Characterization of PCB Plated-Thru-Hole Reliability using Statistical Analysis

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Abstract
Various test methods are used to characterize the PCB plated-thru-hole reliability. One such method is the Interconnect Stress Test (IST). The results from this test are often used to qualify PCB materials and/or fabricators. This paper will discuss how certain statistical analysis techniques may be used to decipher the results, and predict capabilities of PCB materials and/or processes.

Introduction
Reliability testing for PWBs is a tricky business. Prediction of expected part life, and estimates of expected performance characteristics rely on the use of statistical techniques. These tests are destructive, and therefore must be conducted on a small subgroup. The balance that must be struck is to generate just enough information to be confident of the predictions, and no more. Too few samples leads to large uncertainty about the quality of the predictions, while too many samples is wasteful.

Background
IST testing has become popular over the past few years as a way to get accelerated thermal reliability information. The expectation is that, relative to traditional thermal cycling which can take weeks, IST can be completed within days and with little loss of resolution. This paper does not address any comparisons between IST and the traditional thermal cycling test. The focus here is to describe an analysis technique to utilize the IST results to better ends than what is typically done.

Although much faster than the traditional thermal cycling test, IST suffers from the significant drawback that the sample size is limited by the size of the test fixture. The typical sample size is six coupons, a miserably small sample size for most people's comfort. The time savings are substantial, so it is desirable to do the best possible given the constraint.

The most common method for IST analysis is to collect the cycles to failure results for the six samples and publish the average. This seems like a reasonable course of action, but in reality there are some assumptions behind it that are not supportable giving the typical nature of reliability data. Specifically, reporting an average relies on the assumption that the underlying distribution from which the data is pulled is normally distributed. How can we be sure that if all boards were tested the results would fit the normal curve approximation? One way would be to test all of the boards. This of course cannot be done, but it would lead to the most certainty about the shape of the population and the resulting expected performance characteristics of the application.

For the IST reliability situation, there is a natural constraint for the sample size as the unit holds six coupons. Since you can't test them all, and the unit holds six, the temptation is to run the six to failure and report the average. What is missing is that if the actual underlying population is non-normal, the predictions about the untested balance of the population will be misleading.

The question addressed here is: Given that the convenient sample size is six, can Weibull analysis be used to improve upon the reliability information that can be deduced from the limited data as compared to the typical conclusions that result from the normal approximation?

Procedure
To answer the question, the following method is employed:

1. Gather IST results from a variety of applications and raw material types.
2. Calculate the best-fit curve for each set of six results using first the normal assumption and then the Weibull assumption.
3. Compare the goodness of fit pairwise using the Anderson-Darling test.
4. Ensure that, given a hypothetical distribution specifically generated to simulate the typical Weibull characteristics generated from the IST test case results, random samples of six would yield similar goodness of fit data, with results from the Weibull assumption being statistically better.
5. Quantify the improvement obtained using the Weibull assumption.

IST Test Case Data

Data is collected randomly from a broad spectrum of applications. In this manner, the specifics of the board designs and raw material choices are divorced from the question of the applicability of the analysis technique. To simplify the discussion, only results for which all samples failed prior to the end of the test are included. Although the techniques can be used to accommodate right-censored data where some of the samples have not failed at the time the test is stopped, they are not needed to answer the question of the usefulness of the Weibull approximation in this situation. Seventy-two sets of IST results are included in the analysis to follow.

Fitting Normal and Weibull Curves

Many statistical analysis programs are available that can be used to fit data. The program used for this project is Minitab™.

Fitting the 72 sets of data using the normal approximation gives three characteristics of interest: Average, standard deviation and goodness-of-fit. The average is simply an estimate of the mean time to failure for the underlying population, while the standard deviation is a measure of the spread of the data. Minitab™ also offers an Anderson-Darling (AD) calculation as an estimate of the goodness-of-fit. The AD calculation quantifies just how closely the data points cluster around the linearized normal curve as transformed on the graph. The test gives more weight to data at the tail ends of the distribution, and the lower the number, the better the data fits the calculated curve. *Figure 1* shows an example of the Minitab™ output for one set of samples:

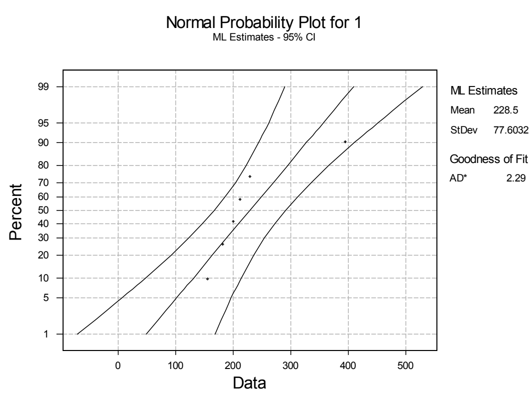

Figure 1 – Normal Probability Plot, Sample 1

Fitting the data using the Weibull assumptions requires a bit more explanation. See *figure 2* below for the Weibull output for the same data used in *figure 1*.

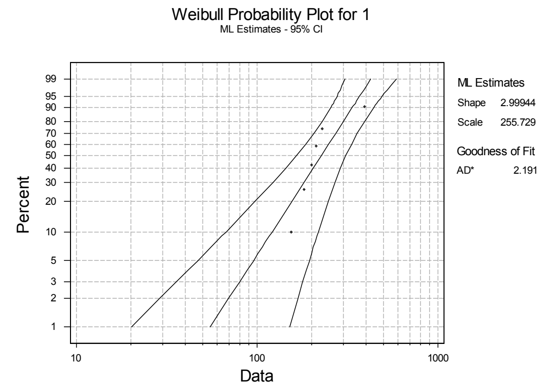

Figure 2 – Weibull Probability Plot, Sample 1

The Minitab™ output gives three statistics: Shape, Scale and AD goodness-of-fit. The first two are parameters that are used in the Weibull calculations for describing the resulting curve, similar to how the average and standard deviation are used to characterize the normal curve.

The Weibull probability density function is as follows (*):

$$f(x) = \alpha\beta^{\alpha}x^{(\alpha-1)}\exp[-(\beta x)^{\alpha}]$$

α = shape
β = scale

The function is flexible enough to describe many common reliability tendencies, and in this application it tends to generate skewed mound-shaped curves that tail off to the right. As an example, the physical implication is that, relative to the normal curve which is symmetrical about the mean, there will be a clustering of samples that fail early and a tendency of samples that work well to continue to last. *See figure 3* for the Weibull curve for the data in *figure 2*.

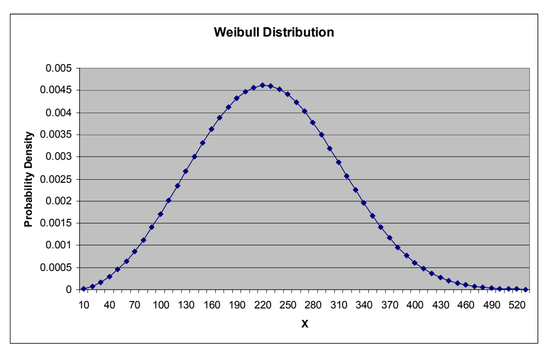

Figure 3 – Weibull Curve, Sample 1

Notice that the curve does not seem to be all that different than a typical normal curve. To determine if the Weibull approximation does indeed give a better picture, comparisons are made between the AD goodness-of-fit on a pairwise basis for the set of 72 IST results.

Comparison of Normal and Weibull Results

The Normal and Weibull statistics are collected in Appendix A. In order to determine which approximation better describes the data, I use a paired t-test. Since I know that the lower the AD statistic, the better the data fits the curve, I use a null hypothesis where the means of the AD statistics are the same, with the alternative being that the Weibull AD statistics are lower. This amounts to a one-tailed test. A control chart of the paired differences is found in *figure 4*:

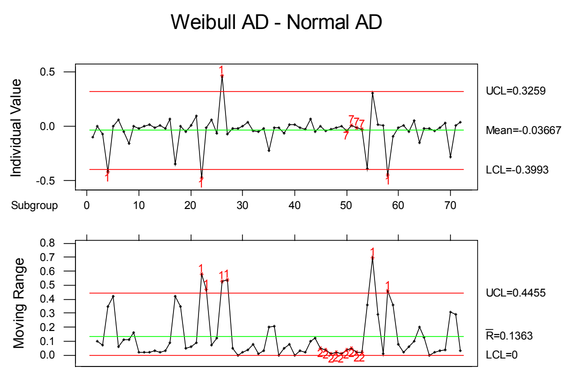

Figure 4 – Paired Differences

The AD paired difference data is interesting. There is a cluster of data close to zero, and then a handful that seem to be substantially different than the rest. The upward spikes are instances where the normal approximation is better, and the downward spikes are instances where the Weibull approximation is better. To compare, the t-test results are presented in *table 1*:

Table 1: T-Test Results

Paired T-Test and CI: Anderson-Darling Weibull, Anderson-Darling Normal

Paired T for Anderson-Darling Weibull - Anderson-Darling Normal

	N	Mean	StDev	SE Mean
Anderson-Dar	72	2.0114	0.2220	0.0262
Anderson-Dar	72	2.0481	0.2367	0.0279
Difference	72	-0.0367	0.1392	0.0164

95% upper bound for mean difference: -0.0093
T-Test of mean difference = 0 (vs < 0): T-Value = -2.24 P-Value = 0.014

The t-test yields a p-value of 0.014, which is equivalent to saying that there is substantial evidence to reject the null hypothesis and conclude that the Weibull approximation gives a better description of the data than the normal approximation.

To confirm that the unusually high and low data points found in *figure 4* do not substantially influence the t-test conclusions, I sequentially removed the unusual data until the following subset of the pairwise AD differences remained (*figure 5*):

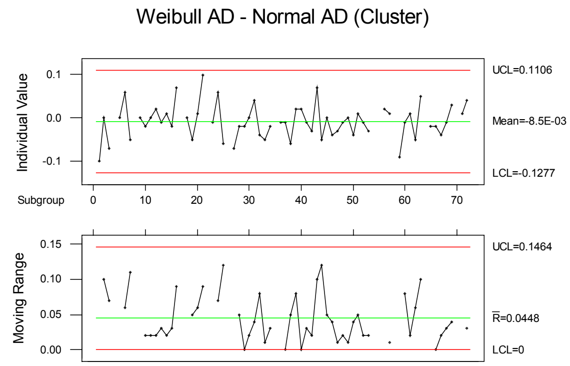

Figure 5 – Paired Differences, Clustered

The resulting p-value for the reduced sample set of 61 data points included in *figure 5* is 0.047. This result is still significant enough to reject the null hypothesis and conclude that the Weibull approximation is better.

Confirming the Results

With statistically lower AD measures, it is clear that for the test cases here, the Weibull calculations give a better fit to a broad variety of six-sample IST data than if a normal distribution is used. Several questions still remain:

1. Are the AD statistics representative of what should be expected from random six-sample sets of a known Weibull distribution of similar shape and scale?
2. Do the random six-sample sets result in statistically better fits with Weibull analysis than with normal analysis?

To explore these ideas, I generated 1000 random data points in Minitab™ with an intended Weibull distribution of shape two and scale 250. The Weibull probability plot generated from the 1000 random samples is included in *figure 6*.

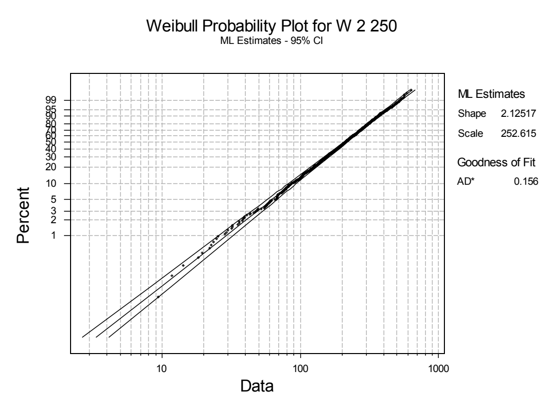

Figure 6 – Weibull Fit to Weibull Simulation

The AD value for this data is predictably low (0.156) as the data was created to emulate a Weibull function of shape 2 and scale 250. As a comparison, see the results from the same set of data if tested for a fit using the normal assumption (*figure 7*).

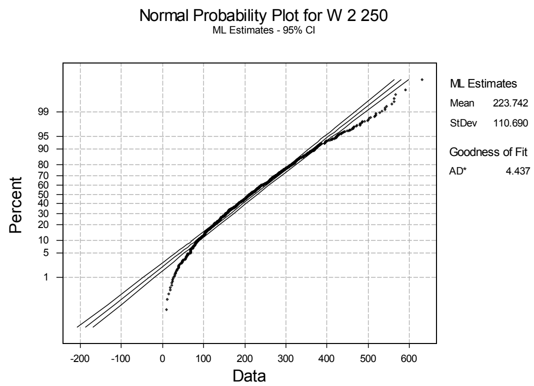

Figure 7 – Normal Fit to Weibull Simulation

Clearly the data does not sit as close to the line as it does in *figure 6*, and the AD value of 4.437 indicates the significant lack of fit.

Now, with evidence that the complete simulation data set clearly follows a Weibull distribution and clearly does not follow a normal distribution, I generated 100 random sets of six samples for analysis. Following the same approach as described in the section titled *Fitting Normal and Weibull Curves*, I generated the data set presented in Appendix B.

A summary of the data from Appendix B is provided in *table 2*.

Table 2: Simulation Results

Simulation	W Shape	W Scale	W AD	MTTF	N Avg	N AD
Average	2.87151	258.51	1.96879	231.44	230.862	1.99973
Max	9.57	382	2.432	344	342	2.548
Min	1.26	102	1.789	94	94.2	1.803

Notice that in *table 2*, a "W" stands for Weibull, an "N" stands for Normal, and MTTF indicates Mean Time to Failure.

It should be mentioned that the scale factor corresponds to the threshold at which 63.2% of the population will have failed. To determine the MTTF, simply find the point on the cumulative distribution function corresponding to 0.5. This is done for the data in Appendix B by straightforward calculation within Minitab™, but the details are not covered here.

Several items stand out. First, although the simulation data was designed to have a shape of 2 and a scale of 250, and *figure 6* shows the data to best fit a Weibull curve of shape 2.13 and scale 253, the average Weibull shape for the 100 sets of six was 2.87. This can be seen graphically in *figure 8*.

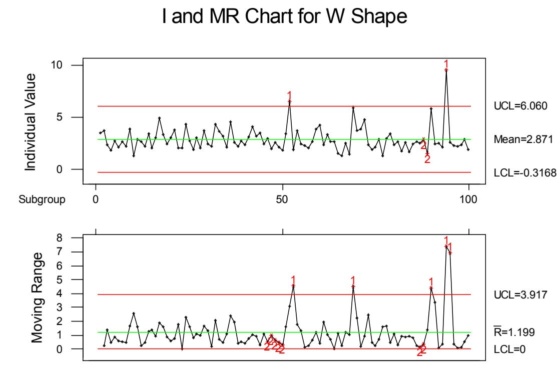

Figure 8 – Shape for Weibull Simulation Subsets

In addition to the fact that the shape values are higher than expected, the variation between subsets is also substantial. This is a direct result of the challenges of using such small data sets.

Similar results are seen in the scale data presented in *figure 9*.

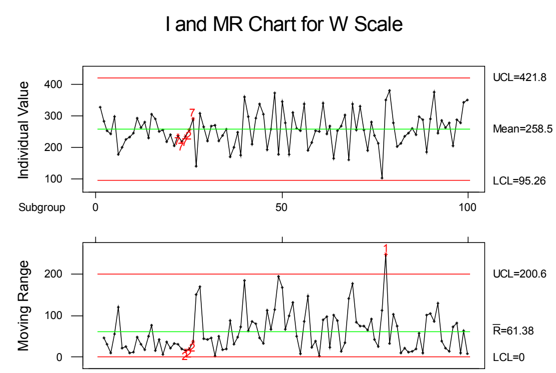

Figure 9 – Scale for Weibull Simulation Subsets

Using just six samples at a time, it is reasonable to expect that scale factors as high as 422 and as low as 95 could be found at any given time.

Finally, the AD results are presented in *figure 10*.

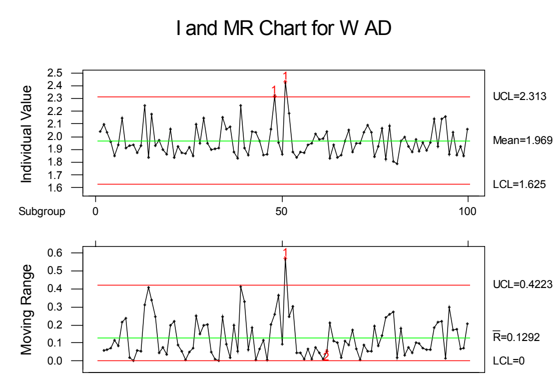

Figure 10 – AD for Weibull Simulation Subsets

It is clear that for any given set of six random samples from the particular known Weibull distribution used in the simulation, the resulting AD can be expected to be anywhere between 1.62 and 2.31, with an average at 1.97. So, the answer to question number 1 in this section is yes the AD statistics are within the expected range, but they are consistently on the high side. The most likely explanation for this is that the Weibull approximation, although reasonable, it is not exact. To say it another way, the underlying data set does not quite follow a Weibull distribution.

Now, consider the second question. Although the Weibull approximation is not exact for IST data, is it a better fit than the normal distribution? To answer this, consider the same t-test as in the section titled *Comparison of Normal and Weibull Results*. The results for the t-test are presented in *table 3*.

Table 3: Simulation T-Test Results

Paired T-Test and CI: Weibull AD, Normal AD

Paired T for Weibull AD - Normal AD

	N	Mean	StDev	SE Mean
Weibull AD	100	1.9688	0.1198	0.0120
Normal AD	100	1.9997	0.1321	0.0132
Difference	100	-0.03094	0.06319	0.00632

95% upper bound for mean difference: -0.02045
T-Test of mean difference = 0 (vs < 0): T-Value = -4.90 P-Value = 0.000

With a p-value of 0.000, the conclusion is that for the known Weibull distribution in the simulation, Weibull analysis will yield a statistically better fit than using the normal approximation, even when using a sample size as small as six.

Implications

From the arguments above there is statistical evidence to support using Weibull analysis on six-sample IST results, but how much advantage is gained? To answer this, consider the following control chart for the simulation subsets comparing the average cycles to failure as calculated first with the normal approximation, and subsequently by the Weibull approximation (*figure 11*).

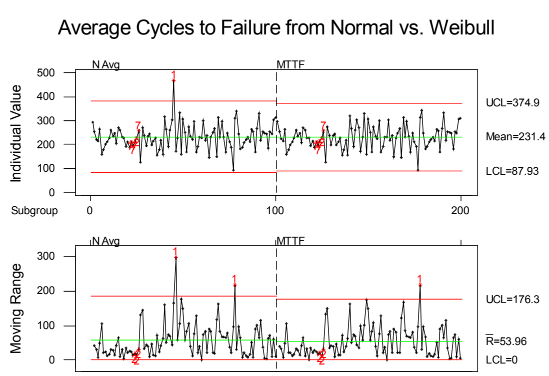

Figure 11 – Cycles to Failure Comparison

There is no identifiable difference in the mean (t-test p-value = 0.479), but there is a slight improvement in the variation. The amount of this improvement is 5.4%. For any given set of six samples, the odds are that the mean cycles to failure as calculated with Weibull analysis will be closer to the true population mean than if calculated using normal analysis.

Conclusions

Predicting plated thru-hole reliability characteristics for PWBs is inherently challenging due to the natural constraints in the IST testing protocol. Given the limitation in sample size, a 5.4% improvement in the ability to predict average cycles to failure can be gained simply by using Weibull analysis in place of normal analysis.

Acknowledgments

Thank you to the PWB shops that provided the IST data used in this paper. For confidentiality purposes, they remain unnamed. Thanks also to Sean Mirshafiei and Kathy Kelly of Isola Laminate Systems for their research and guidance.

(*) From Jim Dancer's presentation titled "PTH Reliability and Accelerated Test Methods" as published on PWB Interconnect Solutions' web site at pwbcorp.com

Appendix A

Shape	Scale	Anderson-Darling Weibull	Normal Mean	Anderson-Darling Normal
3.00	255.7	2.19	228.0	2.29
4.73	275.0	2.04	251.0	2.04
10.27	60.7	2.33	57.3	2.40
1.05	172.0	2.37	168.0	2.79
4.20	243.0	1.92	222.0	1.92
2.60	116.0	1.95	103.0	1.89
2.41	303.0	1.94	268.0	1.99
1.85	56.4	1.98	49.7	2.14
5.88	652.0	1.92	602.0	1.92
6.99	102.0	1.90	95.5	1.92
11.12	307.0	1.84	294.0	1.84
4.95	267.0	1.92	246.0	1.90
3.89	212.0	2.07	192.0	2.08
4.80	153.0	2.22	141.0	2.21
5.70	196.0	1.96	181.0	1.98
3.25	182.0	2.36	162.0	2.29
1.33	226.0	2.15	205.0	2.50
2.36	148.0	1.88	131.0	1.88
3.70	137.0	2.02	124.0	2.07
4.16	350.0	1.96	318.0	1.95
2.60	335.0	2.00	299.0	1.90
0.87	128.0	1.87	139.0	2.35
5.90	166.0	1.85	153.0	1.86
2.59	98.7	2.06	87.3	2.00
3.00	43.4	1.86	38.7	1.92
1.51	194.0	2.48	181.0	2.01
2.38	117.0	1.89	104.0	1.96
4.64	213.0	1.86	194.0	1.88
3.05	156.0	1.86	136.0	1.88
5.57	149.0	1.90	137.0	1.90
3.73	27.7	2.00	25.0	1.96
3.04	257.0	2.02	228.0	2.06
2.62	299.0	1.81	265.0	1.86
6.62	161.0	1.81	150.0	1.83
1.65	204.0	2.02	181.0	2.24
8.12	28.7	1.91	27.0	1.92
8.10	194.0	1.88	183.0	1.89
3.81	258.0	2.15	234.0	2.21
4.29	128.0	2.14	116.0	2.12
6.18	235.0	2.15	219.0	2.13
3.97	212.0	1.79	192.0	1.80
3.16	249.0	1.85	222.0	1.88
1.89	116.0	2.08	104.0	2.01
3.59	147.0	2.07	132.0	2.12
3.88	37.8	2.02	34.0	2.02
2.12	162.0	1.85	143.0	1.89

5.45	218.0	2.17	200.0	2.20
4.84	361.0	1.90	330.0	1.91
1.99	247.0	1.90	218.0	1.90
1.13	114.0	1.96	109.0	2.00
4.53	185.0	1.96	168.0	1.95
3.79	698.0	1.86	628.0	1.87
7.22	276.0	1.95	259.0	1.98
1.02	224.0	2.12	222.0	2.51
1.98	114.0	3.42	105.0	3.11
38.20	45.6	1.86	45.0	1.84
6.77	200.0	2.02	186.0	2.01
1.08	76.9	2.02	74.3	2.47
1.84	68.6	1.96	60.8	2.05
8.04	92.6	1.83	87.2	1.84
4.38	186.0	2.08	169.0	2.07
1.33	185.0	1.86	171.0	1.91
9.57	378.0	1.96	360.0	1.91
2.43	120.0	2.14	106.0	2.29
5.88	99.0	1.91	92.0	1.93
4.46	282.0	2.07	258.0	2.09
3.79	353.0	1.93	319.0	1.97
4.03	179.0	1.87	162.0	1.88
1.47	84.0	1.96	76.0	1.93
1.43	36.3	2.24	32.5	2.52
5.80	355.0	1.90	329.0	1.89
9.60	432.0	1.87	411.0	1.83

Appendix B

Simulation	W Shape	W Scale	W AD	MTTF	N Avg	N AD
C194	3.47	329	2.043	296	295	2.104
C195	3.71	283	2.100	256	254	2.074
C196	2.32	253	2.036	224	223	2.171
C197	1.84	243	1.963	216	215	2.097
C198	2.71	298	1.849	265	264	1.872
C199	2.12	178	1.934	158	157	2.041
C200	2.67	200	2.148	178	177	2.136
C201	2.19	225	1.912	199	200	1.882
C202	3.84	234	1.932	212	212	1.911
C203	1.28	246	1.933	228	229	2.007
C204	2.89	293	1.876	261	260	1.886
C205	2.65	263	1.931	234	233	2.012
C206	2.18	280	2.244	248	247	2.417
C207	3.45	230	1.837	207	206	1.841
C208	2.08	307	2.176	272	270	2.291
C209	3.02	292	1.928	261	260	1.928
C210	4.92	250	1.973	229	230	1.959
C211	3.31	256	1.897	229	228	1.892
C212	2.45	219	1.859	194	193	1.919
C213	3.03	240	2.057	215	213	2.060
C214	3.80	207	1.835	187	187	1.853
C215	2.05	238	1.925	211	210	2.035
C216	2.02	219	1.872	194	195	1.823
C217	4.30	235	1.869	214	213	1.871
C218	2.72	255	1.917	227	227	1.918
C219	1.91	291	1.848	258	258	1.898
C220	3.03	140	2.100	125	126	2.034
C221	2.03	309	1.949	274	272	2.099
C222	3.71	265	2.149	239	239	2.089
C223	2.41	222	1.947	197	196	1.921
C224	2.23	268	1.899	237	236	1.960
C225	4.32	271	1.907	246	246	1.929
C226	3.64	221	1.909	199	199	1.914
C227	3.20	238	2.154	213	214	2.235
C228	2.13	258	2.063	228	227	2.061
C229	4.55	170	2.081	156	155	2.074
C230	2.60	201	1.883	179	178	1.955
C231	2.20	248	1.831	219	219	1.838
C232	2.74	176	2.245	156	157	2.197
C233	2.33	361	1.914	319	318	1.954
C234	3.08	298	1.853	267	266	1.899
C235	4.12	212	2.039	193	192	2.012
C236	3.18	293	2.036	262	261	2.007
C237	3.49	339	1.969	305	305	2.019
C238	2.40	306	1.854	271	270	1.908
C239	2.95	193	1.859	172	171	1.888
C240	1.96	259	2.060	230	228	2.239
C241	2.59	374	2.320	332	335	2.191
C242	2.11	179	1.954	158	158	2.013

C243	1.79	346	1.860	308	308	1.908
C244	3.41	279	2.432	251	251	2.548
C245	6.49	179	2.187	167	167	2.186
C246	1.93	310	1.883	275	274	1.975
C247	3.71	261	1.840	236	235	1.833
C248	2.39	253	1.883	224	223	1.942
C249	2.27	339	1.873	300	298	1.950
C250	2.02	192	1.938	170	169	2.036
C251	2.67	216	1.946	192	191	1.991
C252	3.88	254	2.023	230	230	2.076
C253	4.27	252	1.978	230	229	1.994
C254	2.32	342	1.987	303	302	2.012
C255	3.35	244	2.039	219	218	2.064
C256	2.64	268	1.828	239	238	1.854
C257	2.66	167	1.939	148	147	1.976
C258	1.50	254	1.838	229	230	1.837
C259	1.26	268	1.856	249	250	1.890
C260	2.47	303	1.966	269	268	2.021
C261	1.44	162	2.055	147	150	1.928
C262	5.95	339	1.883	315	314	1.921
C263	3.70	255	1.948	230	230	1.924
C264	3.87	330	1.951	299	298	1.946
C265	4.81	255	2.038	233	232	2.034
C266	2.35	190	2.090	169	168	2.228
C267	1.90	281	2.036	249	247	2.070
C268	2.16	239	1.842	212	211	1.863
C269	2.88	214	1.926	191	190	1.983
C270	1.28	102	2.067	94	94	2.211
C271	2.94	350	1.825	313	312	1.861
C272	3.43	382	2.084	344	342	2.090
C273	2.32	279	1.809	247	246	1.874
C274	2.64	204	1.789	181	181	1.803
C275	1.72	214	1.968	191	189	2.133
C276	2.57	236	1.998	210	209	2.101
C277	1.66	247	1.924	221	222	1.929
C278	2.44	260	1.881	231	230	1.898
C279	2.65	241	1.981	214	213	2.066
C280	2.50	298	1.884	265	264	1.951
C281	2.85	288	1.953	257	256	2.023
C282	1.48	186	1.892	168	167	1.967
C283	5.86	291	1.953	269	268	1.999
C284	2.46	376	2.138	334	332	2.274
C285	2.51	246	1.923	218	217	1.956
C286	2.14	285	2.141	253	253	2.044
C287	9.57	264	2.157	251	249	2.134
C288	2.59	278	1.859	247	246	1.834
C289	2.26	206	2.033	183	184	1.943
C290	2.20	289	1.855	256	255	1.867
C291	2.32	279	1.921	247	246	1.889
C292	2.85	343	1.852	306	305	1.885
C293	1.89	350	2.058	310	314	1.917