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SUMMARY

The current method for making corrections to the standard time-temperature curve has been examined. Using numerical heat flow calculations, the accuracy of the method was compared with that of a modified method considered by the ASTM Task Group on Alternatives to the Time-Temperature Curve. An improved method was developed which gives more accurate results than either the current method or the Task Group proposed modification.

The time-temperature correction currently incorporated in ASTM E-119 standard was originally developed by S.H. Ingberg in 1946. He based the method on three tests conducted by the Portland Cement Association in the 1930's. He also was correctly cognizant of the fact that heat flow to a wall in a simple case is determined by the dimensionless Fourier number:

$$Fo = \frac{k}{\rho C_p} \frac{t}{x^2}$$

where k= thermal conductivity, ρ= density, C_p= heat capacity, t= time, and x= thickness or distance from exposed face.

On this basis he proposed that the correction (in %) to be added to the indicated endurance period to obtain the rated period is

$$\Delta = \frac{2}{3} \left(\frac{A-A_s}{L+A_s}\right) x100\%$$

where A = the area under the actual curve for the first 3/4 of the indicated period, A_s = the area under the standard curve for the same length of time, and L= 30 °C-hr. Hereafter, the current ASTM method will be referred to as the "3/4 method."

The Task Group on Alternatives to the Time-Temperature Curve has proposed a modification which would consist of changing the 2/3 factor to 1.0 and also considering the total period, not just the first 3/4 of the period. This method will be referred to as the "4/4 method."

Ingberg's original reason for specifying only 3/4 of the period has to do with the Fourier number. According to this, if we impress a step-function temperature deviation on the furnace gas curve, the temperature at any point in the wall will be proportional (although not quite linearly) to the gas-temperature deviation and the time between when we first apply the increment and when we measure the given point within the wall. Thus the largest effect will be due to temperature errors at the beginning of the test and the least effect of any towards the end.

Heat transfer in an actual wall is highly complex and not easily predicted by analytical means. There are two main reasons for this. The thermophysical properties (conductivity, emissivity, etc) of any building material are not constants, but rather non-linear functions of temperature (and very poorly known at the present time, one might add). Second, the process of heat transfer within a test furnace is not simple. Both radiation and convection are involved, and again cannot be represented by constant transfer coefficients.

However, if we ignore such practical deviations and consider constant properties the problem becomes somewhat more tractable.

An additional proviso that must be emphasized is that any such correction method is predicated on the assumption that the material fails by "thermal" criteria on the back face, while remaining integral throughout. It should not exhibit burning, melting, fall-off, etc. Such a restriction is not currently within the E-119 method, but on considerations of material behavior definitely should be included.

Thirty years ago Ingberg did not have available to him computer numerical techniques for solving heat flow problems. To investigate this question numerically I considered an idealized brick wall of the following description--

thickness= 4 inches
density= 1900 kg/m^3
diffusivity= 0.002 m^2/hr
emissivity= 0.70

Eleven computer runs were then made using a one-dimensional heat flow program. This program treats both radiative and convective boundary conditions on both the furnace side and the unexposed face. "Thermal" failure in the E-119 standard is determined by thermocouple readings under asbestos pads. To simulate that condition, failure (139°C rise above 20°C ambient) was determined not at the unexposed face but rather 0.36 inches inside. This represented temperatures about 25°C higher than the back face and was judged a suitable simulation.

The reference test (Run A) consisted of a correct ASTM E-119 curve. It must be noted that the E-119 curve is specified in terms of slow-response thermocouple readings; whereas, to be consistent, heat flow programs need gas temperatures with no lag. This can be quite well approximated at the University of California test furnace by measuring gas temperatures with fast-response thermocouples, while at the same time following the E-119 curve exactly with the E-119 thermocouples. This produces a good indication of the true gas temperatures for a test run under E-119 standard conditions.

These values are approximately as follows (exact determination is not material for the present study).

Time (hr)	Gas temperature (°C)	Slow thermocouple temperature (°C)
0	20	20
.10	655	571
.20	746	726
.30	787	781
.40	819	816
.50	843	843
.60	865	865
.70	884	884
.80	900	900
.90	914	914
1.00	927	927

In this connection it should be mentioned that the value of including the L term in a correction formula appears to be dubious. The quantity L was Ingberg's determination of the total area by which the "fast" curve exceeds the E-119 curve, namely 30°C-hr. From our measurements this should, in fact, be closer to 18°C-hr. However, the reason for having such a term at all is not persuasive. Granted that there is a difference of L between the fast and the slow curves, it would seem that the errors on the fast curve would be also correspondingly greater than on the slow curve; thus, the ratio should not be modified. In any case, the only effect of an additive term in the denominator is to increase the possible correction for short duration tests. This is not needed since the standard only allows for correction to tests of 1/2 hour or longer.

The cases that have been examined are as follows

Run	Deviation	
A	E-119 standard; no deviation	
B	10% high	0-1.0 hr
C	20% high	0-0.5 hr
D	20% high	0.5-1.0 hr
E	10% low	0-1.0 hr
F	20% low	0-0.5 hr
G	20% low	0.5-1.0 hr
H	20% high	0-0.25 hr
J	20% high	0.25-0.5 hr
K	20% high	0.5-0.75 hr
L	20% high	0.75-1.0 hr

In each run temperatures were standard, as given on the previous page, except during that portion of the period where a given deviation is applied, as listed.

The results have been treated by three methods: the 3/4 method, the 4/4 method, and by a slightly more refined method ("improved method") which gives the best results.

The different correction methods can be compared on an weighting factor diagram, plotting the weighting of curve-area errors as a function of time within the test period (see figure). By looking at the weighting factor curve it can be seen that what is needed is a method which gives far more weight to errors in the beginning of the test than those at the end. Ingberg attempted to do this by simply zero-weighting the data for the last quarter. An "ideal" approach would be to perform an integral.

$$\Delta = 2\int_0^{t_x} (\theta-\theta_s)\left(1-\frac{t}{t_x}\right) dt \quad \times 100\%$$

where θ = actual temperature, θ_s = standard temperature, t= time of measurement, t_x= length of indicated period. In practice this would be set forth as

$$\Delta = 2\sum_j (\theta_j-\theta_{js})\left(1-\frac{t_j}{t_x}\right)\left(\frac{t_{j+1}-t_{j-1}}{2}\right) \quad \times 100\%$$

where the readings j are summed from the first one to the last one. For hand computation such a method would be quite tedious.

A simpler approach is to divide the period into four quarters and assign a single, constant weighting factor within each. Also, it can be more convenient to define the quarters on the basis of the desired rated period and let the fourth quarter be lightly short or long, as the case may be. The equation becomes

$$\Delta = \frac{1.75\cdot(A_1-A_{1S}) + 1.30\cdot(A_2-A_{2S}) + 0.75\cdot(A_3-A_{3S}) + 0.25\cdot(A_4-A_{4S})}{A} \times 100\%$$

The denominator is taken as A, not A_S, since that produces best agreement of results. A table of calculations is enclosed, showing these calculations for the proposed improved method. A comparison of the computer program heat flow results (see table) with the 3/4 method, the 4/4 method and the improved method shows that the average residual error for the improved method is 0.62% compared with 1.89% for 3/4 method and 3.02% for the 4/4 method. Thus it appears that the improved method would offer a definite accuracy improvement, about a factor of three over the current 3/4 method.

Proposed improved E-119 section 5.3

5.3 When the indicated resistance period is 1/2 h or over, determined by the average or maximum temperature rise on the unexposed surface or within the test sample, or by failure under load, a correction shall be applied for variation of the furnace exposure from that prescribed, where it will affect the classification, by adding to the indicated period a correction term D, defined as follows

$$D = I \frac{1.75(A_1 - A_{1s}) + 1.30(A_2 - A_{2s}) + 0.75(A_3 - A_{3s}) + 0.25(A_4 - A_{4s})}{A}$$

where:

I = indicated fire resistance period

A = total area under the curve of indicated average furnace temperature

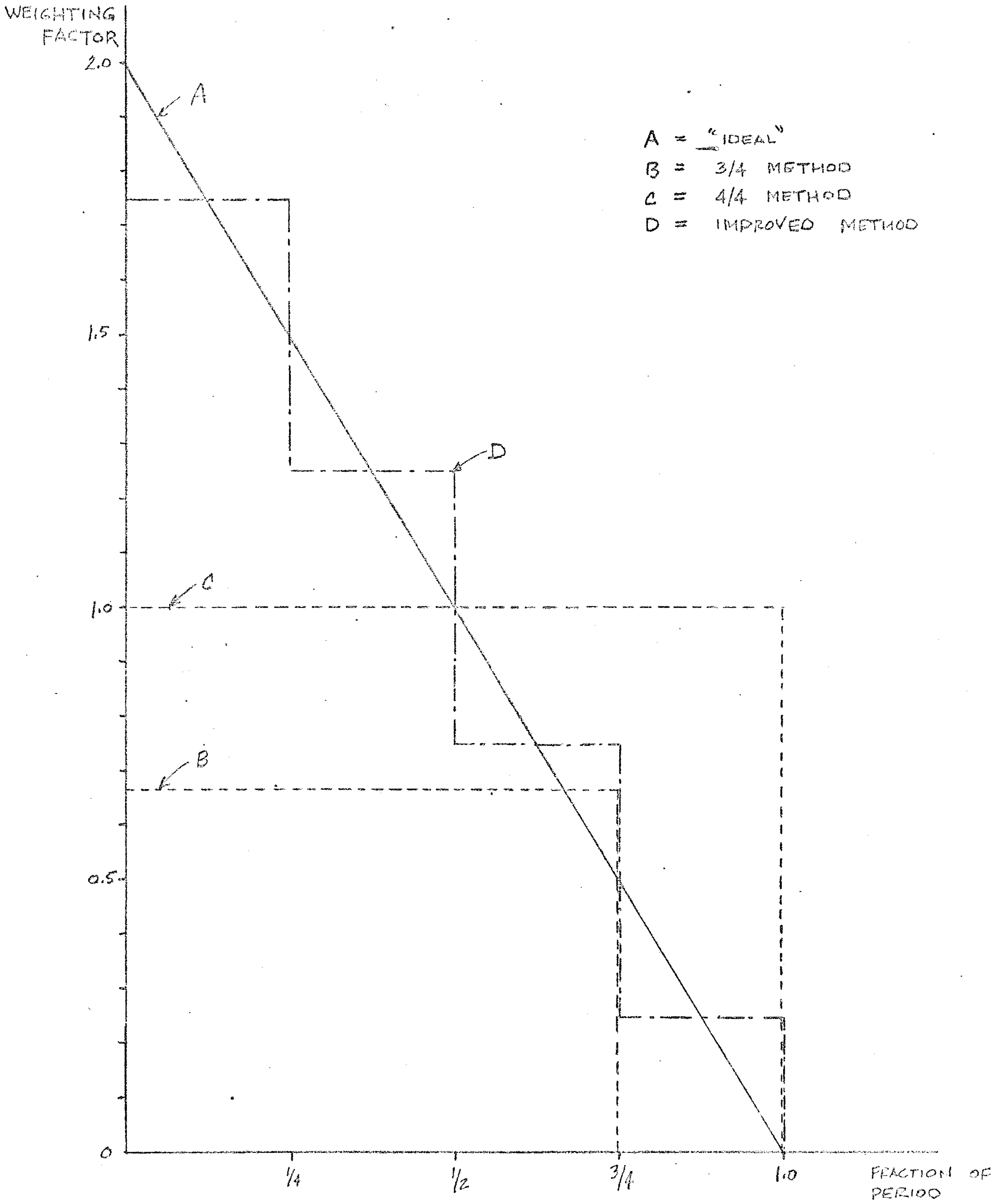
A_j = area under the curve of indicated average furnace temperature for the j-th quarter

A_{js} = area under the standard furnace curve for the j-th quarter

The quarters may either each be 1/4 of the indicated period; or the first, second, and third quarters may each be 1/4 of the desired rating period, with the fourth quarter consisting of the remaining portion of the indicated period.

Results of computer heat flow simulation

Run	Indicated time to rise 139°C (hr)	Temp. at one hour (°C)	Endurance difference, as % of indicated period	A_s (°C-hr)	A (°C-hr)	$A-A_s$ (°C-hr)
A	1.04	150	--	800	800	--
B	0.96	170	-8.3	726	799	+73
C	0.92	178	-13.1	691	757	+66
D	0.99	163	-5.0	752	837	+85
E	1.14	130	8.8	890	814	-76
F	1.15	123	9.6	900	834	-66
G	1.11	139	6.3	862	775	-87
H	0.98	163	-6.1	745	771	+26
J	0.97	166	-7.2	735	775	+40
K	0.99	161	-5.0	752	794	+42
L	1.028	152	-1.17	788	832	+44


WEIGHTING FACTOR
2.0
1.5
1.0
0.5
0
1/4
1/2
3/4
1.0
FRACTION OF PERIOD
A
B
C
D
A = "IDEAL"
B = 3/4 METHOD
C = 4/4 METHOD
D = IMPROVED METHOD

Calculation of endurance corrections according to proposed improved method

Run	$A_1-A_{1_s}$	$1.75(A_1-A_{1_s})$	$A_2-A_{2_s}$	$1.30(A_2-A_{2_s})$	$A_3-A_{3_s}$	$0.75(A_3-A_{3_s})$	$A_4-A_{4_s}$	$0.25(A_4-A_{4_s})$	$\sum_{1-4}$	$\frac{\sum_{1-4}}{A}$
A	--	--	--	--	--	--	--	--	--	--
B	13	22.6	20	25.0	21	15.8	21	5.2	68.6	0.086
C	26	45.4	40	50.0	--	--	--	--	95.4	0.126
D	--	--	--	--	42	31.4	44	11.0	42.4	0.050
E	-13	-22.6	-20	-25.0	-21	-15.8	-22	-5.6	-69.0	-0.084
F	-26	-45.4	-40	-50.0	--	--	--	--	-95.4	-0.114
G	--	--	--	--	-42	-31.4	-44	-11.0	-42.4	-0.054
H	26	45.4	--	--	--	--	--	--	45.4	0.058
J	--	--	40	50.0	--	--	--	--	50.0	0.064
K	--	--	--	--	42	31.4	--	--	31.4	0.040
L	--	--	--	--	--	--	44	11.0	11.0	0.0132

Comparison of correction methods

Run	Actual endurance error, %	Percent of indicated period to be added to obtain corrected period			Residual error, percent		
		3/4 method	4/4 method	Improved method	3/4 method	4/4 method	Improved method
A	--	--	--	--	--	--	--
B	-8.3	6.4	9.6	8.6	-1.9	1.6	0.3
C	-13.1	8.5	9.1	12.6	-4.6	-4.0	-0.5
D	-5.0	4.9	10.9	5.0	-0.1	5.9	.0
E	8.8	-6.3	-8.2	-8.4	2.5	0.6	0.4
F	9.6	-6.6	-7.1	-11.4	3.0	2.5	-1.8
G	6.3	-5.9	-12.6	-5.4	0.4	-6.3	0.9
H	-6.1	3.1	3.4	5.8	-3.0	-2.7	-0.3
J	-7.2	4.9	5.2	6.4	-2.3	-2.0	-0.8
K	-5.0	4.7	5.4	4.0	-0.3	0.4	-1.0
L	-1.17	0.32	5.4	1.32	-0.75	4.23	0.15
				Average residual error	1.89	3.02	0.62

APPENDIX

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PROBLEMS WITH NON-HOMOGENEOUS CONSTRUCTION

The sample calculations given above were premised on the supposition that the specimen is geometrically homogeneous and that thermal conductivity, density, and heat capacity are constants independent of temperature. This is the only case for which dimensionless quantities, such as the Fourier number, can be strictly applied and used to simplify calculations.

In practice, the thermophysical properties of even a single, homogeneous material are often significantly temperature-dependent. In addition, practical assemblies may utilize sandwich construction of several different materials, may contain void spaces (with or without convective currents, depending on the presence of insulation), and may use moist materials.

Conceptually, the first case does not present any difficulties. The wall can be divided into slices and the concept of a Fourier number applied within each. In the second case, within the void spaces heat is transferred by radiation and convection in addition to conduction. For any one specific geometry these effects could be represented by an equivalent fictitous conductivity, as a function of temperature. In the last case, there is a coupled problem of mass flow of the water that has to be solved along with the heat flow equations.

One main reason why fire testing has not been replaced by calculations is that while the principles involved in performing such calculations are mostly known, to compute precise--not just relative--numbers would require a knowledge of the thermophysical properties much more extensive than is available now. It would also be noticed that even in a plane wall there may be three-dimensional effects, such as fall-off or delamination. Finally, there are still some serious gaps in available theoretical models: in sandwich materials, contact resistance cannot be calculated; in cavity walls, convective currents cannot easily be estimated, especially if the cavities are not perfectly sealed; in moist walls, there is no suitable theory yet available for modeling moisture flows during fire exposure.

In view of these serious obstacles facing any rigorous calculation there has not been much interest in compiling even preliminary data for common materials and modes of construction that could be used for rough calculation.

To be able, nonetheless, to obtain some estimate for corrections in slightly less idealized walls, I chose to consider a simplified version of the moisture flow porblem. In this approach moisture is assumed not to migrate until a wall slice reaches 373 °K. Then that slice is held at that temperature until 540 cal/g have been added; whereupon, the moisture is considered to have all left along a plane perpendicular to the heat flow direction. That slice is now dry and heat flow proceeds normally.

The moist wall case was judged to be the best additional trial of the correction scheme since it represents the worst deviation from a constant Fourier number. Not only is C_p not a constant, but it has, in fact, a singularity. Thus in practice most non-combustible, non-melting assemblies should give results better behaved than this limiting case.

The properties of the wall chosen for analysis were--

thickness = 2.0 in.
density = 1900 kg/m^3
diffusivity = 0.002 m^2/hr.
emissivity = 0.30
water content = 15% by weight

Eleven computer runs were made modeling different exposure errors. The runs are labelled AW to LW and represent the same exposures as runs A to L for the dry walls.

The results indicate that the closest corrections are obtained from the improved method for moist walls also.

Finally I would like to again emphasize that no correction method can logically be applied to walls that contain an appreciable amount of combustible material. The behavior of combustible walls, especially multi-layered ones, is so complex that it would be imprudent to rely on the use of simple approximate rules, derived for non-combustible materials.

APPENDIX

RESULTS OF COMPUTER HEAT FLOW SIMULATION

RUN	INDICATED TIME TO RISE 139°C (hr.)	TEMPERATURE AT ONE HOUR (°C)	ENDURANCE DIFFERENCE, AS % OF INDICATED PERIOD	A_s (°C-hr.)	A (°C-hr.)	$A-A_s$ (°C-hr.)
AW	1.00	159	--	762	762	--
BW	0.91	281	-9.9	681	749	68
CW	0.86	283	-16.3	639	705	66
DW	0.92	279	-8.7	691	763	72
EW	1.13	100	11.5	880	804	-76
FW	1.14	100	12.3	890	804	-86
HW	0.94	223	-6.4	710	736	26
JW	0.93	236	-7.5	700	740	40
KW	0.93	244	-7.5	700	742	42
LW	0.98	207	-2.04	745	785	40

APPENDIX

CALCULATION OF ENDURANCE CORRECTIONS ACCORDING TO PROPOSED IMPROVED METHOD

RUN	$A_1-A_{1_s}$	$1.75(A_1-A_{1_s})$	$A_2-A_{2_s}$	$1.30(A_2-A_{2_s})$	$A_3-A_{3_s}$	$0.75(A_3-A_{3_s})$	$A_4-A_{4_s}$	$0.25(A_4-A_{4_s})$	Σ_{1-4}	$\frac{\Sigma_{1-4}}{A}$
AW	--	--	--	--	--	--	--	--	--	--
BW	13	22.6	20	25.0	21	15.8	14	3.5	66.9	0.089
CW	26	45.4	40	50.0	--	--	--	--	95.4	0.135
DW	--	--	--	--	42	31.4	30	7.5	38.9	0.051
EW	-13	-22.6	-20	-25.0	-21	-15.8	-22	-5.6	-69.0	-0.086
FW	-26	-45.4	-40	-50.0	--	--	--	--	-95.4	-0.119
GW	--	--	--	--	-42	-31.4	-44	-11.0	-42.4	-0.053
HW	26	45.4	--	--	--	--	--	--	45.4	0.062
JW	--	--	40	50.0	--	--	--	--	50.0	0.068
KW	--	--	--	--	42	31.4	--	--	31.4	0.042
LW	--	--	--	--	--	--	40	10.0	10.0	0.0127

APPENDIX

COMPARISON OF CORRECTION METHODS

ACTUAL ENDURANCE		PERCENT OF INDICATED PERIOD TO BE ADDED TO OBTAIN CORRECTED PERIOD			RESIDUAL ERROR, PERCENT		
RUN	Error,%	3/4 method	4/4 method	Improved method	3/4 method	4/4 method	Improved method
AW	--	--	--	--	--	--	--
BW	-9.9	6.3	9.6	8.9	-3.6	-0.3	-1.0
CW	-16.3	9.0	9.9	13.5	-7.3	-6.4	-2.8
DW	-8.7	4.1	10.0	5.1	-4.6	1.3	-3.6
EW	11.5	-6.4	-8.4	-8.6	5.1	3.1	2.9
FW	10.7	-6.7	-7.3	-11.9	4.0	3.4	-1.2
GW	12.3	-6.2	-9.3	-5.3	6.1	3.0	7.0
HW	-6.4	3.2	3.5	6.2	-3.2	-2.9	-0.2
JW	-7.5	4.9	5.5	6.8	-2.6	-2.0	-0.7
KW	-7.5	3.9	5.8	4.2	-3.6	-1.7	-3.3
LW	-2.04	0.0	5.2	1.27	-2.04	3.16	-0.77
		AVERAGE RESIDUAL ERROR, Runs AW-LW			4.21	2.73	2.35
		AVERAGE RESIDUAL ERROR, Runs A-L			1.89	3.02	0.62
		COMBINED AVERAGE			3.05	2.88	1.49