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CURRENCY FLAW SEVERITY

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ABSTRACT

A survey of currency flaw severity was carried out using 300 notes and 37 judges. Each judge assigned each note to one of five flaw severity categories. These categories correspond to severity grades of 1 to 5 with 1 equivalent to "always accepted" and 5 "never accepted". An average flaw severity grade for each note was obtained by taking the mean of the severity grades assigned to that note by the 37 judges. Thus, each note has a single numerical real-number flaw grade between 1 and 5. Mathematical modeling of the currency flaw survey results is continuing with some very promising initial results. Our present model handles common excess ink and missing ink flaw types quite well. We plan to extend the model to ink level, mash, setoff and blanket impression flaw types.

FLAW SURVEY

Data collection in the flaw survey utilized 37 judges representing several different occupational categories inside and outside of the U.S. Bureau of Engraving and Printing (BEP) including management, press operators, currency inspectors, quality assurance personnel, engravers, and research scientists. These judges sorted 300 currency samples into five groups, based on their opinion of the flaw severity on each sample: (1) always accepted; a threshold acceptance/rejection range with three subdivisions based on printing quality: (2) good, (3) fair, and (4) poor; and finally, (5) always rejected.

The 300 specimens covered 31 graded sequences of typical flaws, including light print, slywipe, mash, blanket impression, setoff, and various breaks, and were presented in a random order to the judges. The 300 banknotes of various denominations were mounted on light green 5" x 8" cards. Each card contained a label underneath the note naming the flaw type on which that note was to be judged. About one-half of the specimens had natural printing flaws taken from blank engraved sheets that had been rejected by currency examiners. The remainder were "designer" flaws made on new one dollar banknotes obtained at a local bank.

One hour was scheduled for each of the 37 survey participants with about 50 minutes allotted for flaw judging and about 10 minutes for explanation and recording of results. The individual judge's decisions were recorded from bar codes on the backs of the specimen cards using a lap-top portable computer

with attached bar code reader. A subset of the data collected is given in Table 1 which includes histograms of the judges' responses for each note and the average numerical scores.

SURVEY RESULTS

An infrequent problem was bimodality in the grading histogram of certain notes, i.e. some judges gave a note a good grade while others rejected it. One cause of bimodality is that a few of the flaws were too well camouflaged, making them difficult to find. One case in particular has a large portrait background break which seems to be part of Washington's hair unless compared with a normal note. About half the judges rated it acceptable and the other half unacceptable. Another interesting example was a major slywipe on the shoulder of Hamilton's coat. It appeared to be a natural shadow, reminiscent of Rembrandt's style of shading, and was missed by all but three judges. It came to light during the regression modeling, described below, when a very large difference between its calculated and observed values was noted.

Liberal judges on the left hand side of Table 1 tend to find marginal flaws acceptable while conservatives on the right hand side tend to find the same flaws unacceptable. Almost two-thirds of the 300 notes were found absolutely acceptable by the most liberal judge whereas over two-thirds were absolutely unacceptable to the most conservative judge. This trend was at first rather disturbing until we realized that a person's opinion on currency flaws is fully as subjective as his opinions on politics or art appreciation and that most people have very narrow regions which they consider "marginal" in any judgment task.

The instances where all judges found a note always acceptable (average grade near one) or always unacceptable (average grade near five) were considered uninteresting and removed from the data set. Outlier notes, usually due to flaw camouflage effects and which were unusual in terms of the disagreement among the judges, and judges who were less consistent in their assignment of grades to similar notes were identified by a series of statistical tests. Retaining only slywipe and break type flaws, the data matrix was then reduced temporarily to 175 notes by 31 judges to insure a robust data set for the initial flaw modeling stages. Additional notes were also deleted later in the analysis when the discrepancies between observed and calculated values were clearly out of line with those found for related notes in a series.

FLAW MEASUREMENTS

For each of the selected notes, the x and y dimensions for equivalent flaw area rectangles, the flaw optical density, and the currency region types covered by the flaw components were determined through careful visual comparison with calibration standards. The dimensions were estimated to 0.1 millimeter and the density to about 2 to 3 percent. The notes were segmented into 10 generic regions. Breaks were given a negative density value equal to the equivalent density of the missing ink image over the area of the flaw component. Flaws can consist of several flaw components in different note

regions. Setoff, mash, ink level, and blanket impression flaws have not been modeled at present. Measurements on a subset of the notes used in the following discussion are given in Table 3.

MATHEMATICAL MODEL

We then formulated a model correlating the derived flaw severity grades with the physical parameters for the flaw. The parameter coefficients were obtained by nonlinear least-squares refinement using observations from 175 slywipe and break flawed notes. The flaw characteristic parameters, observed severity factors from the flaw survey, and calculated severity factors from the model defined below are given in Table 3 for the same notes tabulated in Table 1.

The current flaw model has the form

$$Fc = Bi[T + \Sigma\Sigma_{jk} R_j \, f(D_{jk})g(A_{jk})]^{1/w} \qquad (1)$$

The sum is taken over all flaw components jk with

$$f(D_{jk}) = |D_{jk}|^u \qquad (2)$$

and

$$g(A_{jk}) = A_{jk}^v \qquad (3)$$

with symbols defined as:

Fc -- Calculated flaw severity
Bi -- Scale factor for note denomination i
R_j -- Scale factor for region j
D_{jk} -- Measured density for flaw component k in region j
$|D_{jk}|$ denotes the absolute value of D_{jk}
(excess ink flaw has positive D_{jk})
(ink loss flaw has negative D_{jk})
A_{jk} -- Measured area for flaw component k in region j in mm^2
T,u,v,w -- coefficients for entire data set
(x^u etc. denotes raising x to the u th power)
(T,u,v, and w are approximately .003, 1.6, 0.72, and 4.6)

Eq. (1) may be rewritten using natural (base e) logarithms (ℓn) and exponentials (exp) as

$$\exp[w(\ell n(Fc)-\ell n(Bi)] = T + \Sigma\Sigma_{jk} R_j \, f(D_{jk})g(A_{jk}) \; . \qquad (4)$$

In Eq. (4) we note that the left hand side has the form exp[(x - y)/z] which increases exponentially with x = ℓn(Fc). The variables y = ℓn(Bi) and z = 1/w

shift the flaw scale along the exponential curve and change the spacing between successive grades, respectively. The right hand side of (4) is a sum of flaw component products with the region scale factor, flaw density, and flaw area functions as factors in the products.

EQUISEVERITY CONTOUR PLOTS

For the single-flaw single-region case, the summation may be omitted and the expression rearranges to

$$\ell n\{\exp[w(\ell n(Fc) - \ell n(Bi))] - T\} - \ell n(R_j) = u\ell n|D_{jk}| + v\ \ell n(A_{jk}) \ . \quad (5)$$

The right hand side (RHS) of (5) can be rearranged further to allow tabulating Fc as a function of density and the square root of area.

$$RHS = u\ \ell n|D_{jk}| + 2v\ \ell n(\sqrt{A_{jk}}) \quad (6)$$

This expression provides a convenient formulation for graphical representation to illustrate flaw severity, F, as a function of density and the square root of area. Note that the right hand side set equal to a constant is the equation for a straight line. This means that constant severity levels will appear as straight lines when flaw severity values are tabulated in $\ell n|D_{jk}|$ vs. $\ell n(\sqrt{A_{jk}})$ form and contoured. Such tabular plots are shown in Figs. 1 and 2 to illustrate our numerical results for two regions. The denomination used is the one dollar note which has a denomination scale factor of 4.2.

EXAMPLES

The figures may be used to approximate flaw severity when the note has a single flaw in a single region. Some interesting generalizations may be obtained from the figures. For example, suppose we choose the flaw severity rejection level, Fr, as Fr = 3.1. Figure 1 for the open substrate region shows that flaws (a) 1 mm by 1mm with density 0.63 (i.e., 63%), (b) 10 mm by 10 mm (or 1 mm by 100 mm) with density 0.08, and (c) 100 mm by 100 mm with density 0.01 will all have about the same appearance and are at the borderline for rejection. Lathework flaws (Figure 2) of severity 3.1 would be of minimum area 2.5 mm by 2.5 mm with density 1.0 (i.e., maximum possible density). An equivalent 10 mm by 10 mm lathework flaw would have a density of 0.32.

CONCLUSIONS

Successful flaw surveys require careful experimental design with appropriate selection of specimens, judges, and analytical methods. Most judges tended to

find a narrow threshold range between acceptable and unacceptable. We found no close correlation between occupation and the conservative or liberal nature of a judge's viewpoint.

Analytical modeling of flaw severity based on physically measurable quantities seems to be a realistic goal and we plan to extend our present model to make it a sound basis for automatic currency inspection systems.

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Figure 1. Contour plot for open substrate (OS) region.

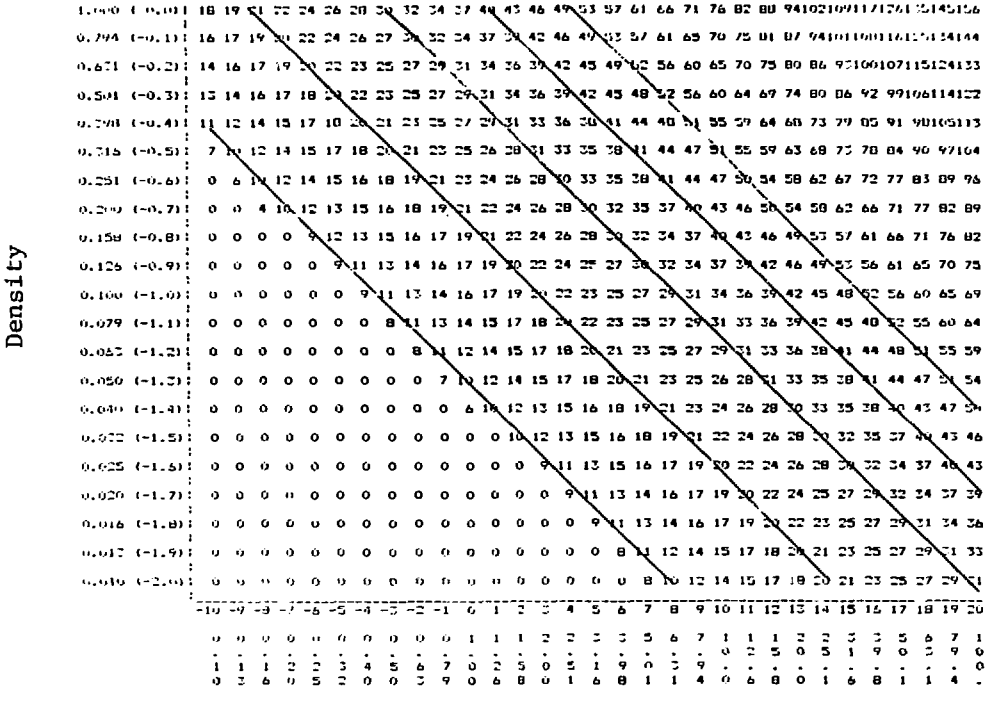

Figure 2. Contour plot for lathework (LW) region.

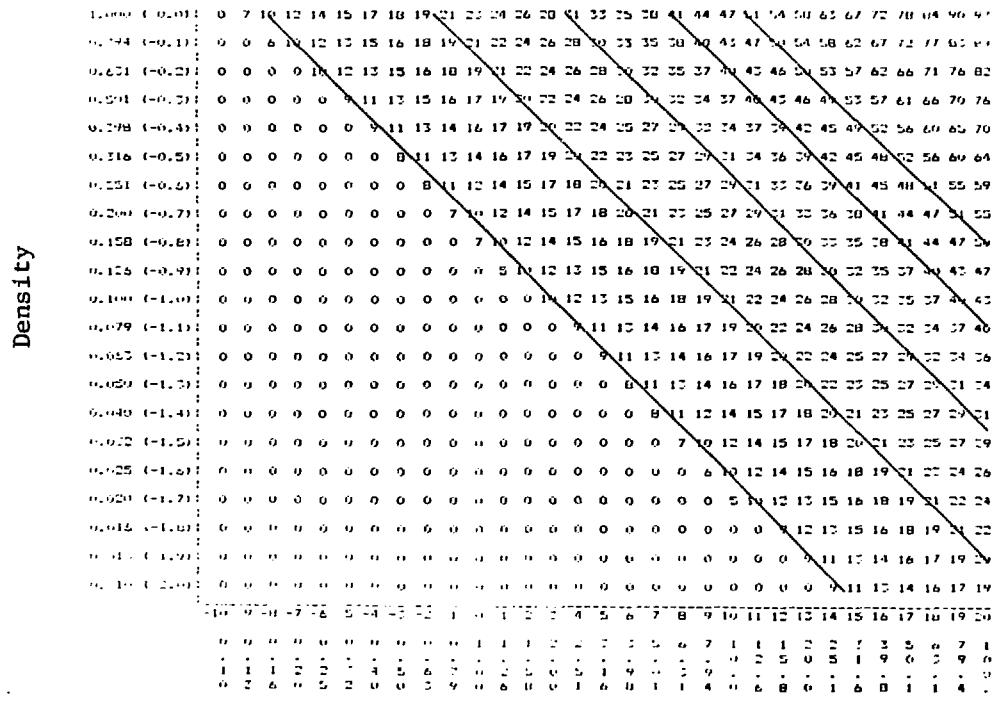

TABLE 1

RESULTS OF FLAW SURVEY

Table 1 summarizes the individual participants' grades, histogram, and collective average for three series of notes used in the survey. Each note series is ordered by severity level from least to greatest. The ordering was determined by an arbitrated side-by-side comparison of the notes within the series. Column 3 gives the individual note number which was used for data collection and inventory purposes. Columns 4 and 5 give the denomination and note side, respectively. The histogram values represent the number of times each grade was awarded to the note by the judges in order of increasing grade (1 - 5) from left to right. The "Ave" column gives the average of the individual grades for the note and "Var" gives an approximation for the internal consistency for the note with a smaller Var indicating greater internal consistency. The following symbols are used:

Denomination	Note Side
I - 1	F - Front
V - 5	B - Back
X - 10	
T - 20	
L - 50	
C - 100	

Note	Information			Individual Grades	Histogram					Ave	Var
Graded severity series Ha: Coat Break, Front, $1											
Ha	1	128	I F	11111111121221232222432322445 45	11	11	3	4	2	2.19	0.8
Ha	2	127	I F	11111111121211221242225323444 45	13	9	2	5	2	2.16	0.9
Ha	3	132	I F	11111111121312232242335334545 45	11	6	6	4	4	2.48	0.9
Ha	4	131	I F	11111211131231232242445333545 45	10	6	6	5	4	2.58	0.9
Ha	5	130	I F	11111111123231232452545335545 45	10	5	5	4	7	2.77	1.0
Ha	6	129	I F	11111111121331222452544434555 5	11	5	3	6	6	2.71	1.0
Ha	7	126	I F	11111111122322244452543444445 55	9	6	2	9	5	2.84	0.9
Ha	8	136	I F	11111212122341332452535544555 55	8	6	4	4	9	3.00	1.0
Ha	9	137	I F	13114111132343343454545445555 55	7	1	6	8	9	3.35	0.9
Ha	10	138	I F	12211211122343344454545344555 55	6	5	4	8	8	3.23	0.8
Ha	11	134	I F	12111311231344235454545444555 55	7	3	4	8	9	3.29	0.8
Ha	12	139	I F	13131332143445345542545544555 55	4	2	6	8	11	3.65	0.9
Ha	13	133	I F	14435242212445555555555455555 55	2	4	1	6	18	4.10	0.9
Ha	14	140	I F	14555243454445455555555555555 55	1	1	1	7	21	4.48	1.0
Ha	15	135	I F	15555255554455455555555555555 55	1	1	0	3	26	4.68	1.0
				xx x x xx x x xxx	x			x		x	xx
1				2			3			4	5

Graded severity series Ih: Slywipe, ink spot drawn down, lathework, Front, $1

Ih	1	162	I	F	11111111111112111121314411221l4	23	4	1	3	0	1.48	0.8
Ih	2	275	I	F	1111111111312321334114244441555	15	3	4	6	3	2.32	1.1
Ih	3	161	I	F	2111111112221122512244431545445	12	8	1	6	4	2.42	1.1
Ih	4	296	I	F	1111111111232311315444234415555	14	3	4	5	5	2.48	1.2
Ih	5	219	I	F	11111112133123331343342444555555	10	4	7	5	5	2.71	0.9
Ih	6	220	I	F	21111111134112132444454445545	12	3	3	9	4	2.68	1.1
Ih	7	181	I	F	11122111333344335445542254555555	6	4	6	6	9	3.26	0.9
Ih	8	211	I	F	11124113223343325254455544555555	5	5	5	6	10	3.35	0.9
Ih	9	142	I	F	34121233334225335354545555555555	2	4	8	4	13	3.71	0.8
Ih	10	146	I	F	14154143434355545455545555555555	3	0	3	9	16	4.13	0.9
Ih	11	196	I	F	13455443354445555454555555555555	1	0	3	8	19	4.42	0.8
Ih	12	147	I	F	13454253545455525555555555555555	1	2	2	4	22	4.42	0.9

```
      x              x x x   x         x x       x         x     x
1-----------------2-----------------3-----------------4-----------------5
```

Graded severity series Iq: Slywipe, substrate blemishes, Front, Higher denominations

Iq	1	186	X	F	11111111111121222122223224311145	17	9	2	2	1	1.74	0.9
Iq	2	261	V	F	11111211222441222332332l4445335	9	9	6	5	2	2.42	0.9
Iq	3	273	T	F	11111212123113431344445543543555	10	3	6	7	5	2.81	1.0
Iq	4	259	X	F	11121113342314533445444444455	7	2	5	12	5	3.19	0.9
Iq	5	295	X	F	12152211235214323444534553443555	5	6	6	7	7	3.16	1.1
Iq	6	197	V	F	12132112222252331533145555555555	6	8	5	1	11	3.10	1.1
Iq	7	281	X	F	32121132344414344434535535455555	4	3	7	9	8	3.45	0.9
Iq	8	252	V	F	11445145523555435543545555555555	3	1	3	6	18	4.13	1.1
Iq	9	272	V	F	33325144444444455545555555555555	1	1	3	10	16	4.26	0.7
Iq	10	288	X	F	34154142355545355455544555455555	2	1	3	8	17	4.19	1.0
Iq	11	163	T	F	13414345554353543525355555555455	2	1	6	6	16	4.06	1.1
Iq	12	256	X	F	44445155535455445555555555555555	1	0	1	7	22	4.58	1.0

```
            x           x         x    xxx    x          x xxx       x
1-----------------2-----------------3-----------------4-----------------5
```

TABLE 2

The following numerical values for note regions, R_j, and equation scale factors were derived in this analysis:

PF = 1.1312 - Portrait face: face and hair
PB = 1.2834 - Portrait light: shirt and collar
PD = 0.7045 - Portrait dark: coat and background
OS = 0.5800 - Open substrate: outer border, inner substrate
ES = 0.2846 - Enclosed substrate: white lettering
LW = 0.0630 - Lathework: mechanically produced background design
SW = 0.3057 - Scene work: note back scene or great seal patterns, excluding crosshatch background
CH = 0.2595 - Crosshatch: Great Seal background, leafy decorations, shading around bottom denomination panel
SP = 1.1140 - Small print: signatures, titles, and other small print in inner substrate
LP = 0.1109 - Large print: in Federal Reserve Note panel and the United States of America banner (not needed for slywipes)

Coefficients for entire data set:

T = 0.003045 - Summation translation coefficient
w = 4.6062 - Severity scaling coefficient
v = 0.7235 - Area transformation coefficient
u = 1.6171 - Density transformation coefficient

TABLE 3

Regression calculation for calculated (Fc) flaw severity based on visually estimated flaw density (D), flaw area as rectangular width times length (W x L), flaw multiplicity (M), and note denomination (B). 175 Slywipe-flawed and break-flawed notes were used in the calculation. Refer to the text for the empirical mathematical model used. Note that individual coefficients were used for each currency region and note denomination. The observed flaw severity (Fo) given is the severity grade average from the 31 most self-consistent judges. The average disagreement between observed and calculated is 12% of the average observed value. The inventory number (N), the flaw series (S), the denomination (B), the side containing the flaw (s), and the ORNL assigned rank (R) are given for cross comparisons with previous results.

S	R	N	B	s	D	W	L	M	RE	Fo	Fc	Fo-Fc
Ha	1	128	1	F	-.40	0.5	1.0	1.0	PD	2.19	2.48	-0.29
Ha	2	127	1	F	-.30	0.4	0.4	1.0	PD	2.16	1.98	0.18
					-.30	0.2	0.2	1.0	PD			
Ha	3	132	1	F	-.20	0.2	0.2	5.0	PD	2.48	2.08	0.40
					-.20	0.5	0.5	1.0	PD			
Ha	4	131	1	F	-.30	0.9	1.0	1.0	PD	2.58	2.54	0.04
					-.30	0.2	0.2	1.0	PD			
					-.30	0.1	0.1	1.0	PD			
Ha	5	130	1	F	-.40	1.4	2.0	1.0	PD	2.77	3.27	-0.50
Ha	6	129	1	F	-.40	1.0	0.8	1.0	PD	2.71	2.68	0.03
Ha	7	126	1	F	-.40	2.8	1.0	1.0	PD	2.84	3.27	-0.43
Ha	9	137	1	F	-.30	0.5	0.5	4.0	PD	3.35	3.01	0.34
					-.30	0.2	1.0	2.0	PD			
					-.30	0.1	0.1	6.0	PD			
Ha	10	138	1	F	-.40	0.9	0.9	1.0	PD	3.23	3.21	0.02
					-.40	0.8	1.0	1.0	PD			
					-.40	0.1	0.1	6.0	PD			
Ha	11	134	1	F	-.40	3.7	1.0	1.0	PD	3.29	3.42	-0.13
Ha	12	139	1	F	-.30	1.0	0.5	1.0	PD	3.65	3.16	0.49
					-.30	0.3	0.3	10.0	PD			
					-.40	1.0	0.2	1.0	PD			
Ha	13	133	1	F	-.40	1.0	1.2	2.0	PD	4.10	4.10	-0.00
					-.40	0.8	0.5	5.0	PD			
					-.40	0.2	0.2	11.0	PD			
Ha	14	140	1	F	-.20	3.0	3.0	1.0	PD	4.48	3.93	0.55
					-.20	4.0	1.0	1.0	PD			
					-.20	1.3	2.0	1.0	PD			
					-.20	2.0	3.0	1.0	PD			
					-.20	0.1	0.1	4.0	PD			
					-.50	0.5	0.5	1.0	PD			
Ha	15	135	1	F	-.30	1.7	5.0	1.0	PD	4.68	4.68	0.00
					-.30	3.0	0.7	1.0	PD			
					-.30	2.0	4.0	1.0	PD			
					-.30	0.3	2.0	1.0	PD			
					-.30	0.9	0.9	1.0	PD			
					-.30	0.2	0.2	5.0	PD			
					-.30	3.0	2.5	1.0	PD			

Ih	1	162	1	F	.55	0.8	0.8	2.0	LW	1.48	1.96 -0.48
Ih	2	275	1	F	.55	1.0	1.0	1.0	CH	2.32	3.09 -0.77
					.40	1.0	4.0	1.0	CH		
Ih	3	161	1	F	.55	1.0	3.0	1.0	LW	2.42	2.35 0.07
					.55	0.3	3.0	1.0	LW		
Ih	4	296	1	F	.45	0.8	5.0	1.0	LW	2.48	2.73 -0.25
					.45	0.4	4.0	1.0	CH		
Ih	5	219	1	F	.45	1.5	5.0	1.0	LW	2.71	3.07 -0.36
					.45	1.0	3.5	1.0	CH		
Ih	6	220	1	F	.45	1.5	13.0	1.0	LW	2.68	3.39 -0.71
					.35	1.5	6.5	1.0	CH		
Ih	7	181	1	F	.43	1.0	10.0	1.0	LW	3.26	3.82 -0.56
					.43	1.0	2.0	1.0	LW		
					.43	1.0	10.0	1.0	CH		
					.55	1.0	1.0	1.0	OS		
Ih	8	211	1	F	.50	2.0	5.0	1.0	LW	3.35	2.91 0.44
					.50	1.5	5.0	1.0	LW		
Ih	9	142	1	F	.18	1.5	8.0	1.0	ES	3.71	2.96 0.75
					.18	0.5	2.0	1.0	OS		
					.12	0.3	3.5	1.0	OS		
					.12	0.8	5.0	1.0	OS		
Ih	10	146	1	F	.55	2.5	5.0	1.0	LW	4.13	3.61 0.52
					.55	4.0	5.0	1.0	LW		
					.40	2.0	15.0	1.0	LW		
Ih	11	196	1	F	.43	1.8	11.5	1.0	CH	4.42	4.32 0.10
					.43	1.0	10.0	1.0	CH		
					.43	2.5	5.0	1.0	LW		
					.20	2.0	2.0	1.0	ES		
					.20	1.0	2.0	1.0	ES		
					.25	0.2	1.0	1.0	ES		
					.40	0.8	1.0	1.0	ES		
Ih	12	147	1	F	.25	3.0	2.5	1.0	LW	4.42	3.70 0.72
					.20	7.0	2.0	1.0	LW		
					.25	3.0	2.5	1.0	OS		
					.15	2.0	1.0	1.0	OS		
					.35	1.0	1.0	1.0	ES		
					.20	2.0	2.0	1.0	OS		
					.40	0.8	1.0	1.0	CH		
Iq	1	186	10	F	.55	0.3	0.8	1.0	OS	1.74	2.20 -0.46
Iq	2	261	5	F	.35	0.8	1.0	1.0	ES	2.42	2.06 0.36
Iq	3	273	20	F	.23	0.2	7.0	1.0	OS	2.81	2.20 0.61
Iq	4	259	10	F	.65	1.0	2.5	1.0	OS	3.19	3.40 -0.21
Iq	5	295	10	F	.57	0.4	1.0	3.0	OS	3.16	3.09 0.07
Iq	7	281	10	F	.38	5.0	1.0	2.0	OS	3.45	3.73 -0.28
					.38	0.5	1.0	1.0	OS		
Iq	8	252	5	F	.48	3.0	2.5	1.0	OS	4.13	3.87 0.26
Iq	9	272	5	F	.65	1.0	4.0	1.0	OS	4.26	4.54 -0.28
					.55	1.5	10.0	1.0	ES		
					.15	0.5	7.0	1.0	ES		
Iq	10	288	10	F	.68	0.5	2.0	4.0	OS	4.19	4.05 0.14
Iq	11	163	20	F	.68	2.0	2.0	1.0	OS	4.06	3.83 0.23

DISCLAIMER