3	1.51909	sample35	run3	1.52411	sample56	run3	1.51930
sample14	run4	1.51916	sample35	run4	1.52404	sample56	run4	1.51925
sample14	run5	1.51912	sample35	run5	1.52417	sample56	run5	1.51927
sample14	run6	1.51913	sample35	run6	1.52403	sample56	run6	1.51934
sample14	run7	1.51915	sample35	run7	1.52417	sample56	run7	1.51934
sample14	run8	1.51918	sample35	run8	1.52403	sample56	run8	1.51930
sample15	run1	1.52049	sample36	run1	1.52041	sample57	run1	1.51911
sample15	run2	1.52054	sample36	run2	1.52031	sample57	run2	1.51922
sample15	run3	1.52046	sample36	run3	1.52044	sample57	run3	1.51918
sample15	run4	1.52051	sample36	run4	1.52031	sample57	run4	1.51909
sample15	run5	1.52048	sample36	run5	1.52044	sample57	run5	1.51918
sample15	run6	1.52053	sample36	run6	1.52029	sample57	run6	1.51912
sample15	run7	1.52049	sample36	run7	1.52043	sample57	run7	1.51912
sample15	run8	1.52047	sample36	run8	1.52033	sample57	run8	1.51911
sample16	run1	1.51895	sample37	run1	1.52148	sample58	run1	1.51959
sample16	run2	1.51902	sample37	run2	1.52145	sample58	run2	1.51956
sample16	run3	1.51889	sample37	run3	1.52149	sample58	run3	1.51957
sample16	run4	1.51901	sample37	run4	1.52150	sample58	run4	1.51953
sample16	run5	1.51891	sample37	run5	1.52145	sample58	run5	1.51957
sample16	run6	1.51891	sample37	run6	1.52150	sample58	run6	1.51951
sample16	run7	1.51899	sample37	run7	1.52146	sample58	run7	1.51954
sample16	run8	1.51899	sample37	run8	1.52149	sample58	run8	1.51957
sample17	run1	1.51951	sample38	run1	1.52250	sample59	run1	1.52167
sample17	run2	1.51954	sample38	run2	1.52249	sample59	run2	1.52161
sample17	run3	1.51949	sample38	run3	1.52245	sample59	run3	1.52162
sample17	run4	1.51953	sample38	run4	1.52255	sample59	run4	1.52166
sample17	run5	1.51949	sample38	run5	1.52255	sample59	run5	1.52166
sample17	run6	1.51944	sample38	run6	1.52247	sample59	run6	1.52167
sample17	run7	1.51952	sample38	run7	1.52249	sample59	run7	1.52167
sample17	run8	1.51950	sample38	run8	1.52247	sample59	run8	1.52158
sample18	run1	1.52437	sample39	run1	1.51922	sample60	run1	1.51958
sample18	run2	1.52440	sample39	run2	1.51925	sample60	run2	1.51958
sample18	run3	1.52442	sample39	run3	1.51920	sample60	run3	1.51952
sample18	run4	1.52439	sample39	run4	1.51916	sample60	run4	1.51952
sample18	run5	1.52440	sample39	run5	1.51921	sample60	run5	1.51954
sample18	run6	1.52438	sample39	run6	1.51924	sample60	run6	1.51956
sample18	run7	1.52434	sample39	run7	1.51922	sample60	run7	1.51956
sample18	run8	1.52436	sample39	run8	1.51915	sample60	run8	1.51956
sample19	run1	1.51877	sample40	run1	1.51825	sample61	run1	1.52038
sample19	run2	1.51875	sample40	run2	1.51824	sample61	run2	1.52044
sample19	run3	1.51879	sample40	run3	1.51827	sample61	run3	1.52044
sample19	run4	1.51879	sample40	run4	1.51827	sample61	run4	1.52045
sample19	run5	1.51874	sample40	run5	1.51827	sample61	run5	1.52039
sample19	run6	1.51877	sample40	run6	1.51821	sample61	run6	1.52044
sample19	run7	1.51871	sample40	run7	1.51816	sample61	run7	1.52045
sample19	run8	1.51872	sample40	run8	1.51819	sample61	run8	1.52043
sample20	run1	1.51043	sample41	run1	1.52056	sample62	run1	1.52339
sample20	run2	1.51039	sample41	run2	1.52054	sample62	run2	1.52333
sample20	run3	1.51038	sample41	run3	1.52054	sample62	run3	1.52337
sample20	run4	1.51040	sample41	run4	1.52049	sample62	run4	1.52334
sample20	run5	1.51045	sample41	run5	1.52052	sample62	run5	1.52334
sample20	run6	1.51040	sample41	run6	1.52050	sample62	run6	1.52337
sample20	run7	1.51041	sample41	run7	1.52053	sample62	run7	1.52336
sample20	run8	1.51040	sample41	run8	1.52052	sample62	run8	1.52336
sample21	run1	1.52169	sample42	run1	1.52063	sample63	run1	1.52336

sample21	run2	1.52172	sample42	run2	1.52058	sample63	run2	1.52340
sample21	run3	1.52175	sample42	run3	1.52070	sample63	run3	1.52338
sample21	run4	1.52171	sample42	run4	1.52065	sample63	run4	1.52330
sample21	run5	1.52178	sample42	run5	1.52060	sample63	run5	1.52337
sample21	run6	1.52171	sample42	run6	1.52061	sample63	run6	1.52336
sample21	run7	1.52173	sample42	run7	1.52068	sample63	run7	1.52333
sample21	run8	1.52169	sample42	run8	1.52061	sample63	run8	1.52338

Appendix B



RI
1.510
1.515
1.520
1.525
Bottle
Car Window
Drinking
Laminated
Mirror
Picture Frame
Table
Window
Type

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